CATAPULT
Offshore Renewable Energy

SEABED MOBILITY GUIDANCE

BEST PRACTICE RECOMMENDATIONS FOR OFFSHORE INSTALLATIONS

AUGUST 2026

ORE.CATAPULT.ORG.UK

bp ESB nationalgrid Ørsted RWE ScottishPower Renewables sse Renewables VATTENFALL

PROJECT FUNDERS

This document represents the output of a Joint Industry Project to develop Seabed Mobility Guidance funded by bp, ESB, National Grid, Ørsted, RWE, ScottishPower Renewables, SSE Renewables, and Vattenfall.

ACKNOWLEDGEMENTS

The development of the Seabed Mobility Guidance has been managed by Malcolm Stirling, ORE Catapult.

Technical direction, valued support and feedback has been provided by the project's Technical Advisory Group comprising members from each funding body. This group met quarterly to review progress and discuss forthcoming stages for developing the guidance.

The guidance and supporting appendices have been prepared by:

- Bill Cooper, Cooper Marine Advisors
- Kevin Black, Venterra (Partrac)

With additional contributions from the following lead contributors and organisations:

- Claire Hinton, GoBe
- Craig Jones, Integral
- Dafydd Lloyd-Jones, MarineSpace
- Tony Brooks, ABPmer
- Gustav Pettersson, Hydrofix
- Jack Poleykett, Xodus
- Jamie Irvine, Kent
- Richard Whitehouse, HR Wallingford
- Tom Roetert, Deltares
- Indrasenen Thusyanthan, Saudi Aramco
- Geoff Harrison, 4DGeo

The guidance has also been subject to detailed reviews from:

- Charlotte Strang-Moran, ORE Catapult
- Ralph Manchester, ORE Catapult
- Ana Plana Casado, Ørsted

Citation:
ORE Catapult (2026). Seabed Mobility Guidance. Best Practice Recommendations for Offshore Installations.

EXECUTIVE SUMMARY

Industry guidance is provided to support the assessment of seabed mobility for projects planning to install assets on or under the seabed where knowledge is required of expected changes in the seabed profile over the lifetime of a project. Without such knowledge, projects may face an increased risk of assets being more vulnerable to damage or failure. For example, cables are often buried under the seabed for protection against damage from external threats, such as anchors, however, in areas susceptible to a high level of seabed mobility, the probability of buried cables becoming exposed over their operating period is increased.

Application of this guidance aims to improve project awareness of areas with a mobile seabed and the ability to predict future seabed levels, with this knowledge informing requirements for cable burial or provisions to protect other assets which may be vulnerable to a change in the seabed profile. Projects are recommended to consider the potential risks associated with a mobile seabed from the outset of project development and engage in a process to develop improved understanding and reduce uncertainty.

A framework for delivering an assessment of seabed mobility is provided which recommends a two-stage approach.

- An initial seabed mobility assessment where existing data and information establishes a Conceptual Site Model (CSM), maps the degree of seabed mobility across areas of interest, identifies data gaps to target with subsequent surveys (as relevant), and contributes to the project's risk register. The initial seabed mobility assessment should be undertaken as early as possible during project development. At this time, the assessment is likely to be high-level, mainly qualitative and should clearly identify associated levels of uncertainty.
- A detailed seabed mobility assessment which should aim to reduce levels of uncertainty from the initial seabed mobility assessment by applying new survey data and relevant analytical methods. The outcomes from the detailed assessment should refine the CSM and seabed mobility maps, develop predictions of future seabed levels and review relevant projects risks and associated mitigation. Recommendations should also be made for onward monitoring of seabed levels during the operational phase.

In some cases, the initial seabed mobility assessment may be sufficient to confirm that an area is not subjected to a level of seabed mobility which places assets at risk and a subsequent detailed assessment is not required. Importantly, this assertion should be associated with an appropriate low level of uncertainty.

For the detailed seabed mobility assessment, the prediction of future seabed levels should be delivered within a probabilistic framework which bounds a best estimate within upper and lower estimates based on associated residual uncertainties. During the operational cycle, onward seabed monitoring should provide a basis to review and refine the prediction of future seabed levels.

Notably, this guidance aims to fulfil the link with other guidance, recommend practice and design standards which call for an assessment of seabed mobility.

CONTENTS

GLOSSARY OF TERMS

BEDFORMS	Typically, rhythmic features formed on a sandy seabed which are subject to regular bedload transport. The following table summarises the bedform types identified in this guidance (see Appendix D for additional details).

BEDFORM TYPE	RELATIVE SCALE	TYPICAL WAVELENGTH (m)	TYPICAL CREST HEIGHT (m)
Ripples	Micro	0.1 to 1	0.01 to 0.1
Megaripples	Micro	1 to 30	0.1 to 1
Sandwaves	Meso	30 to 700	1 to 5
Sandbanks	Macro	Up to 15,000	5 to 15

BED SHEAR STRESS	The frictional drag at the seabed due to moving flow (units N/m^2).
BEHAVIOUR ZONES	Sub-divisions of the development area which can be regarded to behave in a similar way within a zone but differently between zones, due to difference in seabed characteristics, metocean conditions, etc.
BEST AVAILABLE	Dataset or information that is regarded as good quality, representative of site conditions, and sufficiently detailed in comparison to alternatives. This should be the primary dataset being considered until a better alternative becomes available.
DATA REGISTER	A data register is a structured document or system used to record, track, and manage critical information throughout a project's life cycle. The data register serves as a central repository for specific data sets that need regular updates and reviews.
DEPTH OF LOWERING	Vertical distance between the top of a buried cable or pipeline and the adjacent undisturbed (mean) seabed level for around a 5 m distance either side of the asset, as established by a post-lay trenching survey.
DESIGN SEABED LEVELS	Typically defined as the Lowest Seabed Level (LSBL) and Highest Seabed Level (HSBL) over the design life.
EDGE SCOUR	Secondary scour around the perimeter of scour protection, especially where there is an abrupt change in seabed roughness and/or profile causing increased turbulence.
HIGH-RESOLUTION	Data with a sufficient interval that captures important details for the intended application. The interval may be spatial or temporal.
LIQUEFACTION	A process whereby the soil strength of unconsolidated sediment is compromised by intense vibration (cyclic loading) which can fluidises the seabed, lead to high rates of sediment transport, and rapid lowering of seabed levels.
LOCAL SCOUR	Local scour can develop around an obstacle where the seabed is susceptible to erosion from local flow accelerations and increased turbulence developed by the presence of the obstacle.
LOW-RESOLUTION	Data with an interval which may omit some important details for the intended application. The interval may be spatial or temporal.
GLOBAL SCOUR	The combined scour effect around multiple piles grouped closely together, e.g., jacket type foundations. Also referred to as pile group scour or dishpan scour.
RISK REGISTER	A risk register is a centralised document or tool that helps project managers to systematically identify, assess, and monitor risks throughout the project lifecycle.
SEABED MOBILITY	Changes in seabed level that are not attributable to the presence of a structure or obstacle (i.e., leading to general seabed scour as opposed to local or global scour).
SPUDCAN	An inverted cone, or other shaped footing, on the base of a jack-up vessel's legs used to displace weight across the seabed.
SURFICIAL SEDIMENTS	The layer of sediments that are on the surface of the seabed and in contact with seawater. These sediments typically represent the top 0.1 m and can be sampled by a mechanical grab.

ABBREVIATIONS AND ACRONYMS

ALARP	As Low As Reasonably Practicable
AGDS	Acoustic Ground Discrimination System
ASBL	Actual Seabed Level
BGS	British Geological Survey
CBRA	Cable Burial Risk Assessment
CFE	Controlled Flow Excavator
CSIP	Cable Specification and Installation Plan. On occasion, the CSIP may also be referred to as the Cable Plan (CaP).
CSM	Conceptual Site Model
EIA	Environmental Impact Assessment (also commonly referred to as Environmental Assessment (EA) of Environmental and Social Impact Assessment (ESIA).
ENVID	ENVironmental Impact IDentification
EPCI	Engineering, Procurement, Construction, and Installation
FEED	Front-End Engineering Design
GBS	Gravity Base Structure
GEBCO	General Bathymetric Chart of the Oceans
HDD	Horizontal Directional Drilling
HSBL	Highest Seabed Level
IEC	International Electrotechnical Commission
IHO	International Hydrographic Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standards
JIP HaSPRO	Joint Industry Project Handbook Scour and Cable Protection Methods
JNCC	Joint Nature Conservation Committee
LIDAR	Light Detection and Ranging
LSBL	Lowest Seabed Level
MBES	Multibeam Echosounder
MFE	Mass Flow Excavator
MSBL	Maximum Seabed Level
NMRL	Non-Mobile Reference Level
O&M	Operational & Maintenance
PDE	Project Design Envelope
PRE-FEED	Pre-Front End Engineering Design
RSBL	Reference Seabed Level
SAC	Special Area of Conservation
SMI	Sediment Mobility Index
THU	Total Horizontal Uncertainty
TVU	Total Vertical Uncertainty
TSHD	Trailing Suction Hopper Dredger
UXO	Unexploded Ordnance
WTG	Wind Turbine Generator

1 INTRODUCTION

1.1 PURPOSE OF THE GUIDANCE

This document serves as a guide for practitioners and developers to support the assessment of seabed mobility where a change in seabed level might pose a risk to the successful development and operation of an offshore project at any location worldwide. These types of projects include, but are not limited to, offshore windfarms, marine renewable energy developments, outfalls, intakes, cables, and pipelines, amongst others.

The guidance is not intended to be prescriptive, rather the main purpose is to bring greater attention to the subject of seabed mobility so that practitioners and developers gain better awareness of the issues which might affect project development and the means to investigate them.

In many cases, the guidance uses offshore windfarms as an example project type to illustrate seabed mobility issues that might be relevant through different stages of project development; however, this is not intended to be exclusive in any respect.

1.2 RELATED ISSUES FALLING OUTSIDE OF THE GUIDANCE

The following issues are not directly covered by the present guidance:

- Issues associated with mechanical disturbance of the seabed (e.g., drilling, dredging, trenching, etc.).
- Local scouring due to the presence of structures placed on the seabed (e.g., around the base of fixed foundations, at cable crossings, cable protection, or anchors for floating foundations, etc.).
- Geotechnical instability, such as slope failure.

1 INTRODUCTION

CONTINUED

1.3 STRUCTURE OF THE GUIDANCE

The guidance is presented with the following structure:

- Section 2 – provides an overview of seabed mobility issues which might affect an offshore project.
- Section 3 – outlines the framework for delivering an assessment of seabed mobility.
- Section 4 – highlights the importance of seabed mobility at each stage of project development from Site Selection through to decommissioning.
- Section 5 – lists the key reference material for the guidance.

In addition, the following technical appendices are provided to offer additional detail for cross-cutting themes applicable to multiple stages of project development:

- Appendix A: Risk Register – to highlight that seabed mobility should be a consideration of the project risk register.
- Appendix B: Data Management – emphasizes the importance to the assessment of seabed mobility.
- Appendix C: Bathymetry – offers relevant insights into collection of bathymetric data by various methods.
- Appendix D: Bedforms – identifies different types and scales of bedform features and their relevance to seabed mobility issues.
- Appendix E: Sediment Data – considers the different types of sediment data applicable to seabed mobility and sediment transport calculations.
- Appendix F: Metocean Data – reviews key metocean data types, approaches to data collection, and potential applications.
- Appendix G: Analytical Approaches – reviews pertinent approaches to investigating seabed mobility and predicting future seabed levels.
- Appendix H: Case Studies – summarises a range of seabed mobility issues affecting project development.
- Appendix I: Seabed Liquefaction – outlines approach to sediment stability assessment in seismically active regions and under cyclic loading.

2 OVERVIEW OF SEABED MOBILITY

Seabed mobility has the potential to occur on beaches, in the nearshore, and offshore, wherever there are surficial sediments which can respond to local metocean conditions. The response may be progressive due to regular tidally driven conditions or more intense during infrequent energetic storms which may develop less predictable changes.

The outcome from a period of seabed mobility may lead to a local increase, decrease or zero net change in the level of the seabed, with the frequency of occurrence, rate, magnitude, and direction of change depending on many factors, including sediment type, water depth, flow magnitude, and wave conditions. In some cases, the thickness of the mobile layer of surficial sediments can also provide a limiting condition to a reduction in seabed levels.

Apart from responding to hydrodynamic forces, there may also be other situations that develop seabed mobility such as slope failure and earthquakes developing liquefaction, although the occurrence and outcomes from these types of situations are likely to be far less predictable.

Notably, not all scales of seabed mobility present a risk to project development, and not all seabed areas are mobile (e.g., areas with a rocky seabed or consolidated sediments, or areas where metocean conditions remain too weak to mobilise surficial sediments).

2.1 RELEVANCE OF SEABED MOBILITY ISSUES TO PROJECT DEVELOPMENT

For this guidance, seabed mobility is taken to be a change in seabed level that may lead to a cost, health and safety, logistical, environmental, or liability implication which could negatively affect project development. Collectively, these consequences are considered as project risks which should be identified in the project-wide risk register, along with suitable mitigation options. Appendix A provides an example structure for a risk register.

Examples of project risks might include, amongst others:

- A construction activity which has the potential to develop an environmental impact on a nature conservation feature, such as a designated sandbank, which requires some form of design mitigation (Consent risk).
- A potential change to engineering requirements that might occur if seabed mobility is not considered from the outset of project development, potentially leading to increased costs and project delays (Detailed Design risk).
- Infilling of temporary excavated pits or trenches occurring more rapidly than anticipated, disrupting consequential construction works (Construction risk).
- Potential reduction of cable burial depths through lowering of the seabed, increasing the risk of cables being dragged by anchors, trawling gear, etc. (Maintenance risk).
- Potential increase of cable burial depth through raising seabed levels, increasing the risk of cable damage due to a reduction in efficiency of heat dissipation (Maintenance risk).

- Potential increase of cable burial depth making recovery problematic for repair (Maintenance risk) or removal (Decommissioning risk).
- General lowering of the seabed in the vicinity of scour protection around foundations or rock armour protection across cables and at cable crossings, destabilising the protection material and reducing performance (Maintenance risk).
- Raising of seabed levels that impedes access to structures located in shallow areas (Construction, Operational, and Decommissioning risk).
- Strong rates of seabed mobility increasing the risk of exposing previously buried unexploded ordnance (UXO), or through the movement of nearby contacts towards assets (Construction, Operational, and Decommissioning risk).
- Archaeological artifacts (including unchartered wrecks) being hidden during initial surveys, but appearing later, whether that is before, during, or after construction (Consent, Construction, and Operational risk).
- Cable exposure in the nearshore, or within a protected area, where remedial cable protection measures (e.g., rock berms) are required which may lead to a detrimental impact on an environmental receptor, such as adjacent coastline or benthic community (Maintenance risk).
- Rapid loss of seabed integrity and level due to liquefaction, affecting assets that rely on a stable seabed (Operational risk).
- Long-term risk of exposure of decommissioned assets left in situ with limited ongoing monitoring (e.g., foundation piles cut-off below the seabed or buried cables).

2.2 TYPICAL PROJECT REQUIREMENTS FOR A SEABED MOBILITY ASSESSMENT

Over the project development cycle, the assessment of seabed mobility should aim to increase knowledge and reduce uncertainty in the following types of information, in particular:

- Identification of areas where seabed levels are highly variable (i.e., high potential risks to assets in this region).
- Identification of area where the seabed appears stable or immobile (i.e., low potential risks to assets in this region).
- The conditions which lead to periods of seabed mobility and their frequency of occurrence.
- Quantification of the rate and magnitude of change in seabed levels that might be expected over the lifetime of the development, noting these changes may be progressive (or periodic), intermittent (or episodic), cyclical, or reversing.
- Predicted future seabed levels (for areas identified with a highly mobile seabed) expressed within a frame of uncertainty (i.e., upper and lower confidence limits). Typically, predictions would be produced at annual increments to span the pre-construction period through to decommissioning.
- Recommendations for onward monitoring to improve system understanding and accuracy of future seabed level predictions (e.g., location(s) and frequency of surveys, etc.).

3.1 RECOMMENDED PRACTICE

The following represents recommended practice for delivery of an assessment of seabed mobility:

- Consider the topic of seabed mobility at the earliest opportunity and ideally from the outset of project development.
- Establish an overall delivery plan (i.e., Seabed Mobility Delivery Plan) for assessing seabed mobility which recognises the potential different information requirements to support each stage of project development.
- Identify limitations in data and information and address on a timely basis so that a subsequent stage of project development can draw on an improved level of understanding.
- Develop and maintain a Conceptual Site Model (CSM) as a statement of process understanding relevant to an assessment of seabed mobility and to help steer supporting data acquisition and analysis.
- Continually validate and maintain predictions of future seabed levels over the operational & maintenance (O&M) period where asset monitoring provides suitable onward observations of seabed levels.
- Provide a transparent record of each stage of assessment, recognising key information may be subject to part of project certification.
- Ensure data management maintains an accessible copy and archive of key information.

3.2 KEY STAGES IN DELIVERING A SEABED MOBILITY ASSESSMENT

The delivery of a seabed mobility assessment should aim to increase knowledge and reduce uncertainty in the subject over the course of project development, with necessary information being available at appropriate times to support relevant project decisions.

Figure 1 provides a flowchart showing key steps and links in the delivery of a typical assessment of seabed mobility, with the associated inputs, process steps and outputs discussed below.

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY

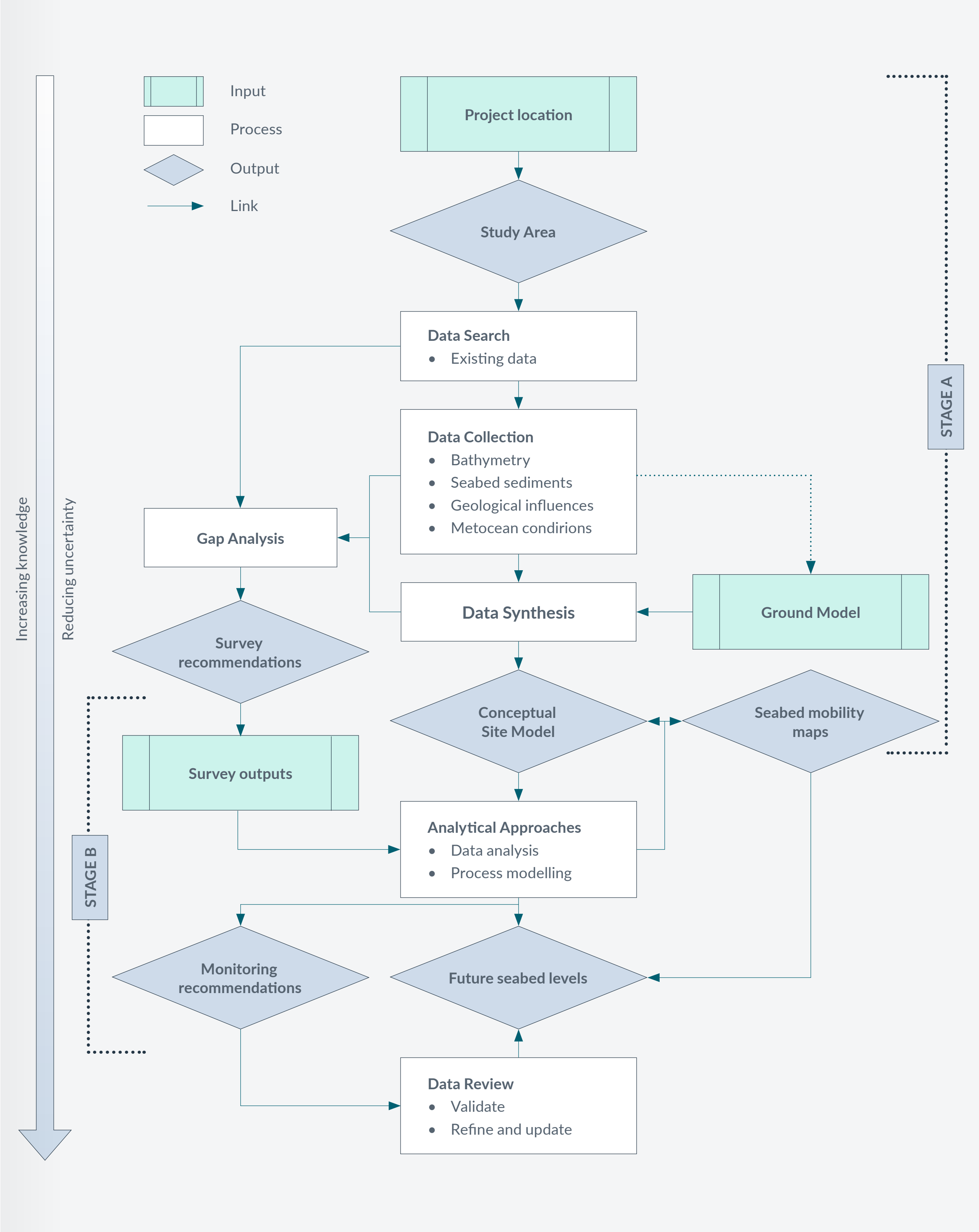


Figure 1 – Flowchart for delivering an assessment of seabed mobility

As shown, the assessment can be grouped into two stages, A and B, which are explained below.

3.2.1 STAGE A – INITIAL SEABED MOBILITY ASSESSMENT

The initial seabed mobility assessment represents the first iteration of the flowchart to the stage of developing the preliminary CSM and seabed mobility maps. The assessment will be facilitated by data available at this time which is expected to result in a largely qualitative and high-level review.

There may be different outcomes and recommendations from the initial seabed mobility assessment depending on the situation being reviewed. A range of example outcomes are summarised in **Table 1**.

Recommendations may vary from deciding no further assessments are required (e.g., Outcome 1 due to a site which is expected to experience a low level of seabed mobility which is unlikely to represent a hazard to buried assets) to a site where a detailed seabed mobility is required to predict future seabed levels throughout an area of interest (e.g., Outcome 7). There may also cases (e.g., Outcome 4) where the initial seabed mobility assessment identifies the potential for medium / high seabed mobility due to a dominantly chaotic system which may limit the capacity to make reliable predictions of future seabed mobility without undue high levels of conservatism. If development were to continue in such areas, then associated O&M issues may be relatively complex and expensive. Avoidance of such areas may be a better outcome than continuing to develop this part of the site.

Table 1 – Example outcomes from an initial seabed mobility assessment

OUTCOME	PRELIMINARY CSM*	SEABED MOBILITY MAPS	UNCERTAINTY	MAIN RECOMMENDATIONS
1	well-understood	overall low mobility	low	no further assessment required beyond the initial assessment
2	partially understood	overall low mobility	medium / high	further assessment recommended to reduce uncertainties / improve CSM to validate initial assertions
3	partially understood / periodic system	some sites with medium mobility	medium / high	further assessment recommended to address uncertainties / improve CSM to validate initial assertions / quantify future seabed levels, as required
4	partially understood / chaotic system	some sites with high mobility	medium / high	further assessment recommended to address uncertainties / clarify areas with high mobility / predictions of future seabed levels in a chaotic system may not be possible with sufficient reliability
5	poorly understood	levels of mobility unclear / unknown	high	further assessment recommended to address uncertainties / improve CSM / quantify future seabed levels, as required
6	well-understood	some sites identified with high mobility	low / medium	undertake detailed assessment to quantify future seabed levels for relevant locations, reduce uncertainties
7	well-understood	overall high mobility	low	undertake detailed assessment to quantify future seabed levels

* See Section 3.2.12 for explanation of levels of Preliminary CSM

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY

CONTINUED

3.2.2 STAGE B – DETAILED SEABED MOBILITY ASSESSMENT

A detailed seabed mobility assessment should be developed according to the recommendations from the initial seabed mobility assessment. Where surveys form part of these recommendations then early completion is recommended so information is available on a timely basis to inform the subsequent detailed seabed mobility assessment.

Typically, a detailed seabed mobility assessment will undertake relevant analytical approaches, leading to improved seabed mobility maps, an updated CSM and predictions of future seabed levels. The outcomes are expected to provide a largely quantitative and more detailed review in comparison to the initial seabed mobility assessment. The detailed seabed mobility assessment may also be subject to refinement and updating as new information becomes available through the construction and O&M phases.

3.2.3 PROJECT LOCATION

The project location is a key input to help establish the extents of a seabed mobility assessment.

For a typical offshore windfarm, the project location is expected to extend from the offshore array area, along the export cable corridor option(s), and to the landfall option(s) at the coastline. The boundaries of the project location are likely to be defined by a lease area with exclusive development rights.

3.2.4 STUDY AREA

The study area (or area of interest) should be established with consideration of the boundaries of the project location, as well as adjacent areas where there are identifiable relationships to updrift and downdrift sedimentary seabed features (e.g., sandwaves).

The study area should be kept under review and refined as the project location is updated and process understanding improves.

3.2.5 DATA SEARCH

An initial activity to support the assessment of seabed mobility should be a data search to help confirm present understanding and data availability for the study area.

Data types of primary interest include:

- **Bathymetry and beach levels** – contemporary and historic.
- **Surficial sediments** – ideally with particle size distributions.
- **Metocean conditions** – observations and modelled data of waves, water levels and flow outputs.
- **Geological influences** – typically limited to surface and near-surface geology.

Data Discovery Portals (e.g., SeaDataNet for in situ observations and Copernicus Marine Data Store for modelled and satellite data) and national Data Archive Centres (DAC) should be consulted for relevant data types.

In addition, other complementary details can also usefully support the assessment of seabed mobility, such as:

- Local knowledge.
- Satellite and aerial imagery where there is clear visibility of features, such as sandbanks and beaches.
- Description of shoreline change at landfall areas. A useful resource for an initial appraisal of shoreline change is ShorelineMonitor Viewer which provides global coverage of long-term shoreline changes over the period 1984 to 2024 (Luijendijk, et al., (2018)).
- Earthquake risk, for an indicator for liquefaction in areas of unconsolidated sediment, as relevant. A useful resource for an initial appraisal of earthquake risk is Interactive Earthquake Browser which provides global coverage of earthquake occurrences from 1970 to the present day (credit: EarthScope Consortium).

- Information from other projects and activities relevant to the project development area, e.g., licensed dredging and disposal activities.

A literature search should also be undertaken at this time to identify relevant studies in the area of interest.

3.2.6 DATA COLLATION

The data identified from a data search needs to be collated so that the best available information helps support baseline understanding across the area of interest.

The criteria for best available information should include a consideration of the following issues:

- Most up to date.
- Highest resolution (spatial and data precision).
- Best quality (lowest level of uncertainty).
- Availability of meta-data and reporting describing the data.

The likelihood is that a combination of best available information from multiple sources is still required to fully cover the area of interest. Accordingly, the data collation process may also need to include a normalisation step so different datasets of the same type can be brought together by adopting a standard convention, for example:

- **Bathymetry data** – conversion to the same units of depth and to a consistent horizontal and vertical datum. This step is especially important when merging land-based observations with marine observations.
- **Sediment data** – conversion to a consistent sediment classification scheme (e.g., Folk (1954)).
- **Metocean data** – adoption of consistent nomenclature for metocean parameters (e.g., definition of significant wave height, etc.).

Collated bathymetry and sediment data are both relevant to the development of seabed mobility maps (Section 3.2.13), with the collated bathymetry also providing an important input to any marine process modelling of the area of interest. Furthermore, the collated bathymetry and sediment data also remain relevant to the development of the Ground Model (Section 3.2.10).

The collated data which is deemed useful to support an assessment of seabed mobility should be logged in a data register. Appendix B provides a more expansive discussion of the importance of data management.

The potential also remains that not all the identified information is needed to complete an initial seabed mobility assessment. Some data may be more applicable to support more detailed studies required at a subsequent stage of project development (e.g., when design requirements are better established).

3.2.7 GAP ANALYSIS

Existing data and information are expected to be sufficient to support an initial assessment of seabed mobility, providing a high-level and largely qualitative overview of key issues suitable to support initial stages of project development, such as Site Selection and Route Selection (e.g., for pipelines and cables). However, the same information may not be adequate for subsequent stages of development.

A gap analysis is the recommended approach to identify shortfalls in existing data and information in terms of addressing a stated set of requirements and to help determine the scope for additional data collection (e.g., via survey recommendations), in so far as these recommendations remain practical and achievable and subsequent surveys can be delivered in a timely manner. Stated requirements should consider those related to achieving a detailed seabed mobility study as well as any additional requirements specific to supporting project consent.

Shortfalls may relate to the absence of data in relevant locations or the existing data being of too low quality to support a subsequent stage of project development. An appreciation of the intended downstream applications of completed datasets (e.g., to support marine process modelling, etc.) is helpful at this time to determine the relevance of any data gaps.

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY
CONTINUED

3.2.8 SURVEY RECOMMENDATIONS

Outcomes from the gap analysis should include survey recommendations which address identified shortfalls in presently available data and information and deliver outputs in a timely manner to support subsequent stages of project development.

Recommendations should be directed towards planned surveys rather than being considered as a separate set of surveys.

Typical project surveys include metocean, geophysical and geotechnical data collection. Benthic surveys may also be relevant where these provide for additional surficial sediment sampling, and associated particle size analysis, to fill identified data gaps. Those involved in the delivery of the seabed mobility assessment should provide their recommendations into the planning of these surveys.

Typical recommendations might include, amongst others:

Bathymetry survey:

- Resolution – requirement for high-resolution multi-beam bathymetry to enable an improved description of relevant bedform features.
- Coverage – 100% coverage[1], especially for areas (or sub-areas) expected to encounter a high likelihood of seabed mobility and where present gaps exist. For sites where there are mobile bedforms with the potential to migrate towards the development area, then consideration should also be made to extending the survey coverage in such directions to cater for future seabed level estimates. Surveys not planning for full coverage may only be advisable where mobile bedforms are not present or where the likelihood for seabed mobility is considered “Low” (i.e., the seabed profile is generally stable), and any subsequent data interpolations to fill gaps remain valid. In case only surveys with partial coverage are considered, the survey recommendations should aim to highlight the impact on the expected prediction uncertainty of future seabed levels, allowing the developer to weigh the cost/benefit ratio of the survey.
- Intertidal surveys for landfall areas – e.g., location and extent of beach profiles, LiDAR coverage, etc.
- Considerations for onward monitoring requirements.
- Appendix C provides additional insights into the collection and uses of bathymetry data.
- Appendix D provides additional insights related to bedforms.

Geophysical surveys:

- Mapping of seabed features.
- Determination of sediment types (e.g., ground-truthed interpretation from an Acoustic Ground Discrimination System (AGDS).
- Sub-bottom profiling to help deduce depth of mobile layer.
- Appendix E provides additional insights into the collection and uses of geophysical data.

Grab sampling of surficial sediments:

- Required to train AGDS.
- Locations for sampling of surficial sediments to improve initial seabed mobility maps.
- Method of sample analysis to confirm detailed grain size distribution, ideally resolved at 0.5 phi intervals.
- Appendix E provides additional insights into the collection and uses of sediment grabs.

Geotechnical surveys (typically undertaken post-consent):

- Location of cores and analysis of sub-soils to help confirm shallow geophysical horizons.

1. Special attention may be required to address a potential spatial gap (also commonly referred to as “the white ribbon”) in the nearshore between beach surveys and marine surveys where vessel draught or surf conditions present a restriction on conventional surveys.

Metocean survey:

- Suitable locations for deployment of metocean devices.
- Key metocean parameters – waves, water levels, and flows. In addition, temperature, salinity, and suspended sediment concentration can also be important.
- Duration and frequency of observations.
- Associated requirements for a calibrating a metocean hindcast model.
- Appendix F provides additional insights into the collection and uses of metocean data.

3.2.9 SURVEY OUTPUTS

Survey outputs should enable subsequent stages of work and are likely to be a primary input required to support the detailed seabed mobility study. The survey outputs should be applied to address data gaps, increase knowledge and reduce uncertainties in the subject.

3.2.10 GROUND MODEL

A Ground Model is a 3-D database of ground conditions compiled from available geophysical and geotechnical data. The Ground Model provides a central reference for the project development area, describing structural geology from the seabed to the pile depth of foundation options. A useful summary of a Ground Model development is provided in Dimmock, et al. (2025).

The development and refinement of a Ground Model is likely to advance in parallel with the assessment of seabed mobility, making use of several common datasets and project surveys. Accordingly, a consistent understanding of seabed sedimentology and shallow geological conditions should be maintained between the two activities.

The likelihood is that the seabed mobility assessment will develop the most detailed understanding of seabed conditions and variability, whereas the Ground Model will develop the most detailed understanding of shallow geological conditions, such as the depth of unconsolidated layers of surficial sediment (e.g., Holocene layer / depth of mobile layer) and associated sub-surface geological controls (i.e., non-erodible layers / depth to rockhead).

3.2.11 DATA SYNTHESIS

Data synthesis is the process of developing an overall understanding derived from an interpretation of complementary data themes, including available literature. For example, combining knowledge of surficial sediments with local metocean conditions helps identify the level of seabed mobility through an evaluation of exceedance of critical shear stress (refer to Appendix G: Analytical Methods). Other examples include establishing asymmetry in metocean conditions and comparing with asymmetry in bedform profiles to help deduce the direction of net sediment (sand) transport.

Key outputs from data synthesis are the CSM and Seabed Mobility Maps.

3.2.12 CONCEPTUAL SITE MODEL

A key output from data synthesis (Section 3.2.11) is the development of a Conceptual Site Model (CSM) (also commonly referred to as System Understanding, or a Conceptual Model) which serves to establish and explain the baseline process understanding influencing seabed mobility across the study area. For the initial seabed mobility assessment (Stage A), the CSM should be considered preliminary and subject to further revision during Stage B, as necessary.

For large development areas exhibiting different characteristics, the CSM can be usefully structured and mapped into discrete behaviour zones. These behaviour zones are sub-divisions of the area of interest which can be regarded to behave in a similar way within a zone but differently between zones. For example, a nearshore shallow water zone would expect to behave differently to an offshore zone.

The Preliminary CSM may achieve different levels of understanding depending on the information available at the time, such as:

- **Poorly-understood** – CSM framework not clearly established due to paucity or low-quality data.
- **Partially understood** – CSM framework is established but with some contradictory evidence.
- **Well-understood** – CSM framework is fully established with clear supporting evidence.

The preliminary CSM (Stage A) should develop a range of working hypotheses of process understanding based on the interpretation of existing information. At this stage, these hypotheses are expected to be largely qualitative and/or semi quantitative. Recommendations should be made to validate these hypotheses with relevant analytical approaches (Section 3.2.14) and survey methods (Section 3.2.8), with the objective of developing a well-understood CSM (Stage B) which validates hypotheses, adds more detailed quantification of seabed mobility issues, improves understanding, and reduces uncertainties, etc.

Examples of seabed mobility issues that should be considered by the CSM (and seabed mobility maps) include, as relevant:

Geological controls:

- Features which are expected to influence the contemporary development of the coastline and seabed, e.g., cliffs and shore platforms, headlands, glacial tunnel valleys, etc.
- The presence of shallow bedrock, or more erosion resistant sub-layers, may provide a limiting condition to the depth of the mobile layer (see Section 3.2.10 – Ground Model).

Bathymetry:

- Review available data to help identify general seabed profile and presence of macro bedforms (e.g., sandwave asymmetry, sandbank typology, etc.) as potential indicators of seabed mobility, in so far as data allows. In addition, stationary seabed obstacles (e.g., wrecks, large boulders, submerged rock outcrops, etc.), where present, may usefully identify patterns of local scouring and net sediment migration, etc.
- Review temporal variation between spatially overlapping surveys representing different dates to help identify observed rates of change. For macro-scale bedforms, migration is typically demonstrated by changes in the horizontal due to migration of crestlines, with general changes in seabed levels demonstrated in the vertical, i.e., lowering or raising of the seabed. Appendix C provides additional insights to the application of bathymetry data.
- Water depth is a primary influence on whether the sediment transport regime is current-dominated or wave-dominated and can therefore be used to inform on different behavioural zones. For example, bedform migration driven by tidal currents in deeper water versus wave-driven processes dominating in shallow waters and along the shoreline.

Surficial sediments:

- The distribution of seabed sediment types for the study area should be determined, including landfall(s). Sandy areas are likely to be more mobile than gravelly areas for similar water depths and metocean conditions. Open sandy shorelines exposed to waves are likely to be more mobile than beaches in sheltered bays with a similar sediment type. Muddy areas may be less mobile than sandy areas for similar metocean conditions. Muddy areas may also indicate a location favouring the deposition of fine sediment which may have become consolidated over time.

Metocean conditions

- Wave and tidal conditions (individually or in combination) are the main drivers for sediment transport for locations where the seabed can respond to the applied bed shear stress.
- Metocean data should be reviewed to identify the relevance of typical conditions (e.g., periodic, seasonal) and episodic events (e.g., storms) to seabed mobility should. At this juncture, the preferred source of information may be a metocean hindcast model providing data over a sufficiently long period and calibrated from the metocean surveys.
- Areas characterised by highly energetic metocean conditions are more likely to experience more frequent and stronger periods of seabed mobility compared to lower energetic areas with an equivalent seabed type.
- Nearshore seabed mobility is expected to be highest during storm events with net transport aligning with prevailing conditions.

Sediment pathways

- Deduce pathways for net sediment transport based on the interpretation of available evidence, such as bedform asymmetry, historical trends, tidal asymmetry, prevailing wave direction, sediment transport modelling, and sediment trends analysis, etc.

Sources and sinks

- Identify sources and sinks (stores) of sediments influencing the planned area of development.

Behaviour zones

- Summarise key properties for sub-divisions of the area of interest which can be regarded to behave in a similar way within a zone but differently between zones (e.g., similar water depth, dominant metocean condition, sediment type, seabed features, sediment pathways, etc.).

Other considerations

- Regions prone to earthquakes (i.e., situations where seabed mobility is not initiated by metocean conditions) are more likely to experience issues such as liquefaction (Appendix I) and slope failure, although the frequency of occurrence of such events is expected to be low.

Figure 2 provides an example of a CSM developed for a site off the Danish coastline relevant to Horns Rev offshore windfarms.

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY
CONTINUED

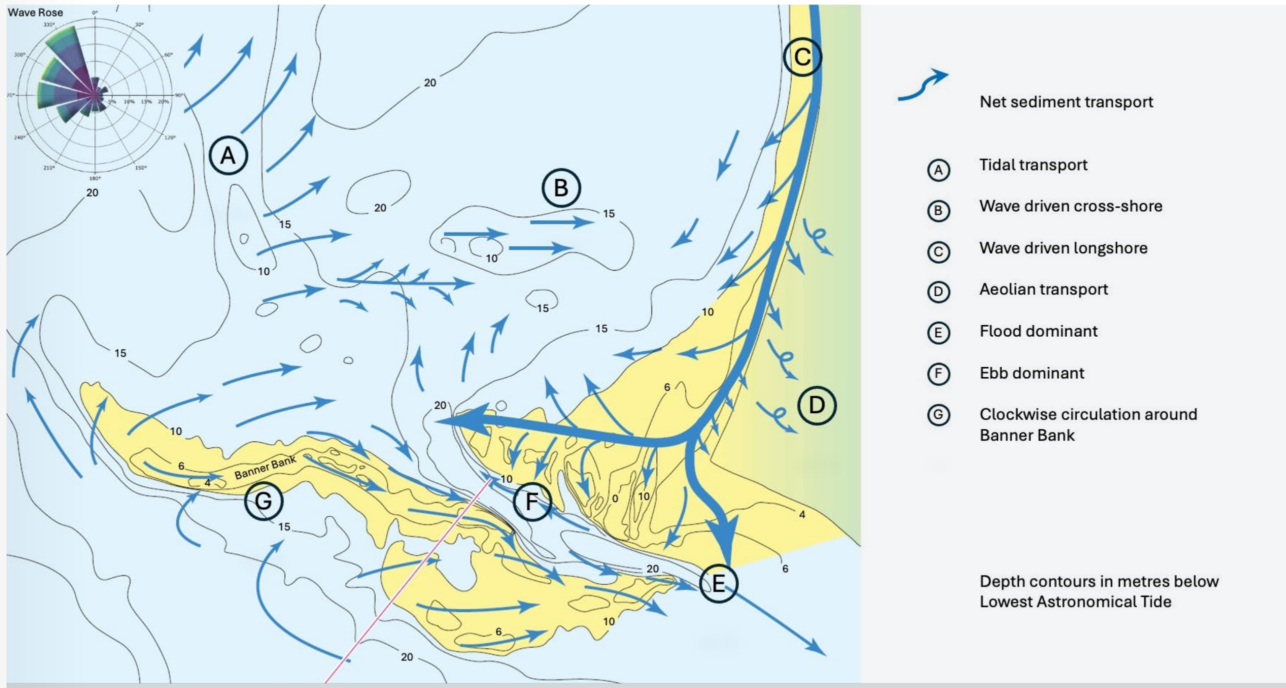


Figure 2 – Net sand transport pathways informing a CSM (after Leth et al., (2004) and DHI MetOcean Data Portal)

Pertinent issues in this example of a seabed mobility map include:

- Seabed mainly comprising of Holocene sands.
- Water depths are relatively shallow with sediments responding to both wave and tidal influences creating a mobile seabed.
- Offshore wave conditions are mainly from the west to northerly sectors, with prevailing waves from north-north-west.
- Inshore, waves approaching obliquely to the open coast drives longshore transport with the prevailing north-north-west developing net southerly transport which helps develop the growth of a headland type spit.
- Westerly winds develop aeolian transport off the beach to feed coastal dunes (sink for sandy sediment).
- A Banner Bank has formed off the headland with a clockwise circulation of sediment transport. Satellite observations show mobile sandwaves forming the crest of this bank. The bank acts as a local store of sandy sediment.
- A narrow tidal channel with strong ebb and flood flows separates the headland from the bank. The strong flows have locally scoured down the seabed to increase local water depths.

The combination of these issues makes seabed mobility relevant to design of scour protection, cables and landfall options.

Further guidance on the development of a CSM is provided in Magalen et al., (2014).

3.2.13 SEABED MOBILITY MAPS

Recommended practice is to develop seabed mobility maps to complement the CSM. These maps should include pertinent details of, where applicable:

- Water depths.
- Surficial sediment types and non-erodible features.
- Presence / absence of mobile bedforms – coverage, types, and key dimensions (e.g., crest height, wavelength, asymmetric profile, etc.).
- Interpreted scale of seabed mobility.
- Uncertainties and limitations in present understanding.

For the interpreted scale of seabed mobility, the recommended approach is to assign a likelihood score. For the initial seabed mobility assessment this may need to be deduced on a qualitative basis. If wave and tidal models are available to support the detailed seabed mobility assessment then this likelihood can be derived on a quantitative basis by determining the level of exceedance of critical bed shear stress for sediment transport and establishing the (dimensionless) Sediment Mobility Index (SMI), after Li, et al., (2009). Further details on the approach to determining bed shear stress and the calculation of the SMI are provided in Appendix G: Analytical Methods.

A suggested scale for the likelihood of seabed mobility is as follows:

- **High** – the area is associated with sediment types or bedform features (i.e. a bedform-rich zone) which are expected to be mobile, e.g., sandwaves, sandbanks, sandy seabeds in areas of strong flows (i.e., high likelihood of the seabed being mobile, or frequently mobile), or wave exposed beaches with a dynamic cross-shore profile. The typical value for SMI representing High mobility is in the range 1 to 2, and 0.5 to 1 for Moderately High. The level of seabed mobility represents a potential hazard to assets.
- **Medium** (or moderate) – the area is associated with properties or features that may be become mobile, but this is likely to be infrequent (e.g., limited to peak / storm conditions). The typical value for SMI representing Moderate mobility is in the range 0.1 to 0.5. The level of seabed mobility represents a potential hazard to assets in some cases.
- **Low** (nil to low) – the area is not associated with any identifiable mobile sediments or bedform features, rather the seabed conditions exhibit general stability (e.g., cohesive sediments or lag deposits). The typical value for SMI representing Low mobility is in the range 0 to 0.1. The level of seabed mobility is not expected to represent a hazard to assets.
- **Unknown** – insufficient information is available at the current stage of project development of classify the level of seabed mobility. This may be a common attribute for initial iteration of the seabed mobility assessment and represents a potential data gap to be addressed for a subsequent stage of development.

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY

CONTINUED

These levels of likelihood should help provide an initial insight into the level of associated risk to project infrastructure, i.e., in general, high seabed mobility presents a greater hazard to project infrastructure than low seabed mobility. Subsequent engineering decisions can be informed by this assessment to help mitigate or reduce associated risks. Whatever the chosen scale, the same levels of seabed mobility likelihood should be applied in the project risk register (Appendix A).

In addition, the level of uncertainty associated with the likelihood of seabed mobility can be usefully qualified (i.e., based on data quality):

- **Low uncertainty** – the data supporting the likelihood score is generally considered robust.
- **Medium uncertainty** – the data supporting the likelihood score is adequate but has some limitations.
- **High uncertainty** – the data supporting the likelihood score is limited, including notable gaps.

Example limitations in data may be due to the paucity of baseline information or attributes such as (too coarse) resolution, (out of date) vintage, or (low precision) accuracy, as determined for data collation (Section 3.2.6). Where available, multiple independent datasets related to the same topic can also be considered where this helps reduce uncertainty based on a general agreement between the information.

When the CSM is updated then subsequent iterations of the seabed mobility maps should also review the definitions of behaviour zones (including spatial extents) and the associated likelihood and uncertainty scores.

Finally, seabed mobility maps usefully inform the requirements for establishing future seabed levels (Section 3.2.15).

3.2.14 ANALYTICAL APPROACHES

Analytical approaches provide the means to address recommendations made from the preliminary CSM and to help validate various hypotheses to improve understanding, increase quantification (e.g., rates and magnitudes of change) and reduce uncertainties.

A key consideration for analytical approaches is the timely availability of adequate site investigation data (i.e. from recommended surveys) to support:

- Data analysis.
- Process modelling.

The outputs from various analytical approaches provide the basis to update the CSM and seabed mobility maps.

The updated CSM should enable the prediction of future seabed levels for relevant locations as well as suitable recommendations for onward monitoring of seabed levels. These predictions should be available at the pre-Construction stage.

Appendix G provides additional details related to various analytical approaches.

3.2.15 FUTURE SEABED LEVELS

A key output from analytical approaches (Appendix G) is the prediction of future seabed levels for relevant areas coincident with the project development. Future seabed levels should typically cover the full period of the development cycle. If a project is subsequently repowered to extend the operational period, then an updated prediction of future seabed levels should be made and based on the data and information available at the time.

Relevant areas include sites where a change in seabed levels might increase the risk to an asset placed on or under the seabed and where sufficient seabed cover is required to protect that asset (i.e. seabed mobility areas mapped as “Medium” and “High”). Areas considered to be stable or immobile may present a low risk to such assets (i.e., seabed mobility mapped as “Low”) and can be considered with lesser detail, in comparison.

In many cases, future seabed levels are likely to vary at a relatively slow rate and can be accounted for with annual predictions. In some cases, rates may be more complex (e.g., seasonal reversal of giant sandwaves in the Taiwan Straits (Roulund, Riezebos, & Saverymuttu, (2023))) and may need to be expressed at a finer temporal interval.

All predictions of future seabed levels will be associated with various sources of uncertainty, which are expected to include:

- Survey accuracy – standard practice is to quantify the accuracy of measurement with an error budget for Total Horizontal Uncertainty (THU) and Total Vertical Uncertainty (TVU), according to IHO (2024).
- Normalising between multiple bathymetric data where different units, datums and projections need to be accounted for.
- Spatial resolution – the profile of a bedform needs to be resolved with high-resolution data and may be under-represented when data resolution is too coarse and misses key features such as crest height.
- Temporal resolution – large temporal intervals between consecutive surveys may inhibit the ability to track the movement of individual bedform features or lead to unsubstantiated assumptions related to historic trends (e.g., a false assumption of linear trends, etc.).
- Analysis method – different methods of analysis, including modelling, can introduce different levels of uncertainty stemming from their underlying assumptions and simplifications.
- When considering sandwave migration, the potential remains for variability in crest height and the shape of the bedform over time. Where data allows, quantifying this variability will help deduce a suitable uncertainty band to apply to the prediction of future seabed levels.

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY
CONTINUED

Recommenced practice is to use an uncertainty budget to transparently account for relevant sources of uncertainties and develop an overall aggregate uncertainty.

The following types of future seabed levels are identified as Design Seabed Levels:

- **LSBL** – the lowest (or deepest) seabed level, determined for a specific location, which is likely to occur at any stage over the prediction period of a project, taking account of various uncertainties (i.e., as a subtraction from the best estimate). LSBL can be used to determine a suitable depth of burial to help ensure cables and pipelines do not become exposed at any time. LSBL helps determine the requirement for an additional extent for scour protection to manage a falling scour apron (Section 4.3.2.5). In some situations, the seabed level abutting scour protection or cable crossings may become slightly lower than the LSBL because of the development of local scour or edge scour. In some cases, LSBL may also be bound by a hard constraint such as the depth of an immobile layer. The lowest value of LSBL during the lifetime of a project can also be referred as the Reference Seabed Level (**RSBL**) or the Non-Mobile Reference Level[2] (**NMRL**).
- **HSBL** – the highest (or shallowest) seabed level, determined for a specific location, likely to occur at any stage over the prediction period, taking account of various uncertainties (i.e., as an addition from the best estimate). HSBL can be used to estimate workability in shallow areas. For locations which abut with scour protection or cable crossings, HSBL may not rise in a similar way due to near-field turbulence developing around the hard obstacles which may be sufficient to locally counteract the wider elevation of seabed levels.
- **BEB** – Best estimate bathymetry, determined for a specific location, tracks the most likely seabed level over the prediction period, bound within the envelope of LSBL and HSBL. Typically, BEB is achieved by extrapolating from the most recent observations and applying the most probable historical trends through to the expected final period of operation. BEB provides a useful insight of variations in future seabed levels to support the most probable Operation and Maintenance costs (e.g., related to lengths of cable and locations that might require re-burial, etc.).

The likelihood is that predictions of future seabed levels will be made several years prior to commencement of project construction, with the following breakdown provided for illustrative purposes only (N.B., actual periods differ by project):

- **Pre-construction** – a lead in period from the time when the prediction of future seabed levels is first made. This may be several years prior to construction (e.g., from T-3 to T+0 years, in the case of three years before start of construction). The initial period of future seabed levels (e.g., at T-3 years) would be based on the latest complete set of survey information without extrapolation. Subsequent surveys offering complete or partial coverage obtained during this period can be used to validate (or adjust, as necessary) predictions of future seabed levels representing corresponding periods up to T+0.
- **Construction** – from T+0 years through to the end of construction. In the case of a 3-year construction period this would be from T+0 to T+3 years.
- **Operational period** – the longest period in the project development cycle, potentially around 25 years, or more. For the illustrative case, this would be T+3 to T+28 years. Asset monitoring of seabed levels during this period (Section 3.2.13) provides an onward basis for data review to refine and update predictions of future seabed levels.
- **Decommissioning period** – a similar duration to construction. For the illustrative case, this may be T+28 to T+30 years. The prediction of future seabed levels for this period will help inform decommissioning plans.

2. The inference is NMRL equates to the depth of an immobile layer, however, that is only true if LSBL reaches this point over the lifetime of the project.

Figure 3 shows an example of predicted future seabed levels at a single location over a period of 38 years. The initial prediction is made three years (T-3 years) ahead of the expected date of construction (T+0 years), at this time the local seabed condition represents the trough level of an advancing sandwave with a crest height of 2 m and a wavelength of 100 m. The initial seabed level is derived from latest survey data as -21.89 m relative to the local vertical datum (negative values representing depth below datum). The sandwave is estimated to be migrating at a rate of 10 m/year on a seabed which is gradually dropping at a rate of 0.02 m/year. The overall level of uncertainty associated with the BEB predictions is assessed to be +/- 2%, cumulatively year on year. After 35 years, BEB is estimated at 21.70 m, HSBL -19.97 m, with LSBL at -23.15 m (N.B., all values are for illustrative purposes only).

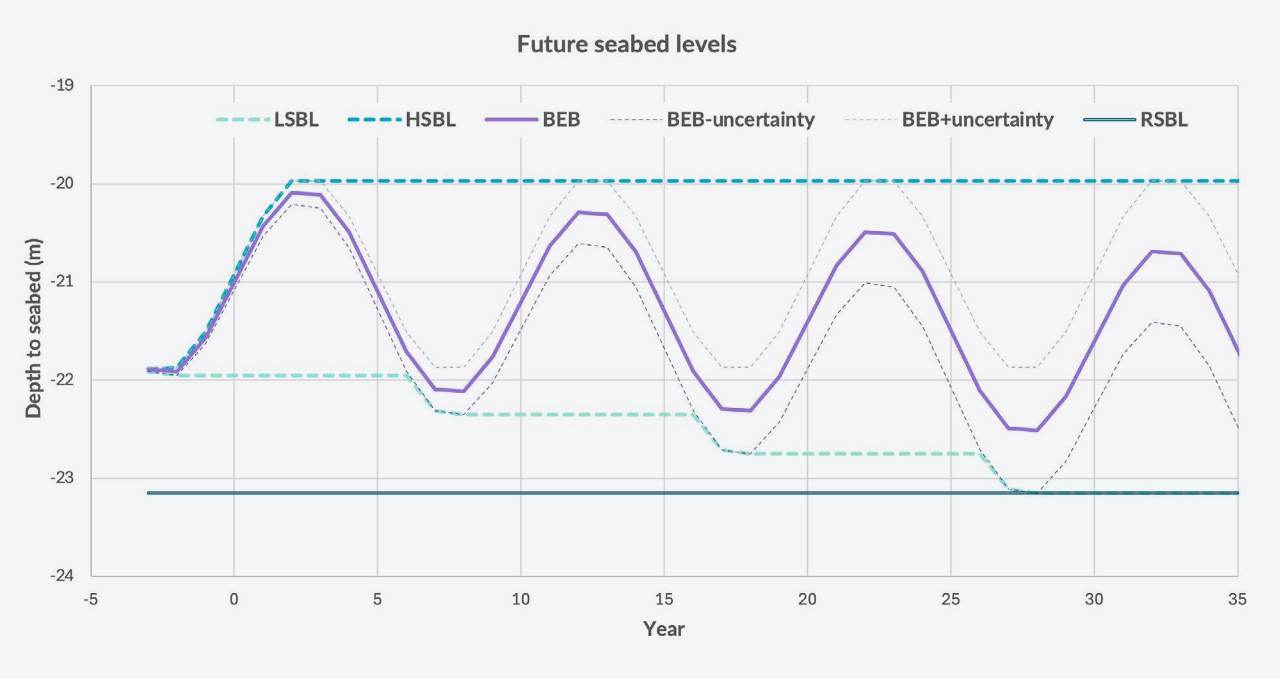


Figure 3 – Example of predicted future seabed levels and design levels (HSBL and LSBL).

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY

CONTINUED

3.2.16 MONITORING RECOMMENDATIONS

A primary aim of monitoring at this time should be to help validate and (if necessary) refine the predictions of future seabed levels and manage (re-base) uncertainties on an onward basis against actual observed seabed levels. The requirements for monitoring should therefore be considerate to the level of uncertainty associated with predictions of future seabed levels. A high level of uncertainty would call for more extensive monitoring and at a higher frequency compared to a situation with a low level of uncertainty.

Monitoring should form part of the project's asset monitoring strategy and provide direct evidence of how the seabed has changed compared to previous surveys and predictions of future seabed levels.

Monitoring recommendations should consider the following issues, as a minimum:

- Specification of survey, e.g., method, data resolution and reporting requirements.
- Area(s) to survey, e.g., focussing on areas where seabed mobility presents a "High" risk to assets.
- Timing of surveys within the year.
- Frequency of subsequent surveys with consideration to the predicted occurrence of cable exposure locations.
- Duration of monitoring programme; commencement data and final date.

Applying relevant risk-based criteria (e.g., minimum depth of cover of buried cables) across the prediction of future seabed levels will help to identify the likely timings(s) and locations(s) when this criterion might be met. This information can then be used to strategically target and pre-plan monitoring provisions to inform budgetary requirements.

An important consideration in the delivery of a monitoring programme is to maintain a consistent survey approach throughout so that data comparisons remain equitable. If the survey or reporting approach requires modification or refinement, then this needs to be justified and documented with potential consequences noted.

3.2.17 DATA REVIEW

A review of data should take place as each monitoring survey is completed. This review should aim to achieve the following:

- Compare current survey results with previous results to determine actual scales of change in seabed levels.
- Compare current survey results with equivalent predictions of future seabed level, noting predictions are expected to relate to an annual change.
- Verify predictions of future seabed levels and associated upper and lower uncertainty limits.

The monitoring – review – refinement approach should be repeated throughout the period of monitoring each time new survey results are forthcoming.

Of note, the temporal resolution of predicted future seabed levels is expected to be an annual interval which means the date of the survey will fall between predictions representing a slightly earlier and slightly later period. Verification of predictions for these periods can be considered proven when the survey levels remain largely bounded by the earlier and later predictions of BEB. If there are outliers, then these should also remain between LSBL and HSBL for these dates which account for uncertainties in the corresponding predictions of BEB.

In case newly acquired data shows a strong deviation from the predicted seabed mobility (either in vertical change or observed migration rates), this issue should be raised as a possible risk to the project and followed up with detailed assessment and potentially an update of the Design Seabed Levels.

3 FRAMEWORK FOR DELIVERING AN ASSESSMENT OF SEABED MOBILITY

CONTINUED

3.3 SEABED MOBILITY DELIVERY PLAN

Recommended practice is to establish an overall delivery plan at the outset of project development to address seabed mobility issues. The delivery plan should be kept under review and remain relevant to support each stage of project development so that so that relevant data, information and knowledge can be continually improved upon and key deliverables are identified and become available on a timely basis to meet project requirements. For example, the seabed mobility plan would identify the requirements for an initial seabed mobility assessment to inform Site Selection, if relevant.

As part of the delivery plan, the data and information supporting the assessment of seabed mobility needs to be carefully managed (see Appendix B – Data Management) and remain available to support subsequent stages of project development, as relevant.

4 PROJECT DEVELOPMENT REQUIREMENTS

4.1 OVERVIEW

For the purpose of this guidance, the project development cycle recognises the following key stages:

- Site Selection (including Project Feasibility)
- Preliminary Design
- Consenting
- Detailed Design
- Construction
- Operation & Maintenance
- Decommissioning (including post-decommissioning)

In most cases, project stages advance on a sequential basis, although preliminary design and consenting often operate in parallel.

Key requirements for seabed mobility information are identified for each of these stages.

4.2 SITE SELECTION

In the present context, Site Selection refers to the stage where a developer identifies a preferred offshore area (or areas) for development[3]. Examples of the type of development include offshore windfarms (fixed or floating), marine renewable energy projects, cables (power or telecoms), or pipelines. For a cable or pipeline, Site Selection is also commonly referred to as Route Selection.

Recommended practice is to provide an initial assessment of seabed mobility (Section 3.2.1) to inform Site Selection. In so far as existing data[4] and information allows, the initial assessment should draw attention to the potential development risks associated with seabed mobility and, where required, support a comparative high-level review between alternative option areas. Potential risks associated with relevant seabed mobility hazards should be recorded in the project risk register (see Appendix A for an example risk register structure) to set out a basis of how the risks should be managed and mitigated through subsequent stages of project development.

4.2.1 EXISTING DEVELOPMENTS

In some cases, Site Selection may relate to an investment decision in an existing operational development or one already under development (e.g., due to a transfer of ownership). A review of seabed mobility remains important to inform the risk profile of onward operating costs and should be delivered as part of an associated due diligence process, as might be relevant.

Ideally, an existing development will have already undertaken a seabed mobility assessment and already benefit from site data and technical understanding (identified from the Data Register), including details where seabed mobility may have contributed to the requirement for remedial actions. Where available, existing studies should be reviewed to inform the due diligence process, otherwise a separate study

3. Many countries have already embarked on national programmes (or Roadmaps) related to thematic development within their maritime boundaries, such as implementing offshore wind roadmaps, and many countries are primed to launch new programmes. In these jurisdictions, sites may already have been identified to prospective developers. Further, existing sites may be subject to applications for extension, and usually these will require a seabed mobility assessment even if one has been conducted for the main site area.
4. In some instances, national programmes might provide contemporary site specific geophysical and/or metocean survey data to assist developers' initial considerations.

may be required to develop the appropriate level of understanding of risks associated with potential seabed mobility issues.

Due diligence is expected to occur later in the development cycle than to support the Site Selection stage. In addition, the investing entity may have different risk criteria than the original developer and may therefore have different ideas about the appropriateness of a selected site.

4.2.2 KEY POINTS FOR SITE SELECTION

An initial seabed mobility assessment is recommended to support Site Selection. The level of assessment that can be achieved at this time will reflect the availability and limitations of existing data and information, with the expectation that a qualitative review will be the most common approach possible. The initial seabed mobility assessment (Section 3.2.1) should include:

- Data search, data collation, and gap analysis to identify limitations in existing information.
  - Log data (and metadata) in data register (Appendix B).
  - Survey recommendations to address data gaps.
- Development of a preliminary CSM.
  - Establish working hypothesis to explain the baseline process understanding influencing seabed mobility.
  - Provide recommendations for analytical methods to validate hypothesis.
- Development of seabed mobility maps to identify locations likely to create risks to installed assets.
  - Log key seabed mobility hazards in risk register (Appendix A).

Where Site Selection makes recommendations for surveys to address data gaps, these surveys need to be scheduled to deliver timely outputs to inform subsequent stages of project development. The general expectation is that these recommendations help inform existing survey plans (e.g., for geophysical and metocean information) rather than develop any separate survey requirements.

4.3 PRELIMINARY DESIGN

Preliminary design (also commonly referred to as Preliminary Front-End Engineering Design or Pre-FEED) establishes high-level design options that can be taken forward for the assessment of environmental impacts as part of the Consenting stage. The feasibility of design options is expected to include a consideration of if, where, how, and when seabed mobility issues might present a potential risk to planned installed assets and the means to mitigate such risks.

Recommended practice is for this stage of work to build on the initial assessment of seabed mobility, likely to have been established for Site Selection, to develop a full assessment of seabed mobility (see Section 3.2.2). The level of study at this time should plan to be more in-depth and comprehensive, employing outputs from project surveys (as recommended from the initial seabed mobility assessment) as well as applying relevant analytical methods (Appendix G). Efforts should also aim to address previous uncertainties and improve overall confidence in initial seabed mobility outputs for the full assessment to provide an updated CSM (Section 3.2.12), seabed mobility maps (Section 3.2.13) and the prediction of future seabed levels (Section 3.2.15).

If the initial seabed mobility assessment considered that the seabed to be generally stable with a "Low" level of seabed mobility for all project areas, but this assertion was made with a "High" level of uncertainty, then this assertion needs to be confirmed against the new project data and more rigorous analysis. If this further analysis confirms a stable seabed with a "Low" level of seabed mobility, with an acceptable "Low" level of uncertainty, then only limited additional work on this topic would be necessary beyond preliminary design.

Once a project receives consent (i.e., all permits and licences enabling the project to be built and operated) then design options are subsequently refined through detailed design to a preferred option (Section 4.5).

4.3.1 GUIDANCE AND STANDARDS

Project design is supported by various guidance, recommended practice, standards and codes published by both national and international organisations. Each project needs to confirm the relevant standards as they might apply. Many of these documents identify a requirement to address seabed mobility (used here as the inclusive term), which might also be expressed using alternative terminologies, including:

- Sediment erosion / deposition.
- Sediment mobility / transport.
- Seabed stability / instability.
- Seabed dynamics / morphology.
- Unstable seabed.
- Seabed movement.
- Bathymetrical changes / changes in seabed elevation / bed level change / morphological change.

A key reference published by the International Electrotechnical Commission (IEC) relevant to offshore wind development is:

IEC 61400-3-1:2019. Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines.

Where this standard refers to the analysis of seabed movement and scour, then reference is made to an associated publication from the International Organization for Standards (ISO):

ISO 19901-4:2025-02. Petroleum and natural gas industries — Specific requirements for offshore structures — Part 4: Geotechnical and foundation design considerations.

For reference, the formation and mitigation of local scour around a foundation is beyond the scope of the present guidance. The exception to this is where the scale of seabed mobility needs to be factored into the design of scour protection (e.g., due to a predicted drop in seabed levels).

Related documents which also refer to seabed mobility issues and provide information to guide the requirements for Preliminary Design include (subject to revision):

Carbon Trust 2015. Cable Burial Risk Assessment Methodology. Guidance for the Preparation of Cable Burial. Depth of Lowering Specification. CTC835, February 2015.

DNV-ST-0359. Subsea power cables for wind power plants. DNV 2021.

DNVGL-RP-0360. Subsea power cables in shallow water. DNV 2021.

DNVGL-ST-0437. Loads and site conditions for wind turbines. DNV 2024.

DNVGL-ST-0126. Support structures for wind turbines. DNV 2021.

DNV-RP-F109. On-bottom stability design of submarine pipelines, cables, and umbilicals. DNV 2021.

DNV-RP-0618. Rock scour protection for monopiles. DNV 2022.

4.3.2 APPLICATION OF SEABED MOBILITY TO INFORM PRELIMINARY DESIGN

Preliminary design should consider seabed mobility issues as they might be relevant to:

- Pipeline and cable routes (including power and telecoms).
- External pipeline and cable protection.
- Seabed levelling requirements in bedform-rich zones.
- Seabed levelling at foundation locations.
- Scour protection design.
- Arrangement of cable crossings.
- Nearshore zone – landfall options.
- UXOs.
- O&M and decommissioning commitments.

Each of these issues is expanded on in the following sections.

