ABWP Phase I Decommissioning

Scour Assessment

Volume 3, Appendix 4.3



RAMBØLL Bright ideas. Sustainable change.

Deltares

Scour assessment



Confidential

Scour assessment

Author(s)
Antine Reddingius

Scour assessment

Client	Ramboll UK
Contact	Sara Méndez Roldán
Project reference	Deltares' proposal, ref. 11212476-001-HYE-0001, dated 18th December 2025 Purchase Order, ref. 1620011606_Deltares 1, dated 19th January 2026
Keywords	Scour, monopile, decommissioning

Document control	
Version	1.0
Date	17-07-2026
Project nr.	11212476-002
Document ID	11212476-002-HYE-0002
Pages	44
Classification	Confidential until further notice
Status	Final

Statement of authority

Authors / Quality assurance	Qualifications	Relevant experience	Role in this project
Antine Reddingius	Advisor/researcher	3.5 years' experience in scour studies at Deltares	Author
Tom Roetert	Sr. Advisor/researcher	10.5 years' experience in seabed mobility studies at Deltares	Project lead
Yorick Broekema	Specialist	PhD in scour, 6 years' experience in scour studies at Deltares	Reviewer
Remon Pot	Department Head	7 years' experience as department head for multiple departments across Deltares	Approver

Summary

In this report a prediction is made for the scour development around the to-be-decommissioned monopiles of Arklow Bank Wind Park (ABWP) Phase 1. Monopiles are proposed to be cut below the seabed level at a depth equivalent to the predicted lowest seabed level (LSBL) in 2070 with probability percentile P2 (see **Volume 3, Appendix 4.1: Seabed Mobility Assessment**), where P2 indicates a non-exceedance percentage of 2%.

Residual monopiles will be retained in a morphodynamically active sandy environment, and given the target cutting depth proposed, there will be a very low probability of these becoming exposed. However, this unlikely scenario of residual monopiles becoming exposed and associated scour development is assessed, and a scour prediction is made using the in-house developed and validated Dynamic Scour Prediction Model (DSPM), altered using the method of Dey *et al.* (2008) to account for the reduced length of the residual monopile that would become exposed. The input of this prediction consists of the static soil, water, and structure parameters provided by Arklow Energy Limited, together with time-varying metocean conditions created in-house. The simulations, consisting of 5000 runs each, were performed twice: once assuming full-length monopiles (functioning as a conservative upper limit) and once assuming reduced-length residual monopiles.

When assuming full-length monopiles, a scour depth between 3.8 m and 7.1 m was predicted (5 – 95% confidence interval), leading to the development of scour holes that may extend between 10.2 m and 28.3 m, respectively, from the monopile. This is a conservative upper limit that is not expected to be reached, as it requires the monopiles to be present at full-length without scour protection, for a time period of at least 2.5 years (time to reach equilibrium scour depth).

When assuming reduced-length residual monopiles, the reduced length of the residual monopile assumed to be exposed was estimated considering the difference between the LSBL ‘P0’ 2070 values (absolute lowest seabed level predicted in 2070 with probability percentile P0) and the ‘P2’ 2070 values (target monopile cutting depth). The predicted scour depth in this case is between 1.3 m and 5.8 m (5 – 95% confidence interval), leading to the development of scour holes which may extend between 3.4 m and 23.4 m from the monopile. The reduction in predicted median scour depth ranges from 0.6 m (T5) to 3.1 m (T3, T7), corresponding to a reduction range from 9.3% (T5), to 64.8% (T7).

The depth, diameter, and timescales of the sediment movements related to the predicted scour holes are significantly smaller than those of the sediment movements of the entire sand bank migration (approx. 50 m diameter scour hole formed in one year compared to the entire Arklow Bank sand bank that moves 6 m in a year). It must be noted that while the DSPM takes into account backfilling due to wave activity, it does not take into account erosion and backfilling due to the sand bank morphological activity. From field observations shown in the Handbook of Scour Protection (Deltares, 2023), it can be concluded that sand waves have not been hindered by the presence of monopiles. Historically, sedimentation and erosion of up to 10 m has been observed due to the movement of Arklow Bank as a whole (see **Volume 3, Appendix 4.1**). Since the scour holes are relatively shallow and the assumed length of any residual monopile exposed is small, Deltares believes that a migrating sand wave (or the migration of the entire Arklow Bank) has the potential to (partially or completely) fill the scour holes and (re-)bury any potentially exposed residual monopile.

Glossary

Term / Abbreviation	Definition
Angle of Repose	Natural steepest angle at which sand remains stable; used to estimate scour hole side slopes.
CDF (Cumulative Density Function)	Function showing the probability of exceedance of variables such as current velocity and wave height.
Cut-off depth	Depth at which monopiles are cut as part of decommissioning works
DSPM (Dynamic Scour Prediction Model)	Deltares' model predicting scour development around monopiles; uses hydrodynamic time-series and equilibrium scour concepts.
Equilibrium scour depth (S_{eq})	The scour depth expected for a specific hydrodynamic event after sufficient time for equilibrium to be reached.
F_k (Hydraulic roughness factor)	Parameter capturing roughness related to sediment size (typically $F_k = 6 \cdot D50$).
Grain size (d_{50})	Median grain diameter of seabed sediment; for ABWP: 200–700 µm.
H_s (Significant wave height)	Statistical measure of wave height.
K_s (Reduction factor)	Reduction factor applied to equilibrium scour depth to account for reduced monopile Residual MP length exposed.
Metocean conditions	Combined meteorological and oceanographic conditions (waves, water level, currents).
Mobility	Value indicating how mobile sediment is
mMSL	Mean Seabed Level in meters
mLAT	Lowest Astronomical Tide in meters. For ABWP Phase 1: LAT = MSL – 1.29 m
OWF (Offshore Wind Farm)	Offshore installation of wind turbines, such as ABWP Phase I.
Scour	Local erosion of seabed material around a structure due to hydrodynamic forces.
Scour hole extent	Horizontal range of the scour depression.
Residual MP length exposed	Height of (remaining) monopile above seabed after cutting
T_p (Peak wave period)	Wave period associated with the highest energy wave component.
U_c (Current velocity)	Flow velocity at the site, used as a hydrodynamic input for scour modelling.
UTM 30U	Coordinate system used for the monopile locations.
WTG (Wind Turbine Generator)	The turbine assembly installed on each monopile. Seven WTGs exist at ABWP. An eight monopile of smaller diameter supports the met mast.

List of abbreviations

Abbreviation	Meaning
ABWP	Arklow Bank Wind Park
CDF	Cumulative Density Function
DSPM	Dynamic Scour Prediction Model
H_s	Significant wave height
LAT	Lowest Astronomical Tide
LSBL	Lowest Seabed Level
MP(s)	Monopile(s)
MSL	Mean Seabed Level
OWF	Offshore Wind Farm
P0	Probability percentile 0
P2	Probability percentile 2
S_{eq}	Equilibrium scour depth
S_{fac}	Ratio between Residual MP length exposed and water depth
T_p	Peak wave period
U_c	Current velocity
WTG(s)	Wind Turbine Generator(s)

Contents

	Summary	**4**
	Glossary	**5**
	List of abbreviations	**6**
	Contents	**7**
1	**Introduction**	**9**
1.1	Background	9
1.2	Objectives	10
1.3	Methodology	10
1.4	Structure of this document	10
2	**Theoretical background**	**11**
2.1	Flow and scour patterns around full-length monopiles	11
2.2	Dynamic scour prediction model (DSPM)	12
2.2.1	General model description	12
2.2.2	Reduction of scour potential due to reduced monopile height	13
3	**Site-specific conditions**	**16**
3.1	Location of ABWP Phase I	16
3.2	Monopile and met mast design	16
3.3	Morphology	16
3.4	Seabed sediment conditions	17
3.5	Metocean data	17
4	**Scour assessment**	**20**
4.1	Scour potential	20
4.2	Model input	20
4.2.1	Input parameters	20
4.2.1.1	Sediment size	20
4.2.1.2	Water depth	21
4.2.1.3	Residual monopile length above seabed level	21
4.2.1.4	Other (static inputs in the DSPM)	22
4.3	Scour prediction full-length monopiles	22
4.4	Scour prediction residual monopiles	23
4.5	Scour hole extent	26
4.6	Interaction with large-scale morphological activity	27
5	**Conclusions**	**29**

References **30**

A **Timeseries of metocean data** **31**

B **Timeseries of scour development full-length monopiles** **36**

C **Timeseries of scour development around exposed residual monopiles** **40**

1 Introduction

1.1 Background

Arklow Bank Wind Park (ABWP) Phase I is an offshore wind farm (OWF) located in the Irish Sea, approximately 10 km off the coast of Arklow, on the east coast of Ireland (see Figure 1.1). Arklow Energy Limited (Arklow Energy) is currently seeking planning permission to decommission ABWP Phase I (hereafter 'the Proposed Works'). The Proposed Works include decommissioning of ABWP Phase I offshore infrastructure (Proposed Works Offshore) and decommissioning of ABWP Phase I onshore infrastructure (Proposed Works Onshore).

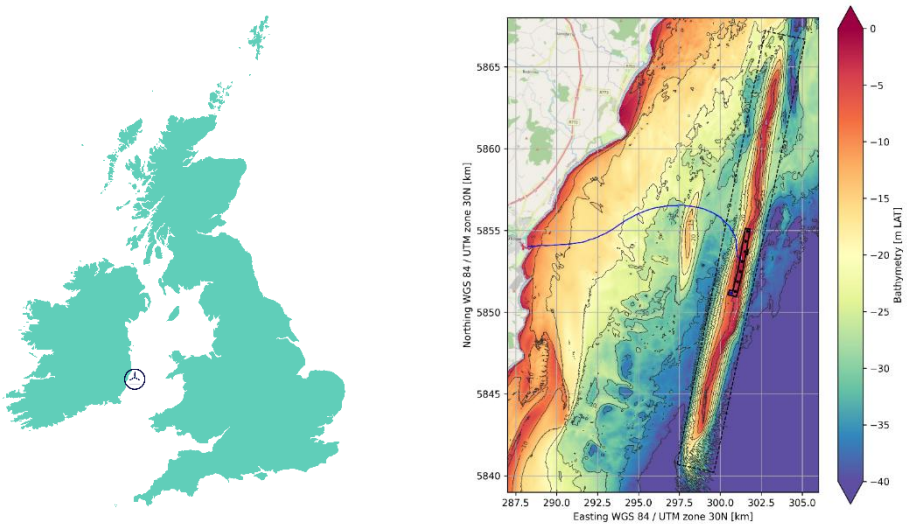


Figure 1.1 Location of ABWP Phase I both on large and smaller scale. Source lefthand image: SSE Renewables (n.d.)

The Proposed Works Offshore include the partial removal of the monopiles. The monopile target cutting depth has been defined using the numerical model developed to inform **Volume 3, Appendix 4.1: Seabed Mobility Assessment**, which predicts the lowest Seabed Level (LSBL) that will be reached at each monopile location within the model timescales (up to 2070).

