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Evaluating the Risk of Collision of Seals Swimming Within Metres of Operating Tidal Turbines

Jessica Montabaranom | Douglas Gillespie | Carol Sparling | Emma Longden | Gordon Hastie

Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, UK

Correspondence: Jessica Montabaranom (jlm35@st-andrews.ac.uk)

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ABSTRACT

We used imaging sonar to continuously monitor wildlife at an operational tidal turbine in the Pentland Firth, Scotland, between May 2022 and June 2023. Of 704 detected seal tracks, 347 occurred during turbine operation and 122 of these were detected directly upstream of the rotating blades in the horizontal plane. Using a series of repeatable and objective questions in a semi-automatic assessment, we characterised factors that were associated with a higher likelihood of collision and assessed the associated risk of collision between each seal track and the rotating blades. Thirty-five tracks (10% of tracks during operation) approached the rotor swept area within 10 m and 16 of these passed through the rotor swept area in the horizontal plane. There is strong evidence to suggest that most of these high-risk tracks passed above, around or possibly through, the turbine without collision. As well as providing useful data to assist in the prediction of collision risk, this approach provides a standardised method to evaluate similar data from other tidal energy sites or species. These outcomes can help inform the consenting process and support the sustainable development of the tidal energy industry.

1 | Introduction

Marine renewable energy (MRE) is a sector growing to meet green energy needs worldwide and contribute to Net Zero targets. In the United Kingdom, there is potential for as much as 11% of energy demands to be met by tidal resources (Coles et al. 2021); this has led to the expansion of the tidal energy industry in coastal, tidally energetic areas (Noble et al. 2025). However, these areas often overlap with important areas for a range of marine animals (Benjamins et al. 2015) such that they present potential ecological impacts to marine wildlife, some of which remain poorly understood (Copping et al. 2020). At present, globally, there are 40 tidal projects where ecological monitoring has been implemented to quantify potential impacts (Garavelli et al. 2024). The majority of tidal turbines being installed underwater are horizontal axis turbines that broadly resemble small wind turbines. Just as some bird species can collide with wind turbine blades (Zimmerling et al. 2013), a key concern for tidal turbines is the risk of collision between animals and the rotating blades of the turbine, leading to injury or fatality (Sparling et al. 2015; Copping et al. 2023). Given their large size and diving behaviour to depths at which tidal turbines are deployed, marine mammals may be particularly at risk from collisions with tidal turbine rotors.

Pinnipeds are abundant in coastal areas of many countries that are seeking to develop tidal energy. They are known to use strong tidal areas as foraging opportunities (harbour seals *Phoca vitulina*, in the United States/Canada (Zamon 2001; Zamon 2003) and in Scotland (Hastie et al. 2018), grey seals *Halichoerus grypus*, in the United Kingdom (Thompson et al. 1991)) and as travelling corridors (fur seals *Callorhinus ursinus*, in Alaska (Lea et al. 2009)). Stellar sea lions (*Eumetopias jubatus*) in the North Pacific frequent regions of high tidal flows (Mathews and Adkison 2010). Globally, pinnipeds are protected in such a way that makes them a primary interest for collision risk assessments. In Europe, species listed under the Annex II European Habitats Directive (Council Directive 92/43/EEC) receive additional protection and require monitoring to limit possible negative impacts. In other countries exploring tidal resources, such as the United States, the National Environmental Policy Act (NEPA 1969) requires the evaluation of potential anthropogenic impacts on all pinnipeds protected by the Marine Mammal Protection Act (1972). In Canada, the Marine Mammal Regulations (Marine Mammal Regulations, SOR/2018-78) can be triggered by an impact assessment, regulating interactions between pinnipeds and anthropogenic projects.

To estimate the potential impacts of future tidal turbine developments, collision risk models (CRMs) have been developed to help quantify the risk of collision between marine wildlife and the rotating blades of the device (e.g., Band 2016). CRMs require a number of biotic and abiotic parameters to assess this risk including estimates of animal abundance, animal swim speed, turbine rotor diameter and turbine blade speed. An important scalar in this model is the avoidance rate; here defined as the fraction of animals that would actively avoid a turbine, compared to a baseline condition if animals were swimming unaware of its presence. However, for pinnipeds, there is currently a paucity of empirical data to effectively set this avoidance rate scalar. There are a small number of studies that report changes in the distributions of harbour seals tagged with GPS tags in response to: a single demonstrator turbine (Joy et al. 2018), playbacks of tidal turbine sounds (Hastie et al. 2018) and a small turbine array (Onoufriou et al. 2021). Although these studies represent good progress in our understanding of how harbour seals behave in response to operating turbines at macroscale (hundreds of metres) and mesoscale (tens of metres) scales, information on the microscale (metres) underwater movements of individual seals around operating turbines has remained a critical research gap with respect to deriving avoidance rates and understanding the potential impacts of tidal turbines.

This gap partly stems from the limitations of suitable monitoring technologies to track pinnipeds underwater at the temporal and spatial scales required to quantify microscale avoidance. For species that vocalise regularly, such as harbour porpoises, passive acoustic monitoring (PAM) has been employed (Gillespie et al. 2021; Palmer et al. 2021; Gillespie et al. 2022). However, PAM is ineffective for species that vocalise irregularly like most pinnipeds. For non-vocal species, multibeam imaging sonars have the potential to track underwater animal movements (e.g., seal (Hastie et al. 2019), manatee (Gonzalez-Socoloske and Olivera-Gómez 2023)). These produce high spatio-temporal resolution images over an area in front of the sonar, which updates several times a second, so can be used to detect and track silent animals in turbid environments. Gillespie et al. (2022) developed and deployed an underwater monitoring platform which consisted of two multibeam imaging sonars to monitor wildlife around a tidal turbine in the Pentland Firth, Scotland. This system was used successfully to monitor seal occurrence around an operational turbine at a mesoscale (Montabaranom et al. 2025) and measure changes in occurrence as a result of turbine operation. Another reason for this gap is the difficulty of addressing uncertainties associated with microscale information. Although some level of residual uncertainty is inevitable given the limitations of current monitoring technology, a structured framework is critical for enabling decision-makers to act on the best available information. Such a framework can also guide various stakeholders in enhancing the understanding of the risk parameters.

