Contract AE0262

Scroby Sands Offshore Wind Farm –

Coastal Processes Monitoring.

Final Report for the Department of Trade and Industry

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AE0262 - Executive Summary

Issue

Over the last decade, the development of Offshore Wind Farms (OWF) has received significant attention. In March 2002, a FEPA licence was granted for the development of the first UK OWF, within coastal waters, at Scroby Sands, Great Yarmouth, Norfolk. This site was regarded at the time as the worst-case scenario in terms of potential impacts on coastal processes, involving the emplacement of 30 turbines situated upon monopile foundations 4.2 m in diameter in an environment with fast tidal currents and mobile bed sediments. During this licensing process, two environmental issues arose of major potential importance to the development of the adjacent inshore region, namely:

a) the potential for the OWF to cause wave focussing on parts of the adjacent coastline (studied in the Defra-funded project AE1227), and;
b) the potential for the OWF to alter sediment transport and consequently affect the stability of large-scale coastal geomorphic features, such as the sandbanks themselves and the associated channels.

This project performed research to investigate the latter issue, of sediment transport and sandbank stability.

Work performed

A programme of research and monitoring was undertaken at the Scroby Sands OWF, to observe, measure and quantify potential impacts of OWFs on coastal processes. This was achieved by a series of seabed surveys (side-scan sonar, swathe bathymetry) and deployment of seabed landers (Cefas 'MiniLanders') before, during and after construction of the OWF. These have been used to provide evidence of changes in seabed bathymetry, bedforms, currents, waves and suspended sediment concentrations that may lead to disturbance of sedimentary environments or sediment transport pathways.

Generic framework for regulators and developers

One of the main aims of this work was to assist in the creation of a generic framework for use by both regulators and developers in assessing coastal processes issues within the EIA process and relating to any consequent FEPA licence conditions, particularly those related to monitoring.

a) The EIA process

Regulators and developers need to understand the coastal processes at a site and to quantify the relevant processes. To support this, they need:

i. Time-series of swathe bathymetric surveys over the whole site and any export cables. This should also be placed into the historic context, using analysis of historical charts;
ii. Shear-stress exceedance diagrams for key locations within the OWF and along the export cable route;

iii. Particle-size information for sediments from representative locations within the OWF and along export cable routes. Alternatively, particle settling velocities would suffice;
iv. Estimation of the size and shape of scour pits and wakes and the nature of any emplaced scour protection;
v. Estimation of the disturbance caused by the construction of the wind farm, caused by, for example, jetting, ploughing, 'grouting in' or from seabed levelling for gravity-based structures;
vi. Assessment of sub-bottom geophysical acoustic data, which may allow identification of historic directions of sediment transport.

b) Monitoring Strategies

During construction and operation of OWFs, the following monitoring strategies are proposed to be best practice:

i. In locations where sediment is expected to be in transport for significant periods of time, a comprehensive swathe bathymetric survey should be undertaken (ideally a time-series of surveys) which will allow an analysis of sediment transport processes over the bank. Based on bi-annual seasonally linked surveys, these permit quantification of some key aspects of the sediment transport budget, identification of net sediment transport pathways and any potential areas of net erosion or accumulation;
ii. In regions where sediment transport is expected to be generally weak, a selection of representative scour pits should be monitored, and if found to exceed predictions made in the EIA, then a more systematic swathe survey would be undertaken across the area, to be repeated at appropriate intervals;
iii. High-resolution swathe bathymetry surveys of scour pits and associated scour protection measures should be undertaken to identify the extent, volume and integrity of any scour protection used. This would also allow monitoring of any secondary scour pits caused by the scour protection;
iv. Regular swathe bathymetric surveys of the export cable route to check for any cable free-spans (compromise of the cable), exposure (risk to shipping/fishing) or movement from the desired location;
v. During pile-driving, grouting or cabling operations, suspended-sediment monitoring may be required, especially if the surface sediments or the immediate subsurface has a high proportion of easily resuspendable grains (e.g. in chalk), have elevated levels of contaminants or the operations take place near a conservation site (e.g. eelgrass beds, *Zostera marina*) or within a Special Area of Conservation (SAC).

Scroby OWF - Recommendations

We recommend that:

- FEPA licence conditions are emplaced to require that swathe bathymetry surveys are undertaken at six-monthly intervals to provide further evidence of the longer-term dynamics of scour pits and wakes, scour protection and wider-scale changes in bed elevation and patterns of net sediment transport. This data will allow an assessment of the equilibrium of the scour pits across the whole of Scroby Bank. Similarly, longer-term time series of digital elevation models will allow assessment of any changes in the overall bed elevations of Scroby Bank, particularly any creation of cross-bank channels. Swathe bathymetry provides the primary basis to monitor changes in geomorphology and thus is an essential tool for FEPA monitoring. Existing FEPA licence conditions were justified in this instance.

Generic Recommendations

We recommend that:

(a) The design and placement of scour protection in future OWF construction should be considered in more detail, because poorly designed scour protection can lead to secondary scour effects;

(b) Swathe bathymetry surveys should be required as a standard method of monitoring OWFs (and other activities impacting on the seabed, such as port construction, aggregate extraction and disposals of dredged materials) because such surveys provide robust data with which to calculate the volumes of material disturbed and assess the interactions with coastal processes;

(c) Work should be undertaken to assess the magnitude and nature of the impacts on coastal processes of other types of wind-farm foundations (i.e. apart from monopiles) as well as of the structures associated with other energy-extracting devices in the 'wet renewables' sector (e.g. tidal and wave devices). Understanding of the impacts of monopile-based OWFs is improving. However, future OWFs may use a combination of hybrid or tripod structures and/or larger gravity-based structures (GBS). Further work is required to assess the magnitude and nature of the impacts of these structures on coastal processes. Similarly, the impact of fixed or moving structures for other wet renewables is also poorly known and needs to be assessed;

Summary of Impacts

Scale (m)	Type of Impact	Significant Impact?
0 – 100	Scour Pits	Yes, as predicted by EIA
100 – 1000	Scour Wakes	Not significant wrt total bank volume change
> 1000	Sandbank Morphology	No evidence

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GLOSSARY AND ACRONYMS

ACM	Acoustic Current Meter (Falmouth Scientific Inc.)
ADCP	Acoustic Doppler Current Profiler (RDI)
ADP	Acoustic Doppler Profiler (Nortek)
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CPA	Coast Protection Act, 1949
CTD	Conductivity, Temperature and Depth
DEM, DTM	Digital Elevation Model or Digital Terrain Model
EIA	Environment Impact Assessment – part of the Environmental Statement
FSI	Falmouth Scientific Instruments
FEPA	Food and Environment Protection Act II, 1985
FTU	Formazin Turbidity Unit
GBS	Gravity-Based Structure
OBS	Optical Backscatter Sensor – used to measure silts in suspension
OWF	Offshore Wind Farm
PSA	Particle Size Analysis
SAC	Special Area of Conservation

1.0 Background

The UK Government promotes electricity production from renewable sources, with a target to increase production from this source to 10% by the year 2010, and 20% by 2020. The development of Offshore Wind Farms (OWF) has consequently received significant attention, and a decision was made in March 2002 to grant a FEPA licence to developers of an offshore wind farm within coastal waters, on Scroby Sands, off Great Yarmouth. However, during the licensing process, two environmental issues arose of major potential importance to the adjacent inshore region, namely the potential for the OWF to cause wave focussing on the adjacent coastline (studied in the project AE1227), and for the OWF to alter sediment transport and consequently affect the stability of large-scale coastal geomorphic features, such as the sandbanks themselves and the associated channels. This project details research to resolve the latter issue, of sediment transport and sandbank stability.

Within this project and the related Defra-funded project AE1227, there were insufficient funds to monitor sediment and wave conditions at even a small number of the proposed OWFs. Therefore, a single site was chosen, in which to concentrate resources and effort. The selection of the Scroby OWF site was supported by the findings of the ABPmer/ETSU report (ABPmer, 2002) which, in terms of potential impacts on coastal processes, had identified Scroby Sands as the worst-case scenario of the Round 1 developments.

In 2003, when this project started, there was no consensus on the magnitude and significance of the impacts of OWFs on sediment transport and sandbank stability. The data from the project were used by the licensee to validate the models used in the environmental impact assessment as a condition of the FEPA licence. The issue has potentially significant consequences for coastline management, particularly for those coastlines that may be susceptible to coastal erosion. At present, theoretical calculations and modelling are only able to deliver predictions of sediment transport in such environments with low confidence. Further, under the specifications of the next generation of wind farms (Round 2), where far greater arrays of turbines are proposed, the potential changes to geomorphic features take on a greater significance. Consequently, there was an urgent requirement to improve the scientific understanding of sediment transport issues through observation and subsequent validation of theoretical calculations, to develop knowledge to help create a generic framework relevant to wind farm development and the assessment of coastal processes, and hence to inform the FEPA licensing process.

The project was primarily designed to aid licensing decisions and UK policy and advice on OWF development (FEPA 1985), thereby supporting Defra as the agency responsible for the sustainable development of the marine and coastal environment. Researchers and consultants can draw on these unique field measurements and use the enhanced scientific understanding gained from the provision of the generic information in order to test the validity of sediment transport models.

1.1 Project Purpose

The provision by Cefas of "coastal process" advice relating to the Scroby Sands Environmental Statement (ES) highlighted areas where our present level of understanding was particularly deficient. These included:

- assessment of the change to sediment transport magnitudes and pathways;
- verification and validation of wave and tide numerical models in shallow water associated with sandbanks;
- diffraction of waves as a consequence of a wind farm array (detailed in a separate report to Defra, A1227).

Improved knowledge in these areas would build confidence in predictions relating to future developments. Indeed, with Round 2 of wind farm developments now underway, we know that future developments will involve arrays spread out over larger areas of the coastal zone, with increased numbers of turbines of larger dimensions (e.g. London Array, 245 km^2, ~300 turbines and 5 m monopile foundation diameter). It is therefore vital that our understanding of the impacts of these developments on coastal processes and nearshore sedimentation, and ultimately on the configuration of the coastline are well understood before significant demands are again placed on the consenting process. Presently there is reliance on limited sediment transport data to validate the predictions of the numerical models used to quantify changes to sediment transport that occur as a direct result of the construction of an offshore wind farm. Indeed, theoretical estimates may differ from field measurements by a factor of 10 (ABPmer, 2005a).

The site of Scroby Sands on the East Anglian coast is a particularly dynamic environment where significant quantities of material are frequently in suspension under fast tidal currents, and where numerous sandbanks are in a state of continuous change. As a consequence, predictions of changes in the morphology of marine sandbanks and the morphology of the coastline are here at their most difficult. It was not readily apparent that theoretical estimates and the suite of models available to developers and their consultants adequately represented the magnitude and pathways of sediment transport, particularly in the vicinity of sandbanks, and also when issues of scale of coastal processes and model resolution may be in opposition. By providing appropriate field measurements that will enable subsequent testing of the previous estimates of sediment transport, this research has aimed to address these deficiencies.

This research will aid licensing decisions (FEPA 1985) in relation to wind farm developments. There is an urgent need to supply, through this R&D, high-quality advice to Defra relating to Round 2 developments, but also to use measurements relating to construction of the Round 1 wind farms (i.e. through the Scroby Sands site) to feed into the numerical modelling studies, and thus provide results for use in the provision of advice for the second round developments. This research addresses future demands, in an attempt to improve future efficiencies in advice provision.

1.1.1 Objectives

As defined in the original agreed CSG7 project proposal (dated Jan. 2003), the scientific objectives were:

1. To collect a dataset of waves and currents over a spring/neap cycle on sandbanks for use in calibration and validation of numerical models for potential impacts of wind farms;
2. To assess gross changes in sediment transport during winter and summer seasons pre- and post- construction to compare any effects due to wind farm construction;
3. To undertake suspended sediment monitoring during wind farm construction using a combination of OBS profiles and water samples (with "in-kind" help from the developers – e.g. access to piling vessels during construction), to monitor potential effects of piling and ship movements;
4. To liaise with numerical modellers on the implementation of the validation and to help develop further models if results indicate poor performance. There is no specific modelling effort in this proposal. Developers and users of numerical models (HR, ABPMer, Posfords, Halcrow amongst others) will be invited to test their own models against these new datasets. These datasets will help "benchmark" the models and identify strengths and weaknesses inherent in each modelling approach. This will provide "in-kind" support from industry through their consultants;
5. To produce a GIS showing the sedimentological and hydrographic distributions for use in interpretation and licensing procedures. Maps of individual bedforms (megaripples, sandwaves etc) will be created from the interpreted side-scan sonar records as in the Southern North Sea Sediment Transport Study (see www.sns2.org for full details). Five snap-shots of the bedforms should enable detection of any gross changes of sediment transport regime and make a comparison with natural seasonal and interannual variations. This information may also help in zone management of OWFs in relation to monitoring and assessing the impact of scour protection around each monopole;
6. To interpret the significance of findings for the management of wind farm licensing.

These objectives were kept under constant review through ongoing communication with Defra. Changes in the programme of construction that Powergen (now "E.ON") undertook at Scroby Bank resulted in some significant changes in the dates of some project milestones.

1.2 Scientific Context

The calibration of current numerical sediment transport models rely on a small set of observations in relatively deep water (>20 m) and moderate tidal currents. In this project, it was planned to extend the range of conditions under which these numerical models have been validated. Specifically, it was aimed to collect wave, current and suspended sediment data before and after the construction of a wind farm, taking data in winter and summer seasons from the "top" of Scroby Sands sandbank, offshore at a control site and inshore of Scroby Sands in a channel. Additional side-scan and bathymetric surveys were undertaken over a number of field campaigns. These datasets are of high quality, with water, sediment and depth records taken for purposes of instrument calibration, quality checking and model validation. For instance, the platforms for measuring current and suspended sediment had roll, pitch and compass sensors to check for movement of the frame as well as sediment traps (Booner tubes) for post-deployment calibration of OBS sensors in a turbidity tank.

1.3 Scroby Sands Offshore Wind Farm

The Scroby Sand OWF was developed by E.ON UK (formerly PowerGen Offshore Renewables) and consists of 30 monopiles of diameter 4.2 m driven up to 30 m into the seabed. The nearest monopile is located only 2.3 km from the shore (Wind turbine number 01 west, across Yarmouth Roads). Each monopile supports a tower and nacelle containing a 2 MW Vestas V80 turbine and three blades. Initial studies identified Scroby Sands as a potential site for an OWF in 1993-4, such that an anemometry mast was installed in 1995. Scroby Sands was the first OWF to receive planning consent through FEPA and CPA as well as under the Electricity Act.

The construction process took just under a year (Table 1) with three export cables bringing power ashore. The minimum distance between monopiles is 320 m, between turbines 17 and 21 (Figure 1).

Activity	Dates
Piling	Nov 2003 to Feb 2004
Installation of Turbines	April 2004 to May 2004
Installation of Intra-Array Cables	May 2004 to Aug 2004
Installation of Export Cables	May 2004 to Aug 2004

Table 1 - Construction Timetable for Scroby Sands OWF.