4.3.2.1 Cables routes (inter-array and export cables)

Cable route options will be established based on minimising the cable length whilst avoiding potential hazards, where possible, such as a highly mobile seabed which may lead to cable exposure or excessive cable burial.

A Cable Burial Risk Assessments (CBRA) provides the means to determine the risk of cable failure due to external threats such as anchor strike or trawl nets. A structured methodology for developing a CBRA is published in Carbon Trust (2015). The CBRA incorporates an assessment of seabed mobility to determine acceptable burial depths that mitigate external risks. In this regard, the variability in future seabed levels over the project lifecycle needs to be considered in a CBRA.

An initial CBRA is recommended for preliminary design to provide early identification of the risks and constraints for buried cables. The initial CBRA can help identify areas where the target cable burial may be difficult to achieve, as well as the areas where there may be a high probability that buried cables might become exposed in the future (e.g., from sandwave migration).

The choice of target cable burial depths can consider various strategies, or a combination of strategies for areas with different risks of seabed mobility:

- **Bury and forget** – cable burial depth is selected to minimise the risk of exposure over the lifetime of the development by considering the full range of possible future seabed levels (i.e., HSBL to LSBL, with acceptable uncertainties). The benefits of this strategy include achieving the lowest risk of cable damage due to external threats, minimal chance of requiring reburial campaigns, and reduced need for asset monitoring. The disadvantages include a likely deeper burial depth compared with other strategies, and periods when seabed mobility may increase the burial depth reducing the capacity for cable cooling, plus increased difficulties for cable repairs and removal on decommissioning, if required.
- **Bury and maintain** – an adequate burial depth is established for an initial period (e.g., first few years) associated with acceptable uncertainties in estimates of LSBL (N.B., long-term estimates may be associated with unacceptable high levels of uncertainty which introduce high cost and practical implications). This strategy requires routine monitoring across areas with "High" seabed mobility and a remediation plan to rebury and protect exposed cables.
- **Managed risk due to occasional reduction to depth of cover due to migrating bedforms** – this strategy is associated with increased risk of cable damage from external threats but may avoid re-routing cables associated with increased costs. This strategy is only likely to be viable when the periods with reduced coverage are of minimal duration, and the cable does not become fully exposed. This strategy also requires routine monitoring across areas with "High" seabed mobility and a remediation plan to rebury and protect exposed cables.

There is also a risk of occasional or permanent increases to depth of cover (predicted or unpredicted) due to migrating bedforms which may limit cable heat dissipation or make the removal of cables problematic at the time of repair of decommissioning. Some countries may impose environmental regulations which place a limit to increases in seabed temperature due to heat dissipation (e.g., the guideline 2 K criterion in Germany which stipulates that temperatures above a buried cable 200 mm below the seabed must not exceed two degrees Kelvin). In such situations, the choice of depth of cover for cable installation should anticipate periods of potential increase.

In some cases, the cable may be laid in a pre-cut trench and rely on natural backfill to cover the cable. In such cases, the rate of natural backfill along the trench can be qualitatively informed by the CSM and seabed mobility maps with areas indicated with a high seabed mobility interpreted with a high rate and probability of natural backfill and low seabed mobility areas with a low rate and probability.

4.3.2.2 External cable protection

For the locations where cable burial is not possible, or where buried cables become exposed by seabed mobility, then external cable protection may be required. Standard types of external cable protection include rock armour or concrete mattresses. Cable protection is likely to have a trapezoidal cross section and result in discrete low-profile ridges (rock berms), where used.

Provisions for cable protection should be established as part of Preliminary Design with the consequence on the marine environment considered as part of the consenting stage. These provisions should consider the maximum volumes required over the operational lifetime of the asset, as well as the likely locations involved. Seabed mobility maps and predictions of future seabed levels will help identify the areas with the highest likelihood of cable exposure, as well as the expected date when this might occur. These provisions are likely to be conservative at this juncture, but subject to review and refinement post-consent as part of detailed design.

4.3.2.3 Seabed levelling

Seabed levelling may be required to flatten the seabed to help facilitate the installation of cables, pipelines, foundations or scour protection. Seabed levelling may also be commonly referred to as pre-sweeping, seabed profiling or sandwave clearance.

In the case of sandwaves, levelling helps remove steep seabed slopes that might impeded cable laying tools, as well as to help achieve burial to the required depth below a mobile layer. A similar requirement for seabed levelling exists to flatten the seabed for laying pipelines on the seabed.

Preliminary Design considerations related to seabed levelling include, as relevant:

- Seabed mapping to identify the areas involved and the scale of the features to be cleared, including an estimate of clearance volumes.
- Determining suitable methods for bedform clearance, including options for potential spoil disposal where dredging is considered.
- Potential constraints to clearance, including estimating the likely period for bedform recovery to help determine time window for subsequent engineering works.

If the area of clearance is associated with a potential environmental impact, then the activity may also need to be assessed within the consenting stage of the development.

4.3.2.4 Seabed levelling at foundation locations

For fixed foundations, the likely seabed level at the planned date of installation should be informed from the prediction of future seabed levels to inform foundation design, as well as the lowest seabed level (i.e., LSBL) over the operational period to help determine a suitable pile embedment depth.

Areas identified with a "Low" level of seabed mobility are expected to maintain consistent seabed levels over the period prior to installation whereas an area assessed with a "High" seabed mobility may experience a relevant change in seabed level. For example, a net lowering of seabed levels could reduce the embedment depth of piled foundation options. Conversely, a raised seabed level may require seabed levelling prior to installation.

4.3.2.5 Stability of scour protection

The function of scour protection is to mitigate the development of local scour around fixed foundations and prevent a drop in seabed levels that might otherwise risk structural stability. Whilst local scour is not an immediate consideration of this guidance, the fate of scour protection on a mobile seabed remains relevant.

Scour protection is normally placed radially around the foundation to form an armoured apron to prevent erosion due to scouring processes. The extent and volume of scour protection in areas with a risk of a lowering seabed should consider a provision to accommodate a falling apron which can subsequently armour the side slopes of the scour protection mound. Further consideration of this issue is offered in:

DNV-RP-0618: Rock scour protection for monopiles. DNV, 2022.

Handbook of Scour and Cable Protection methods. Deltares, 2023.

In some cases, the option for seabed preparation to locally remove potentially mobile sediment down to LSBL may be preferable to relying on a falling apron, however, this option may have other practical and environmental limitations if the difference between BEB at the time of dredging to LSBL is too large.

All scour protection solutions should include a monitoring and action plan for remediation if performance is compromised.

4.3.2.6 Arrangement of cable crossings

The planning and design of a project's cable layout (e.g., inter-array and export cables) will need to identify the number and location of existing assets (e.g., cables and pipelines, buried or unburied) which need to be crossed and protected with rock berms. In addition, the project's own layout may introduce additional crossings.

The planned cable crossings need to be adequately evaluated for potential seabed mobility issues which may affect the berm stability, as well as the potential development of edge scour around the perimeter of the crossing design. Additional considerations may be necessary where cable crossings are coincident with areas of sandwaves. Whilst some seabed preparation in areas of sandwaves may be possible to level the seabed to aid the installation of cables and rock berms, there may be constraints and exclusions imposed by the existing asset (i.e., the subject of a crossing agreement) which prevents abutting sandwaves from being cleared. In these cases, the rock berm should be preferentially located in the trough of the sandwave rather than at the crest, if feasible.

Present experience in areas of high seabed mobility indicate that a flow aligned rock berm may reduce the scale of edge scour compared with crossings aligned obliquely to incident flows. Roulund et al. (2018) studied field data in Morecambe Bay to quantify the likelihood of scour around rock berms. Two parallel cable crossing berms installed on a sub-tidal channel slope experienced general seabed lowering associated with lateral migration of the channel. This migration increased the height of the berms relative to the local seabed level. In addition, excessive scour was observed in the gap between the berms. A review of local metocean data revealed a flow asymmetry which led to scour developing away from the berms in a preferential direction aligned with the strongest currents. The non dimensional bed shear stress from the tidal flow, quantified by the Shields parameter (Shields, (1936)), was found to control the scour. In this case, if the Shields parameter exceeded > 0.3 then the field observations indicated that the risk of scour increased significantly, and for > 0.4 significant scour developed (N.B., such threshold conditions should be considered on a site-specific basis, where relevant – see Appendix G). A key observation from this study was that, even when seabed lowering occurred, a rock berm aligned more parallel to the ambient flows experienced a reduced level of edge scouring compared to single or double berms aligned obliquely to the flow.

4.3.2.7 Nearshore zone – landfall options

Landfall options for export cables require evaluation of the stability of the nearshore zone over the project lifetime. This exercise forms part of a cable landfall assessment.

The seaward limit of the nearshore zone can be usefully defined by the outer 'depth of closure'; the depth where the influence of wave action on cross-shore sediment transport is on average insignificant compared to other influences (see Coastal Wiki and Section F.4.7 for more details). The landward limit is defined as high water. Accordingly, the nearshore zone includes both the shallow subtidal and intertidal.

Since a typical project lifetime spans several decades then accounting for the long-term variability of the shoreline is also important as this can modify the position of high water. This variability may be due to a combination of recession (net erosion), progradation (net accretion) or sea level rise. Notably, the landward location of the export cable transition joint bay needs to be located sufficiently distant from a receding coastline.

Evidence of shoreline change along the intertidal should be sought from past monitoring, such as beach profiles, LiDAR surveys, and aerial images. Satellite observations may also provide useful supplementary information. Appendix C – Bathymetry Data discusses this topic in further detail. In the absence of local evidence, a global assessment of past and future shoreline trends (2020 to 2100) is available from Vousdoukas, et al., (2020).

Comparable evidence of past monitoring for the shallow sub-tidal and surf zone is generally limited due to draught restrictions on survey vessels and is a common data gap between offshore and intertidal surveys. Of note, sub-tidal observations typically reference a vertical offshore datum, such as Chart Datum, whereas inter-tidal observations generally reference a land-based datum. Accordingly, data collation across the nearshore zone needs to pay particular attention when converting information to a consistent datum.

Suitable landfall options in the nearshore zone should be selected according to an appreciation of local coastal morphology and ground conditions (with consideration to the Ground Model – Section 3.2.10). Typical landfall options include:

- Open-cut trenching with temporary cofferdam and backfill. Open coasts with well-developed net littoral transport that use temporary cofferdams have the potential to create sediment trapping on the updrift side of the works. The build-up of sediment may then require mechanical bypassing to manage and alleviate the potential for localised downdrift erosion due to the temporary lack of sediment supply. Any such requirements for environmental mitigation need to be identified from consenting activities, designed and planned for.
- Trenching and burial machine.
- Pull in rollers and cut & fill. Ideally suited to sites with wide intertidal flats.
- Horizontal Directional Drilling (HDD) cable ducts. Suited to sites with soft cliffs, shingle barriers, or saltmarshes to avoid disturbance to these features, however, the feasibility of this option requires comprehensive information of ground conditions. HDD also requires design of offshore exit pits which need to be excavated. During punch-out there may also be a release of drilling muds (e.g., bentonite) in the exit pits.

An example of a landfall assessment which appeared to have underestimated the variability of nearshore conditions is demonstrated by Wave Hub. The export cable landfall from this offshore renewable energy test centre is located on Hayle Beach at a site adjacent to the eastern side of Hayle Estuary, North Cornwall. In August 2011, sections of cable at the base of sand dunes, around high water, became exposed when beach levels dropped by over 2 m (the target depth of cable burial in 2010 using a trenching and burial machine) (**Figure 4**).

Other cable exposures related to this project also occurred in the sub-tidal within St. Ives Bay which have subsequently been covered with rock dumps and rock bags.

Figure 4 – Exposed export cables at Hayle beach landfall (acknowledgement; Save our Sand)

4.3.3 UXO

The suite of project surveys which is expected to be available currently is likely to include a UXO survey where the presence of UXO is anticipated within the development area. UXOs may be identified as seabed contacts from side-scan surveys and detected as surface or near-surface contacts by a magnetometer survey. A highly mobile seabed may cover and uncover these contacts; however, recent research has suggested that the UXO is unlikely to become mobilised by wave induced forces alone (Menzel, Wolters, & Drews, (2025)). Understanding the depth of the mobile layer at this time can assist the design of a UXO survey.

Relevant guidance related to UXO issues presently includes:

CIRIA (2015). C754, Assessment and management of unexploded ordnance (UXO) risk in the marine environment, 2015.

Carbon Trust (2020). Guidance for geophysical surveying for UXO and boulders supporting cable installation Offshore Wind Accelerator. April 2020.

4.3.4 O&M AND DECOMMISSIONING COMMITMENTS

Seabed mobility maps and future seabed levels will help inform commitments to O&M and decommissioning periods.

An asset monitoring programme should be designed for the O&M stage according to the areas with highest levels of seabed mobility with the frequency of re-survey reflecting areas identified with rapidly varying seabed levels. Each set of monitoring data should then be reviewed to help validate and refine predictions of future seabed levels, and to review operational requirements.

An initial outline of decommissioning commitments should also be established as part of preliminary design by considering the anticipated state of the seabed over the long-term. For example, if future seabed levels appear stable, then leaving buried assets in situ may be a viable option.

These issues are discussed more fully in Section 4.7 – Operation & Maintenance and Section 4.8 – Decommissioning.

4.3.5 KEY POINTS FOR PRELIMINARY DESIGN

A detailed seabed mobility assessment is recommended to support preliminary design which builds on an initial seabed mobility assessment and includes prediction of future seabed levels and updated seabed mobility maps relevant to inform initial design of assets placed onto or buried under the seabed.

If the project wishes to retain flexibility through to detailed design, then preliminary design should establish multiple options (collectively termed the Project Design Envelope). Notably, the risk to assets due to a mobile seabed may vary between options.

If high levels of uncertainty remain in the detailed seabed mobility assessment, then preliminary design options should include appropriate levels of conservatism. Suitable recommendations should be made (e.g., additional data collection and further analysis) so that improved understanding becomes available to support detailed design which addresses such uncertainty to an acceptable level and enables a reduction of conservatism.

4.4 CONSENTING

Consenting is the project stage which secures relevant licences and permits to construct, operate, and decommission an offshore development. Specific consent conditions are expected to vary by country and by activity and should be verified on a case-by-case basis.

A common requirement is to support the application for consents with relevant technical studies which assess the impact of the proposed development on the marine environment, including issues related to seabed mobility, where relevant. These studies may also be a legal, financial, and / or an insurance requirement, although not all projects may require a detailed level of assessment.

4.4.1 SCREENING

Screening helps determine whether a proposed development should be subject to an Environmental Impact Assessment (EIA) and, if so, at what level of detail. An approach to environmental screening is provided in:

The World Bank (1993). Environmental Assessment Sourcebook. Updates 1993. Numbers 1 – 5. Report No. 21923. Environmental Department.

Number 2, Environmental Screening of the Sourcebook sets out three categories of potential impact:

- Category A requires a full EIA if the project is likely to have significant negative environmental impacts or impacts may occur over a wide area, as well as a high level of social impact.
- Category B is where the project is likely to have less environmental and social impacts than Category A and only needs a reduced level of EIA.
- Category C has minimal to no negative environmental or social impacts, and no EIA is required.

Importantly, country level requirements may supersede these categories and identify different screening criteria.

Screening should be based on the best available information at the time in order that an informed opinion can be made by the relevant authorities, providing sufficient detail on the project type and components, location and extent, duration of activity, sensitivity of local environmental issues, nature and magnitude of anticipated impacts, and possible mitigation measures.

In isolation, issues related to seabed mobility are unlikely to be a determining factor influencing the screening decision, however, substantial seabed preparation activities which might lead to a potential adverse effect to sensitive environmental receptors are likely to contribute towards Category A.

If project screening allows the consenting authority to confirm that an EIA is not required to support Consenting, then no further environmental assessments would be required beyond this stage.

4.4.2 CONSENTING GUIDANCE AND STANDARDS

If the Screening stage (Section 4.4.1) confirms the requirement for a full EIA (also commonly referred to as an Environmental Assessment (EA) or Environmental and Social Impact Assessment (ESIA)) then the scope of this assessment is expected to cover a broad and inclusive range of studies relevant to issues where the development might lead to a potential risk to sensitive environmental receptors.

The range of studies required for the EIA is expected to include a consideration of potential impacts on marine processes (i.e., physical changes in the coastal and marine environment, including effects on seabed mobility), amongst other topics. Presently available marine processes guidance which recognises the issue of seabed mobility (or other equivalent terms) includes:

Cefas (2012). Guidelines for Data Acquisition to Support Marine Environmental Assessments of Offshore Renewable Energy Projects.

Brooks, A.J., Whitehead, P.A., Lambkin, D.O. (2018). Guidance on Best Practice for Marine and Coastal Physical Processes Baseline Survey and Monitoring Requirements to inform EIA of Major Development Projects. NRW Report No: 243, 119 pp, Natural Resources Wales, Cardiff.

Lambkin, D.O., Harris, J.M., Cooper, W.S. and Coates, T. (2009). Coastal Process Modelling for Offshore Wind Farm Environmental Impact Assessment: Best Practice Guidance. COWRIE.

Natural Resources Wales (2024). GN019. Completing a coastal or physical processes assessment for small-scale projects. Guidance note. Version 1.

Natural Resources Wales (2025). GN041. Marine Physical Processes Guidance to inform Environmental Impact Assessment (EIA). Version 2.

Pye, K., Blott, S., Brown, J. (2017). Advice to Inform Development of Guidance on Marine, Coastal and Estuarine Physical Processes Numerical Modelling Assessments. NRW Report No: 208, 139 pp, Natural Resources Wales, Cardiff.

Scottish Government (2026). Offshore Wind Environmental Impact Assessment in Shelf Seas: Guidelines for the Assessment of Changes to Marine Physical Processes. Report produced by ABPmer with support from Cooper Marine Advisors on behalf of the Scottish Government. January 2026.

In particular, the importance of establishing the baseline understanding of seabed mobility is recognised, as well as the potential for interruptions to sediment pathways which might adversely impact downdrift receptors (e.g., sandbanks, etc.).

4.4.3 ENVIRONMENTAL IMPACT IDENTIFICATION

An ENVironmental Impact IDentification (ENVID) is a recommended step at the outset of the Consenting stage, with the objective of identifying and describing potential environmental hazards that may arise or interfere with any aspect of the proposed development. Offshore considerations may include identification of areas with challenging seabed features (e.g., mobile sandwaves, sandbanks, migrating channels, etc.), as well as any Protected Areas (e.g., designated features such as subtidal sandbanks). Associated measures (e.g., cable protection) that may prevent, control, or mitigate the identified hazards, in addition to monitoring schemes, should also be considered. The output from the ENVID can usefully inform the project's risk register (Appendix A).

An ENVID is typically held as a workshop, attended by multi-disciplined groups (including but not limited to technical specialists, engineers, and project managers) and informed by available information available at the time, ideally the initial seabed mobility study (Section 3.2.1).

4.4.4 SCOPING

If an EIA becomes a confirmed requirement, then a scoping exercise should be undertaken with the objective of establishing the issues that are likely to be of most importance (i.e., scoped in) for the EIA phase and removes those that are justifiably of little concern (i.e., scoped out on the basis of presenting sufficient, pre-existing evidence of no significant impact).

A scoping report aids the consultation process and provides the opportunity for stakeholders to express their views which can then support the scoping opinion from the regulatory body. The scoping report will cover all relevant EIA topics, including marine and coastal processes, and is expected to set out the following issues (informed by the initial seabed mobility assessment – Section 3.2.1):

- High-level summary of the type and purpose of the development, including options for installation (including seabed preparation, etc.) and decommissioning. At this point, information available from Preliminary Design is likely to be provisional and subject to further refinement.
- A study area, informed by the likely extent of relevant pathways (including those related to suspended sediment and bedload transport) and location of linked seabed environmental receptors (e.g., sandbanks).
- An overview of the baseline sediment environment and functioning of relevant environmental receptors within the study area.
- The environmental issues and effects to be considered in the EIA, along with the justification for any issues that can be scoped out.
- Potential for cumulative and in-combination effects.
- Data and information required to support the assessment, including an outline for new surveys (as identified from the initial seabed mobility assessment – Section 3.2.1).
- An outline of the proposed methods for assessment (including source-pathway-receptor approach, marine process modelling, evidence-based approach, etc.).
- Limitations in the information and approach and how they will be accounted for.
- Criteria that will be used to determine significance of effects.
- Approach to mitigation.

The scoping opinion, provided back to the developer by the regulator, should be considered to help finalise the scope for the EIA process.

4.4.5 EIA

Seabed mobility issues are expected to be part of the marine and coastal processes EIA topic (also commonly referred to as marine geology, oceanography, and physical processes). Notably, this topic is likely to inform other EIA topics which require an interpretation of how potential changes in marine and coastal process (including those related to seabed mobility) might impact other types of environmental receptors, such as the benthic environment, etc.

The following review focuses on potential seabed mobility issues pertinent to an EIA, although not all issues are expected to apply in every case. Guidance identified in Section 4.4.2 should be considered where a more complete consideration of marine and coastal processes is required for non-seabed mobility related issues, including effects on stratification, sediment plumes, etc.

4.4.5.1 Inputs to support the EIA

The EIA process will draw from the scoping phase, consultation, the initial seabed mobility study, new surveys, and the Project Design Envelope (Section 4.4.5.3) to deliver the impact assessment. The availability of relevant data to support the consenting stage should be identifiable from the project's data register (Appendix B) where information has already been collated.

An additional data type which frequently supports EIA is the evidence base of environmental monitoring collated from earlier projects. If the available evidence represents a comparable project activity in a comparable environmental setting, then a comparable outcome would be expected in the proposed case. On this basis, a simplified evidence-based approach can be considered as an alternative, or complementary to, standard analytical approaches.

4.4.5.2 Baseline

A baseline description for the study area should draw on the latest version of the seabed mobility assessment and include a description of the form and function of related seabed environmental receptors (e.g., designated sandbanks, etc.).

Inherently, baseline understanding will be developed from information obtained from the pre-construction period, however, the recommended definition for EIA purposes is the baseline represents conditions that are expected to occur if no development was to take place, and for an equivalent period. Accordingly, the baseline description should take account of pre-construction, construction, operational, and decommissioning periods, along with a post-decommissioning recovery period, with consideration of natural variability over these durations including climate change factors, as relevant.

Project specific seabed environmental receptors susceptible to changes in seabed mobility should be identified as part of the Scoping process (Section 4.4.4). Examples may include the adjacent coastline, protected wrecks (marine archaeology topic), seabed features with a marine protected area such as a sub-tidal sandbank, etc., as well as ecological interests such as marine benthos. The relationship of each receptor with the inherent variability in baseline conditions should be established to help determine a normal level of tolerance.

The baseline description of seabed mobility issues related to for marine and coastal processes is expected to cover the following issues, as relevant and in accordance with local guidance:

- Geological setting, including notable hard constraints, such as rocky headlands, seabed out crops and shallow sub-crops.
- Bathymetry and seabed profile.
- Description of surficial sediment type(s).
- Seabed features (e.g., mobile bedforms, channels, troughs, etc.).
- Metocean conditions (typical and extreme).
- Sediment transport pathways.
- Adjacent coastline geomorphology and long-term behaviour.
- Relationship with marine and coastal processes receptors.
- Climate change influences on marine processes relevant to the project lifetime and future baseline conditions.
- Data limitations / key assumptions.

4.4.5.3 Project Design Envelope

Key inputs to the EIA process are the design options developed by preliminary design (Section 4.3) for structures planned to be installed on the seabed and methods, including cable routes, landfalls, array layouts, as applicable. These options are collectively termed the Project Design Envelope (PDE) which also establishes the methods of installation and removal. Achieving consent for the full PDE retains flexibility for the project going forward into Detailed Design.

The typical approach is to appraise the activities planned for each stage of project development to help identify the option within the PDE which is likely to lead to the most severe environmental impact. This option is typically known as the maximum design scenario (also commonly referred to as the maximum-case scenario, worst-case scenario, or the realistic worst-case). The assumption is that if maximum design scenario has no significant impact on environmental receptors, and can achieve consent, then all other options with a lesser scale of environmental impact would also be acceptable. Notably, inherent conservatism in the PDE will carry through to the selection and assessment of the maximum design scenario.

Design information available at this time remains high level and indicative and may be subject to revision for various reasons (e.g., design mitigation or design refinement) may lead to the requirement to reconfirm the maximum design scenario. For example, the estimated areas and volumes of sediment planned for seabed levelling may be updated due to improvements in baseline information, refinements in method of calculation, etc.

4.4.5.4 Impact Assessment Methodology

The purpose of the impact assessment is to determine how the development (represented by the maximum design scenario) might alter baseline conditions (independently and in-combination with other activities) and whether these changes are considered to lead to a significant impact on an associated environmental receptor.

A recognised method to support the impact assessment is to apply the source-pathway-receptor (SPR) approach:

- **Source** – a description of the source of effects.
- **Pathway** – the process which enables the source of effects to propagate further afield, e.g., tidal advection, seabed mobility, etc.
- **Receptor** – an environmental feature which is sensitive to a change in conditions attributed to the source (via the pathway).

Changes are typically deduced by considering how the baseline conditions could be modified in terms of the magnitude, direction (positive / negative), extent, and duration of effects associated with the development. Reversibility of changes and recovery of baseline conditions is also relevant when the source of any effect ceases. Examples of the type of changes in baseline seabed mobility conditions might include a modified substrate type, seabed level, bedform characteristics, sediment transport pathways, or the rate of deposition / erosion, etc. The interpretation of such changes should be considered relative to baseline variability and the tolerance of associated environmental receptors. If impacts on receptors are considered significant then appropriate forms of mitigations in design approaches should be considered which require feedback with preliminary design.

Coastal and marine process modelling can provide a useful framework to support the SPR approach where sources and pathways can be simulated and the magnitude of changes determined at the location of receptors. However, there may also be cases where other analytical methods may need to be considered, either independently or in conjunction with such models. Further details on recommended Analytical Methods are provided in Appendix G.

4.4.5.5 Construction issues

The construction activities outlined in the PDE are likely to include various localised seabed preparations and excavations across the development area to install cables, pipelines or foundations, along with ancillaries such as scour protection and cable protection measures.

a. Landfall and nearshore works

In the case of landfall works, the primary receptor is expected to be the adjacent coastline and beach processes across the littoral zone, as relevant. Landfall works are generally spatially limited to the nearshore and intertidal area, as well as being short-term. Once completed littoral processes are expected to recover relatively quickly, especially if the baseline demonstrates a high level of seabed mobility.

For example, the installation of temporary cofferdams could act as a barrier and disrupt longshore drift, leading to a build-up of sediment and creating an interruption of down-drift supply with an associated increase of erosion rates, etc. Mitigation of potential impacts could include mechanical bypassing of the build-up of sediment from the updrift side of any temporary obstacles, placing material on the downdrift side to alleviate concerns of localised erosion. This mitigation may only be necessary if large sediment volumes are involved and temporary works are in place for a relatively long period.

In the case of HDD options at landfall, the excavation of nearshore exit pits in the nearshore could lead to stockpiling of material on the adjacent seabed as a temporary spoil mound which may locally modify flows and waves with associated effects on adjacent beach processes and morphology. Prior to backfilling, some material may also be lost from the mound by erosion, and the exit pits may also experience some infilling prior to completion of works.

b. Seabed levelling

Preliminary Design will establish the locations requiring seabed levelling (Section 4.3.2.3) to assist installation of assets (e.g., cables, foundations, scour protection, etc.), an estimate of the associated amounts of material to be cleared away, as well as the potential methods to achieve the required outcome. The EIA will consider the potential effects of this activity on the marine environment.

Seabed levelling may be achieved by several methods with the option of using a trailing suction hopper dredger (TSHD) generally considered to represent the maximum design scenario due to the associated level of seabed disturbance (both at source and location of subsequent disposal) compared with other options such as mass flow excavator (MFE).

In relation to seabed mobility issues, the perceived concern is that if seabed levelling by TSHD removes large sediment volumes from an area this might modify the local sediment budget and the characteristics of that area, as well as leading to potential changes to associated sediment pathways. The chances for such modifications to occur depend on the scale of planned activities and details of the local sedimentary system. The recommended strategy is to dispose the dredged sediment within the same 'local system' to retain and minimise net loss to the sediment budget and return dredged material to the seabed 'updrift' of the location of removal to aid seabed recovery, if required.

Additional concerns could relate to the disposal of dredgings leading to the formation of spoil mounds smothering seabed receptors (e.g., benthic communities, marine archaeology, etc.), and their longevity in modifying the local seabed profile and conditions. The capacity of local sediment regime to redistribute the spoil mound material elsewhere also provides an important indicator to the longevity of the spoil mound. For example, a spoil mound formed of coarse sediments disposed onto a seabed of fine sediments would expect to be longer lasting than fine sediments disposed onto a seabed of coarse sediments. If the disposal was retained within the local system, then the spoil mound is likely to integrate better with ambient seabed conditions.

When seabed levelling is required for sandwave clearance in areas linked to an environmental receptor (e.g., designated sandbank) then the EIA may require a consideration of sandwave recovery. The rate of sandwave recovery is likely to be a best estimate at this time, based on existing details such as sediment availability, sediment transport rates and directions, and also from the evidence base from previous projects. If high uncertainties remain in this estimate, then demonstrating sandwave recovery may become a consent condition involving monitoring provisions. Appendix D includes additional details related to monitoring sandwave recovery.

c. Cable burial

In most cases, export and inter-array cables are expected to be buried to a specified depth below seabed (the 'depth of lowering') to protect the cable from external threats. Trenching tools will be selected according to the sediment conditions likely to be encountered, noting the depth of lowering may vary along cable routes depending on the soil conditions and threats to cables.

An initial assessment of cable burial requirements is recommended to support preliminary design (e.g., an initial CBRA, see Section 4.3.2.1) and to inform the EIA. This assessment will help demonstrate that the potential for cable exposure due to seabed mobility is sufficiently well understood and mitigated by the proposed burial depth. The assessment should also provide the basis to determine suitable provisions for reburial and use of external cable protection during the operational stage.

4.4.5.6 Operational issues

a. External cable protection

Preliminary design will determine the requirements for external cable protection where burial may not be possible (Section 4.3.2.2), with additional provisions to manage exposed cables (e.g., due to seabed mobility) during the operational stage.

The EIA will consider the type and volume of cable protection measures, the intended seabed profile when deployed, and the likely locations where these measures will be required. The perceived environmental concerns with the use of external cable protection include:

- The introduction of hard substrates (e.g., rock armour, concrete mattresses, etc.) in areas not previously associated with that type of habitat.
- The potential interruption to bedload sediment pathways due to the vertical profile of cable protection creating a shallow profile ridge.

For UK environmentally sensitive areas JNCC and Natural England (2022) suggest that consideration is made of the angle at which cables approach the coast where external cable protection is likely to be needed. The recommendation is that external cable protection placed in a dynamic shallow environment should avoid being perpendicular to the direction of sediment transport pathways (e.g., the long side of the rock protection should avoid being parallel with the orientation of flow-transverse bedforms or the general direction of littoral drift) as this may interrupt these pathways and potentially lead to the development of local scour pits along the toe of the cable protection.

Apart from environmental concerns, these scour pits may also affect the stability of rock berms.

If consented provisions for external cable protection become exhausted during the operational stage, then an additional consent may be required to extend these provisions.

Wave Hub is a testing facility for wave energy convertors and was installed in 2010 off Hayle, North Cornwall, UK. The project provides an example where a section of export cable subsequently became exposed on the beach (Section 4.3.2.7), as well as a surface laid section in the sub-tidal which developed free-spans over a 110 m section (KP 3.8 to KP 3.9) in a water depth of around 19 m (CD). The original cable installation was informed by a geophysical survey with burial planned from landfall out to the seaward limit of sand cover across St. Ives Bay. Beyond the shelter of St Ives Bay, the sandy sediment thins over rock, with the cable extending further offshore surface laid with rock dumping to fix the cable in place. Since installation, the following works have been required:

- In 2011, six rock mattresses were installed to stabilise the export cable between KP 3.8 and KP 5.1 in the transition area between the sandy and rocky areas.
- In 2014, an inspection survey observed free-spanning and cable exposure between some of the rock mattresses (Insight Marine Projects, (2014)).
- In 2015, a total of 105 filter units (rock filled mesh bags) were used to further protect the cable which reduced local water depths to around 18 m (CD), equating to around 5% shallowing (Mojo Maritime, (2015)). The remedial work was subject to a separate marine licence. **Figure 5** shows the area with recent rock dumping, along with evidence of megaripples and rocky outcrops.

Cable exposure in the sub-tidal is believed to have originated due to the local seabed substrate preventing complete cable burial at the time of installation, whereas exposure in the intertidal was due to an underestimation of storm induced variability of beach levels.

4 PROJECT DEVELOPMENT REQUIREMENTS
CONTINUED

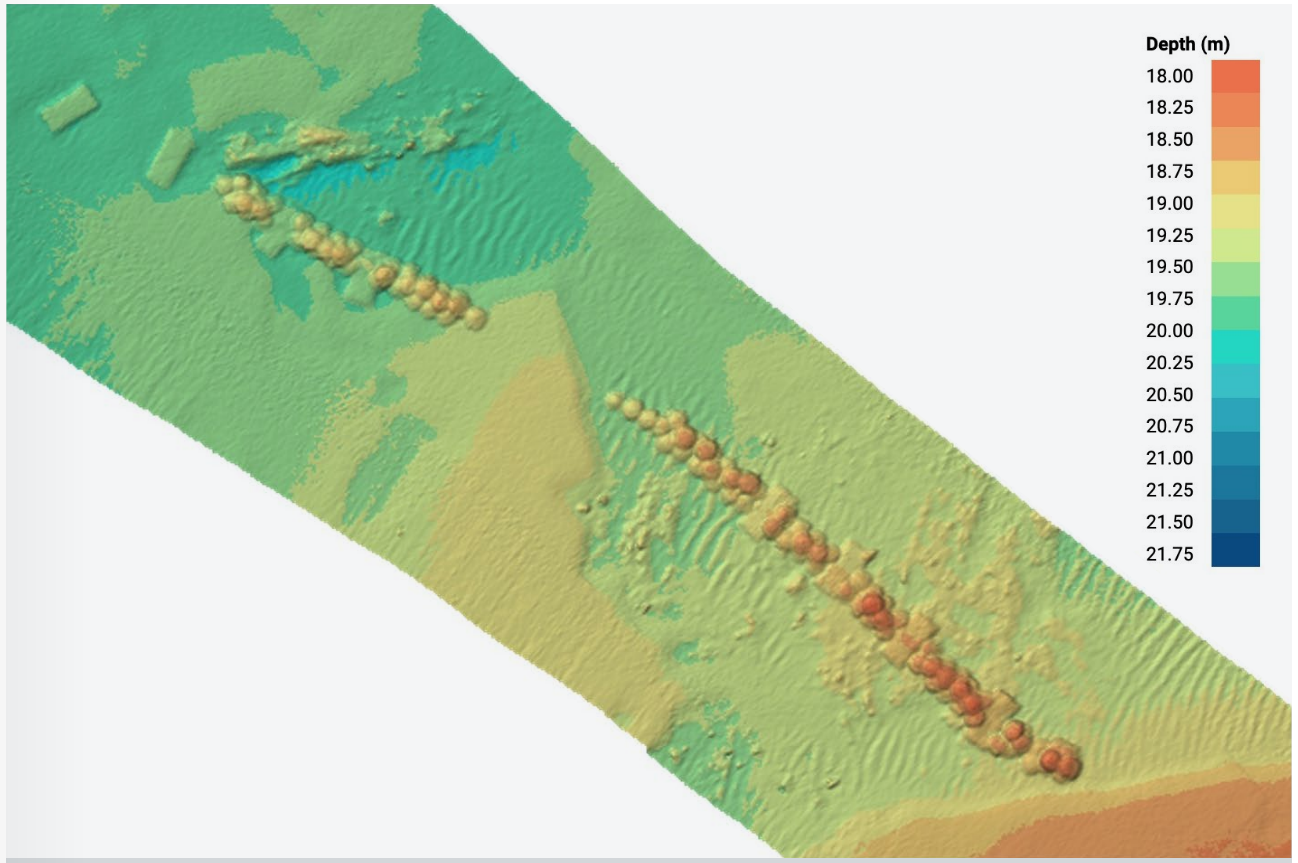


Figure 5 – Post-construction installation of external cable protection at Wave Hub (Mojo Maritime, (2015))

b. Cable crossings

Similar environmental concerns are likely for cable crossings to those expressed for external cable protection (Section 4.4.5.6.a). Where the likely locations required for remedial external cable protection are provisional at this juncture, those related to crossings will be at specific locations related to existing assets. In addition, the configuration of a cable crossing will typically be in a cross formation instead of a linear alignment.

c. Fixed foundations

During the operational stage, the presence of fixed foundations on a mobile seabed has the potential to develop local scour due to flow acceleration around the structure and increased turbulence created in the near field. Local scour typically achieves an equilibrium condition in the short-term. In some case, the scouring process can also lead to the formation of "scour tails" represented by an additional modification to the profile of the seabed extending downdrift of each foundation by few hundred metres. Various forms of scour tails have been observed in different situations, including an extended shallow depression, an area with increased deposition, or an area with enhanced bedform development. Local scour and the formation of scour tails are additional to any change in seabed levels due to seabed mobility. Local scour is typically mitigated with suitably designed scour protection to maintain structural stability (Section 4.3.2.5).

Apart from local scouring, an array of foundations with scour protection (where present) has the potential to cause drag and blockage effects which may cumulatively modify flows or waves at the array-scale, potentially influencing rates of sediment transport and affecting seabed mobility over a wider area. The consequence of this effect may need to be considered for the EIA, especially where there are adjacent environmental receptors which could be sensitive to a change in conditions. Coastal process models can provide an effective tool to support this type of investigation, noting that the short-term effects due to array-scale blockage may be relatively small but progressive over the medium to long term. This may require modelling to cover a suitable duration to determine any discernible net changes to the baseline condition.

d. Floating foundations

Floating foundations are expected to be located in deeper water than those used for fixed foundations and where seabed conditions are likely to be relatively benign, characterised by weaker flows and with wave effects dissipating much higher in the water column. The level of seabed mobility is typically considered “Low” (Section 3.2.13) for such locations, noting that if bedforms are identified in the development area they are likely to be moribund (immobile) features.

Floating foundations and platforms may modify surface waves and flows, but they will not directly interfere with seabed mobility; however, their mooring arrangements and cables will still be connected to the seabed by some means (e.g., anchoring devices) which may protrude above the seabed to interfere with seabed processes. Local scour is unlikely to be a threat to these structures.

When there is slack in mooring lines or anchor chains used to secure a floating platform, this may lead to occasional touch-down with an associated period of the line being swept across the seabed. This contact may lead to some abrasion to the mooring lines or anchor chains, as well as mobilising surficial sediment. In some cases, this process may develop a shallow trench. A review of seabed trenches formed at the location of floating platforms is provided in Rui et al. (2023). The rate and extent of trench development is likely to be influenced by local sediment properties with highest rates of development and extents anticipated to occur in areas with erodible sediment.

In most cases, the impact of floating foundations on seabed mobility can be scoped out from the EIA unless there is an immediate risk to an identified receptor.

4.4.5.7 Decommissioning issues

Preliminary design should establish a high-level decommissioning plan based on presently available methods, technology, and legislation.

Environmental concerns related to seabed mobility during decommissioning are likely to include short-term seabed disturbances during the decommissioning activity and the ability for the seabed to recover to a future baseline after decommissioning is completed. A further concern over the longer-term related to seabed mobility is the potential exposure of cut piles or cables left in situ.

The actual decommissioning requirements can only be confirmed at the end of the lease period which may be 25 to 40 years in the future. Available technologies and legislation are expected to have evolved in this period. Section 4.8 provides additional insights related to decommissioning issues.

a. Cables

In cases where buried cables are removed this may be achieved by pulling out and cutting off short sections. In some cases, the overburden covering the cable will need to be removed first using tools such as MFE. In areas with high seabed mobility, the rate of seabed recovery post-decommissioning is expected to be relatively quick.

Sections of cables covered with rock armour are most likely to remain in situ, as will cable crossings, although recovery of external cable protection materials and cables may be possible in some cases.

b. Foundations

There are a variety of foundation types, both fixed and floating. Some foundations can be readily removed (e.g., suction bucket caissons, gravity bases, etc.) while other piled foundations may be more challenging.

Piled foundations which are left in situ are typically cut to a required depth below the seabed. For an area with a level of seabed mobility indicated as High this depth should be considered relative to the lowest seabed level (LSBL) to avoid exposure of the cut pile in the future.

The removal of foundation sections from above the seabed ceases any array-scale drag effects on waves and flows previously experienced during the operational stage.

4.4.5.8 Environmental Statement

The Environmental Statement (also known as Environmental Impact Assessment Report, Environmental Impact Statement, Environmental Impact Report, or similar) will report on the outcomes from the EIA process. Seabed mobility issues should be included in the marine and coastal processes chapter, as relevant. Where uncertainties remain in the impact assessment, proposals should be put forward for potential mitigation and monitoring.

4.4.5.9 Licence conditions

When consent is confirmed, there may be associated licence conditions which feed into the detailed design stage (design mitigation) and / or establish a requirement for environmental monitoring to obtain evidence of actual effects during the operational stage.

For example, Race Bank Offshore Wind Farm was consented with a requirement to demonstrate sandwave recovery for areas dredged within the Inner Dowsing, Race Bank and North Ridge Special Area of Conservation (SAC) and to help validate assertions made in the EIA (Larsen, Roulund, & McIntyre, 2019).

4.4.6 KEY POINTS FOR CONSENTING

Consenting activities should expect to move forwards in tandem with preliminary design. This enables the ongoing development of design options to inform consenting activities at appropriate times and allows for feedback and design mitigation of potentially unacceptable impacts, where necessary.

Whilst consenting and preliminary design are generally separate workstreams, expected to be led by different technical teams, there are clear benefits for thematic topics which span both workstreams, such as seabed mobility, to be delivered by the same specialists.

The scope and purpose of a detailed seabed mobility study is typically more aligned to preliminary design than consenting. The main common requirements relate to the baseline understanding developed for the updated CSM (Section 3.2.12) and seabed mobility maps (Section 3.2.13).

Consenting activities assess the options developed by preliminary design. Where there are multiple options then the consenting stage will typically assess what is determined to be the worst-case option of the PDE (Section 4.4.5.3) to ensure the greatest scale of impact is considered. Accordingly, all other design options are considered to lead to a lesser scale of impact, in comparison.

Any inherent conservatism in design at this stage will carry through to the evaluation of potential environmental impacts. This conservatism is also necessary as a contingency so that refined values related to the final design, established post-consent, will not be greater and risk invalidating the basis of consent.

While preliminary design focuses on survivability of installed assets under extreme environmental conditions, technical studies supporting the consenting stage will typically focus on the consequence of these designs across adjacent areas under typical environmental conditions which are expected to occur within the timeframe of the project, through to decommissioning.

Finally, post-construction asset monitoring that might be required through the operational stage may also be relevant to support specific licence conditions on the consent agreements that might require similar types of monitoring.

4.5 DETAILED DESIGN

Detailed design selects and finalises the design options advanced from the consented Project Design Envelope, including confirming the location and specification of installed structures, cable routes, installation techniques, and landfall strategies, as applicable.

Additional investigation can be considered at this time, especially if new data and information has become available in the interim (e.g., geotechnical investigations), and this can usefully reduce uncertainties to a manageable level. For example, refining, verifying and updating the assessment of seabed mobility undertaken for preliminary design.

Once completed, the detailed design, and key supporting studies, is typically reviewed by an independent certifying body to verify that the proposed work meets predefined standards for quality, safety, and performance.

4.5.1 POST-CONSENT REQUIREMENTS

In some jurisdictions, the consenting stage may set requirements for submission of final design options and plans prior to construction. An example of such a document relevant to seabed mobility considerations is the Cable Specification and Installation Plan (CSIP) which specifies final technical parameters including, routing, clearance requirements, burial strategy, installation methodology, and monitoring plans, mitigation provisions for cable exposure, etc. The CSIP will also be informed by the final CBRA (Section 4.3.2.1). On occasion, the CSIP may also be referred to as the Cable Plan (CaP). If such plans/reports are a confirmed requirement then necessary information is collated and the required outputs should be developed during the detailed design stage to prevent delays in construction.

4.5.2 DATA AND INFORMATION

New data and information should be identified where this can usefully update the initial seabed mobility assessment which is likely to have been developed to support preliminary design and help reduce uncertainties. This data and information may be from new project surveys, or third-party routine monitoring in the area, as well as more recent publications.

In addition, other developments or activities which have occurred in the interim, or are planned for, should be identified and accounted for where these may have an influence on local seabed mobility.

4.5.2.1 Bathymetric data

Additional bathymetry data may have become available in the period since future seabed levels were initially developed which can be used to help verify the predictions for this period. Subject to programme, bespoke surveys could also be considered early in the detailed design stage where this data can help verify future seabed levels, trends and rates of change in seabed levels and/or sandwave migration rates, as relevant.

4.5.2.2 Geotechnical observations / boreholes

Unless already available, geotechnical surveys are commonly scheduled early in detailed design to collect sediment cores (e.g., boreholes, vibrocores, etc.) at strategically important sites, such as planned pile locations. This data helps validate previously interpreted shallow geophysical properties (e.g., reducing uncertainties due to assumed speed of sound, etc.) and in the further development of the project Ground Model (Section 3.2.10).

Where cores coincide with areas with a mobile seabed then the depth of erodible and non-erodible layers should be identifiable. The Ground Model will provide the spatial description of these layers across the project site.

In addition, the likelihood is that sediment characteristics until this point have been based on surficial grab samples only, with this information used to infer near-surface sediment properties. These assumptions can be verified if soil testing is available in upper sections of the core to offer other useful information such as sub-surface particle size analysis, shear strength, bulk density, dry density, etc.

4.5.2.3 Metocean conditions

If metocean instruments have been deployed on site for the duration since preliminary design, or ongoing monitoring programmes remain available in the general area from third-party deployments, then additional metocean information will be available at this time which may be useful in updating previous metocean analysis. These refinements can then be considered in relation to the CSM, as applicable.

4.5.2.4 Other site investigations

The project may decide to commission field trials for planned construction activities which may also yield useful information related to seabed mobility. For example, to confirm optimum installation methods for seabed preparation and installation. The need for, and benefit of, these types of investigations is entirely project specific and should be evaluated accordingly.

4.5.2.5 More recent publications

Where a previous phase of seabed mobility assessment has drawn from third-party publications then latest revisions should be considered to verify if key information has been updated.

Applicable guidance and standards are likely to be the same as those used to support preliminary design (Section 4.3.1); however, confirmation should be made of any changes and updates in the interim.

Latest reports from the Intergovernmental Panel on Climate Change (IPCC) may have been published in the interim to provide improved insights on future climate conditions, such as revised rates of sea level rise, the frequency and intensity of storm conditions, hurricanes, or tropical storms, etc.

4.5.3 UPDATING SEABED MOBILITY ASSESSMENT

At this stage, a detailed seabed mobility assessment is likely to have already been undertaken based on data and information available at the time. The main outputs from this assessment (i.e., CSM, seabed mobility maps, and predicted future seabed levels) should be updated, as necessary, based on the availability of new data and information (Section 4.5.2) to help reduce uncertainty. For example, if new bathymetry data is available with complete or partial coverage of areas of interest then this information provides an important opportunity to validate, refine or update the predicted future seabed levels, as well as rebasing the associated uncertainties.

4.5.4 KEY POINTS FOR DETAILED DESIGN

For efficiency, seabed mobility assessments which are required to support detailed design should aim to provide suitable updates and extensions to work which has previously supported preliminary design. The main aim is to improve confidence and reduce uncertainties in key outputs, such as future seabed levels, and make these outputs ready for independent certification.

The amount of effort required to perform updates and extensions will reflect on the amount of new survey data and information which has emerged in the interim, as well as the length of time since preliminary design was completed. A further consideration at this time is to account for any design or monitoring conditions arising from the consenting stage.

If there is still a high level of uncertainty which cannot be easily reduced at this time, then guidance should be provided to set out how to manage this uncertainty going forwards. For example, informing monitoring campaigns planned for the construction and/or O&M stages.

4.6 CONSTRUCTION

The construction stage comprises the installation of the specified structures at the consented locations and/or routes, following agreed installation techniques, procedures and strategies. This process is generally led by Engineering, Procurement, Construction, and Installation (EPCI) contractors. Cables (or pipelines) and substructure are often installed by different contractors with different vessels, equipment and procedures.

At this juncture, an appropriate understanding of seabed mobility should be well-documented with any identified residual risks or uncertainties sufficiently understood so that they can be appropriately mitigated or reduced to a manageable level. Residual risks detailed by the most up to date version of the seabed mobility assessment should be actively assessed to ensure that installation activities proceed in accordance with design assumptions and consent conditions.

Risks and uncertainties associated with seabed mobility should be clearly identified and considered through construction documentation, such as the:

- Foundation (or Anchor) installation plan.
- CSIP which outlines routing, burial depth targets, installation methodology, and monitoring provisions tailored to site-specific seabed mobility conditions.

These requirements ensure that construction proceeds in a manner that is both technically robust and environmentally compliant in accordance with consenting and detailed design assumptions.

4.6.1 CONSTRUCTION RESPONSIBILITIES

In the construction stage, the certified design is installed by marine contractors using agreed techniques. Inherently, for the project to have progressed to the construction stage and achieved design certification, relevant seabed mobility issues will have been appropriately assessed, and risks mitigated with an appropriate level of confidence. Relevant details from the latest seabed mobility assessment, and any residual risks and uncertainties, should be effectively communicated to the installation contractor and associated users of the data and information.

During the construction stage, the detailed design must be implemented in strict accordance with applicable (inter)national legislation, industry standards, and developer-specific requirements, all of which aim to mitigate risks to both assets and the environment. Construction activities must reflect approved mitigation measures, including sediment control strategies, and protected species safeguards, as required. While design requirements will have been established during earlier phases (i.e. preliminary and detailed design, and consenting), any updates or additions, particularly those related to environmental mitigation and compliance with conditions attributed to a marine licence or permit, must be fully integrated into construction planning and execution.

During the construction stage, compliance with conditions set during the consenting stage must be demonstrated through the submission of post-consent documentation, which is often a pre-requisite for commencing physical works. These documents serve to confirm that regulatory, environmental, and technical obligations are being met. A key example is the CSIP which outlines essential construction stage details including cable routing, clearance zones, burial depth targets, installation methodologies, and monitoring strategies. These plans are reviewed by regulators to ensure that construction activities will proceed in accordance with approved mitigation measures and technical standards. Timely preparation and submission of these documents are critical to avoid delays and ensure regulatory compliance throughout the construction process.

4.6.2 CONSTRUCTION PROCESSES

The construction process generally comprises the following stages:

- Pre-construction survey to confirm conditions prior to construction operations.
- Seabed preparation works.
- Infrastructure installation (i.e., foundations, cables, pipelines, scour protection, etc.).

Notably, the construction process is expected to elapse several years from start to end. The anticipated variability of seabed levels, and associated construction risks, over this period should be considered to assist construction planning.

4.6.2.1 Seabed preparation works

There is a general requirement for cable laying tools to lay cables/pipelines on a relatively flat seabed (with low cable tension) to provide stability, prevent free-spanning and reduce potential trenching issues due to steep slopes. This may require the removal or 'smoothing' of mobile bedforms, especially sandwaves.

Targeted seabed preparation may be also required at the location of foundations. This activity is required to ensure the stability and integrity of foundations and scour protection by providing a level seafloor for the landing of the foundation (especially gravity base foundations) and/or installation equipment.

Pre-construction bathymetric data is required to confirm the present status of the target areas, optimise planning of the 'flattening' operations and to help minimise the volume of disturbed sediments. These operations can be undertaken using TSHDs, specialised dredging vessels, MFE, CFE, or seabed ploughs to level uneven seabed topography or to expose stable seabed layers coincident with RSBL (Section 3.2.15). An example of sandwave levelling for inter-array cables is shown in **Figure 6**.

Sandwave levelling will result in a temporary modification to the seabed profile with subsequent activities needing to be completed before the adjacent bedforms migrate across the levelled areas and sandwave recovery commences. In situations with a rapidly migrating seabed this interval may be relatively short. Appendix D provides additional insights to the issue of sandwave recovery.

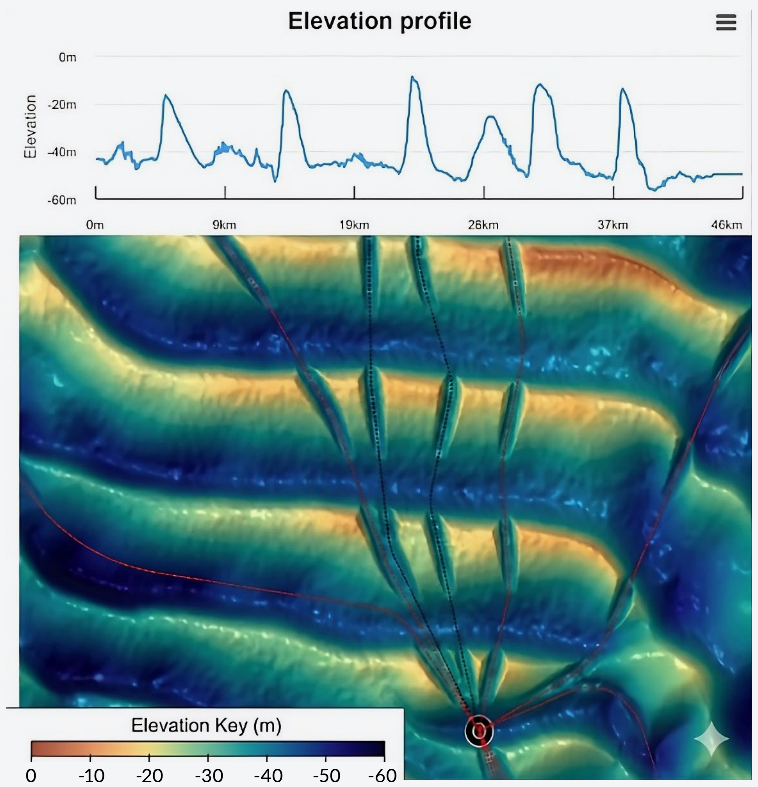


Figure 6 – Example of sandwave levelling in Taiwan Straits

4.6.2.2 Foundation / anchor installation

There are a wide variety of fixed foundation and floating system anchors that could be implemented for offshore developments. **Table 2** provides an outline of installation activities for some of the more common options related to offshore wind farms and installation of wind turbine generators (WTG).

TYPE	VESSEL / EQUIPMENT	POTENTIAL INSTALLATION SEQUENCE	INITIAL SEABED MOBILITY CONSTRUCTION SENSITIVITY RANKING
Driven monopile	Floating or jack-up Generally, vessel mounted gripper (no seabed frame)	1. Visual seabed inspection 2. Install scour protection (usually filter layer) 3. Monopile control (usually gripper attached to vessel) 4. Touch down onto seabed 5. Driving to target depth 6. Install armour layer	Low for floating vessels Medium for jack-up vessel
Drill & grout monopile	Usually jack up Generally, seabed frame to provide reaction for drilling	1. Visual seabed inspection 2. Drilling rig onto seabed 3. Drill rock socket 4. Install pile into rock socket 5. Grout 6. Install scour protection	Low – mobility usually less of an issue for ‘rocky’ sites)
Pre-piled jacket	Floating or jack-up	1. Visual seabed inspection / preparation for piling frame 2. Piling frame onto seabed 3. Drive piles 4. Install scour protection 5. Install jacket	Medium to high – piling frames and jack ups potentially sensitive to slopes and bathymetry changes
Post-piled jacket	Floating or jack-up	1. Visual seabed inspection / preparation for jacket mudmats 2. Lower jacket to seabed 3. Drive piles 4. Install scour protection	Medium to high – mudmats sensitive to slopes and bathymetry changes
Suction bucket jacket	Floating or jack-up	1. Visual seabed inspection 2. Lower jacket to seabed 3. Suction installation 4. Install scour protection	Low to medium – suction buckets less sensitive to bathymetry, particularly if base grouted
Gravity Base	Floating or jack-up	1. Visual seabed inspection 2. Seabed preparation – generally dredging and gravel bed installation 3. Lower gravity base structure (GBS) to seabed 4. Install scour protection	High – level seabed and gravel beds are generally required
Drag anchor	Floating	1. Inspect anchor trajectory 2. Lower anchor to seabed 3. Install anchor to design tension and/or design location (drag distance 50 to 200 m)	Low
WTG (fixed)	Jack-up	1. Visual seabed inspection 2. Jack up (spud-cans onto seabed and raise hull out of water) 3. Install WTG 4. Jack down (lower hull to sea level and raise spud-cans)	Medium – relatively flat seabed is required (slopes less than 5 deg)

Table 2 – Foundation / anchor type installation

4 PROJECT DEVELOPMENT REQUIREMENTS
CONTINUED

4.6.2.3 Cable / pipeline installation

Table 3 summarises details related to four common cable / pipeline construction methods.

TYPE	SEQUENCE / COMMENTARY*
Surface laid product	1. Lay product on seabed Generally, for large diameter pipelines in shallower water or products in deep water with low risk (or short sections in shallow water with reduced risks). Significant slopes could result in stability issues with the potential to roll or slide down slope (or reduced metocean on-bottom stability). Bedforms could result in free-spanning between peaks.
Pre-trenching	1. Create trench usually V-shaped pipeline plough 2. Lay product in trench 3. Possible backfill pass to cover product Generally, for pipelines where catenary into a trench could be an issue or areas with significant risk of obstructions such as boulders.
Simultaneous lay and trench	1. Lay product on seabed 2. Trencher operating a short distance behind touchdown point (same vessel laying cable and operating trencher) Significant slopes associated with bedforms could result in trencher stability issues with the potential slide down slope or reduced burial at slope changes.
Post-lay trenching	1. Lay product on seabed 2. Trencher operating at a later time (different vessel) Significant slopes associated with bedforms could result in trencher stability issues with the potential slide down slope or reduced burial at slope changes.

Table 3 – Cable/pipeline installation methods

*Note: These descriptions are indicative and could vary.

4.6.2.4 Natural backfill of trenches

Some types of trenching equipment can leave the cable exposed in an open trench for a period after trenching operations. The shape and depth of the trench provides some initial protection, but the cable is often still at risk, therefore, studies should be undertaken to determine the likelihood of natural backfill due to local sediment transport. If rate of backfill is considered too slow, then alternatives such as a backfill plough may be considered if the risk profile is deemed unacceptable.

Methods to evaluate the rate of natural backfill include that presented by Fredsφe (1979) which considers factors including the trench geometry and background sediment transport under various forcing conditions. The general conclusion is that gravity infill by bedload transport is the dominant process required for natural backfill. Accordingly, areas previously indicated with “High” likelihood of sediment mobility are expected to experience the fastest rates of backfill.

4.6.3 SUMMARY OF SEABED MOBILITY DATA REQUIREMENTS FOR CONSTRUCTION

Table 4 summarises the recommended seabed mobility information to support construction planning.

RECOMMENDED DATA	DISCUSSION
Bedform migration – normal conditions Bedform migration – storm conditions	Information including: • Anticipated migration rate. • Potential impact on vertical seabed elevation and slopes. • Confidence level. Inform timescales for pre-construction survey and seabed preparations works, activities more sensitive to seabed mobility should have higher confidence levels and more detailed planning than less sensitive activities.
Rate of sediment transport	Information including: • Indicative sediment transport rates. • Metocean conditions. • Confidence levels. Inform natural backfill of any seabed depressions such as: • Dredged / flattened areas for foundation or scour protection placement. • Cable / pipeline trenches. Sandwave recovery.
Vertical level change due to sedimentation / erosion	Rate and magnitude of anticipated seabed elevation change in areas devoid of bedforms and potential confidence level. Potential influence on vessel choice or foundation detailed design.

Table 4 – Construction – recommended seabed mobility data

4.6.3.1 Example influences of seabed mobility on construction process planning

Two example sites are outlined to illustrate how the seabed mobility information should be considered and applied.

Site A – Floating offshore wind development using drag anchors

An initial seabed mobility assessment indicates the following:

- Deep water and relatively benign metocean conditions at the seabed.
- Stable 'clayey' seabed with no notable mobile bedforms.
- Seabed mobility maps classify area with "Low" likelihood of mobility.
- Planned use of drag anchors for floating structures (therefore low consequence due to mobility).

Site B – Fixed bottom offshore wind development using GBS foundations with gravel beds

A detailed seabed mobility assessment indicates the following:

- Shallow water (20 to 30 m) and energetic metocean conditions at the seabed.
- Sandy seabed with notable mobile features:
  - Megaripples with an average migration rate of 30 m per year
  - Increased bedload transport and 'backfill' during storm events.
- Seabed mobility maps classify area with "High" likelihood of mobility.

Table 5 provides a summary of key issues influencing construction planning for the two example sites.

REVIEW CRITERIA	SITE A	SITE B
Seabed mobility maps Likelihood of seabed mobility	Low	High – mobile bedforms observed.
Consequence of mobility	Low	High – flat seabed required an no significant sediment on top of gravel base.
Required data	Initial seabed mobility assessment is acceptable for evaluating construction risk and planning activities.	Detailed seabed mobility assessment with high confidence levels is required.
Pre-construction survey Confirm location conditions and allow final planning of seabed preparation and installation operations.	No significant restrictions. Timing – within 6 months of installation.	Timing – within 1 month of seabed preparation. Resultant feature positional uncertainty (THU). Suggested lateral buffer outside preparation area (THU + bedform migration rate) to identify features that could migrate into area considered.
Seabed preparation	Final inspection and removal of potential obstructions. No significant restrictions. Timing – within 6 months of installation.	Dredging and placement of gravel bed. Either increased lateral envelope or reduced timescales to reduce risk. For example: Clear megaripples from within 3 m of edge of GBS bed and install within 1 week: 2% chance of megaripple migrating onto gravel bed.
Construction	Limited	Inspection to check conditions within limits. Mitigation work required, if not i.e., sediment removal from gravel bed.
Post-construction	Low risk but inspection survey of anchor trajectory 6 months after installation could help inform mobility / cable trench backfill requirements.	High risk for 'edge scour' and cable routes therefore regular surveys likely to be required (e.g., annually). When edge scour has reached an equilibrium then monitoring at this location can reduce to a lower frequency, as appropriate.

Table 5 – Example – construction planning accounting for mobility risk

4.6.4 MANAGING DATA AND INFORMATION

4.6.4.1 Risk register

At the construction stage, risks associated with a mobile seabed (as detailed in the project risk register – Appendix A) should be reviewed to ensure that relevant issues are sufficiently well-understood to ensure they are managed appropriately when planning activities.

4.6.4.2 Data collection during construction stage

Data acquired during the construction stage should be logged in the project data register (Appendix B). Data relevant to seabed mobility is expected to include pre- and post-construction bathymetric surveys, as well as operational metocean monitoring to support safe offshore operations.

4.6.4.3 Data reviews and updates

Pre-construction bathymetric surveys are typically performed ahead of installation to verify the seabed conditions align with expectations and to confirm the absence of hazards. Post-construction bathymetric surveys are conducted to confirm the 'as-built' scenario aligns with design specifications. These surveys are important to help further validate (and refine, if necessary) the prediction of future seabed levels and that actual measured levels remain within the predicted band of HSBL to LSBL.

The CSM (Section 3.2.12) will have previously established the relevance of typical and storm-related metocean conditions to seabed mobility. If storm conditions (individually or in succession) monitored during the construction period exceed or differ in character to those previously considered, then the consequence of these events should be examined. Ideally, post-construction surveys can support this assessment, as appropriate.

4.6.4.4 Reconsidering seabed mobility information at the construction stage

If pre-construction seabed levels fall outside the predicted envelope of future seabed levels for this time period (N.B. this is considered to be an exceptional circumstance where events beyond present knowledge have occurred), then a detailed review of the detailed seabed mobility assessment is required (employing new data) and risks reassessed. If the tolerance in design is exceeded, then mitigation measures or engineering interventions should be implemented prior to installation. These interventions may include:

- Review construction schedules, such as reducing the time between seabed preparation and installation to minimise the risk of significant seabed elevation changes occurring between construction phases.
- Adapt seabed preparation and burial strategies.
- Installation of additional scour protection or placement of additional rock protection to stabilise the seabed.
- Enhanced monitoring of seabed-structure interaction during and after installation.

Such changes may require a variation to a consent conditions, marine licences and/or permits.

4.6.5 KEY POINTS FOR CONSTRUCTION

All data and information related to the seabed mobility assessment (as identified from the project's data register – Appendix B), along with risks associated with a mobile seabed, should be shared with the contractors responsible for delivering the construction stage. At this time, the assessment of seabed mobility should be comprehensive with all remaining uncertainties identified and manageable. These uncertainties should also be reflected in the detailed design.

Pre-construction surveys provide an important opportunity to validate the predicted future seabed levels for this time period ahead of any works commencing on site. This exercise is critical to ensuring the design remains within acceptable tolerances of predicted seabed levels.

4.7 OPERATION & MAINTENANCE

The O&M stage is the longest phase of the project cycle.

Operational planning provides proactive measures to support the project.

Maintenance is a combination of proactive measures and reactive measures (e.g., to rebury exposed cables).

4.7.1 OPERATIONAL PLANNING

In the context of seabed mobility, operational planning should consider the combination of:

- Risks associated with seabed mobility occurring during the O&M stage identified from the risk register (Appendix A).
- Predicted future seabed levels should be available for areas previously mapped with a "High" and "Medium" likelihood of seabed mobility (Section 3.2.10). These predictions should extend over the full duration of the O&M stage with an adequate spatial and temporal resolution. Notably, predictions of future seabed levels during the initial O&M stage will be associated with a higher level of confidence (less uncertainty) than predictions towards the end of the O&M stage which are subject to a high level of compound uncertainty.