The second probability percentile (P2) LSBL has been selected as the monopile target cutting depth, considered to represent a very low and rare seabed level value that will minimise post-decommissioning monopile exposure risks.

The currently present scour protection, in the form of sandbags, are also proposed to be partially removed as part of Proposed Works Offshore. The sandbags that are visible at the time of decommissioning are planned to be removed. Once the visible scour protection is removed and the monopiles are cut, unprotected residual monopiles will remain *in situ*. Although the monopile target cutting depth minimises the likelihood of residual monopiles becoming exposed, due to the dynamic morphological activity of the Arklow Bank sandbank, there is potential for short lengths of residual monopiles becoming exposed. The exact probability of this scenario is associated with the monopile target cutting depth, given that this depth represents the second probability percentile 'P2' seabed level in 2070, there is a 2% chance that the seabed becomes lower than this level according to model predictions (**see Volume 2, Appendix 4.1**). Since the visible scour protection will have been removed as part

of the Proposed Works Offshore, scour may still occur if the residual monopiles become exposed. In that case, it is possible that the buried scour protection becomes exposed and will reduce or stop further scouring. In the present study, these buried scour protections are not taken into account – scour is assumed to be free without anything stopping the scouring process.

Ramboll UK Limited has asked Deltares to perform a scour assessment to gain insight into the scour potential around the residual monopiles in the unlikely event that these become exposed post-decommissioning, and assess whether scour potential would be localised (with minimal impact on seabed dynamics) or otherwise. This scour assessment has been prepared to support **Volume 2, Chapter 4: Coastal Processes, Water and Sediment Quality** of the Environmental Impact Assessment Report (EIAR).

1.2 Objectives

The objective of this study is defined as:

> *Assessment of the scour hole development (maximum depth, time scale, and scour hole extent) around ABWP Phase I residual monopiles without considering scour protection, and the interaction with large-scale morphological activity.*

1.3 Methodology

The scour hole development around residual monopiles is assessed based on a desk study using a scour prediction model, previously developed by Deltares for monopile foundations and validated by means of field measurements at Luchterduinen OWF (Raaijmakers, 2014).

The model takes into account the residual monopiles post-decommissioning, i.e. the potential length of monopile exposed is shorter (see Table 4.1). Moreover, the scour prediction model has been applied in such a way that a sensitivity range for several input parameters is accounted for. With this synthetic approach, the prediction does not only result in a best-estimate value but also includes a sensitivity range for the local scour development at each residual monopile location.

1.4 Structure of this document

Theoretical background on the scouring process is given in Section 2. Available data on site conditions at the locations of the monopiles is described in Section 3. Scour depth estimates are discussed in Section 4. Finally, conclusions are given in Section 5.

2 Theoretical background

To predict scour development around monopiles, Deltares uses the in-house developed Dynamic Scour Prediction Model (DSPM) as described in, for example, Rudolph *et al.* (2008). In the current study, the DSPM is applied to assess scour development around the residual monopile foundations in the unlikely case that these become exposed. This chapter provides a brief description of scour development around monopiles (Section 2.1) to define some often-used terminology. Following this theoretical background on scour development, the implementation of this in the DSPM is described in Section 2.2.

2.1 Flow and scour patterns around full-length monopiles

In current flow conditions, several flow features develop around monopiles. These features include: a downflow at the upstream side of the monopile, which rolls up and is transported downwards towards the base of the monopile, resulting in a horseshoe vortex on the seabed around the monopile. At the downstream side of the monopile vortex shedding due to flow separation is also a distinct phenomenon. These flow features are illustrated in Figure 2.1. This disturbance of the flow around the monopile will amplify the bed shear stress and either result in scour (in absence of a scour protection) or an amplified load on the scour protection.

Besides the local flow patterns at the upstream and downstream sides of the monopile, contracting streamlines around the monopile (due to flow obstruction by the monopile itself) will cause flow acceleration along the sides of the foundation. This flow contraction will locally increase the bed shear stress, causing a higher load on the bed material, which can be either the original seabed or an applied scour protection. Flow deceleration in the wake of the monopile will locally increase the turbulence and thereby cause an increase of the bed shear stress here as well.

In a relatively shallow water depth, extreme storm events generally result in larger flow velocities at the bed than flow-only conditions, due to the combined action of current and large waves. However, in these storm events the flow features that develop (see Figure 2.1) are continuously broken off due to the reversal of the wave-induced flow. In general, it is therefore observed that scour depths tend to become deepest in tidal conditions.

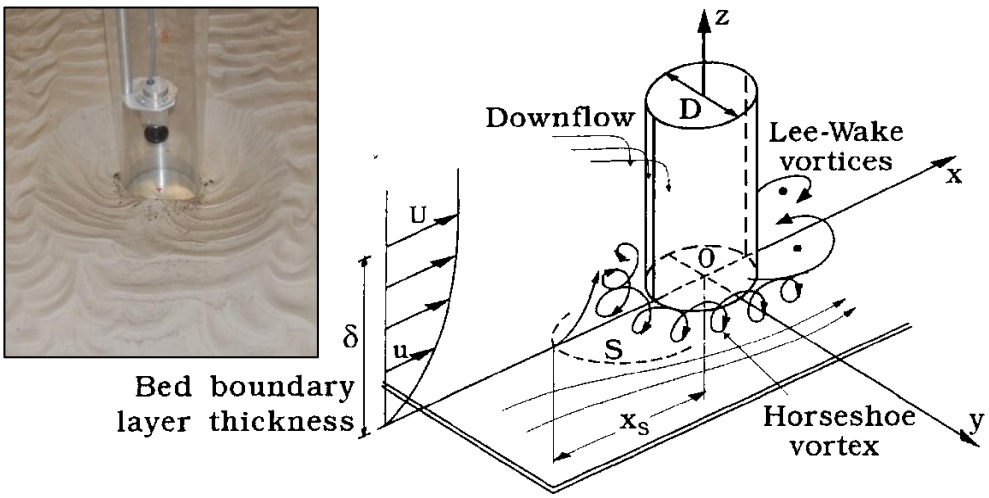


Figure 2.1 Flow pattern of a current flowing around a cylindrical pile (Sumer & Fredsøe, 2002); the upper left insert shows a scour hole in a scale model test with a (transparent) monopile.

2.2 Dynamic scour prediction model (DSPM)

2.2.1 General model description

Deltares has developed the DSPM for monopile foundations. The input of this prediction model consists of static soil, water and structure parameters and time-varying metocean conditions. Within the DSPM the hydrodynamic time series are discretized into transient individual events, each with their own equilibrium scour depth (S_{eq}) and corresponding time scale (T). In each discretized time step (n) the scour depth (S) partly develops towards this corresponding equilibrium scour depth in the given time step (dt). In the next time step (n+1) another condition applies, with its own equilibrium scour depth and time scale and the scour depth develops towards this new equilibrium scour depth. The equation below describes this scour development in time:

$$S_{n+1} = S_{eq,n+1} + (S_n - S_{eq,n+1}) exp\left(-\frac{dt}{T}\right) \quad (2.1)$$

The DSPM was validated for monopile foundations using scour measurements from the Luchterduinen Wind Farm, located offshore The Netherlands (Raaijmakers, 2014). Figure 2.2 presents the simulated scour development (blue line) and measured scour development (red and yellow line) for two locations in this wind farm. Predicted scour and backfilling events align with the observed trends and the resulting scour development is very similar (note: the y-axis is from 0 m to 6 m).

There are some differences between Luchterduinen OWF and ABWP Phase I. Notably, Luchterduinen OWF is located in the southern part of the North Sea, whereas ABWP Phase I sits on a morphodynamically active sand bank in the Irish sea. The tidal regimes, seabed levels, and seabed dynamics are different between the two OWFs. The DSPM computes the equilibrium scour depth using the formulae of Sheppard et al. (2006) for current-dominated conditions and Raaijmakers & Rudolph (2008) for combined current-wave climates. For each timestep in the metocean timeseries it is determined whether the metocean conditions are current-dominated or if they classify as a combined wave-current condition. The inflow mobilities of the experiments of Sheppard et al. (2006) range between 0.33 and 33.5. The inflow mobilities of the experiments of Raaijmakers & Rudolph (2008) range between 3.8 and 29.0. At ABWP Phase I, the inflow mobilities of the hindcast used in the present study ranges from 0.0 to 36.0, with a mean value of 6.6 and a standard deviation of 4.2. The vast majority of the conditions therefore fall within range of tested conditions on which the DSPM is based, with the exception of a couple of individual outliers. Deltares does not expect those outliers to significantly impact the scour depth prediction, therefore justifying the use of the DSPM for determining scour depth at the foundations at ABWP.

If the Client has field data available of seabed level and metocean conditions of the lifetime at ABWP Phase I, Deltares could perform a check whether a scour prediction performed with the DSPM corresponds to the field data. However, Deltares does not think this is a necessary works, as the DSPM has been validated before for relatively comparable metocean conditions. Deltares has confidence in the outcome of that validation.

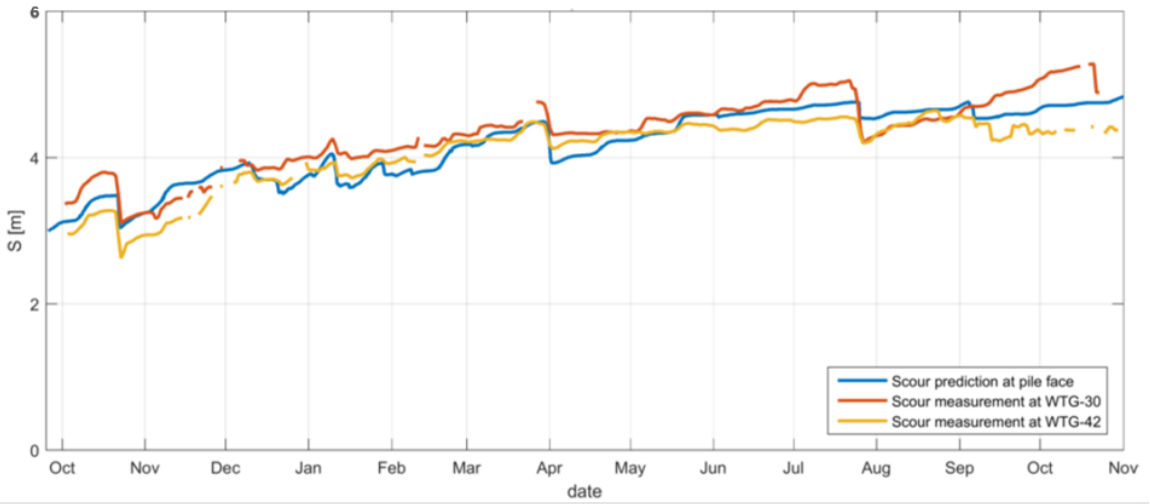


Figure 2.2 Scour development as measured in Luchterduinen OWF at WTG-30 and WTG-42 and simulated by means of the DSPM (1 simulation) (Raaijmakers, 2014)