As the UK hosts the largest operating array with full scale devices (Garavelli et al. 2024), it offers the opportunity to evaluate the ecological impacts tidal devices may have on seals. There are two species of seals widely found in the UK: grey seals and harbour seals, both of which have been reported to regularly use high tidal flow areas (Thompson et al. 1991; Hastie et al. 2016). These are protected by national legislation including the Marine Scotland Act 2010 and through the designation of Special Areas of Conservation (SAC).

In this study we used high resolution imaging sonar to analyse seal tracks within tens of metres of an operational tidal turbine in the Pentland Firth and characterise the tracks in terms of their movements and proximity to the turbine rotors. The objectives of the study were to investigate the number and nature of seal tracks approaching the blades within a micro spatial scale (< 10 m) and evaluate the risk of collision of each seal track detected within a meso spatial scale (10s of m) of the turbine using a standardised Collision Risk Interaction Scoring Protocol (CRISP).

2 | Methods

2.1 | Data Collection

The Inner Sound is a channel in the Pentland Firth between the Scottish mainland and the island of Stroma. Tidal flow speeds in this channel regularly exceed 4 ms^{-1} (Goddijn-Murphy et al. 2013). An array of four 1.5 MW tidal turbines was installed by MeyGen, SAE Renewables (now Ampeak Energy) and has been operational since 2016 (Figure 1).

This study focused on monitoring one of the turbines which has three blades of 9 m length with a rotor centre 14 m above the seafloor. The turbine support structure (TSS) sits on the seabed at a depth of approximately 33 m at peak low tide and 36 m at peak high tide. The turbine begins operating at tidal flow speeds above 1.2 ms^{-1} with rotation speeds increasing with flow from 6 to 14 rpm, giving blade tip speeds between 5.7 and 13.2 ms^{-1}. During slack tides, the blades may rotate slowly (< 1.5 rpm; blade tip speeds < 1.4 ms^{-1}). For the purpose of this study, we defined non-operational as rpm < 4 or operational as rpm ≥ 4.

To characterise the number and nature of interactions between marine mammals and the operating turbine in a low visibility environment, an underwater platform integrating multibeam imaging sonar and passive acoustics (High Current Underwater Platform [HiCUP]; Gillespie et al. 2022) was deployed on the seabed 30 m North of the turbine oriented so that two Tritech Gemini 720is imaging sonars were pointing towards the turbine, with the predominately East–West direction of flow being across the sonar image. Each sonar covered a 120° horizontal swath, with a −3 dB vertical beam width of 20°. The two sonars covered the same area in the horizontal plane, but were offset vertically by 15° to cover the full height of the turbine rotors and allow for detection of a target at any water depth. The system was connected to shore via a subsea umbilical cable forming part of the

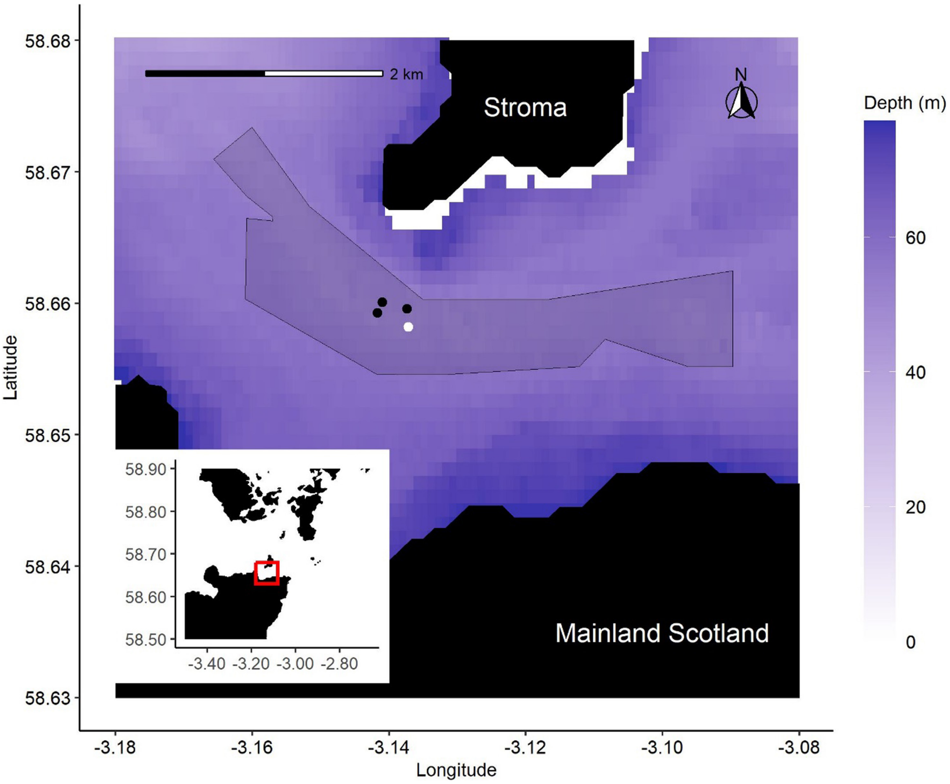

FIGURE 1 | Map of the MeyGen lease area and the Phase 1 turbines. The shaded area represents the lease area and the turbines are represented by the circles. The white circle represents the monitored turbine.

turbines infrastructure, which provided power to the platform and fibre-optic communications. Raw unprocessed data were collected using a PC in the onshore substation. Data were collected at a frame rate of ~10 frames per second (5 per second per sonar) using Tritech Genesis software (V1.7.3.37). The system was monitored remotely using remote desktop software and data archived to external hard drives for external data processing. The set-up, described in Montabaranom et al. (2025), allowed for almost continuous 24/7 monitoring from May 2022 to June 2023. Turbine operation data (orientation of the blades, rotation speed) and modelled tidal flow velocity data were provided by the site operator. The sonars collected data over 338 days between May 2022 and April 2023. Only data collected at a frame rate of ≥ 3.3 frames per second were used for analysis, resulting in 240 days of usable data.