4.7.2 OPERATIONAL MONITORING

For sites identified with notable seabed mobility issues (reference seabed mobility maps – Section 3.2.13), the O&M stage is expected to include strategic monitoring (e.g., high-resolution bathymetry surveys) to confirm assets placed on or directly under the seabed remain sufficiently protected.

The frequency of operational monitoring is a project-specific consideration and could be conducted on either a routine basis or an adaptive basis according to a review of the data obtained. The initial planned frequency of monitoring surveys should consider both the associated seabed mobility risks and the predicted future seabed levels. For example, a high-value asset vulnerable to exposure in an area predicted with a highly mobile seabed would expect to be monitored at a high frequency.

4.7.3 CONSENT CONDITIONS

In the case where consent conditions require post-construction monitoring to demonstrate the response of the seabed to interventions (e.g., sandwave recovery following seabed levelling), then opportunities to combine with operational monitoring should be explored. The review and reporting of the monitoring will remain a separate exercise in line with the objective of consent requirements.

4.7.4 DATA REVIEW

Data which is obtained from operational monitoring, as well as to satisfy any consent conditions, should be logged in the data register (Appendix B).

The monitoring data should be reviewed against the associated period of predicted future seabed levels to help validate, refine and update the predictions, as appropriate (Figure 1 and Section 3.2.14). In particular, this review should consider if the associated uncertainties should be adjusted.

The Monitoring – Review – Refinement approach should be repeated throughout the period of operational monitoring each time new survey results are forthcoming.

4.7.5 RECONSIDERING SEABED MOBILITY INFORMATION DURING THE O&M STAGE

If the data review during the O&M stage demonstrates the actual variation of seabed levels falls outside of the predicted envelope of future seabed levels, then a review and update to the seabed mobility assessment and future seabed levels may be required. In addition, engineering interventions may be required such as additional rock armour or scour protection in the case of an exceptional lowering of seabed levels below the anticipated LSBL.

4.7.6 KEY POINTS FOR O&M

The prediction of future seabed levels provides key information to support O&M planning.

The advancing through the O&M stage brings the prediction of future seabed levels into action and enables these predictions to be verified and updated as necessary.

4 PROJECT DEVELOPMENT REQUIREMENTS

CONTINUED

4.8 DECOMMISSIONING

Decommissioning involves the removal of structures from the seabed at the end of the project cycle where this is practical and safe to do so, and where there is legal obligation. Decommissioning activities occur at the end of the project cycle, noting in some cases this may have been extended where re-powering has occurred. Nevertheless, decommissioning requirements should be considered during the entire design process.

Decommissioning requirements are likely to be country specific (defined in the lease agreement), project specific (subject to the types of installations) and related to the ease of asset removal (cost, logistical, and environmental considerations) at the time. Note, decommissioning in some projects may require a prior EIA. As a minimum, country specific requirements are expected to comply with International Maritime Organization (IMO) guidelines (IMO, (1989)), or successor publications. The default expectation for decommissioning is full removal, although exceptions can be considered on a case-by-case basis. These exceptions may include leaving specific assets in situ such as cables and scour protection as well as piles cut below the seabed.

In the case that some seabed infrastructure remains on the seabed then this requires such obstacles to be marked on nautical charts and properly marked with aids to navigation.

4.8.1 DECOMMISSIONING PLANNING

The decommissioning stage is expected to include a planning phase which considers the logistical basis for removing cables and structures from the seabed. The planning phase is likely to commence towards the end of the operational stage. This plan will need to recognise agreed environmental constraints and international requirements. In some cases, partial decommissioning may be preferred instead of full decommissioning, especially if seabed mobility has increased burial depths over cables.

Of note, during the consenting stage, the EIA would have previously provided a high-level assessment of the potential environmental impacts during the decommissioning stage, based on information available at the time. This assessment should be reconsidered for the decommissioning plan and based on updated details and methods available at this date. Regulators may also wish the assessment to address the post-decommissioning seabed recovery phase.

The risk register (Appendix A) should identify legacy risks for any structures left in situ (e.g., exposure of a pile foundation cut below seabed level) and the assigned responsibility for managing these risks.

Notably, the prediction of future seabed levels is not expected to extend beyond the period of project decommissioning.

4.8.2 MONITORING FOR DECOMMISSIONING

A pre-decommissioning survey is required to confirm the status of the seabed at this time to help finalise planned works.

Once the project has been decommissioned then further post-decommissioning monitoring may be required for a limited period (a possible consent condition) to help demonstrate seabed recovery, or that any structures left in situ do not become exposed.

Thereafter, any additional monitoring would be on a risk basis to ensure any assets remaining in situ do not become a hazard to other parties (e.g., fishing interests).

All surveys should be recorded in the project's data register (Appendix B).

5 REFERENCES

Carbon Trust. (2015). Cable Burial Risk Assessment Methodology. Report CTC835, February 2015.

Dimmock, P. S., Sharma, S., Tam, T., Tapper, L., Vanneste, M., Klinkvort, R.T., . . . Hill, A.W. (2025). A ground modelling framework for offshore wind farm developments. Proceedings of ISFOG 2025. 5th International Symposium on Frontiers in Offshore Geotechnics. June 913 2025. Nates, France.

Folk, R.L. (1954). The Distinction between Grain Size and Mineral Composition in Sedimentary-Rock Nomenclature. The Journal of Geology, 62(4), 344-359.

Fredsφe, J. (1979). Natural Backfilling of Pipeline Trenches. Journal of Petroleum Technology, 31(10), 1223-1230.

IHO. (2024). Standards for Hydrographic Surveys. S-44 Edition 6.2.0.

IMO. (1989). Guidelines and Standards for the removal of offshore installations and structures on the Continental Shelf and in the Exclusive Economic Zone. Resolution A.672(16).

Insight Marine Projects. (2014). Export Cable Survey Report. Wave Hub. 2014 Bathymetric Cable Route Survey. REP-0198-J64572.

JNCC and Natural England. (2022). Nature conservation considerations and environmental best practice for subsea cables for English Inshore and UK offshore waters.

Larsen, S., Roulund, A. and McIntyre, D.L. (2019). Regeneration of partially dredged sandwaves. Coastal Sediments 2019, (pp. 3026 - 3038).

Leth, J.O., Larsen, B. and Anthony, D. (2004). Sediment distribution and transport in the shallow coastal waters along the west coast of Denmark. GEUS Bulletin, 4. doi: https://doi.org/10.34194/geusb.v4.4779

Li, M.Z., Zou, Q., Hannah, C., Perrie, W., Prescott, R. and Toulany, B. (2009). Numerical Modelling of Seabed Disturbance and Sediment Mobility with applications to Morphodynamics on the Storm-dominated Sable Island Bank, Scotian Shelf. Geological Survey of Canada.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G. and Aarninkhof, S. (2018). The State of the World's Beaches. Scientific Reports, 8(6641).

Magalen, J., Jones, C. and Roberts, J. (2014). Offshore Wind Guidance Document: Oceanography and Sediment Stability. Development of a Conceptual Site Model. Sandie report SAND2014-15239. Version 1.

Menzel, P., Wolters, G. and Drews, A. (2025). Real scale experiments on the wave-induced burial and mobilization of Unexploded Ordnance on the seafloor. Applied Ocean Research, 154(104342). Retrieved from https://doi.org/10.1016/j.apor.2024.104342

Mojo Maritime. (2015). Operations Summary Report. Wave Hub Cable Protection Works for WaveHub. MR-6186-002.

Roulund, A., Jenson, P., Marten, K. and Whitehouse, R. (2018). Scour and seabed changes at cable protection rock berms – Field observations. ICSE 2018 (9th International Conference on Scour and Erosion). Taipei, Taiwan.

Roulund, A., Riezebos, H.J, and Saverymuttu, K. (2023). Foundation installation in sandwave fields. Field observations of sandwave regeneration and sediment infill. ISSMGE. Proceedings of the 11th International Conference on Scour and Erosion.

Rui, S., Zhou, W., Shen, K. and Guo, Z. (2023). Review on Seabed Trenches Induced by Mooring Lines and Analyses of Anchor Bearing Capacity. Journal of Marine Science, 22, 296-310.

Shields, A. (1936). Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. Mitteilungen der Preußischen Versuchsanstalt für Wasserbau und Schliffbau, Berlin, 26.

Vousdoukas, M.I., Ranasinghe, R., Mentaschi, L., Plomaritis, T.A., Athanasiou, P., Luijendijk, A. and Feyen, L. (2020). Sandy coastlines under threat of erosion. Nature Climate Change, 10, 260-263. doi:10.1038/s41558-020-0697-0

APPENDIX A: RISK REGISTER

A project risk register is a key risk management tool to help manage and monitor project risks.

The following guidance is relevant to project risk management:

IEC (2025). International Standard. Managing risk in projects – Application guidelines. IEC 62198. Edition 3.

ISO (2021). Risk Management – a practical guide. ISO 31000:2018.

Both documents provide relevant guidance in the application of a risk register.

An example structure for a risk register is shown below with dummy entries, noting risks associated with seabed mobility[1] will be one of many project categories.

In some situations, likelihood may also be referred to as probability, i.e., the chance that the hazard might occur. In the present example, the likelihood level is scored from Low to High. Similarly, impact may also be referred to as severity, i.e., the amount of damage or disruption, and is also scored from Low to High. The level of risk (or priority level) is simply the product of likelihood and impact.

The scale of likelihood for seabed mobility should match that deduced when producing seabed mobility maps (Section 3.2.13).

Risks should be reviewed regularly, at least for each stage of project development, and mitigation actions implemented to help reduce risks to an acceptable level or As Low As Reasonably Practicable (ALARP). For some risks, this may take a number of mitigation steps and separate actions.

APPENDIX A: RISK REGISTER

CONTINUED

Likelihood	low		high	
3	3	6	9	high
2	2	4	6	
1	1	2	3	low
	1	2	3	

Impact

Risks	
9	high
4	medium
1	Low

Id	Hazard	Category	Consequence	Likelihood	Impact	Risk		Mitigation	Rank	Phase	Uncertainty	Owner	Date of last review
1	Seabed lowering leading to cable exposure at landfall	Seabed mobility	Increased likelihood of cable exposure	3	3	9	high	Cable protection	1	Operation	Low	Developer	01-Jan-26
2	Sandwave migration across array	Seabed mobility	Increased likelihood of cable exposure	2	2	4	medium	Monitor	2	Operation	Low	Developer	01-Jan-26
3	Changes in sandbank profile	Seabed mobility	Restricted access to some sites	1	1	1	low	Monitor	3	Operation	Low	Developer	01-Jan-26

1. Seabed mobility is a natural hazard which may develop a risk to an asset placed on or buried into the seabed.

APPENDIX B: DATA MANAGEMENT

CONTENTS

ABBREVIATIONS AND ACRONYMS

ACP	American Clean Power Association
IMarEST	Institute of Marine Engineering, Science and Technology
MEDIN	Marine Environmental Data and Information Network
ORSIG	Offshore Renewable Special Interest Group
OSIG	Offshore Site Investigation and Geotechnics
SUT	Society for Underwater Technology

B.1 OVERVIEW

The expectation is that extensive amounts of technical data and information will be required to support project development for a variety of topics, including seabed mobility. The amount of information is also expected to increase as the project advances, especially as marine surveys are commissioned and completed, creating a challenge for data management.

All the data represents a significant investment and important project asset, both in cost and time taken obtain, especially in relation to marine surveys. Data management provides a means to help protect the value of this asset over the duration of the project and into the future.

A useful guide to data management practices is provided in:

OceanWise (2023). 10 Steps to Achieving Marine Data Management Success. A guide to achieving marine data management best practice. Version 2.

Further guidance related to data management specific to offshore geotechnical and geophysical data is included in SUT OSIG (2022), and for metocean data in ORSIG (2024) and ACP (2024).

B.2 CONSIDERATIONS RELATED TO SEABED MOBILITY ASSESSMENTS

An assessment of seabed mobility will require a variety of data types including geotechnical, geophysical, metocean, and other environmental parameters sourced from:

- Existing data and information collated from relevant data sources which is expected to have licence and copyright conditions.
- Project data will generally be required to supplement existing data (e.g., to offer better detail, updated, and address previously identified data gaps).

Inevitably, the assessment of seabed mobility develops new outputs from the analysis and application of the primary data. Notably this includes predictions of future seabed levels. These outputs are likely to be developed in stages and undergo updates and enhancements as the project advances. In particular, each version of the output should identify the primary data which has been used (including prior versions of the output, if applicable), the method of derivation, uncertainties that remain, and any limitations of use.

B.3 RECOMMENDED PRACTICE

The following represents recommended practice related to conducting a seabed mobility assessment:

- The expectation is the project will already have a data management plan in operation, enabling adoption of existing data management practices.
- The topic of seabed mobility should be recognised in the project-wide data register and identify the end-users of key data and information.
- Key outputs developed from the assessment of seabed mobility should be logged in the data register with appropriate metadata in accordance with relevant standards (e.g., MEDIN (2022) and ISO (2014)).
- Version control is important so that updated information is easily identifiable to the wider project.
- Long term data storage is required to maintain the availability of key deliverables (i.e., data and reports), such as the prediction of future seabed levels (and associated updates) so they remain accessible to the project at all times.

B.4 REFERENCES

ACP (2024). ACP U.S. Offshore Wind Metocean Conditions Characterization Recommended Practices. ACP OCRP-3-2024. August 2024.

ISO (2014). Geographic information — Metadata Part 1: Fundamentals. ISO 19115-1:2014.

MEDIN (2022). Guidance notes for the production of discovery metadata for the Marine Environmental Data and Information Network (MEDIN). Version 3.1.2.

OceanWise (2023). 10 Steps to Achieving Marine Data Management Success. A guide to achieving marine data management best practice. Version 2.

ORSIG (2024). Metocean Procedures Guide for Offshore Renewables. Issue 3. IMarEST.

SUT OSIG (2022). Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments. Editor: Cook, M. Society for Underwater Technology (SUT), London.

CONTENTS

ABBREVIATIONS AND ACRONYMS

ASCI	American Standard Code for Information Interchange
ATLAS	Advanced Topographic Laser Altimeter System
AUV	Autonomous Underwater Vehicle
BATHYELLI	Bathymétrie rapportée à l'ellipsoïde (Marine Bathymetry referenced to the Ellipsoid)
BLAST	Bringing Land And Sea Together
CHP	Civil Hydrographic Programme
CD	Chart Datum
CO/C-O	Corrected Offset value
CSV	Comma Separated Values
CW	Continuous Wave
DGNSS	Differential GNSS
DIMCON	DIMensional CONtrol
DVL	Doppler Velocity Logger
FM	Frequency Modulated
GAMS	GNSS Azimuth Measurement Subsystem
GIS	Geographic Information System
GLONASS	Global Navigation Satellite System (Russian)
GNSS	Global Navigation Satellite System
GCP	Ground Control Points
GeoTIFF	Geographic Tagged Image File Format
GPS	Global Positioning System
GSF	Generic Sensor Format
LAT	Lowest Astronomical Tide
LARS	Launch and Recovery System
LAS	LASer (File format)
LAZ	LasZip (Compressed LAS file format)
LiDAR	Light Detection and Ranging or laser imaging, detection, and ranging
IHO	International Hydrographic Organization
IMCA	International Maritime Contractor Association
INS	Inertial Navigation System
MBES	Multibeam Echo Sounder
MCA	Maritime and Coastguard Agency
MEDIN	Marine Environmental Data & Information Network
MRU	Motion Reference Unit
NASA	National Aeronautics and Space Administration
OSIG	Offshore Site Investigation and Geotechnics
PEP	Project Execution Plan

ABBREVIATIONS AND ACRONYMS CONTINUED

PPK	Precise Point Kinematic
PPP	Precise Point Positioning
PPS	Pulse Per Second
QA	Quality Assurance
QC	Quality Control
RGB	Red, Green and Blue
RTK	Real-Time Kinematic
ROV	Remotely Operated Vehicle
ROTV	Remotely Operated Towed Vehicle
SAR	Synthetic Aperture Radar
SBAS	Satellite-Based Augmentation System
SBES	Single Beam Echo Sounder
SD	Standard Deviation
SOW	Scope of Work
SSS	Side Scan Sonar
SUT	Society for Underwater Technology
SVP	Sound Velocity Profile
SVS	Sound Velocity Sensor
TIN	Triangulated Irregular Network
THU	Total Horizontal Uncertainty
TVU	Total Vertical Uncertainty
UAV	Uncrewed Aerial Vehicle
UKHO	United Kingdom Hydrographic Office
UPS	Uninterruptible Power Supply
USBL	Ultra-Short Baseline
USV	Uncrewed Surface Vessel
VORF	Vertical Offshore Reference Frame
XTF	Extended Triton Format

APPENDIX C: BATHYMETRY
CONTINUED

C.1 OVERVIEW

The collection of bathymetric data via hydrographic survey is an important component of offshore site characterisation, and it provides critically important information used to assess the nature of the site in terms of seabed mobility, hydrodynamic energy and seabed level change. Bathymetry data can be combined with information which characterises the ocean (Appendix F: Metocean Data) and seabed conditions (Appendix D: Bedforms and Appendix E: Sediment Data) to support various analytical approaches (Appendix G) underpinning an assessment of seabed mobility. It is fundamentally important that bathymetric data used in seabed mobility assessments is accurate and of high quality.

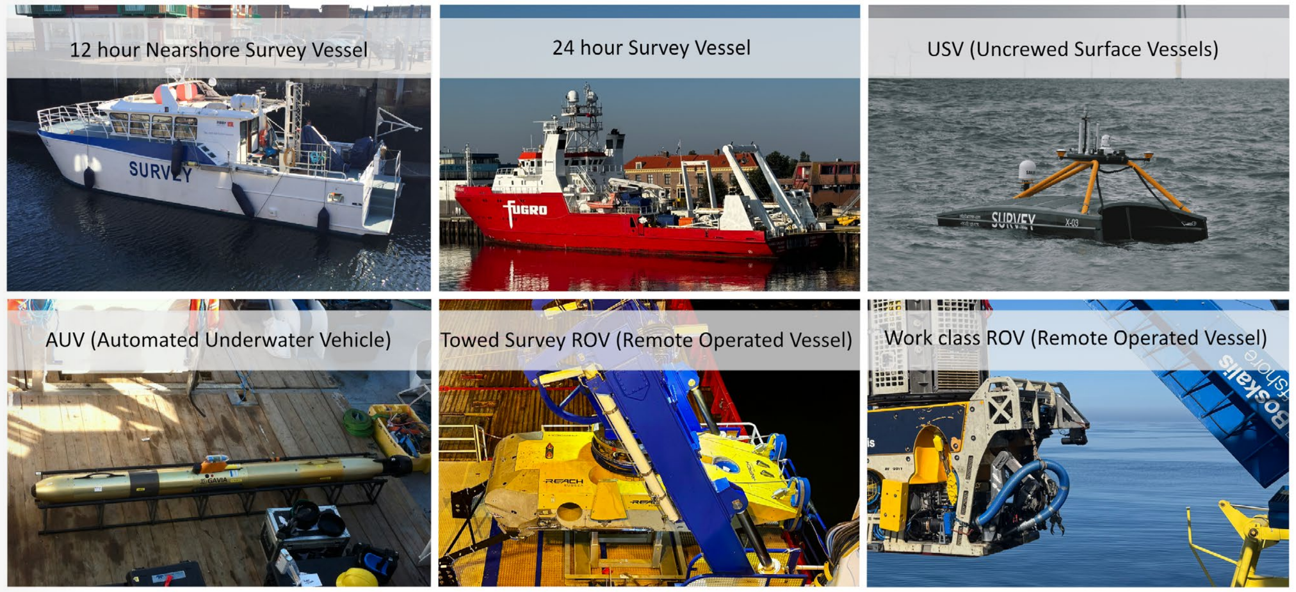
This appendix focuses on summarising key thematic areas as they relate to, or influence, the provision of high-quality bathymetric datasets for use within a seabed mobility context. It does not provide a complete or a highly detailed review of hydrographic survey as a topic (the reader is referred to Guyer, (2022); see also IMCA (2015) and OSIG (2022).

Key areas include the survey platforms used for the acquisition of bathymetry data, as well as the accompanying survey instruments. To keep the appendix more concise, it will mainly concentrate on multibeam echosounders, which are the most commonly used instruments for seabed mobility studies, but other types of sounding collection methods are also touched upon. Descriptions of multibeam echosounder (MBES) system options and equipment functions, as well as possible errors, are provided to provide a foundation to groups involved in scope development and tender evaluation, as well as downstream users of the data within seabed mobility assessments. This Appendix also provides some examples of how gridded resolutions and horizontal and vertical error in bathymetry data affect aspects of investigation during seabed mobility studies, like seabed volume changes and monitoring of (mobile) seabed features, e.g., megaripples, sandwaves and sandbanks[1].

C.2 SURVEY PLATFORMS

The survey platform must be suitable and sufficient for the work, either with equipment pre-installed or the capability to mobilise equipment to complete the required operation. There are numerous survey platforms that use different methodologies to acquire bathymetric data. However, knowing which platform best suits the specific survey requirements is key to being cost-effective and acquiring high-quality data.

Figure C.1 MBES marine platform examples.



1. Please note where graphics contain no attribution they have been drawn in-house.

CREWED SURVEY VESSEL

Survey vessels come in a variety of shapes and sizes; these vessels may be a dedicated survey platform or a vessel of opportunity. The following are headline items to be considered for crewed survey vessels:

- Survey vessels often operate on a 12-hour or 24-hour basis, depending on accommodation requirements:
  - Larger 24-hour vessels with deeper keels are generally more stable, with greater operational weather windows, and have accommodation onboard, but have greater operating costs and are restricted in shallow waters.
  - Smaller boats can access shallow environments but are more susceptible to wind and sea conditions. As they are smaller, there is often no accommodation and limited/no welfare facilities onboard, and restrictions on hours of rest limit the vessel work window to 12-hour operations and this should include transit, vessel admin and travel between the vessel and accommodation
- Non-standard survey vessels are described as 'vessels of opportunity'. Vessels of opportunity may require a refit to mobilise part or the full survey spread, which may not be present at the time of the vessel charter. A dedicated pre-mobilised survey platform may have cheaper mobilisation costs than a vessel of opportunity.
- Common features on survey vessels can include a moonpool and A-Frame for controlled equipment deployment and recovery, a survey pole for mounting equipment (multibeam system, etc.), a GNSS mast, and hull-mounted equipment (multibeam, etc.).
- There needs to be sufficient space to safely mount the required equipment, including all computing/display equipment (mountings need to be secure against and protect sensitive equipment from vessel movement). There also needs to be sufficient space for the survey and vessel crew to operate their equipment with a dedicated survey desk.
- Sufficient power needs to be available for all of the survey equipment, as well as the other ship's equipment. It is strongly recommended that UPS power be available to protect sensitive equipment from drops and/or surges in power.
- When the survey and bridge crews are physically separated, sufficient internal communications are required to allow ready two-way communication between both parties.
- Vessels must conform to the regulations of the country in which they are registered. For example, MCA coding is applicable to the United Kingdom. Clients may require foreign vessels to be coded to the country of operation and may have their own internal audit for accepting the vessel on a project.

UNCREWED SURFACE VESSEL

Uncrewed Surface Vessels (USVs) are becoming more commonplace in the industry and are increasingly utilised on commercial projects. Where a survey vessel would traditionally be crewed, a USV can perform the same operation with operators in remote locations, and smaller USVs are being used in shallower regions at and near landfall locations, and in intertidal regions where larger vessels cannot survey. USV technology is continuously developed and improved, with rapid changes year-on-year. There is no single, idealised design, and lately the USVs have been increasing in size and weather capability.

- USVs are categorised between nearshore and offshore capability:
  - Nearshore USVs are generally restricted by the size of the vessel, and fuel and battery capacity. As they are small at present, they can be restricted in their operational extent, with their battery life and weather tolerance reduced, compared to larger vessels. Typically, a small vessel can easily be deployed by 1-2 persons, with an operator local to the survey operation, often controlling operations by line of sight.

  - Offshore USVs have increased endurance and over-the-horizon communications, requiring satellite communications. The online survey team and marine crew are in remote locations with remote data centres. Offshore USVs require a shoreside crew to assist with recovery and maintenance when the USV is alongside.
- USV legislation is in continual development and released to ensure USV platforms are being suitably regulated.
- USVs can be multifunctional in their ability and can support offshore operations in a multitude of ways. This includes collecting data alongside a standard operated vessel.

REMOTELY OPERATED VEHICLES

Remotely Operated Vehicles (ROVs) operate subsea with a tether for communications to a surface vessel, with Remotely Operated Towed Vehicles (ROTVs) towed by the tether. ROVs are steered using their thrusters to stay on the survey acquisition line and, depending on version, the ROTV can either be steered by thrusters, flaps or by surface vessel position whilst towing to stay on survey acquisition line. They are deployed and recovered via a Launch and Recovery System (LARS) and work at depth. Different ROVs vary in their functionality, and their current/speed and depth rating, therefore it is important to know the work site operational parameters. They can be mobilised with a suite of instrumentation which supports the scope of work and are used throughout the marine industry in multiple sectors. By working close to the seabed, data quality and resolution can be increased compared to sensors mounted on a surface vessel; however, vertical and horizontal accuracy, when as a minimum a USBL system is used, are more prone to errors (due to the added error propagation through an additional positioning system). To help constrain these errors, ROVs typically employ additional sensors including INS, pressure sensors, DVLs, etc.

AUTONOMOUS UNDERWATER VEHICLES

Autonomous Underwater Vehicles (AUVs) are untethered subsea vehicles which work at depth. The advantage of doing so is that it removes the influence of limiting factors such as surface conditions, as well as increasing resolution due to the closer proximity to the seabed. The disadvantage is that they are completely uncrewed and have reduced communication ability when at depth. As with ROVs, operating close to the seabed improves data quality and resolution. Positioning of the AUV is restricted; with no GNSS solution when submerged, it is reliant on high accuracy motion sensors and may have to return to the surface to use GNSS signal to recalculate its position at regular intervals. If there is subsea infrastructure within the survey zone of known position, then the survey dataset can be anchored to this, significantly improving the georeference foundation.

They can be mobilised with a suite of survey instrumentation to work to the employer's scope of work.

AUVs may work with a combination of crewed vessels and USVs to operate in the field. It may be common practice in the future to have a crewed mothership, with USVs supporting the AUVs in the field. However, due to having to use pressure sensors, INS and DVLs, the accuracy of the data will not match a well setup vessel, so quality will likely differ between the different datasets.

CREWED AND UNCREWED AERIAL VEHICLES (UAVS)

Aircraft and aerial drones are being utilised on projects with payloads to capture large areas of data and model ground conditions. Photogrammetry is being used to map land surveys and create point clouds from aerial imagery, while LiDAR uses pulses of light to measure distances and create 3D models. Aircraft and drone surveys are restricted by either the battery or fuel capacity of the systems, and the weight of the payload, as well as flying time for pilots. They can be operational in shallow water environments where the seabed is visible, including intertidal areas, but are more typically utilised for onshore surveys.

C.3 SURVEY SENSORS AND SOFTWARE

An array of sensor technologies and software is used to collect bathymetric data. **Table C.1** provides a brief summary of equipment/software that could be involved in collecting bathymetry data from either a surface vessel or subsea vehicle, highlighting the role or the relevance to the seabed mobility context. Understanding the equipment and software involved in collecting and processing bathymetric data is essential for groups involved in scope development and tender evaluation, as well as downstream users of the data within seabed mobility assessments.

Table C.1 Systems used for bathymetry data collection.

SYSTEM	SURFACE	SUBSEA	AERIAL	ROLE IN SEABED MOBILITY DATA COLLECTION
Multibeam Echosounder (MBES) system	✓	✓		Uses sonar to measure the bathymetry.
LiDAR	✓		✓	Alternative method for measuring bathymetry in shallow, low turbidity environments, using laser measurements instead of sonar. It can be used on surface vehicles to capture exposed seabed, but it is less useful for seabed mobility studies and is mainly used to capture land-based features (buildings, walls, cliffs, etc.).
Photogrammetry	✓		✓	For intertidal areas and shallow, clear waters.
Global Navigation Satellite System (GNSS)	✓	✓	✓	Provides horizontal and vertical positioning.
GNSS Corrections	✓	✓	✓	Corrections for the GNSS to improve the positioning from metric to centimetric accuracy (RTK, PPK or post-processed etc.) These corrections can be created on site by setting up a base station or streamed via internet or satellite signal from a third party.
Heading Sensor	✓	✓	✓	Provides yaw orientation.
Motion Reference Unit (MRU)	✓	✓	✓	Provides pitch and roll orientation.
Inertial Navigation System (INS)	✓	✓	✓	A single interface that integrates all position and orientation data. Can mitigate GNSS masking around structures, but is more beneficial when used on subsea vehicles and in conjunction with USBL, pressure sensors, DVLs, etc.
Sound Velocity Sensor (SVS)	✓	✓		Provides real time speed of sound values at the sonar for the multibeam to use in the beam forming process.
Sound Velocity Profiler (SVP)	✓	✓	✓[1]	Provides a full water column speed of sound profile for acquisition and processing software to perform refraction corrections.
Survey Computer	✓	✓	✓	Hardware necessary to run all acquisition software and store the resulting data.
Ultra-Short Baseline (USBL)		✓		Uses two-way sound ranging between a transducer and beacon(s) to position subsea equipment.
Pressure Sensor		✓		Used to constrain the vertical position (depth) of a subsea vehicle (altimers also used to measure depth to seabed).
Doppler Velocity Log (DVL)	✓	✓	✓	Uses shifts in sound frequencies to calculate the relative direction and speed of movement underwater. Often integrated with INS/USBL and other subsea positioning systems.
Acquisition Software	✓	✓	✓	Most sensors listed above will have their own dedicated software to control and monitor their output. Outputs are often integrated into a single acquisition software to control and manage the survey.

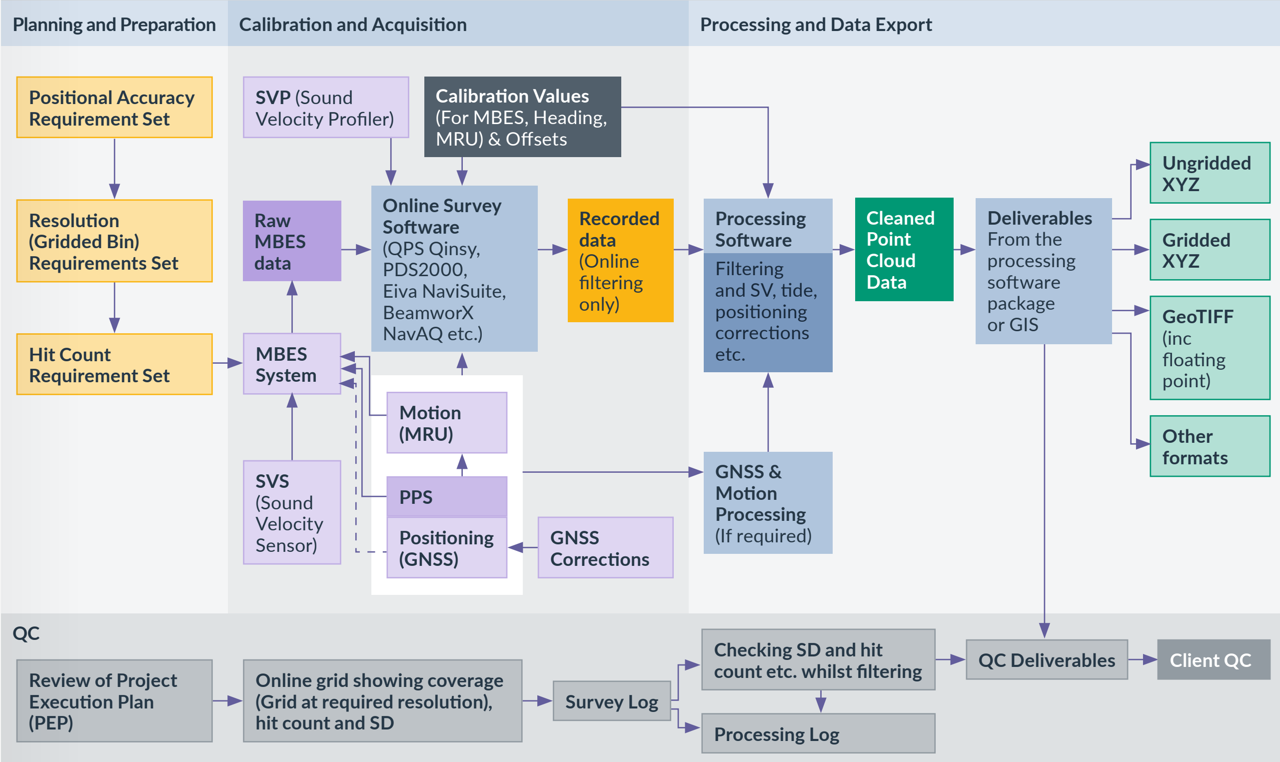
1- SVP data can be used to correct LiDAR refraction paths, but is not essential, as refraction effects are minimal

APPENDIX C: BATHYMETRY
CONTINUED

C.3.1 MULTIBEAM SYSTEMS AND DATA ACQUISITION

Multibeam systems are at the centre of most bathymetric surveys. The multibeam works in conjunction with other systems on the vessel (see **Table C.1** and **Figure C.3**), with the system data brought together and recorded in the online survey software. The acquired data is imported into the processing software to be corrected and filtered, and then exported to the required formats. **Figure C.2** presents a high-level overview showing the typical flow of bathymetry data and the accompanying sensor data from start to finished product.

Figure C.2 Bathymetry data flow example.



The following sections describe how multibeam systems work. **Table C.2** provides a basic explanation of the numerous technical terms associated with the operation of MBES systems and highlights the relevance to applications within a seabed mobility context.

Figure C.3 Multibeam setup example.

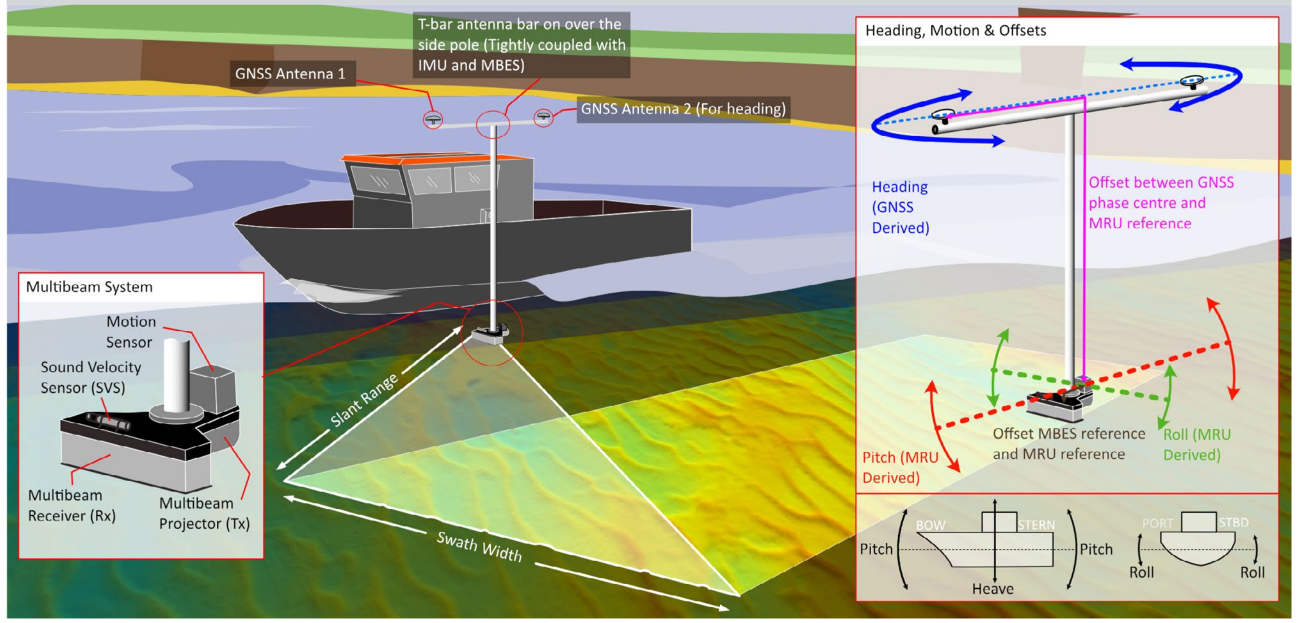
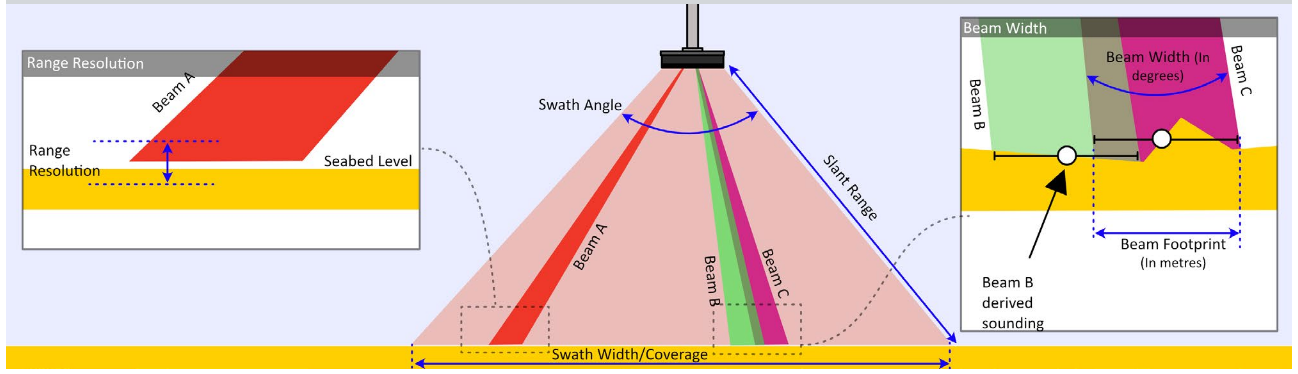


Table C.2 Multibeam system terms.

TERM	EXPLANATION	RELEVANCE TO SEABED MOBILITY CONTEXT
Backscatter	Backscatter data is a measure of the intensity of the returned ping, rather than the range calculations made for bathymetry data, and can be collected by most modern multibeam systems.	Backscatter can provide information on changes in seabed substrate, as the intensity of the returned signal is affected by the hardness and roughness of the seabed (which can be of some use in determining the nature and composition of the seafloor, especially in instances where the signals can be ground-truthed using sediment samples).
Beam Stabilisation	Roll, pitch and yaw stabilisation	Will increase weather window for seabed mobility surveys by ensuring even beam distribution across track, along track and relative to the planned line position, even as the sonar is rotating at the surface.
Beam Width	Each beam has a given footprint. The size of the footprint is critical as the sonar cannot differentiate bed levels within a given footprint, with the ensonified area reduced to a single point bottom detection. Beam width is measured in degrees, representing the rate of divergence from the transmitter, and thus the footprint size is range dependent. High end sonars typically have tight beam width angles, which increase resolution. An example of a typical high end multibeam echo sounder would be 1.0°x1.0°, 0.5°x0.5° or smaller. Low frequency systems have larger beam widths, which decreases resolution. See **Figure C.4**	Tighter beam width increases the horizontal and vertical accuracy and will provide sharper seabed features; as water depth increases, the beam width increases. A tighter beam width is important for inspection surveys (pipeline, debris surveys, etc.) where detail is key, whereas seabed mobility requires a more generalised overview. Larger beam widths decrease resolution, but the overall cost is reduced from a high-end multibeam echosounder. Therefore, tight beam width angles should rarely be a deciding factor in regard to seabed mobility planning. Beam footprint is smallest below the transducer and increases at the outer edges of the swath due to greater range.
Gridded/ Gridding	Data that has been reduced to a grid representation surface at a certain resolution, i.e. multiple detection points reduced to a single representative point, over a given area. Grids can be gridded to represent average, shallowest or deepest surfaces (See **Figure C.5**), or associated statistics	Gridded data is the main dataset that will be used for seabed analysis. There are different gridding methods that can have different effects when gridded XYZ's or un-gridded data is gridded.
Frequency	This is the sound frequency at which the sonar operates; the range for multibeam systems is typically between 12-800 kHz. Systems can be FM (Frequency Modulated), CW (Continuous Wave), or both. For seabed mobility surveys, both systems can be considered equal.	Lower frequencies offer larger ranges and thus better performance in deep water (100s of metres), but this increases beam widths (reducing precision). A narrower beam width can be achieved with higher frequencies, but a good argument is needed for using frequencies above 450 kHz in seabed mobility, as the smaller beam widths offer no significant benefit, while range must be reduced due to increased noise.
Gridding Resolution / Gridding Bin	This is the size of the grids in a gridded surface. Can be expressed as pixel resolution, metre squared, or metres per bin (Example: 1 m x 1 m = 1 m² = 1 mBin). See **Figure C.5**	Resolution will determine what features can be resolved.
Hit Count / Sounding Density	The number of soundings in a set area. See **Figure C.5**	A higher hit count is more critical for inspection work, etc., but a hit count of more than 1 ensures that the bin is less influenced by noise and is more important as the size of the bins increases.
MBES SSS	Multibeam Side Scan Sonar Data (SSS) can also be recorded in most modern multibeam systems and can be useful in shallow water or deeper water if on a remotely operated vehicle. Producing similar data as a true Side Scan Sonar system.	It can be useful for determining features and seabed roughness and hardness.
Multi-Detect	Multi-detect can be useful in certain circumstances. Multi-detect functionality allows a system to identify more than one detection point per beam.	It can be useful in areas covered by vegetation growth, where the multibeam might have issues detecting the seabed, as the primary return will likely be from the vegetation floating above.
Number of Beams	The number of beams that can be produced and measured, per ping. Extra soundings can be created digitally and therefore listed sounding capability might not match the number of beams.	More beams results in more detection points, densifying the coverage, which means coverage can be increased, whilst still meeting density requirements.
Ping Rate	The number of sound pulses (pings) a sonar emits per second.	A higher ping rate means more soundings per second, which means denser data or an increase in survey speed, depending on the required density.
Point Cloud	Is the un-gridded sounding data (all soundings) and can include unfiltered or filtered soundings.	Can be useful if re-gridding the data at different resolutions or producing average, shallowest or deepest surfaces (see **Figure C.5**).
Range Resolution	How accurately the sonar can define a bottom detection point in the direction of the ping (nominally, vertically). See **Figure C.4**.	The lower the number, the higher the (vertical) accuracy. Modern systems are capable of millimetre scale resolution.
Slant Range	Distance from the transducer down to the bottom detection point (See **Figure C.4**).	As slant range increases, ping rate decreases, which means a decrease in along track resolution (density).
Sounding	Each beam produces 1 sounding (though multiple soundings per beam are possible for systems with multi-detect options).	Each sounding represents a depth measurement for a beam (see multi-detect above).
Swath Angle (Swath Width/ Coverage)	The angular sector that the beams can be distributed over, which affects the swath width depending on water depth (See **Figure C.4**).	When swath angles increase, ping rate decreases (see 'Slant range' above) and across track sounding density decreases. Data quality at the swath edges also tends to decrease due to refraction effects and beams spreading to accommodate the larger acquisition area. This should be considered when survey planning is carried out in regard to line spacing and water depth.

APPENDIX C: BATHYMETRY
CONTINUED

Figure C.4 Beam resolution and footprint.



A multibeam echosounder measures bathymetry using sonar. It produces a series of pings (one ping = one pulse of sound), with each ping focused and directed into multiple separate beam paths (hence, 'multibeam'). The system emits each ping from a transmitter, then waits to record any returned echoes at a receiver. The two-way travel time for each beam, per ping, is recorded and, together with the speed of sound through the water, the multibeam system calculates the distance each beam has travelled and converts this to a depth below the sonar. Complex beam forming algorithms calculate these time and distance calculations in real-time within the topside unit (computer) of the MBES system.

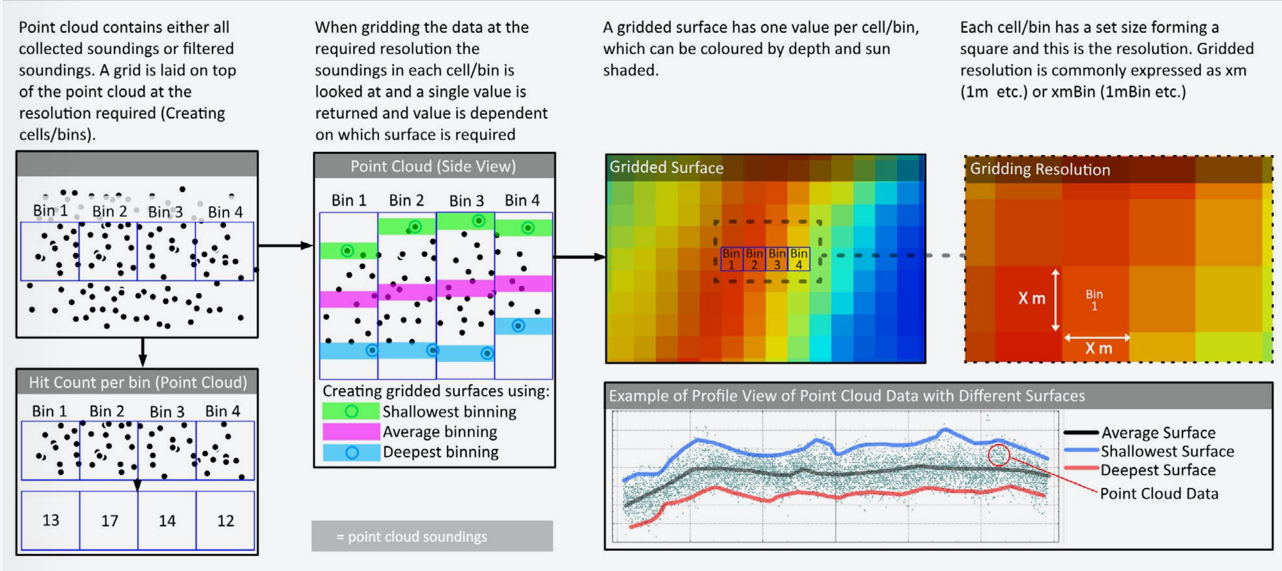
The survey software stores the returns as a sounding. The number of soundings returned per ping will be dependent on the number of beams that the system is capable of outputting (see 'Across track beam distribution/resolution' for more information). The number of soundings along track will be dependent on several factors like ping rate, vessel speed, conditions, stabilisation features, etc. (see 'Along track beam distribution/resolution' for more information).

The un-gridded data, which is all the collected soundings, creates what is called a 'point cloud', which can then be gridded to the required resolution, either during processing or in real time during acquisition, with the latter being useful for seeing that full coverage is being achieved at the required resolution. Information such as hit count and standard deviation can also be gridded for online monitoring or during processing QC.

Data resolution is defined for gridded data as the size of each grid square. The resolution is determined by the acquired point data and is split into a grid square. These squares are also commonly called cells or bins, and the resolution is commonly stated as (x) m but could also be (x) cm or as (x) mBin (metres per bin). Gridding examples and requirements for seabed mobility studies, including for individual seabed feature requirements, can be found in Section C.4.7.

APPENDIX C: BATHYMETRY
CONTINUED

Figure C.5 Gridding, resolution and soundings.

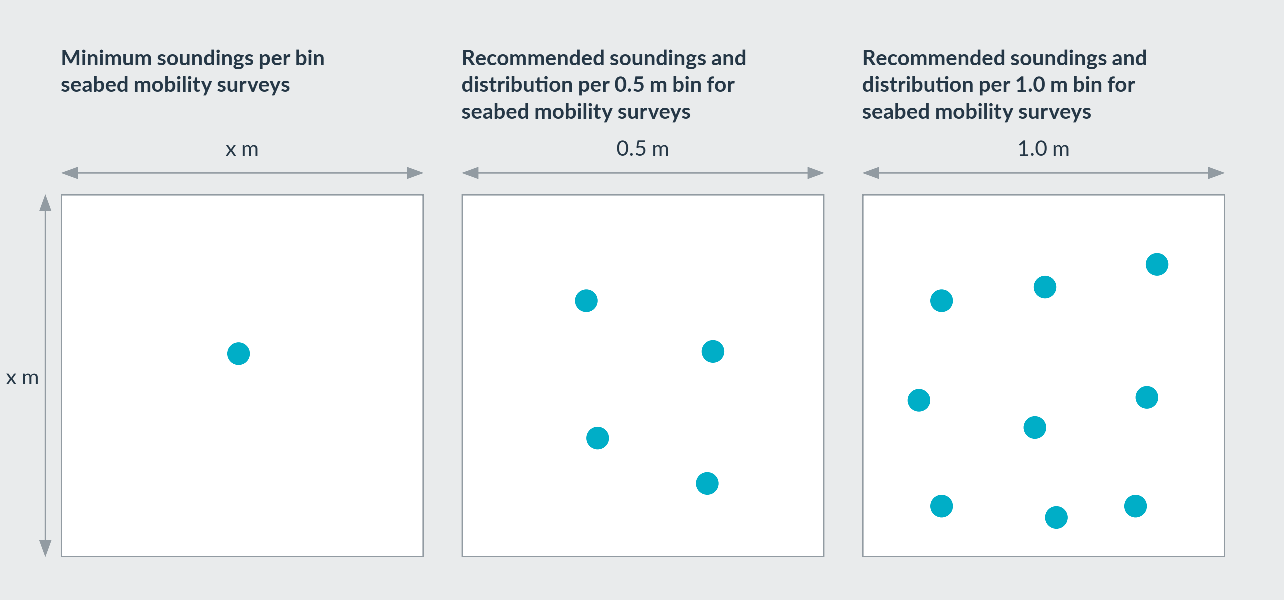


There are different options when the soundings are being gridded, the most common option being average/mean surface, but shallowest and deepest surfaces can also be gridded (see **Figure C.5**). Average/ mean surface will usually be the best surface for seabed mobility studies as it produces the most reliable surface when there is plenty of overlap and the data aligns well in the vertical and horizontal plane. Shallowest surface tends to be utilised more for data required for engineering, navigation purposes and observing targets on the seabed. Shallowest and deepest method are also used for thinning, which is a method for gridding, which keeps the positioning of that sounding in the gridding box. The most common position of a gridded soundings is centre of grid box/ bin, but survey software can also output the corner of the gridding box, though most GIS programs expect centre of bin to be the position given.

For gridding, it is beneficial to have the soundings distributed evenly across the seafloor, although the quality of the returns is critical, it is better to have high quality data with a few gaps than full coverage with low quality data (due to a noisy environment, etc.). For seabed mobility studies, one sounding per bin is the minimum requirement to represent the bathymetry within, but increasing to 9 or greater soundings per 1 m bin (3 across x 3 along), or 3 or greater per 0.5 m bin gives redundancy for noise, allows valid statistics-based processing, and leaves the option to increase the resolution if desired (See **Figure C.5** and **Figure C.6** for hit count examples).

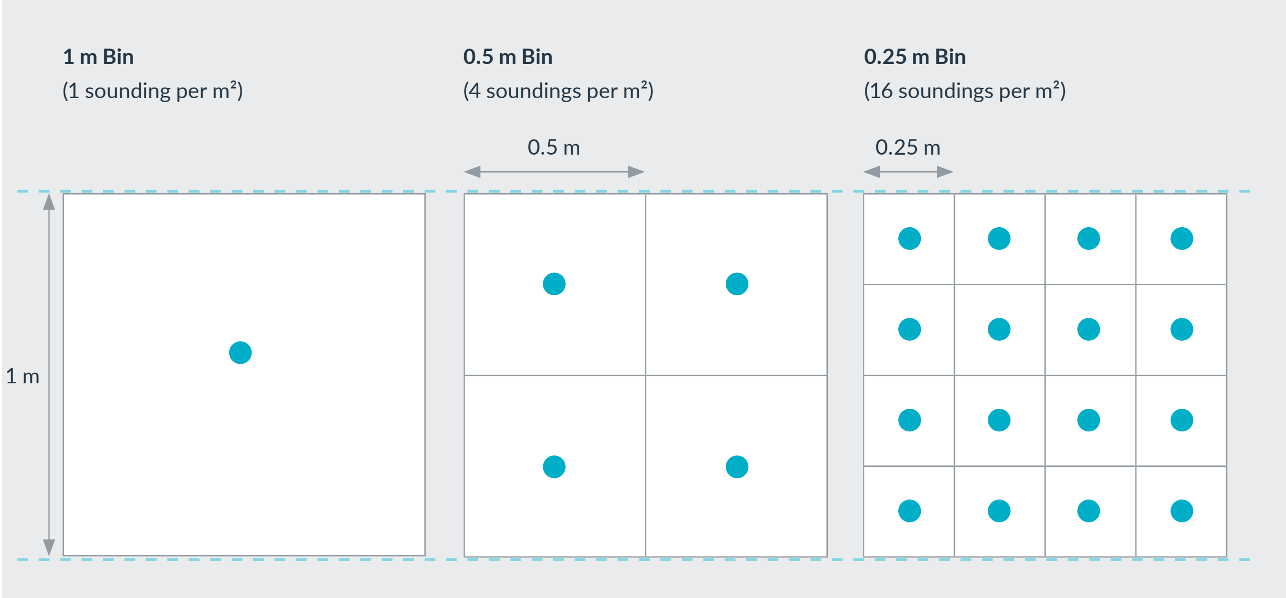
As the resolution increases, there will be a reduction in hit count per cell, which could lead to gaps in data coverage. Measures can be taken to increase hit count by limiting line spacing, survey speed, increasing overlap, etc., which will increase survey time and therefore cost.

Figure C.6 Hit count example.



Storage is an important part of the seabed mobility study life cycle, as all acquired data has to be stored safely on the acquisition vessel, then transferred safely and fully to shore, followed by the transfer to the client/end user. At all these stages, it is important that backups are kept, and this includes the ongoing processing. Apart from the amount of data changing depending on the system used, storage location, etc., the required resolution dictates the amount of storage required. Increasing the resolution by halving the cell size roughly quadruples the required storage.

Figure C.7 Increase of soundings per metre as bin size decreases (based on one sounding per bin).

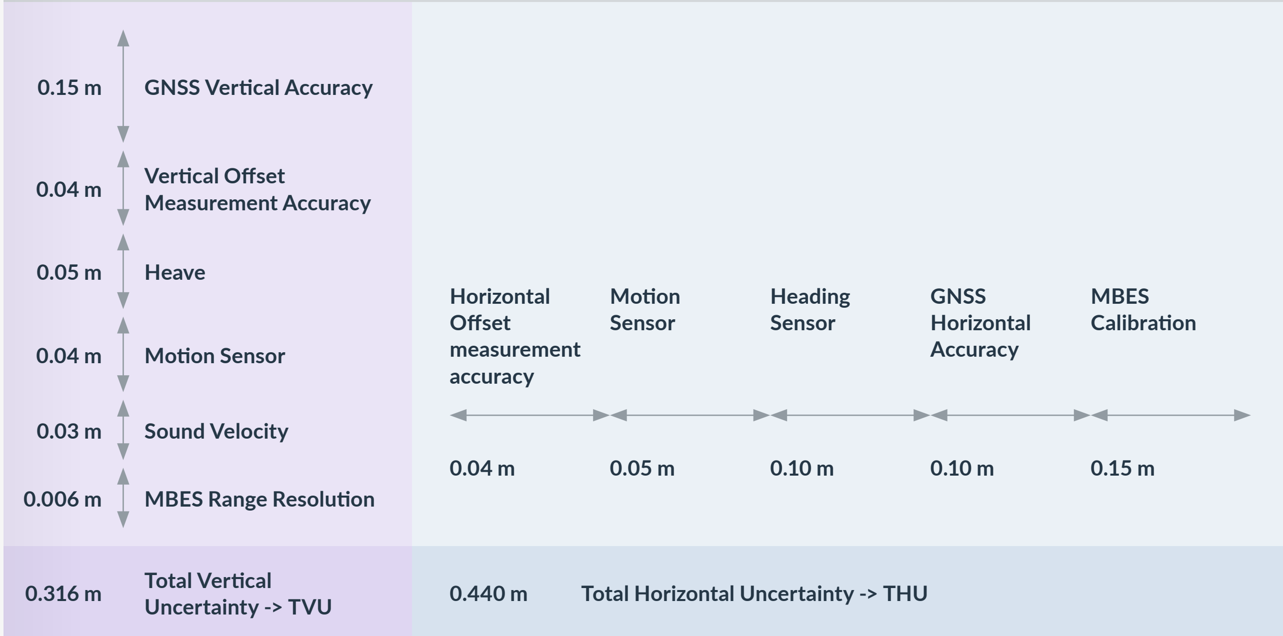


Storage requirements also increase when other multibeam outputs like backscatter/snippets, etc. are required (for example, adding backscatter can roughly double the amount of data recorded, despite the number of beams/ soundings remaining the same).

The accuracy of the data is important, whatever is required, but as the resolution is increased, the importance of quality and accuracy also increases. The accuracy required for these soundings is usually described in terms of Total Horizontal/Vertical Uncertainty (THU/TVU), which is derived from the sum of the key accuracies of the different sensors within a given acquisition system. This is not just the accuracy of the GNSS position solution (which includes corrections utilised) but combines all the systems that are used to position each sounding, including the sonar specifications themselves, the motion compensation, sound velocity, etc., as well as the survey software used to collect it and mobilisation/calibration parameters.

It is important to remember that while highly useful, THU/TVU is a modelled parameter and, while representative, does not give a completely accurate measure of accuracy. There are available standards, such as IHO S44, that sets THU and TVU requirements depending on depth, which can assist in setting the requirements, but it has to be noted that these specifications are primarily designed for safety of navigation and will not provide the required accuracy for seabed mobility studies in most situations (see C.6.1 Specifications and Guides for further information).

Figure C.8 Simplified vessel mounted example of how THU and TVU values are derived.



C.3.2 OTHER BATHYMETRIC SYSTEMS

Interferometric

Interferometric bathymetry systems (also known as bathymetric side scans) are a valid tool for seabed mobility studies (GeoSwath, Edgetech 6205, etc.) and are well suited for large area surveys as well as shallow water surveys due to generally having wider swath capability compared to MBES systems. Due to the way an interferometric bathymetry system works, there tends to be a gap in the nadir caused by the time difference between adjacent returns toward the centre of the swath being below the detection threshold of the sonar, which means that the return cannot be calculated. This gap increases as the water depth increases. It must be noted that interferometric systems tend to struggle to match multibeam definition below 1 m resolution if a detailed survey is required for seabed mobility studies.

Single Beam Echo Sounder

The Single Beam Echo Sounder (SBES) is the precursor to the MBES and a cost-effective means of collecting coarse, low-resolution bathymetry data for use in a seabed mobility context. A SBES system creates 1 sounding per ping, whilst MBES systems usually create hundreds or even thousands of soundings per transducer per ping. In shallow, difficult to access areas, this may be all that is practically possible, but where bed level changes are appreciable (>~0.5-1 m), it may be of sufficient resolution to be of benefit. Resolution can be increased by tightening line spacing and increasing the number of survey lines in an area.

Bathymetric LiDAR

LiDAR, which uses green lasers, can map the seabed when it is exposed during low water or through clear water (limited by turbidity, etc.). It can be mounted on a vessel, a land-based vehicle, an aerial vehicle, or by satellite. It is less commonly used for seabed mobility studies, as it is most reliable in shallow or intertidal areas (useful for sand migration, erosion studies, etc.), and therefore, there are fewer details on LiDAR in this appendix. However there are some further details in Section C.5, but useful details are also from other sources, for example, the 'Airborne Lidar: A Tutorial for 2025, Part III: Bathymetric lidar' by the LiDAR Magazine and also the 'Validation and application of Airborne LiDAR Bathymetry (ALB) technology for improved management and monitoring of Norwegian rivers and lakes' by the Norwegian Water Resources and Energy Directorate.

C.4 SURVEY PLANNING, RESOLUTION, ACCURACY AND DATA QUALITY

Seabed mobility assessments use bathymetric data, in conjunction with other data types, e.g., metocean, to characterise a site in terms of the likelihood of sediment transport and the associated morphological (bed level) change. It is critical that these assessments use accurate, high-quality data, and hence it is useful to have some understanding of the primary and secondary influences on bathymetric data quality by, for example, sensors, environmental factors, geodesy, planning or processing approaches. The following sections examine these influences in more detail.

C.4.1 GEODESY, HORIZONTAL AND VERTICAL DATUMS

Geodesy is the science of measuring and representing the Earth, including its geometric shape, orientation in space, and gravitational field. In marine and hydrographic surveying, geodesy provides the fundamental framework for all horizontal and vertical spatial positioning. A project's Coordinate Reference System (CRS) defines the geodetic datum to which all survey results are aligned, and it is essential that this CRS remains consistent throughout the project to avoid introducing horizontal and vertical error.

CRSs are based on spherical mathematical models of the Earth known as ellipsoids. These ellipsoids approximate the Earth's shape but are tailored to specific regions because the Earth is not a perfect sphere. As a result, different CRS models exist at continental, national, and global scales. Converting between CRSs requires applying defined transformation parameters that accurately reproject coordinate positions from one ellipsoid to another. If these transformation parameters are applied

incorrectly, the resulting positional errors can range from a few millimetres to hundreds of metres—or even hundreds of kilometres in extreme cases. The use of ETRS89 is recommended for seabed mobility studies in European waters as it considers the movement of the Eurasian tectonic plate, making it well suited as a European Datum.

Examples of common CRS:

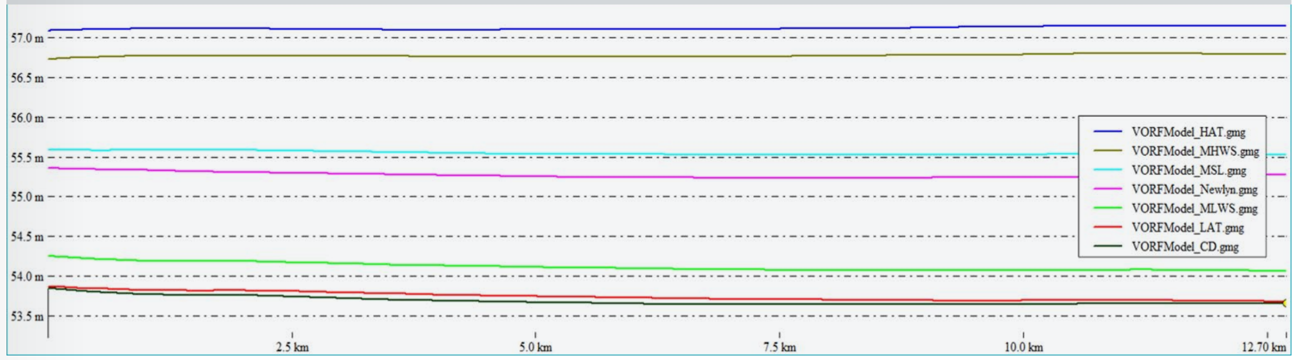
- **WGS84** – Global standard model
- **ETRS89** – European regional model
- **NAD 83** – The North American Datum
- **Airy 1830** – Historical UK ellipsoid
- **ED50** – European Datum of 1950, traditionally used in North Sea Oil and Gas

An Ellipsoidal position becomes a horizontal Easting Northing position when it is referenced to a projection. A projection is a 2D plane which represents the spherical Earth on a flat plane. The Universal Transverse Mercator (UTM) projection is the most common projection utilised throughout the hydrographic industry. Projections are split into UTM zones to reduce distortions, as a single flat plane cannot be accurately placed onto a spherical ellipsoid.

Examples of common UK projections are listed below:

- Universal Transverse Mercator Zone 29 North (UTM29N)
- Universal Transverse Mercator Zone 30 North (UTM30N)
- Ordnance Survey National Grid (OSGB36) / British National Grid (BNG)

Figure C.9 Vertical datum difference example.



A contractor should demonstrate that their geodetic configuration has been correctly established prior to conducting survey operations. This forms an essential part of the mobilisation checks carried out before operations begin on site. Although geodetic parameters may appear straightforward on paper, incorrect setup at project kick off can introduce significant horizontal and vertical errors that persist throughout the dataset.

A vertical datum will also be defined for the project to maintain a consistent reference level for depth measurements. Different vertical datums are selected depending on project requirements. A vertical datum is created by applying an offset to an ellipsoidal height to generate a constant vertical level to which heights can be referenced. In the case of seabed mobility, a vertical datum will be provided through the Vertical Offshore Reference Frame (VORF) or similar models. For example,

- **Chart Datum (CD)** is the specific low-water reference plane used for nautical charts, representing the level below which the tide rarely falls.
- **Lowest Astronomical Tide (LAT)** is the lowest level the tide will reach over a 19-year period under normal meteorological conditions.

Therefore, whilst similar in principle, there are differences in vertical height datums. LAT is the common industry standard datum. The below figure presents an example level of VORF models highlighting differences between various vertical datums.

C.4.2 SENSOR INFLUENCES ON DATA QUALITY

Data quality is a balance between accuracy and precision (See **Figure C.10**), as higher accuracy and lower precision could be acceptable for one survey campaign, but for multiple survey campaigns, then high accuracy and high precision is more important. It is influenced by many factors and one of the largest influences are the sensors, which include the type of sensor, the quality of the installation, and calibrations and the environment around them. **Table C.3** and **Table C.4** describes potential issues arising from sensor inaccuracies and how they have downstream consequences for the accuracy and quality of the data. These tables offer suggestions and approaches to resolve these issues, which should be judiciously considered during the writing of technical specifications, planning, and mobilisation.