2.2.2 Reduction of scour potential due to reduced monopile height

The DSPM uses scour prediction equations based on full-length monopiles. When the length of a monopile above seabed level decreases, the flow around the monopile becomes different. Instead of being fully forced around the monopile, part of the flow can move over the monopile. This reduces the amplification of flow at the sides of the monopile. However, due to flow passing over a blunt object, flow separation in vertical direction on the downstream side of the monopile occurs. This is associated with vortex shedding and increased turbulence intensity in the wake of the pile. Therefore, the reduction in scour depth due to reduced flow amplification around the monopiles is, for certain monopile lengths, negated by the effect of vertical flow separation, which explains the non-linear relation between monopile length and scour depth reduction. This is illustrated in Figure 2.3 (figure taken from Dey et al. (2008)). To account for the reduced monopile length, the equilibrium scour depth as calculated in each timestep (see Section 2.2.1) is multiplied by a reduction factor following from Dey et al. (2008). This reduction factor is calculated as follows:

$$K_s = 1 - 0.73\,S_{fac} + 3.63 S_{fac}^2 - 12.8\,S_{fac}^3 + 17.23\,S_{fac}^4 - 8.33\,S_{fac}^5 \quad (2.2)$$

In which K_s is the reduction factor, and S_{fac} is the ratio between Residual MP length exposed and water depth, defined as:

$$S_{fac} = \frac{h_w - h_{pile}}{h_w} \quad (2.3)$$

Figure 2.4 shows this relation between the ratio between monopile length above seabed level and water depth, and the reduction factor. When the monopile length above seabed level nears zero, S_{fac} nears 1 and the reduction factor nears zero (and thus the resulting scour nears zero). When the monopile length above seabed level nears the water depth, the reduction factor is high, resulting in less scour depth reduction.

It must be noted that the physical experiments performed by Dey et al. (2008) only included steady unidirectional flow conditions, whereas in the current study combined wave-flow climates are used. Furthermore, the ratio between monopile length above the seabed level and water depth of T1 and T5 fall outside the range of ratios tested by Dey et al. (2008) (T1: 0.924, T5: 0.915, Dey et al. (2008): 0 – 0.88). The ratio between the monopile length above the seabed level and the monopile diameter is different between Dey et al. (2008) and the current study: in Dey et al. (2008), the monopile length above the seabed level is always

at least 1 time the monopile diameter. In the current study, the monopile length above the seabed level is at least 0.1674D (T3), and at most 1D (met mast).

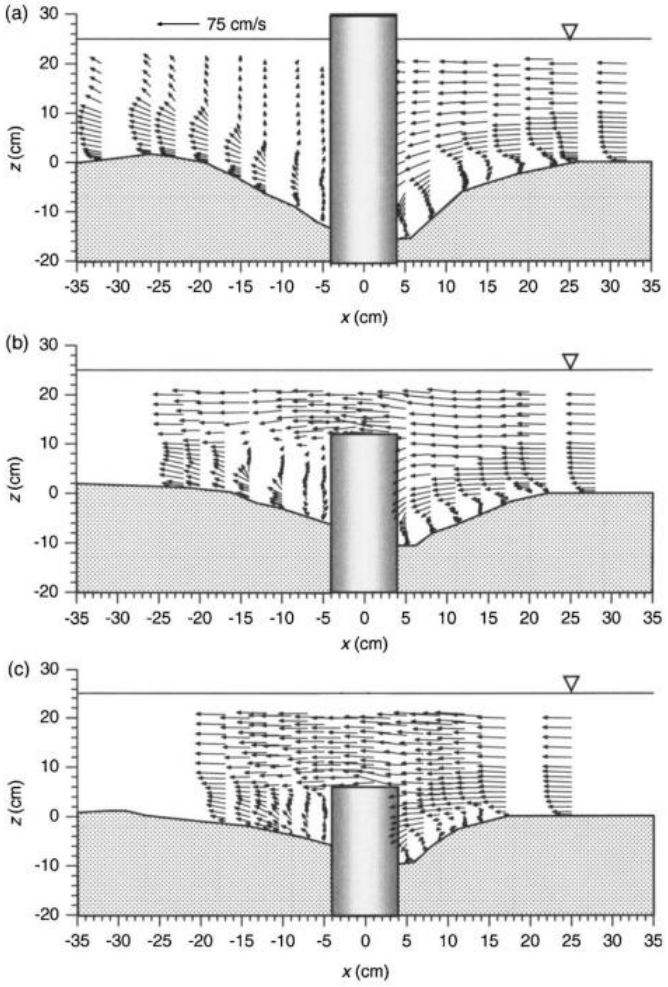


Figure 2.3 Velocity vectors along vertical plane of symmetry of circular cylinders for three cases. Figure source: Dey et al. (2008).

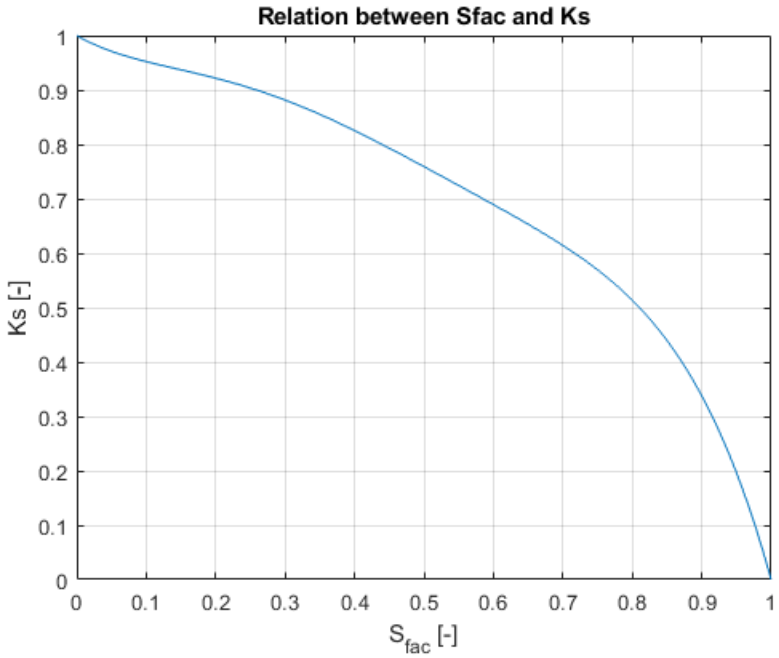


Figure 2.4 Relation between S_{fac} and K_s.

3 Site-specific conditions

3.1 Location of ABWP Phase I

ABWP Phase I is located in the Irish Sea, approximately 10 km off the coast of Arklow (see Figure 1.1. The exact locations (UTM 30N) of the monopiles are shown in Table 3.1.

Table 3.1 Location of the monopiles.

Pile name	Easting UTM-30N [m]	Northing UTM-30N [m]
Met mast	300663.39	5851175.78
T1	300905.86	5851277.21
T2	301043.35	5851884.18
T3	301205.03	5852487.07
T4	301318.50	5853104.32
T5	301523.18	5853705.46
T6	301539.51	5854332.88
T7	301645.43	5854950.44

3.2 Monopile and met mast design

The monopiles have a diameter of 5.1 m. The met mast has a diameter of 1.8 m. The design penetration depth of the monopiles is between 28.95 m and 29.65 m, for design seabed levels of between -4.0 and -6.3 m MSL (GE Wind Energy, 2003). The actual penetration depth at installation is expected to be greater. Note that these values for the seabed levels are different from the ones used for the scour assessment, as the scour assessment uses the lowest expected seabed level in 2070. Furthermore note that there is a difference between LAT and MSL of 1.29 m. So LAT = MSL – 1.29 m.

3.3 Morphology

Arklow Bank is situated in a morphologically active area. Figure 3.1 shows the crest of Arklow Bank at ABWP Phase I over a time period between 1984 and 2025. Over the past forty years, the crest has moved differently at different locations, both in speed and direction. In some locations, the direction of movement has changed (started westward, became eastward, or the other way around).

It is likely that this seabed movement will lead to lowering of seabed levels at monopile locations at some point in time. It may in turn also lead to heightening of the seabed levels. In the present study, the morphology is not taken into account. This is a model limitation - the DSPM assumes a flat seabed without morphological changes. For a detailed morphological study, refer to Volume 3, Appendix 4.1. Implementing morphological changes into the DSPM would require further research and an elaborate model re-write, which is not included in the present scope of work. The expected interaction between the scour holes and the large-scale morphology is discussed qualitatively in Section 4.6.

In the current study it is assumed that no initial scour will be present after decommissioning the monopiles. It should be noted that after over 20 years of operation with sandbag scour protection in place, it is very possible that the seabed around each monopile is uneven, with

local depressions. However, in the model, the initial seabed level (as will be discussed in Section 4.2) is assumed to be a flat seabed with the expected seabed level 'P0' in 2070.

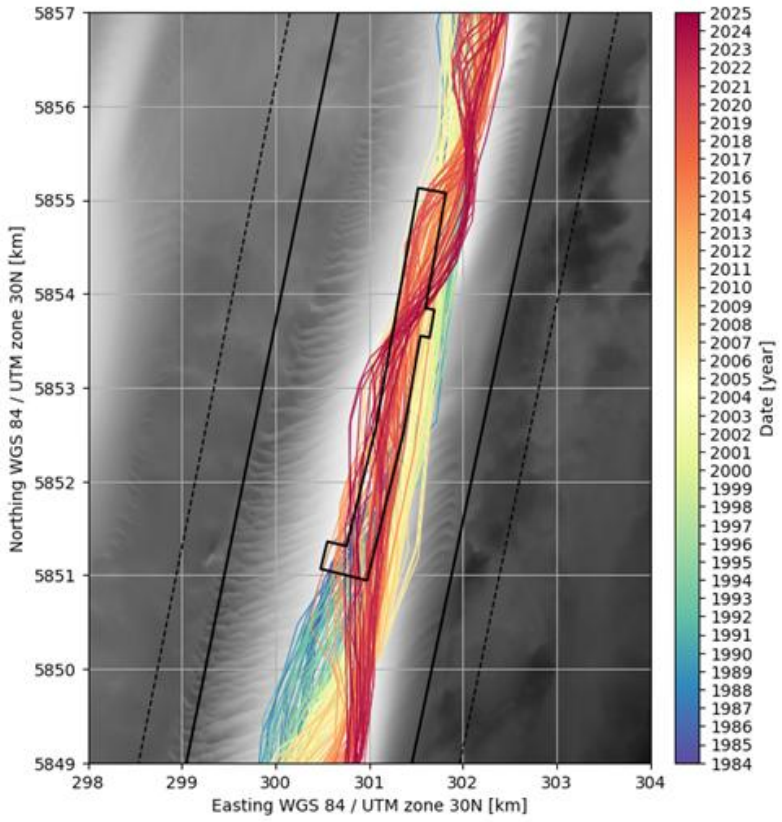


Figure 3.1 Crest of Arklow Bank at ABWP Phase I over the period 1984-2025 (Deltares, 2026).

3.4 Seabed sediment conditions

The seabed at ABWP Phase I consists of fine to coarse sand with median grain diameters (d_{50}) of 200-700 µm (GE Wind Energy, 2003).