2.2 | Data Processing and Risk Scoring

All raw sonar data were processed post hoc with the track detection algorithms described in (Gillespie et al. 2023) running as a module within the PAMGuard software (Gillespie et al. 2026). This algorithm is not species specific and was designed to detect all potential animal tracks in the sonar data. The algorithm made large numbers of false detections, caused by moving turbine parts and the shedding of turbulence from the tips of the turbine blades. The algorithm could also sometimes include regions of false detection as part of a genuine animal track. Further, a single animal track would often be broken into multiple smaller track segments by the algorithm, for instance as the animal moved vertically or its orientation changed thus altering its intensity in the sonar image. All tracks together with the raw sonar data were therefore reviewed and annotated manually using the PAMGuard Viewer. The reviewer manually joined track segments into what are predicted to be single animal tracks which form the basis of our analysis. In effect, these are saved as a sequence of time stamped XY locations with an associated series of ancillary data (e.g., distance of the detection from the sonar, angle, duration of track segment …). Tracks were assigned a species group (e.g., seal, diving bird, fish and elasmobranch) and a confidence score (CS) of from 1 (low) to 5 (high) depending on how confident the trained reviewer was of the classification. Seal tracks with a CS of ≥ 2 were used in the analysis, similarly to Montabaranom et al. (2025).

In addition to reviewing all tracks in the PAMGuard Viewer, a bespoke 2D display interface was developed in MATLAB (R2024b) to assist with the analysis of microscale movements to the turbine (Figure 2). This interface allowed for quick reviewing of each animal track, its position relative to the turbine, its direction of travel and speed relative to the tidal flow and the relative intensity of the detections on the upper and lower sonars, providing an indication of vertical position.

The risk of collision between each seal track and the turbine rotors was characterised using a combination of automated outputs based on track location and manual review. The characteristics of each track were stepped through a decision tree process (Collision Risk Interaction Scoring Protocol: CRISP; Figure 3) which consists of a series of standardised and repeatable questions leading to 17 risk categories. This classified the tracks according to their relative risk of collision, with each step being associated with a higher risk.

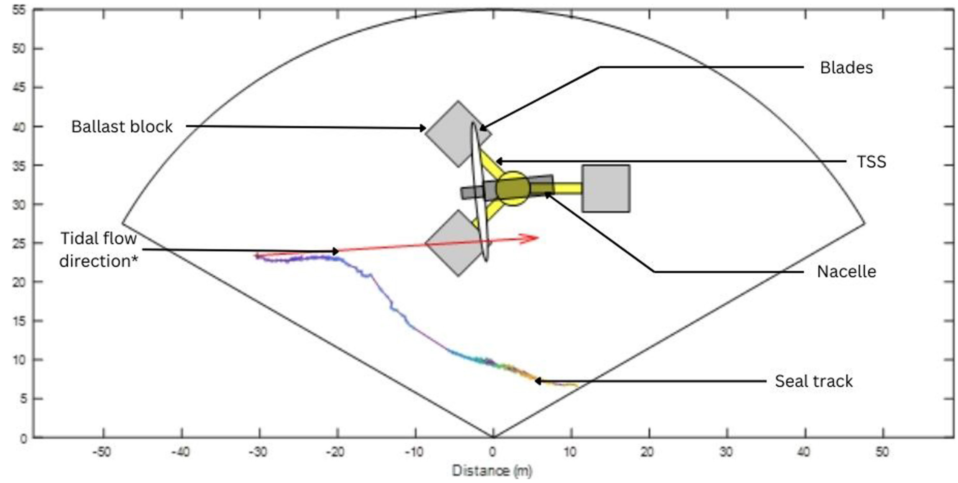

FIGURE 2 | Plan view of an example seal track avoiding the turbine in the MATLAB interface during the ebb tide. The grey and yellow structure in the centre of the swath represents the turbine support structure. The direction of tidal flow is shown by the red arrow, the length of which is the distance that would have been travelled by the seal over the duration of the track were it passively drifting*. The track is colour coded to show the temporal progression of the movement where the blue dots represent the start of a track and yellow the end.