Figure C.10 Accuracy vs precision.

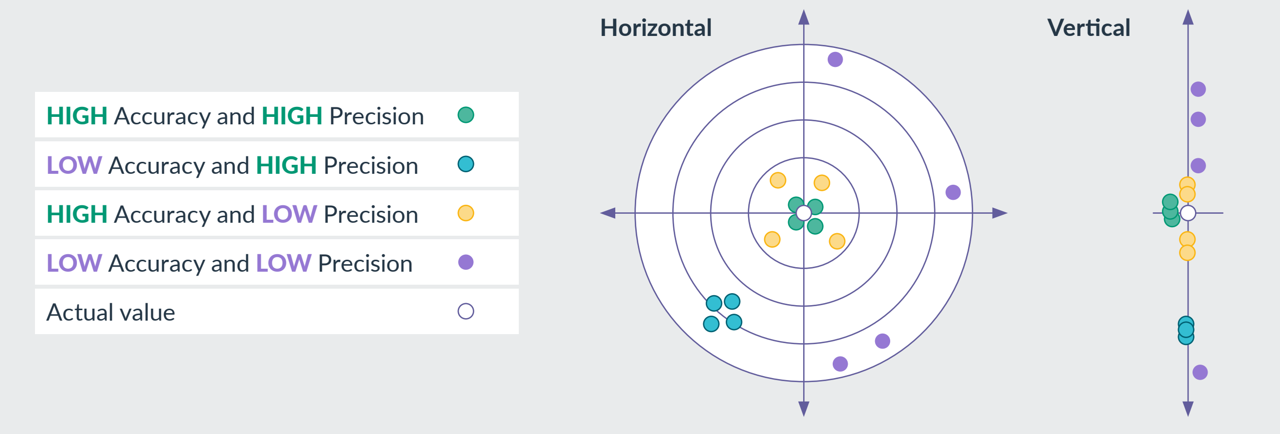


Table C.3 Sensor influences on accuracy and quality.

SYSTEM AND PURPOSE	POSSIBLE ISSUES AND EFFECTS ON SEABED MOBILITY STUDIES	SOLUTIONS
Global Navigation Satellite System (GNSS) Provides a point position at the antenna, usually utilising a combination of the GPS (USA), GLONASS (Russia), Galileo (EU) & BeiDou (China) satellite constellations.	GNSS antennas mounted at an incorrect location on the vessel position will be assigned at the incorrect node location in the survey software. In the same way as incorrectly measuring an offset, this will cause the survey software to locate the data in the incorrect location. This may cause a horizontal and/or vertical offset, which could be misinterpreted as actual seabed mobility.	Static position check: the onboard system is checked against the position provided by an independent system (typically, an RTK enabled GNSS roving receiver). The two systems should log their respective positions simultaneously, with the offset between the two being known accurately.
	Degraded, poor quality or missing corrections resulting in poor positional accuracy.	Online monitoring of solution status, with post-processing of position solution as needed.
	The accuracy of the positioning, both horizontal and vertical, will also depend on the corrections used. With no corrections, typical accuracies between 5 and 10 m are achievable. DGNSS and SBAS refines this up to sub metre accuracy, whilst RTK/PPP gives cm level accuracy.	Use more accurate internet based or satellite based corrections like RTK, PPP and PPP-RTK, or post process the positioning data.
Heading sensor Provides survey platform movement compensation for yaw (rotation around the Z axis).	Could cause misalignment in the data between overlapping lines. Errors will become more evident as resolution/ranges increase.	As multibeam range/ water depths increase, as well as increasing resolution, the accuracy/ performance of the heading sensor needs to be improved. Should be aligned with the vessel frame and preferably subject to a dimensional survey for CO values. For INS system GAMS – INS systems use the position received from a primary and secondary antenna to calculate the offset between them. This baseline is then used to give heading orientation, but DIMCON values are preferable as they will be more accurate.
Multibeam Echosounder	Misalignment to the MRU will propagate through to poorly positioned and misaligned data. Latency causing positional errors and motion artefacts in data.	PPS from the GNSS should always be supplied to the multibeam system and motion sensor to reduce latency between the systems. Carry out patch test – an industry standard methodology for using sonar data to resolve angular offsets between the MRU and the sonar, as well as any latency in the recording system. Requires multiple lines to be sailed over an area that includes both flat, featureless ground and a feature with steep vertical relief (bank, boulder, wreck, etc.). Software then calculates the angular offsets in all three dimensions by varying the values to achieve the best point cloud matches between lines. Test should be performed in water depths greater than or equal to the depths seen during acquisition, to ensure that offsets are suitably resolved for the slant ranges seen online. Although it is possible to update patch test values during data processing, it is important to have representative values applied in online software, to ensure that real-time coverage plots produced are accurate to ensure that gaps in coverage do not occur.
Motion Sensor Provides orientation data when the vessel pitches, rolls and heaves.	Motion artefacts and misalignment of the data due to possible misalignment between the GNSS & multibeam, inverted sign conventions for entered CO values, and received data into survey software. Motion artefacts can become more evident as the water depth increases due to longer lever arms. (offset distances between the system's reference point). Low sample rate or system latency will lead to data being poorly orientated relative to the rate of movement.	Should be aligned with the vessel frame and preferably subject to a full dimensional control survey for CO values. Align with multibeam system using dimensional survey (multibeam calibration to verify values) and/or multibeam calibration. Check sign conventions in the survey software and that CO values have been applied correctly. Use higher accuracy/ sample rate systems when higher resolution is required or working in deeper water depths.

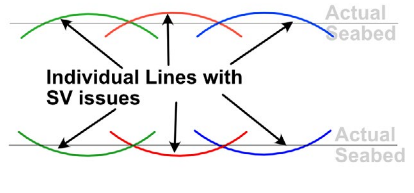
SYSTEM AND PURPOSE	POSSIBLE ISSUES AND EFFECTS ON SEABED MOBILITY STUDIES	SOLUTIONS
Sound Velocity Sensor (SVS) The Sound Velocity Sensor (SVS) is situated close to the transducer, and provides real time sound speed of sound velocities which are used in the beamforming process.	Without accurate SVS data, the transducer cannot accurately distribute the beams as intended, leading to uneven beam patterns and worsening signal to noise ratios.  Figure C.11 Sound velocity error	All sensors are required to have valid manufacturer calibration certificates (less than 2 years old). Should be checked against SVP during mobilisation.
Sound Velocity Profiler (SVP) The Sound Velocity Profiler provides the sound velocity at set intervals through the full water column. This is used by the processing software to correct for refraction through the water column between the transducer and the seabed, ensuring that the calculated bottom detection point is accurately positioned.	Incorrect SVP values can cause incorrect positioning of the bottom detections, which causes varying degree of bottom distortion to the seabed mobility data, which can be described as "frowning" or "smiling" as shown in the diagram above (**Figure C.11**). Note that inaccuracies introduced are in all 3 dimensions. Refraction effects increase with further lateral travel; swath widths need to be reduced as water depths increase to limit their effects.	SVPs should be collected regularly, at a minimum twice a day, and more frequently if SVS vs SVP differences exceed 2 m/s, or significant differences are noticed between different casts. When working in complex tidal areas or when there are significant distances between profiles, SVPs should be collected more frequently, and the locations of the sampling should be evenly distributed. All sensors are required to have valid manufacturer calibration certificates (less than 2 years old).

Table C.4 Sensor settings influences on accuracy and quality.

SENSOR SETTING	POSSIBLE ISSUES AND EFFECTS ON SEABED MOBILITY STUDIES	SOLUTIONS
Geodetic parameters Transformation parameters applied in acquisition software to convert the raw GNSS position (typically WGS84 lat/long) to the desired project coordinate system.	Incorrectly applied parameters will transpose the entire dataset to an incorrect position. This may not be apparent during acquisition but will result in the data being misaligned with previous datasets, preventing accurate comparisons. Errors can be on scales anywhere from cm's to 1000's of km.	Geodetic parameter test: a single test coordinate, usually given as WGS84 lat/long/ellipsoidal height (corresponding to raw GNSS observables), is input to the acquisition system and the resulting output coordinate after transformations have been applied is compared against an expected value. If available, cross checks to previous datasets over fixed objects (bedrock, infrastructure, etc.). Time based 7 or 14 parameter transformation addresses the temporal offset between surveys and any associated offsets due to tectonic drift.. A time based parameter transformation would transform data acquired in WGS84 to ETRS89.
Offset Accuracy All of the individual sensors (GNSS antennas, MRU, MBES) are physically separated. In order to convert a GNSS position at the antenna to a ping position on the seabed, all these offsets must be measured and input into the acquisition software.	Errors in XYZ measurements will not only propagate directly through to ping position but can introduce angular offsets that increase over longer ranges. Pings will be incorrectly positioned on the seabed and overlapping data will be misaligned. Causes issues when calibrating sensors, further compounding the problem.	Offsets must be measured as accurately as practicable for the vessel/ project. For small boats, with small offsets with clear line of sight, tape measures and laser distance measures are often sufficient. However, for larger vessels, a full Dimensional Control (DIMCON) survey, using traditional land surveying techniques, is required. Some systems, like SBGs & POS MVs, can calculate the main GNSS lever arms during calibrations, which can be useful, especially if the IMU is close to the MBES transducers. Carry out a node check.

SENSOR SETTING	POSSIBLE ISSUES AND EFFECTS ON SEABED MOBILITY STUDIES	SOLUTIONS
Physical fixtures The position of all components in the system needs to be fixed and known in order for accurate bathymetry values to be calculated.	Vibration/varying offset between transducer/ MRU/ antenna (non-rigid mountings, non-repeatable deployment of components) can create artefacts in the data, often making a flat seafloor appear uneven.	Ensure all fittings are fixed, rigid, stiff and, especially for recoverable over the side survey poles, deployment position is repeatable. Reduce survey speed and/or work in calmer sea conditions to reduce forces placed on components.
Seabed Tracking Multibeam systems use algorithms to track the bottom based on previous and adjacent pings, to reduce the effects of noise.	On occasions, there could be issues tracking the seabed due to items in the water column (debris, vegetation, fluid mud, etc.), which will give a noisy seabed or an incorrect seabed level. Kelp, etc. will usually grow on non-mobile surfaces, but these surfaces are useful for checking levels between surveys. Poor tracking can also be the result of inadequate sonar settings, e.g., power settings too low for the depth of water, leading to poor returns.	Strong filtering can be utilised, which is likely to involve manual filtering at first. Some multibeam systems offer multi-detect, which will record different seabed detections, which can improve the filtering and, in turn, provide a correct level. Online monitoring by an experienced surveyor, especially in complex/ challenging acquisition environments.

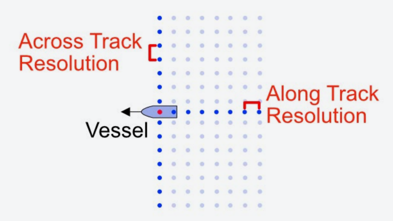
Table C.5 Environmental influences on accuracy and quality.

ENVIRONMENTAL INFLUENCE	POSSIBLE ISSUES AND EFFECTS ON SEABED MOBILITY STUDIES	SOLUTIONS
Pycnoclines (haloclines, thermoclines etc.)	This can cause unpredictable sound velocity refractions, which will cause depth errors.	They can be stronger during certain seasons, so seasonal survey planning can be a benefit. More sound velocity profiles and splitting the survey areas into smaller areas to make it easier to use the SV profiles valid for that area.
Sound velocity	See **Table C.3**	
Suspended sediments	This will reduce penetration, thereby reducing the depth that can be mapped by LiDAR systems.	Utilise low waters to maximise the intertidal zone and to maximise depth penetration where there is still water cover.
Turbulence/aeration Could happen around the transducer due to shallow waters, prop wash, pitching during poor weather, etc.	This can cause excessive noise in the data, to the point of inhibiting bottom detection altogether.	Lower the multibeam transducer further into the water or remount at a different location. If that is not possible, reduce speed and/or work in calmer sea conditions.
Interference Interference from other systems on the vessel (vessels echo sounder, etc.) or in the survey area.	This can cause excessive noise in the data.	Turn off the system interfering with the MBES system or change the frequency in either the MBES or the interfering system.

C.4.3 RESOLUTION: INFLUENCING FACTORS AND ASSOCIATED CONSIDERATIONS

Resolution requirements vary depending on what features need to be observed. Given that seabed mobility assessments account for megaripple-scale features (see Appendix D: Bedforms) in terms of error parameters used in predictions of future bed levels, megaripples are generally considered being the smallest feature of concern in assessments. To assist in achieving the resolution of the gridded data, it is beneficial to understand the nature of along track and across track resolution of individual lines (**Figure C.12**). The following section describes some of the effects on across and along track resolution, as well as how stabilisation and line planning help in gaining the best resolution.

Figure C.12 Across and along track resolution.



Across track beam distribution/resolution

Across track sounding density is principally dependent on the number soundings/beams per ping (not ping rate) and the swath width. While some multibeam systems allow the operator to reduce the number of beams, there is always a maximum number for a given system. More beams results in denser data coverage. However, the wider the swath, the greater the distance between soundings, and lower the sounding density. Unless the swath angle is adjusted, the swath width will increase as the water depth increases and therefore the beam spacing increases. The distribution of the soundings within the swath can also be controlled in the multibeam settings and can be set as either equiangular (beams are separated at equal angles at the transducer, making coverage denser at the nadir and sparser at the swath edges) or equidistant (beam are evenly spaced across the seafloor), as shown in **Figure C.13**. For seabed mobility studies, equidistant distribution is preferable to obtain more even sonification of the seabed (equiangular is mainly for inspection work, when a higher density of coverage in the nadir zone is beneficial for pipeline inspection surveys, etc.).

Across track density can also be increased by adding a second multibeam transducer, which is commonly called a dual head setup. 'Dual head' should not be confused with 'dual swath'; dual swath refers to transducers that can output two parallel swath during the same ping (Note: dual head setup with dual swath is possible).

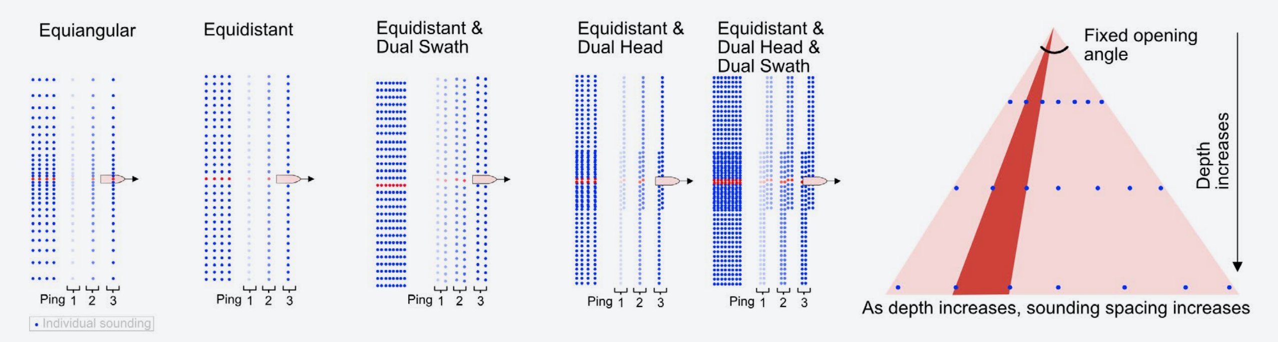
Along track beam distribution/resolution

Along track distribution is primarily controlled by ping rate and vessel speed over ground; increasing ping rate or decreasing vessel speed increases sounding density. While different systems have different maximum ping rates, the achievable ping rate is usually limited by the maximum slant range with ping rate decreasing as slant range increases: the greater the slant range, the longer the two-way travel time for a ping and thus the lower the ping rate (some systems simply use the maximum range to the lower seabed tracking gate, while others use the maximum range to the furthest bottom detection).

It is important to note that, as well as the water depth itself, as swath widths are increased, slant ranges increase and ping rates decrease; as a result, while wider swaths may cover greater areas in one pass, they reduce both the across track and the along track resolutions.

In shallower water (less than 10-15 m), resolution and coverage is more likely to be limited by the maximum swath angle that the system can achieve (often the transducers are tilted to overcome maximum swath angle), as well as the grazing angle (the angle of incidence between the beam and the seafloor) and increasing refraction (high grazing angles and refraction, occurring at the edges of wide swaths, reduce signal quality and accuracy), making ping rates largely academic to data quality.

Figure C.13 Beam distribution.



APPENDIX C: BATHYMETRY
CONTINUED

If resolution requirements allow, as ping rate increases, survey speed can also be increased, allowing the same resolution data to be collected in less time; conversely, as ping rates reduce, vessel speeds need to be reduced to maintain resolution.

Dual swath can also assist in increasing the along track resolution but should not be confused with dual head/transducer setup that increases the across track resolution.

Stabilisation

To assist with the good distribution of soundings in both the across and along track directions, there are several types of stabilisation available depending on individual system capabilities. Transducers are capable of directing beams in the opposite direction to vessel motion, using real time data from the motion compensation sensors, to negate the effect of the vessel motion and maintain even ping distribution on the seafloor.

Most modern multibeam systems offer a roll stabilisation capability (**Figure C.14**); this option should always be utilised for seabed mobility surveys, as it evenly spreads the across track beams along a survey line, helping ensure that coverage along the line is straight. This, in turn, enables wider line spacing, as less overlap is required to cover gaps caused by the rolling of the transducer/vessel, and to some extent simplifies processing when it comes to resolving tidal and SVP issues, because a distinct swath edge makes it easier to observe mismatches.

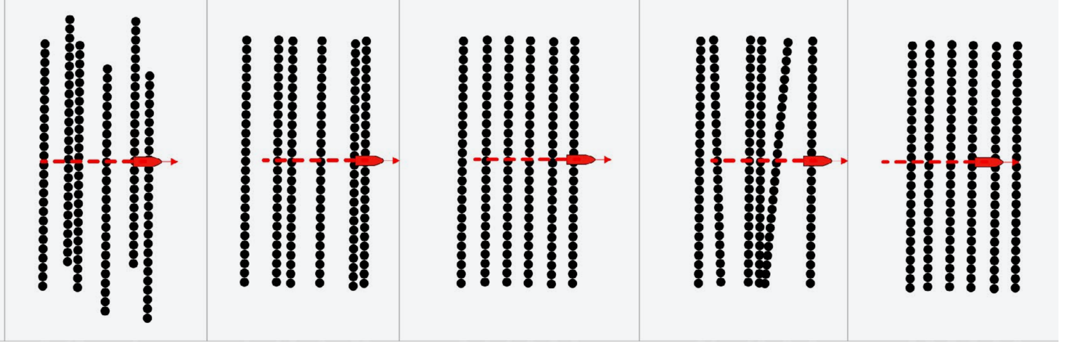
Transducer pitch and yaw stabilisation options further assist in evenly spreading out the beams, which improves beam distribution in the datasets. Systems with these capabilities are rarer and typically higher specification (and thus higher cost) units but are becoming more commonly available. Pitch stabilisation distributes the pings more evenly along track, while yaw stabilisation stabilises the sounding spread in both across and along track.

The benefits of stabilisation increase as the sea conditions worsen, when water depth increases, and when higher resolution is required. The benefits of stabilisation for seabed mobility data collection are:

- Increased working window in relation to wind and sea conditions
  - Decreases the chance of infill being required as conditions worsen and allows for higher resolution bins or higher hit count per bin; this is also important when water depth increases (as vessel rotation is exaggerated over distance).
- Increased survey speed (if resolution requirements allow)
  - No requirement to reduce speed to decrease the chance of gaps

Figure C.14 Stabilisation options.

Roll Stabilisation	✗	✓	✓	✓	✓
Pitch Stabilisation	✗	✗	✓	✓	✓
Yaw Stabilisation	n/a	n/a	n/a	✗	✓



Vessels can also be stabilised with, for example, antiroll tanks, active fins and gyroscopic stabilisers. This would provide a stable platform that can negate the use of stabilisers in the MBES system, but more preferably would improve overall stability by combining both.

Overlap

Line planning needs to take into account water depth and scope of work requirements. Line spacing will usually decrease when resolution requirements increase. If line spacing decreases, costs increase, as it subsequently takes longer to survey the required area; it is therefore important to set a sensible resolution requirement. Apart from increasing resolution, acquiring 100% overlap with adjacent lines allows noise in the dataset to be more easily distinguished from real data and filtered away, while complex structures that might initially be identified as noise (wrecks, etc.) will be clearly identified in the data with overlapping lines. However, for seabed mobility surveys, over filtering is, for the most part, not a significant concern (though care must be taken not to remove the crests of megaripples and sandwaves), as identifying debris, etc. is not the priority; as such, 100% overlap would normally be in excess to requirements.

Overlap can also help to increase resolution in deeper water where ping rates are lower, though high overall accuracy is important for this. In general, for a good setup system that meets resolution requirements, a 10% to 20% overlap is typically sufficient, as it allows review of depth alignment and beamforming issues, etc. Full overlap can assist in providing mobility rates in highly mobile sites, where sediment migration is significant enough to change bed levels between successive survey lines. In such environments, care also needs to be taken if data is collected over multiple tides/days, as the seabed could have changed considerably; survey areas should be split into subsets, with survey lines should be run systematically from one side to the other, with extra care to avoid infill passes, or if necessary, also acquire them during the same period of survey activity.

C.4.4 SURVEY PLANNING INFLUENCES ON DATA QUALITY

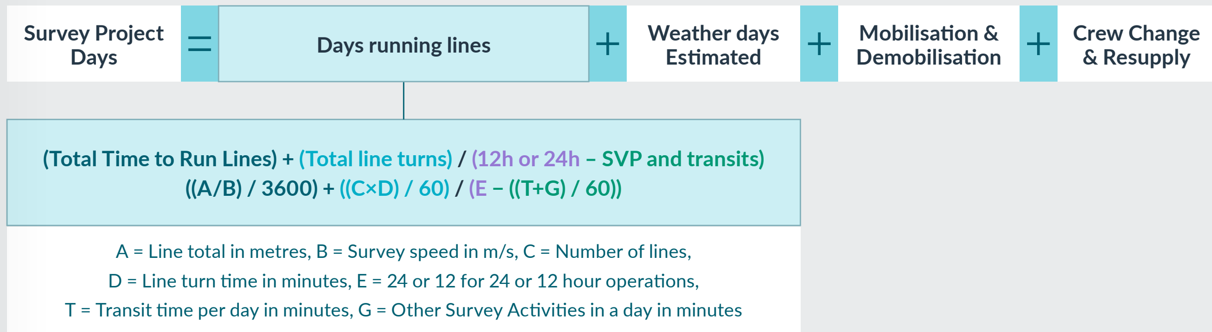
A key part of successful data acquisition is proper survey planning, which optimises both data quality and survey duration and, in turn, overall project cost. Some items have already been mentioned in 'Resolution: Influencing Factors and Associated Considerations' section, **Table C.6** expands on this and lists factors that need to be taken into account when planning lines and what effects they could have in regard to seabed mobility studies.

Table C.6 Considerations for line planning.

FACTOR	IMPORTANCE
Water depth/ ping rate	Ping rate will decrease as water depth increases, and to achieve resolution, line spacing might have to be decreased.
Usable swath width	Linked to the ping rate for in-line resolution, and the water depth for cross track resolution. Refraction effects and other effects become limiting factors at very wide angles/ high slant ranges.
Overlap/ ping density required	Full overlap might be required for density/resolution. It might also be needed when pitch and/or yaw stabilisation is not available, and ping distribution becomes uneven.
Currents	While typically more of an issue when towing equipment, for multibeam surveys, coverage can be decreased due to vessel crabbing. Currents can also cause issues with line steering. If possible, lines should be orientated with prevailing current direction.
Contours	Where possible, follow contours to maintain a fixed swath width to make overlap to next line consistent (less likely to leave coverage holes).
Obstructions (infrastructure, marine traffic, etc.)	Any line plan needs to account for any potential hazards in the survey area, while ensuring coverage is as complete as possible.
Splitting into survey blocks	This is beneficial for larger survey areas as well as smaller ones with high rates of seabed mobility. A parallel line later in the day or on another day, could suffer a vertical shift error on the overlap due to change in seabed level during the survey period, so it is better to keep the busts localised to the edges of the survey areas. Splitting into survey areas could also assist in processing (requires less powerful workstations and allowing dividing between multiple processors) and distributing the final product.

Survey duration for the project can be calculated after a line plan has been created. This can help with planning or for cost estimation. Weather days can be hard to estimate, and average weather data for that time period has to be used, but it should also be taken into account that different equipment and vessels can perform differently during worse weather conditions. **Figure C.15** is an example of a survey duration equation that summarises some of the planning considerations.

Figure C.15 Survey duration calculation example.



Durations can be a live spreadsheet during acquisition, and items like line turn times can be adjusted during acquisition to produce a more accurate result.

C.4.5 SURVEY INTERVALS

Another important factor specific to seabed mobility studies is the interval at which repeat surveys will be conducted. It is possible to track sandwaves over a few years, and this can be tracked in a usual project development phase of a 2 to 4 years. However, but this might have to be expanded, and it is possible that larger features, like sandbanks can have a slower rate of migration and would therefore need longer periods of monitoring. It is also possible that movement can change depending on seasonal changes as well as changes of structures around the area of study (seabed changes or new man-made structures).
This could be driven by:

- The expected rate of movement of the seabed: highly mobile areas might need to be mapped more frequently, whilst larger structures like sandbanks might only require larger intervals, but over a longer period of time (see Appendix D: Bedforms).
  - Monitoring can start with more frequent surveys and then reduce as a better understanding of seabed movement is achieved.
  - Intra-annual variations or reversals
  - Construction in or around the site of monitoring could change the mobility, and therefore the monitoring might need to be extended, etc.
- The resolution of the survey: coarser resolution will, by definition, be unable to precisely detect horizontal changes on scales below the bin size. Note that this applies to both the planned acquisition and any previous datasets that will be used for comparison.
- Financial constraints: a balance will likely always be needed between obtaining the desired amount of data and the cost of doing so.

C.4.6 SURVEY REQUIREMENTS AND DELIVERABLE RECOMMENDATIONS

When specifying equipment and data accuracy, these must be achievable, and the Contractor selected assessed on their ability to meet the specifications. The risk of over specifying, apart from risking items being omitted, is that it could stifle innovation, which is important for improving performance and cost. Checks would be required at the mobilisation stage, as well as during acquisition, and finally during data delivery. **Table C.7** provides an example list of requirements for acquiring seabed mobility data, but it also needs to be tailored to the specific requirements.

As presented in **Table C.7**, checks should ideally always be made over a subsea benchmark. This could be exposed bedrock, subsea infrastructure or other fixed, known objects on the seabed. This is the best way to ensure that the survey setup is correct and that data from each survey will be comparable. When obtaining historical data from another source, the requested data should ideally extend over a non-mobile seabed if possible.

Table C.7 Example technical requirements.

	RECOMMENDATIONS	CALIBRATIONS AND VERIFICATIONS	NOTES
Horizontal Datum	ETRS89	Coordinate conversion check in the survey software with the provided coordinates.	Takes tectonic plate movement into account.
Vertical Models	Relevant Vertical Offshore Reference Frame models	Model value provided and checked at a given position or part of the check over a known area of the seabed.	UKHO VORF, BATHYELLI, BLAST, DTU23, etc.
Vertical Datum	LAT (Lowest Astronomical Tide) and CD (Chart Datum)		Most commonly used vertical datums.
Timing	Motion sensor and multibeam Interfaced with PPS	Multibeam calibration latency check.	To make sure that there is no latency in the overall system.
Positional Horizontal Accuracy	RTK, PPP or PPK	Verification of the positioning system against a known benchmark. Comparison between primary and secondary GNSS systems.	GNSS corrections are widely available and can be integrated with most modern GNSS systems. Having good positioning is a good starting point for a survey setup and acquiring quality data.
Positional Vertical Accuracy			
Horizontal Bathymetry Accuracy	IHO Exclusive Order or better	THU check on the bathymetry data.	Important when considering slowly moving bedforms.
Vertical Bathymetry Accuracy	IHO Exclusive Order or better	TVU check on the bathymetry data. Check over a known non mobile surface (rock outcrop, subsea infrastructure, etc.).	An undulating non-mobile surface can also be used for checking horizontal accuracy.
Sound Velocity	± 0.05 m/s (resolution 0.005 m/s) SVS co-mounted with multibeam	Calibration certificate less than 2 years old.	If further reassurance is needed, then all SV sensors could be checked against each other.
Resolution	As required	GeoTIFF showing no holes at max survey depth. No noise or interference from other sensors or vessels.	
Hit Count	As required	Hit count surface (floating GeoTIFF).	
Overlap	As required		At least 20%.
Backscatter	If required Option: factory calibrated backscatter multibeam transducer	Demonstrate that it is being recorded.	Could be recorded and only processed if required. Factory calibrated backscatter multibeam transducer could limit systems and contractors, as it is still not common enough.

APPENDIX C: BATHYMETRY
CONTINUED

Data deliverables can be split into daily QC deliverables and final data and QC delivery (**Table C.8** Whether an internal survey is carried out or verifying the work of contractors, daily QC of the data is essential. Where an internal survey was performed, QC data would be available online in real time in the survey software, so the exports might not be needed. The processed data formats requested should be compatible with the software that will be used to evaluate and study the seabed mobility data, and that format might not be included in **Table C.8**.

Table C.8 Recommended data deliverables.

TYPE	DAILY QC DELIV	FINAL DELIV	FORMAT	NOTES
Raw data		✓	Generic (GSF, XTF) with inclusion of positioning and motion recommended But can also be a preferred format or the multibeam system's own format. Positioning and motion files need to be provided if not in the provided raw files.	Possessing the raw data is beneficial for quality control/ reprocessing if needed, or for future tools that might be able to get more out of the data etc. GSF and XTF are generic formats that can be exported from most survey packages and read by most survey processing packages. Offsets and calibration results in the mobilisation report. Raw data should include calibration lines.
Processed, gridded XYZ data		✓	XYZ Ascii (comma-delimited or preferred delimitation characters), CSV, LAS or similar compressed format.	Contains a single XYZ position for each grid cell. Position of sounding should be the centre of the gridding box (the other option is the corner of the box (cell origin)).
Processed, un-gridded XYZ Point Cloud		✓	LAS or similar compressed format.	Contains XYZ positions for every good ping during acquisition (Filtered data). Compressed format preferred due to the size of the file when uncompressed.
GeoTIFF of average surface image	✓	✓	Floating-Point .tiff format (cloud optimised) with compression.	If required, the shallowest and deepest surface can also be requested. However, these surfaces can also be created from the un-gridded point cloud.
Metadata		✓	Ascii or set industry format (MEDIN discovery metadata standard, etc.,).	Contain items like: grid resolution (cell size), gridding point (cell origin or centre), z value represented (max, min or mean) and coordinate reference system, to include both horizontal and vertical datums etc.
GeoTIFF/ Gridded XYZ of hit count	✓	✓	Floating point .tiff format (cloud optimised) with compression OR Processed, gridded XYZ point cloud.	The hit count grid could be provided at a slightly lower bin size to give some flexibility/simplification if every bin does not need to be filled. Cell/bin centre positioning preferred.
GeoTIFF/ Gridded XYZ of standard deviation (SD)	✓	✓	Floating point .tiff format (cloud optimised) with compression OR Processed, gridded XYZ point cloud.	
SVP	✓	✓	Ascii	
Floating GeoTIFF/ Gridded XYZ of THU and TVU		✓	Floating-Point .tiff format (cloud optimised) with compression OR Processed, gridded XYZ point cloud.	
Rejected, un-gridded XYZ Point Cloud	Optional	✓	LAS or similar compressed format.	In addition to the filtered un-gridded XYZ cloud data, rejected points XYZ cloud data could be an option as a requirement, but less important for seabed mobility studies.

If required, backscatter or/and SSS mosaics can be requested in the GeoTIFF format.

GeoTIFF and floating GeoTIFF note: Standard GeoTiffs are not recommended as they offer less flexibility and always have to be accompanied by a colour scale, because instead of the actual Z value, only the RGB colour value for each cell is provided. Floating point GeoTIFF can be handled and manipulated in the same way as ASCII data in most GIS software.

C.4.7 THE EFFECT OF RESOLUTION AND SURVEY ERRORS ON SEABED MOBILITY APPLICATIONS

The following sections provide simplified examples of how resolution and survey errors can affect seabed mobility studies. This will help clarify how accuracy requirements and issues can affect the bathymetry data used to infer aspects of seabed mobility.

The effect of resolution on the accuracy of resolving seabed features

As mentioned in Appendix D, the study of seabed mobility involves consideration of seabed bedform structures like ripples, megaripples, sandwaves, sandbanks, etc. These can all indicate seabed mobility and, through assessments such as linear transects or planform analyses, will also provide mobility rates and directions, especially when comparing datasets recorded at different times (time-lapse imagery). An obvious point is that the smaller the features that require monitoring, the higher the resolution required. It is less likely that ripples will be monitored for most seabed mobility studies, but if ripples were a requirement, then better than 0.50 m Bins would be required, as shown in **Figure C.16** (TIN-based gridding).

Megaripples are clearly defined in most resolutions up to 2 m Bin, dependent on their exact size. Defining the crests will be no issue for most resolutions, but accuracy will decrease as the resolution decreases, with the accuracy around ± 0.5 m for 1 m Bin datasets and ± 1 m for 2 m Bin datasets as shown in **Figure C.17** (TIN-based gridding). Requirements will be dependent on the timescale the megaripples need to be monitored for, as higher resolution intervals would require higher resolution data.

Figure C.16 Resolution effect on small mobility features (Ripples – 3 cm high)

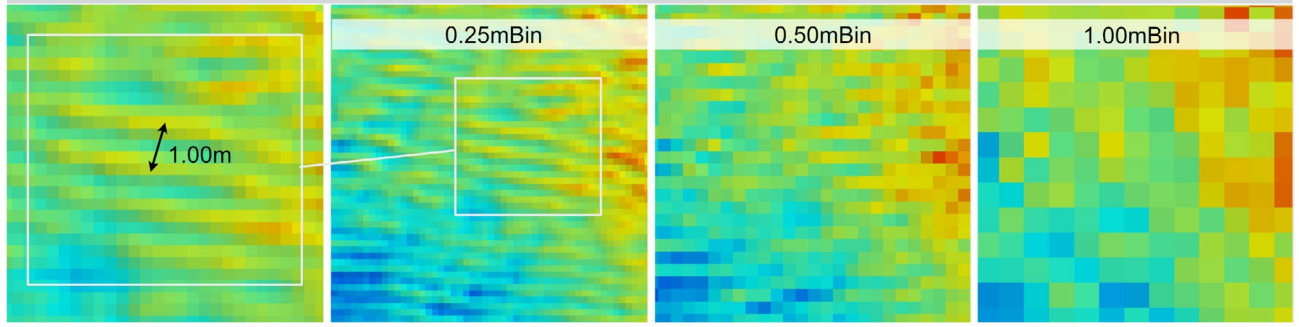
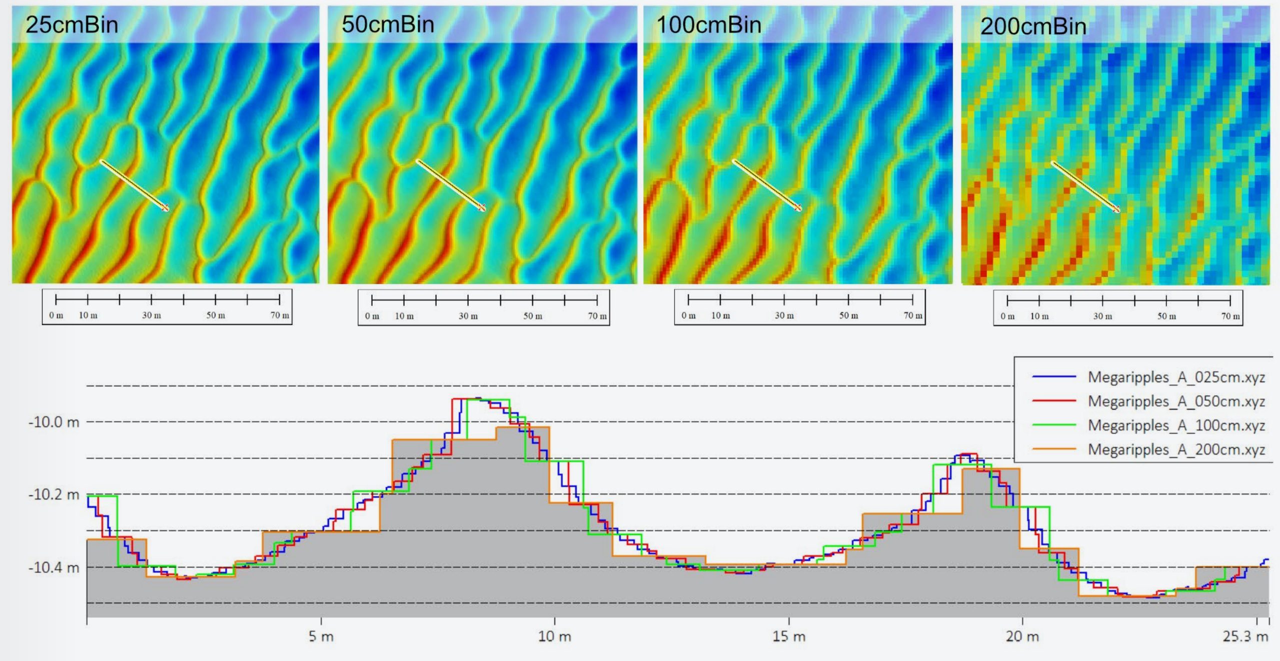
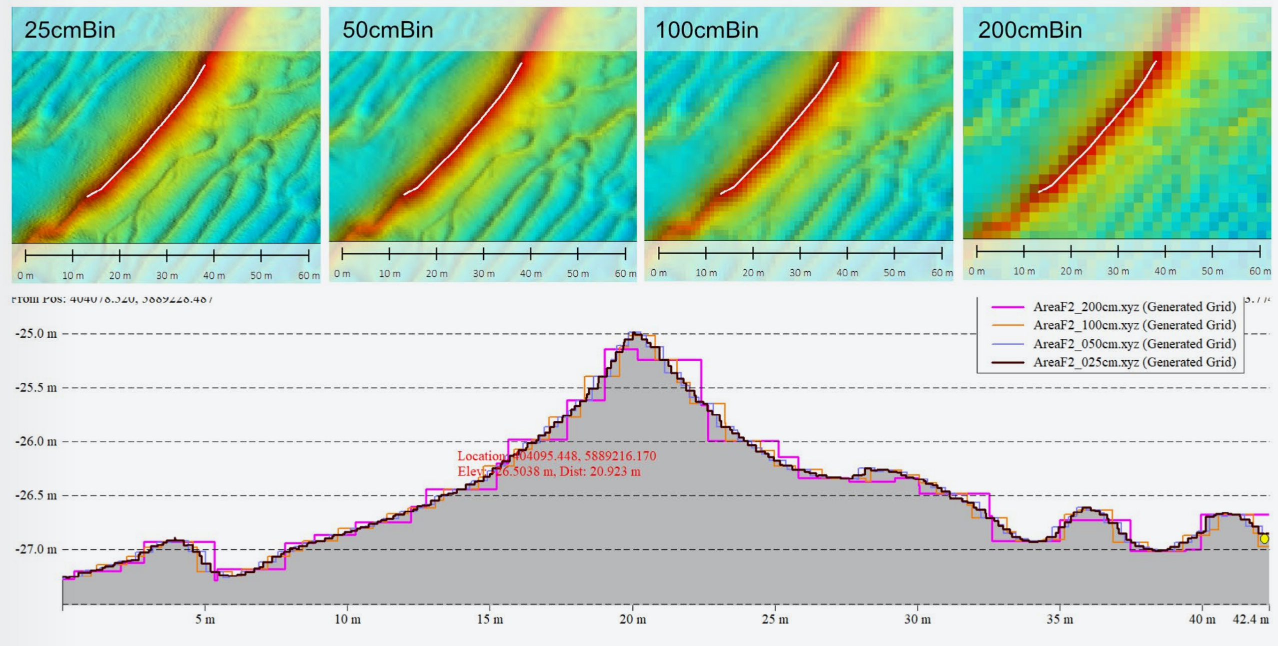


Figure C.17 Resolution effect on megaripples (megaripples – up to 50 cm high)



Larger features, like sandwaves and sandbanks, are easier to track through different datasets and data resolutions, as shown in **Figure C.18** (TIN-based gridding). Larger features are less influenced by resolution; however, if the tracking involves slow rates of around 2 m a year, then better accuracy and lower resolutions are more important.

Figure C.18 Resolution effect on picking the ridge of a sandwave and the cross profile across the feature



It must be remembered that resolutions are limited ultimately by positioning accuracy, as anything at a higher resolution becomes less useful as positioning accuracy decreases, as results can be distorted by mismatched and poorly located data. A simplified example is having a dataset with a resolution of 0.5 m, but the overlapping lines have a position accuracy of ±1.0 m, which could, in extreme circumstances, be the same has having a dataset at 1 m resolution. When picking sandwave crests for migration rate and direction, like megaripples, the relative accuracy relative to resolution decreases as the resolution increases (accuracy around ± 0.5 m for 1 m Bin datasets and ± 1 m for 2 m Bin datasets). Minimum resolution for sandwaves should be 2 m (1 m if slower rates of mobility need to be tracked).

Sandbanks are large features, and therefore, a lower resolution could be used, but to monitor yearly migration, a higher resolution is required. Therefore, it is advised that the resolution is 0.5 m or better, as mobility rates for sandbanks are around 1 m/year. With higher resolution, higher positional accuracy is also required.

It should be noted that different types of gridding can have a positive or negative effect on datasets in cases of low-density data, poor precision or low-resolution data (different types of gridding methods are not covered in this appendix). In general, standard gridding methods like triangulation, etc., will be good enough for most seabed mobility studies.

The effect on seabed volume change calculations

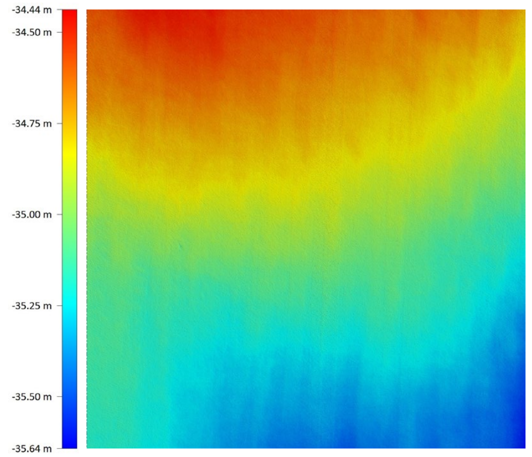
When investigating seabed change in an area, two gridded surfaces are subtracted from each other, which creates a difference surface that can be used for volume calculations or feature change detection (often used for trenching, etc.). From the difference surfaces, volumes of change can be calculated, as well as trends in bedform migration rate and direction. The accuracy of this difference grid is going to be dependent on the resolution, accuracy and the nature of the seabed terrain. However, high accuracy might not be needed for certain uses of the datasets, like migration detection and the rate of migration.

Table C.9 provides some examples of volume calculations and the effect of different resolutions and errors on those comparisons, to give an idea of the effects on difference datasets. For the comparisons, surface 1 and surface 2 are derived from the same dataset, but at different resolutions and induced horizontal and vertical errors for comparative examples.

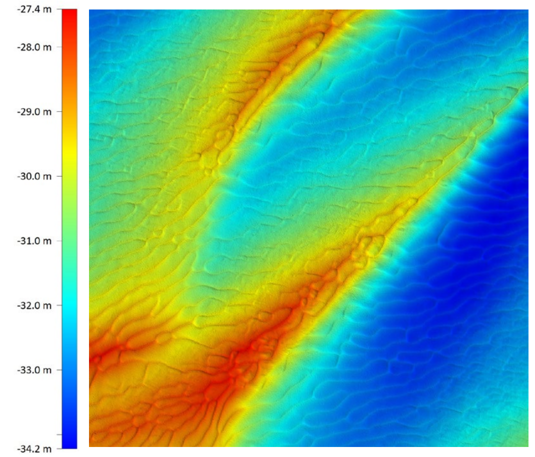
Table C.9 Volume calculation examples

REF	SURFACE 1	SURFACE 2	DIFFERENCE SURFACE 1 SUBTRACTED BY SURFACE 2 (CUBIC METRES)			
			AREA A		AREA B	
			NET VOLUME DIFFERENCE	TOTAL VOLUME = FILL + CUT	NET VOLUME DIFFERENCE	TOTAL VOLUME = FILL + CUT
1	0.25 mBin	0.25 mBin	0		0	
2	0.25 mBin	0.50 mBin	**-40**	572 = 266 + 306	**-58**	1463 = 702 + 761
3	0.25 mBin	1.00 mBin	**-40**	572 = 266 + 306	**-57**	2186 = 1065 + 1122
4	0.25 mBin	2.00 mBin	**-40**	572 = 266 + 306	**-52**	3769 = 1859 + 1910
5	0.25 mBin	4.00 mBin	**-103**	576 = 287 + 390	**-14**	6690 = 3338 + 3352
6	0.25 mBin	0.25 mBin +10 cm Z shift	**8978**	8978 = 8978 + 0	**8978**	8978 = 8978 + 0
7	0.25 mBin	0.25 mBin +0.50 m XY shift	**-113**	530 = 209 + 322	**-169**	3269 = 1550 + 1719
8	0.25 mBin	0.25 mBin +1.00 m XY shift	**-226**	612 = 193 + 419	**-338**	6288 = 2975 + 3313
9	0.25 mBin	0.25 mBin +0.50 m XY & 10 cm Z shift	**8861**	8861 = 8861 + 0	**8805**	8889 = 8847 + 42
10	0.50 mBin	0.50 mBin +0.50 m XY shift	**-112**	565 = 227 + 339	**-171**	3241 = 1535 – 1706
11	1.00 mBin	1.00 mBin +0.50 m XY shift	**-118**	544 = 213 – 331	**-173**	3035 = 1431 – 1604

Area A (300 m x 300 m) Vertical range 1.2 m



Area B (300 m x 300 m) Vertical range 6.8 m



- Resolution usually has a minimal effect on difference calculations for datasets with resolutions below 4 mBin in regard to net volume. However, total volume errors, related to using difference resolutions increases as the complexity of the seabed increases (**Table C.9** Ref 2, 3, 4 & 5). Comparing historical datasets at different resolutions is not problematic, especially over larger areas.
  - However, if items over smaller areas are tracked, like trench excavation-infilling studies, then resolution is more important. If the resolution is decreased, the smaller features that are around the same size as the gridding resolution are smoothed out.
    - Line by line accuracy (SD), with each line matching its neighbour's level, is more important than datum accuracy.
- When a vertical shift survey error is added, larger differences in volume calculations would be observed than would be seen with using different resolutions (**Table C.9** Ref 6).
  - The 10 cm vertical shift in the example is the average accuracy of a GNSS system and could be a typical error seen in a well setup survey setup. The vertical error could be larger dependent on offsets, calibration values etc.
  - As vertical errors have the largest effect;
    - It would be advisable to use the same derived surface in regard to shallow, average and deep surface (See **Figure C.5**)
    - Tidal datums and vertical datum reduction methods of the datasets need to be taken into account.
- Horizontal errors (XY) have a much smaller effect on the volume calculations than vertical errors (**Table C.9** Ref 6, 7 & 8). Even increasing the resolutions with a horizontal survey error does not affect the results significantly (**Table C.9** Ref 7, 8, 10 & 11).

Resolution and Precision Summary

When specifying the resolution required, the general rule is that the larger the feature is, the lower the resolution can be. When looking at accuracy, theoretically the accuracy can be less for larger features, coupled with lower resolutions. However, as resolution and accuracy decrease, the accuracy of measuring megaripples and sandwave crests is variable and dependent on how defined the crest is. Whatever the size of the feature that needs to be measured, the aim should always be to acquire high accuracy data. However, for bathymetric subtraction (difference grids), vertical errors can have a more substantial effect than horizontal errors in a relatively flat area or at lower resolutions. The issue with smaller features and higher resolutions is that any error will cause mismatches in overlapping lines which will destroy the detail to varying degrees. **Table C.10** gives some guidance on what resolution and accuracy should be used depending on what needs to be studied, but the requirements of seabed mobility studies can vary greatly. However, it can be counter-productive to excessively reduce survey accuracy requirements, as what is achieved in reality is usually less accurate than specification, and best accuracy should always be strived for whatever the situation (within commercial boundaries).

Table C.10 Resolution and accuracy summary.

FEATURE/TASK	RESOLUTION	ACCURACY	NOTES
Bathymetric subtraction – Volume calculations	≤ 0.5 m for smaller features	High accuracy.	Features like trenches. Colour scale range can help mask the inaccuracies for visual purposes.
	≤ 4.0 m for large area calculations	Vertical accuracy is more important in flatter areas than horizontal accuracy.	
Bathymetric subtraction – Migration calculations	Depends on the features to be studied, therefore refer below	Accuracy can be relaxed slightly as long as the movement to be measured is more than 2 m.	It can be relaxed further depending on the size of the features and faster rates of movement. The question is whether the same feature can be identified in multiple datasets.
Ripples	≤ 0.5 m	High accuracy.	The higher the accuracy, the clearer the crests will be. More defined crests need lower data resolutions.
Megaripples	2 m for crest accuracy of ±1 m 1 m for crest accuracy of ±0.5 m	Accuracy should be equal to or better than the resolution.	
Sandwaves	2 m for crest accuracy of ±1 m 1 m for crest accuracy of ±0.5 m		
Sandbanks	≤ 0.5 m	High accuracy.	Due to the slow rate of movement, higher resolution and accuracy is required (dependent on time between datasets).

C.5 OTHER SOURCES OF SEABED MOBILITY DATA

While use of multibeam systems remains the prevailing source of bathymetry, data for seabed mobility can also be acquired by other means and these are detailed in this section and summarised in **Table C.11**.

Table C.11 Other sources of bathymetry

OTHER SOURCES OF BATHYMETRY		DESCRIPTION	STRENGTH	WEAKNESS
Aerial LiDAR		Bathymetric LiDAR employs green LiDAR to allow scanning through the water column up to 40 m water depth.	Can be cheaper for large area surveys. Can survey areas that can be harder to reach with conventional vessel-based setups.	Penetration depends on water turbidity. Typically, a few metres is achievable, with very clear water a maximum possible depth of 40 m is achievable.
Satellite Data	LIDAR	Bathymetric LiDAR employs green LiDAR to allow scanning through the water column.	Large area datasets.	Penetration depends on water turbidity.
Satellite Data	Bathymetry From Wave Propagation	Uses the relationship between length, speed and period of waves to calculate the depth.	Large area datasets.	Grid size is typically 50-200 m at depths up to 25-35 m, so more suitable for large feature monitoring like sandbanks over long periods.
Satellite Data	Photogrammetry	3D data is created from multiple photos taken at different positions.	Large area datasets.	Limited to where the seabed can be seen visibly and with enough definition. Achievable depth accuracy is less than that of LiDAR.
Satellite Data	Radiative Transfer Equation Inversion	Uses the full pathway of the light, combined with a full environmental model, to detail refraction and other propagation effects, to derive a position for the reflection point on the seabed; multiple light spectra can be employed.	Resolution available up to 1.3 m.	Depth limited to optical shallow water.
Nautical Charts		Chart with soundings and contours created from combined depth surveys of varying methodology and accuracy (from lead line to bathymetry).	Large scale features.	Sounding depths predominantly focus on the shallowest point. Different datasets stitched together from different dates (Could be several 100 years difference).
Historical Datasets		Predominantly, data collected for nautical chart creation is now available for download.	Large areas available Older datasets that can be compared with freshly collected data.	It might only be the latest versions available, but for seabed studies, having access to older datasets can be beneficial. Accuracy and resolution tends to decrease with older datasets Consideration for different horizontal and vertical geodetic datums.

C.5.1 AERIAL LiDAR

Bathymetric LiDAR employs green LiDAR (typically 532 nm wavelength) to allow scanning through the water column (near-infra red wavelengths, used by most LiDAR units, cannot penetrate water). Advantages include high acquisition rates, with aerial mounted systems able to cover a given area orders of magnitude quicker than marine vessels, and accessibility, with systems able to acquire data in shallow and remote areas inaccessible to most or all marine vessels, with seamless transitions between marine, intertidal and terrestrial environments. Disadvantages are limited depth penetration, with maximum possible depth measurements to around 40 m of water; however, this is affected significantly by turbidity and other factors and can reduce depth penetration to only a few metres. Depth penetration is commonly measured in Secchi depths, where 1 Secchi is the depth to which a standard black and white plate can be lowered and still be visually observed. LiDAR systems can operate, at most, up to ~2 Secchi depths. Precision can be reduced compared to sonar systems, often seeing decimetre scale TVU and metre scale THU, and reduced coverage density (i.e. fewer pings per square metre), especially when operating at higher altitudes. Recent advances in smaller units that can be operated from UAVs mean these issues can be overcome, with data comparable to multibeam systems.

C.5.2 SATELLITE DATA

Remote sensing via satellites can be broadly broken down into two categories: passive and active sensors. Passive sensors rely on observing existing electromagnetic energy radiated from the earth, e.g., visible light being recorded by a camera. Active sensors emit their own source of electromagnetic energy, the return signal of which is measured; in the case of satellite-based systems, these are either Synthetic Aperture Radar (SAR) or Light Detection and Ranging (LiDAR) systems. The frequencies employed by SAR systems cannot penetrate the water surface, while LiDAR systems employing green wavelengths can. Conversely, SAR systems are capable of penetrating atmospheric gases and clouds, whereas LiDAR requires a visually clear atmosphere. The following methodologies can employ satellite derived data to calculate bathymetry levels.

For more information see IHO's B-13 Edition 1.0.0 Guidance to Satellite-Derived Bathymetry document.

LiDAR

The principal is the same as described in C.5.1, relying on more focussed beams. Systems include NASA's ATLAS satellite.

Bathymetry From Wave Propagation

Uses the relationship between length, speed and period of waves to calculate the depth. Can only achieve horizontal resolution equal to the ocean wave's wavelength in depths of half the wavelength in theory; in practice, grid size is typically 50-200 m at depths up to 25-35 m, making it largely unsuitable for sediment mobility analysis. Data on the wave forms can be obtained by SAR or photographic data.

Photogrammetry

As per other utilisation of photogrammetry, a stereo pair of images are required, in which distinct features can be co-located. This requires very high-resolution imagery to accurately identify and locate features, meaning the resulting resolution is subsequently a function of the original image resolution. The measurable depth range is limited to optically shallow waters, i.e. depths at which the seafloor can be seen visually. Accuracies can only be optimised with the presence of Ground Control Points (GCPs) in the imagery, i.e. visible points with a known position, ideally with an even distribution through the site (unlikely for bathymetric data).

Radiative Transfer Equation Inversion

Uses the full pathway of the light, combined with a full environmental model, to detail refraction and other propagation effects to derive a position for the reflection point on the seabed; multiple light spectra can be employed. The resolution is again dependent on the resolution of the imagery; currently, data is available down to a 1.3 m grid resolution, and again, can only map in optically shallow water. The methodology is also reliant on accurate modelling of all relevant atmospheric conditions both in air and water; these factors can be derived either from existing databases or derived from observed data.

C.5.3 NAUTICAL CHARTS

Nautical charts can be used as a source of bathymetric data, mainly for large scale seabed features; however, there are several factors to consider in their use. Firstly, they are created with the primary purpose of facilitating safe navigation at sea, and as such, sounding depths predominantly focus on the shallowest points; however, contours are generally not shallowest biased. Complex structures are likely to be simplified to the shallowest point and the detail lost in the interpretation. As with other data sources, the provenance of the survey from which the chart is derived also needs to be considered; charts may be based on outdated survey data (years or even decades old) but also can be composites of different surveys that can span hundreds of years, and therefore it is not always a snapshot of the seabed at one time. Methodologies have changed over the years with increasing technology – from lead lines to SBES systems and then to MBES systems and from hand drawn to using computers as well as new tidal reduction methods. Each method has its own accuracy considerations, and so positional accuracy, tidal reduction and density of the data (interpolation) and any difference in acquisition year between the different data sources needs to be considered. Bathymetric data used to create the charts can now be downloaded which therefore makes most modern charts redundant in regard to seabed mobility studies (See C.5.4).

The document 'UKHO_Survey_Specification_Seabed Mapping' (V1.2_June22) provides detailed insight into survey specifications for charting and could be considered another independent source which the reader can refer to.

C.5.4 HISTORICAL DATASETS

Traditionally, it has not been easy to assess historical data due to the lack of important metadata as well as the lower resolution of the datasets. However, in more recent years, increasing amounts of higher quality digital data has become available, either publicly or for purchase. Increasing efforts are being made to collate datasets collected by various agencies, such as the MCA's Civil Hydrography Program in the UK (around 50 years of data available digitally).

Data from sources like the Civil Hydrography Program will be of a certain standard, due to their stringent requirements, but it is good practice to treat any data equally and carry out checks. The following checks should as a minimum be considered to provide some confidence in the data:

- Metadata
- Geodetics – horizontal and vertical datums
- Resolution
- Any other supporting data like standard deviation grids, conformance to existing standards (such as the IHO) etc.
- Mobilisation reports
- Comparison of data sets over non-mobile seabed (rock outcrops, etc.).

SUT OSIG (2022) provides further guidance on best practise for reviewing historic bathymetric datasets for quality.

C.6 STANDARDS, GUIDES AND TECHNICAL SCOPES OF WORK

C.6.1 SPECIFICATIONS AND GUIDES

This section contains a summary of some specifications and guides that exist in the industry.

IHO S44

The IHO S44 document (currently revision 6.2.0) defines the international standards applicable to hydrographic surveys and the minimum requirements for meeting each specification Order laid out therein. While internationally recognised and the linchpin of many specifications, it is worth noting that the specifications are "designed to improve the safety of navigation, knowledge and protection of the marine environment". While this is a broad statement, the emphasis is on producing data for charting and safety of navigation. This leads to biases in the requirements, most notably an order of magnitude difference between the horizontal and vertical position thresholds.

Table C.12 TVU examples at different depths with different IHO orders.

DEPTH (M)	DEPTH TVU (M)			HORIZONTAL THU (M)		
	ORDER 1A	SPECIAL ORDER	EXCLUSIVE ORDER	ORDER 1A	SPECIAL ORDER	EXCLUSIVE ORDER
5	0.5	0.25	0.15	5.25	2	1
10	0.52	0.26	0.17	5.50	2	1
25	0.60	0.31	0.24	6.25	2	1
50	0.82	0.45	0.40	7.50	2	1
100	1.39	0.79	0.76	10.00	2	1

Note that for Special and Exclusive Orders, THU is depth independent and fixed at 2 m and 1 m, respectively. In terms of seabed mobility analysis, if IHO specifications are going to be used, 'Exclusive Order' should be the minimum specified in the technical scope of works. If more accurate levels are needed, the IHO Matrix can be utilised to define a custom specification with tighter THU/TVU requirements.

Civil Hydrography Program Specification

At its core, the Civil Hydrographic Programme (CHP) specification uses the IHO 1a as its basis. However, there are extensive refinements as to the accepted definitions, naming conventions, data formats and reporting structure. Overall, the driver for doing so is to create a singular survey specification for all submissions to the CHP that guarantees a minimum quality as well as a format standard for all data received. In doing so, it not only takes the statistics-based quality indicators of IHO 1a but puts requirements on various aspects of conducting a survey, including crewing and certifications, geodetic parameters, calibrations, and deliverables contents and formats.

While the CHP specifications provide a good example framework, note that there are various factors that are specific to their requirements and are unnecessarily restrictive if not required, for example, mandating data delivery in CARIS HIPS processing software databases.

International Maritime Contractor Association (IMCA)

The IMCA aims to improve safety and performance throughout the entire marine contracting industry. As part of this, they publish extensive documentation, including best practice guidelines, based on the latest available information. Of principal interest to seabed mobility are the following:

IMCA S 003 – Guidelines for the use of multibeam for offshore surveys

IMCA S 029 – Guidelines for the measurement of depth of burial

These, and other documents, are published at https://www.imca-int.com/resources/technical-library/; note that documents are only available to members.

Society for Underwater Technology OSIG-Guidance-Notes

The SUT OSIG (2022) provides a concise summary of a multibeam system setup and requirements, with relevant cross-references to seabed mobility studies.

C.7 CONCLUDING REMARKS/ RECOMMENDATIONS

Bathymetry data is one of the primary datasets underpinning all seabed mobility studies. The aim should always be to collect the highest quality data possible, whether by acquiring new data or sourcing historical data, but the priority should be ensuring the data aligns with the project requirements. This appendix goes into detail and provides the reader with guidance and insight into how to achieve bathymetric survey acquisition to achieve high level seabed mobility surveys, whether the reader is the surveyor or the client commissioning seabed mobility studies. It is recommended that, if further knowledge is required, the references in this appendix provide additional reading.

There are numerous survey platform options; most will have no issues accommodating a bathymetry system, and most will collect highly detailed seabed mobility data. There are advantages and disadvantages for each platform; for example, smaller uncrewed platforms can reach less accessible places but will be more susceptible to weather influences, while subsea platforms can collect higher resolution data in deeper water. However, moving from a surface platform to a subsea platform (AUV's, ROV's and ROTV's) can increase cost and greater expertise is needed for them to collect good data. Cost is something that must be considered, and consideration for the platform, how and if it is crewed, the presence of support vessels, and provision for a technical onshore team and persons in a remote data centre must be considered. With contracts often split between acquisition phases they can become complex with different payment bands.

The standard marine based platform is not the only option, there are also the options of satellite, crewed and uncrewed aerial LiDAR. However, these options are predominantly limited to shallower areas, depending on water clarity, which is unfortunately rare in places like Europe. That said, they can have their place for monitoring beach and intertidal seabed mobility.

With the survey platform considered, there are numerous sensor options that can be deployed. Individual manufacturer sensor/systems cannot be recommended, but one of the primary items to consider, is that the combined performance specifications of the equipment is compatible with the required technical specifications. Calculating the theoretical THU and TVU of the chosen equipment at the start can offer assurance that, theoretically, the technical specifications will be met. It is important to remember that the accuracy specifications listed by manufacturers will be derived from perfect conditions in a testing centre and will, on most occasions, not reflect reality. To ensure the equipment can best achieve its potential, it is critical that the equipment is set up precisely and calibrated when required. Good calibrations at the start of a project will make it easier to assess and collect good data. Furthermore, verifications will add confidence to the setup and will reassure the client that quality data is being achieved (see **Table C.7** for more detailed recommendations). A final check, such as a subsea benchmark, a solid feature (bedrock or constructed structures) would be able to confirm and verify setups between different survey campaigns and prove a contractor's survey setup is correct.

CRS's must be consistent throughout a project, as an incorrect CRS will induce error into the survey data. It is recommended that a CRS such as ETRS89 is used for the horizontal datum for European projects as it considers the tectonic plates movement (note that if WGS84 & ETRS89 datasets are mixed false feature migration might be observed). It is recommended that vertical datum models are used (e.g., VORF) and singular values are only used on small areas, and this is especially important for volume and difference comparisons.

There are many feature options available on different MBES systems, with varying degrees of benefit to the data collected. The minimum feature requirements should be roll stabilisation, equidistant beam distribution and time sync. However, it is up to the survey contractor to maximise the usage of any features available to assist in meeting the required technical specifications.

Resolution is dependent on the scale of the seabed features that are the subject of the seabed mobility study. Higher resolution can help in identifying features more easily, as well as helping to increase accuracy and precision when down sampling. However, there is a cost associated with increasing resolution, which is primarily due to an increase in acquisition time. An increase in survey duration will predominantly be associated with the survey setup being used, hit count requirements and water depth.

Resolution may be the central requirement of all data, but resolution does not matter if the quality and accuracy are below expectations. Lower resolution data can mask inaccuracies in positioning and other artefacts, but lower resolution can in many circumstances be used for volume comparisons, etc. Higher accuracy and lower precision could be acceptable for one survey campaign, but for multiple survey campaigns, then high accuracy and high precision is important.

The following gives the recommended resolutions for identifying and tracking the following seabed features (this is a higher specification than required in many cases):

- **Megaripples:** ≤ 2 m resolution
- **Sandwaves:** ≥2 m resolution (≥1 m for slower migration rates)
- **Sandbanks:** ≥2 m resolution (≥0.5 m to monitor yearly migration more accurately)
- **Volume/difference:** ≤ 0.5 m for smaller features & ≤ 4.0 m for large area calculations

Data density depends on the quality of the setup and environmental conditions; if these are good, 1 sounding per bin (at the required resolution) is sufficient for seabed mobility studies. Having more soundings per bin can become more beneficial if there is more environmental noise in the data, and it can therefore make it easier to filter this noise out. Another possible benefit is that the resolution could be increased (with some interpolation if needed and if the footprint is not too large). 1 sounding per bin is enough in many circumstances, but it is still recommended that at least 3 soundings per bin is achieved for seabed mobility data if possible.

To assist in gathering denser and higher resolution data the following should be considered, but the importance will be dependent on the technical requirements (across track and along track distribution/resolution) and will be more important for the surveyors carrying out the surveys:

- A system that can produce a higher number of beams per ping (could involve using a dual head setup etc.)
- High ping rate (speed over ground worth considering as well)
- Dual swath and dual head
- Pitch and yaw stabilisation, on top of roll stabilisation (better sounding distribution can be achieved in worsening sea conditions).

A minimum of 20% data overlap should be enough on a high-level survey setup for making sure data is tying in and for spotting any issues (full overlap is only needed for inspection, UXO surveys etc.).