3.5 Metocean data

The timeseries of the hydrodynamic conditions were created in-house for this scour assessment for each monopile. In Deltares (2025), the Arklow Bank sand bank morphodynamic model was developed and discussed – this model also outputs the metocean data that is used in the current study. The morphodynamic model is composed of coupled flow, wave, and sediment transport modules. For a more in-depth explanation of this model, please refer to Deltares (2025). The timeseries cover the period between January 1st, 2000 and January 4th, 2020 with an interval of one hour. One year of this 20-year data set of T1 is presented in Figure 3.2. Timeseries for the other monopiles are shown in Appendix A. Shown are the water level (η), significant wave height (H_s), peak period (T_p), and current velocity (U_c). Figure 3.3 shows the cumulative density functions (CDFs) of all monopiles for the (absolute value of the) current velocity and significant wave height.

The CDFs show a difference in the current velocities between the multiple monopile locations. Current velocities can vary locally due to the location of the monopile – whether the monopile is situated on top of the sand bank, or more on the east or western side of the sand bank. Also, the water depth for all monopiles is not the same, which can impact the current velocity. The water depth over ABWP Phase I is discussed in Section 4.2.1.

The currently used metocean data is not a forecast for the future. As such, more extreme metocean conditions due to climate change are not included in the present study. A short sensitivity study using DSPM shows that increasing the significant wave height and peak period while keeping the current velocity the same (with respect to the metocean conditions described the current section) for a full-length monopile, results in the same maximum and 95% non-exceedance value for equilibrium scour depth, but more backfilling events and thus lower median predicted scour depths. In the case of residual monopile with short sections becoming exposed following decommissioning, a reduced maximum scour depth was predicted, as well as a reduced median predicted scour depth. For a more in-depth analysis and comparison, a timeseries of metocean forecast including climate change consequences is required.

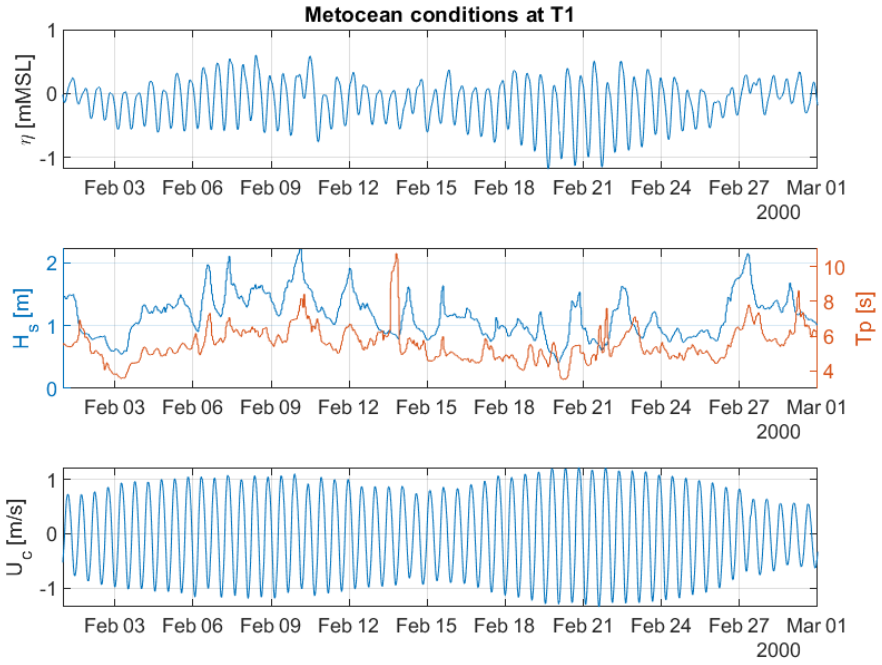


Figure 3.2 One month of metocean conditions at WTG T1

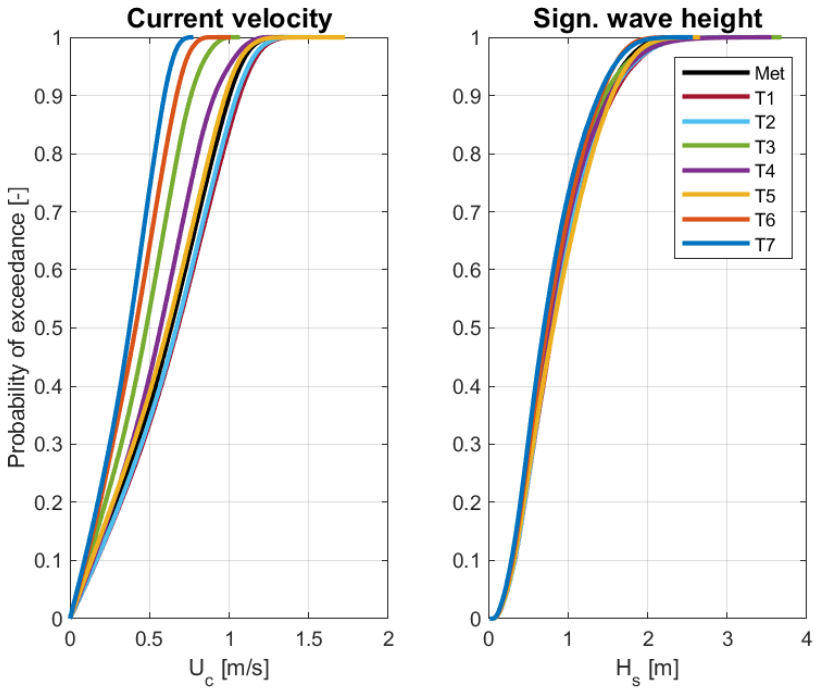


Figure 3.3 Cumulative Density Plot of current velocity (absolute value) and significant wave height for all WTGs and met mast

4 Scour assessment

In this chapter, scour prediction results are presented for residual monopiles post-decommissioning (in the unlikely case that these become exposed), as well as for full-length monopiles (if monopiles were not removed, to serve as a conservative upper limit). These are short term developments of scour of up to 3 years. Additionally, the long-term implication due to interaction with large-scale morphological activity is discussed.

4.1 Scour potential

The scour potential at the locations of the monopiles is influenced by the erodibility of the seabed and the local hydrodynamic conditions. According to the given seabed sediment description (see Section 3.4), the seabed in which scour is expected to occur consists of medium sand with an estimated median grain size in the range of 200 – 700 µm. This seabed material is susceptible to erosion if the acting hydrodynamic load exceeds the resistance of the bed material. Therefore, the relative seabed mobility near the monopile (ratio between the acting hydraulic load and the resistance of the bed material) is assessed.

Note that the mobility of the seabed increases significantly under wave conditions. However, scour potential under combined waves and currents, is significantly less compared to a current-only condition since flow features that result in the local scour holes around the foundation piles are continuously broken off due to the reversal of the wave-induced flow (Sumer et al, 1992). Furthermore, waves tend to induce backfilling of the scour hole, which also contributes to the shallower scour depth for combined wave-current conditions. The DSPM considers a current-wave climate.

4.2 Model input

The local scour depth is predicted by means of Deltares' developed DSPM, see Section 2.2. Instead of a single time series of the hydrodynamic conditions and a single input for the seabed sediment parameters, a sensitivity range for these parameters is included. By doing so, the prediction does not only result in a median value but also includes a sensitivity range for the local scour development at each monopile location. The selected input parameters and the scour results are discussed in the Sections 4.2 – Section 4.5.

The scour prediction is performed using the DSPM by taking samples of below described input parameters within the applied sensitivity ranges. For each simulation, a random start time is chosen within the available hydrodynamic time series. In total, 5000 combinations are made of periods of 3 years. The duration of the simulation is chosen such that the equilibrium scour depth is reached for each monopile. The large number of simulations decreases the uncertainties with respect to scour depths and relevant timescales.

4.2.1 Input parameters

4.2.1.1 Sediment size

Due to the recorded variability of grain sizes within the topsoil layer (where scour is expected to occur), a characteristic median grain size is selected for the scour assessment between 200 µm – 700 µm (with a uniform distribution). This is discussed in Section 3.4. Note that grain sizes below 100 µm are not considered in the present approach since this is outside the applicability range of the DSPM. Due to the cohesiveness of those even finer sediments, the

erodibility is expected to become less, making this range a conservative estimate for scour development.

4.2.1.2 Water depth

For the water depth, the 2070 ‘P0’ water depth prediction from Deltares’ morphological assessment was used (Deltares, 2025), see also Volume 3, Appendix 4.1 and Table 4.1.

4.2.1.3 Residual monopile length above seabed level

In the unlikely scenario that residual monopiles become exposed post-decommissioning, due to morphological activity (see Section 3.3), short lengths of residual monopiles exposed are estimated considering the monopile target cutting depth, i.e. the 2070 ‘P2’ water depth prediction (Deltares, 2025), also presented in Volume 3, Appendix 4.1, and the 2070 ‘P0’, noting that the likelihood of the water depth becoming larger than the P0 value is 0% according to the morphological model calculations. The resulting residual monopile lengths are shown in Table 4.1 and visualised in Figure 4.1.

Table 4.1 Multiple water depth predictions for 2070 (Deltares, 2025, 2026).

Pile name	Water depth P0 [mLAT]	Water depth P2 [mLAT]	Residual MP length exposed (P0-P2) [m]
Met mast	-12.35	-10.55	1.80
T1	-10.38	-8.34	2.04
T2	-7.99	-6.59	1.40
T3	-9.39	-8.55	0.84
T4	-9.17	-8.09	1.08
T5	-9.41	-6.67	2.74
T6	-10.11	-8.89	1.22
T7	-10.52	-9.75	0.77

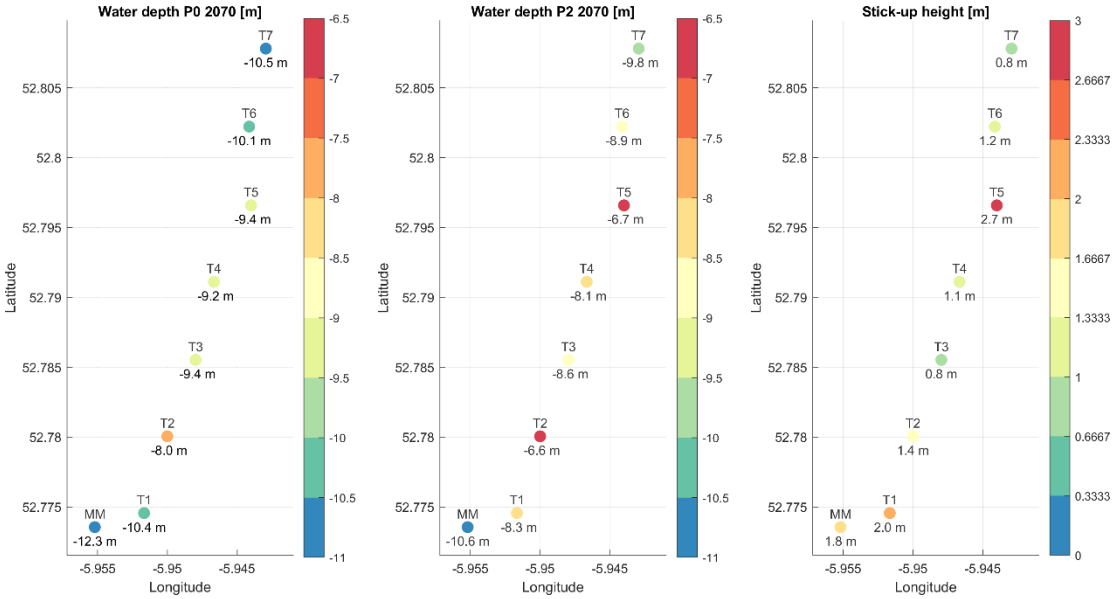


Figure 4.1 Visualisation of the water depth P0 and P2 values, as well as the Residual MP length exposed of the MPs after decommissioning.