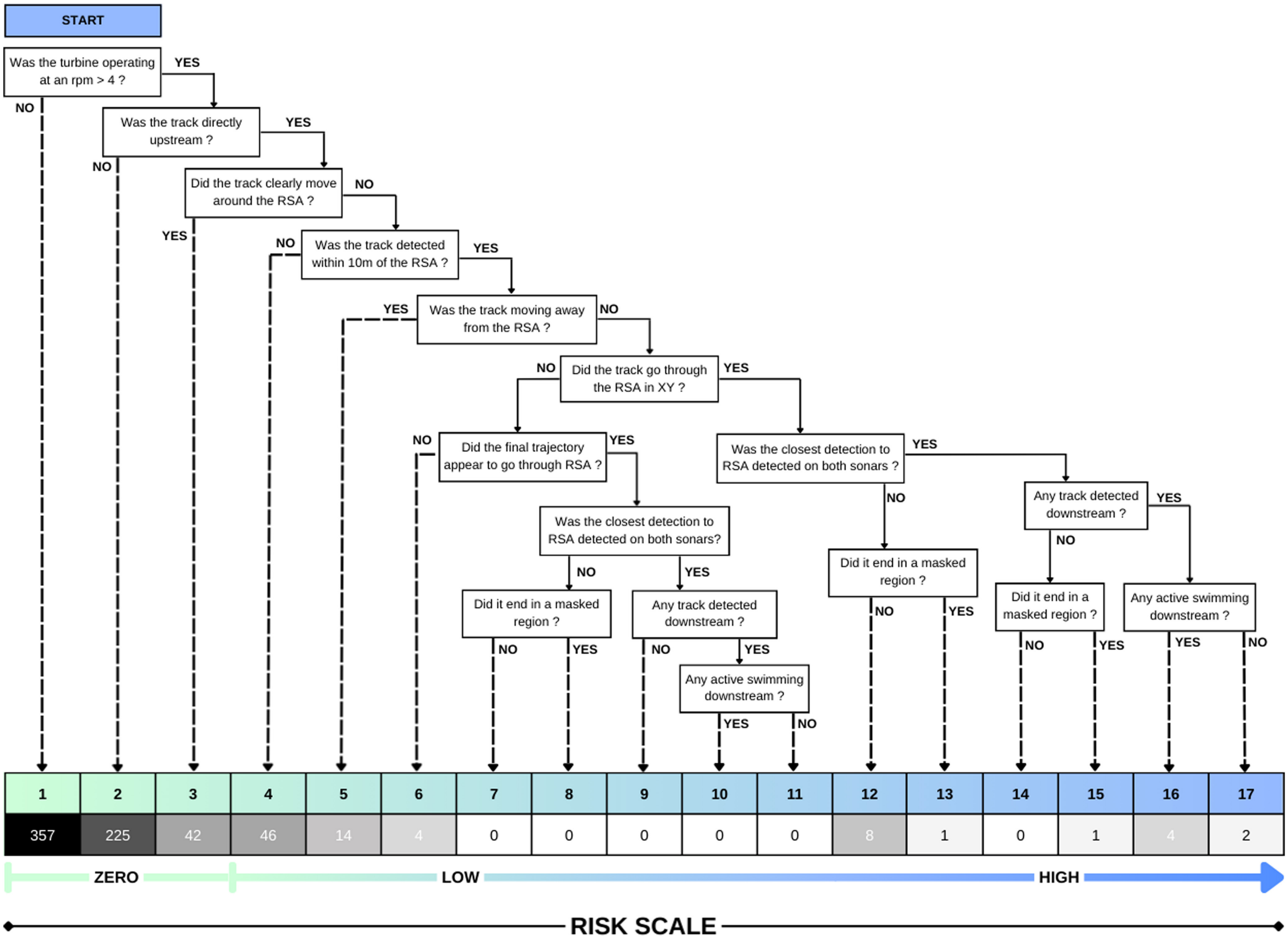

FIGURE 3 | Schematic showing the Collision Risk Interaction Scoring Protocol (CRISP) flowchart. The flowchart is constituted of 17 risk categories, of ascending risk from left to right, CRISP 1 as the lowest risk and CRISP 17 as the highest risk of collision. Each step is defined by a question. Tracks present in CRISP 1–4 are processed automatically. Tracks ending in CRISP 5 and above required additional manual assessment. The numbers displayed below each CRISP score in the table correspond to the number of seal tracks categorised into the adjacent CRISP score. These are also coloured coded from black to white, black being the highest number of tracks in one category and white as zero tracks. For example, 357 seal tracks were detected when the turbine was not operating at an rpm > 4 and categorised as CRISP 1 and colour coded as black. *Note:* a higher risk of collision does not mean that a collision occurred.

The first steps of the CRISP utilise the automated outputs, while the later higher-risk decision points were reliant on the manual review and more subjective assessments of behaviour.

The automatic analysis outputs were based on the tracks' characteristics in relation to six regions around the turbine (Figure 4—zones labelled A to F), with the Rotor Swept Area (RSA: Box A in Figure 4) defined as the area in the horizontal (XY) plane within +/− 2 m of the rotor position and 1 m beyond the blade tips, i.e., a 4 m × 20 m box around the blades. This is approximately the equivalent of a seal body length in front of and behind the rotor and over a seal body width to the side, thus allowing some level of precaution. An algorithm using point detections from the track determined which regions (Figure 4: A—F) the seal moved through (Table 1) to automatically assign a preliminary risk score to each track. Due to the nature of the mechanism of the tidal turbine and the rotors changing position depending on whether the tidal flow is on the ebb or the flood, the rotor position rotates to face the incoming flow. As the designated zones from A—F are relative to the rotating blades, these zones change according to the position of the rotors and therefore the incoming tidal flow, as shown in Figure 4. Vertical information from the dual sonars was not used in the automatic assessment. The automatic analysis was designed to be precautionary. For example, a track was sometimes automatically assigned as high-risk due to its proximity to the blades; however, the manual review would show clear avoidance of collision in the raw sonar data which was not captured by the movement detector. This resulted in the track being ultimately assigned to a lower CRISP category.

All seal tracks were manually reviewed by three experienced auditors (JM, DG and GH) using both the MATLAB and the PAMGuard Viewer interfaces. This review used the CRISP decision points and included: an assessment of the swim direction, its likely vertical position in the water column, swim behaviour both upstream and downstream of the rotors, whether there was additional track visible in the raw data that was not detected by the detection algorithm, and whether the track entered a region of the display masked by parts of the turbine structure. The masked regions include the ballast blocks and TSS, the nacelle and the area directly behind the blades. For tracks with detections on the upstream and downstream sides of the rotors, we also evaluated relative track speed. The water flow directly behind the rotors slows substantially as energy is extracted (Fraser Johnson, pers. Comm.), such that a track that exhibited a reduction in speed was considered as evidence that the seal passed through the rotors. This information was unclear for most tracks but did help characterise outcomes for some. The review process also accounted for detection of tracks downstream of the RSA when investigating the outcome of a track that went