Survey specifications should be realistic and not be a script of unachievable standards. They should be tailored to the project survey requirements and make sure that they do not discourage innovation that could be beneficial. Whatever the requirements for the seabed mobility study, aiming slightly higher than the minimum specification builds some tolerance into planning, as perfect results are rarely achieved for either 100% of the specified requirements or 100% of the time.

Having specifications and a planned setup also requires good survey planning to produce good data cost effectively – water depth, currents, weather and environment are also important considerations when planning.

Thorough QC/QA throughout the collection, processing, reporting, and exporting of the final data is essential, as it demonstrates product quality and builds confidence that the final deliverables will be fit for purpose. At a minimum, the following data deliverables should be considered:

- Average gridded surface at the required surface
- Standard Deviation surface (more important than THU and TVU surfaces)
- Hit count (if deemed needed)

Final data deliverables should comprise gridded data, un-gridded and a QA dataset as a minimum. For the gridded data, average, shallowest or deepest gridded surfaces can have advantages in certain circumstances, but the average surface is the best option in most circumstances (assist in removing errors in collected data etc.). Most standard gridding methods should suffice for standard seabed mobility survey data. The following is the minimum deliverables with regards to data type and formats (See also **Table C.8**), but the format needs to be compatible with the systems being used to analyse the seabed mobility data:

- Processed average surface gridded data in XYZ format
- Processed un-gridded data in compressed format
- Processed average surface gridded Floating 32bit GeoTIFF
- SD GeoTIFF/ Gridded XYZ of standard deviation (SD)

Comparison analysis can now be performed easily within GIS systems, and by following this guidance appendix, it is likely that the provided datasets will already be in the required formats. The majority of software available will perform 2D and 3D analysis, difference grids, seabed mobile feature mapping (sandwave crests, etc.) and slope analysis which are important considerations for seabed mobility studies.

Primary acquisition data collected by a survey platform is not always more important than historical data; historical data from external sources and a contractor's own historical database can also be reviewed for seabed mobility studies. The data can be used as a method of understanding trends over a longer period of time. It is possible that historical data can be less accurate and have lower resolution, so care needs to be taken. Any historical data, even from a few years ago, should be reviewed thoroughly with a QA and QC process, like any new survey data received from a contractor.

If the minimum requirements in this concluding section are applied and historical datasets are reviewed with appropriate care, then the resulting seabed mobility datasets will be robust and suitable for analysing trends. While the guidance provided here is intentionally concise, achieving the required scope of work specifications in practice depends on selecting the correct survey platform for the operation, identifying the appropriate equipment, configuring the equipment correctly, collecting good quality data, processing it to a high standard and producing deliverables in line with client expectations. Experience on both the client and survey contractor's side will recognise that delivering high quality data requires collaboration and careful execution from both parties.

APPENDIX C: BATHYMETRY
CONTINUED

C.8 REFERENCES

Airborne Lidar: A Tutorial for 2025, Part III: Bathymetric lidar. (2025) Published by the LIDAR Magazine. [online] Available at: https://lidarmag.com/PDF/LIDARMagazine_Mandlburger-AirborneLidarPart3_Spring2025.pdf [Accessed 2026].

Guidance to Satellite-Derived Bathymetry B-13 Edition 1.0.0. (2024). [online] Published by the International Hydrographic Organization. Available at: https://iho.int/uploads/user/pubs/bathy/B_13_Ed100_032024.pdf.

Guyer, J.P. (2022). An Introduction to Hydrographic Survey Techniques for Professional Engineers. Independent Publisher.

Hydrographic Survey Specification (Seabed Mapping). (2022). [online] UK Hydrographic Office. Available at:- https://assets.admiralty.co.uk/public/documents/2023-07/UKHO_Survey_Specification_Seabed%20Mapping_V1.2_June22.pdf?VersionId=J_VrJkub8BjPYnnu8UrwSmTzITge3E_7.

IMCA S 003 Guidelines for the use of multibeam echosounders for offshore surveys. (2015). [online] IMCA. Available at: https://www.imca-int.com/resources/technical-library/document/d75ac45a-c55b-ee11-8def-6045bdd2c3b2/ [Accessed 2026].

IMCA S 029 Guidelines for the measurement of depth of burial. (2022). [online] IMCA. Available at: https://www.imca-int.com/resources/technical-library/document/d2325a5b-c55b-ee11-8def-6045bdc208e3/ [Accessed 2026].

International Hydrographic Organization Standards for Hydrographic Surveys S-44 Edition 6.2.0 Published by the International Hydrographic Organization 4b quai Antoine 1 International Hydrographic Organization Standards for Hydrographic Surveys. (2024). [online] International Hydrographic Organization. Available at: https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.2.0_adopted.pdf.

SUT OSIG (2022). Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments. Editor: Cook, M. Society for Underwater Technology (SUT), London.

UK Civil Hydrography Programme Survey Specification. (2022). [online] 105 Commercial Road, Southampton, Hampshire, SO15 1EG, UK: Maritime & Coastguard Agency. Available at: https://assets.publishing.service.gov.uk/media/66c5b4596bd4274a15d7660d/UK_CHP_Survey_Specification_2022.pdf [Accessed 2026].

Validation and application of Airborne LiDAR Bathymetry (ALB) technology for improved management and monitoring of Norwegian rivers and lakes. (2023). Published by The Norwegian Water Resources and Energy Directorate (NVE). [online] Available at: https://publikasjoner.nve.no/rapport/2023/rapport2023_02.pdf [Accessed 2026].

APPENDIX D: BEDFORMS

CONTENTS

ABBREVIATIONS AND ACRONYMS

EIA	Environmental Impact Assessment
MBES	Multibeam Echosounder
RFI	Ripple Form Index
RSD	Rippled Scour Depression
RSI	Ripple Symmetry Index
SAS	Synthetic Aperture Sonar
SBP	Sub-Bottom Profiling
SSS	Side-Scan Sonar
UHRS	Ultra-High-Resolution Surveys

D.1 OVERVIEW

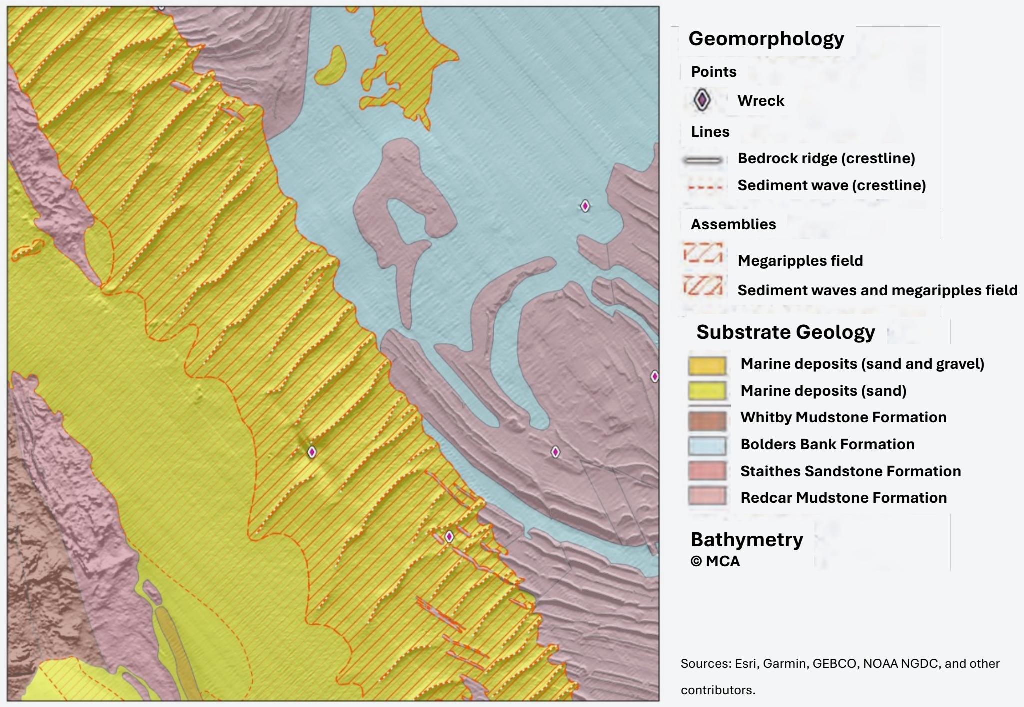
Bedforms are commonly observed as rhythmic arrangements of mobile sediment which form a distinctive pattern on the seabed. They are typically composed of well-sorted, unconsolidated sediment which can vary in size from medium sands (>250 microns diameter) to gravels (pebble sized). The mobility of bedforms can present a potential geohazard where assets need a stable seabed.

The presence, size, and mobility of bedforms can vary depending on local conditions, principally by sediment type, sediment availability, water depth, and wave and tidal conditions. Accordingly, there are differences in the scale of bedforms and their behaviour between nearshore and offshore environments, and within estuaries.

The appendix provides insights related to bedforms required to support an assessment of seabed mobility. Additional considerations related to offshore bedforms is provided in Section 3 – Bedforms, Offshore Tidal Sands: Processes and Deposits (Stride, 1982), with Vaucher & Dashtgard (2022) providing a useful review of nearshore bedforms.

A geophysical survey should map the area of interest and identify locations with / without any bedform coverage, including a classification of these features where they are present. This information is generally reproduced as a 'Seabed Features' chart. **Figure D.1** provides an example chart with a classification scheme of various interpreted geomorphological features, including bedform properties and geological context.

Figure D.1 Example seabed features chart (source: BGS GeoIndex Offshore, Contains British Geological Survey material © UKRI)



APPENDIX D: BEDFORMS
CONTINUED

D.2 BEDFORM GEOMETRY

D.2.1 CROSS-SECTION

The mobility of bedforms develops from bedload transport moving sediment across the surface of the seabed. The core of the bedform (i.e., subsurface materials below the crest) will not be immediately subject to any transport, and larger bedforms (i.e., sandwaves and sandbanks) with larger cores move at comparatively slower rates.

During a period of unidirectional flow, this transport creates erosion of the updrift stoss slope of a flow transverse bedform towards the crest and deposition on the downdrift (steeper) lee slope into the trough. This pattern of erosion and deposition leads to an asymmetric cross-sectional profile and migration of the bedform in the direction of dominant flow (**Figure D.2**).

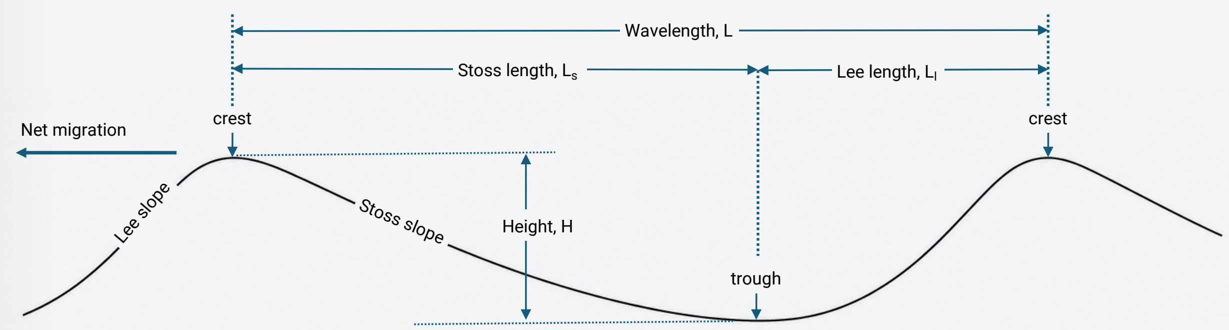
Parameterisation of bedforms can be established by various metrics deduced from the feature when viewed in cross-section:

- Stoss length, L_s
- Lee length, L_L
- Wavelength, L: horizontal distance between adjacent crests (equivalent to $L_s + L_L$)
- Height, H: vertical distance between crest and trough
- Ripple Form Index (RFI): ratio of wavelength over height, L/H
- Ripple Symmetry Index (RSI): ratio of stoss length over lee length, L_S / L_L
- Asymmetry Index (A): $(L_S - L_L) / L$ (when A is close to 0 the sandwave is considered symmetrical)

In addition, the cross-section shape may vary between situations. For example, a trochoidal shaped sandwave will exhibit a well-defined sharp crest along with a flat trough, whereas a sinusoidal symmetrical sandwave will appear more rounded, in comparison.

In situations where sediment supply is limited, the trough might reach the depth of mobile sediment and expose a non-erodible sub-layer which potentially distorts the assessment of crest height.

Figure D.2 Typical cross-sectional profile of an asymmetric flow transverse bedform



Under regular tidal conditions, there is typically a period of flow reversal which switches the direction of bedload transport. If both ebb and flood phases of tidal flows occur in opposite directions (i.e., 180° out of phase) and are of equal magnitude and duration, then the net effect on bedload transport is commonly demonstrated with a symmetrical form of lee and stoss slopes with effectively nil net migration (i.e., RSI is close to 1).

In most cases, there are small differences between ebb and flood phases of tidal flows (i.e., differences in magnitude, direction and / or duration) which lead to net migration of the bedform in the direction of dominant flow and leading to the development of an asymmetric form (steeper gradient lee slope and shallower gradient stoss slope), as shown in **Figure D.2**.

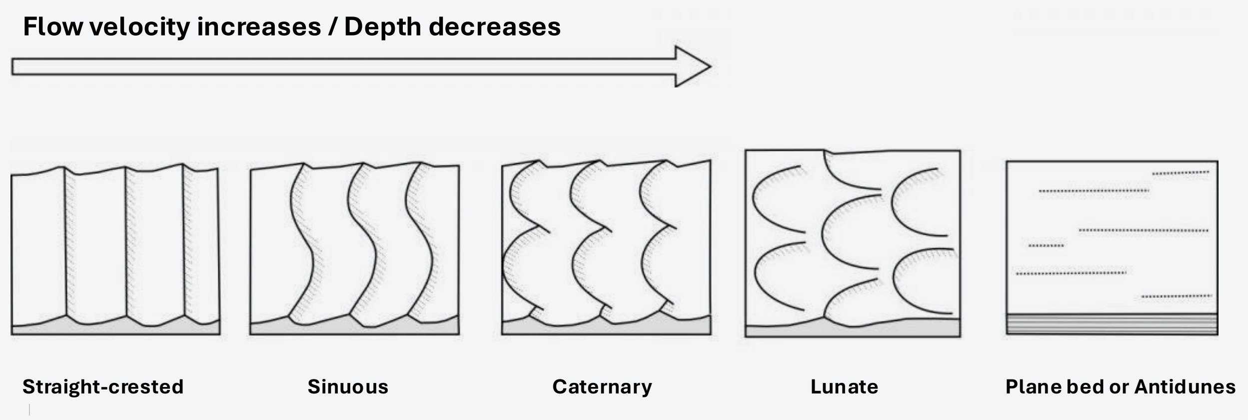
In some situations, the asymmetric form may also reverse between the flood and ebb phases of the tide, although this effect is typically limited to smaller scale flow transverse bedforms. Giant sandwaves found to the north of Changyun Ridge, Taiwan Strait, show a seasonal reversal in form due to a winter reversal of the dominant flow direction (Roulund, Riezebos, & Saverymuttu, (2023)).

If flows become too strong, then small-scale bedforms may also become washed out. Episodic periods of strong winds and / or large waves can also lead to modified bedload conditions and disrupt the regular behaviour of tides leading to possible destructive effects on the bedform (e.g., lowering of the crest).

D.2.2 PLAN FORM

The plan shape of bedforms reflects a dynamic equilibrium with local environmental conditions, with differences in shape expected where there is a difference in bed shear stress and rate of sediment transport. **Figure D.3** presents a schematic of the main observed variations in crest shape associated with increasing flow speed and / or a reducing water depth.

Figure D.3 Geometry of bedforms (after https://geologyistheway.com/sedimentary/bedforms-ripple-marks-and-dunes/)



At high flow speeds, with associated high rates of sediment transport, bedforms may eventually be washed away to leave a plane (smooth) bed. On some occasions, larger individual features might exist independently in this series, such as isolated crescent shaped Barchan dunes (Couldrey et al., (2020)), which are similar in form to lunate shaped bedforms with "horns" that point in the down-drift direction.

D.3 BEDFORM CLASSIFICATION

At the present time, there is no universally recognised bedform classification scheme, either in terms of standard nomenclature of bedform type or the parameters and values used to support differentiation in the scale of such features. Accordingly, the classification scheme presented in **Table D.1** represents a compilation of approaches commonly applied by the authors of this guidance which are also considered consistent with recent seabed morphology studies (e.g., Knappen (2005), Deltares (2023)).

Table D.1 Summary of bedform types and typical scales.

BEDFORM TYPE	FORMATION	RELATIVE SCALE	TYPICAL WAVELENGTH (M)	TYPICAL CREST HEIGHT (M)	OBSERVABLE CHANGE IN:	TYPICAL MOBILITY RATES
Ripples	Transverse to wave and tidal flows	Micro	0.1 to 1	0.01 to 0.1	Hours	~1 m/day
Megaripples	Transverse to tidal flows	Micro	1 to 30	0.1 to 1	Hours to days	~100 m/year
Sandwaves	Transverse to dominant tidal flows	Meso	30 to 700	1 to 5	Days, years to decades	< 10 m/year
Sandbanks	Aligned to dominant tidal flows	Macro	Up to 15,000	5 to 15	Years, decades to centuries	< 1 m/year

For consistency, this bedform classification scheme is adopted throughout the present guidance. The ranges presented for typical wavelength and crest height are offered for general reference only, noting there may be circumstances where these values differ in project-based report. Other bedform classification schemes also exist which may be based on different terminologies and slightly different thresholds of wavelength and crest height (e.g., Ashley, (1990) and BOEM, (2024)).

Notably, bedforms do not always exist as a singular type, with smaller scale (micro) features commonly found across larger scale (meso and macro) bedforms. For example, ripples and megaripples are commonly superimposed on sandwaves, and sandwaves on sandbanks.

Detecting the presence of bedforms may be possible from a variety of survey methods including side-scan sonar (SSS), synthetic aperture sonar (SAS), single beam and multi-beam echosounder surveys (MBES), however, the ability to resolve any feature depends on equipment configuration and the scale of bedforms present. In addition, sub-bottom profiling (SBP), using techniques such as Ultra-High-Resolution Surveys (UHRS), may also reveal useful information about the depth of the mobile layer.

D.3.1 RIPPLES

Ripples are the smallest (micro) type of bedform with wavelengths up to around 1 m and crest heights up to around 0.1 m. Areas with ripples form rapidly under suitable wave or tidal conditions and may also disperse quickly when conditions exceed their criteria for formation. They are typically observed as a sheet of features demonstrating a response of the seabed rather than being observed as an isolated bedform. Due to their relatively small size, they cannot be fully resolved with a conventional MBES. The mobility of ripples is the most rapid of any bedform type and occurs over a period of minutes to hours when flow conditions allow.

D.3.2 MEGARIPPLES

Megaripples are regarded as a similar type of micro-scale bedform feature as ripples, but are an order of magnitude larger with wavelengths up to around 30 m and crest heights up to around 1 m. They generally form as a group of features under tidal conditions and are the smallest bedform which can be realistically resolved by a high-resolution MBES survey. The mobility of megaripples is expected to be observed over a period of hours to days when flow conditions allow.

D.3.3 SANDWAVES

Sandwaves (also occasionally referred to as sand waves, sediment waves, dunes or giant-current ripples) are meso-scale features with wavelengths up to around 700 to 1,000 m and crest heights typically up to 5 m, but greater in some cases. The relative scale of sandwaves (based on crest height relative to trough, H) can also be classified as follows:

- **Small:** crest height around 1 m.
- **Large:** crest height around 5 m.
- **Giant:** crest height much greater than 5 m and up to 22.5 m in some cases (e.g., Taiwan Strait, Zhou et al., (2020)), with an associated longer wavelength.

These heights generally represent an equilibrium condition relative to ambient environmental conditions, however, variations in both height and shape might occur under extreme conditions or when there may be a deficit in the local sediment budget (i.e., sand is being lost from the area).

The migration of sandwaves can be observed over a period of days (small sandwaves) to decades (large sandwaves). Where present, individual sandwaves are typically well-resolved from MBES surveys and their migration and development can normally be tracked through successive surveys obtained over a suitable time interval (Section D.4.2).

Where there is asymmetry in the cross-section profile of sandwaves, this can help deduce a direction of net migration. However, in some situations sandwave asymmetry is known to reverse between ebb and flood phases of the tide, or a balance in ebb and flood influence can produce a more symmetrical profile.

Ripples and megaripples frequently form over the surface of larger sandwaves with the convergence of these smaller scale bedforms being a typical instigating process for the development of sandwaves. However, megaripples may not be so evident on the stoss slope of distinctly asymmetric sandwaves due to slope induced transport.

Mobile sandwaves are considered to be the bedform type that presents the greatest hazard to cables (laying and burial). This is due to their relative scale, shape and rate of migration:

- **Shape** – where present, steep sandwave slopes may inhibit certain trenching tools.
- **Scale** – the height of a sandwave relative to the general seabed level is likely to be comparable or greater than the planned burial depth of a cable, therefore, to avoid potential cable exposure due to sandwave migration, burial needs to be below the level of a sandwave trough (i.e., below the depth of the mobile layer).
- **Sandwave migration** – the rate of sandwave migration is relevant to the operational timescales of most project types which means the position of the sandwave crest and trough can be expected to move over this duration and therefore needs to be accounted for in the planning of cable burial.

D.3.4 SANDBANKS

Sandbanks (also commonly referred to as sand banks) are (near) flow aligned macro-scale elongated bedforms. At a high-level, sandbanks typically develop from the convergence of multiple sandwaves to form a local circulation cell and store of non-cohesive sandy sediments. Sandbanks can be usefully classified with a typology which helps to explain their origin(s) and functioning with contemporary metocean processes (Dyer and Huntley, (1999); Kenyon and Cooper, (2005)).

The form of an offshore sandbank can generally be apportioned into:

- **Base** – the deepest part of the feature which is also likely to exhibit the lowest level of mobility. The base can be regarded as quais-stationary under a consistent set of environmental conditions.
- **Flanks** – sloping sides on the bank. In the northern hemisphere, sand transport can be preferentially influenced by a clockwise Coriolis force that helps maintain the sediment cell (anticlockwise in the southern hemisphere). This process is typically demonstrated by the migration of asymmetric sandwaves in opposing directions along either flank of the sandbank which collectively feeds the crest of the bank (Kenyon & Cooper, (2005)). An inactive moribund sandbank is likely to be devoid of asymmetric sandwaves. If there is a difference in slope on opposing flanks this may indicate a long-term net movement of the bank in the direction of the steeper slope.
- **Swatchway** – (also referred to as spitway or gat) commonly found in longer sandbanks. A swatchway is identifiable as a low point along the crestline of the bank which encourages strong cross-bank flows, especially where there is a water level head difference either side of the bank. Cross-bank flows locally limit the development of sandwaves and help maintain a shallow cross-bank channel which is only accessible to navigation by shallow draught vessels around times of high water. Swatchways are likely to migrate in position over the long-term.
- **Head** – associated with the originating (updrift) location of the bank, such as an adjacent headland. The head of the bank may show variability associated with sandwave migration and sediment circulation around the bank and provide the location for sediment to enter or exit the sandbank (external pathway). The head may also be limited from wider migration if controlled by adjacent geological features.
- **Tail** – the location where the bank is shown to be “tailing” off to merge with the general (downdrift) profile of the surrounding seabed. The tail may show variability associated with sandwave migration and sediment circulation around the bank and provide the location for sediment to leave the sandbank (external pathway).
- **Crest** – a flow aligned feature and the shallowest part of the bank which is typically sustained by sandwaves migrating along the flanks of the bank. The crest is likely to exhibit the greatest mobility overall. Shallow crests exposed to waves may have a relatively smooth profile where smaller scale bedforms are easily washed away which also limits the further vertical development of the bank.

Sandbanks which are formed in estuarine environments exist in a system bounded by shorelines and carved through with tidal channels. In wide estuaries this often creates distinct ebb and flood channels which are liable to meander and can reshape the form and location of estuarine sandbanks. This behaviour may be less predictable and more severe compared with the stability of offshore sandbanks. Robin Rigg offshore windfarm is an example where a migrating channel infringed on the north-east part of the array, rapidly reducing local seabed levels by around 15 m and leading to the premature decommissioning of the topsides of two wind turbines (G+ Offshore Wind, (2017)).

D.3.5 OTHER BEDFORM TYPES

Apart from previously described migrating bedforms, other types of bedforms may also be observed such as Rippled Scour Depressions (RSD).

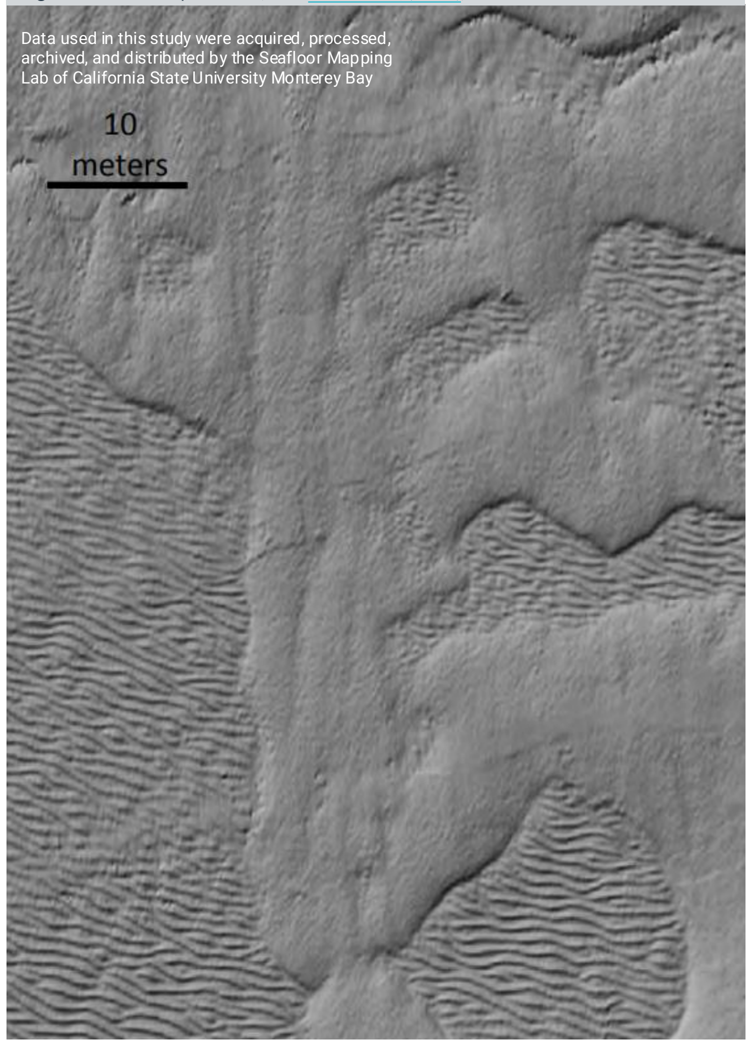
RSDs are characterised by a local and well-defined drop in the seabed level (typically between 0.4 to 1.0 m). The base of RSDs are typically covered by coarse-grained (shelly) ripples which tend to be larger in wavelength than comparable bedforms which may be present on the surrounding seabed. This contrast gives them a higher reflectivity on SSS.

RSDs are believed to be caused by storms scouring away a thin mobile layer of finer unconsolidated sediments to a base of coarser sediment (Davis et al., (2013)). They are typically 10s to 100s of metres wide and generally occur in water depths between 5 to 80 m but have also been observed as deep as 160 m. RSD may also be ephemeral, forming and infilling within a common area.

The occurrence of RSD is relevant as a geohazard if there is a potential risk of a rapid loss of cover (of the mobile layer) over a buried cable.

Figure D.4 shows an example set of RSDs observed off the coast of California, USA.

Figure D.4 Example RSDs (from Davis et al., (2011)).



D.4 BEDFORM MIGRATION

Where a development coincides with larger scale mobile bedforms (i.e., sandwaves and sandbanks) then the migration of these features over the duration of the development (e.g., periods of 25 to 40 years) is relevant to assets placed on or just under the seabed. For example:

- Occasions with a potential loss of cover from a buried cable.
- Occasions with excess burial over a buried cable.
- Stability and performance of scour protection.

An estimate of the long-term rate of net migration can be deduced by reviewing a series of historical bathymetry information spanning a suitable duration and with sufficient time intervals. The assumption is that these migration rates are preserved going forwards for an equivalent period.

In some cases, identified bedforms may have originally developed under former environmental conditions which have subsequently become more benign, leaving a moribund (inactive / relic) feature with no observable migration. Moribund bedforms are likely to have been formed during the marine transgression and have subsequently become more deeply submerged by a rapidly rising sea level leaving the feature stranded under a weaker set of contemporary metocean conditions which are insufficient to develop bedload transport. Moribund sandwaves near the limit of developing bedload transport may still have megaripples present on their surface which exhibit some mobility. Moribund sandbanks also tend to be devoid of smaller scale bedforms.

D.4.1 SANDBANK MIGRATION

For sandbanks, a recommended approach is to source available data from bathymetric surveys and charts that span a relevant period (e.g., several decades, or more; see Appendix C for a more comprehensive discussion of bathymetry). Suitable data types include published charts, single beam and multibeam bathymetric echosounder surveys (MBES). The available data can be developed into a set of common sandbank features with the migration of these features tracked at each interval over the data period. For example, for each dataset, a set of depth contours can be established at common levels from the sandbank base to crest. The spatial coverage and extents of these features can then be reviewed over time. This review can be useful to establish observed limits of the feature (e.g., maximum and minimum levels or spatial extents, etc.). This approach is best served when the available data spans a suitable period (i.e., several decades to reflect the anticipated rates of mobility) with a regular time interval that offers a minimum of at least four time points, ideally more if a reliable trend through the data is required.

D.4.2 SANDWAVE MIGRATION

The general assumption is the net migration of sandwaves occurs with small incremental steps achieved during each tidal cycle and determined by a slight imbalance (residual) in peak flows (and/or directions) between ebb and flood phases creating tidal asymmetry. Depending on local conditions, sandwaves can exhibit different behaviours:

- **Continuous** – net migration occurs gradually over time under the influence of tidal flows, often expressed with a constant migration rate (e.g., 1 m/year). There may still be differences in the specific migration rate between spring and neap tides, and depending on meteorological conditions, but mostly the migration will be continuous in the same direction with a similar rate when averaged over a long enough period (e.g., typically a year). This case offers the least uncertainty for extrapolation of bed level dynamics.

- **Cyclic** – net migration rate may exhibit seasonal reversal in direction with an associated modified shape (e.g., seasonal sandwave reversal in the Taiwan Straits (Roulund, Riezebos, & Saverymuttu, (2023)). In such cases, care should be taken when deriving net migration rates for future seabed levels if the available observations do not represent both periods of migration.
- **Event driven** – sandwave migration may be infrequent and event-driven, related to specific high energy episodic events, such as current-related storm surges, tropical storms, hurricanes, tsunamis, or rare combinations of such conditions. Moreover, the term 'extreme' is applied here relative to typical conditions. For example, in an area where the threshold of motion for sediment transport is generally not reached by typical conditions, the infrequent occurrence of an 'extreme' event of limited strength which exceeds conditions for mobility might be able to have a relatively large influence on seabed dynamics. Importantly, evidence for event driven migration may not necessarily be evident in available seabed observations noting this is not a guarantee that such an area would be unaffected by an extreme event. A consideration of the long term metocean conditions would be helpful in such cases to demonstrate if such events are capable of mobilising the seabed (Appendix G).

A combination of data review and numerical analysis can be applied to help establish the type of bedform behaviour acting in the area of interest. A review of bathymetric surveys can provide an initial insight of bedform dynamics, however, if successive surveys are taken in the same season, then evidence of seasonal variations may be overlooked. An analysis of the hydrodynamic conditions coincident with the survey periods can help provide useful insights into the strength and direction of (residual) currents and sediment transport acting in the period, as well as the significance of more extreme conditions over the longer term.

In contrast to the analysis of sandbank migration, data types to support the analysis of sandwave migration are limited to higher resolution surveys which can clearly identify distinctive features of this bedform, notably the alignment and height of sandwave crests and troughs. This data requirement typically limits suitable data to high-resolution MBES which is only likely to be available for the recent past. Of note, the depth and position of sandwave troughs are likely to be less distinctive features than crests in survey data. Once sandwave crests are identified, their alignments can be reviewed in plan and compared between surveys to help deduce a rate of migration. Appendix G – Analytical methods provides additional details on the approach to determining rates of bedform migration.

D.5 SANDWAVE RECOVERY

Sandwave recovery relates to the reformation (regeneration) of bedforms following their removal (or partial removal) as part of the construction activity, such as for seabed levelling. The rate of sandwave recovery in the short-term is relevant to planned cable laying activities to ensure that sufficient time remains to proceed with cable laying once the sandwaves are cleared. Sandwave recovery over the medium to long-term may be an Environmental Impact Assessment (EIA) interest in specific areas where there is a relationship to a sensitive environmental feature, such as a sediment pathway connecting with a designated sandbank.

An initial estimate of the period for sandwave recovery may be required as part of the EIA, or as a pre-consent condition. This initial estimate is likely to be relatively generic and based on theoretical considerations. Where this estimate is prone to a high level of uncertainty then post-consent monitoring conditions may be required to obtain actual evidence of sandwave recovery to help substantiate the original claims.

D.5.1 MONITORING AREAS

Whilst sandwave levelling (also commonly referred to as sweeping or clearance) may be required in several places, and potentially over relatively long cable lengths, the monitoring required to demonstrate sandwave recovery can be optimised to representative location(s) along a cable route (rather than the entire route) and according to issues such as:

- A difference in environmental setting and scale of sandwaves, noting larger bedforms may generally take longer to recover. The assumption being similar areas will exhibit similar behaviours.
- A difference in the angle of the trench axis relative to the crest orientation of the sandwave.
- Upstream sediment supply, along with a consideration to the location of any post-dredging sediment disposal.
- Metocean conditions (e.g., water depth, tidal variation in water level, wave, and current influences).

D.5.2 PRE-CONSTRUCTION

Pre-construction MBES surveys are required to establish the baseline conditions which also represent the target conditions for recovery. The pre-construction survey will be used to establish the scale of sandwaves present and the requirements for removal to enable cable laying. If there are a succession of pre-construction surveys covering a suitable period (e.g., years to decades) then the migration rates of distinctive features (e.g., crest locations) can be estimated.

The pre-construction profile of sandwaves is considered to represent an equilibrium condition under a given set of conditions.

D.5.3 AS-BUILT

The contractor responsible for sandwave levelling generally validates the completion of their works with an as-built survey. If this survey is readily available, then this represents T+0 months in the timeline of sandwave recovery. Ideally, the full scope of this survey should be confirmed and agreed with other parties leading the assessment of sandwave recovery.

D.5.4 POST-CONSTRUCTION

Sandwave recovery can be best demonstrated by monitoring the relevant seabed locations with successive MBES surveys obtained at suitable intervals and for a sufficient period of time. These intervals and periods should be selected on a case-by-case basis. For example, a set of smaller sandwaves is generally expected to (re)form quicker and migrate faster than a set of larger sandwaves.

The rate of recovery is not expected to be linear. Initially, recovery is expected to be demonstrated by the rapid formation of smaller bedforms developing into larger bedforms (e.g., megaripples converging into sandwaves), followed by the progressive development of sandwaves towards their equilibrium conditions established from pre-construction surveys.

D.5.5 RECOMMENDED MONITORING APPROACH

The recommendation is for an initial survey at around one month (T+1 month) after the as-built conditions (post-construction). In this period, there is an expectation this survey would be able to confirm an initial period of bedform (re)formation (e.g., megaripples begin to form) in response to at least one full lunar cycle of tidal influences.

Subsequent surveys should be repeated at a suitable interval so that further bedform development can be determined. These routine surveys will support the analysis of trends between a common feature (i.e., a feature which can be consistently identified between successive surveys, such as the height of a common sandwave crest) and / or a relevant parameter (e.g., increase in sandwave volume). For example, subsequent surveys for smaller sandwaves exhibiting a relatively fast migration rate could be repeated at intervals of one or two months until the trajectory of recovery is clearly established, thereafter, the survey interval could be increased. In comparison, larger sandwaves which migrate more slowly the survey intervals may several months.

For larger sandwaves, which are likely to have a relatively low recovery rate, subsequent surveys at intervals longer than one month may be more appropriate, such as every two months (T+3 months, T+5 month, etc.) for an initial period then every three months.

Actual sandwave recovery can be best demonstrated by a monitoring programme based on a set of MBES surveys conducted at a suitable interval and over a sufficient period. An example of this type of survey is provided from Race Bank Offshore Wind Farm (Larsen et al., (2019)). Two recovery metrics were considered:

- **Regeneration of sandwaves based on volume changes** – the original sandwave levelling activity removed a volume of sand by dredging a 16 m wide corridor near perpendicular through a set of sandwaves. Subsequent analysis considered the change in sediment volume post-dredging through analysis of a series of surveys at intervals spanning a period of up to 10 months, with intervals ranging from days to weeks to months.
- **Regeneration of sandwaves based on sandwave height recovery** – the same survey data were analysed to consider the rate of sandwave growth in height.

Both methods of analysis demonstrated an asymptotic rate of recovery.

D.6 REFERENCES

Ashley, G. (1990). Classification of large-scale subaqueous bedforms: a new look at an old problem. SEPM Bedforms and Bedding Structures Research Group. Journal of Sedimentary Research, Vol. 60, No. 1. pp. 160-172.

BOEM (2024). Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585.

Couldrey, A.J., Benson, T., Knaapen, M.A.F., Marten, K.V. and Whitehouse, R.J.S. (2020). Morphological evolution of a barchan dune migrating past an offshore wind farm foundation. Earth Surface Processes and Landforms. https://doi.org/10.1002/esp.4937.

Davis, C.D., Mueller C.B.A. and Kvitek R.G. (2011). Not all sand is created equal: A case for updating California's Marine Life Protection Act habitat classification. Seafloor Mapping Lab.

Davis, A.C.D., Kvitek, R.G., Mueller, C.B.A., Young, M.A., Storlazzi, C.D. and Phillips, E.L. (2013). Distribution and abundance of rippled scour depressions along the California coast. Continental Shelf Research. Volume 69.

Deltares (2023). Handbook of Scour and Cable Protection Methods. JIP HaSPro.

Dyer, K.R. and Huntley, D.A. (1999). The origin, classification and modelling of sand banks and ridges. Continental Shelf Research. 19 (10), 1285–1330.

G+ Offshore Wind (2017). WTG decommissioning project Robin Rigg offshore wind farm. Case study. G+ Global Offshore Wind Health and Safety Organisation.

Larsen, S.M., Roulund, A. and McIntyre, D.L. (2019). Regeneration of partially dredged sandwaves. International Conference on Coastal Sediments 2019. pp 3026-3039.

Kenyon, N.H. and Cooper, B. (2005). Sand banks, sand transport and offshore wind farms. UK Government. Department of Energy & Climate Change. London. 106 pp.

Knappen, M.A.F. (2005). Sandwave migration predictor based on shape information. Journal of Geophysical Research, 110, F04S11 (doi:10.1029/2004JF000195).

Roulund, A., Riezebos, H.J. and Saverymuttu, K. (2023). Foundation installation in sandwave fields. Field observations of sandwave regeneration and sediment infill. ISSMGE. Proceedings of the 11th International Conference on Scour and Erosion.

Stride, A.H. (1982). Offshore Tidal Sands: Processes and deposits.

Vaucher, R. and Dashtgard, S.E. (2022). Nearshore Bedforms. In: Shroder, J.J.F. (Ed.), Treatise on Geomorphology, vol. 8. Elsevier, Academic Press, pp. 230–246.

Zhou, J., Wu, Z., Zhao, D., Guan, W., Zhu, C. and Flemming, B. (2020). Giant sand waves on the Taiwan Banks, southern Taiwan Strait: Distribution, morphometric relationships, and hydrologic influence factors in a tide-dominated environment. Marine Geology. Volume 427.

APPENDIX E: SEDIMENT DATA

CONTENTS

APPENDIX E: SEDIMENT DATA

CONTINUED

ABBREVIATIONS AND ACRONYMS

AGDS	Acoustic Ground Discrimination System
BGS	British Geological Survey
BOEM	Bureau of Ocean Energy Management
DTLR	Department for Transport, Local Government and the Regions
EMODnet	European Marine Observation and Data Network
ISO	International Organization for Standardization
PSA	Particle Size Analysis
PSD	Particle Size Distribution
Shom	Service hydrographique et océanographique de la marine
SUT	Society for Underwater Technology
UHRS	Ultra-High-Resolution Seismic
UK	United Kingdom
UKHO	United Kingdom Hydrographic Office
USACE	United States Army Corps of Engineers

E.1 OVERVIEW

A detailed consideration of seabed mobility requires suitable information which helps establish the physical properties of the contributing surficial sediments. These properties notably include grain size, sediment composition, particle density, and bulk density (wet and dry). This information can be combined with associated metocean data (Appendix F) to offer further insights to seabed mobility, for example to help quantify bed shear stress influences on the seabed and the corresponding potential for sediment mobility (Appendix G).

The appendix provides insights related to sediment data required to support an assessment of seabed mobility. Additional considerations related to coastal sediment properties are also available from Chapter 1 of the Coastal Engineering Manual (USACE, (2002)).

E.2 DATA COVERAGE

A typical marine project which includes export cables is likely to cover a large area which may include landfalls, offshore routes, and offshore production sites. Inevitably, sediment properties will vary between and across each of these locations which requires sufficient sediment data to resolve spatial heterogeneity.

Data coverage should also consider the requirements to resolve potential vertical variations in sediment properties from the surface of the seabed to the depth of the mobile layer[1]. Further details related to determining the depth of the mobile layer are provided in Appendix G.

For some applications, there may also be a benefit to extend data coverage to include surrounding areas where an assessment of adjacent locations can help improve the overall understanding of the project setting. For example, identifying sediment sources and sinks, and updrift and downdrift sediment transport pathways can help establish a better contextual setting.

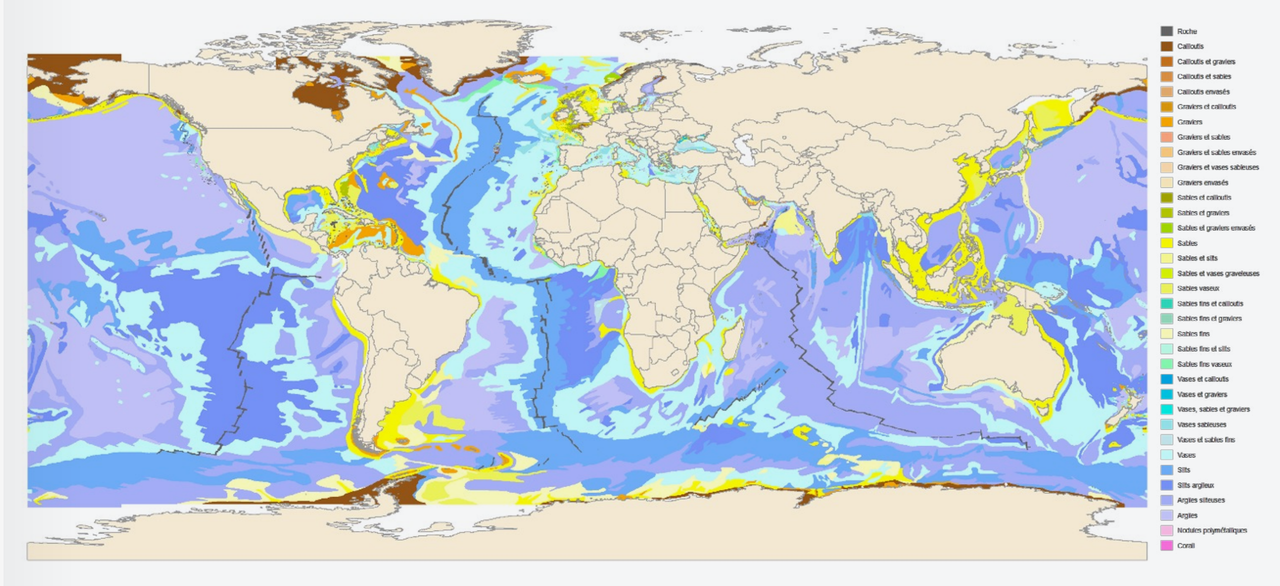
E.3 DATA SOURCES

Once the required data coverage is established (Section E.2) then data searches can identify the suitability of available information for the area of interest. For a typical project, this information is likely to be collated from a variety of sources, including:

- Broad-scale mapping of sediment composition across the general area. This type of information is typically available from national institutes. Mapping is generally based on a collation of information and helps support the description of a regional setting. This information is expected to be largely qualitative. For European waters (including the Mediterranean), the European Marine Observation and Data Network (EMODnet) provide a collation of national maps of various relevant themes, including "Seabed Substrate". If national maps are not readily available then an option with global coverage is the Worldwide Seabed Sediment Map (**Figure E.1**), published by Shom (2026), noting this information is very high-level and may have limited utility.

1. The mobile layer (also commonly referred to as the dynamic or active layer) is where the seabed may be subject to variability in level (i.e. increase or decrease over the lifetime of the development). In some cases, the depth of the mobile layer may be limited by the depth of immobile sediments or shallow sub-cropping rock. Geophysical evidence (i.e. sub-bottom profiling) can help resolve the depth of the mobile layer.

Figure E.1 Worldwide Seabed Sediment Map (source: Shom, 2026, https://dx.doi.org/10.17183/HOM_GEOL_SEDIM_MONDIALE)



For some areas, navigation charts (available globally) may also include supplementary information with occasional symbols which indicate the main sediment type e.g., S = Sand, etc., as well as a symbol indicating the presence of sandwaves (UK Hydrographic Office, (2020)), however, the absence of these symbols does not imply the absence of these features.

- Previous geophysical and geotechnical surveys overlapping with the area of interest. Data accessibility from third parties may be an issue in some cases.
- Project specific geophysical and geotechnical surveys for the area of interest. On occasion, additional surficial sediment samples may be collected for benthic surveys. These data types provide the most detailed and up-to-date information delivered according to a bespoke specification that satisfies project requirements.

E.3.1 GEOPHYSICAL SURVEY

Geophysical surveys are largely achieved by acoustic based monitoring (e.g., side-scan, multi-beam, sub-bottom profiling, etc.) covering the project area. The data collected requires specialist post-processing and interpretation to help develop standard outputs such as seabed sediments and seabed features charts. Appendix C provides additional details related to bathymetry data.

Spatial mapping of seabed sediment distributions can be achieved from the interpretation of multi-beam backscatter and/or side-scan outputs. This interpretation is conducted by an acoustic ground discrimination system (AGDS) which should also be supervised (ground-truthed) with a suitable spread of sediment grab samples (Section E.5.2). The method of interpretation (supervised or unsupervised), the applied sediment classification scheme, and the basis of ground-truthing, should all be fully explained in the associated geophysical survey report. Unsupervised interpretations of sediment type should always be considered with caution.

Seabed features charts are deduced from an interpretation of multi-beam soundings and/or side-scan outputs. Amongst other information, they typically include mapping of areas with bedforms resolved as megaripples and sandwaves. Areas with megaripples are typically represented with simple polygon symbology. Individual sandwaves may be represented as resolved crest lines and include additional symbology to distinguish between lee and stoss slopes, if these features are clearly distinguishable. The method of interpretation of bedforms, their classification and symbology should all be fully explained in the associated geophysical report.

Sub-bottom profiling provides acoustic interpretation of seabed layers of sediment and rock. The depth of layers below seabed is determined from an assumed speed of sound reflected from the interface between different sediment densities, noting that the occurrence of gas pockets can interfere with this process and lead to blanking zones (i.e. sound does not penetrate below the blanking zone). Ultra-High-Resolution Seismic (UHRS) surveys are best-suited to resolving shallow-seabed conditions relevant to the identification of the depth of the mobile layer, buried channels, and sub-cropping rock. SUT OSIG (2022) quote vertical resolution of UHRS systems as high as 0.05 m. Sub-bottom profiling is an important dataset to support the development of a Ground Model.

E.3.2 GEOTECHNICAL SURVEY

Geotechnical surveys are typically phased to support reconnaissance or detailed design and project construction. These surveys should be planned with consideration of a preceding geophysical survey and to help complement and validate prior interpretations of seabed conditions at relevant locations. Where available, existing geotechnical data for the area can also be considered.

Geotechnical surveys involve collection of shallow cores and/or longer boreholes from discrete locations, with various sediment properties determined later in an accredited testing laboratory (e.g., sediment bulk density, grain size, particle density, etc.). The number, location and types of samples depend on site conditions and project requirements. The geotechnical observations also form an important part of developing a Ground Model.

Recently, innovative laboratory methods such as the Erosion Function Apparatus (Briaud et al., (2002)) have been used at offshore windfarm sites in Taiwan and Japan to measure directly the downcore profile of critical stress and erosion rate. This is especially useful at these sites as the sediments are cemented silts and sand, and prediction of stability indices using established approaches is problematic.

Useful guidance related to geophysical and geotechnical surveys are provided in the following references:

BOEM (2024). Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585.

SUT (2022). Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments.

E.4 DATA QUALITY

The quality of available data should be considered to determine any potential limitations in the application of that data. Data quality is likely to be linked to:

- Age of information: Data from modern instruments would expect to provide improved precision and definition compared to equivalent measurements of more than a decade old.
- Spatial resolution: Sparse data coverage may lead to erroneous spatial interpolations becoming dominant.
- Post-processing, interpretation, and reporting: Geophysical data requires careful post-processing and interpretation by experienced technicians. In addition, approaches to reporting of geophysical results may differ slightly between organisations due to in-house practices. Individually and collectively these issues can influence the quality of outputs.

APPENDIX E: SEDIMENT DATA
CONTINUED

E.5 SEDIMENT PARAMETERS

Key sediment parameters relevant to seabed mobility include grain size, sediment composition, particle density, and bulk density (wet and dry).

E.5.1 GRAIN SIZE

Surficial sediments will comprise particles with a range of grain sizes. Sediment class is the macro unit of clastic sediments and corresponds to either gravel, sand, or mud.

- Gravels are coarse sediments with a grain size larger than 2 mm.
- Sands transition from coarse to fine grained sediments in the range < 2 mm to > 1/16 mm.
- Muds (inclusive of silts and clays) are fine sediments with grain sizes < 1/16 mm.

Grain size is also frequently expressed in phi units where the conversion between particle size (S) in mm to phi (Φ) is $-\log_2 S$. The Wentworth Scale is a recognised classification scheme for sediment grain size and type (**Table E.1**).

Table E.1 Classification of sediment grade (after Wentworth, (1922)).

MILLIMETRES (mm)	MICRON (µm)	PHI (Φ)	WENTWORTH SIZE CLASS
			Gravel
4096	4,096,000	-12	
			boulder
256	256,000	-8	
			cobble
64	64,000	-6	
			pebble
4	4,000	-2	
			granule
2	2,000	-1	
			Sand
			very coarse sand
1	1,000	0	
			coarse sand
1/2	500	1	
			medium sand
1/4	250	2	
			fine sand
1/8	125	3	
			very fine sand
1/16	63	4	
			Mud
			coarse silt
1/32	31	5	
			medium silt
1/64	16	6	
			fine silt
1/128	8	7	
			very fine silt
1/256	4	8	
			clay

The Wentworth Scale uses an upper and lower limit for a corresponding grain size. For example, sediment grain sizes in the range ½ to ¼ mm equate to medium sand. For sand to mud sized sediments, the scale increment reduces by a factor of two for each subsequent sediment grade.

Other sediment classification schemes for particle size commonly applied in geotechnical investigations for engineering purposes include the Unified Soil Classification System (USCS) and European Soil Classification System (ESCS), as adopted by:

> *ISO 14688-1:2017 Geotechnical investigation and testing – Identification and classification of soil. Part 1: Identification and description.*

> *ISO 14688-2:2017 Geotechnical investigation and testing – Identification and classification of soil. Part 2: Principles for a classification.*

A useful comparison between different sediment classification schemes is provided in van Heteren & Van Lanker (2015).

E.5.2 GRAB SAMPLES

The standard method to examine the composition of surficial sediments, and establish contributing grain sizes, is by collection of a grab sample.

The type of grab should be selected to optimise performance on anticipated ground conditions, achieve a suitable depth of penetration, recover an adequate sediment volume, as well as deliver other requirements such as sampling of macro benthos, where relevant. The type of grab may also influence the efficiency of sediment recovery, especially if stones prevent full closure of the grab (e.g., potential loss of fines). In addition, a grab sampling campaign which prioritises on recovery of benthic fauna may have used a grab which has shortfalls for complete physical characterisation of sediment grain size. A useful review of grab samplers is provided in DTLR (2002).

Depending on the type of grab and soil conditions, the retained sediment sample generally represents the top layer of surface sediments up to a depth of around 20 cm (generally < 20 cm). If deeper samples are required, then a corer (e.g., vibro-corer or geotechnical drill corer) should be used.

Once a grab is landed, good practice is to record the sample with a unique identification code, time and date, volume and obtain a photographic record.

E.5.3 PARTICLE SIZE ANALYSIS

Particle size analysis (PSA) determines the resolution of the particle size distribution of a soil sample obtained by the grab (or down a sediment core). The favoured method is laser diffraction over standard sieving; however, this technique is only suited to sand, silt, and clay sized sediments. Particle sizes larger than 2 mm (gravels) need to be analysed separately using sieves. A key advantage of using laser diffraction is that the particle size distribution can be well-resolved into fine increments, such as ¼ or ½ phi, as required.

The international standard for particle size analysis using laser diffraction is:

> *ISO 13320:2020. Particle size analysis – Laser diffraction methods. Edition 2, 2020.*

Alternatively, gravels and sands can be analysed with sieves, with the finer fraction of silts and clays (material < 63 µm) requiring separate analysis, e.g., using a hydrometer. Typically, the practical limit of a single sieve stack is eight sieves of reducing size (top to bottom) which may limit the ability to fully resolve a particle size distribution compared with laser diffraction, unless multiple stacks are used.

The international standard for the use of sieves and hydrometer is:

> *ISO 17892-4:2016. Geotechnical investigation and testing – Laboratory testing of soil. Part 4: Determination of particle size distribution. Edition 1, 2016.*

Special attention also needs to be made where shell and bioclastic shell fragments are present in the grab sample. These fragments may require separate analysis if they are not the dominant part of the sample otherwise the resulting particle size distribution may indicate the presence of gravelly sediment where in fact this is not the case. In the case of a benthic survey, a sieve table with a 5 or 10 mm mesh size can be used onboard to separate macro benthic fauna and shells from the sediment sample.

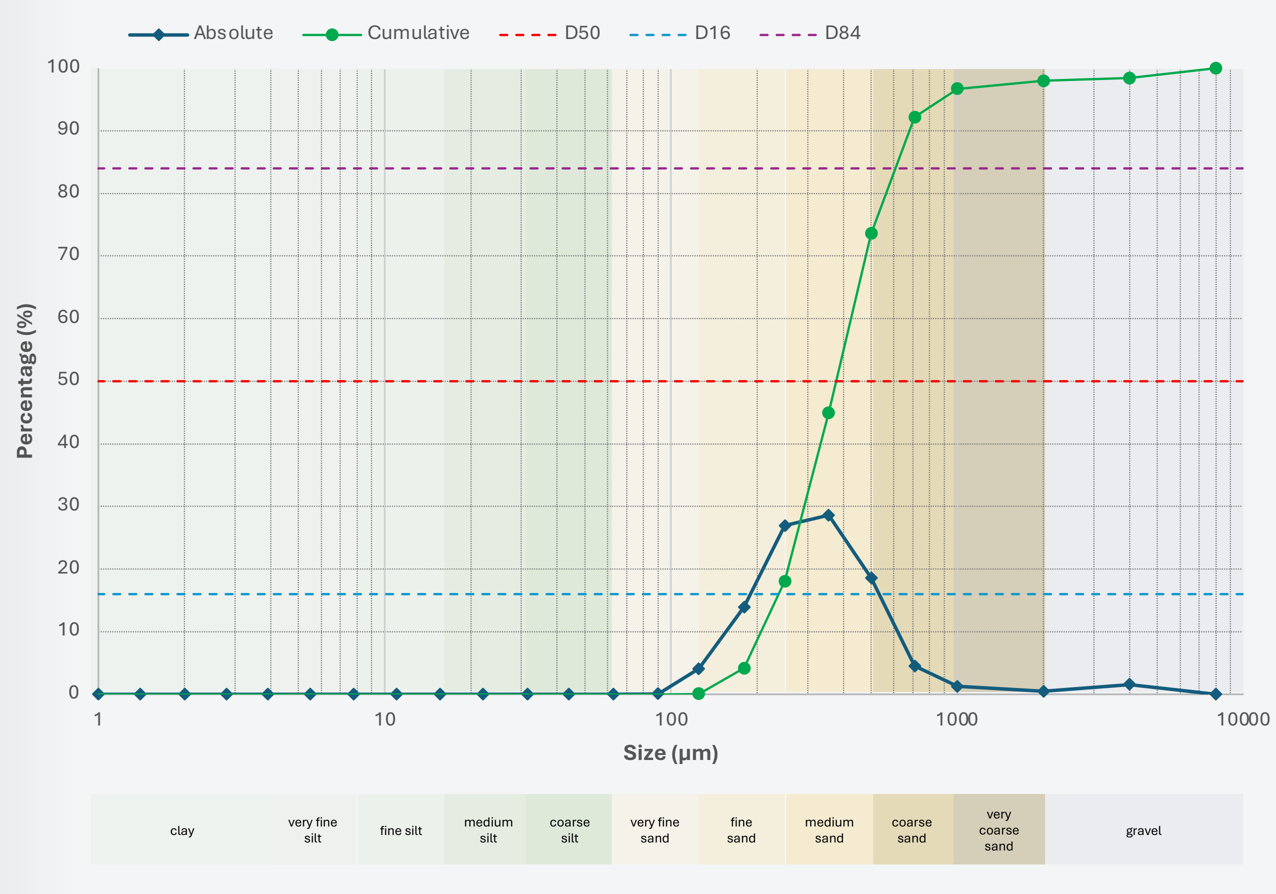
E.5.3.1 Particle size distribution

The standard output from PSA will be a particle size distribution (PSD) expressed as the absolute percentage occurrence of grains present within appropriate size intervals. Additionally, this information can also be expressed as a cumulative distribution (**Figure E.2**).

The absolute distribution provides a clear visualisation of peak(s) and helps identify if the sample is unimodal (single dominant sediment type), bimodal (two dominant sediment types with distinctive grain sizes (e.g., muds and gravels), or multimodal (several peaks).

The cumulative distribution is the typical output used in geotechnical laboratory reports and provides a graphical basis to help deduce some standard sediment parameters, such as D50 (the median size in the sediment distribution where 50% of the sediment fraction is larger and 50% smaller), D16 or D84, etc. D50 is considered as the representative sediment size in a sample, however, this assertion is most valid for a unimodal sample with a narrow distribution (i.e. well-sorted). D50 is a commonly applied parameter in sediment transport models.

Figure E.2 Example plot of particle size distribution (absolute and cumulative distributions)



E.5.3.2 Statistical parameters

Standard statistical parameters to help describe a sediment grain size distribution include:

- **Mean:** arithmetic average particle size of a sample.
- **D50:** median grain size at which 50% of the particles are finer and 50% are larger.
- **D16:** the particle diameter where 16% of the sediment is finer than this size. D16 is often used to represent the "fine" end of the distribution.
- **D84:** the particle diameter where 84% of the sediment is finer than this size. D84 is frequently used to represent the "coarse" end of the distribution.
- **Standard Deviation:** measure of the spread of particle sizes around the median, indicating the degree of sorting. The sorting coefficient can be defined by $\sigma_g = \sqrt{\frac{D_{84}}{D_{16}}}$, for metric units, or $\frac{D_{84}-D_{16}}{2}$, for phi units.
- **Skewness:** indicates the asymmetry of the grain size distribution around the mean.
- **Kurtosis:** measures the peakedness or tailedness of the grain size distribution.
- % gravel, sand, and mud (silt + clay).

A helpful description for the derivation of these values is provided in Blott and Pye (2001).

E.5.3.3 Quality considerations

Inevitably, a collated dataset of particle size information will be a product of various grabs, methods of analysis, and the resolution of reported particle size distribution. Where possible, the provenance of information should be obtained to help establish the usefulness of the sediment data. Ideally, this information is summarised in a meta-data report associated with the dataset.

E.5.4 SEDIMENT TEXTURAL COMPOSITION

There are several classification schemes for marine sediment including Shepard (1954), Folk (1954), as well as some national variants. Notably, EMODnet mapping of surficial sediments adopts the Folk classification scheme after a concerted effort to normalise many different classification schemes for European maritime areas.

The Folk classification scheme is a well-recognised approach to describing sediment composition based on the relative contribution (percentage by weight) of gravel, sand, and mud in a sample. These percentage values are a standard output provided from particle size analysis with the size terms for each sediment type based on Wentworth (1922), see Section E.5.1.

The Folk scheme uses fifteen textural classes, as follows:

FOLK (15 CLASSES)	ABBREVIATION
Gravel	G
Sandy gravel	sG
Muddy sandy gravel	msG
Muddy gravel	mG
Gravelly sand	gS
Gravelly muddy sand	gmS
Gravelly mud	gM
Slightly gravelly sand	(g)S
Slightly gravelly muddy sand	(g)mS
Slightly gravelly sandy mud	(g)sM
Slightly gravelly mud	(g)M
Sand	S
Muddy sand	mS
Sandy mud	sM
Mud	M

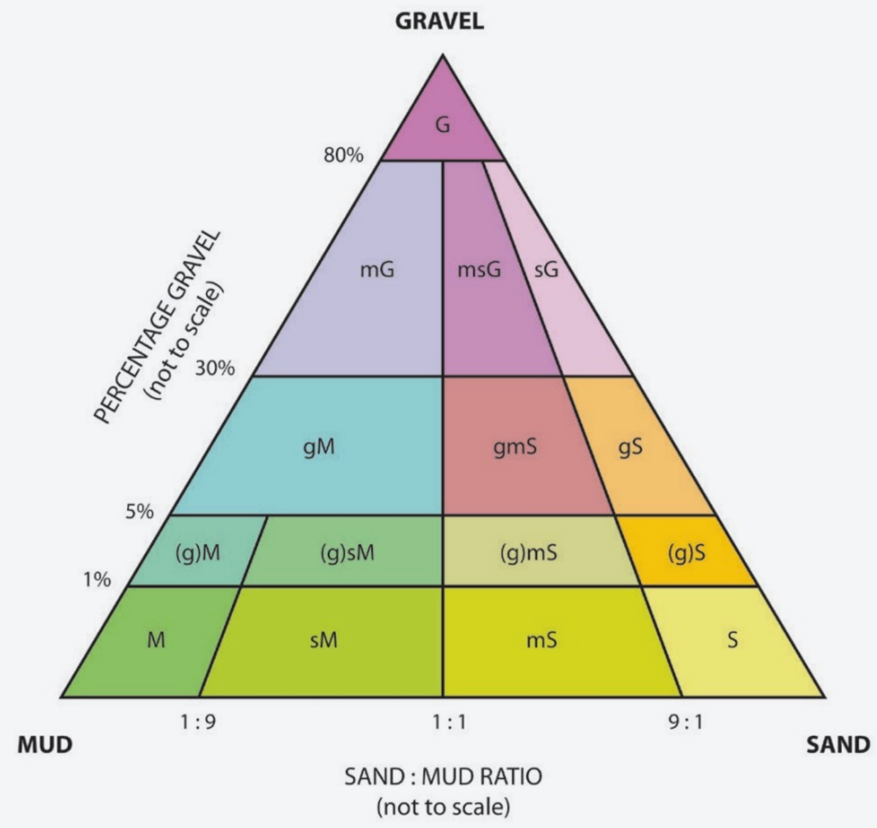
When these textural groups are used to develop maps of surficial sediment then an additional textural group for rock / hard ground is added to represent (immobile) areas without any surficial sediments. N.B. rock does not immediately imply bedrock and may be rocky material found at the sea surface.

The Folk classes can be presented on a ternary diagram (**Figure E.3**) based on the relative contributions of gravel, sand, and mud. N.B. The colour attribute of each sediment class presented in this figure is associated with British Geological Survey (BGS) publications (e.g., BGS, (2012)), although other colour schemes are commonplace.

Folk established the various classes to help indicate the effects of transport on sediment grains. The gravel content is considered to reflect the highest current velocity at the time of deposition, along with the maximum grain size of the sample. The proportion of sand and mud helps indicate the amount of winnowing at the site of deposition, noting other interpretations are also possible.

The limits of "slightly gravelly…" were originally defined by Folk between 'trace' (e.g., 0.01%) to 5%, however, BGS redefined this limit as 1 to 5%. The sediment classification tool GRADISTAT (Blott and Pye, (2001)) defines the threshold of trace as > 0%. Accordingly, any compilation of information from different sources may need to re-establish a common definition for "slightly gravel…" to avoid potential misalignment.

Figure E.3 BGS modified Folk triangle for sediment classification (after Folk (1954))



Various simplifications of the original Folk classification are also now commonplace. These simplifications are based on a reduced number of sediment classes (e.g., six or four) (Kaskela et al., (2019)). For these reduced levels of Folk, the contributions from muddy gravel, muddy sandy gravel, gravelly mud, and gravelly muddy sand are termed mixed sediments.

Other sediment classification schemes for textural composition commonly applied in geotechnical investigations include:

ISO 14688-1:2017 Geotechnical investigation and testing — Identification and classification of soil. Part 1: Identification and description.