4.2.1.4 Other (static inputs in the DSPM)

Besides the parameters discussed above (monopile diameter, sediment size and metocean conditions), other input parameters are also used in the DSPM simulations. An overview of the parameters, together with the full range of considered values and the assumed probability distribution, is presented in Table 4.2. All those parameters are used uncorrelated in the DSPM simulations. The time scale factors in the table (T_{factor} and B_{factor}) are applied on the computed timescales for each hydrodynamic condition in the timeseries. These factors capture the uncertainty in the timescale predictions.

Table 4.2 DSPM input parameters varied using Monte Carlo simulations. Parameters: μ mean value for normal distributions; σ, standard deviation for normal distributions.

Input parameter	Unit	Description	Variation range / statistical distribution
Hydrodynamic conditions		Metocean conditions	Timeseries of 3 years sampled at different start dates
Median grain size, d50	[m]	Median diameter of the sediment	Range d50 = 200 – 700 * 10^{-6} m Uniform distribution
Sediment density, ρ_s	[kg/m^3]	Specific density of sediment	Range ρ_s = 2600 – 2700 kg/m$^{3;}$ Normal distribution; Parameters: μ=2650 kg/m^3, σ = 16.7 kg/m^3
Water density, ρ_w	[kg/m^3]	Specific density of water	Range ρ_w = 1020 – 1030 kg/m$^{3;}$ Normal distribution; Parameters: μ=1025 kg/m^3, σ = 1.67 kg/m^3
Hydraulic roughness factor, F_k	[-]	Roughness height related to sediment size (typically F_k = 6*D_{50})	Range F_k = 2 - 10; Normal distribution; Parameters: μ=6, σ = 1.3
Flow transition, $U_{rel;bound}$	[-]	Relative velocity (U_{rel}) where transition between wave- and current -dominated scour occurs	Range $U_{rel;bound}$ = 0.4 – 0.6; Normal distribution; parameters μ=0.5, σ = 0.03
Mobility threshold, MOB_{thresh}	[-]	Threshold value of mobility for initiation of motion	Range MOB_{thresh} = 0.4 – 0.6; Normal distribution; parameters μ=0.5, σ = 0.03
Scour time scale factor, T_{factor}	[-]	Time scale factor related to current- and wave-dominated scour	Range T_{factor} = 1 - 20; Uniform distribution
Backfilling time scale factor, B_{factor}	[-]	Time scale factor related to current- and wave-dominated backfilling	Range T_{factor} = 1 - 20; Uniform distribution

4.3 Scour prediction full-length monopiles

To compare the effect of reducing monopile height and to have a baseline prediction for comparison, the DSPM was run using full-length monopiles. The timeseries of predicted scour depth of T1 is shown in Figure 4.2. The timeseries of the other MPs are shown in Appendix B. For T1, the equilibrium scour depth lies between 5.8 m and 7.1 m (5%-95% non-exceedance values) with a median depth of 6.5 m. The equilibrium is reached after approximately half a year. For all monopiles the equilibrium is reached in a maximum of 2.5 years. Note that the full prediction bandwidth (indicated in light grey) relates to a scour depth of approximately 8.2 m. The predictions in the light grey band are considered unlikely to occur, but these cannot be completely excluded and are thus shown for completeness.

The predicted equilibrium scour depth for each turbine is shown in Figure 4.3 and Table 4.3. The figure shows the 5%, 50%, and 95% non-exceedance value. The table shows these values and also the maximum expected scour over the simulated time. The predicted median equilibrium scour depth is between 4.8 m (T7) and 6.5 m (T1) for the WTG monopiles, and 2.7 m for the met mast monopile.

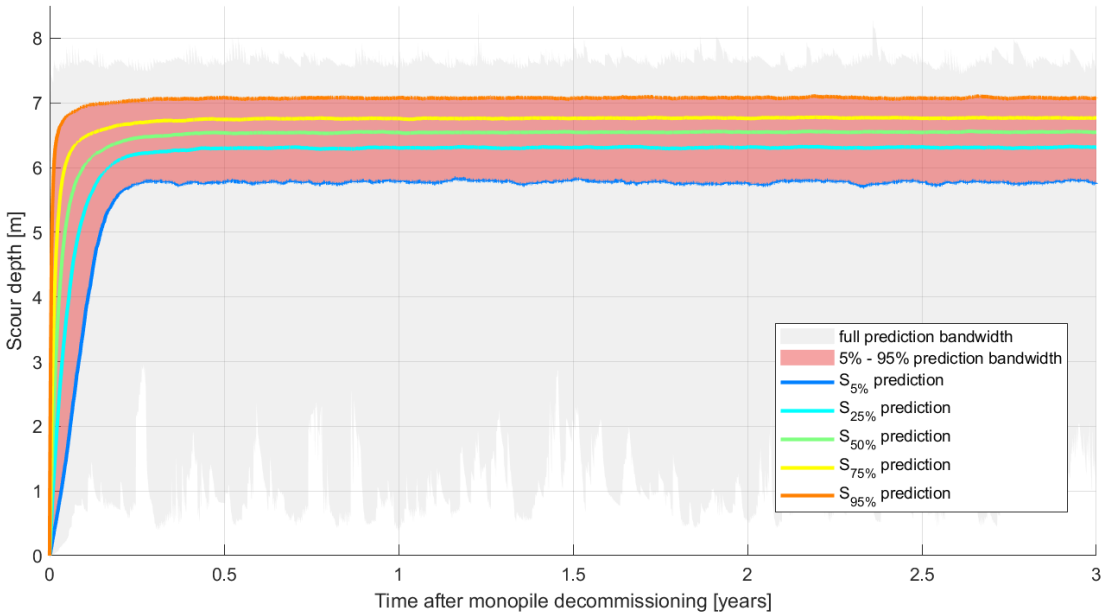


Figure 4.2 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T1, assuming a full-length monopile.

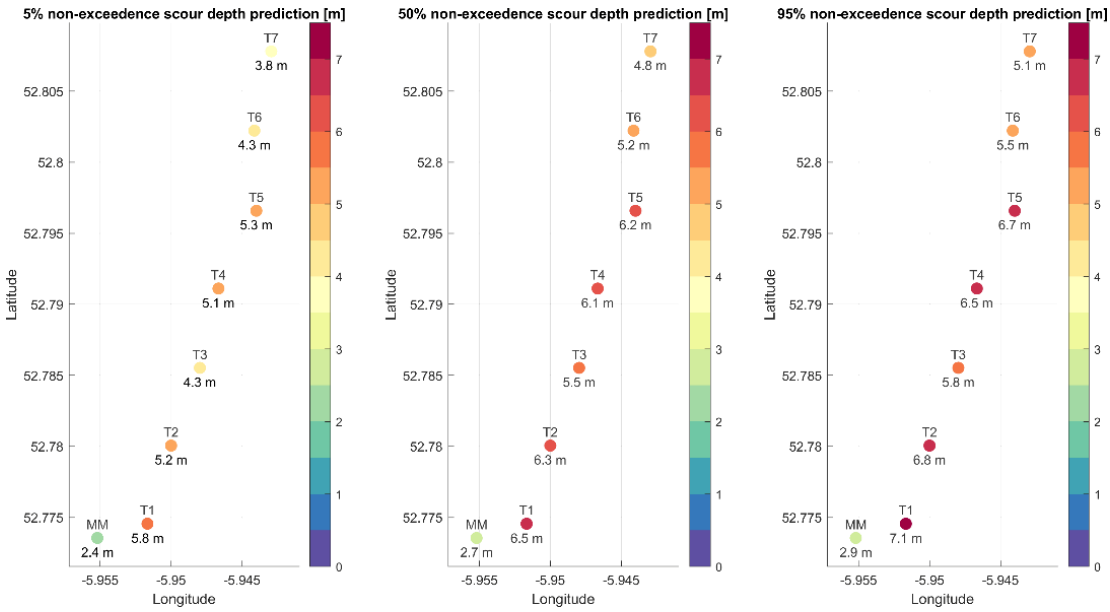


Figure 4.3 Predicted equilibrium scour depth at all eight monopiles assuming full-length monopiles. From left to right: 5% non-exceedance depth, 50% non-exceedance depth, and 95% non-exceedance depth.

4.4 Scour prediction residual monopiles

The scour prediction results when taking into account the unlikely exposure of residual monopiles post-decommissioning are presented here. The timeseries of predicted scour depth at T1 is shown in Figure 4.2. Compared to the full-length monopile, the scour happens at a similar rate. This is because the method for calculating the time scales has not been altered in the DSPM. In Dey et al. (2008), the effect of cutting off the monopiles on scour depth is discussed, but no mention is made on timescales. The 95% non-exceedance predicted scour depth is smaller (5.0 m, compared to 7.1 m). The timeseries for all residual monopiles can be

found in Appendix C. For all residual monopiles, the equilibrium scour depth is reached within 2 years.

The predicted scour depth for all residual monopiles is shown spatially in Figure 4.5. The median predicted scour depth is between 1.7 m (T7) and 5.6 m (T5) for the WTG residual monopiles, and 1.6 m for the met mast residual monopile. The difference in predicted equilibrium scour depth between the two scenarios is shown in Figure 4.6. The difference is calculated as such:

$$\Delta S_{eq} = S_{eq,full\ length} - S_{eq,cut} \tag{4.1}$$

For all residual monopiles, a reduction in predicted scour depth was predicted. The smallest difference in median predicted scour depth is observed at T5 (0.6 m difference for the 50% non-exceedance scour depth prediction, Residual MP length exposed 2.7 m). The largest difference in median predicted scour depth is observed at T3 and T7 (both residual monopile length above seabed level: 0.8 m): 3.1 m less scour predicted than with a full-height monopile. The reduction in predicted median scour depth, expressed in percentages, ranges from 9.3% (T5) to 64.8% (T7).

It must be noted that while the DSPM takes into account backfilling due to wave activity, it does not take into account erosion and backfilling due to morphological activity. It is possible that the created scour holes will become shallower over time as Arklow Bank migrates at the locations of the monopiles. This could potentially lead to filling the scour hole and burying of any residual monopiles exposed, depending on the depth of the scour hole and the residual monopile length above seabed level exposed.