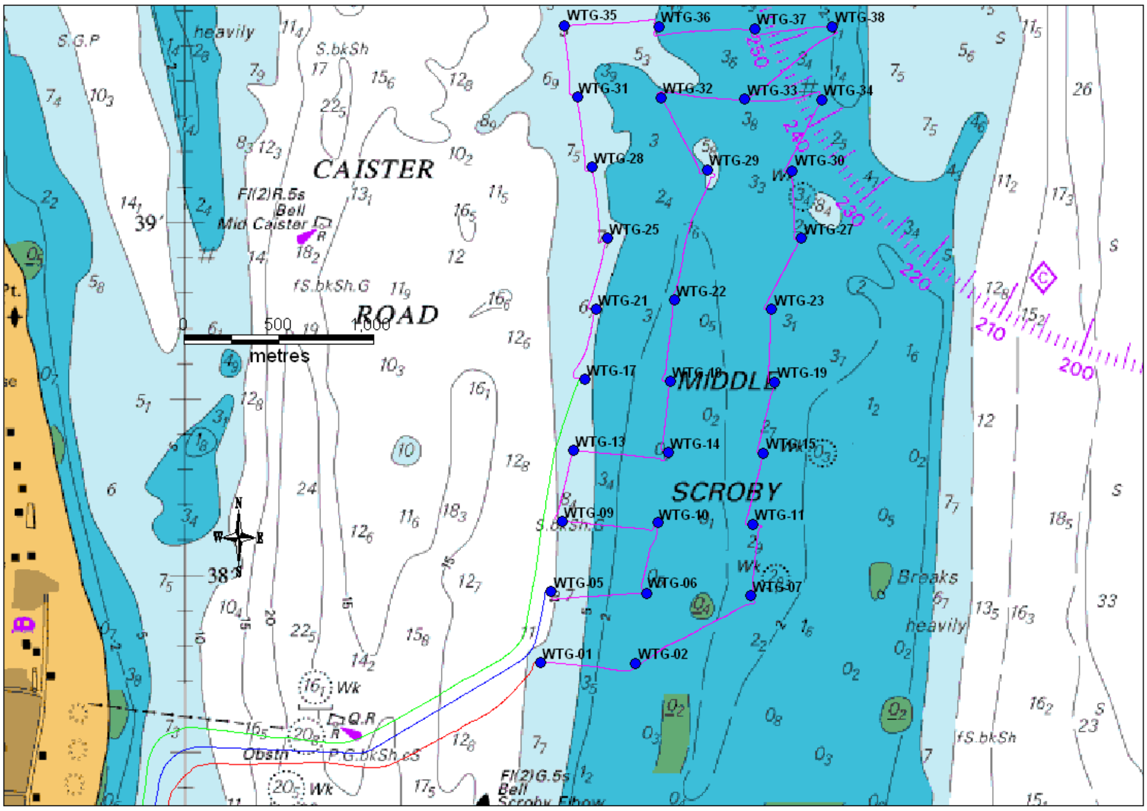

Figure 1 – Bathymetric chart showing the layout of Scroby Sands OWF, turbine numbers (WTG-01-WTG-30) and the location of intra-array cables (magenta) and export cables (green, blue, red).

1.4 Survey Rationale

A range of issues were considered in designing the field programme, including those of timing, the prevailing hydrodynamic processes, and the key sedimentary processes.

1.4.1 Timing (construction activity, seasons)

To assess the impact of the construction of the OWF, it was necessary to have field data representing periods before, during and after construction, and it is these periods that form the major divisions of the data collected. It was also important to consider seasonal variation, especially because the region is subject to episodic winter storms, which are likely to be important in controlling sediment transport and sandbank morphology. A seasonal component to the work was thus included, to provide comparable information on conditions in summer and winter.

1.4.2 Hydrodynamic Processes (tides, waves)

Tidal currents at this region are very strong, and largely flow in coast-parallel directions. Waves largely approach the area from the NE, so that the area west of Scroby Sands is relatively sheltered, especially at low tide when parts of Scroby

Sands are exposed. Changes in the elevation and shape of Scroby Sands might alter the nature of tidal flows and waves to the west and at the coastline.

1.4.3 Sedimentary Processes (bedforms, sandbank morphology, coastal impacts)

Important issues include the nature of sediment transport at the sandbank. There is a hierarchy of sedimentary bedforms at the site, from current ripples up to the whole sandbank itself. Bed sediment transport can be assessed by measuring the presence and nature of the dominant metre-scale sedimentary bedforms (megaripples and sandwaves) through spatial surveys. These bedforms contribute to the overall morphology of the sandbank, which, as noted above, influences the nature of sediment transport in the coastal zone and along the beaches.

1.4.4 Survey Design

In the light of the above factors, the work programme (Table 2) included deployment of a series of seabed landers to obtain hydrodynamic data from before, during and after construction of the OWF. Deployment sites (Figure 5) included:

- a site seawards (E) of the bank, to measure incoming waves ('Offshore');
- a site on the bank within the boundaries of the OWF ('Scroby Bank');
- a site landward (W) of the bank between it and the Caister shoreline ('Caister Road'), and;
- a site landward (SW) of the bank to give information on conditions that might influence the northern part of the Great Yarmouth shoreline, particularly regarding the passage of waves ('Yarmouth Road').

The Caister Road site was chosen to be occupied during all deployments to provide continuity in the record of nearshore conditions before, during and after construction of the OWF.

In addition, a series of spatial surveys was undertaken to map the bedforms and bathymetry of the area, using side-scan sonar and swath-mapping techniques respectively. To date (Feb. 2006), four surveys have been performed, with three datasets analysed in detail, representing periods before, during and after construction.

2.0 Survey Methods

Three campaigns of seabed lander deployments were undertaken. The Cefas MiniLander (Figure 2) is a flexible seabed frame capable of accommodating a variety of instruments and sensors for long periods of time (months) in hydrodynamically harsh environments. The MiniLander was especially suitable for deployments on Scroby Sands because the bearing pressure on the seabed can be varied by altering the size of the feet and the weight of lead ballast. Thus, a balance can be achieved between stabilising the MiniLander on the seabed and overweighing it, risking sinking and partial burial in the highly mobile sand.

		2003				2004				2005			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Survey Technique													
Seabed Landers													
Side-Scan Sonar													
Swathe Bathymetry	<--April 2002												
Construction Activity													
Piling													
Turbines													
Cables													

Table 2 – Timeline showing coastal processes monitoring and constructional activities of the Scroby Sands OWF.

2.1 Hydrodynamics and Sediment Transport

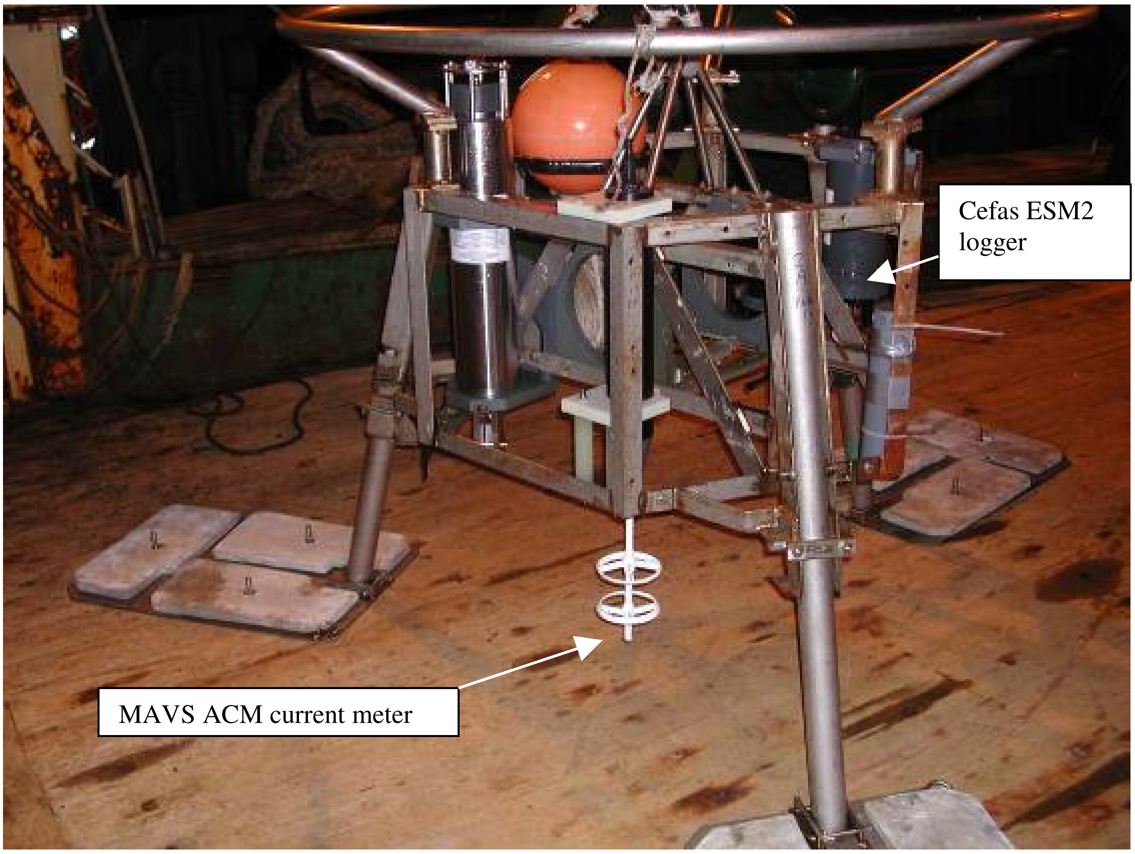

Figure 2 - Cefas MiniLander being prepared for deployment on RV Corystes. The Cefas ESM2 logger is mounted on the right edge of the lander with one OBS mounted in front on the lower rail. A MAVS ACM current meter is mounted in the centre of the lander below the cage. Upward looking Nortek ADP is hidden behind the acoustic release.

Three main instruments were housed on the MiniLander:

- a Cefas ESM2 logger, recording data from a Seapoint OBS (optical backscatter sensor);
- an upward-looking RDI ADCP or alternatively an upward-looking Nortek AquaDopp ADP profiler;
- a FSI or MAVS Acoustic Current Meter (ACM) near the seabed.

The Cefas ESM2 logger records data delivered to it by a Seapoint OBS. The ESM2 logger is a burst logger, which recorded 1024 samples every 30 minutes with a sampling frequency of 1 Hz (compared with a typical sequential logger which might record one value every 30 minutes). This 'burst mode' enables a higher degree of analysis and confidence to be drawn from the data (e.g. error statistics) and to analyse within each burst dataset for transitory events. The gain of the Seapoint OBS sensor is controlled by a smart algorithm then enables changes in the gain settings of the sensors within a burst ("on-the fly gain control"). This enables a large range of suspended sediment concentrations to be recorded (from a few mg/l to 800 mg/l) without loss of resolution.

The RDI ADCP is a 1200 kHz Sentinel instrument widely used by the oceanographic community to measure profiles of currents from the sensor head upwards towards the surface. Deployed looking upwards, current data from the basal and upper 10% of the water column are lost, due to transducer ringing and side-lobe interference respectively.

The FSI ACM and MAVS current meters are travel-time current meters, with no moving parts and thus ideally suited to environments with high concentrations of suspended sediment, and is used to measure currents at a single point close to the seabed. A FSI conductivity and temperature sensor and a Druck pressure sensor were used to measure tidal variations, and, because the water is relatively shallow, the wave height and period.

The Nortek 1 MHz AquaDopp ADP profiler produces a profile of current from the seabed to the surface (minus the first 10% and last 10%, in common with the RDI ADCP). Further, in shallow water (< 20 m), it provides estimates of the significant wave height, period and direction.

Each MiniLander was also equipped with a Booner tube or passive sediment trap to collect suspended sediment samples for later calibration of OBS sensors in a turbidity tank and particle size analysis.

2.2 Sediment Characterisation

A grab sediment sample survey was undertaken on the 24th April 2003 using a Day grab to collect surface samples of sediment and to characterise the environmental setting. These were subject to particle size analysis by wet sieve analysis (Figure 4, Table 11). All the sediment samples except those from Yarmouth Roads (SS9 and SS10) have low proportions of very fine sands and are mainly comprised of medium sands. SS9 and SS10, on the export cable across Yarmouth Roads are in deeper water and thus less exposed to wave action. Sediment samples were also taken in 1998 (Unicomarine, 1998).

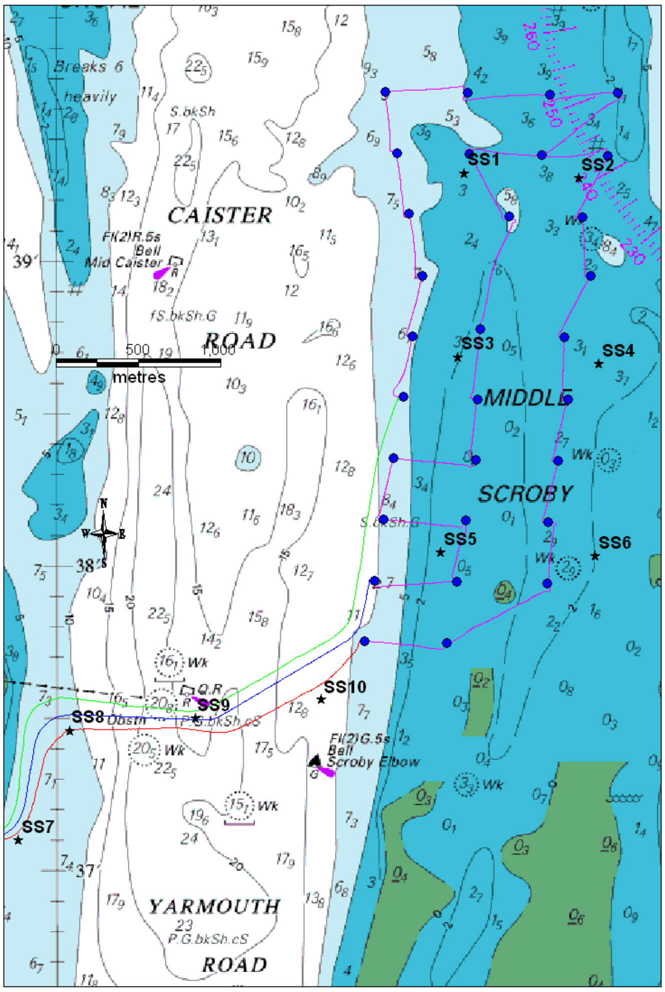

Figure 3 - Chart showing the positions of the sediment samples (SS) taken on 24th April 2003 using a Day grab within the Scroby Sands OWF and along export cable route.

2.3 Site Locations

Details of the hydrodynamic survey locations are described below (Figure 5, Table 3) All deployments of MiniLanders were made as close as possible to these sites, allowing for vessel operational constraints.

Location	Position	Mean Water Depth (m)
Offshore	52° 38.58′ N, 1° 49.08′ E	19
Scroby Bank	52° 38.98′ N, 1° 47.56′ E	7
Caister Road	52° 38.85′ N, 1° 45.46′ E	20
Yarmouth Road	52° 37.14′ N, 1° 45.12′ E	10

Table 3 - Location and depths of MiniLander deployment sites.