ISO 14688-2:2017 Geotechnical investigation and testing — Identification and classification of soil. Part 2: Principles for a classification.

Where there is a requirement to compile a generalised sediment map for a specific area using different datasets represented by different classification schemes, then a common scheme needs to be adopted.

E.5.5 GRAIN DENSITY

Grain density (or particle density) represents the mass of the solid sediment particles divided by their volume (units of kg/m^3). Grain density is important in various sediment transport applications, not least in determining settling velocity.

The commonly applied default grain density is 2,650 kg/m^3 which is consistent with quartz, a mineral forming sand. Notably, grain density can vary depending on the presence of other minerals and are typically in the range 1,700 to 2,900 kg/m^3. Shell and coral fragments are mainly carbonate based and have a density in the range 2,700 to 2,900 kg/m^3, however, this may reduce dramatically for skeletal corals containing voids as a bulk density.

Standards for determining grain density include:

ISO 18747-1:2018. Determination of particle density by sedimentation methods. Part 1: Isopycnic interpolation approach. Edition 1, 2018.

ISO 18747-2:2019. Determination of particle density by sedimentation methods. Part 2: Multi-velocity approach. Edition 1, 2019.

Grain density is often applied with ambient water density (i.e. seawater) to deduce the (dimensionless) specific density (or specific gravity) of sediment.

E.5.6 BULK DENSITY

Bulk density represents the mass of sediment particles per unit volume (units of kg/m^3), including voids (pores / porosity) between sediment particles. Bulk density can be determined from cores and expressed as wet (with seawater) or dry (no seawater/water) values.

Bulk density is an important quantity in determining the mass of sediment that may be mobile when changes in sediment volume are being examined.

For a specific sediment body, bulk density can increase over time and with depth of burial due to compaction and dewatering / loss of porewater but can also reduce when material is disturbed. For example, according to Terzaghi et al. (1996) the wet bulk density of uniform sand (loose) is around 1.89 kg/m^3 and for uniform sand (dense) this increases to around 2.09 kg/m^3.

Standards for determining dry bulk density of sediment include:

ISO 11272:2017. Soil quality — Determination of dry bulk density. Edition 2, 2017.

ISO 17892-2:2014. Geotechnical investigation and testing — Laboratory testing of soil. Part 2: Determination of bulk density. Edition 1, 2014.

E.6 REFERENCES

BGS (2021). User Guide: BGS Seabed Sediments 250k Dataset. British Geological Survey Open Report, OR/21/010. 25pp.

Blott, S.J. and Pye, K. (2001). Gradistat: A Grain Size Distribution and Statistics Package for the Analysis of Unconsolidated Sediments. Earth Surface Processes and Landforms, 26, 1237-1248.

BOEM (2024). Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585.

Briaud, J.L., Ting, F.C.K., Chen, H.C., Cao, Y., Han. S.W. and Kwak, K.W. (2002). Erosion Function Apparatus for Scour Rate Predictions. Journal of Geotechnical and Geoenvironmental Engineering, Volume 127, Issue 2.

DTLR. (2002). Guidelines for the conduct of benthic studies at aggregate dredging sites.

Folk, R.L. (1954). The distinction between grain size and mineral composition in sedimentary-rock nomenclature: The Journal of Geology, v. 62, no. 4, p. 344–359.

Kaskela, A.M., Kotilainen, A.T., Alanen, U., Cooper, R., Green, S., Guinan, J., van Heteren, S., Kihlman, S., Van Lancker, V., Stevenson, A. and the EMODnet Geology Partners. (2019). Picking Up the Pieces – Harmonising and Collating Seabed Substrate Data for European Maritime Areas. Geosciences, 9(2), 84.

Shepard, F.P. (1954). Nomenclature based on sand-silt-clay ratios: Journal of Sedimentary Petrology, v. 24, p. 151-158.

Shom (2026). Carte sédimentaire Mondiale Descriptif de contenu du produit. Janvier 2026.

SUT OSIG (2022). Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments. Editor: Cook, M. Society for Underwater Technology (SUT), London.

Terzaghi, K., Peck, R.B. and Mesri, G. (1996). Soil Mechanics in Engineering Practice. Third Edition.

van Heteren, S. and Van Lancker, V. (2015). Collaborative Seabed-Habitat Mapping: Uncertainty in Sediment Data as an Obstacle in Harmonization. In P. Diviacco, P. Fox, C. Pshenichny, and A. Leadbetter (Eds.), Collaborative Knowledge in Scientific Research Networks (pp. 154-176). IGI Global Scientific Publishing. https://doi.org/10.4018/978-1-4666-6567-5.ch008.

Wentworth, C.K. (1922). A Scale of Grade and Class Terms for Clastic Sediments. The Journal of Geology, Volume 30, No. 5. pp. 377–392.

UKHO (2020). Admiralty. Symbols and Abbreviations used on Paper Charts. NP5011. The official IHO guidance manual INTI. 8th Edition.

USACE (2002). Coastal Engineering Manual. EM 1110-2-1-1100 (Part III).

CONTENTS

ABBREVIATIONS AND ACRONYMS

ADCP	Acoustic Doppler Current Profiler
BODC	British Oceanographic Data Centre
CMEMS	Copernicus Marine Environment Monitoring Service
CSM	Conceptual Site Model
DoC	Depth of Closure
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
EO	Earth Observations
EVA	Extreme Value Analysis
FEED	Front-End Engineering Design
F-LiDAR	Floating LiDAR
H_s, H_{sig}	Significant wave height
H_{max}	Maximum wave height
Hz	hetrz
ICES	International Council for the Exploration of the Sea
IOC	Intergovernmental Oceanographic Commission
ISO	International Standards Organisation
LiDAR	Light Detection and Ranging
OWEKH	Offshore Wind Evidence and Knowledge Hub
MDE	Marine Data Exchange
NOAA	National Oceanic and Atmospheric Administration
QA	Quality Assurance
QARTOD	Quality Assurance/Quality Control of Real-Time Oceanographic Data
QC	Quality Control
RP	Return Period
SCA	Site Condition Assessment
SIMORC	System of Industry Metocean Data for the Offshore and Research Communities
T_z/T_p	Zero crossing wave period / peak wave period
T_{m02}	Mean absolute wave period
U_{bot}	Bottom wave orbital velocity
UNESCO	United Nations Educational, Scientific and Cultural Organization
VHF	Very High Frequency
WOD	World Ocean Database

F.1 OVERVIEW

Metocean data, encompassing meteorological and oceanographic data, is primarily concerned with quantifying weather and sea conditions and the physical aspects of the water column. This data is essential for understanding the dynamic processes that occur in marine environments (Leggett, (2024)), including those that drive sediment transport at the seabed (Masselink and Hughes, (2003)). Metocean conditions are established from a range of parameters including waves, flows, winds, water levels, and seawater properties (e.g., temperature, salinity, turbidity, etc.). Metocean data can be combined with information which characterise seabed conditions (Appendix C: Bathymetry, Appendix D: Bedforms and Appendix E: Sediment Data) to support various analytical approaches (Appendix G: Analytical Methods) underpinning an assessment of seabed mobility.

This appendix provides an overview of the key metocean parameters relevant to the assessment of seabed mobility, the types of instruments and sensors used to collect such data and considerations for survey approaches, together with some examples illustrating the practical application. A very good introduction to coastal processes, including metocean data and sediment transport mechanisms and processes, is given in Park et al. (2008) and Cooper et al. (2008). These studies provide a useful introduction to metocean data and their utility to support marine renewable developments.

F.2 METOCEAN DATA

Within the context of seabed mobility, metocean data is essential for understanding the frictional (drag) forces, also known as 'shear stress', acting on the seabed. Frictional drag forces at the seabed arise from tidal and/or wave driven flows. Waves give rise to oscillatory water motions that translate through the water column. In deep water conditions, these motions do not reach the seabed, however, in intermediate and shallow water conditions these motions give rise to wave orbital flows that reach the seabed (bottom orbital velocity, U_{bot}). The magnitude of wave orbital flows is a function of wave height, period and water depth and rapidly increases into shallow water. Additionally, tidal flows, and the associated frictional drag forces, can be enhanced during periods of storm surges where intensified meteorological forcing increases the overall tidal current speeds and enhance near-bed frictional drag forces. In situations where wave and/or tidal flows are of sufficient magnitude then periods of sediment transport can occur, resulting in seabed mobility.

F.2.1 DESCRIPTIONS OF SEA STATES (WAVE CONDITIONS)

Sea states describe the overall condition of the sea surface, primarily determined by wave activity. Natural waves in the sea comprise a spectrum of wave heights, periods and directions. Definitions of these terms are as follows:

Wave Height: The vertical distance between the crest and trough of a wave. Larger waves contain greater energy, increasing the potential for sediment mobilisation and transport on the seabed. Key definitions include:

- *Significant wave height* ([1]H_s, H_{sig}) is equal to the average of the highest one third of the waves.
- *Maximum wave height* (H_{max}) refers to the largest single wave observed during a specified averaging period.

Wave Period and Length: Wave period refers to the time between consecutive wave crests, while wavelength is the horizontal distance between two consecutive crests. Longer-period, longer-wavelength waves penetrate deeper into the water and can interact with the seabed over a wider area, whereas shorter, wind-driven waves primarily influence the nearshore zone[2]. Key definitions include:

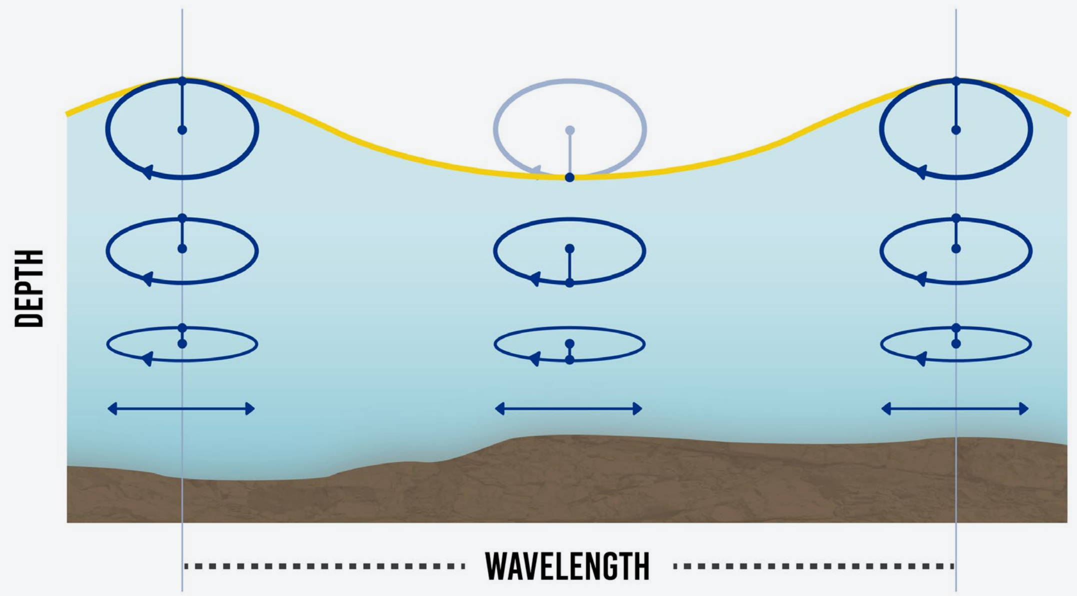
- *Zero up-crossing period* (T_z T_{m02}) is the mean wave period through the spectral record (T_z is used in most sediment transport applications).
- *Peak period* (T_p) refers to the time interval between successive wave crests (or troughs) of the dominant / most energetic wave in a wave spectrum.

Wave Direction[3]**:** The direction from which waves approach influences sediment transport patterns and, similar to other wave metrics, a number of differing wave parameters can be computed according to requirements. For example, direction for the T_p wave may be relevant to some applications, whereas a more general mean value for wave direction may simply be all that is necessary. Waves approaching at an angle to the coastline will be refracted due to interaction with the seabed. Waves can cause longshore drift, a process where sediments move parallel to the coast, reshaping beaches and seabed features over time where a residual angle to the coast exists when the waves eventually break. Fetch, which is the distance over which a wind can generate surface waves, is also an important factor; longer fetches can lead to higher wave heights and longer period waves, with itinerant consequences for seabed mobility.

Wave Orbital Velocities: There are orbital motions that originate at the sea surface but quickly dissipate over depth. Where these orbitals interact with the seabed, we are in intermediate to shallow water conditions and the orbital becomes more elongated in shape to sweep the seabed back and forth; and this sweeping process can lead to sediment transport (**Figure F.1**). The magnitude of these (orbital) velocities depends on wave height and period, as well as water depth. The orbital velocities can be expressed as a bed shear stress.

1. There is some variation in notation, even for the same parameter, in the industry; this is often a function of different methods of computation. Legget (2024) offers a brief overview of these. Care should be taken to understand specific parameter definitions being used for specific datasets, particularly where historic datasets are being used.
2. The distinction between long-period (swell) and short-period (wind-sea) waves is generally taken as a zero-crossing period (T_z) of approximately 7-8 s (Leggett, (2024)). While the precise cutoff may vary slightly between organisations and study contexts, a threshold of 7-8 s is widely used in practical seabed mobility assessments as a simple means of distinguishing locally generated wind waves from incoming swell. Where a more robust treatment of the full wave spectrum is required (e.g., for complex shoreline geomophologies), the reader is referred to established sea–swell separation approaches based on spectral partitioning, wave-age criteria, or steepness-based algorithms, as described in the metocean literature. For example, steepness-based separation methods are outlined by Hwang et al. (2012), and operational spectral-partitioning guidance is provided by NOAA's National Data Buoy Center (https://www.ndbc.noaa.gov/faq/windsea.shtml). These methods offer more detailed classification approach for mixed seas, particularly where multiple wave systems coexist or where site conditions require a more physically rigorous approach.
3. There is a convention in terms of direction for both wave and current parameters; 'direction' for waves always refers to the direction the waves are coming *from*. Conversely, 'direction' for currents is always the direction the current is going *to*.

Figure F.1 Orbital water motions associated with surface waves, showing the progressive flattening of orbits with depth in shallow water, and associated oscillatory motions at the seabed.



APPENDIX F: METOCEAN DATA
CONTINUED

F.2.2 SOURCES OF METOCEAN DATA

There are three fundamental sources of metocean data:

1. On-Site Measurements,
2. Remote Sensing, and
3. Numerical Models.

Each presents strengths and weaknesses when it comes to characterising the metocean conditions of a specified area, and most commonly a project would access metocean data from each of these sources (assuming availability). A brief summary of these are given in **Table F.1**. Examples of marine data management schemes which enable access to these metocean data types at national, regional and global scales are presented in **Table F.2**.

Table F.1 Strengths and limitations of metocean data sources

DATA SOURCE	STRENGTHS	LIMITATIONS
On-Site Measurements (in situ)	• Provides high accuracy and real-time data. • Direct measurement of physical parameters (most accurate representation).	• Limited spatial coverage; often requires extensive networks. • Potentially limited in temporal duration. • Can be costly and labour-intensive to deploy and maintain. • Vulnerable to equipment failure (loss of data).
Remote Sensing	• Wide spatial coverage, allowing for large area monitoring. • Non-invasive data collection methods.	• May have lower temporal resolution compared to in situ data. • Can be influenced by external factors (e.g., atmospheric conditions) • Surface observation only
Numerical Models (Re-analysis, hindcasts, forecasts)	• Provides predictions for future (forecast), past conditions (hindcast) and long-term trends. • Can simulate various scenarios and processes. • Broad spatial coverage • Useful for integrating different data types (i.e. in situ observations and satellite data).	• Validity dependent on the quality of input data and assumptions made in the model. • 2D assumptions have limited applicability. • Can not represent unresolved small-scale (sub-grid) influences. • Requires expertise for interpretation and validation.

Table F.2 Examples of marine data management schemes which enable access to metocean data at national, regional and global scales

DATA SOURCE	TYPE OF DATA AVAILABLE	DATABASE SCALE	DESCRIPTION	LINK
British Oceanographic Data Centre (BODC)	in situ	National	Database of UK oceanographic data (e.g., sea states, water levels, currents, etc.).	https://www.bodc.ac.uk/
UK Gov/CEFAS	in situ	National	Network of marine data buoys (principally waves).	WaveNet – Cefas (Centre for Environment, Fisheries and Aquaculture Science)
Offshore Wind Evidence and Knowledge Hub (OWEKH)	in situ	National	Provides a digital platform for UK renewable energy projects to share survey data and research studies relating to the marine environment.	https://owekh.com/
The Crown Estate's Marine Data Exchange (MDE)	in situ	National	Provides a digital platform for UK renewable energy projects to share survey data and research studies relating to the marine environment.	https://www.marinedataexchange.co.uk/
European Marine Observation and Data Network (EMODnet)	in situ, remote sensing, model	Regional	Provides access to in situ, remote sensing, and model data for a variety of end users, with coverage across the continental European shelf.	https://emodnet.ec.europa.eu/en
National Oceanic and Atmospheric Administration (NOAA)	in situ, remote sensing, model	Regional	Provides multiple platforms to access in situ, remote sensing, and model data relating to the metocean environment across North America and US territories. Select data also available for global locations.	https://www.noaa.gov/
SeaDataNet	in situ, remote sensing, model	Regional	Provides access to in situ , remote sensing, and model data, linking more than 110 national oceanographic data centres and marine data centres from 35 countries riparian to global seas.	https://www.seadatanet.org/
Copernicus Marine Environment Monitoring Service (CMEMS)	in situ, remote sensing, model	Global	Gives access to both global in situ, remote sensing, and model data, providing information on the physical state of oceans and regional seas.	https://marine.copernicus.eu/
European Centre for Medium-Range Weather Forecasts (ECMWF)	Model	Global	ERA 5 global reanalysis database provides metocean parameters from 1940 to present.	https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5
International Council for the Exploration of the Sea (ICES)	in situ, remote sensing, model	Global	In a similar approach to CMEMS, they provide a variety of marine datasets applicable to a multitude of end users.	https://www.ices.dk/
System of industry metocean data for the offshore and research communities (SIMORC)	in situ	Global	Database of global wind, waves, currents and sea levels originating from oil & gas developments.	http://www.simorc.com/
World Ocean Database (WOD)	in situ	Global	WOD is the world's largest collection of uniformly formatted, quality controlled, publicly available ocean profile data.	https://www.ncei.noaa.gov/products/world-ocean-database

F.2.2.1 On-Site Measurements

On-site measurements, also referred to as in situ, relates to measurements that are acquired at the location of interest and are commonly accepted to provide the most accurate and reliable description of metocean conditions at a particular site.

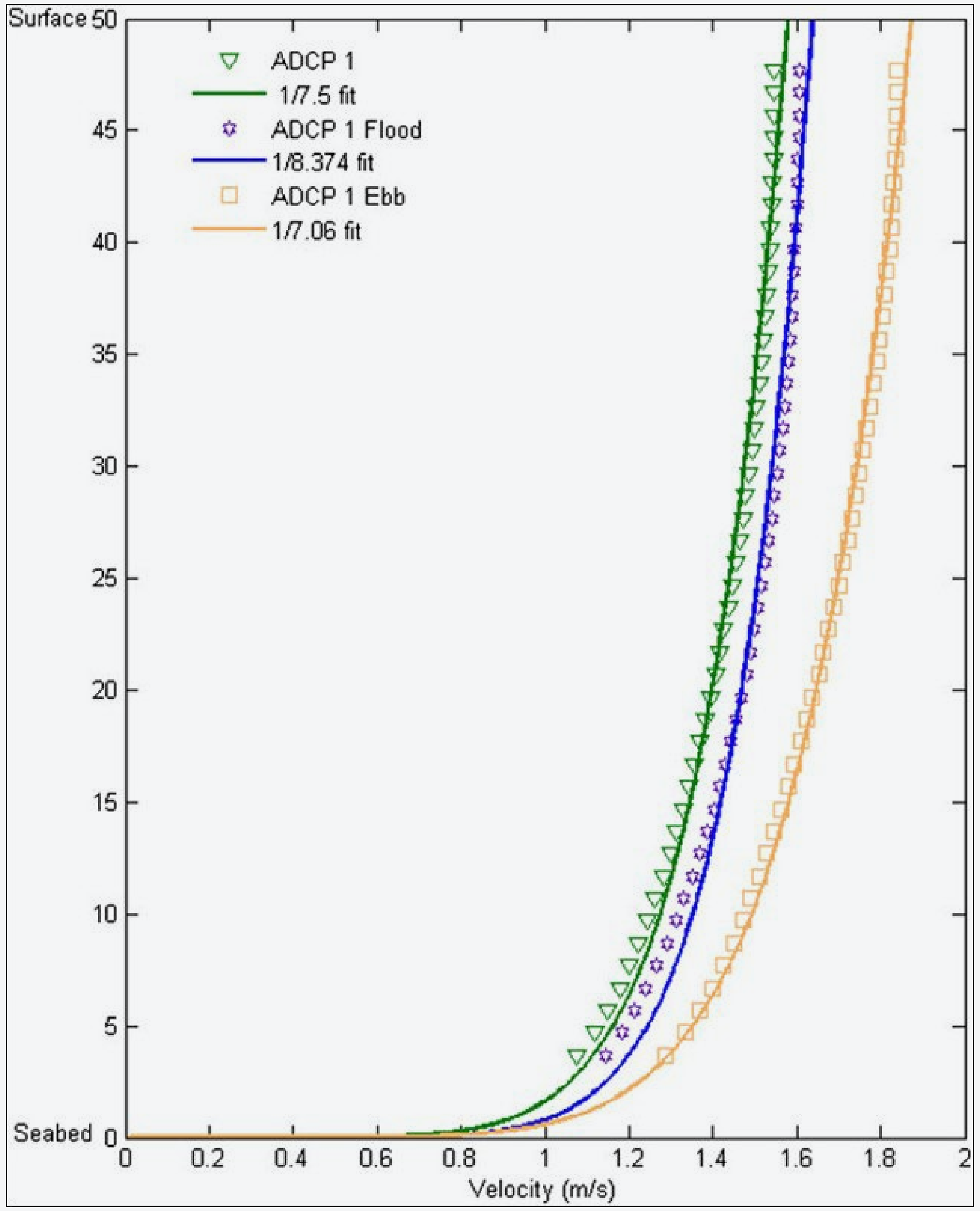
A campaign of on-site metocean measurements should be anticipated as part of the survey suite undertaken for project development. The recommended scope of any metocean survey to support an assessment of seabed mobility should be developed from a gap analysis (Section 3.2.5 of main document) and associated survey recommendations (Section 3.2.6 of main document). Survey recommendations should identify the suite of metocean parameters to be measured, the deployment sites, and the duration of deployments. These recommendations should be based on a clear strategy of how these measurements will be applied to support subsequent assessments of seabed mobility. For example, if the initial Conceptual Site Model (CSM) (Section 3.2.9 of main document) suggested the hypothesis of a clockwise circulation of residual flow being critical to support the development of a sandbank feature then deployment sites might be recommended towards the flanks on either side of the bank in order to measure these conditions and help corroborate this hypothesis. For a different situation, an area of interest with comparatively homogenous seabed conditions may only require a single metocean deployment with a duration which aims to capture a representative set of conditions. One to two instrument packages are usually deployed at some point along the export cable routes to provide an indication of the metocean conditions into shallower waters, and to provide useful data points for calibration-validation of numerical (wave/current/sediment transport) models. In all cases, the final choice on the number of deployments, their location, and method of deployment (e.g., surface versus bed mounted equipment) would be determined as part of the survey logistical planning (e.g., ensuring equipment would not be lost due to burial from rapid seabed mobility, etc.).

A range of modern, resilient, fast-response, self-powered and self-logging sensors (often equipped with satellite or VHF real-time data relay capacity) are used to collect metocean data. For waves, surface-following spherical or discoidal wave buoys have been used for many years and are now considered a mature technology (**Figure F.3**). These systems usually collect data on the height, period and direction of waves for a period of 30 minutes. Data are stored onboard at a very high frequency (Hz), whereas lower resolution calculated summary data are transmitted at the end of the 30 min period. Buoys are typically powered by solar panels and rechargeable batteries, which enable them to remain deployed for extended periods. A useful introduction to measuring waves in the ocean is provided by Nortek (2025a).

Instruments termed Acoustic Doppler Current Profilers (ADCPs) are most commonly used to collect information on currents. These operate by releasing an acoustic pulse into the water column and collect velocity data (a 'profile') at a number of depth intervals (bins) through the water column. Velocity profiles form the basis of one of the mainstream methods for calculating bed shear stress, the key parameter relevant to seabed mobility assessments. A velocity profile (**Figure F.2**) also provides a better estimation of the depth-mean velocity, a metric commonly found within numerical models for currents and sediment transport (Lambkin et al., (2009))[4].

4. This is strictly only valid for well-mixed tidal conditions where the direction of flow is uniform from surface to bed. It is not valid, for example, for deep, stratified seas which may also have non-tidal baroclinic flows.

Figure F.2 The vertical profile of current velocity in the ocean due to the formation of a near-bed 'boundary layer' within which flow is retarded due to drag at the seabed. Note the lowermost 2 m near the seabed, and the region from ca. 40-50 m, suffer a lack of data due to limitations of the measurement technique.

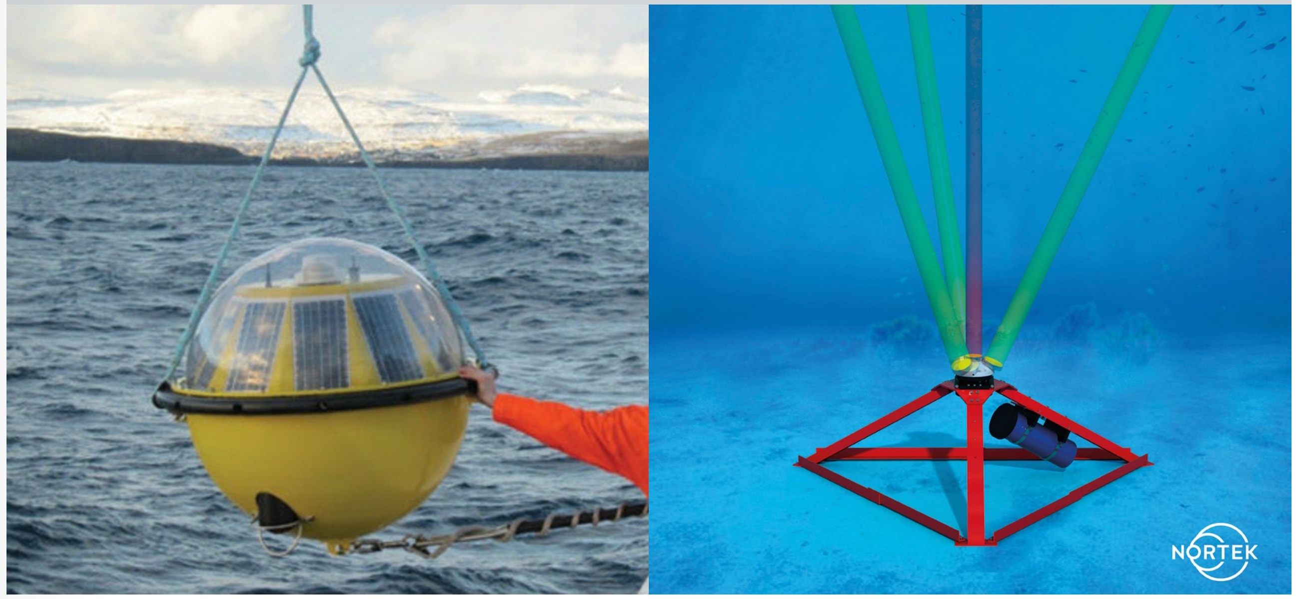


Typically, the instruments are mounted within low profile pyramidal frames which are deployed onto the seabed to be upward looking, and are not configured to provide data in real-time (**Figure F.3**; right-hand side). Additional battery and memory pods can be integrated to provide much longer measurement durations. The acoustic technique can also be configured to measure point velocities (rather than profiles), and most ADCPs have additional (spare) channels which can accommodate turbidity (or other) sensors (useful in assessing sediment transport processes). A useful introduction to measuring currents in the ocean is provided by Nortek (2025b).

Most recently, manufacturers of these systems have introduced hybrid instruments, such as wave buoys equipped with ancillary downward looking ADCPs to measure currents (see **Figure F.3**; left-hand side), and ADCP systems which require no interfacing to other systems, but which can be configured to also measure waves. A useful introduction to measuring currents with waves together in the ocean is provided by Nortek (2025c).

The invention (in the 1980's) and evolution of ADCP technologies to the present time has transformed our ability to measure, and therefore understand better, ocean waves, currents and turbulence. However, these sophisticated tools do exhibit some notable disadvantages. An important factor to note in relation to the use of ADCPs for measuring vertical velocity profiles is the presence of a 'blanking zone' close to the transducer head[5] and a 'side lobe interference' zone at the sea surface (see **Figure 2**). Accurate velocity data cannot be collected in these regions which means that an instrument will record an incomplete profile; whilst this is of minor importance at the sea surface, this is an issue in the near-bed region where sediment transport occurs. One pragmatic solution to this issue is to mount a separate single point current meter onto the bed frame to collect velocity data closer to the bed; otherwise, a mathematical approach to dealing with this data gap is possible (see Section F.4.1).

Figure F.3 Left: a wave buoy equipped also to measure currents (the ADCP is the black protruding object on the underside); Right: schematic of a bed frame upward looking ADCP to measure currents (and waves). Reproduced with permission from Nortek.



5. The 'blanking zone' represents the region close to the transducer head during which the acoustic beam is still forming.

Other metocean parameters that are collected with field-based sensors, but which have only an indirect link to seabed mobility, include wind velocity (profile) and water surface level. Buoy-based floating LiDAR (Light Detection and Ranging) systems are used for high-resolution, real-time wind profile measurements (to several hundred metres above the sea surface). IEA Wind TCP (2017) provide a good introduction to the F-LiDAR (floating LiDAR) technology. Offshore tidal levels are measured by bed-frame mounted ADCP's (see **Figure 3**, right-hand side) but typically data are also from tide gauge instruments[6] in nearby Ports. Port tide gauges are invaluable for monitoring tidal cycles, storm surges, and long-term sea-level rise (all of which factor in seabed mobility assessments), and they can do so because they are permanently mounted sensors in comparatively well protected locations.

F.2.2.2 Remote Sensing

Remote sensing involves acquiring data from a distance, typically through satellites (Earth Observation, EO) or ground- and aerial-based radar systems (i.e. any location other than in situ). Remote sensing allows for extensive spatial coverage, providing valuable insights on water levels, sea states, and wind parameters over large area, and it can operate in all weathers. However, it can be limited by temporal and spatial resolution, predominantly as a result of delays between repeat satellite passes, and data may be captured at coarse grid resolutions. There is a growing global database of remote sensing data, which is useful for the characterisation of offshore site hydrodynamic conditions, especially when combined with model and/or in situ measurement databases.

F.2.2.3 Numerical Modelling

Numerical models are based on the mathematical representations of physical processes, such as wave transformation, sediment transport and current flows, on computers. Numerical models provide extensive datasets[7] on numerous parameters relevant to seabed mobility, including wave metrics, flow fields and bed stress; they are powerful tool for understanding changes to the metocean environment from short-term impacts, such as storms, and longer-term, broader scale meteorological, geomorphological and oceanographic patterns. These models offer significant advancements in spatial resolution and temporal accuracy, however, their reliability, and thus their overall value, depends heavily on the availability of in situ data within the model domain for calibration and validation. Without adequate real-world data to fine-tune and verify their performance, the accuracy of model predictions cannot be validated. A data mining exercise is usually done to source (historic) in situ data records which are suitable for model calibration-validation. If a project is commissioning a contemporary data acquisition programme, then this data should also be used in any calibration-validation exercise (in combination with the historic in situ data), particularly if it contains data from multiple differing locations within a site. STOWA/RIZA (1999), Lambkin et al. (2009) and Pye et al. (2017) present frameworks for the quantitative evaluation of numerical model predictive performance.

A more in-depth description of numerical modelling for offshore site characterisation, and with some reference to seabed mobility and sediment transport, is to be found in Pye et al. (2017).

6. One of the principal uses of Port-based tide gauge water level data is in the calibration-validation of numerical models; this is achieved by selecting a model node which is closest to the Port location and comparing the gauge data with model predictions. Discrete water level and the timing of specific events (e.g., high water) are commonly examined.
7. In many cases the models produce 40+ year hindcast records for all metocean parameters for every point within the model.

APPENDIX F: METOCEAN DATA
CONTINUED

Extreme Climate

Within the context of metocean site characterisation, two terms are used to describe offshore conditions: 'operational', and 'extreme'. The term 'operational' describes the shorter term (days-weeks; seasonal) aspects of the wind-wave-current climate; the term 'extreme' refers to the rarer, more energetic conditions which may develop at the site, encompassing the concept of return period (RP[8]). Storms are often associated with a return period e.g., a 50-yr RP[9]. The linkage to seabed processes and mobility is direct. Calmer periods are generally found to be progressive and constructive, whereas storm conditions can lead to rapid, large-scale sediment transport/bed level change due to potential high magnitude bed stresses. Such events need to be considered within any assessment; it is important not to view the issue simply as a matter of statistics. Aspects such as the duration of a storm, the nature of potential cumulative effects on the seabed due to recurrent storms and timeframes for seabed recovery are important factors within any seabed mobility assessment.

To characterise the wind-wave-current climate during these storm / extreme events, a formal process known as Extreme Value Analysis (EVA) is performed; this is a statistical method which uses a limited term time-series dataset to deduce the probability of events at, or beyond, the range of the data. For a more technical description of EVA methodologies, refer to the EVA Technical Reference by DHI (2024).

F.2.3 DATA QUALITY

In seabed mobility studies the accuracy and reliability of data are paramount; the confidence and robustness of the overall study is intrinsically linked to the quality of the data used. The processes of Quality Assurance (QA) and Quality Control (QC) are central to ensuring that the data collected, processed, and used in these studies (from whichever of the three identified sources) meets stringent standards, providing a solid foundation for decision-making and subsequent application.

Quality Assurance represents the sum total assurance framework that should be in place to deliver robust metocean datasets to projects. Across the offshore wind industry accreditation by the International Standards Organization (ISO) represents the presence of a suitable QA framework, although there are other bodies. QC, on the other hand, involves the specific ongoing evaluation and verification of data once collection begins. QC measures address real-time and post-deployment data, using standardised tests to detect anomalies, identify gaps, and flag suspicious values, and there are a variety of data quality evaluation schemes of varying degrees of complexity used e.g., the Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) flagging scheme (U.S. Integrated Ocean Observing System (2020), Schlitzer (2025) and SeaDataNet (2010)), based on the IOC 54.v3 flagging standard (Intergovernmental Oceanographic Commission (IOC) of UNESCO(2013)). Metadata proformas which (should always) accompany any dataset form a central element of good data quality (an absence of this specific documentation should elicit concerns over data quality).

Further information related to data quality management may be found in Appendix B: Data Management.

8. The return period is inversely related to the event's probability of occurrence in any given year. For instance, a 100-year wave event has a 1% probability of occurring in any given year, while a 10-year wave event has a 10% chance. The results of extreme value analysis may incorporate various return periods, including but not limited to 10, 50 and 100 years for relevant metocean parameters.
9. It is important to consider limitations associated with predictions for the magnitude of future, low probability extreme events, as we do not have a complete understanding of how climate change will impact here, and there are some contra-indications. For example, we may assume that storms increase in their magnitude increasing the rate of sediment transport, but at the same time sea level is rising so reducing wave influence at the seabed; in this example, it is not a simple matter to judge the net impact on seabed mobility. This topic is relevant but beyond the scope of the Guidance.

F.3 METOCEAN SURVEYS VIS-À-VIS SEABED MOBILITY

It is recognised, firstly, that rarely is metocean data collected specifically and directly in support of a seabed mobility assessment, rather it is collected and used to support a multitude of purposes (engineering, consenting, etc.) across the many stages of a development. For example, for Site Selection one typically expects to use existing datasets, for Preliminary Design into Consenting one might commission a comprehensive metocean survey, through Construction and O&M there may simply be a semi-permanent buoy to feed operational requirements, etc. This means that a project will have, at some stage, a body of metocean data usually sufficient to inform a seabed mobility assessment, with detailed time-series records for wave conditions, current magnitudes, and water level variations. There are some standard industry expectations for metocean data based around at least one year of data for waves, to be able to deduce a cycle of seasonal influences, and at least 30 days of current data, which then provides a basis for harmonic analysis[10]. In addition, inclusion of near bed turbidity monitors and specification of a conversion programme[11] to document periods of seabed disturbance (in this case, elevated concentrations of near bed turbidity associated with suspended sediment of finer grain sizes responding to peak conditions) through at least a year is usually prescribed.

If the survey specification has been informed by the EIA scoping process, this usually produces robust datasets suitable for supporting seabed mobility purposes, with monitoring at one to three locations typically to capture spatial variability in metocean conditions[12]. Ideally, extensive measurements over longer periods (>1 year; thereby capturing two winter periods) with broad spatial coverage yield the most accurate and comprehensive record of the metocean environment. However, often financial and time constraints necessitate compromises between an ideal survey and what is considered to be acceptable to both project economics and project uncertainty. Because of its importance to data quality all survey programmes should have regular service visits (e.g., quarterly), to check on instruments and recover data (even where the data are transmitted in real-time).

Achieving a successful offshore metocean data acquisition programme involves numerous, interdependent people from a range of backgrounds functioning as a team. Office based persons will address areas such as permitting, stakeholder consultations, vessel audits, fisheries liaison and obtaining weather forecasts for the survey period. Deployment, operation, and maintenance activities will be performed by experienced personnel adhering to industry standards and instrument manufacturer's recommendations. Rigorous instrument validation, calibration, and routine maintenance are necessary to prevent failures, and to facilitate one of the most common activities in seabed mobility analysis (calibration-validation of numerical wave-current-sediment transport models). Although collected survey datasets will have been initially processed by the survey contractor, in receiving metocean datasets to undertake a seabed mobility assessment, a thorough due diligence processing of all available information must be conducted in order to establish data quality; this may be supported by a Gap Analysis, which addresses data gaps and the consequences for a mobility study.

10. Tidal harmonic analysis is a mathematical method used to describe and predict tides (the regular rise and fall of sea level) by decomposing observed tidal data into a sum of sinusoidal components where each is associated with a known astronomical cause.
11. 'Conversion' is the process of converting raw turbidity readings into near-bed suspended sediment concentrations (in mgl^{-1}).
12. Aspects such as spatial variation in metocean conditions will likely have been identified earlier in the project (e.g., during Site Selection), probably on the basis of conceptual site models, and other data e.g., bathymetry, shoreline, literature sources etc. Where multiple monitoring locations for the collection of new data are specified, it is common to place one of these somewhere along the export cable route / inshore where conditions are anticipated to be different; this may also serve to better test any numerical model performance where it is being developed.

F.3.1 METOCEAN SURVEY REPORTS

Factual (not interpretive) reports should always accompany acquired metocean datasets (in tandem with Metadata documentation for the various datasets). The specifics in terms of content within these reports are ultimately a function of the Client's specification. However, as a minimum and as a guide the below are considered central:

- **Executive Summary**
- **Introduction** – background to project
- **Scope of work** – original technical specification
- **Site** – location, details, characteristics; licenses
- **Logistics** – deployment-servicing-recovery statistics-standards
- **Data availability summary** – reasons for any data loss
- **QA-QC procedures** – standards; methods
- **Results** – graphs, charts, tables etc. showing data
- **Summary**
- **Bibliography**

F.4 EXAMPLE APPLICATIONS OF METOCEAN DATA SUPPORTING AN ASSESSMENT OF SEABED MOBILITY

Metocean datasets provide a range of valuable inputs that support the assessment of seabed mobility. They allow for the direct interpretation of key indicators such as tidal asymmetry, the magnitude and direction of residual tidal flows, near-bed wave-generated orbital velocities (used to confirm the relevance of wave action to seabed stirring), and the depth of closure that defines the offshore limit of nearshore wave influence. Velocity profiles can also be examined to infer the presence of seabed processes that shape the structure of the benthic boundary layer. Metocean observations are further used to corroborate conceptual sediment mobility hypotheses and to support the calibration and validation of coastal process models. When combined with other datasets, metocean measurements can be applied to evaluate parameters such as bed-shear-stress exceedance and other metrics relevant to sediment transport. Further detail on analytical methods that employ metocean data is provided in Appendix G.

F.4.1 VELOCITY PROFILES

The use of ADCP instruments to collect data on the vertical profile of flow velocity has some limitations (see Section F.2.2.1). The most relevant of these within the context of seabed mobility is the inability to collect detailed velocity data in the very near-bed region. A simple approach commonly used to remedy this (described in detail in DNV-RP-C205) involves fitting a curve (log/power law) to the lowermost 10-20% of the profile to provide velocity values in the missing segments (**Figure F.2**). Missing segments arise close to the seabed due to a 'blanking zone' close to the transducer head, which is a region across which the acoustic pulse takes to become fully formed, and a 'side lobe interference' zone at the sea surface (see **Figure F.2**); the side lobes are a consequence of the reflection of some of the acoustic energy at the sea surface-air interface. Close to the sea surface, the velocities in missing bins/segments can be estimated simply through application of U(z) = Udave x 1.073, where Udave is the depth average velocity.

One key consideration also here is that this approach is strictly valid only for steady flow in well-mixed conditions, and marine currents are rarely steady (Park et al., (2008)); tidal currents, in particular, change in direction with time and accelerate from what may effectively be zero speed at slack water towards a maximum speed and then decelerate again. However, for most situations these periods correspond to a lower potential for sediment transport so this may not be a major issue.

Once a full profile has been reconstructed using these methods, several downstream derivations are possible:

1. a value for the depth-mean velocity (the velocity metric typically used in the computation of bed stress) can be obtained analytically[13]; and
2. a value for bed stress and roughness parameter can be deduced (using the wall law method (Park et al. (2008)). Bed stress is discussed in greater detail in Appendix G: Analytical Methods.

F.4.2 TIDAL ASYMMETRY

Tidal currents on shelf seas are rarely symmetrical; asymmetry can be a change in magnitude, duration or direction between ebb and flood. Instances of the current during the flood stage being stronger than the current during the ebb stage, for example, is referred to as flood dominance, while the opposite case is called ebb dominance (**Figure F.4**). Asymmetry of the tidal regime can, over the longer term, drive net circulation patterns and even minimal differences in asymmetry can lead to a net transport of sediment in one direction. For finer sediment moved in suspension the asymmetry can result in significant quantities of sediment leaving a site which (if not sustained by a roughly equal import of sediment), may lead to net seabed erosion. For coarser sediments such as sands which form into bedforms, the unequal velocity between the flood and ebb currents drives

13. It is of interest that a useful representative value for the depth mean velocity is given by the velocity at 0.32*h*, where h is water depth (Sousby, (1997)).

APPENDIX F: METOCEAN DATA
CONTINUED

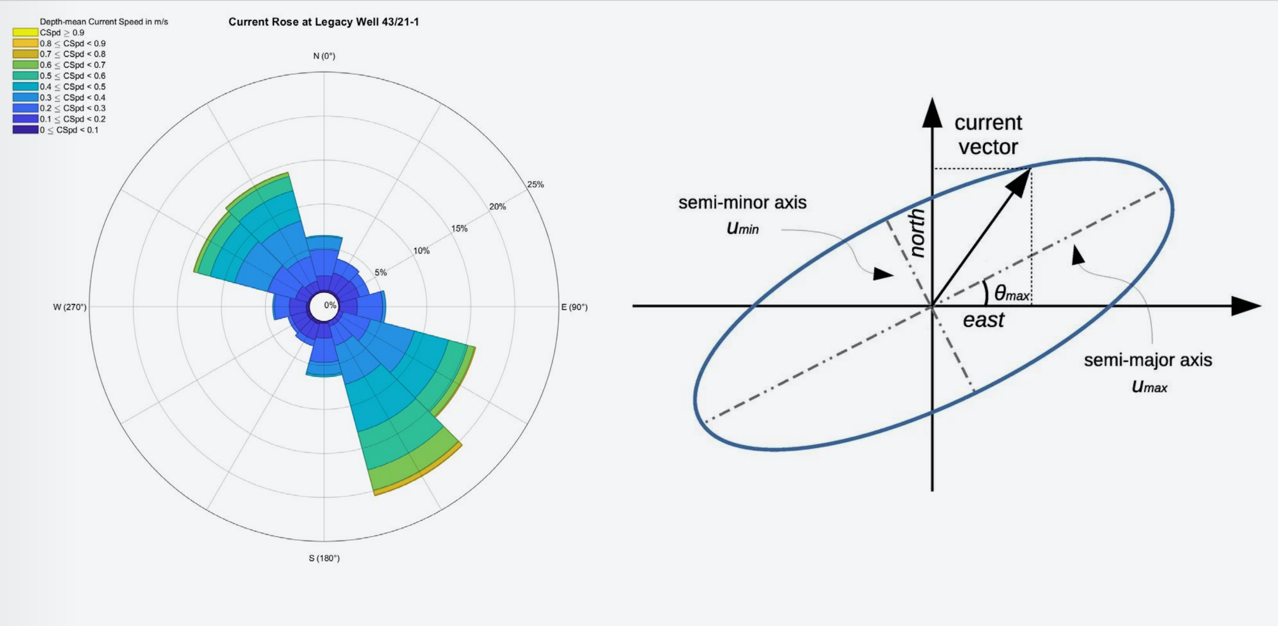
migration in a preferred direction. For these reasons, a comprehensive assessment of a site (for example during the development and improvement of a site Conceptual Site Model [CSM] early within a project) will include a quantitative analysis of the tidal regime in terms of its symmetry. Useful plots which visualise asymmetry include rose (or polar) plots and tidal ellipse plots. Some projects go a step further and include sediment concentration information within this analysis, generating in the process [net] sediment flux maps. The metocean data used in this analysis can derive from either in situ, time-series measurements of currents, or from numerical models of the site hydrodynamics generated for consenting (EIA) or engineering (pre-FEED/FEED) purposes.

Ten Brinke (1990) provides a useful discussion of tidal asymmetry and fine suspended sediment transport.

F.4.3 NON-TIDAL RESIDUAL FLOWS

A comprehensive seabed mobility assessment will include a consideration of the importance of water motions which are *not* related to normal tidal motions e.g., currents driven by storm-induced changes in sea level and wind stress. They are part of the **non-tidal residual flow** but specifically linked to extreme weather events. Tides, and therefore the creation of tidal currents, are driven by astronomical forcing due to the gravitational properties and motions of the Sun and Moon. Surge-related non-tidal currents are storm-driven flows that, when combined with waves (and also periods of spring tides), produce the most critical seabed mobility issues. In regions like the North Sea, non-tidal surge currents can sometimes dominate water movement during storms, exceeding tidal currents and causing severe impacts at the seabed in terms of morphological adjustment. Information on the magnitude and frequency of storm surges can be derived is where there are long-term water level data sources (e.g., from port tide gauges). However, a more quantitative, frequency-magnitude investigation of surge currents can be achieved within a seabed mobility assessment via a combination of numerical modelling and analysis of long-term metocean in situ datasets study. This methodology, which may involve harmonic analysis

Figure F.4 Left: A 'rose plot' for current amplitude, indicating a flow dominance in terms of amplitude and duration to the southeast; Right Schematic representation of current data in terms of the tidal ellipse.



of tidal current datasets, can separate the tidal and non-tidal currents. Assessment of non-tidal residual flows and consideration of their relevance to seabed mobility issues is an important, constituent part of a comprehensive site assessment and will form part of the Conceptual Site Model.

F.4.4 SUPPORT CALIBRATION – VALIDATION OF COASTAL PROCESS MODELS

Coastal process models are sophisticated computer models that enable engineers and scientists to simulate and predict real world coastal dynamics across tides, waves, currents, sediments and morphology. These models capture, in great detail, the relevant ocean physics (including non-linear interactions e.g., characteristic of waves and currents in combination) and extend from offshore, deep water boundaries to the high water datum at the coast. Brooks et al. (2018) provide a useful reference work on the use of models for offshore modelling and Best Practise. However, before they can be used with any confidence, all models require calibration and validation using real world data to assess how accurately they can predict parameters of interest ('model performance'). Refer to Section F.2.2.3.

F.4.5 WAVE ORBITAL INFLUENCE AT THE SEABED

Orbital flows at the seabed arise due to the presence of waves. Waves are therefore an important consideration in any seabed mobility assessment, and time-series wave data are used extensively to document the importance of waves at a site. An assessment is commonly predicated upon presenting summaries of the importance of waves during the seasons of a year, and then separately waves are considered within the context of rarer, higher energy storm events. A seabed mobility assessment will consider the spectrum of waves that may arise across a site, and together with detailed bathymetry and surficial sedimentology judge the importance of mobilisation of sediments. For many sites, summertime waves do not penetrate to the seabed. Discussions on wave influence are often also split into short sea waves (T_z < 7-8 s) and longer, swell wave conditions.

A key aspect of waves offshore is that they act as agents driving resuspension of sediments but have almost no capacity (unlike tidal currents) to transport sediments laterally. During severe storms, however, tidal and wave-induced currents in combination are powerful agents shaping and re-shaping the form of the seabed.

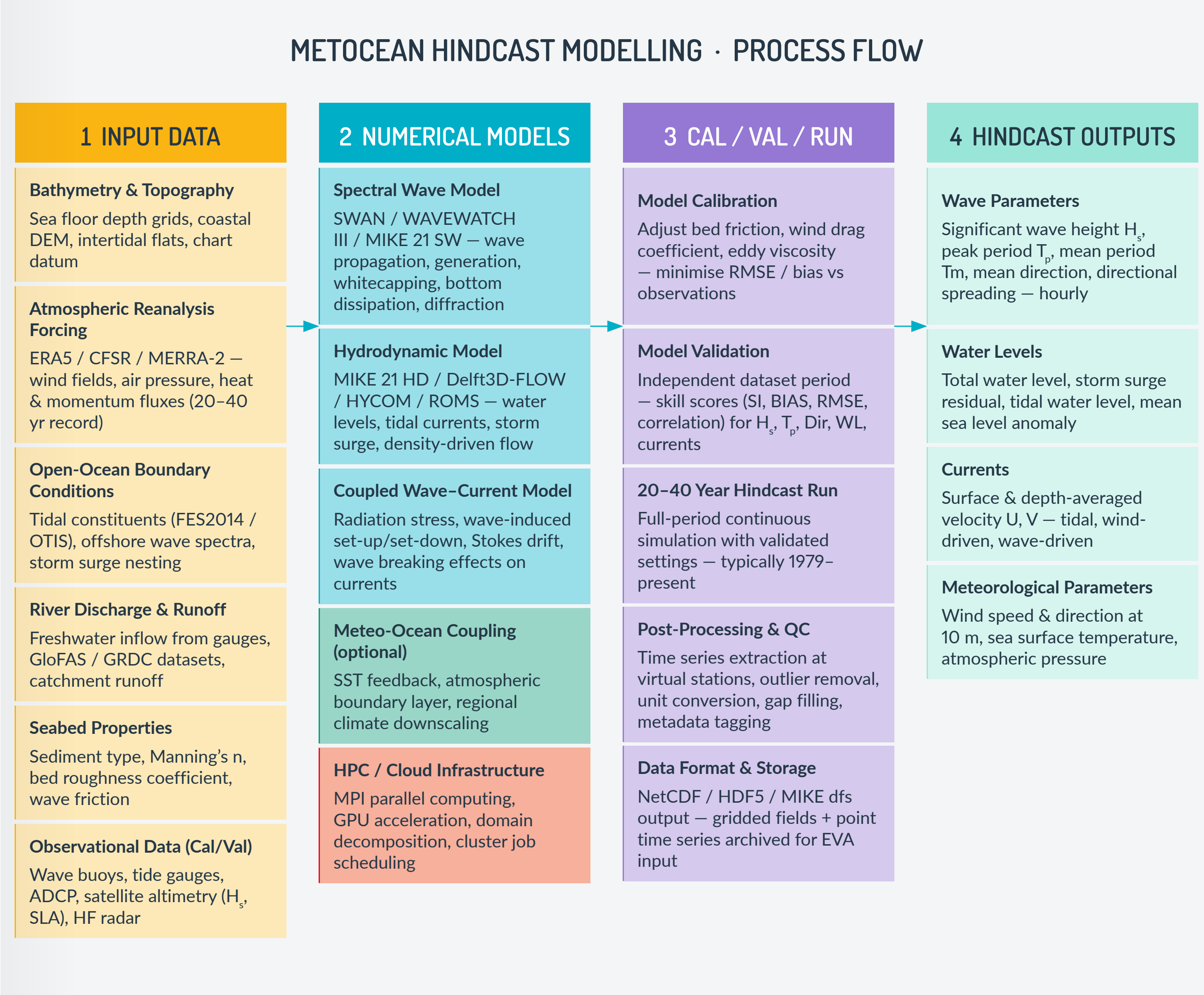
F.4.6 HINDCAST DATASETS AND EXTREME VALUE ANALYSIS (EVA)

Extreme Value Analysis (EVA) for waves and tides is a statistical method used to study rare, high-impact events in the ocean, such as extreme waves and unusually high or low water levels. It is relevant to seabed mobility assessments as more energetic marine conditions will mobilise and transport far greater quantities of bottom sediments. 'Site Condition Assessment' (SCA) is the technical term given to EVA studies for the offshore wind sector. SCA projects are principally modelling studies which utilise all available historic, satellite and in situ metocean data. EVA SCA studies are usually undertaken for engineering design and are consequently highly detailed with hundreds of tables and graphics.

EVA studies rely on the use of **hindcast metocean datasets**; these are very long (most commonly 20-40 years) baseline time series of oceanographic parameters (e.g., current velocity, wave height) and these are created by running a model with all relevant boundary inputs (see **Figure F.5**). The hindcast represents the metocean conditions at high temporal resolution (10 mins – 1 hour) for every model node over the stipulated time period and contains a vast quantity of information. Hindcast datasets support, as noted, full EVA studies, but are used elsewhere too such as engineering design, CSM development, and EIA coastal processes assessments.

It is pertinent to note that whilst seabed mobility specialists utilise this information within seabed mobility assessments, they do not usually generate the hindcast data set, this is done by other specialists (e.g., hydrodynamicists or metocean engineers). This serves to emphasise the point that communication and collaboration between different specialist teams is necessary in order that maximum value is derived from all the available data sources; this applies equally to other data sets also, in addition to the metocean data.

Figure F.5 Process flow diagram showing stages and workstreams behind generation of hindcast metocean datasets.



F.4.7 DEPTH OF CLOSURE FOR NEARSHORE REGIONS

Metocean data form a key part of the specification for the Depth of Closure (DoC), a central metric which is used within seabed mobility assessments to delimit the nearshore (cable landfall/surf) zone from deeper waters (export cable and inter-array zones) and may be considered as the water depth beyond which wave-driven sediment movement is negligible over a given timescale. Inside the DoC the seabed is mobile, with higher risk of cable exposure and reburial cycles; beyond the DoC, the bed is more stable (although still susceptible to mobilisation by currents) and with a lower mobility risk. The DoC is an entirely hydrodynamic metric and uses a wave height/period ratio to derive the closure depth. Hallermeier (1981, 1983) uses the effective wave height just seaward of the breaker zone that is exceeded for 12 hours per year i.e. the significant wave height with a probability of yearly exceedance of 0.137%, with the value of wave period for this wave. Given the statistical nature of this expression, data from a metocean model which provides a suitably long time-series from which to derive these values, is preferred. See Coastal Wiki for further details.

F.4.8 TIMESERIES ANALYSIS OF METOCEAN SURVEY DATA

Prior to any modelling, a direct analysis of timeseries data from a metocean survey may be able to provide useful insights about conditions of seabed mobility, as well as helping to guide the modelling approach. For example,[14] are expected to sample the temporal variability of multiple metocean parameters over a sufficient duration to represent a full cycle of events (e.g., water levels, flows, waves, and near-bed turbidity). Peaks in near-bed turbidity, which can be associated with peaks in waves and / or flows, can be interpreted as a likely indicator of conditions which have developed sediment transport in the benthic boundary layer, leading to an increase in suspended sediment and a tandem potential for bed level change. Similarly, when near-bed turbidity levels are minimal (background levels) then the effect of waves and / or flows may not be sufficient to develop sediment transport into suspension i.e. indicative of a more stable seabed. In some shelf sea environments the situation may be more complex; Jago et al., (1999), for three sites in the North Sea, established nearbed sediment concentration was determined by a combination of local resuspension and advection of a regional horizontal concentration gradient. The situation was further complicated by the presence of a low settling velocity benthic fluff layer on top of the sediment, which added another source term, and occasional stratification of the boundary layer due to elevated sediment concentrations. Such complexity stresses the importance of capturing, conceptually during early project development, as much information about the site characteristics as part of the CSM development.

14. Care is always required where the seabed may be excessively mobile e.g., in shallower, nearshore regions. Within these areas the risk of instrument burial is very real, with the possible outcome being loss of data as well as the instrument[s].

F.5 REFERENCES

Brooks, A.J., Whitehead, P.A. and Lambkin, D.O. (2018). Guidance on Best Practice for Marine and Coastal Physical Processes Baseline Survey and Monitoring Requirements to inform EIA of Major Development Projects. NRW Report No: 243, 119 pp, Natural Resources Wales, Cardiff.

Cooper, W., Saulter, A. and Hodgetts, P. (2008). Guidelines for the use of metocean data through the life cycle of a marine renewable energy development. CIRIA 666.

DHI (2024). Extreme Value Analysis Technical Reference and Documentation. MIKE Powered by DHI.

DNV (2025). DNVGL-RP-C205. Environmental conditions and environmental loads.

Hallermeier, R.J. (1981). A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering 4: 253–277.

Hallermeier, R.J. (1983). Sand transport limits in coastal structure design. Proceedings Coastal Structures '83, American Society of Civil Engineers, pp. 703–716.

Hwang, P.A., Ocampo-Torres, F.J., and García-Nava, H. (2012). Wind sea and swell separation of 1D wave spectrum by a spectrum integration method. Journal of Atmospheric and Oceanic Technology, 29(1), 116-128.

IEA Wind TCP (2017) Expert Group Report on Recommended Practices Chapter 18: FLOATING LIDAR SYSTEMS. 89pp.

Intergovernmental Oceanographic Commission (IOC) of UNESCO. (2013). Ocean data standards, Vol. 3: Recommendation for a quality flag scheme for the exchange of oceanographic and marine meteorological data (IOC Manuals and Guides, 54, Vol. 3). UNESCO.

Jago C.F., Bale A.J., Green M.O., Howarth M.J., Jones S.E., McCave I.N., Millward G.E., Morris A.W., Rowden A.A., Williams J.J., Hydes D., Turner A., Huntley D. and Van Leussen W. (1993). Resuspension Processes and Seston Dynamics, Southern North Sea [and Discussion]. Philosophical Transactions: Physical Sciences and Engineering, 343(1669), 475–491. http://www.jstor.org/stable/54047.

Lambkin, D.O., Harris, J.M., Cooper, W.S. and Coates, T. (2009). Coastal Process Modelling for Offshore Wind Farm Environmental Impact Assessment: Best Practice Guide. COWRIE. (Report No. COWRIE COAST-07-08).

Leggett, I.M. (2024). Understanding Metocean: A user guide for offshore renewables and oil & gas. Whittles Publishing.

Masselink, G. and Hughes, M. (2014). Introduction to Coastal Processes and Geomorphology. Routledge 432pp.

Nortek (2025a). Understanding ocean waves Your guide to measuring and studying ocean wave. 23pp.

Nortek (2025b). Understanding ocean currents. Your guide to measuring and studying ocean currents. 21pp.

Nortek (2025c). Understanding ADCPs A guide to measuring currents, waves & turbulence with acoustic sensors. 66pp.

Park, D., Ed. (2008). Waves, tides and shallow water processes. Open University, 227pp.

Pye, K., Blott, S. and Brown, J. (2017). Advice to Inform Development of Guidance on Marine, Coastal and Estuarine Physical Processes Numerical Modelling Assessments. NRW Report No: 208, 139 pp, Natural Resources Wales, Cardiff.

Schlitzer, R. (2025). Ocean quality flag schemes and mapping between them. Version 1.13. Bremerhaven: Alfred Wegener Institute for Polar and Marine Research.

SeaDataNet. (2010). Data Quality Control Procedures.

Soulsby, R. (1997). Dynamics of Marine Sands. Telford, 201pp.

Southgate, H.N. (1995). The effects of wave chronology on medium and long term coastal morphology. Coastal Engineering, 26(3-4), 251-270.

STOWA/RIZA (1999). Smooth Modelling in Water Management, Good Modelling Practice Handbook. STOWA report 99-05. Dutch Dept. of Public Works, Institute for Inland Water Management and Waste Water Treatment. Report 99.036. ISBN 90-577-056-1.

ten Brinke, W.B.M. (1990). Tidal Asymmetry and Fine Suspended Sediment Transport in the Eastern Scheldt Tidal Basin (The Netherlands). In Estuarine Water Quality Management: Monitoring, Modelling and Research, W. Michaelis (Ed.).

U.S. Integrated Ocean Observing System. (2020). Manual for the Use of Real-Time Oceanographic Data Quality Control Flags, Version 1.2. 24 pp.

APPENDIX G: ANALYTICAL METHODS

CONTENTS

N.B. Figure references are relative to the source material (not in numerical order)

APPENDIX G: ANALYTICAL METHODS

CONTINUED

ABBREVIATIONS AND ACRONYMS

1D	1 Dimensional
2D	2 Dimensional, generally referenced to the horizontal
AEP	Annual Exceedance Probability
CI	Confidence Intervals
CSM	Conceptual Site Model
DTM	Digital Terrain Model
GPS	Global Positioning System
HTA	Historical Trend Analysis
IHO	International Hydrographic Organization
IPCC	Intergovernmental Panel on Climate Change
MBES	Multibeam Echosounder
MFI	Mobility Frequency Index
NASA	National Aeronautics and Space Administration
PSMSL	Permanent Service for Mean Sea Level
SDI	Seabed Disturbance Index
SMF	Seabed Mobility Frequency
SMI	Seabed Mobility Index
RMS	Root Mean Square
THU	Total Horizontal Uncertainty
TVU	Total Vertical Uncertainty

G.1 OVERVIEW

This appendix outlines commonly applied analytical methods to support an assessment of seabed mobility. The likelihood is each project will have a unique set of requirements, as such a specific combination of methods will apply. The requirements for undertaking such analysis should be guided by the preliminary Conceptual Site Model (CSM) which is expected to set out a working hypothesis to explain the process understanding which influences seabed mobility, along with recommendations for analytical methods to help validate these hypotheses, develop quantification of changes in past seabed levels, and the means to extrapolate the variation of seabed levels into the future, as appropriate.

G.1.1 TYPES OF ANALYTICAL METHODS

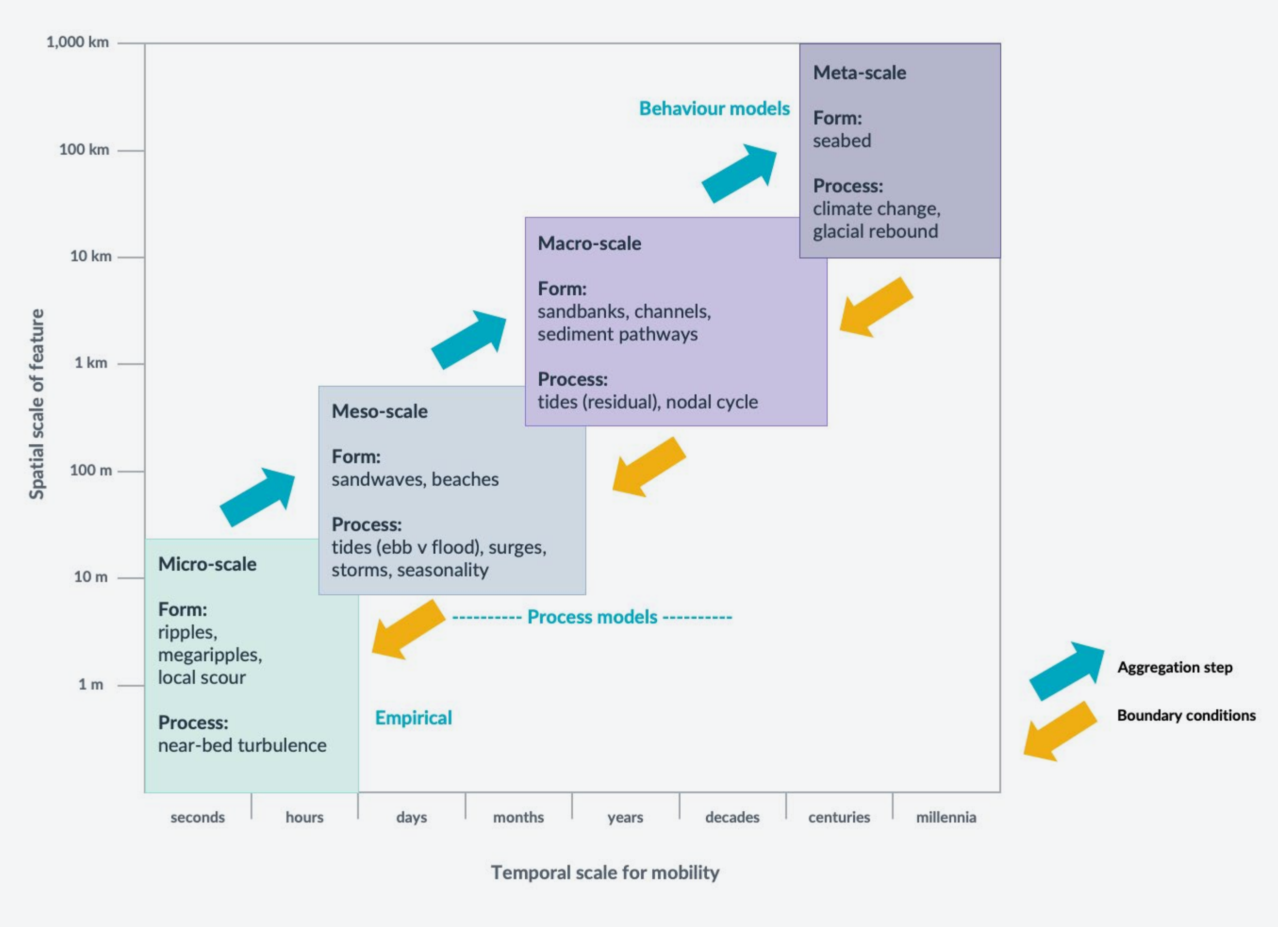
The types of analytical methods relevant to an assessment of seabed mobility can be categorised as follows:

- **Empirical** – data driven approaches
- **Process models** – based on a bottom-up description of the physical processes
- **Top-down approaches** – based on behavioural concepts of large-scale features or processes

Importantly, there is no single analytical method which encapsulates all relevant temporal and spatial scales.