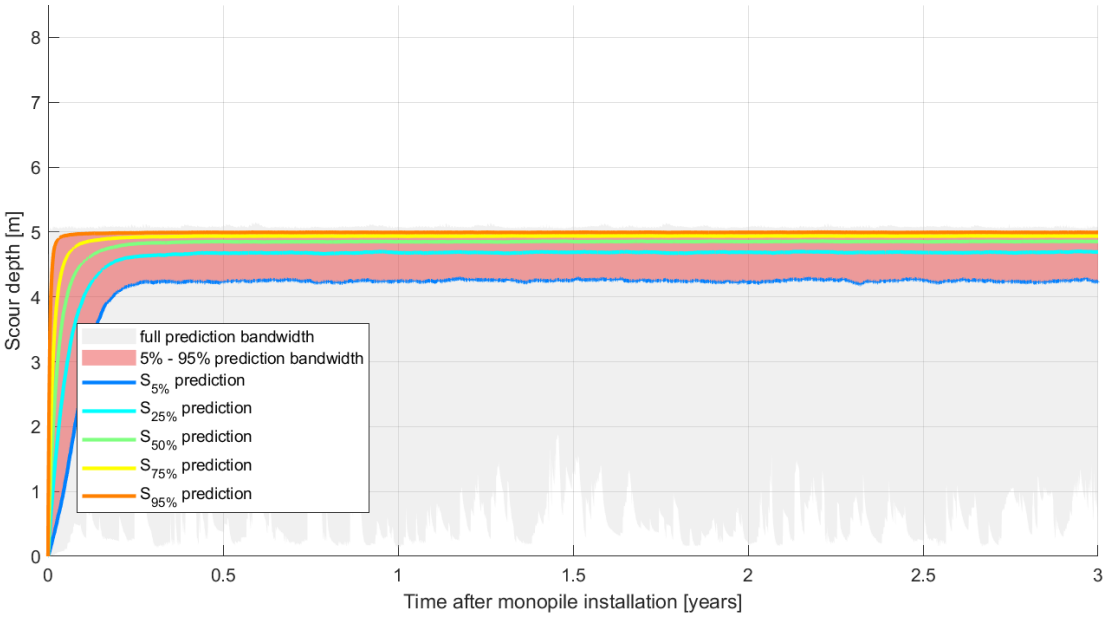


Figure 4.4 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T1, assuming a decommissioned monopile.

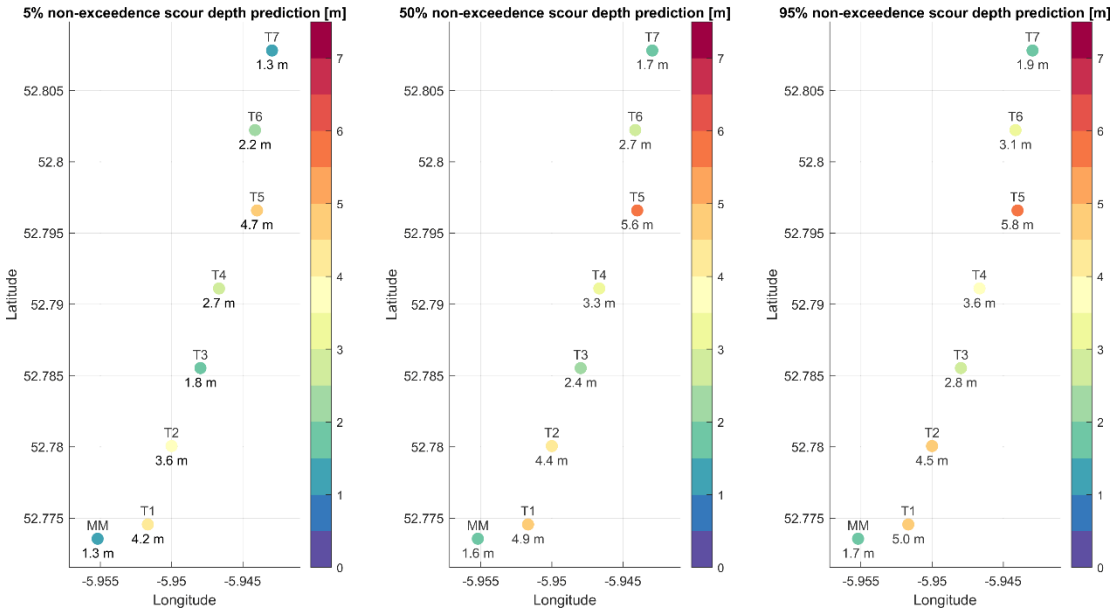


Figure 4.5 Predicted equilibrium scour depth at all eight monopiles assuming decommissioned monopiles. From left to right: 5% non-exceedance depth, 50% non-exceedance depth, and 95% non-exceedance depth.

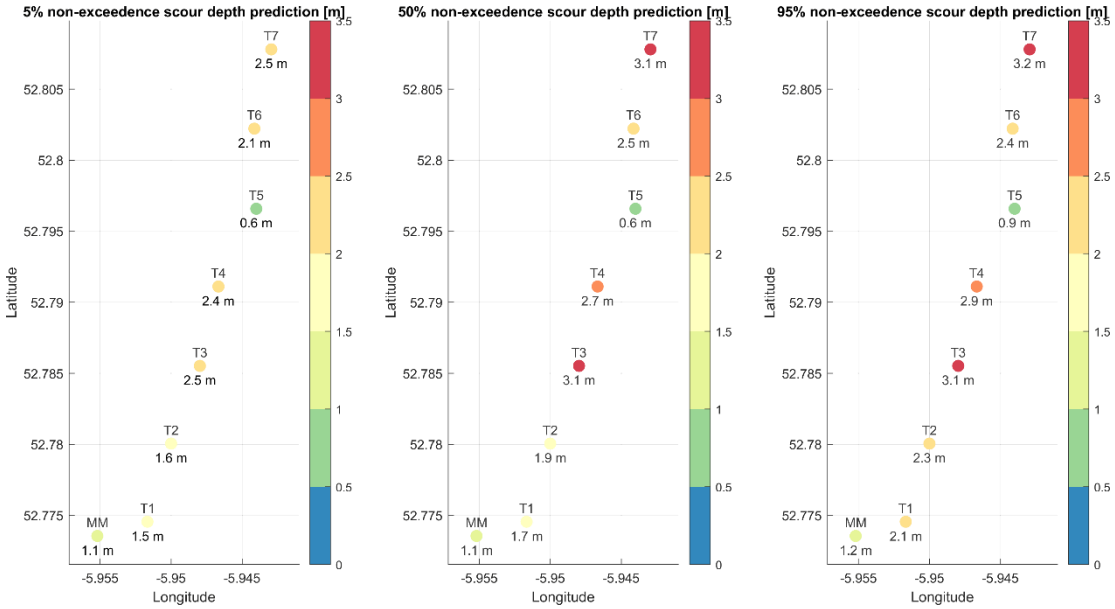


Figure 4.6 Difference in predicted equilibrium scour depth at all eight monopiles after cutting the monopiles ($S_{eq,fulllength}$ - S_{eqcutf}). From left to right: 5% non-exceedance depth, 50% non-exceedance depth, and 95% non-exceedance depth.

Table 4.3 Prediction equilibrium scour depth for 5%, 50%, 95% non-exceedance value, and maximum expected scour depth over the simulated time. Both for full-height MPs and cut MPs.

Pile	Full-height monopiles				Cut monopiles			
	5% non-exc. value [m]	50% non-exc. value [m]	95% non-exc. value [m]	Max. expected scour [m]	5% non-exc. value [m]	50% non-exc. value [m]	95% non-exc. value [m]	Max. expected scour [m]
Met	2.4	2.7	2.9	3.3	1.3	1.6	1.7	1.8
T1	5.8	6.5	7.1	8.4	4.2	4.9	5.0	5.1
T2	5.2	6.3	6.8	8.2	3.6	4.4	4.5	4.7
T3	4.3	5.5	5.8	6.4	1.8	2.4	2.8	3.1
T4	5.1	6.1	6.5	7.3	2.7	3.3	3.6	3.8
T5	5.3	6.2	6.7	9.1	4.7	5.6	5.8	6.0
T6	4.3	5.2	5.5	5.9	2.2	2.7	3.1	3.6
T7	3.8	4.8	5.1	5.4	1.3	1.7	1.9	2.1

4.5 Scour hole extent

The horizontal extent of the scour hole in homogeneous erodible sediment is often described as a function of the scour depth and the scour hole side slope angles:

- Hoffmans and Verheij (1997) suggest that the upstream part of the scour hole formed under current-only conditions has a steeper slope angle than the downstream part. Slope angles are linked to the natural angle of repose of sediment; the upstream and side slopes (in cross flow direction) are approximately equal to the angle of repose.
- According to Hoffmans and Verheij (1997), side slopes formed under tidal conditions are less steep than under a unidirectional current.
- The relation of the scour hole side slope angles with the angle of repose was later used by Harris et al. (2011) to describe the scour hole shapes at offshore foundations, where an angle of 32° is assumed for the steepest (upstream) part of the scour hole.
- In the physical model tests by Whitehouse et al. (2006) and Raaijmakers and Rudolph (2008) side slope angles of 30-35° were observed for scour holes formed under current-only conditions.
- Other studies mention side slopes observed in the field between approximately 26° (1:2 slope ratio) (Raaijmakers, 2016) and 11° (1:5 slope ratio) (Rudolph et al., 2008).

Based on a review of the side-slopes observed in both model tests and in the field, Deltares created a generic scour hole geometry (Figure 4.7). The scour hole extents are normalised with the scour hole equilibrium depth. The schematisation presented in Figure 4.7 shows a minimum scour hole extent of 2.7 times the equilibrium depth and a maximum scour hole extent of 4-7 times the equilibrium depth. It is furthermore noted that this schematization holds for local scour holes. For global scour (general lowering around a single, complex foundation such as jackets) holes usually even shallower slopes are observed. Since global scour is a phenomenon not associated with monopiles (but with jackets and other complex structures), it can be assumed for the current study that the edge of the scour hole is located at an extent of 4 times the pile diameter (in Figure 4.7: at E=4, S=0).

The minimum and maximum expected extent for the scour holes for each monopile, both for a full-height monopile and for a decommissioned monopile, are provided in Table 4.4. In these estimates the 5%-95% ranges of the local scour depth prediction are considered. Note that these figures are indicative and schematic. They do not include morphodynamic processes

such as seabed level changes and the migration of bed forms. Interaction between the scour holes and large-scale morphological activity is discussed in Section 4.6.