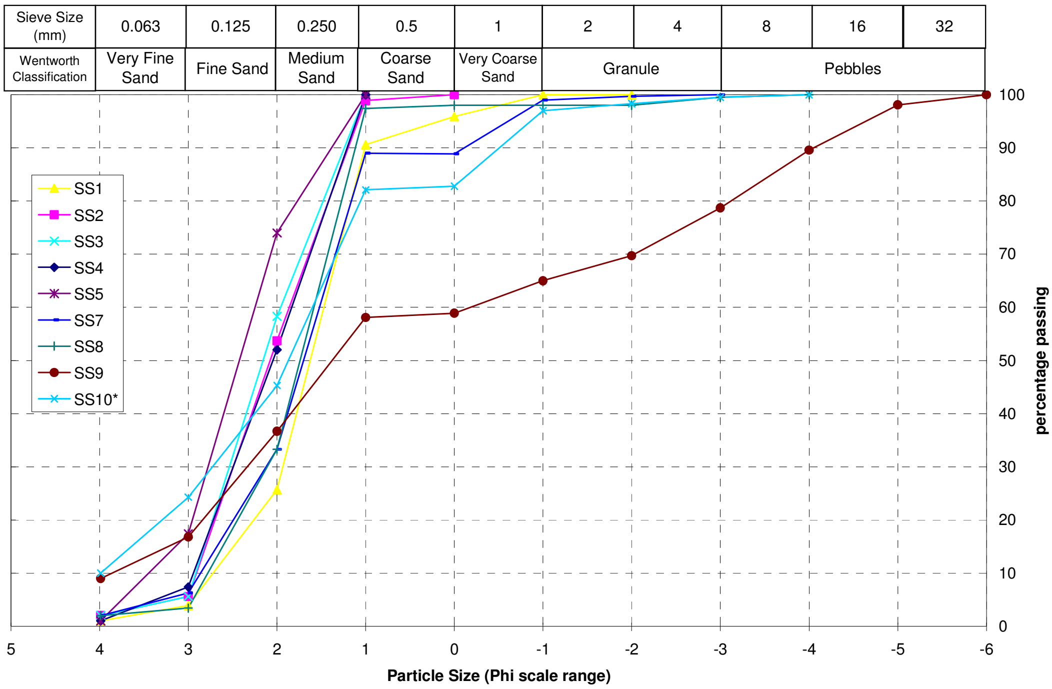

Figure 4 - Particle Size analysis (percentages) from sediment samples taken from Scroby Bank on 24th April 2005 (also shown in Table 11).

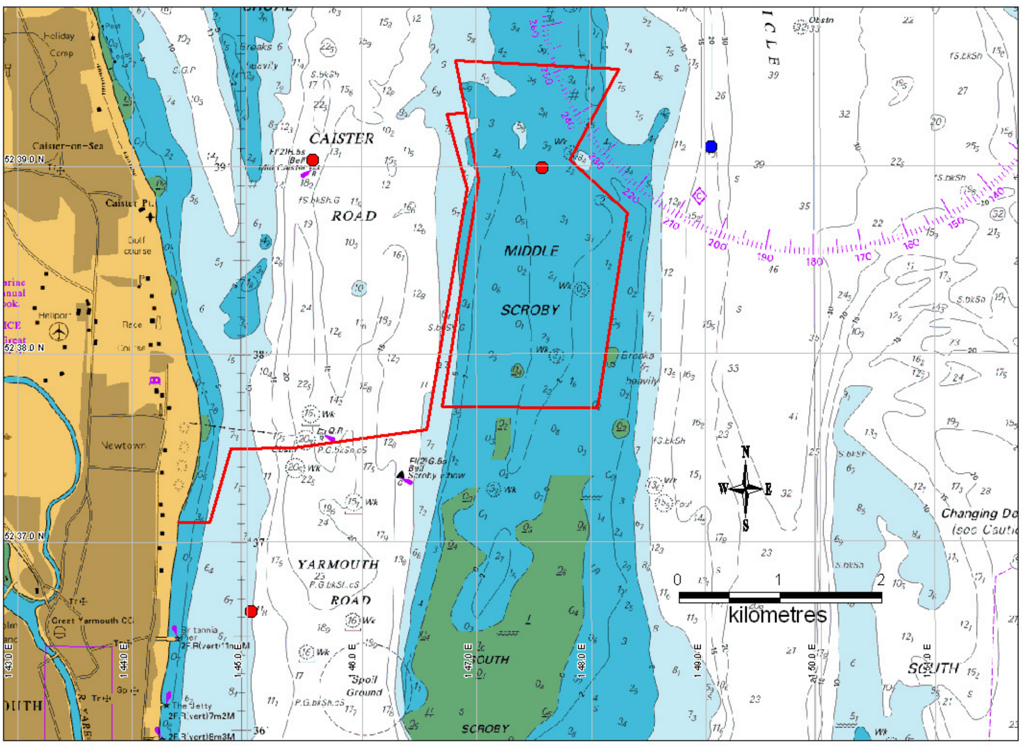

Figure 5 - Chart showing the location of the deployment sites of the MiniLanders. Red dots mark sites: 'Caister Road', 'Yarmouth Road' and 'Scroby Bank'. Blue dot indicates 'Offshore' site. Red lines delineate the geographical extent of the wind farm and the export cable route.

2.3.1 Offshore

This site forms the offshore end of an E-W transect of stations across Scroby Sands. For normal wave directions, wave data here are mostly unaffected by the presence of Scroby Sands, and represent the approaching wave field.

2.3.2 Scroby Bank

This site was chosen to measure conditions within the OWF monopile array itself. It is located approximately at the centre of the array and, as required by the developers (E.ON UK), away from any intra-array cable routes. Located in very shallow water (7 m) and exposed to the dominant NE storms, the seabed conditions at this site were expected to be very mobile. A special mooring configuration was designed in order to ensure that the lander did not become buried and that it would be recoverable. Three recovery systems were used deployed to prevent loss: 22 mm corlene rope with buffs (the normal recovery system), a ground line to the guard-buoy and an emergency acoustic positioning and release system. The shallow-draft vessel RV Flat Holm was used at high tide to deploy and recover the MiniLanders.

2.3.3 Caister Road

This site was chosen the represent the conditions west of Scroby Sands, which is sheltered from waves from the E, but is within the tidally dynamic Caister Road channel. The site was located just NE of the Caister Bank navigational buoy to increase the instrument's safety and reduce any impacts on the local fishing community.

2.3.4 Yarmouth Road

This site was chosen in conjunction with a parallel wave impact study (Defra contract AE1227) to measure conditions SW of the OWF, i.e. behind the bank with respect to the dominant NE storms. The site was located on the 10 m contour, as close as possible to the HF radar mounted on the Brittania Pier, whilst being capable of deployment from Cefas RV Corystes. The wave-spectra data obtained from this instrument provided calibration data for the HF radar as well as a backscatter "target" for calibration of the radar.

2.4 Sediment Distribution and Sedimentary Bedforms

A number of side-scan sonar surveys were undertaken of the Scroby Sands sandbank, using a high-resolution Datasonics Digital side-scan sonar system (SIS-1500). The survey was designed to achieve 100% coverage of the extent of the OWF, including the shallow ridge in the southern half of the turbine array (Figure 6). This was achieved by using a vessel of very shallow draft (MV Compass, owned by Great Yarmouth Port Authority) and by towing the side-scan sonar fish using a soft rope as well as the data coaxial ("soft tow"), allowed the sonar fish to pass over the shallowest regions. 100% coverage was achieved, in water typically of 3-5 m depth, with horizontal ranges varying up to 100 m. Data was recorded within the Triton-ELICS software package for post-processing of the data, and for the creation of side-scan sonar mosaics (as Figure 7).

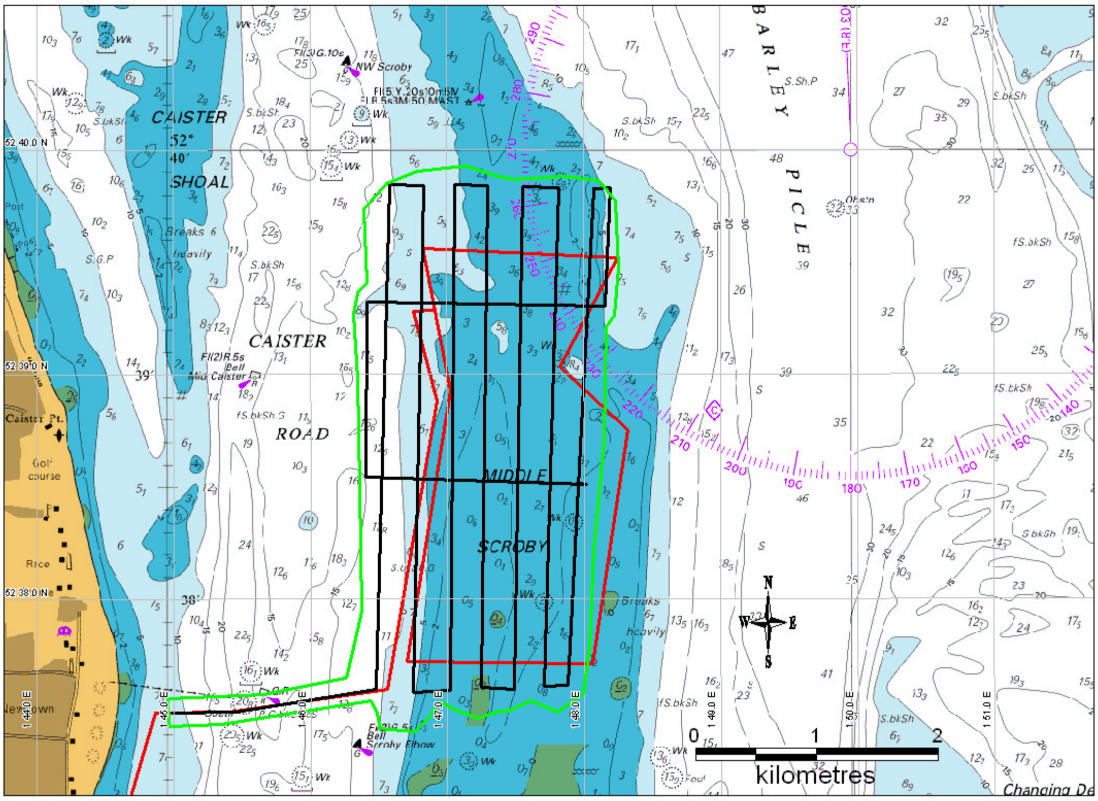

Figure 6 - Chart showing the coverage of the side-scan sonar survey (green line) and tow lines (black).

The major sea-bed features identified from the side-scan records were a sand wave field in the NW corner of the survey area, a series of scour pits associated with the individual monopiles and two wrecks.

Survey	Date	Comments
1	April 2003	Before Construction
2	Oct 2003	During Construction
3	Oct 2005	After Construction

Table 4 - Timetable of the Side-scan sonar surveys of Scroby Bank using the Datasonics SIS-1500 digital.

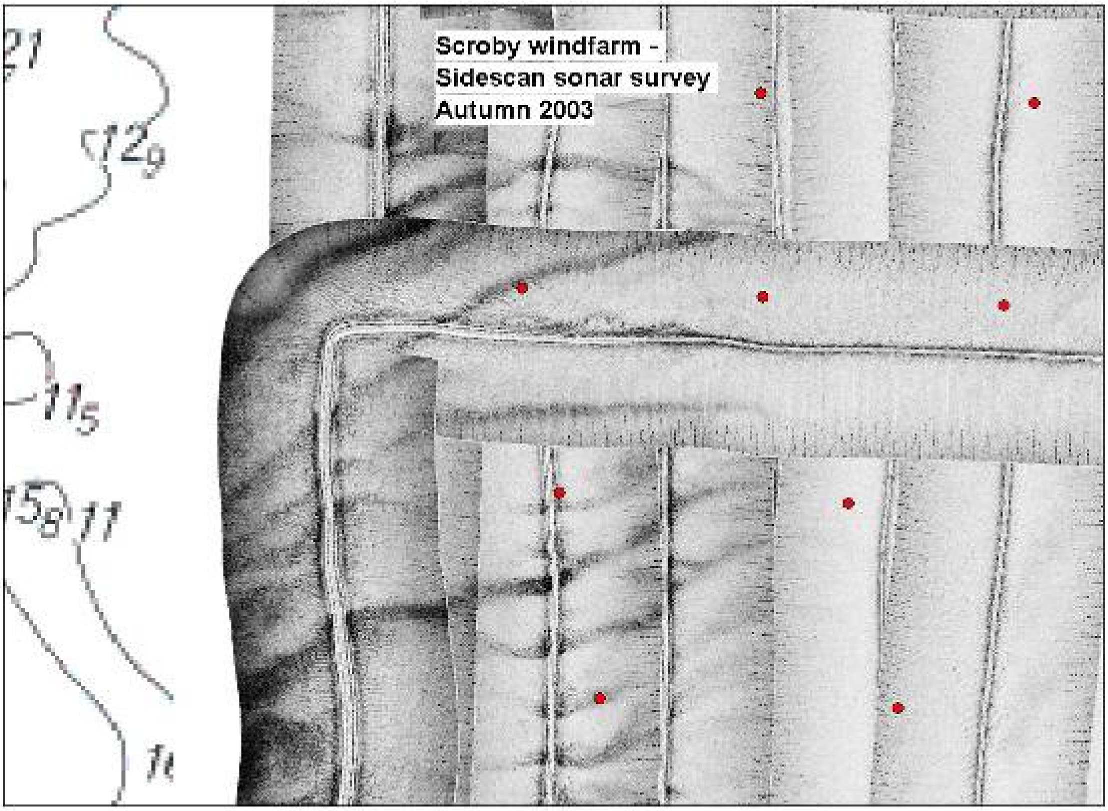

Figure 7 - Image showing the north-east portion of the side-scan sonar survey of Scroby Bank undertaken in August 2003 showing the sand wave field.

2.5 Swathe Bathymetry

The earliest high quality bathymetric survey of Scroby Sands Bank was undertaken by Coastline Surveys for PowerGen in April 2002 as part of a baseline survey. Subsequent swathe bathymetry surveys were undertaken for operation purposes (ship/barge movements) and more latterly as part of the FEPA licence monitoring conditions on six monthly intervals for E.ON (UK). Table 5 gives a timeline and reason for each of the surveys.

Survey	Date	Contractor	Type	Comments
1	April 02	Coastline Surveys	Single Point	Before Construction Baseline
2	March 04	Andrews	Swathe	Pre Scour Protection
3	July 04	Andrews	Swathe	Post Scour Protection
4	Feb 2005	Andrews	Swathe	Winter

Table 5 – Timeline of Bathymetric surveys.

3.0 Results

3.1 Before Construction (First Campaign, April & May 2003)

Four MiniLanders were deployed around the OWF in locations described above and summarised in Table 6. Plots of the individual parameters vary largely in response to the spring-neap-spring period. (The datasets of water temperature, salinity, depth, tidal current speed and direction, significant wave height, wave period and turbidity are not shown in this report, but can be accessed from the Cefas website, at www.cefas.co.uk/renewables). Significant wave heights reached 1.1m on the 14th May 2003. Variations in suspended sediment concentrations reflect the spring-neap cycle and to a lesser extent the minor wave event of the 14th May.

Location	Start Date/ Time	End Date/ Time	Payload	Resulting Datasets	Comments
Offshore	24/04/03 16:00	06/06/03 13:00	ESM2	Temperature, turbidity, salinity, tidal elevation, wave statistics.	
Scroby Bank	24/04/03 15:00	06/06/03 10:00	FSI + ESM2	As above plus near-bed currents	FSI Failed
Caister Road	24/04/03 16:00	06/06/03 10:00	FSI + ESM2	As above	
Yarmouth Road	11/04/03 18:00	06/06/03 09:00	RDI ADCP ESM2	As above plus water column currents	HF Radar calibrator

Table 6 – Start and end times (GMT) of good data returns from the before construction deployment of seabed landers. Passive sediment traps (Booner tubes) were also mounted on each MiniLander.

On each MiniLander were mounted passive sediment traps ('Booner tubes') which allow ambient suspended sediment to enter a tube and as the flows decelerate the suspended sediment fails out of suspension and is caught in the trap. Either the bulk sample or discrete layers (if present) can be used to assist post-deployment calibration of OBS sensors in a turbidity tank.