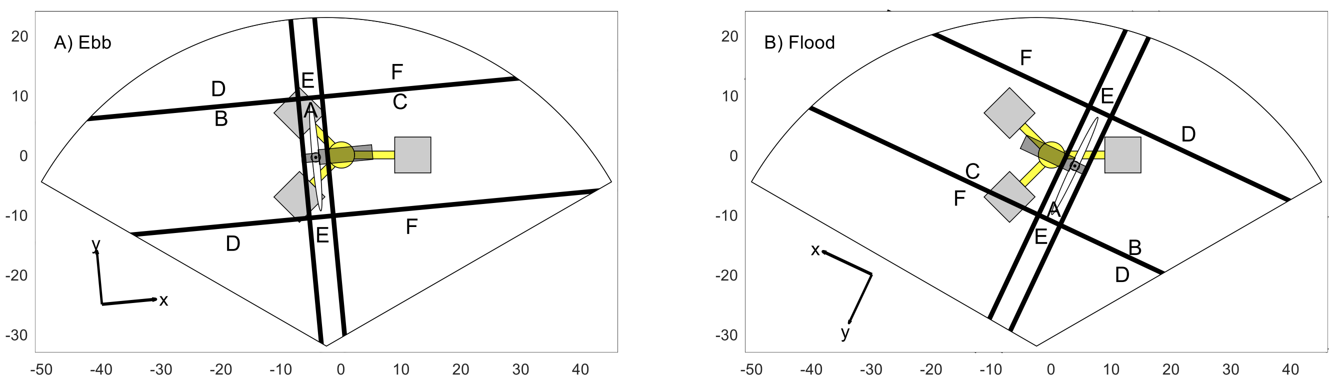

FIGURE 4 | Plan view schematic of six different zones (A to F) around the TSS for Ebb and Flood tides. Zone positions are fixed relative to the turbine rotor, so are in different physical locations on the flood and the ebb tides.

TABLE 1 | Description of how the algorithm classified each track into its corresponding CRISP category based on point detections. All tracks in the higher categories required manual review to determine their final CRISP score. RSA = Rotor Swept Area.

CRISP score	Description of point detections	Point detections in boxes in Figure 2	Type of assessment
1	Turbine not operating	Any	Automatic
2	Points only to side or behind RSA	C + D + E + F	Automatic
3	Started in front of RSA, but clearly passed safely	B + E + F	Automatic
4	Upstream points only with some directly in front of RSA, track disappeared > 10 m from RSA	B OR B + D	Automatic
5	Upstream points only with some directly in front of RSA, track disappeared < 10 m from RSA	B OR B + D	Automatic/manual
6	Passed RSA with points directly in front of or behind, but no data to indicate if it went through or around.	B + C OR B + F OR D + C	Manual
≥ 12	Points directly within RSA	A + any others	Manual

through a masked area. For example, a seal displaying signs of active swimming downstream of the turbine was assumed to have avoided collision.

3 | Results

A total of 704 seal tracks were annotated by the reviewers, with 347 of these when the turbine was operating. These were likely a combination of both grey seals and harbour seals as we are unable to differentiate between species in the sonar data. Compound plots of all tracks recorded during turbine operation are shown in the Supplementary Material. Of the 347 tracks detected while the turbine was operating, 267 (77%) were categorised as zero risk either because they were never directly in front of the rotors or showed clear movement around them (i.e., travelled through Zone E, Figure 2, Table 1). A further 46 tracks detected in front of the rotors disappeared from the sonar images > 10 m upstream from the RSA. As these animals would not have been in a masked region, they were deemed to have been close to the surface or the bottom, where detection probability is likely to be lower. This indicates they were likely to be either above or below the RSA and, therefore, also at a low risk of collision. Of the remaining 35 tracks that were detected upstream and within 10 m of the RSA, 14 clearly moved out from Zone B (directly upstream of the turbine) to Zone D (adjacent upstream of the turbine) and a further 4 had post-track end trajectories towards Zone D. The remaining 16 tracks were detected close to the RSA (Zone A) or had post-track end trajectories heading towards this zone, resulting in them being classified as higher-risk tracks (CRISP scores ≥ 12). Plots and detailed narratives for each of the 16 higher-risk tracks are provided in Supporting Information.

Eight of the high-risk tracks (CRISP 12) were only visible on one sonar and were likely close to either the water surface or the seabed, so are unlikely to have passed through the RSA. The one CRISP 13 track was detected when the lower sonar was not working; however, this track had a very clear speed measurement and did not slow down as it passed the RSA, so we believe it passed above the blades (Figure 5). The one CRISP 15 track turned sharply around 4 m in front of the RSA. The raw data for this track show that the animal then made an additional 180° turn and became increasingly visible on the lower sonar, indicating that it was diving. The track did not end in a masked