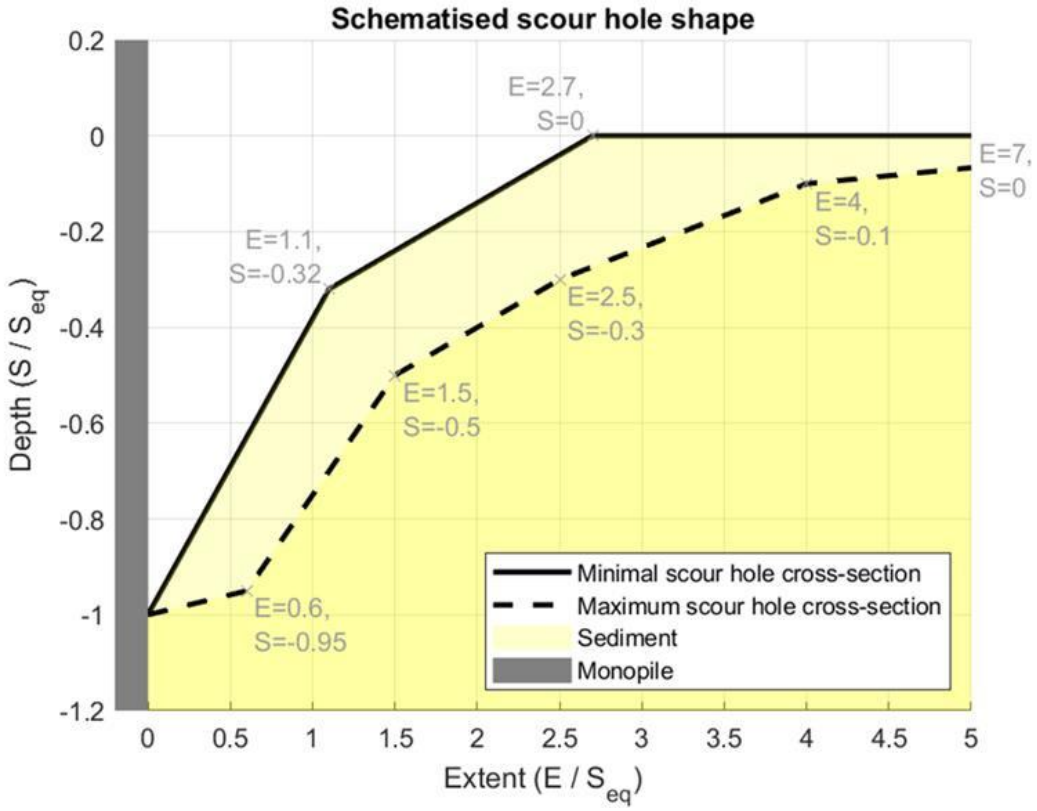


Figure 4.7 Generic scour hole geometry assuming local and global scour. If no global scour is present, it may be assumed that at E=4, S is equal to 0 [-].

Table 4.4 Estimated extent of the scour hole at the eight monopiles, both for a full-length monopile and for a decommissioned monopile.

Pile	Full length monopile		Decommissioned monopile	
	Minimum extent based on 5% non-exceedance scour depth [m]	**Maximum extent based on 95% non-exceedance scour depth [m]**	**Minimum extent based on 5% non-exceedance scour depth [m]**	**Maximum extent based on 95% non-exceedance scour depth [m]**
Met	6.5	11.5	3.6	6.7
T1	15.5	28.3	11.4	20.0
T2	14.0	27.2	9.7	18.1
T3	11.6	23.3	4.9	11.0
T4	13.7	26.0	7.3	14.4
T5	14.2	26.8	12.7	23.4
T6	11.5	21.8	5.9	12.4
T7	10.2	20.5	3.4	7.6

4.6 Interaction with large-scale morphological activity

The DSPM does not factor in morphological activity. To assess the interaction between the local scour around a monopile and the large-scale morphology, insight was taken from field observations as presented in the Handbook for Scour Protection (Deltares, 2023). In Appendix E.7 of the handbook, field surveys are shown for a monopile with a scour protection (height:

approx. 1 m) and a sand wave (height: approximately 4 m) in multiple stages of approach. These surveys show that the sand wave covers the scour protection as a whole. There is no reason to conclude that the presence of the monopile and scour protection hinders the movement of the sand wave. Historically, sedimentation and erosion of up to 10 m has been observed due to the movement of Arklow Bank as a whole, see Volume 3, Appendix 4.1. In Deltares (2025) the mean sand wave height is found to be 3.22 m, with a standard deviation of 1.88 m. The mean sand wave migration rate was found to be 15.39 m/year, with a standard deviation of 5.35 m/year. Deltares concludes that a migrating sand wave, or simply the migration of the entire Arklow Bank, at ABWP Phase I has the potential to simply (partially to completely) fill existing scour holes, and in the unlikely case that residual monopiles become exposed, any associated scour development will not inhibit the ongoing large-scale morphological processes.

5 Conclusions

A prediction for the scour development is made for the seven WTG monopiles and met mast monopile at ABWP Phase I. The prediction was made twice: once assuming full-length monopiles, and once assuming residual monopiles become exposed. The input of this prediction consisted of the static soil, water, and structure parameters provided by the Client, together with time-varying metocean conditions (combined wave-current environments) created in-house.

When assuming full-length monopiles, a scour depth between 3.8 and 7.1 m is predicted (5%-95% confidence interval) depending on the turbine location. This results in scour holes with extents between 10.2 and 28.3 m. This is a scenario that is not expected to happen in the field, as the monopiles would need to be unprotected (scour protection removed) for at least 2.5 years to reach this equilibrium scour depth. As such, these values can be used as conservative upper limits.

When assuming residual monopiles cut at LSBL P2 become exposed (assuming seabed levels reach LSBL P0), the scour depth prediction ranges between 1.3 and 5.8 m (5%-95% confidence interval). This results in scour holes with extents between 3.4 and 23.4 m from the monopile. The reduction in predicted median scour depth ranges from 0.6 m (T5) to 3.1 m (T3, T7), corresponding to a reduction range of 9.3% (T5), to 64.8% (T7).

The depth, diameter, and timescales of the predicted scour holes are significantly smaller than those of sandbank migration (approx. 50 m diameter scour hole formed in one year compared to the entire Arklow Bank sand bank, which has the potential to move 6 m in a year and has shown up to 10 m of erosion/sedimentation due to its movement).

It must be noted that while the DSPM considers wave activity, it does not take into account erosion and backfilling due to morphological activity. From field observations shown in the Handbook of Scour Protection, it can be concluded that sand waves are not hindered by the presence of monopiles. Since the scour holes are relatively shallow, in the unlikely case that residual monopiles become exposed, Deltares believes that a migrating sand wave (or the migration of the entire Arklow Bank) has the potential to fill the scour holes and (re-)bury the any potential residual monopiles exposed.

References

Deltares. (2023). Handbook of Scour and Cable Protection methods. Final report, dated December 2023. Retrieved from https://publications.deltares.nl/Deltares250.pdf.

Deltares. (2025). Arklow Bank Sediment Mobility Assessment. Ref: 11208610-002-HYE-0002_v3.0. Final report, dated: 25 September 2025. Retrieved from https://www.pleanala.ie/publicaccess/FurtherInformation/319864/EIAR%20Vol%20III/abwp2_6_2_arklow_bank_sediment_mobility_assessment_rfi_march_2026.pdf?r=270255

Deltares. (2026). Arklow Bank Phase 1 Seabed Mobility. Ref 11212476-002-HYE-0001_v0.1. Draft report, dated 10 March 2026

Dey, S., Raikar, R. V., & Roy, A. (2008). Scour at submerged cylindrical obstacles under steady flow. *Journal of Hydraulic Engineering, 134*(1), 105-109.

GE Wind Energy. (2003). Design report for the foundation of the GE 3.6 offshore wind turbine at Arklow Bank (Document No. GE3.6_CD_foundation_Arklowxx.ENxx.00, Rev. 00). GE Wind Energy.

Harris, J. M., Whitehouse, R. J. S., & Sutherland, J. (2011). *Marine Scour and Offshore Wind: Lessons Learnt and Future Challenges.* Paper presented at the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering.

Hoffmans, G. J., & Verheij, H. J. (1997). *Scour manual* (Vol. 96): CRC press.

Raaijmakers, T., & Rudolph, D. (2008). *Time-dependent scour development under combined current and waves conditions: Laboratory experiments with online monitoring technique*. In H. Sekiguchi (Ed.), **Proceedings of the 4th International Conference on Scour and Erosion (ICSE-4)** (pp. 152–161). The Japanese Geotechnical Society.

Raaijmakers, T. C. (2014). *Dynamic scour prediction for offshore monopiles; validation against laboratory and field measurements.* Paper presented at the Presentation given at the 7th International Conference on Scour and Erosion, Perth, Australia, 2014.

Raaijmakers, T. C. (2016). *Experiences with omitting scour protection and allowing scour in Eneco Luchterduinen: from scale modelling and field measurements towards a new design method for scour prediction.* Paper presented at the Presentation given at the Winddagen, Rotterdam, Netherlands, 2016.

Raaijmakers, T. C., & Rudolph, D. (2008). *Time-dependent scour development under combined current and waves conditions-laboratory experiments with online monitoring technique.* Paper presented at the Proceedings 4th International Conference on Scour and Erosion (ICSE-4). November 5-7, 2008, Tokyo, Japan.

Rudolph, D., Raaijmakers, T., & Stam, C.-J. (2008). *Time-dependent scour development under combined current and wave conditions–hindcast of field measurements.* Paper presented at the Proceedings Fourth International Conference on Scour and Erosion ICSE.

Sheppard, D. M., & Miller, W. (2006). *Live-bed local pier scour experiments*. **Journal of Hydraulic Engineering, 132**(7), 635–642. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:7(635)

SSE Renewables. (n.d.). *Arklow Bank Wind Park*. https://www.sserenewables.com/offshore-wind/projects/arklow-bank-wind-park/ [sserenewables.com]

Sumer, B. M., & Fredsøe, J. (2002). *The mechanics of scour in the marine environment*. Singapore: World Scientific.

Whitehouse, R., Sutherland, J., & O'Brien, D. (2006). Seabed scour assessment for offshore windfarm.