Figure G.1 shows the (up-scaling and down-scaling) relationship between different analytical approaches relevant to different spatial and temporal scales.

Figure G.1 – Schematic of cascade hierarchy (adapted from Sutherland (2021))



APPENDIX G: ANALYTICAL METHODS
CONTINUED

Whilst the smallest spatial scales referred to on **Figure G.1** include ripples and megaripples which do not present a direct risk to assets placed on or under the seabed, their presence remains relevant to a seabed mobility assessment in terms of indicating an area with mobility, especially where these features are associated with larger scale bedforms.

G.1.2 PROBABILISTIC FRAMEWORK

For locations experiencing a mobile seabed, the prediction of seabed levels over the short, medium and long term cannot be considered absolute given the inherent uncertainties in the underlying data, analytical methods, and the component of random behaviour in driving conditions (e.g., future climate). To manage these uncertainties, future seabed levels need to be expressed within a probabilistic framework which determines the most likely outcome, bound with confidence intervals (CI). This framework should be established by accounting for uncertainties at each stage of developing future seabed levels.

G.2 EMPIRICAL APPROACHES

Empirical approaches used to support seabed mobility assessments typically rely on historical records of past seabed levels representing different time periods which also extend over a sufficiently long duration. A bathymetry change analysis through this data helps deduce:

- Vertical change (positive or negative) in seabed levels.
- Horizontal change in position of a well-resolved feature, such as a coastline, sandwave or sandbank.

Where a clear trend can be established through the period of data then this can be used to support extrapolation of seabed levels into the future. Uncertainty levels are expected to be relatively high in these trends.

Examples of such approaches include, amongst others:

- Historical Trend Analysis
- Sandwave migration analysis

G.2.1 HISTORICAL TREND ANALYSIS

Historical Trend Analysis (HTA) helps establish long-term (i.e., > decadal) changes in the vertical profile of the seabed developed from a comparison between bathymetry data of a common area which represents different time periods. HTA can usefully support the evaluation of large-scale morphological features such as sandbanks and migrating channels, where suitable data is available. Further details related to HTA are available at the Estuary Guide.

a. Data types

HTA can utilise a variety of bathymetry data types which ideally extend over a long historical period with sufficient temporal intervals. These data can be collated from modern surveys, as well as data archives for older surveys and charts, as long as there is a reasonably consistent description of seabed levels throughout.

b. Uncertainties

An initial quality assessment of the source data is required so that issues which may influence the reliability of subsequent analysis are identified and quantified. These issues might include, as relevant:

- Precision of horizontal positioning (e.g., theodolite, radar based, GPS, etc.).
- Precision of vertical measurement (e.g., lead line, single beam, multibeam, etc.).
- Data density / gaps (e.g., potential shallow water restrictions over bank crests leading to data gaps, partially resolved or unresolved sandwaves, etc.).
- Survey date(s).

Appendix C: Bathymetry Data discusses these points in further detail.

c. Data preparation

When collated, the available data should be normalised to a consistent geographic projection, vertical datum, and measurement unit. The prepared data can then be interpolated to form a set of digital terrain models (DTM), each representing a specific date. Change analysis can then be performed through the DTM.

Additional uncertainties can be introduced in the DTM where there is a need to interpolate across data with sparse coverage, as well as with the chosen method of interpolation.

d. Change Analysis

Analysis of vertical change in seabed levels over the period of contributing data can be considered through the set of DTM at specific points and between surfaces. The comparison between surfaces is helpful to identifying locations which exhibit low, medium and high levels of seabed mobility. This information can usefully inform the development of seabed mobility maps (Section 3.2.13).

Analysis of change in the location of large-scale morphological features (e.g., sandbanks, migrating channels, etc.) can be evaluated by considering cross-sections through the feature, as well as comparing the relative position of equivalent depth contours.

The quantification of any change should be associated with the compound level of uncertainty between the contributing datasets.

e. Trends

Evaluation of temporal trends in seabed levels through the period of contributing data can be considered from the set of DTM at specific points. By default, a linear trend is initially considered (i.e., a progressively lowering or rising seabed level), noting a clear trend may not always be established. If a more complex trend is identified, then an alternative non-linear function can be considered, as long as this fully justified.

The quality and reliability of any trend can be related to:

- Number of supporting datasets representing different time periods. Five or more datasets, separated by a suitable time interval, is strongly recommended. A greater number of data point is likely to lead to a more reliable / stable trend.
- The elapsed period (oldest to newest) in the contributing data. A short period may not include the full envelope of variation and may lead to a trend which under-represents future changes.
- Correlation coefficient, R. This coefficient provides an indication of the reliability of the trend. Positive or negative correlation values between 0.9 to 1.0 are considered as very highly correlated and 0.7 to 0.9 highly correlated (Schober et al., (2018)). Correlation coefficients less than 0.7 are likely to carry too much uncertainty for extrapolations over the long term. In such cases, an envelope approach which bounds the variability in past seabed levels may be more suitable than applying a poorly resolved trend, ideally where the available data forming the envelope spans an equivalent period, or longer, as the design life. Confidence intervals can be readily derived from the correlation coefficient and standard error.
- Uncertainties in an individual data point relate to the timestamp of the depth value, horizontal position, vertical datums and measurement accuracy / precision (i.e., observational errors). In some cases, these uncertainties (noise in the data) can be difficult to distinguish from actual changes in seabed levels (signal being looked for), especially when old surveys are used.

Appendix C: Bathymetry Data provides a more detailed overview of factors contributing to, or influencing, the accuracy of point data.

f. Extrapolation of vertical change in seabed level

If a reliable trend can be established, then this can be used to extrapolate forwards to determine the large-scale and long-term component of future seabed levels. This extrapolation should be bound within CI which should be proportional to the uncertainties in each data point. The forward extrapolation period should also be limited to a comparable period as the contributing data.

Care should be taken when the trend has been derived from data spanning a relatively short period. For example, HTA cannot deduce a reliable long-term trend for a site with less than three separate time periods or when supporting data collectively span less than 10 years.

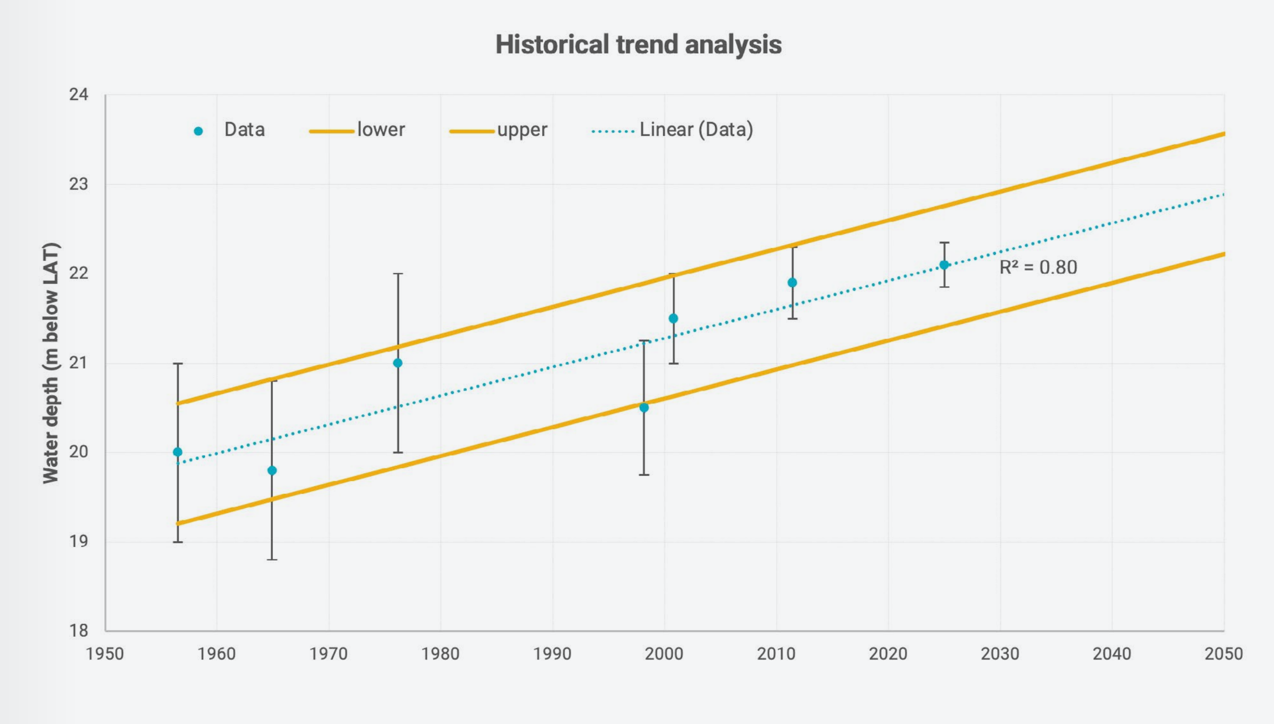
Where data allows, a similar type of analysis can be carried out for the landfall to identify the historical

shoreline behaviour and to support the estimation of future seabed levels across the intertidal zone.

Figure G.2 provides an example of a linear trend developed at a single point through a set of bathymetry data spanning the period 1956 to 2025.

In this example, the earliest dataset is from 1953 when survey methods carried a comparatively higher level of Total Vertical Uncertainty (TVU) (observational precision and errors). In contrast, the newest data corresponds to around 2025 with a lower level of TVU due to modern survey methods achieved with a higher precision. Overall, there are seven separate observational data points spanning a period of around 72 years. A linear trend is developed through the data (dotted line) with a correlation coefficient R^2 of 0.83. The accepted trend is extrapolated forwards by 25 years to 2050. The trend through the observational record is bound within an upper and lower 95% CI.

Figure G.2 – Example HTA



G.2.2 SANDWAVE MIGRATION ANALYSIS

Mobile sandwaves represent meso-scale bedform features (Appendix D) which are susceptible to a change in horizontal position that can generally be observed over the short-term. Other changes might also occur in this period such as a vertical shift in the underlying seabed level and / or a change in height or form of the sandwave. In addition, once assets are installed which protruded above the seabed this may lead to other modifications to the form and orientation of sandwaves.

Sandwave migration is mainly driven by tidally induced bedload transport. The direction of net migration develops from the balance between ebb and flood periods of transport which may vary in magnitude, direction and duration, as well between neap and spring tides. When ebb and flood transport are in balance (in magnitude, duration and direction) this results in largely symmetrical bedforms which remain mobile but with limited net migration. When ebb and flood transport are not in balance then bedforms exhibit an asymmetric form with net migration occurring in the direction of the steeper (forward) lee slope. In most situations, an assumption can be made that the alignment of the sandwave crest is perpendicular to the direction of net transport, although this may not always be the case (e.g., giant sandwaves in the Taiwan Straits).

Sandwave migration analysis requires high-resolution multi-beam echosounder (MBES) data which is able to resolve key properties of the feature (see Appendix C: Section C.4.7), such as clearly discerning the alignment of sandwave crests. Inherently, this limits the qualifying data to contemporary timescales in contrast to HTA which can use a variety of data types, including older single beam data. Since anticipated sandwave migration rates can be observed in the short- to medium-term then the limitation to contemporary data is not considered to be a major constraint.

There are complementary approaches to sandwave migration analysis which can be used together or individually, as follows:

- **1D analysis** – based on comparing cross-sections which show the vertical profile of an individual sandwave for a complete wavelength, crest to crest. This may require several cross-sections to be developed to cover a specific area to account for potential variations between sandwaves of different scales.
- **2D analysis** – based on comparing multiple sandwave crests across the horizontal for a specific area.

In both cases, migration is deduced by determining the horizontal shift required to match with the same bedform feature(s) between successive surveys. This is generally possible if the survey interval is not too long and the form of the same features are reasonably preserved through all the subsequent surveys. These approaches may need to be repeated at several different locations according to variations in local characteristics (i.e., different behaviour zones identified from the CSM) so that areas with different bedform scales are individually assessed.

A set of successive surveys can deduce several estimates of the net migration rate. Ideally, a minimum of three estimates are required so that upper, lower and mean values can be deduced.

a. 1D analysis

This approach is generally most suited to straight crested sandwaves (Appendix D: Section D.2.2).

Cross-section profiles can be sampled at representative locations through the available datasets and over a suitable length (e.g., a minimum of crest-to-crest distance to include at least a full wavelength) whilst ensuring the alignment of each cross-section is taken perpendicular to the crest (N.B. this alignment should also be consistent with the direction of

dominant flows and bedload transport. Misalignment of the cross-section is a source of potential error and increased uncertainty). A comparison can then be made between cross-section profiles to determine the horizontal shift with each profile representing a specific survey and date. The migration rate is then distance travelled over the period. Importantly, the unit of time expressed in the migration rate should be per year, noting the rate would expect to vary within this period day to day, or month to month, due to associated variations in metocean conditions

On the basis that a common and distinct feature can be tracked through time (e.g., forward movement of crest position and height), then the distance travelled by this feature over the time interval between successive surveys provides a basis to estimate the rate of net migration. Alternatively, a best-fit for the full cross-sectional profile can be found by translating the initial cross-section forward to match the subsequent profile with the highest level of correlation (**Figure G.3**).

In this example, 1 m resolution MBES surveys were undertaken on 22 December 2012 and again on 18 November 2013. Highest correlation across the full profile is found by accounting for an 11 m forward shift in the period (quoted to the resolution of the source data). What is also notable, is the crest observed on 18 November 2013 appears to have migrated slightly backward in this period, whereas the levels below the crest maintain a forward migration. Interestingly, megaripples are present on the stoss slope but not on the lee slope.

If there are a series of surveys, then each interval can usefully derive a migration rate with an average rate (and standard deviation) deduced from the full set of information. **Figure G.4** shows a sequence of cross-section profiles obtained from an area of seabed subjected to routine surveys with associated migration rates summarised in **Table G.1**.

Figure G.3 – Determining distance of migration by correlation of 1D profile (figure contains United Kingdom Hydrographic Office data © Crown copyright and database right)

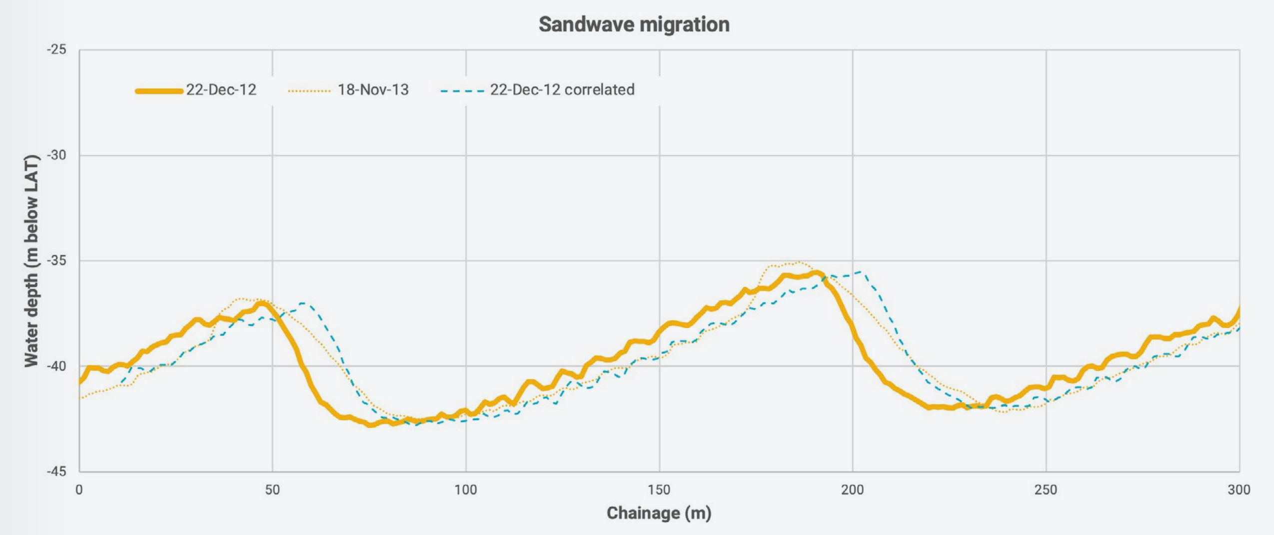


Figure G.4 – Sequence of cross-section profiles from 2012 to 2017 (figure contains United Kingdom Hydrographic Office data © Crown copyright and database right)

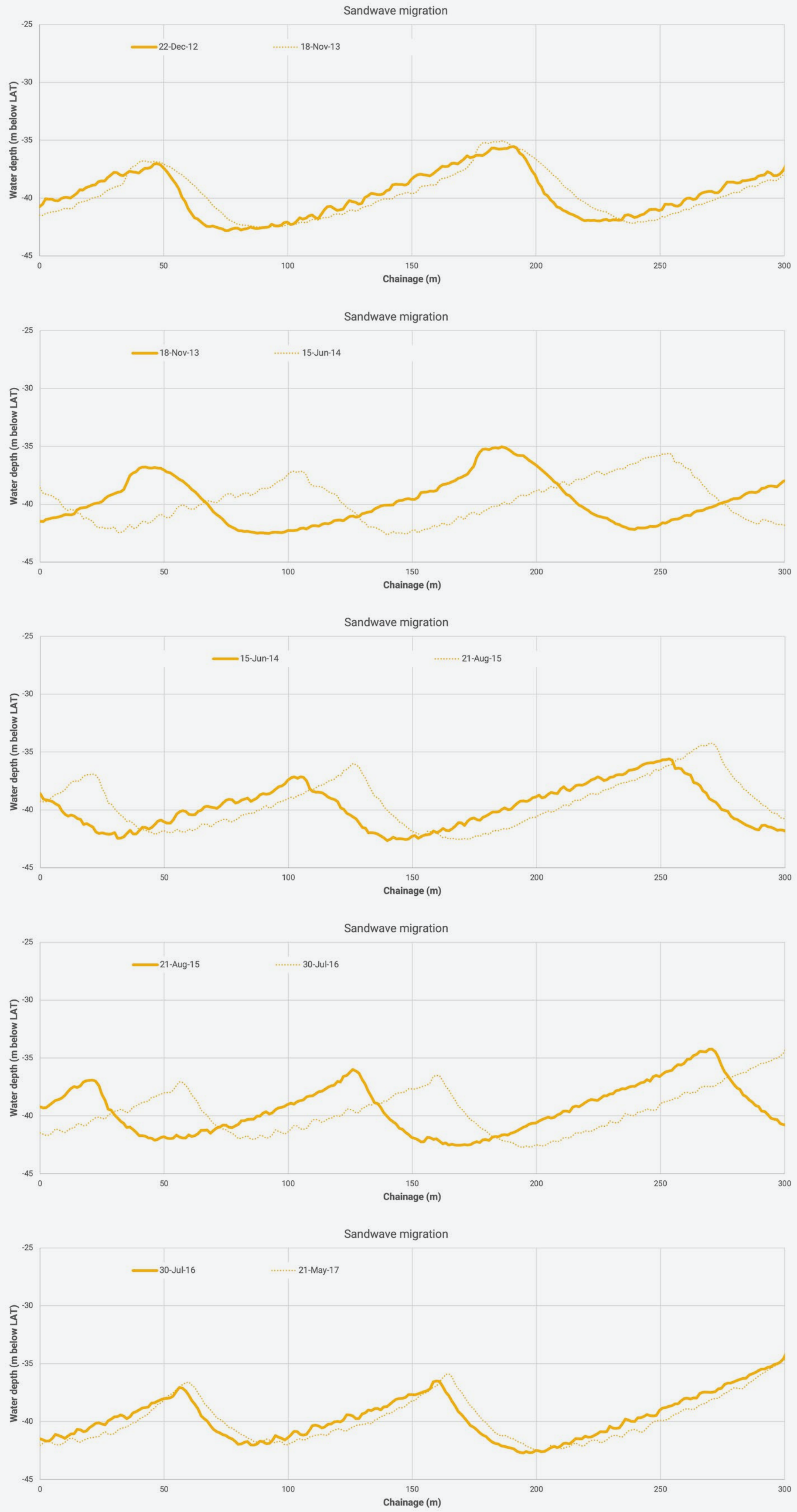


Table G.1 – Summary of sandwave migration rates

DATE #1	DATE #2	ELAPSED PERIOD (YEAR)	DISTANCE (m)	MIGRATION RATE (m/YEAR)
22 December 2012	18 November 2013	0.92	11	12.0
18 November 2013	15 June 2014	0.56	45	80.4
15 June 2014	21 August 2015	1.18	18	15.3
21 August 2015	30 July 2016	0.94	33	35.1
30 July 2016	21 May 2017	0.85	8	9.4

Based on the values presented in **Table G.1**, the average rate of net migration for this set of sandwaves is assessed to be 30 m/year (median of 15 m/year), with a standard deviation of 30 m/year (median deviation of 6 m/year). The large value of standard deviation in this case is due to a non-uniform and highly variable year to year rates occurring in the period. Interestingly, If the analysis was based only on the 2012 (first) and 2017 (last) surveys, this would provide a rate of 26 m/year. Interestingly, if the analysis was based only on the 2012 (first) and 2017 (last) surveys, this would provide a rate of 28 m/year. Collectively, this illustrates the high degree of uncertainty associated with this type of analysis and importance of having multiple datasets covering different dates.

Whilst this analysis focusses on horizontal net migration, a further observation from the cross-sections is that the height of sandwaves increases in the direction of net migration from around 5.5 to 6 m from around 0.0 m chainage, to around 7.5 to 8.0 m toward 300 m chainage. This also appears to occur on a seabed which has a rising incline of around 1 m over this distance (from around -43 to -42 m below LAT).

b. 2D analysis

A 2D cross-correlation approach is suited to all types of sandwaves and is readily achieved using GIS tools to analyse DTM representing sets of sandwave data from different time periods. A detailed description of this approach is provided in Duffy and Hughes-Clarke (2005).

A suitable area of sandwaves is first considered where the horizontal shift in crest position between an initial survey and a subsequent survey can be deduced.

The shifts between successive surveys representing different timesteps determines the distance and direction of sandwave migration over these intervals, and hence a set of associated migration rates is produced.

The best fit in this approach can be determined by applying various shifts to the initial timestep to create new predicted surfaces which are then compared to the subsequent survey. These surfaces can represent bathymetry along with deduced gradient and aspect. The best-fit approach can be quantified by finding the lowest (root mean square) RMS error and a combined RMS for all surfaces (Riezebos, Krogh and Roulund, (2026)). This comparison quantifies the difference between the two survey periods, with the maximum similarity (lowest difference) representing the best-fit, noting this approach considers the full profile of the sandwave and not solely the crest. Ideally, the contributing surveys are fully equivalent in resolution when making this type of comparison.

The quantification of a best fit provides a basis for determining any net change in the underlying seabed level as well as a level of uncertainty in the estimate of a migration rate, noting this is also directly influenced by the resolution of the DTM. The set of migration rates between all successive surveys then provides a basis to derive a mean rate of migration bound within lower and upper uncertainty limits. Equally, trends in the underlying seabed levels will also be determined, if present.

The selection of an area for analysis requires sandwaves to have similar wavelengths and form. If there is distinct spatial variation of these properties, then separate areas need to be defined and examined.

c. Uncertainties in net migration rates

Estimates of the net migration rates of sandwaves are likely to be associated with the highest level of uncertainty in the prediction of future seabed levels. Sources of uncertainty include:

- **Survey accuracy**
  Bathymetry surveys should have a stated accuracy normally expressed as the Total Horizontal Uncertainty (THU) and Total Vertical Uncertainty (TVU). This information is typically provided in the associated survey operational report. The composite of THU and TVU is referred to as Total Propagated Uncertainty (TPU), (IHO, (2024)).
- **Horizontal resolution**
  MBES data reported at 1 m centres represents a horizontal resolution (processed from the raw data point cloud) with an uncertainty of ± 0.5 m in both x and y directions. Where two datasets representing different timestamps are used to estimate the migration rate then the overall horizontal uncertainty is the compound of the two contributing datasets. For example, if dataset A is reported at 1 m centres and dataset B at 0.5 m centres, then the overall limit of accuracy of the horizontal position of a data point representing the crest is (± 0.5) + (± 0.25) = ± 0.75 m in both x and y directions over the time period between the two surveys.
- **Variable bedform shape**
  The form of observed sandwaves will be representative of the environmental conditions which have occurred in the period leading up to the time of surveys. In some situations, surveys following a period of storms may reveal a heavily modified sandwave form compared to pre-storm surveys. Other changes in form may occur between ebb and flood phases of the tide, over the spring and neap cycle, or seasonally. Recommended practice is to deduce the state of environmental conditions leading up to and occurring at the time of each survey so this issue can be considered when deducing the change in position between consecutive surveys. The associated uncertainty due to timing of surveys capturing different bedform shapes is likely to be smallest when the state of environmental conditions are comparable between consecutive surveys, but larger when they are at the most contrasting position (e.g., pre and post storm periods).

  If additional monitoring is required to support the deduction of sandwave migration, then recommended practice is to phase the period of surveys, where possible, with neap tides during summer periods when the crest position is likely to be most stable compared to during periods of springs tides or post-storms.

  An uncertainty factor in net migration due to potential short-term changes in sandwave form should be considered where this is identifiable in the available survey data.
- **Unresolved smaller scale bedforms**
  High-resolution MBES should be able to adequately resolve the form of sandwaves, however, if smaller scale megaripples or ripples (micro-bedforms) are also present across the surface of the sandwave then this scale of bedform may not be fully resolved and potentially adds a small amount of uncertainty to the sandwave associated with the likely scale of the micro-bedforms. For example, unresolved ripples with a height of 0.1 m have the potential to add the same level of uncertainty to the observed sandwave levels.
- **Representative net migration rate**
  Ideally, there are sufficient sandwave surveys representing different dates to help deduce at least three net migration rates (i.e. from four surveys). The set of net migration rates then supports the development of a mean net migration rate bound by upper and lower estimates.

APPENDIX G: ANALYTICAL METHODS
CONTINUED

G.2.3 SANDBANK ANALYSIS

Appendix D describes the generic form of a sandbank. The form and position of sandbanks may evolve over time, albeit relatively slowly compared with smaller scale bedforms, and in many cases their position may also be linked with an associated fixed stable feature (e.g., headland, tidal gyre, outcropping seabed geology, etc.) which led to their development in a specific location.

Sandbank analysis complements HTA, making use of the same data, DTM, and referring to the same account of uncertainties (Section G.2.1).

The series of DTM can then be examined in several complementary ways:

- Differencing in absolute depths between DTMs to reveal losses and gains (Section G.2.1 for HTA).
- Position and aerial extent of a set of contour levels from base to crest.
- Volume of bank above a corresponding set of contour levels.
- Cross-sections perpendicular to the crest of the bank.

In some cases, splitting the length of the bank into sub-areas may be helpful, especially around a swatchway (a naturally formed, shallow channel crossing a sandbank), if present.

a. Differencing

Differencing helps identify parts of the bank experiencing the greatest levels of change in depth. Where this differencing makes use of high-resolution survey data then often the largest differences are associated with more mobile sandwaves moving across the sandbank.

b. Contours

Where the base of the bank can be attributed to a specific depth contour level, then the change in shape, extent and position of that contour through the period of available data can be examined. Further contour levels can be considered from the base to crest to examine the relative stability of different parts of the bank. The likelihood is the upper part of the bank to crest will demonstrate the greatest variability, often on a base that remains relatively stable.

c. Volumetric analysis

A volumetric analysis supports the examination of changes in contour shape, extent and position. In this case, the DTMs can be used to determine the volume of the bank above specific contour levels. Volumetric analysis helps consider if the bank is losing or gaining sediment or remains in balance overall.

d. Cross-sections

Cross-sections help illustrate asymmetry between the flanks of the bank, as well as patterns of change around the crest of the bank.

Values of aerial extent (from contours), bank volume, and cross-sections can be plotted through time to help assess changes in the sandbank which should be considered within an envelope of overall uncertainty. These changes may include patterns of net migration, back and forth oscillatory movement, net gain, net loss or general stability.

G.3 PROCESS BASED APPROACHES

Process based approaches introduce theoretical expressions to develop enhanced understanding not directly available from the data alone. Amoudry and Souza (2011) provide a useful review of the process-based approach.

Process based approaches available to support seabed mobility assessments typically rely on well-established mathematical expressions of relevant behaviours. These approaches may be achieved in spreadsheets, and/or more sophisticated computational models, and supported by a range of relevant site information.

Examples of such approaches include, amongst others:

- Bed shear stress analysis
- Depth of closure (Section F.4.7)
- Morphological modelling

G.3.1 BED SHEAR STRESS ANALYSIS

In a marine environment, bed shear stress represents the force exerted on the seabed through the action of waves and tides which has the potential to initiate sediment transport when the threshold for mobility is exceeded.

Understanding the degree to which the seabed might become mobile (or remain immobile) under the action of waves and tides helps support the definition of seabed mobility maps. In some situations, the indicator for an immobile seabed is also an indicator for an environment likely to experience net deposition.

A detailed description to derive the theoretical bed shear stress due to waves and currents is provided in Soulsby and Clarke (2005). To note, the contribution from currents is typically derived from a depth-average value ($\bar{U}$) which is then scaled to an equivalent seabed flow by accounting for drag forces which are proportional to a bed roughness length. This roughness length has to be selected with consideration to expected contributions from skin friction and form drag, as applicable.

The following bed shear stress values can be estimated for a specific set of wave and current conditions:

τ_c current only bed shear stress

τ_w amplitude of oscillatory bed shear stress due to waves-only

τ_m mean bed shear stress during a wave cycle under combined waves and currents

τ_{rms} root-mean-square amplitude of bed shear stress during a wave cycle under combined waves and currents

τ_{max} maximum bed shear stress during a wave cycle, under combined waves and currents

τ_c and τ_w are useful to assess the individual contributions from currents and waves, respectively, and to help identify if the conditions are tidally dominated, wave dominated, or mixed.

τ_{max} is useful to identify conditions which initiate sediment motion and diffusion very near the bed when values exceed a critical threshold for mobilisation.

a. Critical shear stress

The theoretical critical shear stress (τ_{cr}) which needs to be exceeded to initiate transport of surficial sediment can be established from the threshold Shields (θ_{cr}) parameter by methods outlined in Soulsby (1997). Importantly, this approach is best suited to well-sorted, unconsolidated, non-cohesive sediments ranging from fine sand to gravel.

Where the surficial sediment includes a silt and clay content above 15 to 20% then cohesive properties can begin to influence the soil strength, increasing both shear strength and the critical shear stress for erosion. In this situation, a different parameterisation of threshold conditions is required. Winterwerp and van Kesteren (2004) recommend collection of site-specific measurements of shear strength/critical stress for sites with extensive cohesive deposits. A more detailed treatment of this topic is beyond the scope of this document, but the reader is directed to Mitchener and Torfs (1996), Debnath and Chaudhuri (2010), and Jacobs et al., (2011) for further technical insights. In addition, see Black and Paterson (1997) for an overview of technology which remains relevant to the present day.

b. Shields parameter

The Shields parameter (Shields, (1936)) represents the ratio of the force exerted on a grain by the bed shear stress and the submerged weight of the grain counteracting this force.

The Shields parameter also provides an indication about the resulting mobility conditions (Soulsby, (1997)), as follows:

- $\theta_{max} < \theta_{cr}$ immobile
- $\theta_{cr} \leq \theta_{max} \leq 0.8$ mobile and rippled
- $\theta_{max} > 0.8$ mobile with sheet flow

Where θ_{max} represents the maximum value of θ over a wave cycle and can be readily deduced from τ_{max}.

c. Timeseries analysis

A recommended initial step is to develop a timeseries variation of bed shear stress values for relevant locations. This information may be directly available from a coastal process model or can be calculated from suitable metocean information, such as short-term deployments or long-term hindcasts.

Short-term deployments represent actual observations of metocean variability but may be limited spatially to a few locations and in duration to be able to fully account for infrequent events, such as storms.

Long-term hindcasts represent a synthetic representation of metocean conditions predicted over a larger area and typically cover a period of several decades to help deduce the occurrence of extreme conditions with a greater level of statistical robustness (see Appendix F: Metocean Data Section F4.6). Notably, the long-term hindcast is still dependent on the short-term deployments to demonstrate validation of modelled conditions, however, the basis of validation will be most robust within the range of observed conditions and across the area provided with observations (i.e., predicted events which fall outside of this area or the observation period, and exceed the validation range, should be considered more carefully).

The timeseries variation of bed shear stress provides a basis to identify what type(s) of conditions lead to exceedance of the critical bed shear stress threshold and if these conditions can be identified as:

- Current dominated, when the percentage occurrence of $\tau_c > \tau_{cr}$ is over twice that of $\tau_w > \tau_{cr}$
- Wave dominated, when the percentage occurrence of $\tau_w > \tau_{cr}$ is over twice that of $\tau_c > \tau_{cr}$
- Mixed conditions, when exceedance occurs but neither wave nor currents are dominant
- Immobile, neither wave nor current conditions exceed the critical shear stress at any time

Figure G.5 presents a 10-year timeseries of bed shear stress conditions derived for current only and maximum combined waves and currents. These variations are presented against a reference line for the critical threshold for the motion of surficial sediment based on a sediment grain diameter of 1 mm (equivalent to coarse sand) for this example. N.B. only distributions for τ_c and τ_{max} are shown for clarity.

Figure G.5 – Timeseries variation of bed shear stress showing, current only and maximum shear stress for combined waves and currents (derived from source data from Copernicus Marine Service).

This example indicates that current only conditions do not reach the threshold to initiate mobility of the surficial sediment over the period shown, whereas the maximum combined wave and current bed shear stress exceeds the threshold mostly during periods of winter storms. The profile of these exceedance events can then be examined to better understand the type of conditions leading to sediment mobility.

d. Exceedance Analysis and Seabed Mobility Frequency

Once a timeseries analysis of bed shear stress is available then exceedance analysis can be advanced. Exceedance analysis requires the timeseries to be a suitable duration (i.e., from a long-term metocean hindcasts covering several decades) so that sufficient year-to-year variations produce overall stable statistics, especially for marginal extremes. Only complete years should be included if the intention is to develop an Annual Exceedance Probability (AEP).

The exceedance analysis is created by ranking the timeseries values in decreasing magnitude and associating the ranked order with a percentage exceedance value. Accordingly, the lowest values have exceedance levels approaching 100% and the highest value approaching exceedance levels of 0%. The same data used to present the timeseries variation of bed shear stress (**Figure G.4**) can then be presented as an exceedance distribution (**Figure G.6**). N.B. only distributions for τ_c and τ_{max} are shown for clarity.

This form of analysis provides the basis for determining the Seabed Mobility Frequency (SMF) which represents the percentage of time that seabed sediments are expected to become mobilised by incident waves and currents. SMF may also be expressed as the Mobilisation Frequency Index (MFI).

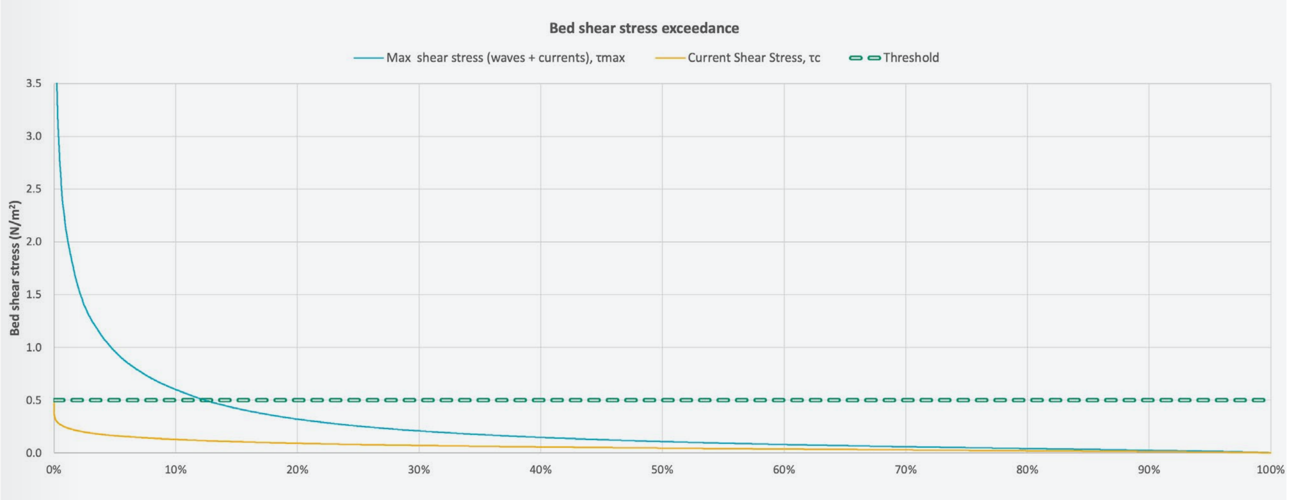
For the example shown in **Figure G.6**, the following values are derived:

- SMF due to currents alone is 0%, noting the current shear stress shown on Figure G.6 does not cross the critical threshold.
- SMF due to waves is estimated to be around 5.6% (not shown on graph), confirming wave dominance.
- SMF due to maximum combined shear stress of waves and currents is estimated to be around 12.9%. This value is shown on **Figure G.6** as the point where the exceedance distribution of τ_{max} crosses the critical threshold.

SMF is most useful for comparative analysis between multiple locations to indicate areas with relatively higher and lower values. However, SMF values of > 50% can be considered High in absolute terms and values < 10% can be considered Low.

In terms of the example shown in **Figure G.6**, these conditions can be considered as approaching Low, due to infrequent storm events.

Figure G.6 – Exceedance probability of bed shear stress, showing current only and maximum shear stress for combined waves and currents.



e. Sediment Mobility Index

The Sediment Mobility Index (SMI) is a dimensionless quantity that indicates the level of sediment mobility, integrating both magnitude and frequency, complementing SMF.

SMI is defined as the mean ratio of τ_m / τ_{cr}, for times when τ_m exceeds τ_{cr}, multiplied by the percentage of time that τ_m exceeds τ_{cr} (i.e., SMF), as described in Li et al. (2009).

The application of SMI is best suited to large coastal areas which require discrimination between areas with different levels of seabed mobility due to exposure to different environmental conditions. Hence, SMI can be used as a tool to support the development of seabed mobility maps. **Table G.2** proposes a scale for use in the interpretation of SMI.

Table G.2 – Proposed SMI Scale

SMI LEVEL	SMI VALUE
Very high	>2
High	1 to 2
Moderately high	0.5 to 1
Moderate	0.1 to 0.5
Low	< 0.1

For the data shown in **Figure G.6**, the value of SMI is deduced as 0.285, equivalent to moderately high.

f. Seabed Disturbance Index

The Seabed Disturbance Index (SDI) quantifies the level of exposure of the seabed to waves and currents, considering both the magnitude and frequency of the bed shear stress.

SDI is defined as the maximum value of the product of $(\tau_m)^{1.5}$ multiplied the percent time (P) for which a given stress is achieved, as described in Li et al. (2009). SDI has units of Nm/s^2.

SDI does not rely on whether the critical threshold for mobilisation is exceeded or not, however, identifying the bed shear stress value associated with the maximum value which defines SDI is possible to help add context.

Table G.3 proposes a scale for use in the interpretation of SDI.

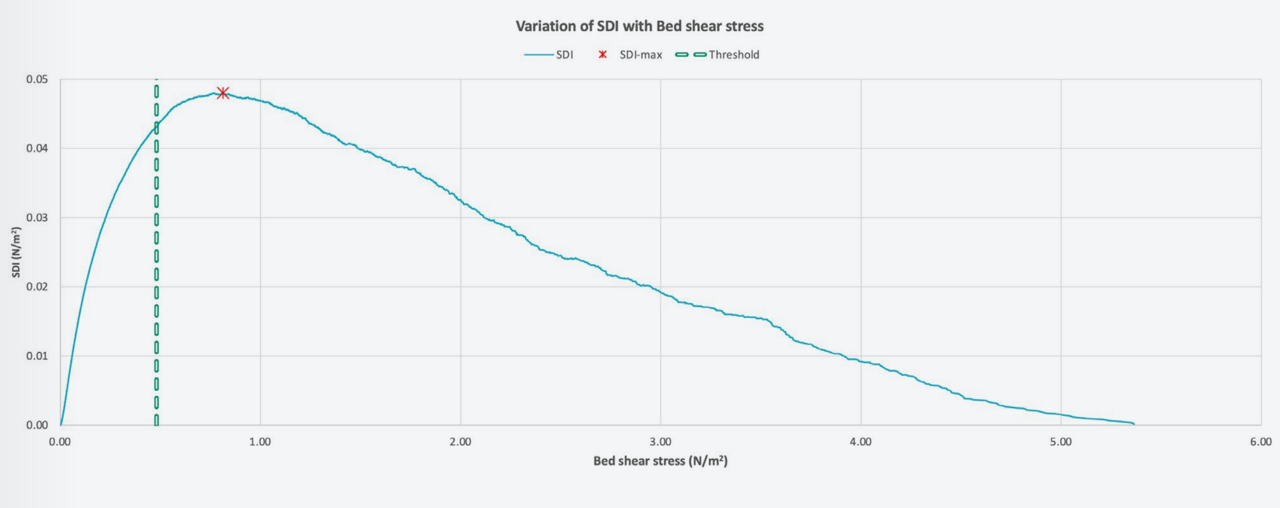
Table G.3 – Proposed SMI Scale

SDI LEVEL	SDI VALUE
High	0.6 to 1.5
Moderately high	0.4 to 0.6
Moderate	0.1 to 0.4
Low	< 0.1

For the data shown in **Figure G.7**, the value of SDI is deduced as 0.048 N/m^2, equivalent to low.

Figure G.7 presents the variation of SDI with associated bed shear stress values for the same data, showing that SDI-max occurs for a bed shear stress of 0.82 N/m^2, which is at a level which exceeds the critical threshold of 0.48 N/m^2 for this example.

Figure G.7 – Variation of SDI versus associated level of bed shear stress.



The recommended approach is to mainly refer to SMI and use SDI in a supporting capacity

G.3.2 PROCESS BASED MORPHOLOGICAL MODELLING

Sediment transport models enable a spatial and temporal description of rates and directions of transport due to waves and currents, with morphological (bed-updating) models providing the means to examine changes in seabed levels due to predicted erosion and deposition. The updated seabed profile is then provided as feedback to the sediment transport model. The performance of morphological models can be validated with reference to the same data used for HTA (Section G.2.1).

Morphological models are useful in advancing the preliminary CSM (Section 3.12), testing the hypothesis and quantifying the relationships between waves, tides and sediment transport.

There are, however, important limitations to note in the application of morphological models:

- The performance of the sediment transport model requires well-calibrated hydrodynamic and wave models. For example, if the evaluation of metocean data identifies important asymmetry between flood and ebb flows, and this effect governs the direction of net transport, then the hydrodynamic model needs to demonstrate similar.
- Even with well-calibrated hydrodynamic and wave models, the reliability of the chosen sediment transport formula is likely to be medium to low, at best. Most morphological models provide a selection of sediment transport formula which might each lead to a different outcome. This is generally attributed to a specific formula having been developed for a given set of experimental conditions which is then used to develop an empirical best-fit expression. Some useful insights into a selection of sediment transport formula is given in Camenen and Larroudé (2003) who note that an estimate of sediment flux is generally considered acceptable when falling within a range of 1/2 to 2 times the experimental data. There may also be merit in comparing outcomes from different sediment transport formula to help quantification of associated uncertainties.
- The description of the seabed profile across the model should ideally represent a specific moment in time rather than a time integrated composite from various sources of bathymetry.

- A variable bed roughness should be considered where there are distinctive changes in the composition of the seabed, noting this detail is likely to be fixed and not subject to any temporal updating.
- The application of the model is best suited to unimodal sediment distributions, like sandy sediments, rather than mixed sediments.
- The mobile layer needs to be considered so that erosion leading to bed-updating and lowering of the seabed is not unlimited.
- The model will not resolve the migration of small scale bedforms, including sandwaves.
- Small errors in computing sediment flux, which lead to bed-updating, can become significant compound errors over time, leading to unreliable deviations over predictions for periods of months or years.

The best use of a morphological model is when a major large-scale change is imposed on the environment (e.g., a long breakwater, or sensitivity due to climate change) which modifies the dynamic equilibrium, and the response to that change needs to be investigated. Most offshore environments are already likely to be in dynamic equilibrium.

For a seabed mobility assessment, a morphological model is most suited to determining general patterns of seabed level variations due to deposition and erosion to corroborate findings from HTA (Section G.2.1). Future scenarios should consider the drivers for change (as outlined in the CSM – Section 3.2.12). For example, if the seabed only responds to storm related effects, then the morphological model can help establish the scales of change for different storm magnitudes, although these changes are unlikely to be within the calibration range of the model. A consideration of the effect of sea level rise should also considered as part of the future scenarios, as relevant. Where bedforms are present, these features should typically be considered in addition to the findings from a morphological model.

A recent PhD published by Pauline Overes (2026) considered the capability of morphological modelling to resolve an area of sandwaves, represent sandwave dynamics and sandwave recovery. A high-resolution 3D modelling approach was required to represent the characteristics of sandwaves with alternative sediment transport formula evaluated to help consider the capability of the modelling tool. This work was achieved with a computationally demanding setup with necessary spatial and temporal limitations.

Additional insights into process based morphological models are available from Coastal Wiki.

G.4 TOP-DOWN APPROACHES

Top-down approaches provide a high-level, broad-scale or long-term perspective of system behaviour. They are generally used alongside bottom-up and process-based models to collectively address relevant timescales, dominant hydrodynamic forcings and spatial extents. Li et al., (2021) define a national scale top-down framework approach to seabed mobility assessment.

Top-down approaches help frame a system response towards a new (dynamic) equilibrium.

Examples of top-down information include rates of sea level rise (future and past), glacial rebound, and shoreline change, etc.

- NASA provides a Sea Level Projection Tool to access The Intergovernmental Panel on Climate Change (IPCC) projections of global and regional future sea levels, relative to a 1995–2014 baseline, as well as other adjustments to account for land movements, etc.
- The Permanent Service for Mean Sea Level (PMSS) provides details of observed sea level rise with a Data Explorer. In some cases, these observations cover a historical period of 100 years or more (e.g., Newlyn, UK), noting data gaps may also be present.
- A useful resource for an initial appraisal of shoreline change is the ShorelineMonitor Viewer which provides global coverage of long-term shoreline changes over the period 1984 to 2024 (Luijendijk, et al., 2018).

Examples of top-down approaches include the Bruun rule (Bruun, (1962)) for shoreface adaptation to sea level rise (see Coastal Wiki), linked with the depth of closure (Section F.4.7). This approach is relevant to landfall areas where consideration needs to be made about the potential landward adjustment of an undefended shoreline over the long-term in response to projected rates of sea level rise.

G.5 SYNTHESIS

Applying a combination of complementary approaches to examine seabed mobility is likely to provide a stronger overall assessment than relying on a single approach, especially where these combine a variety of bottom-up, process-based, and top-down approaches representing different magnitudes of and frequencies of change.

The synthesis is a fundamental part of updating the preliminary CSM to a detailed CSM where analytical methods completed in the intervening period are able to test various hypothesis and better quantify levels of variation in seabed levels to support the determination of future seabed levels (Section 3.2.15). Data synthesis should also account for uncertainties in each contributing source of information.

G.5.1 AGGREGATION OF EXTRAPOLATION METHODS

Due to the varying spatial and temporal scales in complex environments, separate extrapolation methods are often applied to individual components with a combination of results then aggregated. For example, long-term behaviour of a sandbank may be usefully considered with a morphological model, whereas the behaviour of sandwaves may be developed by data driven empirical approaches conducted at a finer spatial scale. The mobility of sandwaves present across a sandbank can then be combined with a consideration of the larger scale changes to provide estimates of future seabed levels.

An important part of estimating future seabed levels is the validation of the extrapolation method(s). In part, this may be possible by considering a prior time period of data (and associated DTM) and using the derived extrapolation method to reach the period with latest observations. In addition, once new data becomes available through subsequent stages of project development, and onward monitoring, then additional validation (and refinement) can be performed. Validation should be judged as successful when observed values from a future period are close to the best estimate of future seabed levels and remain within the uncertainty limits.

G.5.2 ESTIMATING FUTURE SEABED LEVELS

Future seabed levels should be considered for all relevant areas.

a. Initial conditions

The latest bathymetric survey data should provide the initial conditions for determining future seabed levels. This dataset should be consistent with the most up-to-date DTM used for HTA (Section G.2.1). Notably, the latest survey data is expected to precede the start date of construction by a year or more. For areas mapped with "Medium" and "High" seabed mobility, this is expected to require a forward extrapolation to the date of construction.

b. Low mobility

If the assessment has confirmed areas mapped with a "Low" level of seabed mobility, associated with sufficiently high confidence levels (low uncertainty), then future seabed levels are expected to be largely unchanged over the development period and can be defined as the most up-to-date DTM used for HTA. These estimates should be bound within associated uncertainties (i.e., principally the precision of the associated bathymetry data and method of DTM creation).

c. Medium mobility

If the assessment has confirmed areas mapped with a "Medium" level of seabed mobility, associated with sufficiently high confidence levels (low uncertainty), then future seabed levels are expected to vary slowly or infrequently and with a moderate magnitude.

Future seabed levels should be considered at an appropriate interval over the development period (i.e., related to the rate of change) as an extrapolation of initial conditions to develop a series of new DTM.

The extrapolation method should consider the process drivers which develop changes in seabed levels, drawing from trends established from HTA (Section G.2.1) and any morphological modelling (Section G.2.2), as appropriate.

Future seabed levels should be bound with an account of associated uncertainties. These uncertainties may need to be adjusted if the assessment of the mobility level is still associated with a low or moderate level of uncertainty.

d. High mobility

If the assessment has confirmed areas mapped with a "High" level of seabed mobility, associated with sufficiently high confidence levels (low uncertainty), then future seabed levels are expected to vary relatively quickly and with a high magnitude.

Future seabed levels should be considered at an appropriate interval over the development period (i.e., related to the rate of change) as an extrapolation of initial conditions to develop a series of new DTM. Each new DTM is likely to represent an annual increment of change for area with a "High" level of mobility. The extrapolation method should consider the process drivers which develop changes in seabed levels, drawing from trends established from HTA, sandwave and sandbank analysis (Section G.2.1), and any morphological modelling (Section G.2.2), as appropriate.

Future seabed levels should be bound with an account of associated uncertainties, including an account of potential inter-annual variations. These uncertainties may need to be adjusted if the assessment of the mobility level is still associated with a low or moderate level of uncertainty.

G.5.3 BOUNDING UNCERTAINTIES

Uncertainties should be determined as an envelope around any best estimate of future seabed levels and established from an account of contributing sources (e.g., source data, methods of analysis, etc.).

a. Source data

If multiple repeat seabed surveys are available (i.e. five more), these can be explored to estimate statistical variance in seabed levels and characteristics of bedforms (migration, height, shape and extent). The standard method of analysis is to determine the standard deviation within or between datasets, or subsets of the datasets where statistical variance is expected to be distinctly different (e.g., different mapped levels of seabed mobility such as; flat seabed, bedform rich areas, etc.). By analysing the distribution of dynamics and characteristics, the assumption of a normal statistical distribution can be confirmed (assuming sufficient data samples). This information can be used to determine what level of certainty is provided, e.g., by applying twice the standard deviation as an uncertainty band (which is usually applied for normal distributions to arrive at approximately 95% certainty. Importantly, these types of estimations are only valid if the full range of relevant conditions are represented in the measurement data. For example, exclusion of data for bedforms affected by extreme conditions (where relevant) in the dataset can lead to a misinterpretation of the risks.

b. Methods of analysis

Any derivation of seabed levels from source data will introduce a level of additional uncertainty due to the approximations provided in the method of analysis. Examples include developing DTM, extrapolating to future seabed levels,

Additional insights into the uncertainties can be investigated using numerical simulations to test the sensitivity of the seabed to events not represented in the source data.

c. Combining uncertainties

Combining uncertainties can be challenging, especially when relationships between the uncertainties are unknown or difficult to establish. Care should be taken not to be overly conservative while keeping in mind all the risks and possible consequences. Moreover, the combined uncertainty band should be compared to other limiting conditions, such as non-erodible layers, to avoid possible over-estimation.

The simplest way of combining uncertainties is by adding them together, however, this approach might lead to unreasonable levels of conservatism (i.e., assumption of no dependency between different sources of uncertainty). Alternatively, consideration can be made of various scenarios to help determine if certain limits are related and are expected to occur together (i.e., partial or full dependency between uncertainties). For example, the most extreme conditions may occur in winter when the height of smaller bedforms is more limited (due to the stormier conditions).

As an alternative to adding uncertainties, a probabilistic framework can be applied by considering exceedance probabilities for relevant seabed levels and conditions, incorporating multiple sources of uncertainty (e.g., measurement error, natural variability, climate change, etc.).

d. Managing residual uncertainties

For the final Design Seabed Levels, the full timeseries of future seabed levels is usually not provided, rather a pre-defined confidence interval is applied for the lowest (LSBL) and highest (HSBL) seabed levels determined from, for example, the 5% and 95% confidence interval of the estimated future seabed levels. If confidence intervals become too wide and potentially unrealistic, the confidence interval or time horizon may be adapted to reduce the width of the uncertainty bands.

By identifying the main sources of uncertainty early on, dedicated monitoring campaigns can be established to help reduce the conservatism in the design. For example, if the uncertainty is related to the long-term morphological development of large bedform features, the bathymetry can be monitored at specific locations and occasions over the lifetime of the assets. Moreover, in case the impact of storms on the cable coverage is uncertain, arrangements can be made to conduct post-storm surveys.

G.6 REFERENCES

Amoudry, Laurent and Souza, Alejandro. (2011). Deterministic Coastal Morphological and Sediment Transport Modelling: A Review and Discussion. Reviews of Geophysics. Volume 49, Issue 2.

Black, K.S. and Paterson D.M. (1997). Measurement of the erosion potential of cohesive marine sediments: A review of current in situ technology. Journal of Marine Environmental Engineering. 4 (1), 43-84.

Bruun, P. (1962). Sea-level rise as a cause of shore erosion. Proc. Am. Soc. Civ. Eng., J. Water Harbors Div. 88: 117-130.

Camenen B. and Larroudé P. (2003). Comparison of sediment transport formulae for a coastal environment. Coastal Engineering, 48, pp.111-132

Debnath, K. and Chaudhuri, S. (2010). Cohesive Sediment Erosion Threshold: A Review. ISH Journal of Hydraulic Engineering, 16(1), 36–56. doi.org/10.1080/09715010.2010.10514987.

Duffy, P.G. and Hughes-Clarke, J.E. (2005). Application of spatial cross correlation to detection of migration of submarine sand dunes. Journal of Geophysical Research. Volume 110. F F04S12, doi:10.1029/2004JF000192.

IHO. (2024). Standards for Hydrographic Surveys. S-44 Edition 6.20.

Jacobs W., Le Hir P., Van Kesteren W. and Cann P. (2011). Erosion threshold of sand–mud mixtures, Continental Shelf Research, Volume 31, Issue 10, Supplement, Pages S14-S25.

Li, M.Z., Zou, Q., Hannah, C., Perrie, W., Prescott, R. and Toulany, B. (2009). Numerical Modelling of Seabed Disturbance and Sediment Mobility with applications to Morphodynamics on the Storm-dominated Sable Island Bank, Scotian Shelf. Geological Survey of Canada, Open File 6155.

Li,M., Yongsheng, W., Hannah,C.G. and Perrie, W., (2021). Seabed disturbance and sediment mobility due to tidal current and waves on the continental shelf of Canada. Can. J. Earth Sci.58(11):1209-1232.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G. and Aarninkhof, S. (2018). The State of the World's Beaches. Scientific Reports, 8 (6641).

Mitchener, H. and Torfs, H. (1996). Erosion of mud/sand mixtures. Journal of Coastal Engineering, 29: 1-25.

Overes, P.H.P. (2026). A Deep Dive into Sand Wave Dynamics. Using Process-Based Modelling and In Situ Observations. PhD Dissertation, University of Twente.

Riezebos, H.J., Krogh, P.E. and Roulund A. (2026). Prediction of seasonal marine sandwave migration in a bi-modal sandwave field. Marine and River Dune Dynamics (MARID VIII) – 13-15 April 2026 – Enschede, the Netherlands.

Schober P., Boer C. and Schwarte L.A. (2018). Correlation Coefficients: Appropriate Use and Interpretation. Anesth Analg 126(5). Pp 1763-1768.

Shields A. (1936). Anwendung der Ahnlichkeits-Mechanik und der Turbulenzforschung auf die Geschiebebewegung. Preussische Versuchsanstalt fur Wasserbau und Schiffbau, vol. 26, Berlin.

Soulsby, R.L. (1997). Dynamics of marine sands. A manual for practical applications. Thomas Telford.

Soulsby R.L. and Clarke S. (2005). Bed Shear-stresses Under Combined Waves and Currents on Smooth and Rough Beds. Produced within Defra project FD1905 (EstProc). Report TR 137. Rev 1.0.

Sutherland, J. (2021): Coastal tract modelling. Available from http://www.coastalwiki.org/wiki/Coastal_tract_modelling [accessed on 8-05-2026].

Winterwerp, J.C. and van Kesteren, W.G.M. (2004). Introduction to the Physics of Cohesive Sediment in the Marine Environment.: Developments in Sedimentology Series no. 56. xiii + 466 pp.

APPENDIX H: CASE STUDIES

CONTENTS

H.1 OVERVIEW

This appendix presents a series of case studies that demonstrate the practical application of the Seabed Mobility Guidance across the project lifecycle, drawing on offshore wind and transmission projects in morphodynamically active environments to show how seabed mobility shapes site selection, design development, construction, and operations and maintenance. Taken together, the case studies underline that seabed mobility is often a primary driver of long-term engineering risk, particularly in sandwave- and megaripple-dominated settings, and that reliance on static or overly conservative design assumptions can misrepresent this risk, resulting in unnecessary burial depth, increased foundation conservatism, and higher whole-life cost. The examples illustrate the value of long-term, high-resolution bathymetric datasets, repeat surveys, and detailed geophysical, geomorphological and hydrodynamic information for defining realistic envelopes of future seabed variability, and for enabling spatially refined, site-specific assessments of dominant sediment processes. The examples also demonstrate that the early integration of morphodynamic understanding and forward prediction of mobile bedforms into design leads to more resilient, and cost-effective solutions, than approaches based on flat-bed or static seabed assumptions. The overarching lessons from these examples reinforce that robust offshore infrastructure design requires combining empirical seabed analysis with hydrodynamic and sediment-transport modelling, explicitly accounting for uncertainty, and embedding proportionate, adaptive measures such as targeted monitoring and contingency planning to reflect true seabed variability.

N.B. Figure references are relative to the source material (not in numerical order)

H.2 CASE STUDY 1: Cable Route Optimisation for Offshore Wind Farms in Morphodynamics Areas

CABLE ROUTE OPTIMIZATION FOR OFFSHORE WIND FARMS IN MORPHODYNAMICS AREAS	
Source	Deltares (with permission T Roetert)
Site	Hollandse Kust (zuid) Wind Farm Zone (HKZWFZ) – Dutch North Sea Case study focused on Site I (dynamic seabed with sandwaves and megaripples) 45 turbines (8 MW each), mutual spacing ~1,200 m, connected to HKZ Alpha platform
Project date	2016 (study period covers prediction of future seabed levels for 2016–2051)
Illustration of	Cable route optimisation considering seabed morphodynamics (sandwave migration)
Cross reference to Chapter/text	Project development requirements (Section 4); Detailed Design (Section 4.5)
Keywords	Power cables, route optimisation, offshore wind, seabed morphodynamics, renewable energy, coast and risk reduction
Description	**Problem Definition:** Traditional cable routing methods assume a static seabed, ignoring dynamic features such as sandwaves. These bedforms can migrate several metres per year, causing significant seabed lowering or raising over the windfarm lifetime. This poses risks of cable exposure, free spans, thermal stress, and failure, leading to high repair costs and insurance claims (up to 70-80% of cable-related costs). **Approach**: A new optimisation method was developed to incorporate seabed dynamics into cable routing design. The method combines: • **Flat-bed optimisation:** Genetic algorithm to minimise total cable length under static conditions. • **Dynamic-bed optimisation:** Vertical plane (adjust burial depth along cable routes to account for predicted seabed lowering) and Horizontal plane (divert cables around high-risk areas using Dijkstra's shortest-path algorithm and a cost-risk function). **Data sources required:** Long-term bathymetric surveys (at least 20-year coverage), morphodynamic modelling predicting seabed changes for 2016–2051, hydrodynamic and sediment transport modelling, geological data for substrate characterisation. **Case Study Application:** HKZWFZ Site I selected for highest sandwave migration rates and seabed lowering (up to 4 m). Vertical optimisation achieved 46% cost savings and 76% risk reduction compared to fixed burial depth (1.5 m). Horizontal optimisation achieved 30% cost savings and 65% risk reduction, despite slightly longer cable routes.

Example figures

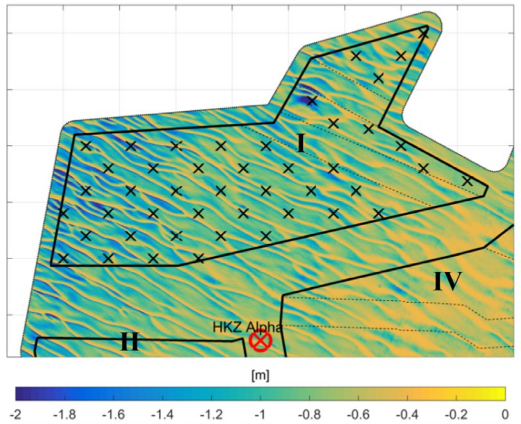


Figure 1 Maximum seabed lowering observed in Site I of the HKZWFZ observed within the period 2016 – 2051. The black crosses denote fictitious turbine locations, while the HKZ Alpha platform is located to the south. Site IDs are identified with roman numerals.

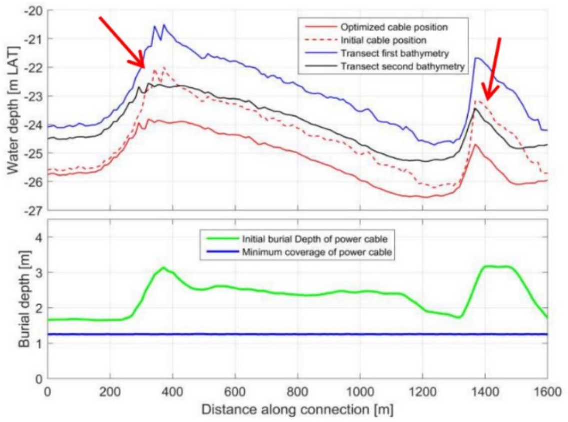


Figure 2 Optimized cable position in vertical plane between two turbines. The top plot depicts the present bathymetry (blue line), lowest seabed level over time including uncertainty (black line), the initial cable position assuming a constant burial depth (dashed red line) and the optimised initial burial depth (green line) and minimum cable coverage over the period considered (fixed blue line). The red arrows indicate locations where the cable can become exposed, when buried at a constant burial depth of 1.5 m.

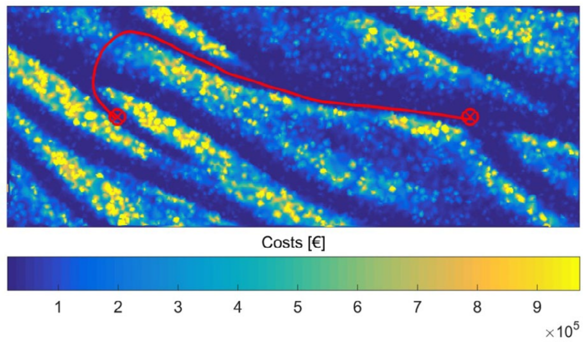


Figure 16 Optimised cable position in the horizontal plane between two turbines. The red line indicated the most optimal route calculated with aid of both the cost function and Dijkstra's algorithm. The grid displayed is calculated by applying the cost function on all edges. Yellow locations indicate areas with significant seabed lowering and higher costs, whereas the dark blue areas represent the cheaper areas subject to little seabed lowering.

Conclusions/ Recommendations

Key Takeaways:

Dynamic seabed conditions significantly influence cable integrity: Migrating sandwaves can cause burial depth variations of up to 4 m, leading to exposure risks, free-spans, and thermal stress if not accounted for.