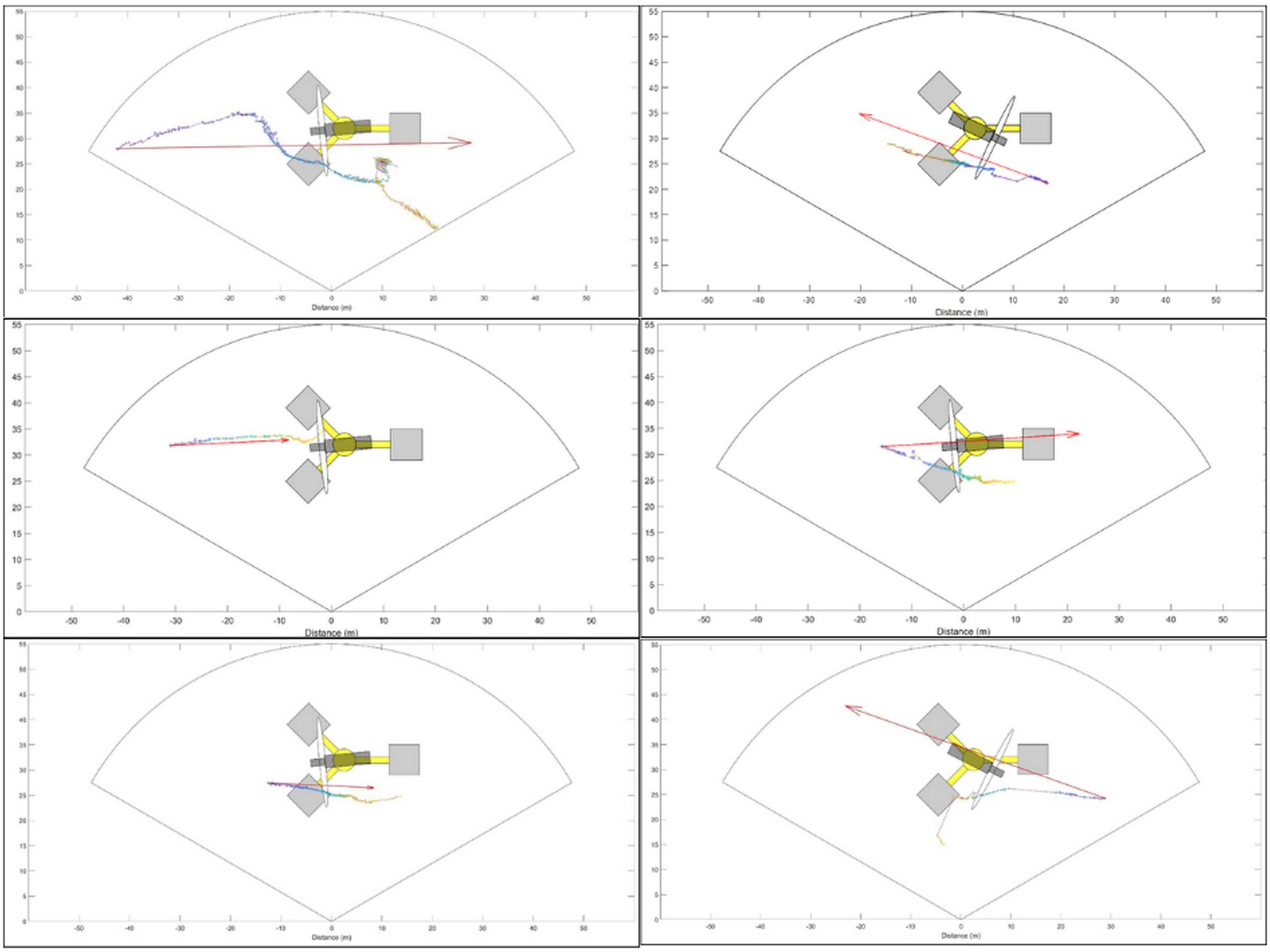

FIGURE 5 | Multipaneled plot showing an example subset of higher CRISP score tracks (6 out of 16). Each plot represents a different higher-risk seal track from our dataset. The track is colour coded to show the temporal progression of the movement where the blue dots represent the start of a track and yellow the end. The 16 higher-risk tracks can be viewed in the Supporting Information. The respective IDs of these tracks (clockwise starting from top left): 23/1988; 33/310; 33/199; 38/244; 19/848; 31/1112.

region and it is believed to have been close to the seabed. Four tracks were given a CRISP score of 16, meaning that they were detected on both sonars and therefore likely to have been at similar depth to the RSA, but displayed active swimming behaviour after passing through the RSA in the XY plane (one only manually, having been partially missed by the detector). Two tracks had the highest CRISP score of 17, indicating that they likely went through the RSA and although they were detected downstream, there was no evidence of active swimming (Figure 5).

4 | Discussion

This study is the first to examine the fine scale movement behaviour of individual seals close (within 30 m) to an operational tidal turbine. It also successfully demonstrates the use of multibeam imaging sonars to track seals in a turbid environment at a fine scale spatial and temporal scale continuously over a period of 12 months. This study characterised the risk of collision between seals and the turbine rotors using a decision tree process constituting both automated analysis outputs and a series of objective and repeatable questions. This allowed the ranking of collision risk for each seal track into one of 17 risk levels. This resulted in 16 'high-risk' tracks, where eight were likely above or below the rotors in the water column and a further four showed active swimming behaviour downstream of the RSA. The lower sonar was not working during one encounter, but speed data indicate that animal did not enter the region of low flow behind the rotors, so was assumed to be above them. Another animal entered an acoustically masked region, but detailed review of the raw data revealed track segments undetected by the movement detector but visible in the raw data, indicating the animal dove to the sea floor. Two other tracks were allocated to the highest risk score, indicating that they are highly likely to have moved directly through the RSA at approximately rotor level. However, importantly from the perspective of understanding seal collision risk, one of the tracks rated in the highest risk category was given a species confidence score of 2, meaning that confidence that the target detected was a seal was relatively low. Upon review of these 16 higher-risk tracks, most track parameters showed that the track was unlikely to have passed through the rotors. This emphasises the importance of contextual information when determining the outcome of a track and evaluating the risk of collision.

In the absence of empirical data, Copping et al. (2023) developed a structured approach to assess collision risk to help guide decision makers and quantify the associated likelihood of a series of events that would result in a fatal collision. Although some of the risk parameters (e.g., animal in close range of the turbine, at turbine depth) identified in the CRISP are similar to those described in their probabilistic framework, our approach differs in that it uses metrics derived from objective questions and automated analyses based on the empirical seal track data to determine numbers of animals at a zero, low and higher risk of collision. The CRISP approach described here therefore builds upon the framework developed by Copping et al. (2023) to quantify risks of collision and can ultimately help regulators and industry to make informed decisions about the risks associated with tidal turbine developments.