3.2 During Construction (Second Campaign – Feb. 2004)

The second deployment of seabed landers aimed to monitoring coastal processes during construction of the OWF. Potential impacts included suspended sediment plumes produced by driving monopiles into the bank, resuspension from shipping activities and cable-ploughing operations. Two locations were occupied, limited by equipment malfunctions. The Yarmouth Road and Caister Road sites were chosen because the former was also needed for HF Radar calibration work (related to AE1227). The payload of each MiniLanders was improved to include single-point instruments near the seabed (FSI ACM) and instruments which took vertical profiles through the water column (Nortek ADPs). Results produced good datasets for this winter period (Table 7).

Location	Start Date/ Time	End Date/ Time	Payload	Resulting Datasets	Comment s
Caister Road	05/02/04 17:00	04/03/04 04:00	FSI + ESM2	Temperature, turbidity, salinity, tidal elevation, wave statistics and nearbed currents	
Yarmouth Road	5/02/04 16:00	18/03/04 11:00	AquaDopp ESM2	As above but with whole water column currents	HF Radar calibrator

Table 7 - Start and end times (GMT) of good data returns from the 2nd Campaign of seabed lander deployments. Passive sediment traps (Booner tubes) are also mounted on each MiniLander.

Wave height reached a maximum of 1.7 m on 22nd Feb 2004 at the Caister Road site. This minor wave event and three others increased the suspended sediment variability for the period of the event before quickly returning to spring-neap variations. Sediment concentrations on Scroby Bank show similar but smaller-scale response to waves.

3.3. After Construction (Third Campaign, Feb. & March 2005)

The final deployment of logging oceanographic instrumentation aimed to record post-construction coastal processes and was also timed to represent a winter season, to match the second 'during construction' deployment. The deployment coincided with a swathe bathymetry survey. The sites chosen were the Caister Road, for continuity with previous deployments, and Scroby Bank. Data returns were excellent (Table 8).

The tidal elevation time-series shows a spring-neap signal typical of the southern North Sea (Figure 8) and a surge event of approximately 70-80 cm on 11th March 2005 at 20:00 GMT. The corresponding significant wave height data shows a series of wave events reaching a maximum H_{sig} of just over 2.1 m on a variety of occasions. Analysis shows that the wave height is modulated by the tidal elevation, decreasing at low tide and increasing again at high tide during the period 23rd to 25th February. This indicates that the waves were breaking over Scroby Bank and is consistent with a condition for wave breaking (wave height/water depth) of ~ 0.78 found in the literature (McCowan, 1894, Dyer, 1986).

Location	Start Date/ Time	End Date/ Time	Payload	Resulting Datasets
Scroby Bank	18/02/05 18:00	19/03/05 14:30	Aquadopp ESM2	Temperature, turbidity, salinity, tidal elevation, wave statistics and whole water column currents
Caister Road	18/02/05 14:00	19/03/05 15:00	Aquadopp ESM2	As above

Table 8 - Start and end times (GMT) of good data returns from the3 rd Campaign of seabed lander deployments. Passive sediment traps (Booner tubes) are also mounted on each MiniLander.

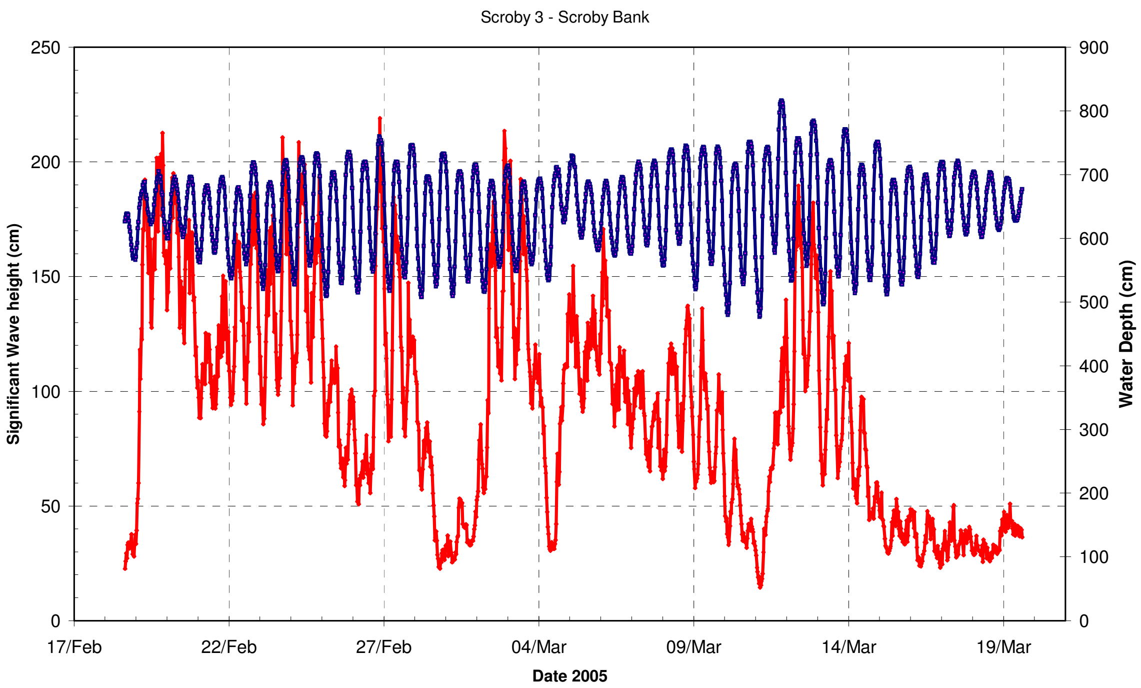

Figure 8 – Time series of burst mean depth and significant wave height as recorded by the Cefas ESM2 burst logger from Scroby Bank.

The time series of current speed profiles from the upward looking ADP for this period are shown in Figure 9. The spring-neap variation in tidal elevation is again present with the wind-driven surge of the 11th March evident. This event is also reflected in fast (~1.4 m/s) current speeds through the whole water column.

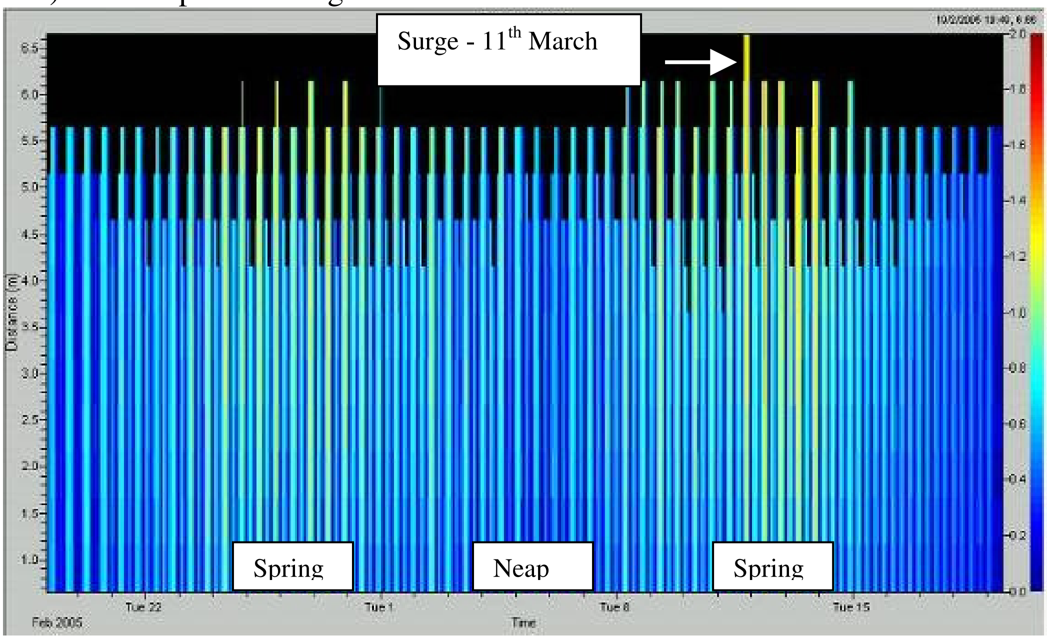

Figure 9 – Time-series of current speed profiles from the upward looking ADP on the Scroby Bank showing the spring - neap cycle and a wind-driven surge of 11th-14th March 2005 at 20:00 GMT. Colour bar on right shows current speeds (m/s).

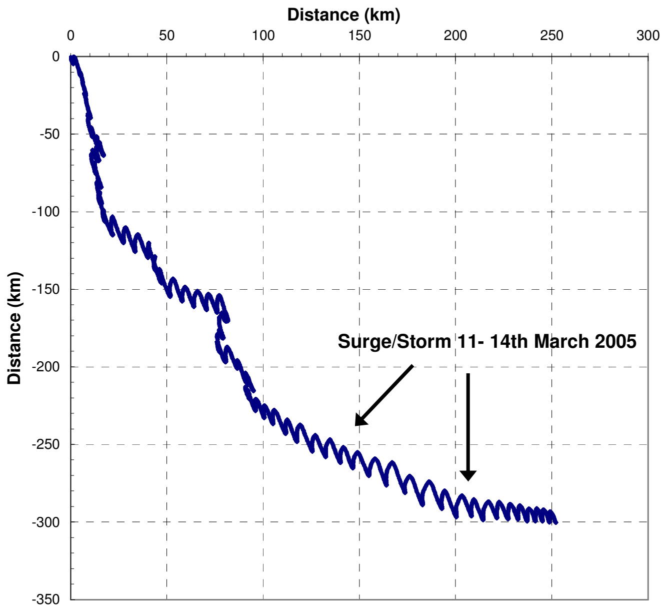

Figure 10 - Progressive Vector Diagram for the Scroby Bank (after construction, third deployment) showing a predominantly southerly residual current. The surge and storm of 11th to 14th March 2005 modifies this to a more south easterly direction.

The residual current direction can be assessed by using a "progressive vector diagram" (PVD) showing the accumulation of the current vectors over the whole of the deployment as shown in Figure 10. Thus, the start of the deployment is at the origin and the end of the deployment 300 km to south and 250 km to the east. The majority of the PVD is in a south or SSE direction. However, the residual transport direction is more easterly during the surge/storm event of 11-14th March 2005.

3.4. Swathe Survey Data

The three swathe bathymetry surveys provide a time-series of the evolution of Scroby Bank over the last two years. The high-resolution datasets (gridded at 1 m centres) have been analysed within the Fledermaus © environment which allows visualisation and analysis of large datasets (see Figure 21 and Figure 22 for examples). The main features that can be identified are (see Appendix A for maps):

Natural Features

(a) Large ridge running north-south along the OWF site;
(b) Sandwave field in the NW corner of the site;
(c) Megaripple fields across the site.

Anthropogenic features

(a) Scour pits associated with monopiles – typical depths up to 5 m with a horizontal diameter of 60 m (Figure 21);
(b) Scour wakes on the eastern monopiles extending from one monopile to the nearest downstream neighbour (Figure 22). The scour wakes are orientated at approximately 30 degrees to the normal N-S tidal direction in line with the surge current direction;
(c) “Scour pans” with a U- shaped profile in the NW corner within the sandwave field compared with the “v-shaped” scour pits in the remainder of the array;
(d) Reduction in bed elevation along the inshore line of monopiles;
(e) Impacts of jetting the intra-array cable close to the monopiles as shown by a trench;
(f) Traces of the ploughing of the intra-array cable across the OWF site;
(g) Secondary scour pits associated with the scour protection deposited to stabilise the monopile;
(h) Wrecks and associated scour pits.

3.5 Data Quality

3.5.1 Data Recording and Coverage

The MiniLander and its associated payload of Nortek Aquadopp ADP and Cefas ESM2 loggers represent industry-standard equipment in the first case and a high precision scientific logger in the second case. The ADP is an industry-standard device and is used routinely to measure wave and currents in shallow (< 20 m) water.

The Cefas ESM2 burst logger is ideal to operate in these high turbid regions as the long bursts of data (10 minutes) give an indication of the short term variability and the “auto gain changing” turbidity sensor allows large variations in suspended sediment concentration without loss of resolution. However, whenever using optical suspended sensors in highly turbid and strong current regions, the sensor is occasional obscured by seaweed and other debris.

The swathe bathymetry data are also of good quality with 100% coverage on most surveys and very few erroneous points. The successful removal of changes in tidal elevation is evident by the lack of mismatches between adjacent lines. Sound velocity profiles were undertaken at regular intervals and no “warping” of the signal can be observed. The system accuracy exceeds that specified in the Special Order specifications, as set out in *IHO Standards for Hydrographic Surveys, Special Publication 44, 4th Edition, April 1998*. Worst-case repeatable accuracy is of the order 10 cm in the vertical and 1 m in the horizontal.

The operation and use of side-scan sonar is difficult in such shallow waters, especially over the crest of Scroby Bank itself. However, the Digital Datasonics SIS-1500 system gave good range and resolution even in these shallow waters and bedforms were readily identifiable.

3.5.2 Data Gaps

There are several sources of data gaps from the monitoring programme, including:

- Swathe surveys were only undertaken when the weather was sufficiently calm for the small survey vessel to operate;
- The aim of the swathe surveys was broad-scale mapping of the whole of the sandbank and its associated bedforms. Thus, accuracy close to the monopiles (up to ~5 m away) is probably impaired due to backscattering from the strong reflectors and shadow effects of the monopiles on the DGPS system;
- The hydrodynamics and sediment transport programme was performed to cover physical scales reflecting the size of the OWF, so that smaller impacts (e.g. 0-10 m scale) were not included;
- Turbidity measurements were not undertaken during construction or cable-burial operations;
- The Offshore wave site was only occupied during pre-construction phase and thus offshore wave statistics are not available for other periods.

3.5.3 Knowledge Gaps

The Offshore site is taken to represent wave conditions on the east side of Scroby Sands sandbank. However, even this site is within the East Anglian bank system and remote wave statistics would be useful to provide background information on the forcing conditions in the southern North Sea. The nearest WaveNet sites are Dowsing to the North and Gabbard to the south and thus not useful in this analysis (WaveNet, www.cefas.co.uk/wavenet).

Long-term wave statistics for the OWF site and export cable routes are also not available which would be useful in assessing extreme wave events. Such data would provide the context in which to assess the wave records collected under this project.

Long-term changes (i.e. >annual) and variability of sediment particle-size distributions over the OWF site and cable route would be useful in defining sediment transport regimes. Sediment particle-size data provides an additional source of data for predicting sediment transport pathways.

4.0 Analysis

4.1 Hydrodynamics

The current and wave height/period time-series from the AquaDopp current profiler have been converted into bed shear stress:

- Generated by currents alone;
- Generated by waves alone, and;
- Generated by currents and waves combined (total), using non-linear wave-current interaction (Soulsby, 1997). Wave directions were not measured by the MiniLanders and the wave direction was assumed to be from the north.

This results in three time-series of bed shear stress (Figure 11). The waves are moderate for this location (H_{sig} 2.1 m) but the mean water depth is small (7 m), so that wave stresses are high and thus the total bed shear stress is dominated by the combination of both waves and tides. Bed shear stresses are capable of resuspending very coarse sand (2 mm diameter, with a τ_{cr} of approximately 3 Nm^{-2}) for sustained periods of time during peaks in bed shear stress (Figure 12).

A useful method of presenting this data is to use an exceedance diagram, which plots the percentage of time that the total bed shear stress exceeds a certain value (Figure 13). For Scroby Bank in winter, the total bed shear stress exceeds 3 Nm^{-2} for 10% of the time and thus is capable of transporting sediments up to 4 mm in size. For the 4 mm fraction, winter storm conditions double the amount of time (from ~ 5% in summer to ~10% in winter) that such gravel can be transported. The Naze site (100 km to the south, off Harwich; SNS2, 2002) is generally subject to lower bed shear stresses, with sands being mobilised around 10% less frequently than at Scroby Bank in summer. For Scroby Bank, with a typical modal size of 250-500 µm, bed shear stresses in excess of 0.4 Nm^{-2} will transport sediment. Therefore, in summer, sediment is in active transport ~80% of the time, compared to ~94% of the time in winter. This high mobility is largely due to the strong tidal currents on the bank which are capable of transporting sand. In winter, storms will increase sediment transport, and probably change the net transport direction. However, once the storm has abated, the background tidal transport will return sediment transport patterns and pathways back to a tidally dominated regime.