- Static design assumptions are inadequate: Traditional routing methods based on a flat seabed underestimate risks and result in higher lifecycle costs.
- Dynamic-bed optimisation is effective: Incorporating seabed morphodynamics into cable routing achieved up to 71% overall cost reduction and substantial risk mitigation in the case study.
- Vertical optimisation is critical: Adjusting burial depth along cable routes to predicted seabed changes minimises exposure risk and failure probability.
- Horizontal optimisation adds value: Routing around high-risk zones (e.g., sandwave crests) further reduces costs and risks, even with slightly longer cable lengths.

Recommendations for Best Practice:

- Integrate morphodynamic analysis into early design stages: Site assessments should include long-term bathymetric data and predictive modelling of seabed evolution.
- Adopt dynamic-bed optimisation tools: Guidance should evolve to require consideration of seabed mobility for cable routing and burial depth specification.
- Specify monitoring and adaptive strategies: Post-installation surveys and contingency plans should be included in consent conditions to validate predictions and manage residual risks.
- Update cost-risk frameworks: Include failure probabilities linked to seabed dynamics in lifecycle cost assessments to inform routing decisions.

Lessons Learned:

Seabed mobility is not a marginal factor; a loss of sediment cover due to seabed mobility can dominate cable failure risk and cost outcomes. Combining vertical and horizontal optimisation provides the greatest benefit; future tools should integrate both in a single algorithm. Sensitivity analysis shows trenching costs and burial depth assumptions are major drivers of total cost; these should be prioritised in design optimisation.

References

Deltares (2016). Morphodynamics of Hollandse Kust (zuid) Wind Farm Zone; Prediction of seabed level changes between 2016 and 2051.

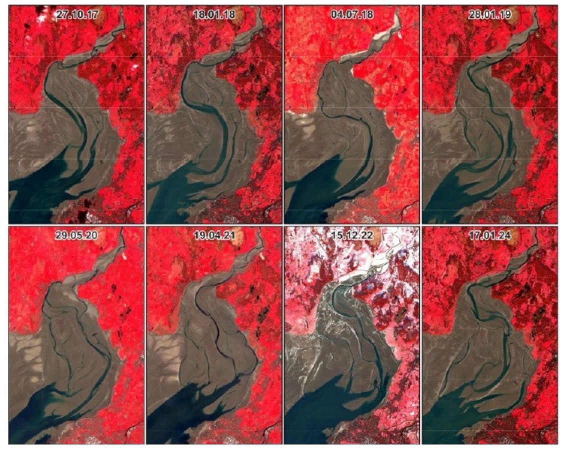
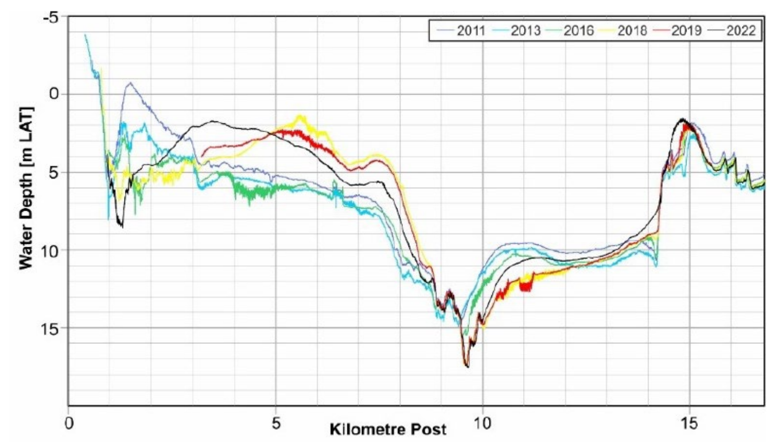
Deltares. (2023). Morphodynamics for IJmuiden Ver Wind Farm Zone. WOZ2220017. Ref: 11208404-002-HYE-0001. Retrieved from https://offshorewind.rvo.nl/files/view/f9b2d778-a723-4c23-8548-7b16b9489074/ijv_20230207_mor_deltares_morphodymics-f.pdf

DNV (2014). Recommended Practice DNV-RP-J301: Subsea Power Cables in Shallow Water Renewable Energy Applications.

Roetert, T.J., Raaijmakers, T.C. and Borsje, B.W. (2017, June 25-30). Cable route optimization for offshore wind farms in morphodynamic areas. Paper presented at the The 27th International Ocean and Polar Engineering Conference, San Francisco, CA, USA.

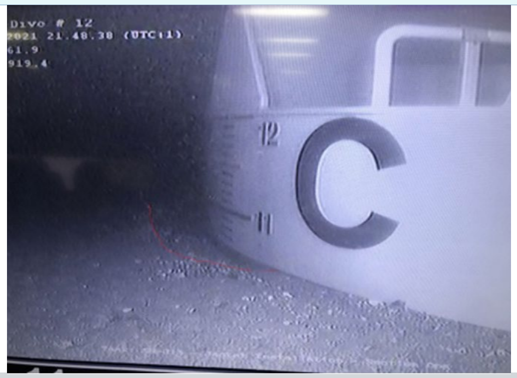
H.3 CASE STUDY 2: Assessment of Subaerial Sediment Mobility and Channel Migration in Morecambe Bay using Sentinel Satellite Timelapse Imagery

ASSESSMENT OF SUBAERIAL SEDIMENT MOBILITY AND CHANNEL MIGRATION IN MORECAMBE BAY USING SENTINEL SATELLITE TIMELAPSE IMAGERY	
Source	Transmission Investment (with permission D Harrison, 4Geo)
Site	Barrow and Ormonde offshore wind farm export cable routes
Project date	Ongoing
Illustration of	High-level assessment of regional morphodynamics to understand offshore seabed mobility
Cross reference to Chapter/text	Project development requirements (Section 4); Site Selection (Section 4.2); Detailed Design (Section 4.5); Operations and Maintenance (Section 4.7)
Keywords	Estuary, satellite imagery, cable exposure, channel migration, public data sources
Description	**Problem Definition:** Since installation, the export cables for the Ormonde and Barrow offshore wind farms have been subject to high degrees of sediment mobility within the outer Morecambe Bay region, with extensive areas of cable exposure and also excessive burial. Such sediment mobility can appear unpredictable when viewing a narrow corridor of hydrographic data around the assets, with years or relatively stable conditions, followed by rapid and significant mobility. **Approach:** To help understand possible causes of the extreme sediment mobility changes, a more regional review of data was conducted, including regional hydrographic data for the offshore section, and satellite imagery for the onshore/intertidal section. The satellite-based review was conducted rapidly using publicly available imagery from the Sentinel-2A satellite, which provides visible, near infrared, and short wave infrared spectral coverage of the Earth's surface every 2-3 days at a horizontal resolution of approximately 10 m. A selection of datasets were extracted during periods of minimal cloud cover and at low tide over the course of seven years (**Figure 1**), to allow for an assessment of seasonal changes in subaerial morphology. Satellite data in this study is particularly useful as it is a huge intertidal region (conventional satellite-derived bathymetry images through shallow, relatively clear water and would not work here). In the case of Morecambe Bay, the data show the outer estuary area to be highly dynamic, with the main river channel and tidal tributaries moving laterally up to 2 km in 12 months. These channels feed into different parts of the submarine area, potentially feeding into different submarine channels and influencing depositional regimes further offshore, resulting in highly variable bathymetry survey results during cable monitoring surveys (**Figure labelled as 2**).

Example Figures	 Figure 1 Sentinel L2A Imagery (False Colour)  Figure 2 Morecambe Bay Export Cable Route Monitoring Survey – Bathymetry Profiles
Conclusions/ Recommendations	**Key Takeaways:** • Data sources such as satellite data provide useful information early in developments, supporting important decision making from the outset and increasing confidence. • Regional estuarine dynamics, particularly rapid lateral channel migration, are the primary drivers of the extreme sediment mobility observed along the export cable routes. • Localised offshore changes (exposure and excessive burial) cannot be interpreted reliably without considering wider morphological processes across outer Morecambe Bay. • Sentinel 2A imagery provides a clear, repeatable and cost free means of identifying multi annual system behaviour that directly influences offshore sediment pathways. **Recommendations for Best Practice:** • Integrate routine satellite-based morphological reviews (e.g., annual or semi annual Sentinel 2A assessments) into standard cable monitoring workflows. • Combine regional remote sensing, hydrographic datasets, and offshore MBES results to create a multi scale, process based understanding of sediment mobility.
References	Case Study kindly supplied by G Harrison, Geo-4D.

H.4 CASE STUDY 3: Impact of Seabed Mobility on Cable Burial for the Seagreen Offshore Wind Farm, UK (North Sea)

IMPACT OF SEABED MOBILITY ON CABLE BURIAL FOR THE SEAGREEN OFFSHORE WIND FARM, UK (NORTH SEA)	
Source	J Irvine Kent / SSE
Site	North Sea
Project date	Example
Illustration of	Over conservatism in modelling / predictions
Cross reference to Chapter/text	Project development requirements (Section 4); Detailed Design (Section 4.5); Construction (Section 4.6)
Keywords	Sediment mobility, conservatism
Description	**Problem Definition:** Initial sediment mobility assessments overstated the degree of seabed mobility across the site due to the cumulative application of conservative assumptions, including overestimated near-bed current velocities, simplified erosion relationships, and uniform use of worst-case geotechnical test results, resulting in potentially unnecessary scour protection and cable burial requirements. **The data gathering campaign included:** • Tidal current measurements • Detailed geophysical survey including high-resolution bathymetry • Geotechnical survey included detailed flume testing to understand sediment erosion risk **The initial sediment mobility assessment indicated that seabed sediments could be highly mobile which in turn led to the following:** • Scour protection required for all WTG foundations • Deeper burial requirements for array cables However, upon detailed review of the data and assessments it was concluded that several conservatisms had been added together that gave a potentially misleading understanding of seabed mobility. **The conservative assumptions included:** • Inaccurate current depth profile which overestimated current speed at seabed • Use of a simplified erosion-current speed relationship which resulted in erosion even at relatively low current velocity, for example 100 m/hour at 0.3 m/s current • Application of the most onerous test results across the entire development area

Description (continued)	The available geophysical data did not identify any significant mobility features, and the risk was re-evaluated following review of the data and assumptions which allowed for a more accurate understanding of conditions. This indicated fine sediments may be prone to 'wash out'; this generally resulted in a 'shelly' crust which provided more resistance. Also, several areas had clays or silts at the seabed which were much more resistant to mobility. Rather than a single conservative assumption for the entire site, a more detailed consideration of depth, current speeds and shallow soils allowed for a refined risk approach across the site being considered that allowed for a reduction in scour protection requirements and reduced cable burial depths in some areas.
Example Figures	 Figure 2 Photograph of the seabed adjacent to foundation structure indicating a stable seabed (i.e. there is no evidence of pronounced seabed scour), comprising dominantly shelly debris.
Conclusions/ Recommendations	**Key Takeaways:** • The initial sediment mobility assessment was overly conservative due to compounded assumptions, including overestimated near bed currents, simplified erosion thresholds, and the blanket application of worst case flume results. • Detailed review of geophysical, geotechnical and hydrodynamic datasets revealed limited evidence of significant seabed mobility, with several areas exhibiting naturally resistant materials such as shelly layers, silts and clays. • A more site specific interpretation which accounts for actual depth varying current speeds and spatially variable sediment properties allowed for a more accurate and less precautionary understanding of mobility risk. **Recommendations for Best Practice:** • Avoid applying single worst case assumptions across an entire development area; instead, adopt a spatially resolved assessment that integrates depth dependent hydrodynamics and detailed shallow soil properties. • Use geophysical evidence of seabed texture and mobility indicators to calibrate or challenge model based erosion predictions before finalising engineering design requirements. • Implement a refined, risk based approach that tailors scour protection and cable burial depths to local conditions, potentially reducing cost, environmental disturbance, and unnecessary conservatism.

Conclusions/ Recommendations (continued)	**Lessons Learned:** • Conservative assumptions, if layered without validation, can produce an exaggerated perception of mobility risk that materially affects design decisions such as scour protection sizing and cable burial depths. • High-resolution geophysical data are critical for checking the validity of model based sediment mobility predictions and should be used to ground truth any simplified erosion formulations. • Site conditions can vary substantially, and recognising the stabilising effect of localised sediment types (e.g., shelly crusts or cohesive soils) is essential for avoiding unnecessary engineering measures.
References	Irvine J. et al., Framework for Evaluating Scour Risk and Optimising Scour Mitigation, XVIII European Conference on Soil Mechanics and Geotechnical Engineering (2024).

H.5 CASE STUDY 4: Impact of Seabed Levelling Within Sections of the Export Cable Route with Special Area Conservation (SAC) Status for the Norfolk Vanguard and Norfolk Boreas Offshore Wind Farm, UK (North Sea)

IMPACT OF SEABED LEVELLING WITHIN SECTIONS OF THE EXPORT CABLE ROUTE WITH SPECIAL AREA CONSERVATION (SAC) STATUS FOR THE NORFOLK VANGUARD AND NORFOLK BOREAS OFFSHORE WIND FARM, UK (NORTH SEA)	
Source	Developer (with permission D Lambkin, ABPmer)
Site	Norfolk Vanguard and Norfolk Boreas Offshore Wind Farm, UK
Project date	N/A
Illustration of	Sandwave clearance for cable lay activities
Cross reference to Chapter/text	Project development requirements (Section 4); Detailed Design (Section 4.5); Consenting; (Section 4.4); Construction (Section 4.6)
Keywords	Sandwaves, sweeping, cable burial, risk management
Description	**Problem Definition:** Stakeholders raised concerns that proposed seabed levelling along sections of the proposed export cable route within the Haisborough, Hammond and Winterton Special Area of Conservation adversely affect associated sandbank systems. (N.B., this requirement was project specific and does not represent a general requirement). **Approach:** A standalone study (ABPmer, (2018)) was undertaken to support the EIA, assessing the effects of sandwave levelling (also referred to as pre-sweeping) upon seabed mobility and specifically to address the following issues: • Potential effects on the local sandwave morphology and evolution. • Potential effects on the seabed morphology and sediment transport regime. • Potential effects or onward effects on the structure and function of the sandwaves and sandbanks within the Haisborough SAC, in relation to the conservation objectives. The study also provided an assessment on the fate of dredged sediments and the likely recoverability of the sandwaves. **Data Sources:** The study drew on the best available data to provide a description of the local morphological regime and, using existing evidence from comparable settings, to consider sandwave recoverability following disturbance. Existing publications, including regional CSM, and high-resolution bathymetry surveys were used to assess seabed mobility in the area of interest. In addition, metocean conditions, sediment samples, and geophysical surveys were used to support bed shear stress and sediment mobility calculations.

Example Figures

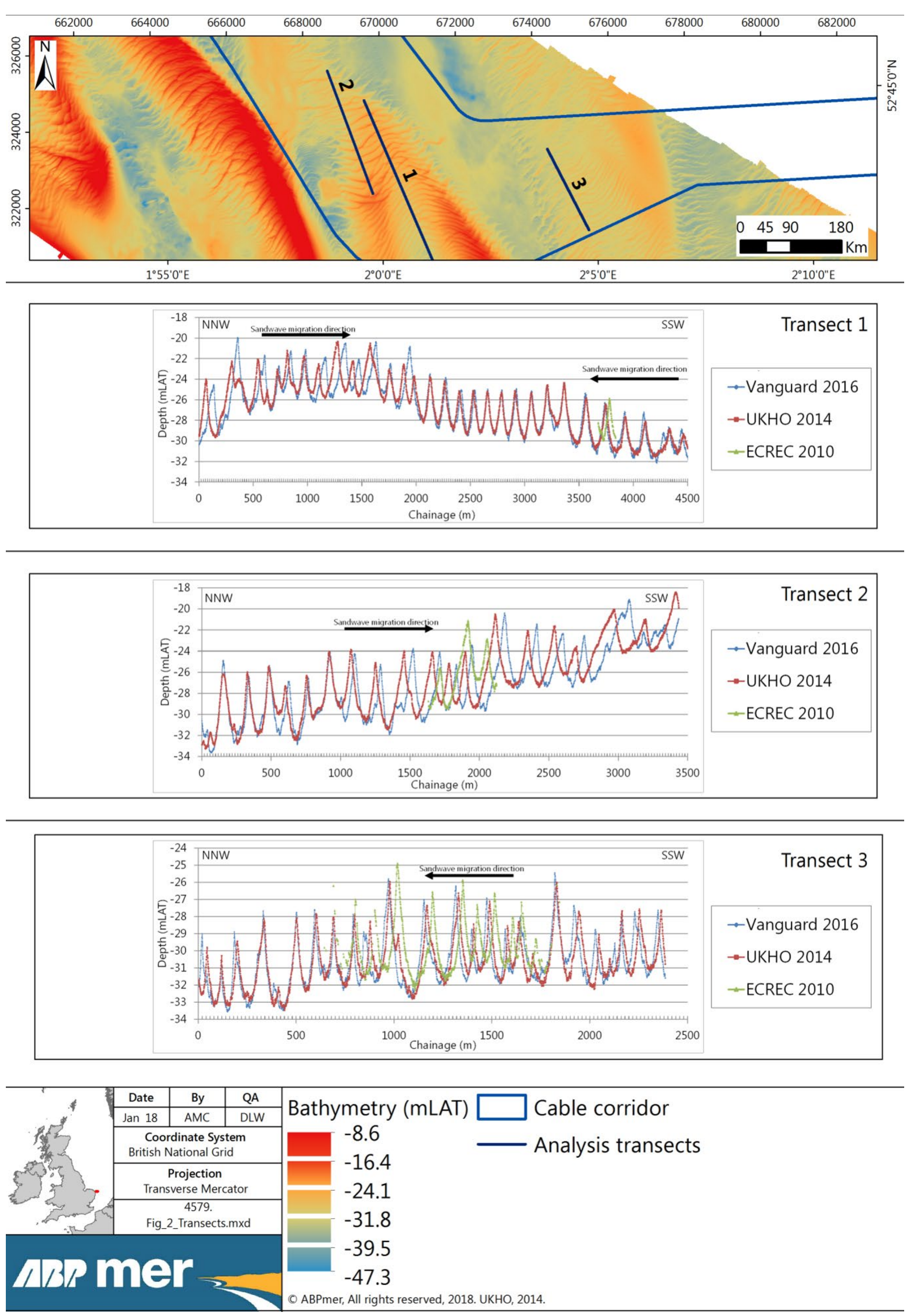


Figure 1 Analysis transects and assessed migration directions (ABPmer, (2018)).

APPENDIX H: CASE STUDIES
CONTINUED

Conclusions/ Recommendations

Key Takeaways:

- The standalone ABPmer (2018) study concluded that localised sandwave levelling within the Haisborough, Hammond and Winterton SAC would not impede long term sandwave form and function, with locally levelled bedforms expected to rebuild similar height and shape as part of the naturally ongoing processes of bedform evolution and migration through the affected area.
- Sediment dredged from sandwave crests is expected to remain within the existing sediment transport pathways of the SAC, ultimately re entering the same bedload regime due to strong, directional transport patterns and local recirculation processes.
- No significant onward effects were predicted on the wider sandbank systems or their functional geomorphology, indicating that pre sweeping, when localised and controlled, does not alter the form or behaviour of the sandwaves or sandbanks beyond the immediate works footprint.

Recommendations for Practice:

- Support EIA assessments in mobile sandbank systems with detailed geomorphological studies that combine high-resolution bathymetry, sediment transport evidence and regional CSM outputs to characterise natural mobility and recovery potential.
- Anticipate that regulators may impose post construction survey conditions, even where impacts are predicted to be negligible, and plan monitoring strategies that meet IHO S44 Order 1a standards within defined cable route and foundation corridors.
- Use system wide sediment transport evidence to communicate the expected fate of dredged material and the natural recovery of sandwaves, helping to address stakeholder concerns and reduce unnecessary conservatism in impact evaluations.

Lessons Learned:

- Even where technical studies provide clear evidence of limited morphological impact, uncertainties may persist for stakeholders and regulators, particularly in designated sites where precautionary approaches dominate.
- High-resolution bathymetry, sediment mobility analyses and evidence from comparable sandwave systems are essential for predicting recoverability and informing assessments in complex sandbank SACs.
- The behaviour of sandwaves following disturbance is strongly governed by regional sediment transport pathways rather than by the localised effects of dredging, underscoring the need to understand system scale processes before drawing conclusions.

References

ABPmer. (2018). Norfolk Vanguard and Norfolk Boreas export cable route: Sandwave bed levelling. ABPmer Report No. R.2920. Prepared for Royal HaskoningDHV.

H.6 CASE STUDY 5: Morphodynamics for Hollandse Kust (west) Wind Farm Zone

MORPHODYNAMICS FOR HOLLANDSE KUST (WEST) WIND FARM ZONE	
Source	RVO / Deltares (with permission RVO)
Site	Hollandse Kust (west) Wind Farm Zone, North Sea
Project date	2020
Illustration of	Sandwave migration and seabed level change prediction
Cross reference to Chapter/text	Project development requirements (Section 4); Detailed Design (Section 4.2); Construction (Section 4.6)
Keywords	Sandwaves, megaripples, LSBL/HSBL, BEB, migration rates, residual transport, scour risk, cable burial
Description	**Problem Definition:** Migrating sandwaves threaten cable integrity (exposure, free spans, overheating) and foundation performance (reduced embedment support, scour protection stability, modal changes). Given full sandwave coverage and strong spatial variability at HKW, reliable predictions of future lowest/highest seabed levels are required for routeing, burial design, jack-up planning and pile/scour design. **Approach:** Data-driven analysis of 36 bathymetric surveys (1991–2019) with composite bathymetries at 5×5 m resolution; quality control and vertical referencing; bedform separation to obtain large-scale, sandwave and megaripple fields. Sandwave migration direction and rate derived via 2D cross-correlation across multiple survey pairs; sandwave heights/lengths from Fourier analysis along ~37k crest transects. Hydrodynamic (DCSM-FM refined to ~50 m) sediment-transport modelling (spring–neap) validated against buoy data to corroborate tide-dominated residual transport patterns. Future/historic bathymetries constructed by iteratively shifting the sandwave field along local mean ±σ directions and rates; LSBL/HSBL formed as lower/upper envelopes, with uncertainty contributions for survey accuracy, finite grid, shape-retention and megaripple variability. **Data Sources:** Long-term bathymetric surveys (at least 20-year coverage), morphodynamic modelling predicting seabed changes for 2018-2019 to 2059, hydrodynamic and sediment transport modelling, geological data for substrate characterisation.

Example Figures

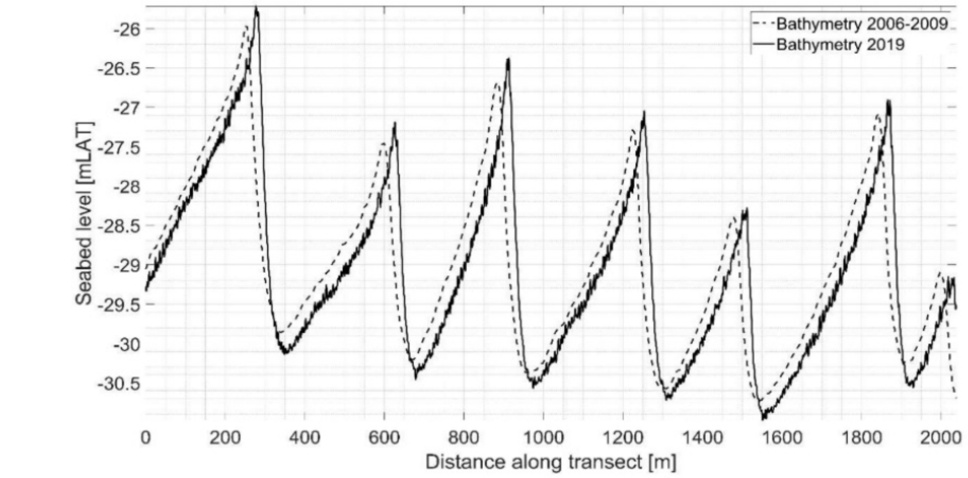


Figure 3.2 Example of seabed levels along a transect in HKW for the period 2006-2009 (dashed line) and 2019 (solid line). Location of the transect is indicated in Figure 3.1. Transect is drawn from south-southwest (left) to north-northeast (right).

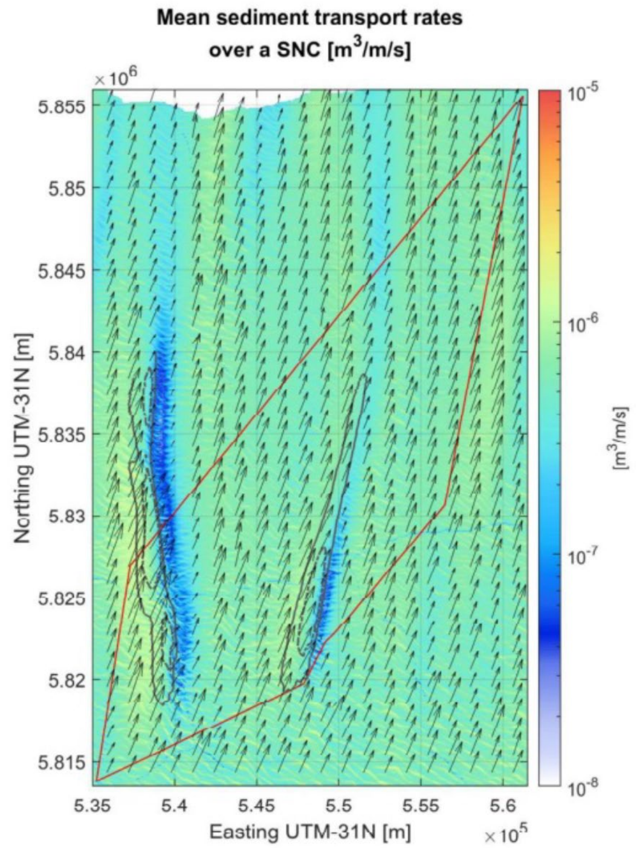


Figure 3.25 Net sediment transport rates magnitudes (colour coded) and direction (vectors), derived by averaging the directions and transport rates over 1 spring-neap cycle. Two contour levels are locally marked (-26 m MSL- grey continuous line and -24 m MSL- grey dotted line) indicating the location of sandbanks.

Example Figures (continued)

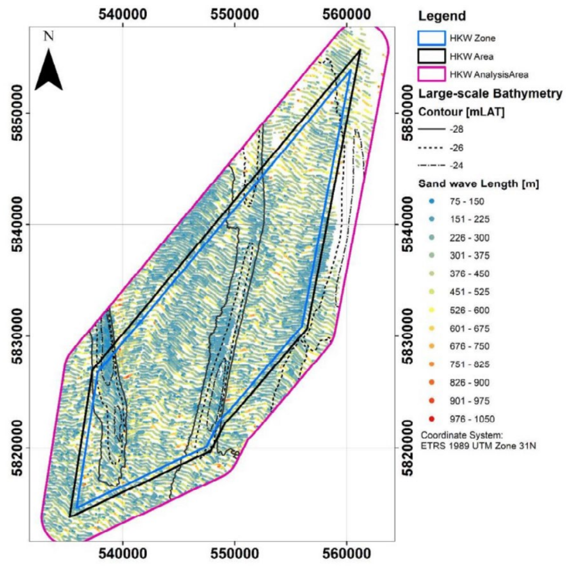


Figure 4.10 Spatial distribution of the mean sandwave length for HKW, based on the 2018-2019 and 2014- 2015 bathymetry. Contour lines indicate locations of sandbanks.

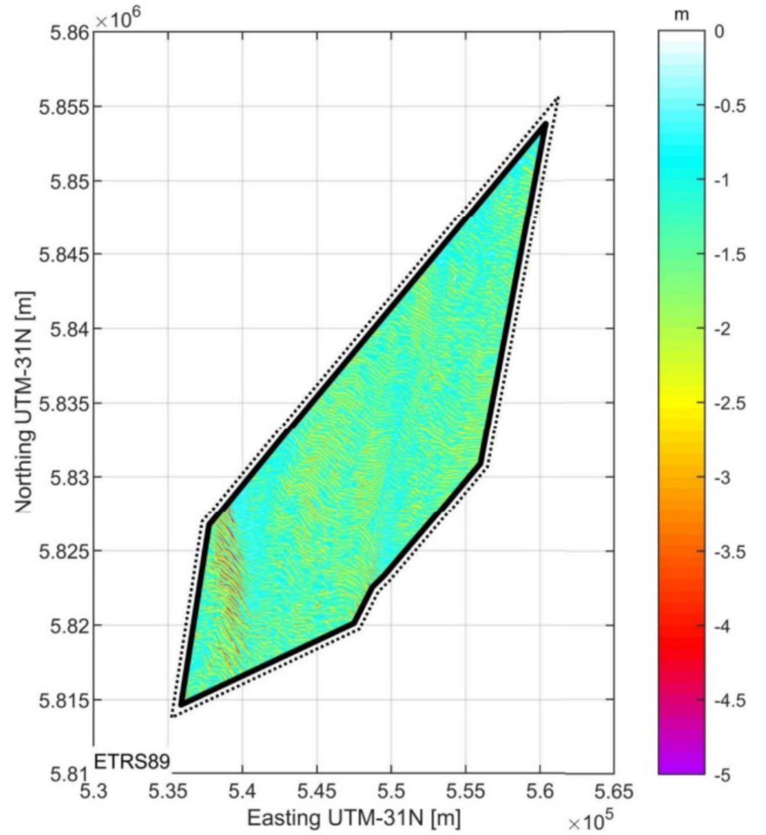


Figure 5.7 The maximum predicted seabed lowering being the difference between the 2018-2019 bathymetry and the LSBL.

APPENDIX H: CASE STUDIES
CONTINUED

Example Figures (continued)

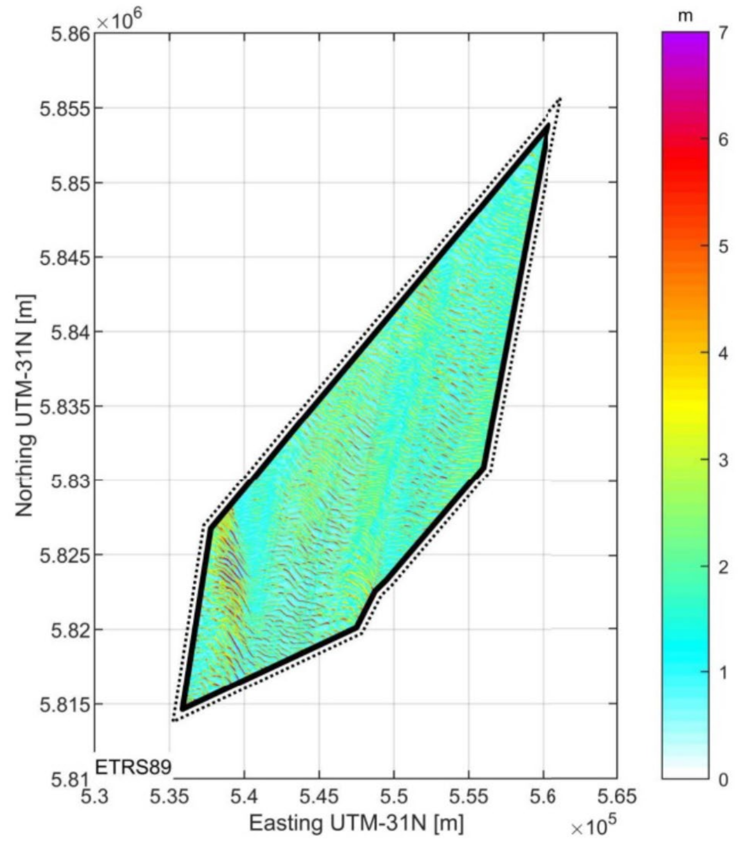


Figure 5.10 The maximum predicted seabed rise being the difference between the 2018-2019 bathymetry and the HSBL.

Conclusions/ Recommendations	**Key Takeaways:** • Sandwave migration: predominantly N–NE (mean ~14°N), typical rates 1.0–3.9 m/yr; local extremes up to ~7 m/yr near bank crests. • Sandwave dimensions: heights 1.4–4.8 m; lengths 160–540 m; higher in south/west, shorter on bank crests. • Large-scale seabed: effectively static over ~25 years (vertical trends within ±0.05–0.10 m/yr colourbars). • Residual transport: coherent N–NE (~20°N), magnitudes modulated by sandbanks (higher on crests, reduced on lee slopes). • Megaripples: crest heights typically 0–0.4 m (troughs 0 to −0.3 m); pronounced seasonal/spatial variability—represent with +0.15/−0.10 m uncertainty. • Future envelopes (2019–2059): 99% non-exceedance seabed lowering up to about −3.2 m (LSBL) and rise up to about +5.3 m (HSBL); local maxima shown of ~−6.7 m lowering and ~+8.6 m rise at crests/troughs respectively (site-wide extremes). **Recommendations for Best Practice:** • Use LSBL at installation year as the design datum for foundations and for cable burial depth setting; avoid locations with large predicted lowering. • Route cables to minimise crossing steep sandwave flanks and western bank crests where migration and gradients peak; consider vertical/horizontal routing optimisation. • Include quantified uncertainty allowances: survey (±0.10 m), finite grid (+0.10/−0.05 m), megaripple (+0.15/−0.10 m), sandwave shape at crests (±0.25 m). • Plan monitoring (e.g., 3–5 year intervals) to validate predictions and trigger adaptive management (re-burial/repair). **Lessons Learned:** • Long term, high-resolution bathymetry is critical in fully sandwave dominated areas. Multi decadal datasets are required to robustly characterise migration rates, directions and extremes, which cannot be inferred from short monitoring periods. • Morphological scale separation improves predictability and design usefulness. Isolating large scale seabed trends from sandwaves and megaripples enables construction of defensible LSBL/HSBL envelopes directly applicable to cable, foundation and jack up design. • Combining empirical bathymetric analysis with hydrodynamic modelling increases confidence. Cross validation of observed sandwave migration with tide dominated transport modelling, alongside explicit uncertainty treatment, is essential for reliable future seabed projections.
References	Deltares (2020). Morphodynamics for Hollandse Kust (west) Wind Farm Zone. RVO.

H.7 CASE STUDY 6: Morphodynamics for Nederwiek Wind Farm Zone

MORPHODYNAMICS FOR NEDERWIEK WIND FARM ZONE	
Source	RVO / Svašek Hydraulics (with permission RVO)
Site	Nederwiek Wind Farm Sites I–III, Dutch North Sea
Project date	2024–2025
Illustration of	Sandbank dynamics, sandwave migration, megaripple behaviour, and predicted seabed level evolution (2023–2073)
Cross reference to Chapter/text	Project development requirements (Section 4); Detailed Design (Section 4.2); Construction (Section 4.6)
Keywords	Sandbanks, sandwaves, megaripples, morphodynamics, sediment transport, seabed mobility, UXO depth, NW-I, NW-II/III
Description	**Problem Definition:** Developers require robust predictions of seabed variability over a 50-year design life. NW-I exhibits migrating sandwaves (1–3 m high; 200–400 m wavelengths; 1–3 m/yr migration), posing risks of: (i) foundation exposure or loss of lateral support; (ii) cable free-spans; (iii) additional burial requirements; (iv) enhanced scour. NW-II/III lacks sandwaves but contains megaripples (0.06–0.11 m) and slowly migrating sandbanks. While mobility is lower, megaripples still repeatedly pass infrastructure, influencing as-laid cable burial and post-lay stability. **Approach:** The study integrates multi-epoch bathymetry (2003/2005 vs. 2023/2024), sediment cores, geological models, and 43 years of hydrodynamic modelling. Sandwave migration rates were derived using three methods—PSTP, SCC and Fourier-based crest tracking—to reduce uncertainty. Megaripple heights were validated using repeat MBES track analysis. Future seabed levels (BEB, LSBL, HSBL) were predicted for 2023–2073 by translating mobile bedforms forward according to spatially varying migration rate/direction fields and applying uncertainty bands (bathymetry TVU/THU, grid resolution, sandwave reshaping, and megaripple envelope). **Data Sources:** Long-term bathymetric surveys (at least 20-year coverage), morphodynamic modelling predicting seabed changes for 2016–2051, hydrodynamic and sediment transport modelling, geological data for substrate characterisation.

Example Figures

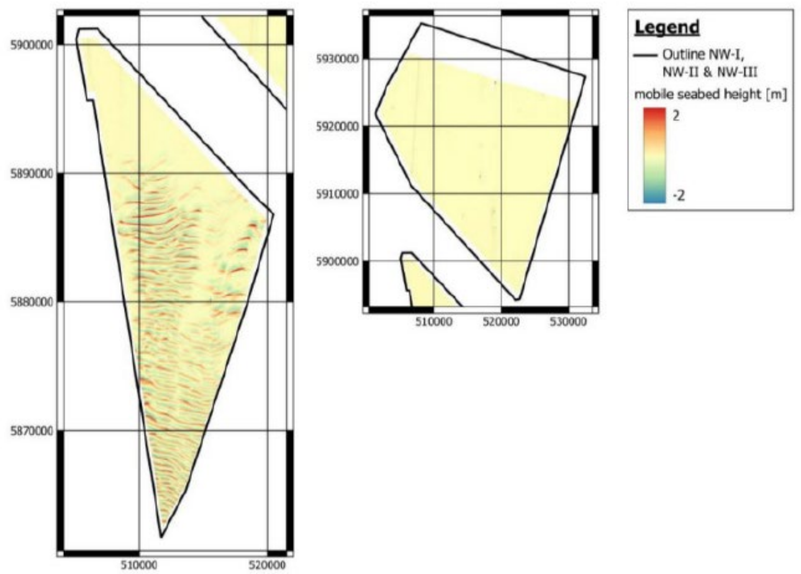


Figure 2 Mobile seabed NW-I (left panel) and NW-II/III site (right panel). The mobile seabed consists of the sandwaves and megaripples only.

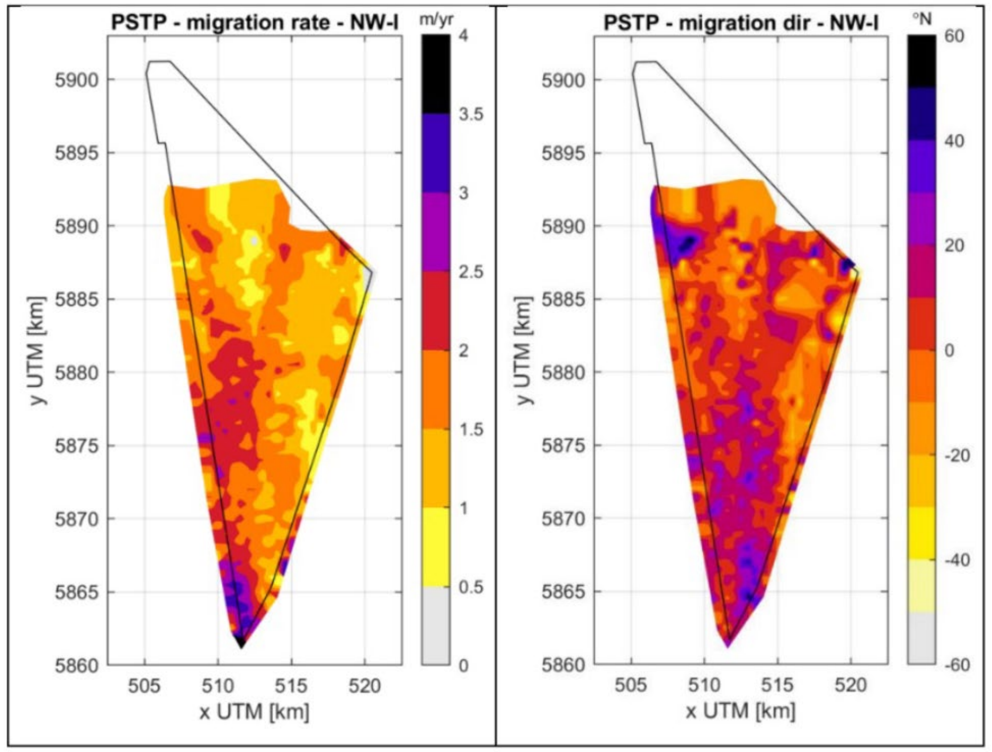


Figure 8-2 The sandwave migration rate (left panel) and migration direction (right panel) on the 20x20m grid.

Example Figures (continued)

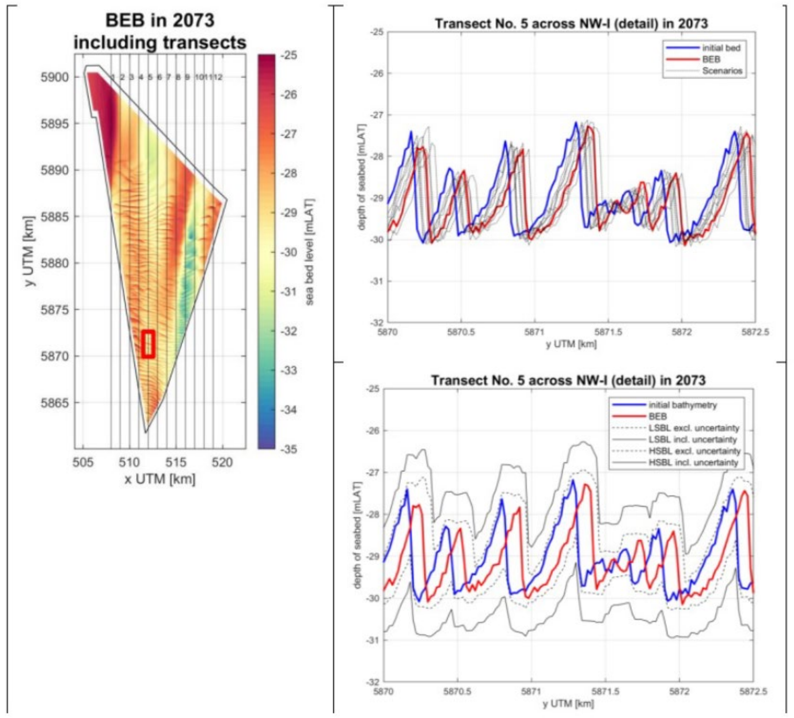


Figure 8-13 Left panel: Overview of transects across NW-I. Right panel: at the top, the results of all nine scenarios are shown with the initial bed (blue) and the BEB (red) highlighted; at the bottom, the BEB, LSBL, and HSBL, including and excluding the uncertainty band.

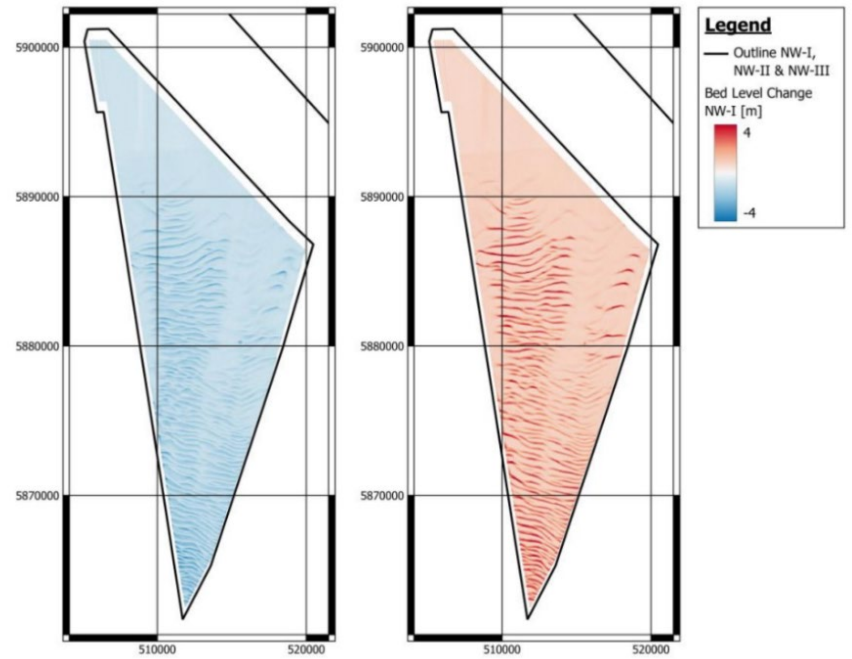


Figure 8-14 Spatial plots of the changes in bed level between the most recent bathymetry and the LSBL (left) and HSBL (right) between 2023 - 2073, including uncertainties.

Conclusions/ Recommendations	**Key Takeaways:** • NW I is highly dynamic with sandwave driven seabed level changes between −3.68 m and +3.95 m (including uncertainties). • NW II/III shows limited mobility, with predicted changes constrained to −0.42 m to +0.41 m. • Sandwave migration direction aligns with residual NNE transport; megaripples exhibit rapid but small scale oscillations. • UXO backward modelling suggests possible burial depths of −4.1 m (NW I) and −0.42 m (NW II/III) relative to modern seabed. **Recommendations for Best Practice:** • NW I requires careful assessment of turbine foundation embedment depth, scour protection triggers, and minimum cable burial depth design. • NW II/III presents lower mobility but megaripple envelopes must be incorporated into burial risk models. • A 2 SD uncertainty band should be applied to all seabed level change predictions. • Future surveys should prioritise high-resolution MBES refresh of NW I at 3–5 year intervals, particularly before installation phases. **Lessons Learned:** • Seabed mobility and associated engineering risk vary strongly across sub zones. NW I is highly dynamic due to migrating sandwaves, requiring explicit LSBL/HSBL forecasting over the full design life, whereas in NW II/III mobility is lower and dominated by megaripples and slow sandbank migration with more limited seabed level change. • Using multiple, independent migration tracking methods reduces uncertainty. Combining PSTP, SCC and Fourier based crest tracking provides more robust estimates of sandwave migration rates and directions, improving confidence in future seabed level envelopes for foundation and cable design. • Forward translation of bedforms with explicit uncertainty bands is an effective design tool. Predicting BEB, LSBL and HSBL by migrating observed bedforms and applying quantified uncertainties (survey accuracy, gridding, reshaping and megaripples) delivers design relevant seabed envelopes applicable to turbines, cables and UXO burial assessments.
References	Svašek Hydraulics (2024). Morphodynamics for Nederwiek Wind Farm Zone. RVO.

APPENDIX I: SEABED LIQUEFACTION

CONTENTS

I.1 SEABED LIQUEFACTION

I.1.1 INTRODUCTION TO LIQUEFACTION

Liquefaction is a term used to describe the phenomena in which the strength and stiffness of soil is lost fully or partially for a limited duration. The field of liquefaction is highly complex and is still a very active research topic. Thus, the detailed insight of liquefaction is beyond the scope of this appendix.

Soil liquefaction can occur due to the following processes:

a) A period of cyclic shear stresses induced on the soil exceeds a critical value such that the generated excess pore pressures which reduces the vertical effective stress in situ soil to almost zero. This occurs either due to dynamic loading (such as earthquake or vibratory loading) or wave-induced loading in seabed.

b) High upwards water flow (due to high hydraulic gradient) reduces the in situ vertical effective stress of the soil to almost zero. This is often known as 'liquefaction by fluidisation'.

Earthquake induced liquefaction can trigger a soil mass flow or submarine landslides even in gentle seabed slopes. This could lead to change in seabed level in large regions affected by the soil flow. The impact of this could lead to several metres of seabed change. Wave induced liquefaction, however, is likely to be limited to areas where the seabed soil was disturbed recently and this is likely to be in trench backfill etc. and seabed level change within the trench etc. could be small in the order of few centimetres to decimetres.

I.1.2 IMPACT OF SOIL LIQUEFACTION

Seabed stability is an important consideration for offshore assets such as foundations and cables. When seabed soil liquefies, the strength and stiffness of the seabed reduces considerably for a short duration. This can impact the seabed level, affect foundations and also affect both buried and surface cables, especially where there is a seabed gradient which may promote down-slope flow of the disturbed sediment slurry. Thus, seabed liquefaction needs to be considered during the design. If the offshore asset is in the region which is prone to seabed liquefaction, and the seabed has topographic variation, the consideration needs to be given to impact of seabed liquefaction on offshore assets.

Although liquefaction arises due to fundamentally different hydraulic processes at the seabed compared to horizontal shear, the process can nonetheless be treated in the same manner and using the same framework (Section 3 – Figure 1). Indeed, for projects determined to be in seismically active areas of the world, consideration of soil liquefaction risks should be assessed in tandem with wave/current-induced risks.

Records of seismic activity / earthquakes should be considered early in the site selection process with reference to suitable databases. A useful resource for an initial appraisal of earthquake risk is Interactive Earthquake Browser (**Figure I.1**) which provides global coverage of earthquake occurrences from 1970 to the present day.

These types of tools can be used to screen if an offshore site has low or high seismic risk, noting there is presently some uncertainty on the minimum magnitude of earthquake which might lead to liquefaction offshore (N.B. on land the minimum magnitude is typically regarded to be around magnitude 5 on the Richter scale) (USGS, 1985).

Depending on the seismic risk, a simplified liquefaction assessment (low risk situation) or a detailed liquefaction assessment (high risk situation) could be undertaken as part of an overall seabed mobility risk assessment. For sites across the north-west part of the European Continental Shelf the risk is effectively nil, and no assessment would be required in such locations.

I.1.3 HOW TO ASSESS SOIL LIQUEFACTION

I.1.3.1 Earthquake-induced soil liquefaction

Liquefaction potential of a site should be undertaken by a technical specialist and can be assessed by different methodologies. The degree of accuracy and reliability of the assessment depends on the methodology and the available input data.

For assessing liquefaction potential of a seabed site, knowledge is required of:

- The site soil type and its properties from seabed to bedrock.
- The magnitude earthquake signal at the bedrock level.

Liquefaction potential assessment can be assessed either by simplified methods or numerical methods (**Figure I.2**). Guidance within the publication of Anastasios et al. (2026) is considered across industry as state-of-the-art at the time of publication of this document.

Figure I.1 – Global coverage of past earthquakes (source: Interactive Earthquake Browser, credit: EarthScope Consortium).

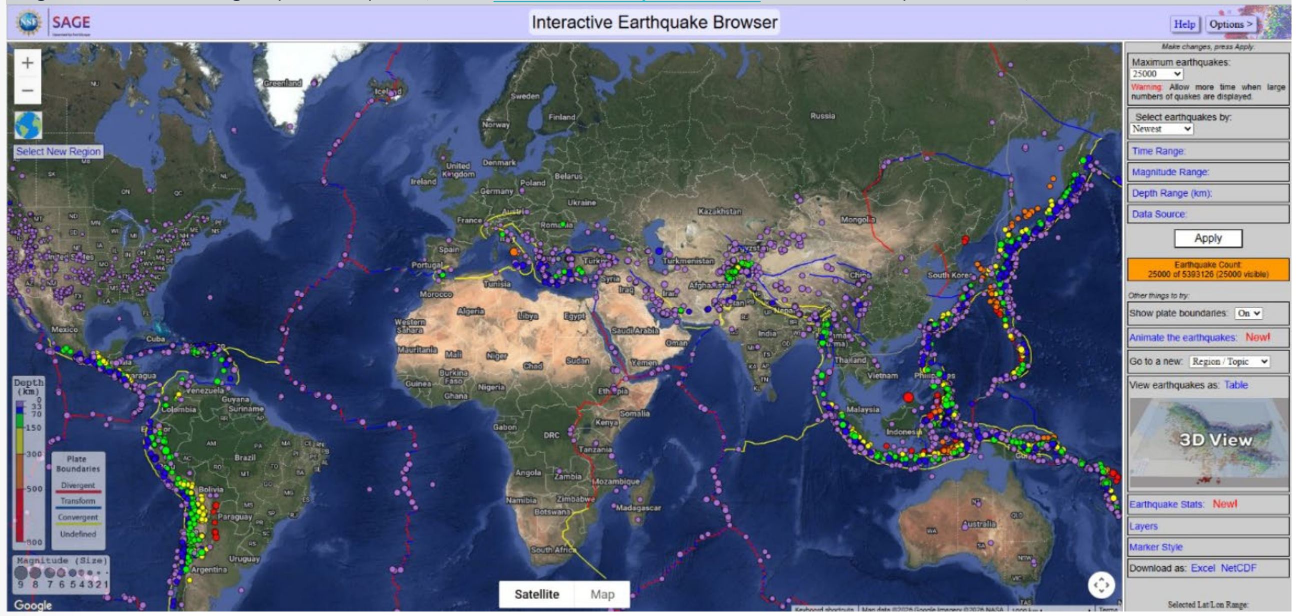
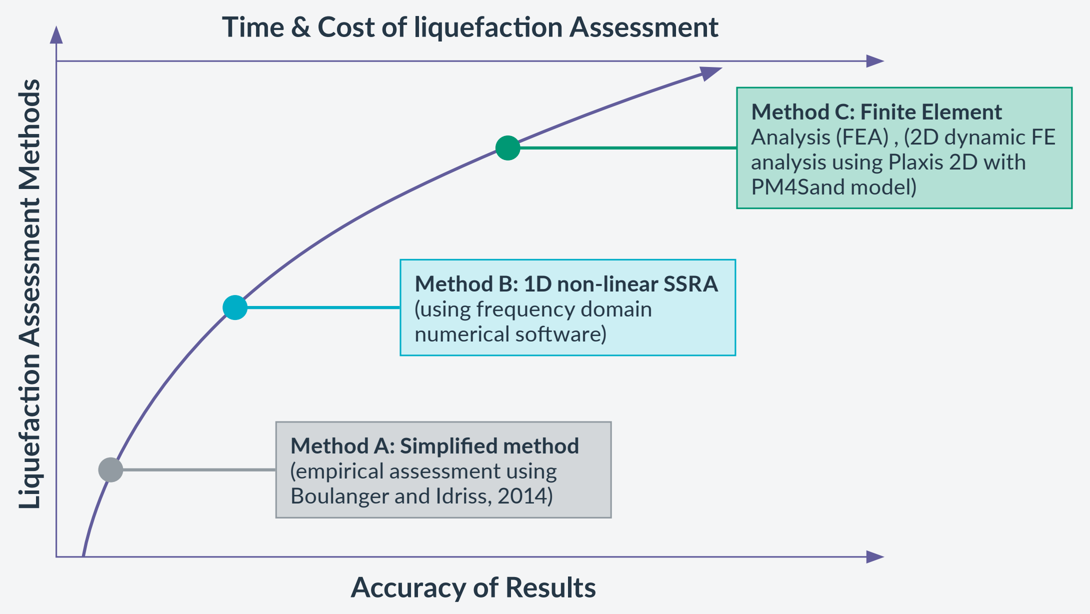


Figure I.2 – Methods for assessing liquefaction potential and their accuracy (Anastasios et al. (2026)).



Simplified methods use semi-empirical equations obtained with historical soil liquefaction data to predict if a site is susceptible to soil liquefaction. In numerical methods, the soil is modelled with an appropriate constitutive model which is able to predict the soil behaviour under seismic loading during a site response analysis. The main benefit of this method is that pore pressure generation during shaking can be traced. However, substantial laboratory testing is needed to obtain the input parameters required, thus this method is mainly used when detailed assessment is needed for projects.

I.1.3.2 Wave-induced soil liquefaction

Wave-induced soil liquefaction is a process that relates to already disturbed soils at the seabed, such as found in trenches which have been infilled. Whilst liquefaction of the surrounding, undisturbed soils is generally unlikely for most shelf sea situations, trenches that have been infilled with soil typically have a lower bulk density, and under certain (energetic) wave conditions cyclic shear stresses can develop on the seabed and when these induced stresses exceed a critical value the seabed soil can liquefy. Where tidal currents may be running, lateral transport of soil may occur leading to bed level change.

The depth to which this wave-induced liquefaction extends depends on the wave characteristics and the relative density of the soil. **Figure I.3** shows a schematic diagram of the seabed liquefaction region. The region most susceptible to liquefaction is the seabed where the wave breaks (waves break when wave steepness, H/L > 1/7 or due to depth limitations when H > d/1.28; where H = wave height, L = wavelength, d = water depth).

Wave-induced liquefaction can be assessed based on the methodology proposed by Ishihara & Yamazaki (1984). The analysis assumes that a train of harmonic waves are travelling over the sloping seafloor in water of decreasing depth from deepwater location towards the shore, the further assumption is that the seabed soil is uniformly deposited in the seabed throughout the depth and through the distance of the wave travel. The wave-induced cyclic shear stresses on the seabed are schematically shown in **Figure I.3**. The procedure to evaluate the seabed liquefaction is also schematically shown in **Figure I.4**. Relative density of the soil is presented by D_r.

Figure I.3 – Wave-induced seabed liquefaction mechanism (For further details refer to Thusyanthan et al. (2018)).

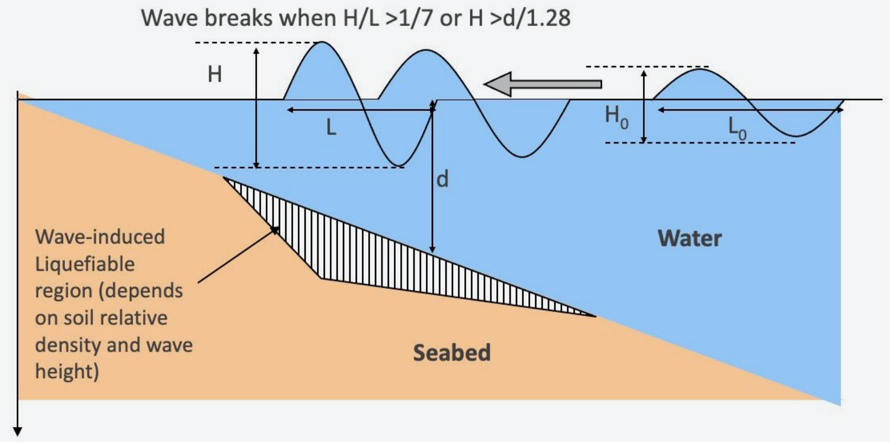
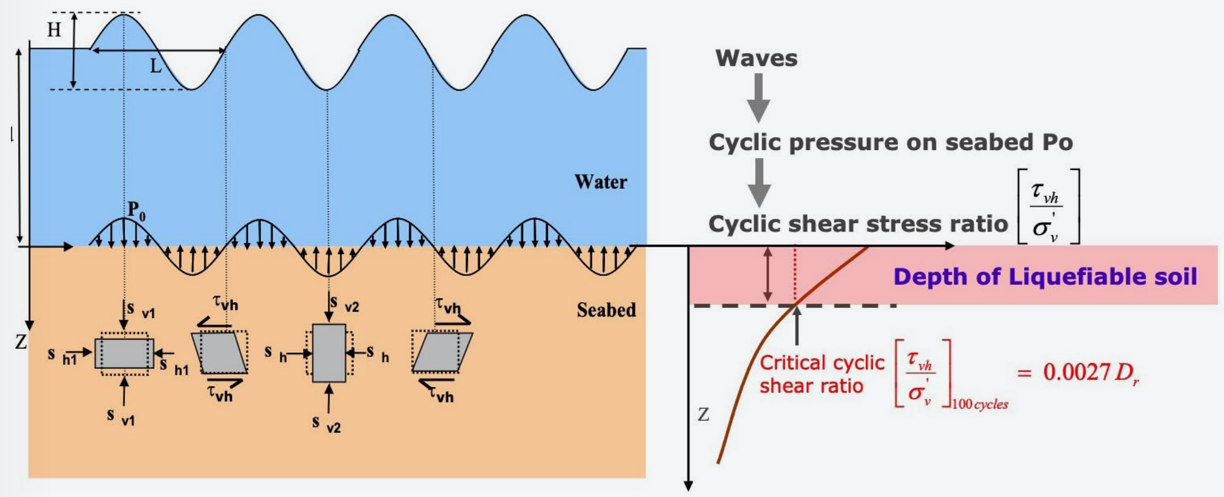


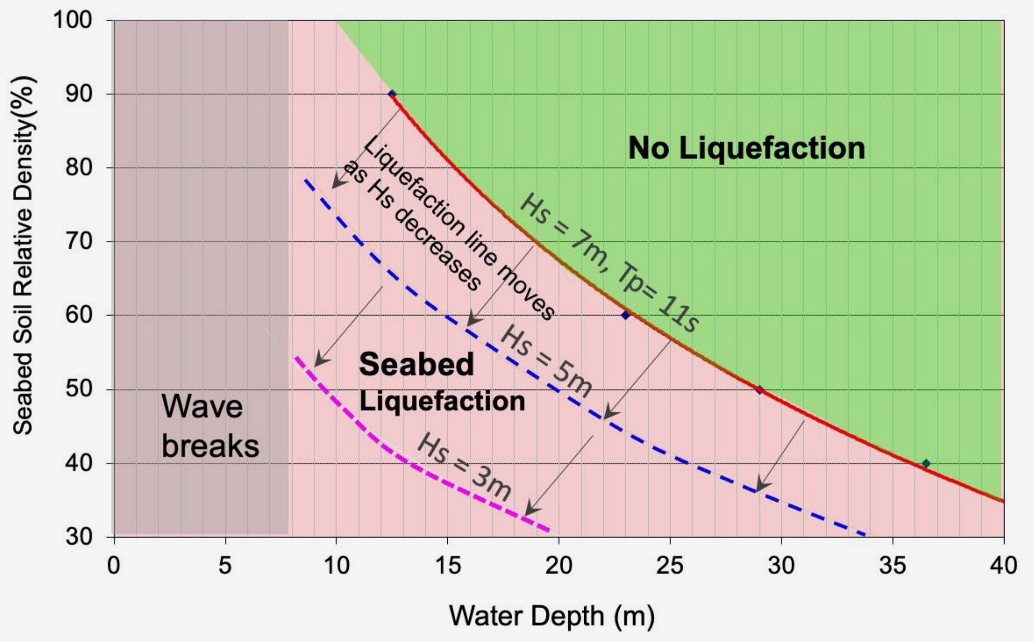
Figure I.4 – (a) Wave-induced cyclic shear stresses, (b) Liquefaction assessment procedure (Thusyanthan et al. (2018)).



In order to provide a design guideline on wave-induced liquefaction, a parametric study was undertaken with significant wave height H_s as 7, 5 and 3 m. The analysis was carried out assuming the seabed sand to be formed of silica sand. The results of the analyses are summarised in **Figure I.5**.

The figure shows seabed liquefaction initiation line for H_s = 7 m, above which no liquefaction will occur for the given wave condition. This line represents the stage at which the seabed is just about to liquefy. If the relative density (D_r) of the seabed is lower than this limiting value, then a thicker layer of the seabed soil will liquefy. If the significant wave height H_s is reduced to 5 m, the limiting line moves down as shown in the figure. While the exact values may vary depending on the seabed sand properties, the results demonstrate the susceptibility of the seabed to wave-induced liquefaction in water depths 10 - 45 m for sandy seabed with significant wave height varying from 3 to 7 m. Therefore, any on-bottom stability assessment of cables and pipelines in sandy seabed in shallow regions would need to first evaluate the seabed liquefaction wave-induced susceptibility. When the seabed liquefies, any buried cable with specific gravity less[1] would tend to float and any seabed laid cable with specific gravity more than 1.7 would sink into the liquefied soils.

Figure I.5 – Wave indued seabed susceptibility (Thusyanthan et al. (2018)).



1. SG of 1.7 is typically acceptable; the aim is to ensure that the cable SG is slightly greater than the soil slurry and so soil testing to obtain the SG of the slurry is recommended.

APPENDIX I: SEABED LIQUEFACTION
CONTINUED

I.2 REFERENCES

Anastasios Batilas, Efstathia Chioti and Indrasenan Thusyanthan (2026). Extent of liquefiable layers: Simplified vs. Numerical methods, Proceedings of the 21st International Conference on Soil Mechanics and Geotechnical Engineering, Vienna 2026.

Boulanger, R.W. and Idriss, I.M. (2016). CPT-Based Liquefaction Triggering Procedure. J. Geotech. Geoenviron. Eng., 142(2).

Ishihara K. and Yamazaki A. (1984). Analysis of Wave-Induced Liquefaction in Seabed Deposits of Sand. Soils and Foundations, Volume 24, Issue 3. Pages 85-100.

Thusyanthan, N.I. and Jegandan, S. (2018). Insight into pipeline on-bottom stability, DNV RP F109 and DNVGL RP F114. Offshore Technology Conference OTC 2018, Houston, USA.

CATAPULT
Offshore Renewable Energy

CONTACT US

info@ore.catapult.org.uk
ore.catapult.org.uk

ENGAGE WITH US

GLASGOW

ORE Catapult
Inovo
121 George Street
Glasgow
G1 1RD

+44 (0)333 004 1400

PEMBROKESHIRE

Marine Energy Engineering
Centre of Excellence (MEECE)
Bridge Innovation Centre
Pembrokeshire Science
& Technology Park
Pembroke Dock, Wales
SA72 6UN

+44 (0)333 004 1400

ABERDEEN

Floating Wind Innovation
Centre (FLOWIC)
ORE Catapult
W-Zero-1
Energy Transition Zone
Altens Industrial Estate
Hareness Road
Aberdeen
AB12 3LE

CORNWALL

Hayle Marine Renewables
Business Park
North Quay
Hayle, Cornwall
TR27 4DD

+44 (0)1872 322 119

GRIMSBY

O&M Centre of Excellence
ORE Catapult, Port Office
Cleethorpe Road
Grimsby
DN31 3LL

+44 (0)333 004 1400

BLYTH

National Renewable
Energy Centre
Offshore House
Albert Street, Blyth
Northumberland
NE24 1LZ

+44 (0)1670 359555

LEVENMOUTH

Levenmouth Demonstration
Turbine
Ajax Way
Leven
KY8 3RS

+44 (0)1670 357649

LOWESTOFT

OrbisEnergy
Wilde Street
Lowestoft
Suffolk
NR32 1XH

+44 (0)1502 563368