The sonars allowed tracking seals in high resolution in the horizontal plane, though provided limited vertical information and were not able to differentiate between grey seals and harbour seals. Although the majority of the tracks provide sufficient evidence to make a decision on the outcome, there are a small number that do not, either because they have entered a masked area (caused by the nacelle, behind the RSA or features on the seafloor) or had insufficient vertical information. Having more detailed three-dimensional information of the tracks that were classified as high-risk would be helpful in determining the outcomes of the close approaches by seals, in a similar way to the use of 3D tracks by the windfarm industry to assess collision risk between birds and wind turbine blades (Therkildsen et al. 2021; Mikami et al. 2022). Furthermore, it was not possible to determine if a collision had occurred on sonar even when it appeared to pass through the RSA. The last step of the CRISP framework highlights that we cannot identify any collisions. There are no steps in the framework that relate back to injury or mortality of a seal because we are unable to distinguish if a seal has collided and has been unharmed or has collided and sustained injuries or has not collided at all. Instead, the CRISP framework provides a structured way to characterise and manage the residual uncertainty surrounding the outcome of each seal track. Additional details describing each step of the framework can be found in the Supplementary Material. Cameras could be used to reduce this uncertainty and provide improved species identification. However, in our study only five out of the 16 higher-risk tracks occurred during hours of daylight, so cameras would only provide limited additional information. Turbid waters caused by high tidal flow speeds would also make using cameras challenging. Investigating other monitoring technologies that are not dependent on imagery would be a useful avenue to explore. For example, installing sensors on the blades of turbines, where detection of contact between the rotating blades and a large object could provide evidence of a collision in a turbid environment and independent of daylight.

From a behavioural response perspective, the majority of the seal tracks detected directly upstream of the turbine showed either clear movement around the turbine or trajectories that indicated they were moving away from the RSA. This suggests seals detected the turbine and exhibited movement behaviour to actively avoid it. As the turbine in this study is known to emit noise over a wide range of frequencies when operating (Risch et al. 2020), it would likely be clearly audible to any marine mammal at distances of 100s of metres. Hastie et al. (2018) demonstrated that harbour seals could detect tidal turbine sounds up to 200 m away and displayed avoidance to the noise. It is possible that the turbine was visible underwater within ~10 m of the turbine and seals' other sensory capabilities may have allowed them to detect changes in hydrodynamics upstream (Dehnhardt et al. 2001; Niesterok et al. 2017). For example, previous studies have shown that seals are able to detect minute water movements from prey up to 180 m downstream using their whiskers (Dehnhardt et al. 1998; Dehnhardt et al. 2001), suggesting they may be able to detect the operational turbine at a larger spatial scale (i.e., mesoscale to macroscale). A better understanding of how seals detect the turbine would help in understanding the transferability of our results to other developments.

CRMs use an avoidance rate parameter, the proportion of animals that are predicted to avoid a turbine, compared to a baseline condition if animals were swimming unaware to its presence. In the absence of empirical information on avoidance rates, a range of avoidance rate values (0%–99%; SNH 2016) is typically applied. In our study, avoidance can be defined as follows:

$$A = 1 - \frac{n}{n_0}$$

where A is the avoidance rate, n is the number of animals that went through the RSA and n_0 is the number that would have gone through the RSA with no avoidance. Although the results presented in the current study provide the basis for calculating avoidance rates incorporating behavioural parameters, which are not currently incorporated into current CRMs, extracting an avoidance rate from the data is far from straightforward. Specifically, questions arise as to what the appropriate numbers are to use for n and n_0. If we only consider data in the horizontal plane, then a suitable number for n from the current study would be 16 (Table 2). However, considering the vertical position, there is evidence to suggest that at least half of these and possibly 6 others, were not at depths covered by the RSA, in which case n might be anywhere between 8 and 2. Similarly for n_0, in the horizontal plane, 122 tracks started directly upstream of the RSA and would have moved through the RSA if they followed the trajectory of the tidal flow. However, it is possible that some animals had started to avoid the RSA before being detected on the sonars, in which case n_0 should include a proportion of the 225 tracks that were scored as no risk (CRISP 2). Alternatively, when we consider the vertical position of the animal, the RSA only covers ~40% of the water column, a proportion of those 122 seals would not have been at depths covered by the RSA, so should be excluded from our count of n_0. In addition, it is important to highlight that these represent avoidance rates only within the scale of the sonar monitoring area (~30 m from the turbine) and do not account for avoidance by seals at larger distances such that they are not detected by the sonar at all. For example, Montabaranom et al. (2025) reported a mean reduction in presence of seals of up to 77% (95% CI: 22%–93%) from these same data when the turbine was operating. Therefore, these avoidance rates are not directly analogous to the avoidance rate typically applied as a scalar in collision risk modelling exercises (SNH 2016) and should not be used in isolation to populate current CRMs. A clear avenue for further research is to review and combine existing information on avoidance rates by marine mammals at macroscale (e.g.,), mesoscale (e.g., Palmer et al. 2021; Montabaranom et al. 2025) and microscale (e.g., Gillespie et al. 2021; current study) scales to derive overall avoidance rates to operational turbines.

Both grey seals and harbour seals regularly use the study area in the Pentland Firth (Carter et al. 2022). There is particular concern surrounding the risk of collision between the blades and harbour seals in Scotland, as many local populations have declined significantly in recent years. Harbour seals in the North Coast and Orkney SMU where the study area is located have undergone an 85% decrease in numbers since the late 1990s (Thompson et al. 2019). Potential biological removal numbers (PBR; Wade 1998) are set for SMUs around Scotland and aim to sustainably manage anthropogenic activities that may impact UK seal populations. For the North Coast and Orkney SMU, a PBR of 8 harbour seals per annum was specified (SCOS 2024). Importantly, it is possible that some of the tracks could have been created by the same animal or by a small number of specialist individuals exploiting increased foraging opportunities at the base of the device, as there is evidence for artificial structures attracting prey and creating an artificial reef effect (Russell et al. 2014). Understanding the proportion of the population using the area in close proximity to the turbine will help determine the population level impacts and further work is required to understand how this may impact local populations, including the risk of collision and subsequent mortality.