The contribution to bed shear stress at Scroby Bank by waves, by tides and by both combined (combined waves and tides using non-linear interaction) is shown in Figure 14. For most moderate shear stresses (~ 0.4 – 1.2 N/m^2), waves contribute more to the total bed shear stress than tides. For high bed shear stresses, the tide forms the main contribution, because wave stresses are limited by the waves having broken in the shallow water on the bank.

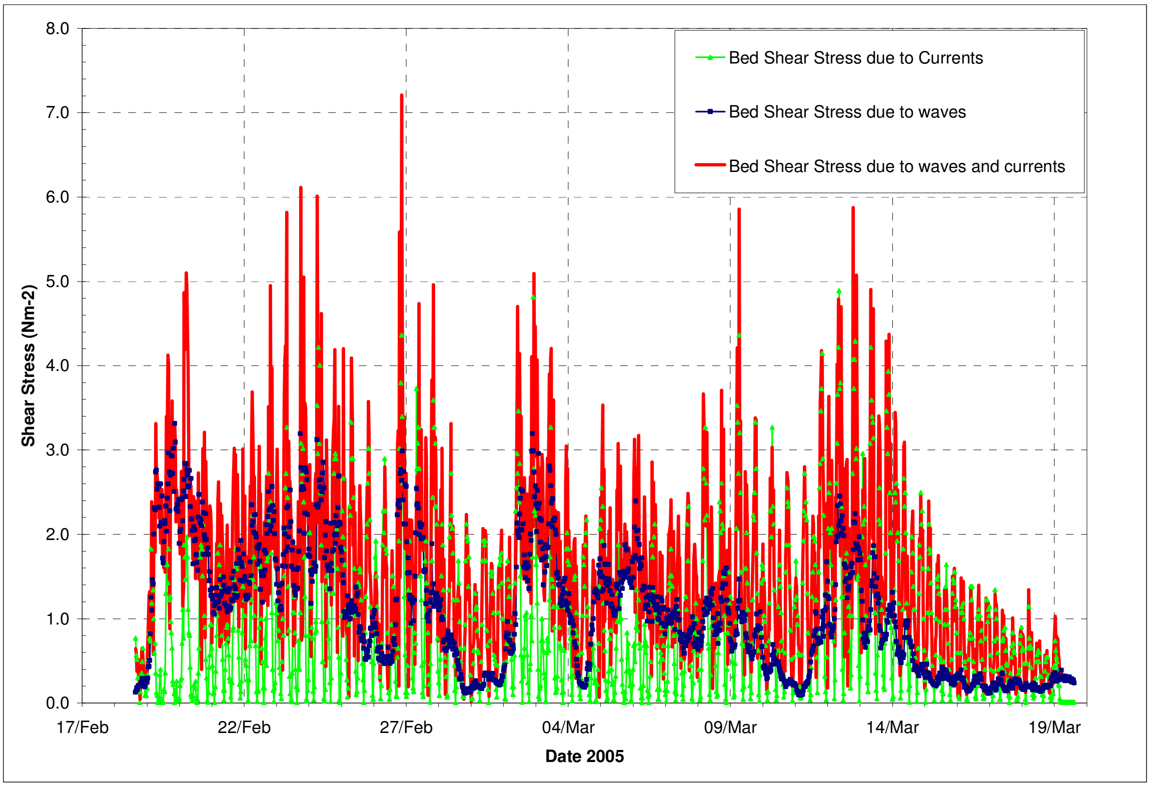

Figure 11 - Time series of bed shear stress from waves, currents and combined wave-currents at Scroby Bank, during the post-construction deployment.

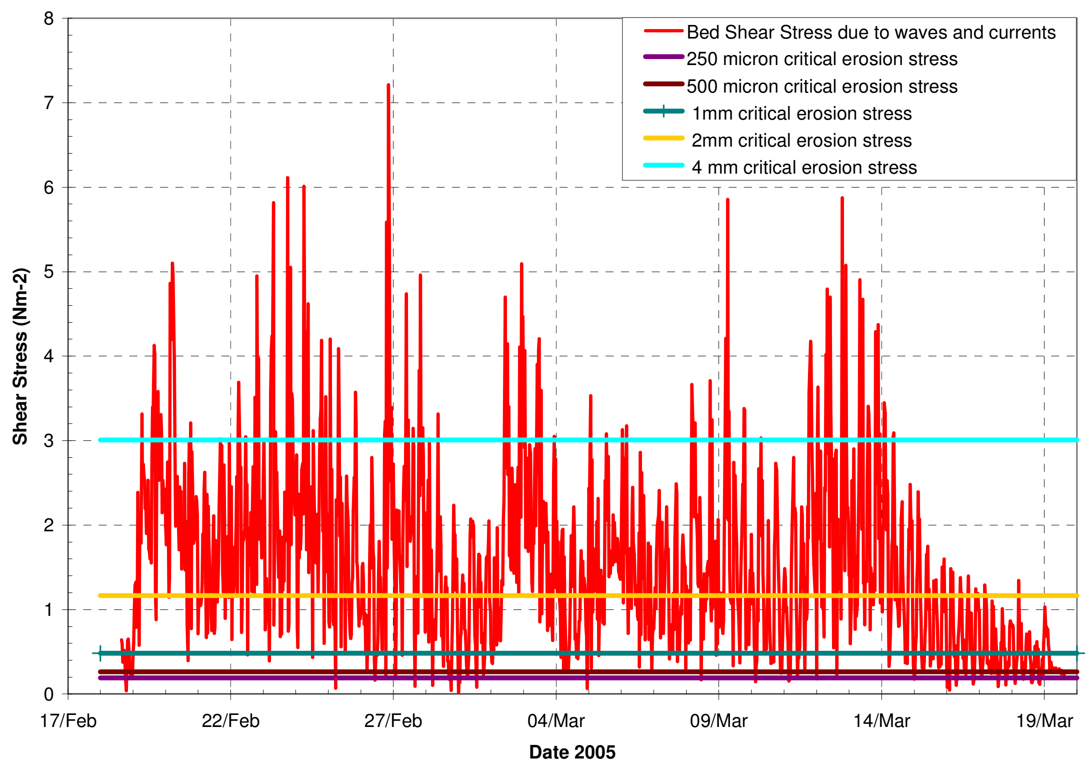

Figure 12 - Bed shear stress due to combined wave and tides, Scroby Bank, with the critical erosion thresholds for various particles sizes (Soulsby, 1997, Figure 21).

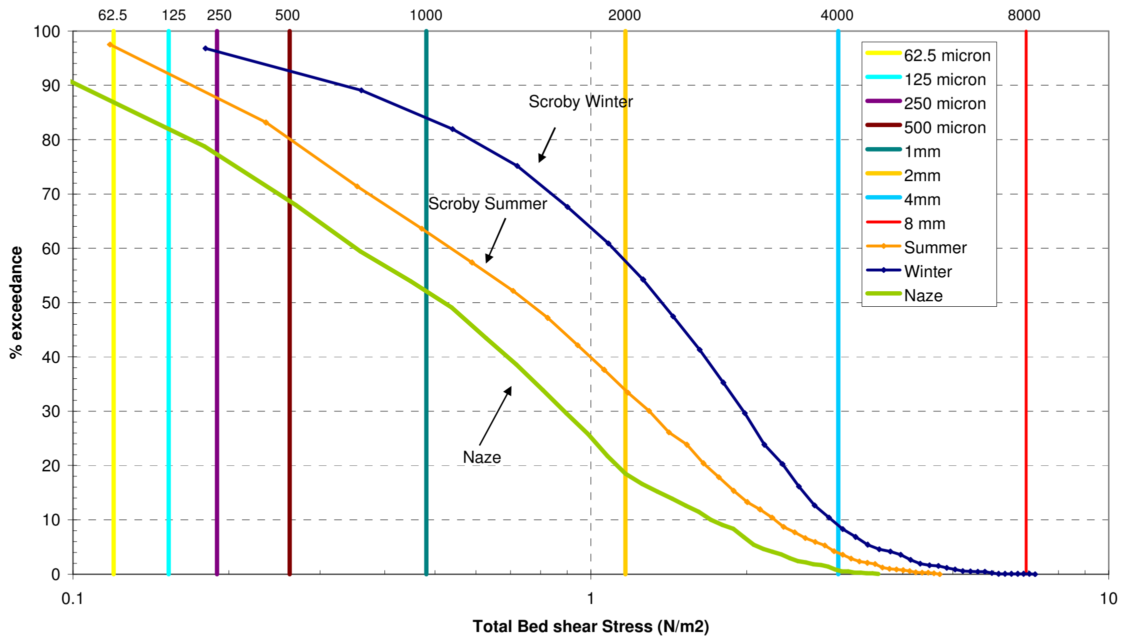

Figure 13 - Total bed shear stress exceedance for winter and summer on Scroby Bank (see Table 9 for dates for the Naze. Vertical lines are the critical bed shear stress for various sizes of sand (Soulsby, 1997, Figure 21).

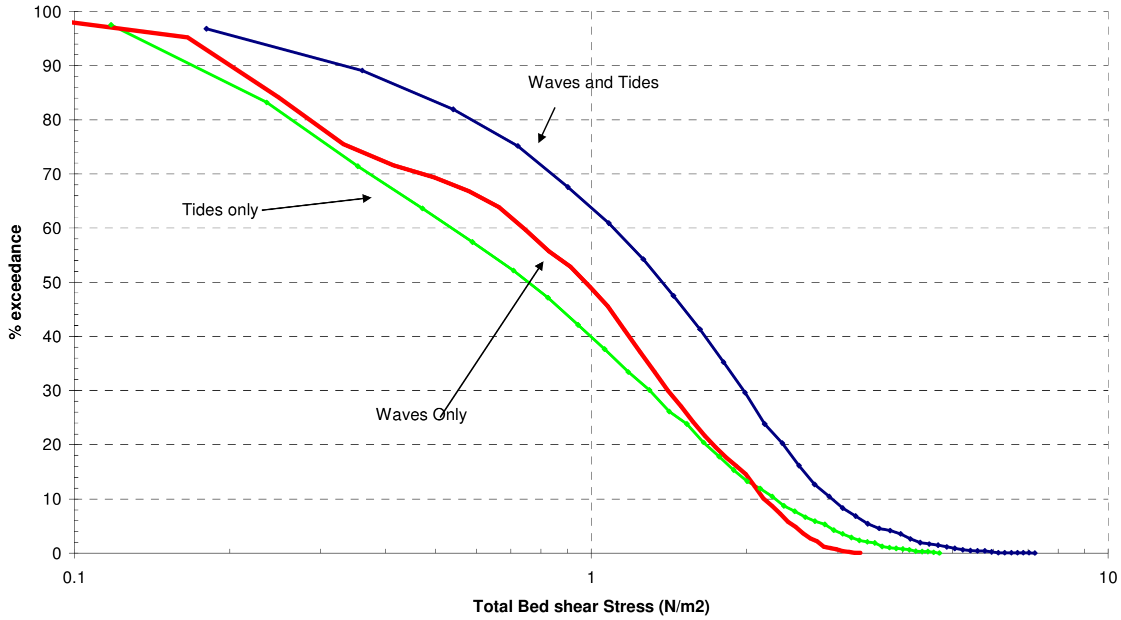

Figure 14 – Bed shear stress due to currents only (green), waves only (red) and currents and waves combined (blue) from the Scroby Bank third campaign

Figure 15 shows the computed total sediment transport rate (Soulsby, 1997) using the Scroby Bank MiniLander deployment (third campaign), using the assumptions that the particle size, the bed roughness and wave direction are all constant throughout the deployment. The maximum sediment transport rate is approximately 9.5 kg m^{-1} s^{-1} during the period 2-3 March.

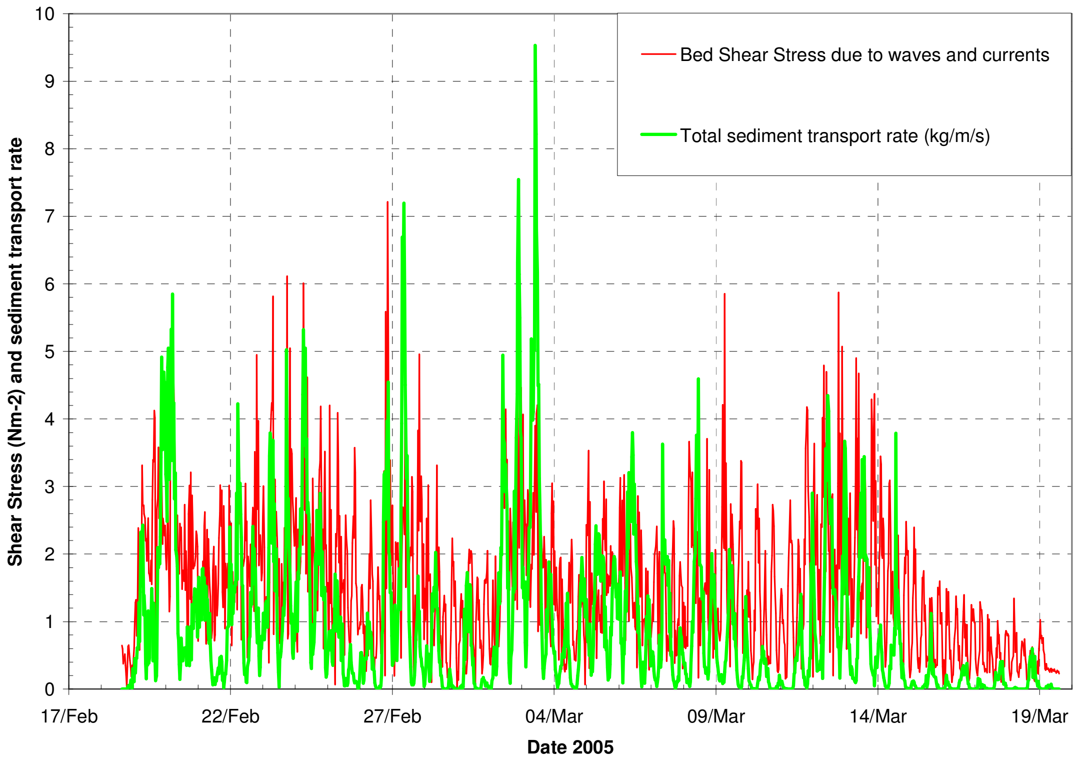

Figure 15. Variation in total bed shear stress, and theoretical total sediment transport rate (assuming 250 µm, constant bed roughness length 0.003 cm, tidal currents speed/directions, wave heights/periods and water depths from the Scroby Bank campaign 3 deployment (Soulsby, 1997). Wave directions are assumed to be from the north.

4.2 Survey Data

4.2.1 Volumetric Changes

The three swathe bathymetry surveys each provide a comparable Digital Elevation Model (DEM) of Scroby Bank, allowing estimates to be made of volumetric changes, either over the whole of Scroby Bank or from selected areas.