In terms of the feasibility of applying our data collection and processing framework to future studies, our results highlight that, although track data from sonars can be processed automatically to some extent, having an expert human reviewer follow a set of repeatable and objective questions was a key part of characterising the relative risks of collision associated with each track. In this study, three reviewers manually examined all tracks detected while the turbine was operating. Based on their locations, the majority of these (77%) were assigned to zero risk categories and a further 18% as likely being low risk. Manual review of those tracks assigned low CRISP scores (less than 5) resulted in not being assigned a higher score, indicating that the automated process will significantly reduce the resource required to review tracks. Of those 50 tracks automatically scored as 5 or more, only 16 remained in high-risk categories after manual review. This indicates that in future studies it may only be necessary to manually check tracks automatically scored as 5 or more, significantly reducing processing times. More importantly, the application of a standardised framework such as CRISP could benefit the transferability of results and allow comparison of the risks of collision between MRE sites and between different species.

The decision tree approach (CRISP) could also be applied to scenarios where adaptive monitoring approaches and timely reporting of potential collisions are required to measure against a threshold level of collisions, such as in environmental mitigation and monitoring plans (e.g., MacAulay et al. 2025). This approach is particularly useful in informing decisions given the uncertainty in whether collisions have

TABLE 2 | Summary table of number of seal tracks at risk and at rotor height, assuming the animals are evenly distributed in the water column.

Scenario	n	n_0	Microscale avoidance
Horizontal position only	16	122	86.9
Vertical position, assuming 40% at RSA depth	8 (worst case)	(0.4*122) 50	84.0
Vertical position, assuming 40% at RSA depth	2 (best case)	(0.4*122) 50	96.0

taken place, a likely scenario given the limitations of currently available technology to confidently assign species and identify actual collisions.

As the tidal energy industry grows, future work should explore the effects at the operational array level rather than from a single turbine. To scale our results to predict risks posed by an array, additional questions arise: would the risks associated with multiple turbines simply scale in proportion to the number of turbines or will it be more complex, depending on individual behaviour and seals learning over repeated encounters. Previous work with harbour porpoises Palmer et al. (2021) showed that their presence was further reduced when all turbines in an array were operating, compared with only one operational device, raising the possibility that higher levels of exclusion might be caused by an array for other species. Given the number of seals tracked past the operational turbine, it is clear that at least a proportion do not consider a small turbine array as an impenetrable barrier; however, this may be different for larger array sizes, depending on the spacing of turbines and on how animals use the area (e.g., travelling or foraging). It will also be important to understand the trade-off between avoidance behaviour to arrays that reduces acute impacts from collision risk but potentially increases chronic impacts through exclusion from important habitats. From this perspective, it will be key to consider how seal responses to arrays might be monitored at a variety of spatial scales and what technologies would be suitable to measure this. Future work should also investigate arrays at sites with different physical characteristics, as bathymetry and the width of the tidal channel may be important factors in determining collision risk, if animals perceive the array as a barrier. For example, an array situated in a wider channel would provide more space to avoid and therefore animals might be less likely to encounter turbines at a closer range. Such data would provide evidence to inform future array design.

This study provides information on the likelihood of seals approaching blades within a few metres, enhancing our knowledge on behavioural responses of seals to turbines and their risk of collision. It also provides a standardised approach to evaluating the risk of collision between seals and a single operational tidal turbine, accessible to regulators, developers, policy makers and other stakeholders. This framework could be transferred to similar monitoring data at other MRE sites and to other species at risk of collision.

Author Contributions

Jessica Montabaranom: writing – original draft, investigation, validation, formal analysis, data curation, visualization, methodology, writing – review and editing. **Douglas Gillespie:** conceptualization, data curation, software, investigation, methodology, formal analysis, validation, visualization, funding acquisition, resources. **Carol Sparling:** conceptualization, funding acquisition, project administration, resources. **Emma Longden:** data curation, investigation, writing – review and editing. **Gordon Hastie:** conceptualization, data curation, investigation, methodology, formal analysis, funding acquisition, resources.

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Ethics Statement

All procedures and data collection were performed in accordance with the relevant guidelines and current regulations and approved by the University of St Andrews School of Biology Ethics Committee (reference number SEC18014).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available via the PURE University of St Andrews Digital Repository: https://doi.org/10.17630/242227af-dc62-4218-847e-8c0e884de587.

The PAMGuard software and plugins are available via Zenodo: https://www.pamguard.org (Gillespie et al. 2026) and https://doi.org/10.5281/zenodo.13627798 (Gillespie 2024).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Turbine support structure schematic with the different risk zones, rotated according to (a) ebb and (b) flood tides. **Figure S2:** Plots of all tracks ($n = 347$) recorded while the turbine was operating divided by risk (Zero, Low or High) and by tide direction. Each track is colour coded starting with blue, ending with yellow in order to indicate swim direction. **Figure S3:** Collision Risk Interaction Scoring Protocol (CRISP) approach for assessing the risk of collision for a seal track, with respective number of tracks that fall into each risk category. The numbers displayed below each CRISP score in the table correspond to the number of seal tracks categorised into the adjacent CRISP score. These are also coloured coded from black to white, black being the highest number of tracks in one category and white as zero tracks. For example, 357 seal tracks were detected when the turbine was not operating at an rpm > 4 and categorised as CRISP 1 and colour coded as black. *Note:* a higher risk of collision does not mean that a collision occurred. The respective number in circles at each step of the framework help guide the user to the list of questions asked below.