In order to assess the significance of the changes in seabed elevation due to scour pits and scour wakes, it is helpful to define an impact zone. Working within the Fledermaus © software environment, cross-sections of the scour pits and wakes can be created and the edges of bathymetric impact identified. This was done for all the scour pits and wakes associated with monopiles. Changes in volumes within these individual impact zones were calculated by subtracting the older DEM from the next newer (Figure 16). Three analysed surveys are available so that two estimates of change in volume can be made (Figure 17). Table 9 shows an overall assessment of individual impacts of monopiles. Two particular features identified are here termed 'Scour Wakes' and 'Scour Pans'.

- Scour Wakes are ~300 m long and 100 m wide with a depth of ~1 m and seem to be of entirely negative relief, and appear on swathe bathymetric images as a "wake" of sediment disturbance (i.e. bedforms) on the seabed (e.g. Figure 22). They probably reflect the direction of net (or peak) bedload sediment transport.

- Scour Pans are similar to scour pits but of greater diameter and with a broad flat central section immediately around the monopile (e.g. WTG-31, ref. Figure 1 and Figure 16). These might be related to variations in the direction of peak flow, but there is little evidence for this or other ideas.

It is important to note that a monopile might have either a scour pan or scour wake, but not both. If a scour wakes is present, then there is always a scour pit close to the turbine foundation. These features are all of negative relief. We have not resolved any evidence for small amounts of accumulation in the survey area.

Feature name	Physical Description	Reference	Typical Volume Change (m^3/monopile)	Comments
Scour Pit	V-shaped pit (5 m depth, 60 m diameter)	Elliott & Gardiner (1981) describe smaller versions in intertidal zones	5,000	Have no positive relief
Scour Wake	Tail of sediment disturbance	--	10,000 – 25,000	Eastern edge of OWF
Scour Pan	U-shaped pit	--	15,000 – 20,000	WTG25 and 26 (NW corner)

Table 9 - Bathymetric features associated with the monopiles and associated volume changes (per monopile) between successive surveys.

Ideally, the significance of the changes in volume associated with the scour pits, pans and wakes would be assessed using data taken before and after construction. However, there are no high-resolution swathe surveys representing the time before construction (only a single line survey in April 2002), comparison can only be made with features within the swathe area.

Within the Fledermaus © software environment, plots of the elevation difference between successive surveys were used to identify regions that had changed significantly between surveys. Three areas across Scroby Bank showed large variation between surveys: the ridge areas in the north and centre of the bank and an area to the west between the monopile lines (Figure 16, Figure 18).

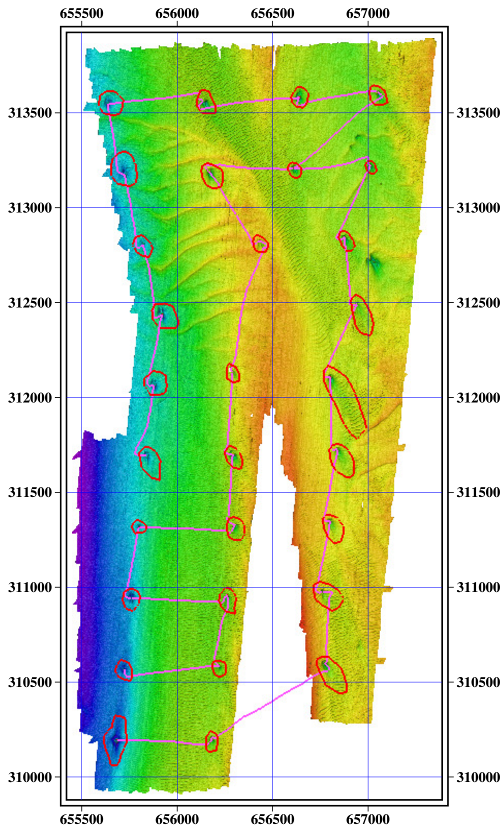

Figure 16 - Image showing the swathe bathymetry surveys of February 2005 along with the impact zone associated with each of the monopiles.

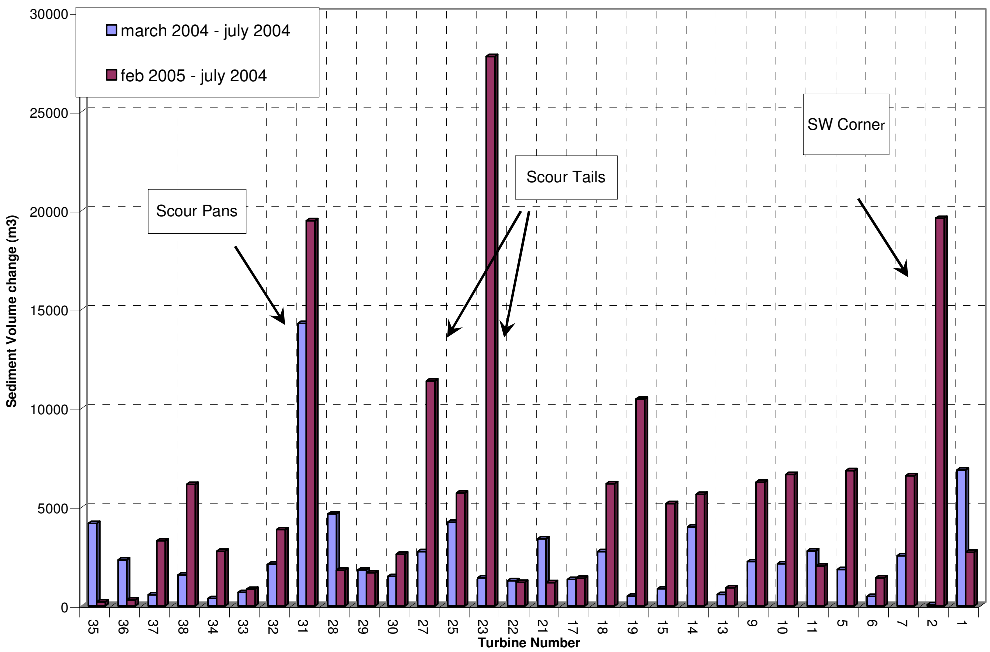

Figure 17 - Chart showing the difference in volumes of the bathymetric impact zones around each monopile over the period March to July 2004 (blue bars) and July 2004 to February 2005 (magenta bars). The locations of each turbine are in Figure 1. The largest changes in volume occurred at turbine 31 on the NW edge of the bank, at turbine 2 on the S end of the bank, and along the E side of the array (turbines 23, 19 and 27).

The volume change between successive swathe surveys are presented in Figure 19) for:

- Each monopile. Volumes are generally < 10,000 m^3;
- All monopiles together. Volumes are < 180,000 m^3;
- The three regions of Figure 18. Typical volume changes between surveys are ~100,000 m^3 for the central and western regions and 400,000 - 600,000 m^3 for the whole survey area;
- The whole of the area.

Thus, the changes in volume due to the presence of the monopiles appear minor when compared with changes in the total bank volume.

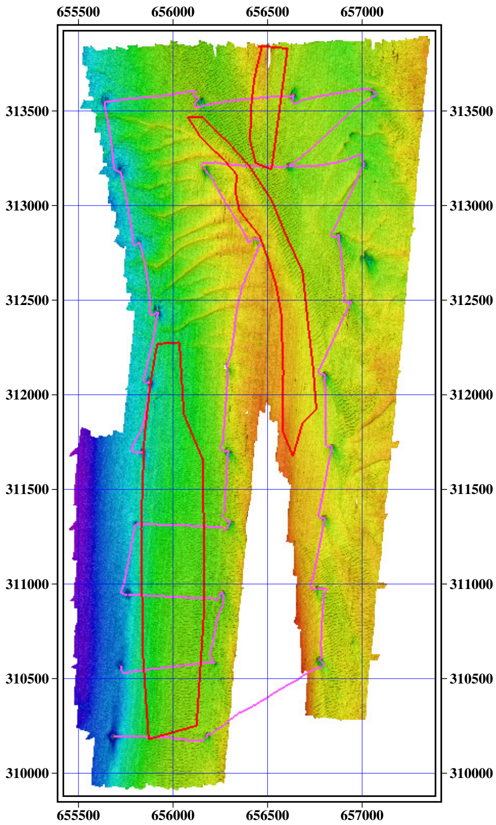

Figure 18 - Image as Figure 16 showing three areas not apparently impacted bathymetrically by the Scroby OWF.

The uncertainties in these estimates of volume change may be assessed by estimating the errors associated with their calculation. For swathe bathymetry surveys, the worst-case repeatable accuracies are of the order of 10 cm (Duncan Mallace, Netsurvey, pers. comm., 2006). Assuming that the whole of the area under consideration is in error (a slice of 10 cm thick), the worst-case volume error bar for the 'All monopiles' case is ~33,000 m^3, i.e. equivalent to 19% and 43% of the volume change for the two differences. The worst-case error bars for the whole of the survey area are close to 100%, because the volume signal being explored is very small compared to the potential volume change of the whole area. Overall, although these worst-case error bars are relatively large, they will probably never be encountered because:

a) the survey quality is good, as judged by the lack of de-tiding errors, coverage and detail, and;
b) the seabed is likely to vary in complex fashion, involving areas of accretion and other areas of erosion, rather than it all changing in the same direction.

In conclusion, the between-survey differences in bathymetry allow changes to be estimated of volume changes associated with scour pits, scour pans and scour wakes. By comparison with those areas of the bank which appear to be removed from any obvious impacts of these features, the bathymetric impact zones associated with the scour pits, pans and wakes are not volumetrically significant.

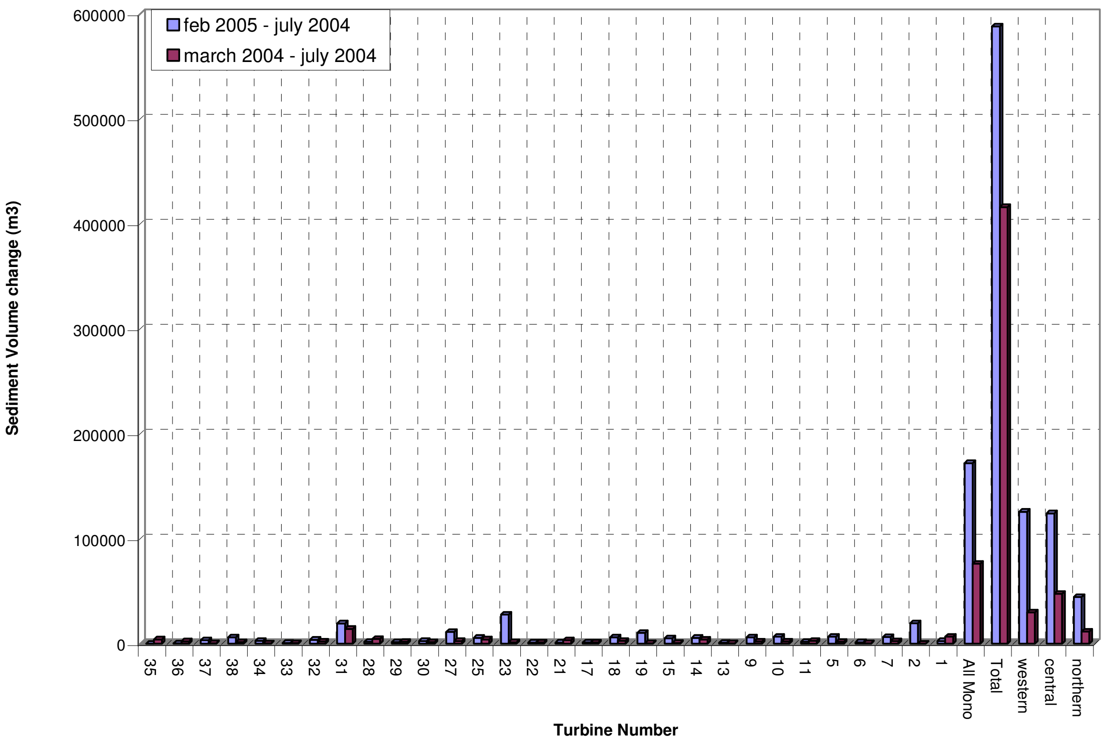

Figure 19 - As Figure 17 but also showing the volume changes over the whole of the survey area and also the three (naturally forced) areas of Figure 18 ('western', 'central' and 'northern'). The total monopile volume change is also displayed as 'All Mono'.

4.2.2 Bedforms

An assessment of the impact of the monopiles on the migration of the sandwave field can be made by comparison of the positions of sandwave crests at successive surveys (from pre-construction surveys through to operational surveys). It might be hypothesised that the sandwaves would be disrupted near the monopiles and their crests segmented, and/or that the sandwave migration would be impeded or accelerated by the presence of the monopiles.

For this analysis, the data from the April 2002 survey is readily suitable, so that four bathymetric surveys are available, in addition to that from the side-scan sonar surveys. A GIS database was constructed of the Scroby Sands area, showing the monopiles, cable infrastructure and results from side-scan and swathe surveys (Figure 6 and Figure 7). The position of the crests of the sandwaves was digitised from the sources identified in Table 4 and Table 5. Comparing the positions of the sandwaves over the surveys shows that:

(a) The pattern, orientation and spacing of crests do not alter significantly between surveys;
(b) The bifurcation of the sandwave crests does not alter significantly between surveys;
(c) An initial assessment does not appear to indicate a major change in sandwave position following the emplacement of the foundations.

Therefore, comparison of the bedforms after construction with those before construction shows no significant changes attributable to the presence of the turbine foundations (other than the presence of various scour-related structures).

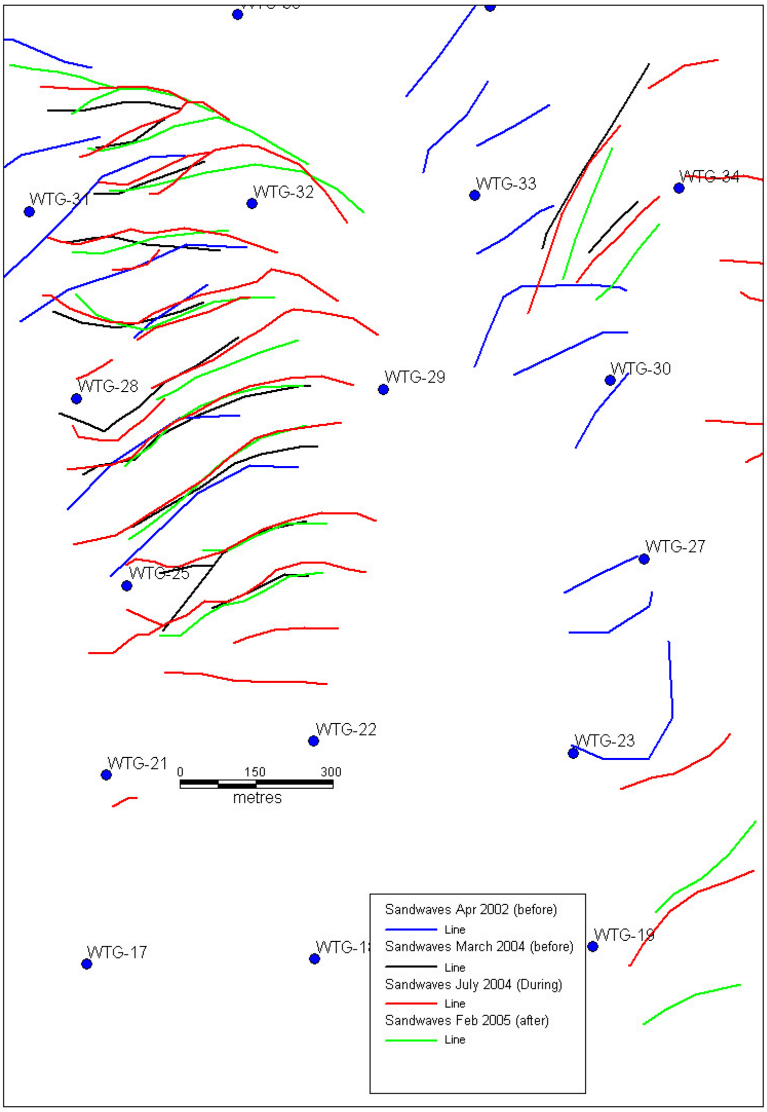

Figure 20 – – The location of sandwave crests in the NE sector of Scroby OWF measured at 4 times between 2002 and 2005 (from GIS database). As an example of change, the position of the sandwave between turbines WTG-28 and WTG-29 only moves ~18 m in four years.

5.0 Conclusions

A key aim of this project was the collection of data on waves, current, tidal elevation and suspended sediment concentrations from representative locations around an OWF situated on a shallow sand bank. This coastal process data was taken at times before, during and after construction of an OWF, to produce:

- An assessment of the change to sediment transport magnitudes and pathways;
- A dataset with which to assist verification and validation of wave and tidal numerical models in shallow water associated with sandbanks;

Over three field campaigns, data has been collected at four field sites, and bathymetric change has been characterised. This data will be used by E.ON UK, through their consultants Halcrow, to validate wave/tide numerical models in shallow water associated with sandbanks, where data was not previously available.

Further, this project aimed to assist the creation of a generic framework to help assess the impacts of wind farm development on coastal processes, and hence to inform the FEPA licensing process. This objective was achieved.

5.1 Outputs

This project has provided a set of coastal process data from before, during and after construction of an OWF, which is available to calibrate numerical models. This was one of the prime aims of the project, because the tops of sand banks are high-energy environments and thus poorly calibrated in numerical models. Further, the survivability of instruments had been questioned by developers. These new datasets have been sent to the developer's consultants, Halcrow, to assist in validation of their models.

The planning, installation and operation of OWF has been a steep learning curve for regulators and developers. This project, along with AE1227, has developed a detailed package of monitoring measures with which to understand and quantify the potential impacts of monopile based OWFs on coastal processes.

Finally, the project provides some reassurance to regulators that decisions on potential environmental impacts in such situations can be supported by evidence.

Presentations:

- Steering Committee, 13 May 2005.
- BWEA wind conference March 2004
- E.On Renewables board 10 October 2005
- Hydrographic Society, University of East Anglia, 24 Nov 2005
- The Impact of Offshore Wind farms on Coastal Processes – Scroby Scour Pits and Scour Wakes. Accepted by ICCE2006, San Diego.

Publications:

- Faire, S., Judd, A., Rees, J. & Larcombe, P. (2006) Regulation of UK Offshore Windfarms. Coastal News - Newsletter of the New Zealand Coastal Society: a Technical Group of IPENZ, 31, 22-22. http://www.coastalsociety.org.nz/pdfs/NZCS31.pdf

5.2 Sediment Transport

Three sets of deployments of seabed MiniLanders at and around Scroby Bank have collected coastal process data before, during and after construction of the Scroby Sands OWF. When combined with side-scan sonar and swathe bathymetry datasets, this allows a good understanding of the hydrodynamic and sediment transport coastal processes which operate on Scroby Bank.

During and following construction of the OWF, a series of installation-related sedimentary changes has been observed:

- Creation of scour pits with depths up to 5 m with diameters up to 60 m;
- Surface marks due to ploughing the intra-array cable;
- Troughs due to jetting from the end of the plough tracks to the sides of the scour pit;
- Scour protection around the base of each monopile (see Figure 24);
- Secondary scour pits associated with the placement of the scour protection
- Trains of bedforms have originated ‘downstream’ of the monopiles (here, to the SE, Figure 25).

Comparison of the three digital elevation models generated from swathe bathymetry surveys has enabled analysis of the scale and relative importance of scour pits, scour pans and scour wakes. By comparison with changes in volume from areas of the bank not impacted by the monopiles (i.e. where only natural processes occur), it has been shown that monopole-induced volume changes are not significant when compared with naturally-occurring changes. Similarly, a comparison of the nature and movement of sandwave crests in the NW part of the bank, from surveys from April 2002 to the present, has shown no significant changes in the position, shape or orientation of the sandwaves.

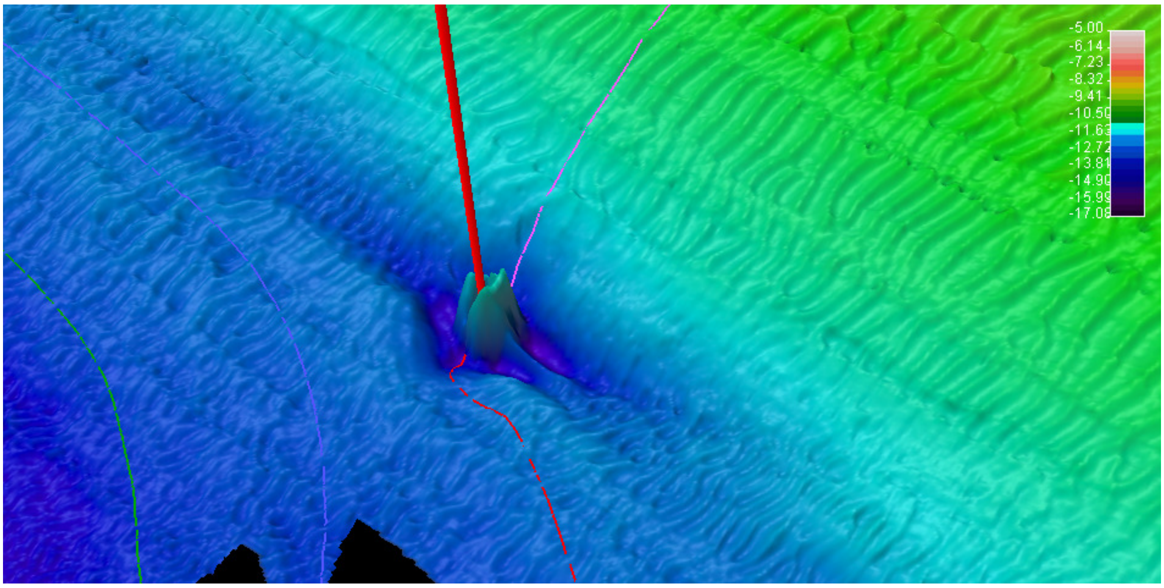

Figure 21 - Fledermaus image showing the scour protection around the base of the monopile (red cylinder ~4.2 m diameter, WTG01), along with the secondary scour pits and the "as laid" intra-array cable route (magenta line) and the export cables (red and green lines).

By combining the results from the swathe bathymetry survey and the MiniLander deployments a good understanding of the dynamics of Scroby Bank can be obtained. The tidal surge of 11th March 2005, when combined with the strong waves reset the sediment transport environment on Scroby Bank from a tidally dominated regime to one of wave domination. Large volumes of sediment infilled the northern edge of many of the scour pits and created scour wakes on the outer (eastern) monopiles. The orientation of the scour wakes was at approximately 30 degrees to the normal tidal direction due to the storm and surge generated currents when the resultant sediment transport direction is south east (see Figure 22 and progressive vector diagram in Figure 10).

The concentration of suspended sediment (SSC) around Scroby wind farm is typically of the order 50 to 100 mg/l due to the strong tides resuspending the sand (indeed, Figure 13 shows that tidal currents are capable of resuspending 500 μm sand ~80% of the time in summer). Thus, any potential impacts due to construction will not be observed above this baseline SSC. It should be noted there are circumstances where the background SSCs are likely to be low (e.g. in environments where there is little or no sediment available for resuspension). In such cases, constructional activities may cause detectable increases in SSCs above background concentrations.

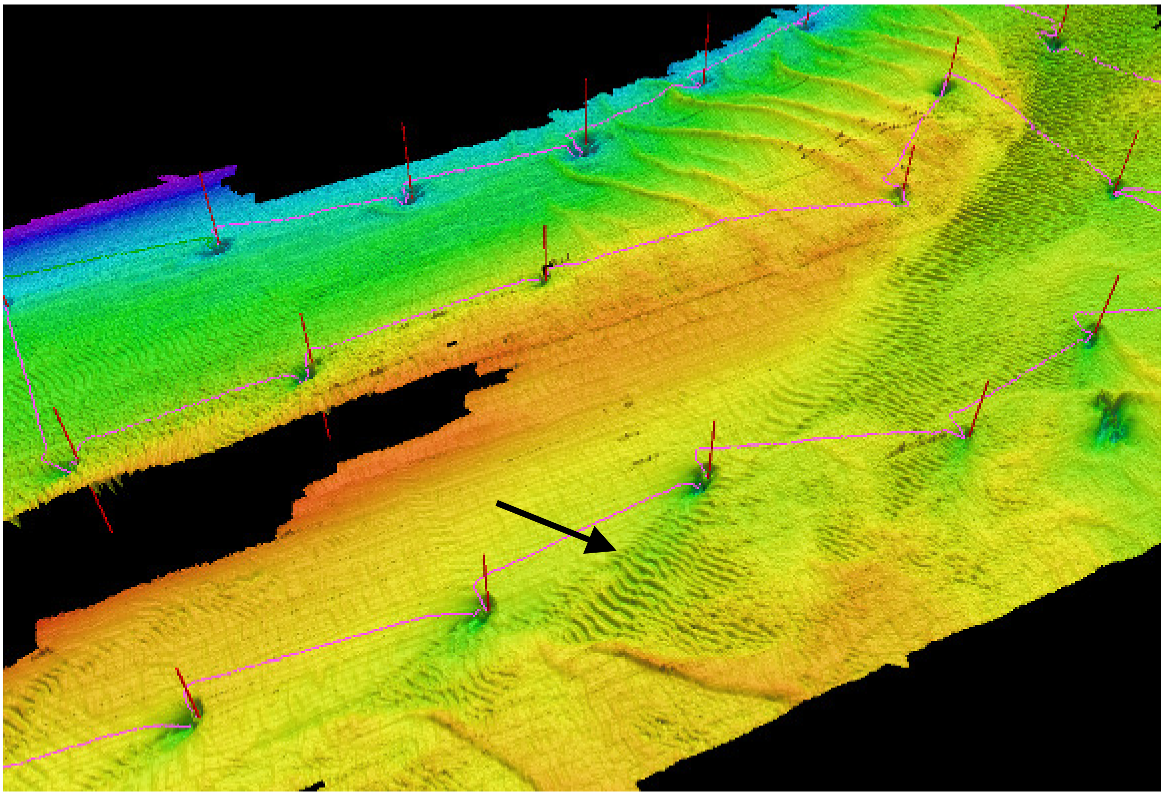

Figure 22 - Fledermaus image looking NW, showing results from the swathe bathymetry survey of February 2005 of the Scroby Sands OWF. Also shown are the monopiles (vertical red cylinders) and intra-array cable route (magenta). The black arrow indicates a scour wake extending SE to the neighbouring monopile. Distance between these monopiles (WTG 19 to WTG23) is ~375 m.

The residual sediment transport is southward, as indicated by the asymmetry of sand waves and the trends of megaripples observed by the side-scan sonar and swathe bathymetry. During a surge/storm event of which began on 11th March 2005, this southerly transport was enhanced in magnitude and changed to a south easterly direction. This implies that if any impact is to be observed on Scroby Sands, it will be in the southern part of the OWF array.

5.3 Uptake by Regulators

This work has indicated that the impacts of monopiles on coastal processes at Scroby Sands OWF are probably limited to scour pits (as predicted by the EIA) and scour wakes. The scour wakes are probably insignificant in comparison to the natural changes which occur at Scroby Bank. No change in overall elevation across the bank has been observed and the bank has appeared to maintain its overall morphology, with no creation of channels across the bank's flanks or crest.

These conclusions provide a degree of confidence to regulators and OWF developers that bathymetric impacts of monopile-based OWFs are probably limited to the order of 100 m around each monopile. Given monopile spacings of over 300 m, such bathymetric impacts are thus unlikely to be cumulative between monopiles and across the turbine array. Monopiles may act to initiate trains of sedimentary bedforms, so that in these terms the impacted area may be much larger and cross the gap between adjacent monopiles (Figure 25). This is likely to be the case particularly along the flanks of sandbanks where net transport rates of bed sediment are high. Such bedform generation is unlikely to alter either the net sediment transport rates along sandbank flanks or the overall sediment budgets of such sandbanks.

Finally, the ABPmer/ETSU report (ABPmer, 2002) had identified Scroby Bank as the worst-case scenario of the Round 1 developments, in terms of potential impacts on coastal processes. The results presented in this report, and the Defra-funded A1227 contract report, together indicate that there is little impact likely on coastal processes in the area. The sedimentary features associated with turbine foundations at Scroby Bank are likely to be typical of those likely to identified in other (but not all) OWFs, but observations elsewhere (e.g. London Array) indicate that the magnitude of the features may be significantly larger.

5.4 Generic Framework

One of the main aims of this work was to assist in the creation of a generic framework for use by both regulators and developers in assessing coastal processes issues within the EIA process and relating to any consequent FEPA licence conditions, particularly those related to monitoring.

5.4.1 EIA process

Sandbanks have been identified as a location to place OWFs because they are often areas that shipping does not enter and being shallow, offer some advantages in their foundation. However, these sandbanks are often very mobile and have implications for the type of construction of OWF, the depth of cable burial and potential impacts on the sediment transport regime. Therefore, for regulators to understand the coastal processes at a site and for regulators to quantify the relevant processes, they would need:

i. Time-series of swathe bathymetric surveys over the whole site and any export cables. This should also be placed into the historic context, using analysis of historical charts;
ii. Shear-stress exceedance diagrams for key locations within the OWF and along the export cable route;
iii. Particle-size information for sediments from representative locations within the OWF and along export cable routes. Alternatively, particle settling velocities would suffice;
iv. Estimation of the size and shape of scour pits and wakes and the nature of any emplaced scour protection;
v. Estimation of the disturbance caused by the construction of the wind farm, caused by, for example, jetting, ploughing, ‘grouting in’ or from seabed levelling for gravity-based structures;
vi. Assessment of sub-bottom geophysical acoustic data, which may allow identification of historic directions of sediment transport.

5.4.2 Monitoring

During construction and operation of OWFs, the following monitoring strategies are proposed to be best practice:

i. In locations where sediment is in transport for significant periods of time, there should be a comprehensive swathe bathymetric survey undertaken (ideally a time-series of surveys) which will allow analysis of sediment transport processes over the bank. Based on bi-annual seasonally linked surveys, these permit quantification of some key aspects of the sediment transport budget, identification of net sediment transport pathways and any areas of net erosion or accumulation;
ii. In regions where sediment transport is generally weak, a selection of representative scour pits should be monitored, and if found to exceed predictions made in the EIA, then a more systematic swathe survey would be undertaken across the area, to be repeated at appropriate intervals;
iii. High-resolution swathe bathymetry surveys of scour pits and associated scour protection measures should be undertaken to identify the extent, volume and integrity of any scour protection used. This would also allow monitoring of any secondary scour pits caused by the scour protection;
iv. Regular swathe bathymetric surveys of the export cable route to check for any cable free-spans (compromise of the cable), exposure (risk to shipping/fishing) or movement from the desired location;
v. During pile-driving, grouting or cabling operations, suspended-sediment monitoring may be required, especially if the surface sediments or the immediate subsurface has a high proportion of easily resuspendable grains, have elevated levels of contaminants or the operations take place near a conservation site (e.g. eelgrass beds, *Zostera marina*) or within a Special Area of Conservation (SAC).

In general swathe surveys could be supplemented by side-scan sonar surveys to give textural information and hence qualitative information on bed roughness.

5.5 Recommendations

Specifically for Scroby Sands, it is recommended that:

(a) FEPA licence conditions are emplaced to require that swathe bathymetry surveys are undertaken at six-monthly intervals to provide further evidence of the longer-term dynamics of scour pits and wakes, scour protection and wider-scale changes in bed elevation and patterns of net sediment transport. This data will allow an assessment of the equilibrium of the scour pits within the whole of Scroby Bank. Similarly, longer-term time series of digital elevation models will allow assessment of any changes in the overall bed elevations of Scroby Bank, particularly any creation of cross-bank channels. Swathe bathymetry provides the primary basis to monitor changes in geomorphology and thus is an essential tool for FEPA monitoring.

More generically, it is recommended that:

(a) The design and placement of scour protection in future wind-farm construction should be considered in more detail, because poorly designed scour protection can lead to secondary scour effects;

(b) Swathe bathymetry surveys should be required as a standard method of monitoring OWFs (and other activities impacting on the seabed, such as port construction, aggregate extraction and disposals of dredged materials) because such surveys provide robust data with which to calculate the volumes of material disturbed and assess the interactions with coastal processes;

(c) Further work should be undertaken to assess the magnitude and nature of the impacts of other types of wind-farm foundations as well as of the structures for other 'wet renewable' energy projects (e.g. tidal and wave devices). Understanding of the impacts of monopile-based OWFs is improving, but future OWFs may use a combination of hybrid or tripod structures and also very large gravity-based structures (GBS). These have significantly larger potential impacts because the surface area obstructing flows is large, and interactions between horizontal and vertical cylinders may increase bed stresses and hence local sediment transport. Further work is required to assess the magnitude and nature of the impacts of these structures on sediment transport. Similarly, the impact of fixed or moving structures for other wet renewables (tidal and wave device – e.g. the rotors of tidal turbines or oscillating columns of wave devices) are also poorly known and need to be assessed;

6.0 References

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7.0 Acknowledgements

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The extensive consultation and comments from reviewers is greatly appreciated.

Appendix A – Swathe Bathymetry

Four Swathe Bathymetry surveys have been undertaken to date (Table 10). Three of these surveys have been analysed in detail and are shown as colour-coded images of the bathymetry. Data has been analysed onto a grid spacing of 1 m.

Survey	Date	Contractor	Type	Comments
1	April 02	Coastline Surveys	Single Point	Before construction
2	March 04	Andrews	Swathe	Pre-Scour Protection
3	July 04	Andrews	Swathe	Post-Scour Protection
4	Feb 2005	Andrews	Swathe	After construction - winter
5	Sept 2005	Andrews	Swathe	After construction – summer (data not available during the contract period)

Table 10 – Timeline of Bathymetric surveys.

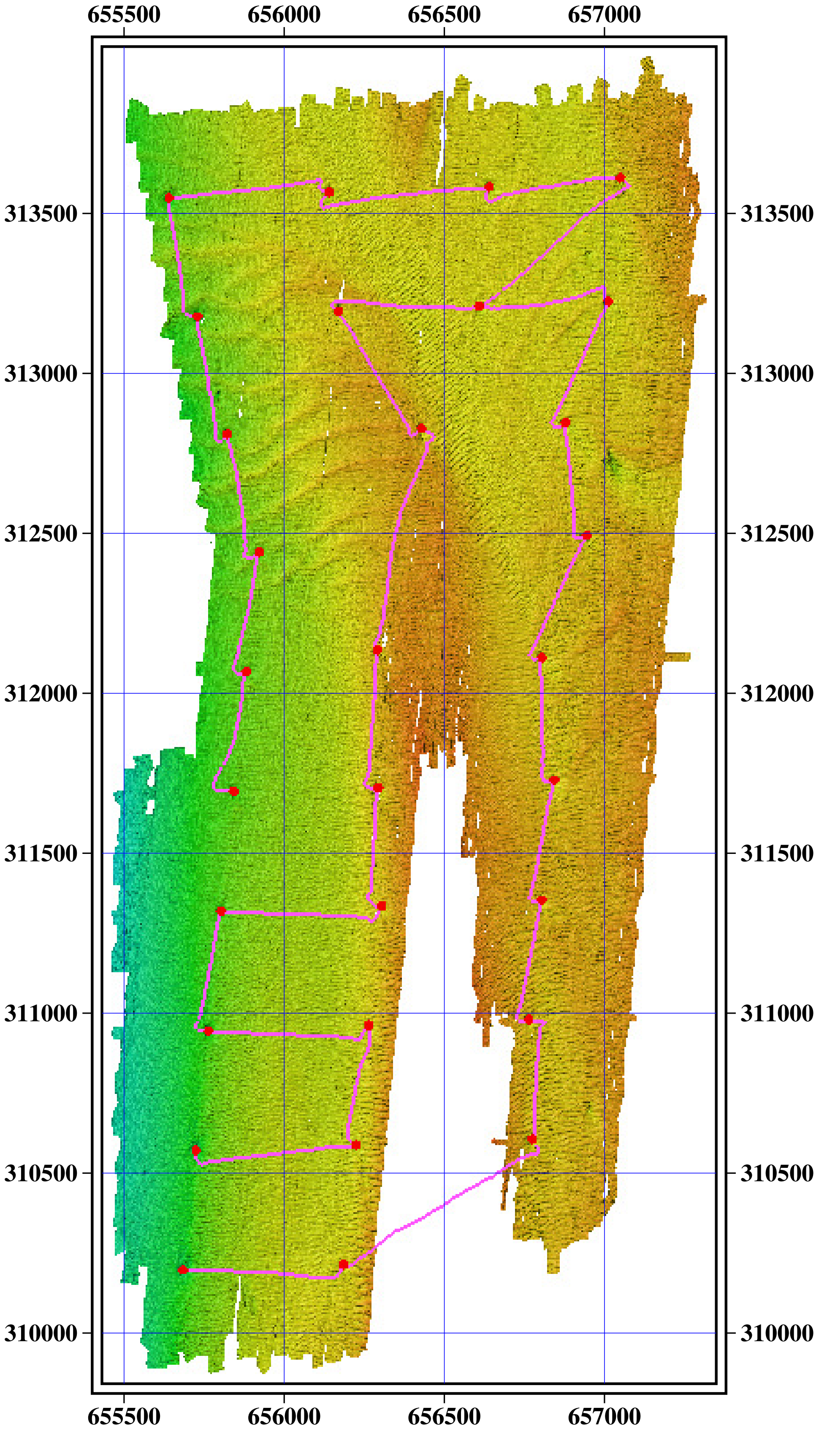

Figure 23 - Scroby Sands Swathe Bathymetry chart from March 2004.

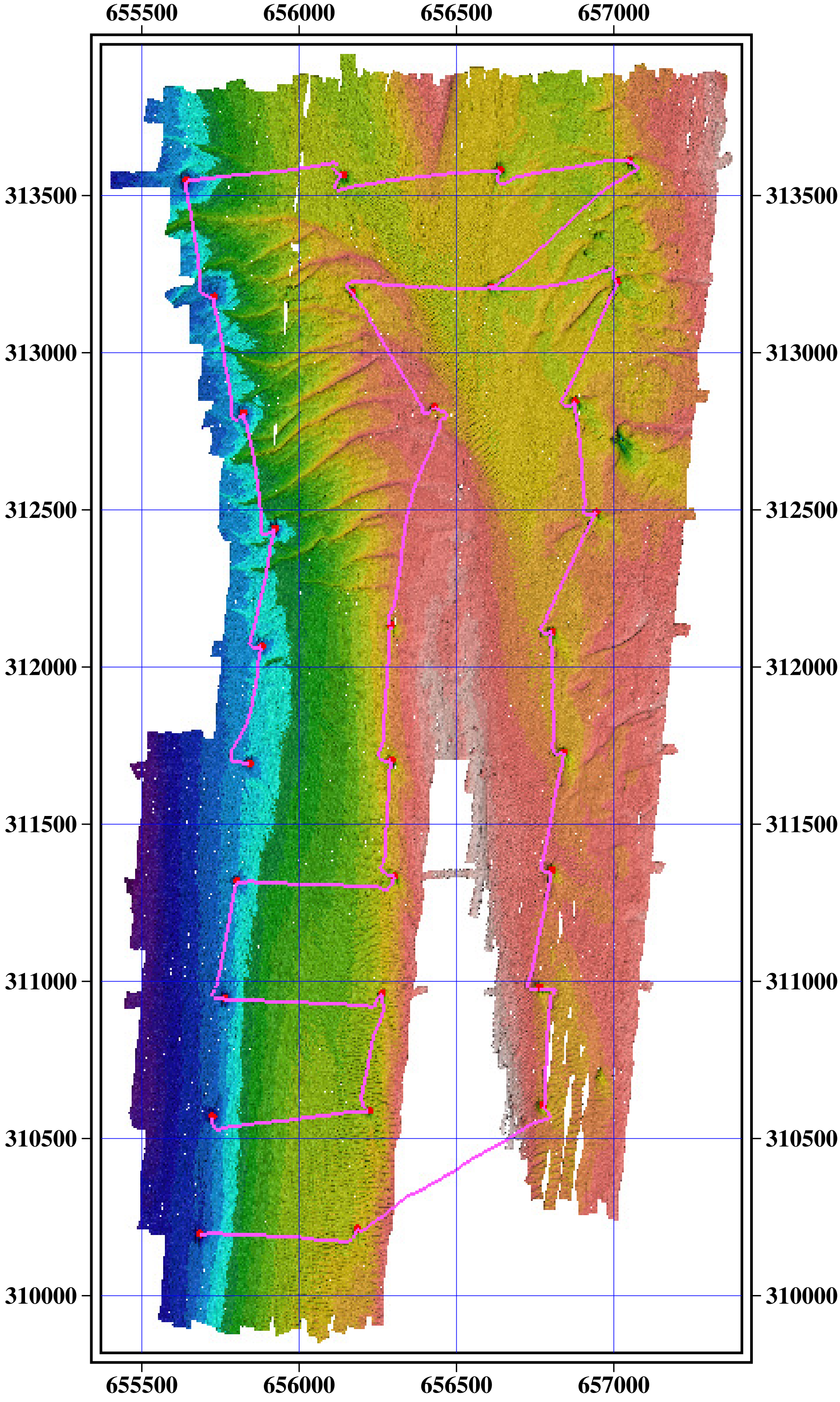

Figure 24 - Scroby Sands Swathe Bathymetry chart from July 2004.

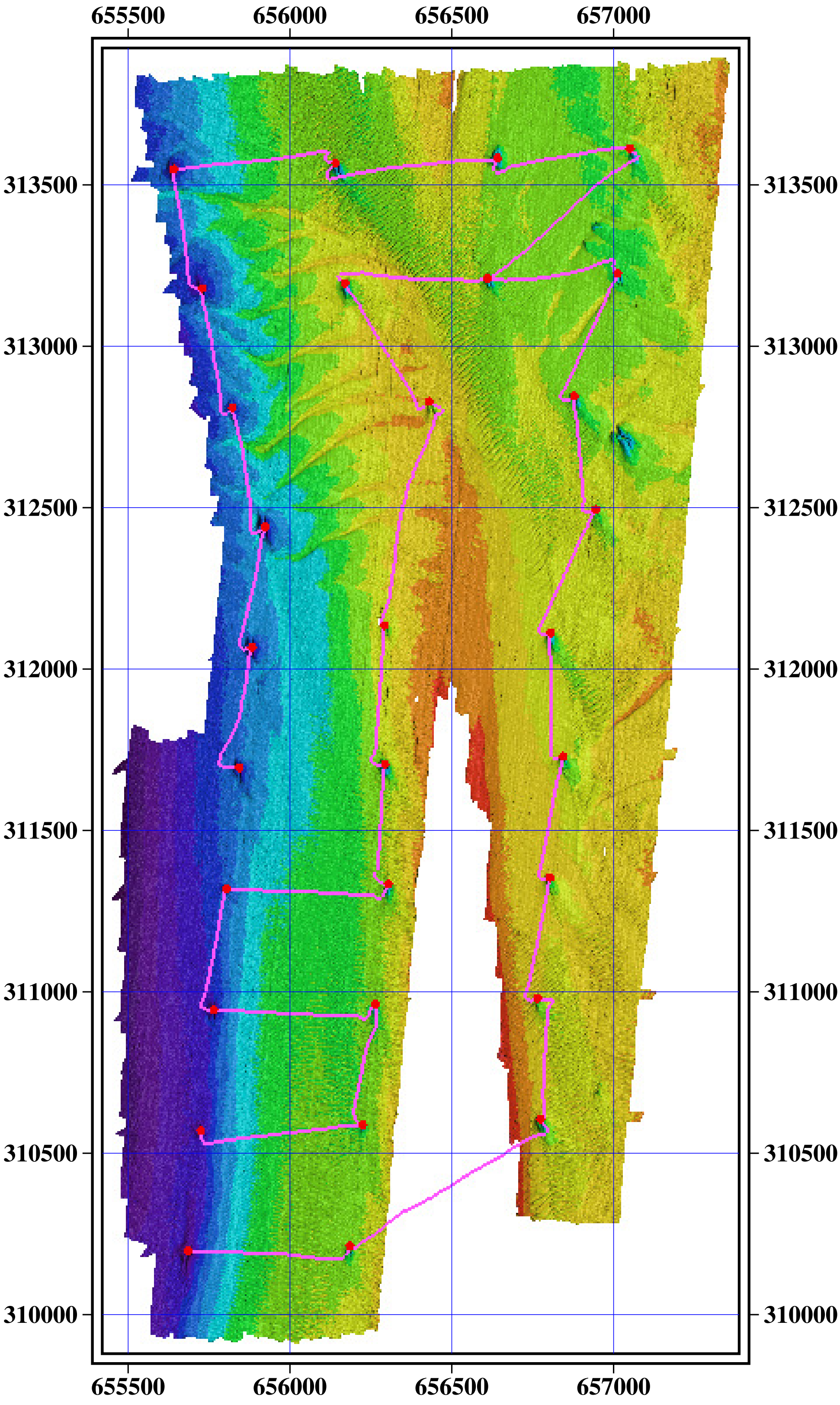

Figure 25 – Scroby Sands Swathe Bathymetry chart from February 2005.

Appendix B – GIS Datasets

A MapInfo © database exists containing the following information

1) Monopile locations as built;
2) Location of the "as laid" export and infra-array cables;
3) Locations and dates of sediment samples;
4) Locations and dates of sandwave crests;
5) Locations of bathymetric impact zones around each monopole;
6) Geo-encoded images (GeoTifs) of the swathe and side-scan sonar imagery.

A Fledermaus © scene exists for the four swathe bathymetry surveys.

Appendix C – Tabulated Particle-Size Analysis

Sieve size (mm)	64	32	16	8	4	2	0	0.5	0.25	0.125	0.063
	-6	-5	-4	-3	-2	-1	0	1	2	3	4
WENTWORTH Classification	Cobbles	Pebbles			Granule		Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand
Sample No.											
SS4								100.0	52.0	7.4	1
SS2							100.0	98.9	53.7	5.6	2
SS1					100.	100.0	95.9	90.6	25.7	3.9	1
SS3								100.0	58.3	5.6	2
SS5								100.0	74.0	17.4	1
SS9	100.0	98.1	89.6	78.7	69.7	65.0	58.9	58.1	36.7	16.8	9
SS8			100.0	99.5	98.0	98.0	98.0	97.4	33.3	3.4	2
SS7				100.0	99.7	99.0	88.9	89.0	33.3	6.3	2
SS10			100.0	99.5	98.3	97.0	82.8	82.1	45.3	24.3	10

Table 11 – Particle Size analysis (percentage passing) from sediment samples taken from Scroby Bank on 24th April 2005.