A Timeseries of metocean data

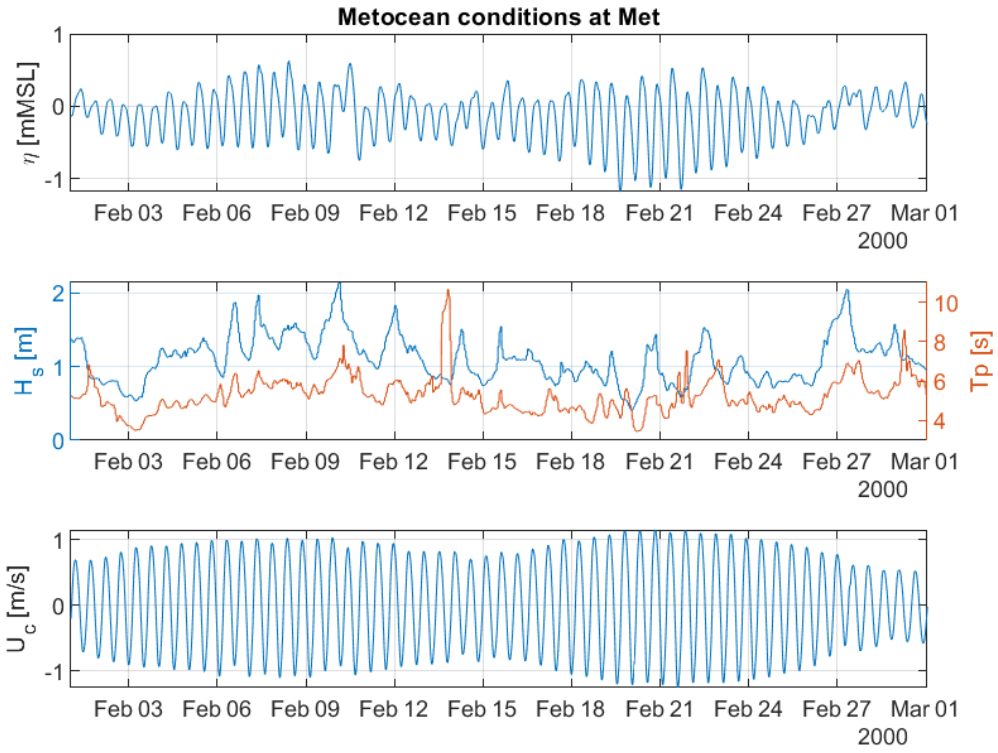


Figure A.1 One month of metocean conditions at the met mast

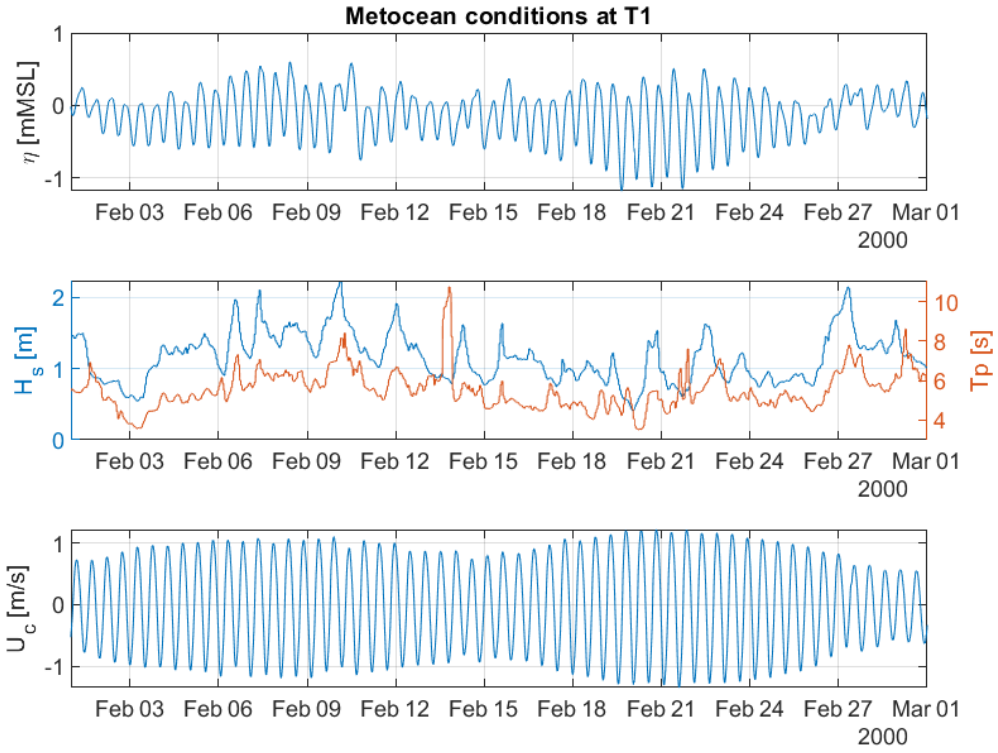


Figure A.2 One month of metocean conditions at T1

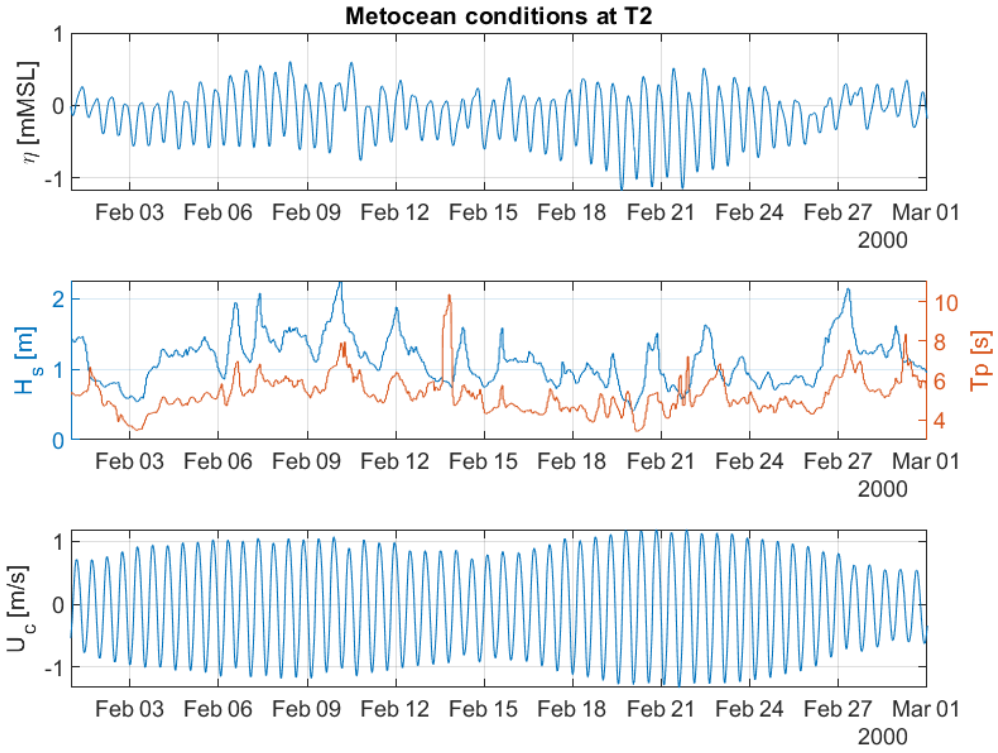


Figure A.3 One month of metocean conditions at T2

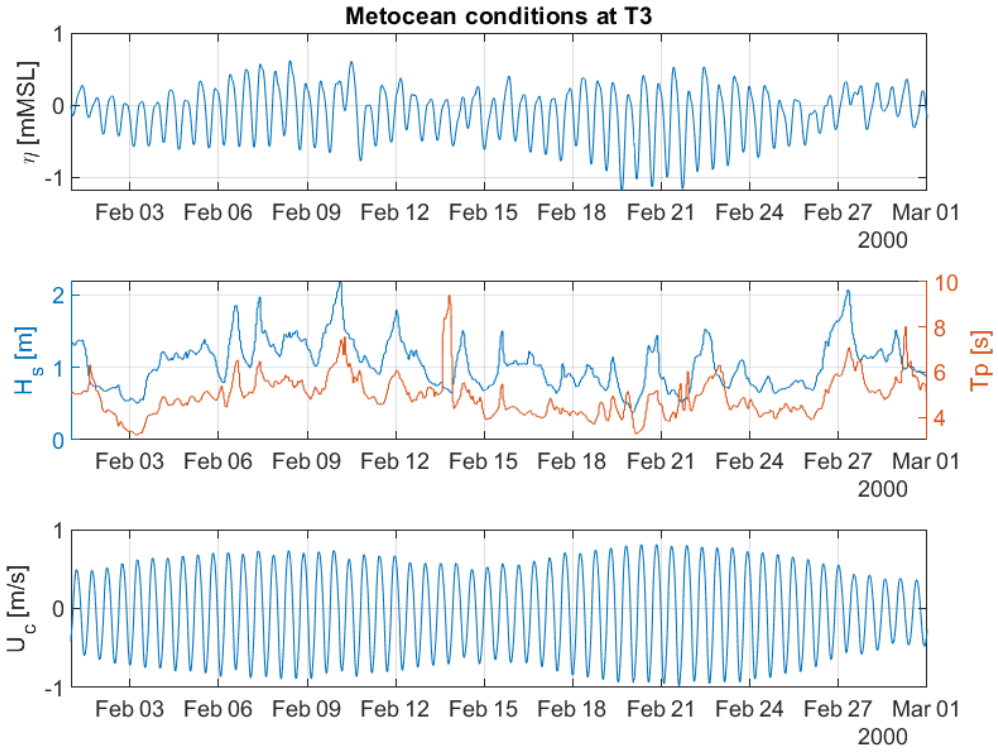


Figure A.4 One month of metocean conditions at T3

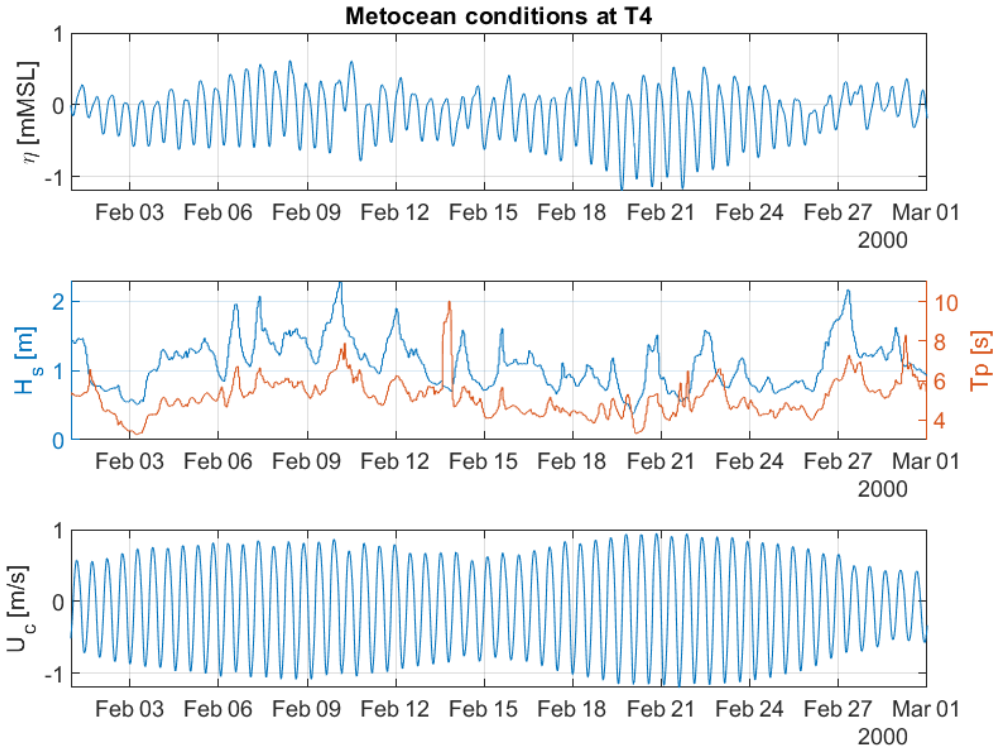


Figure A.5 One month of metocean conditions at T4

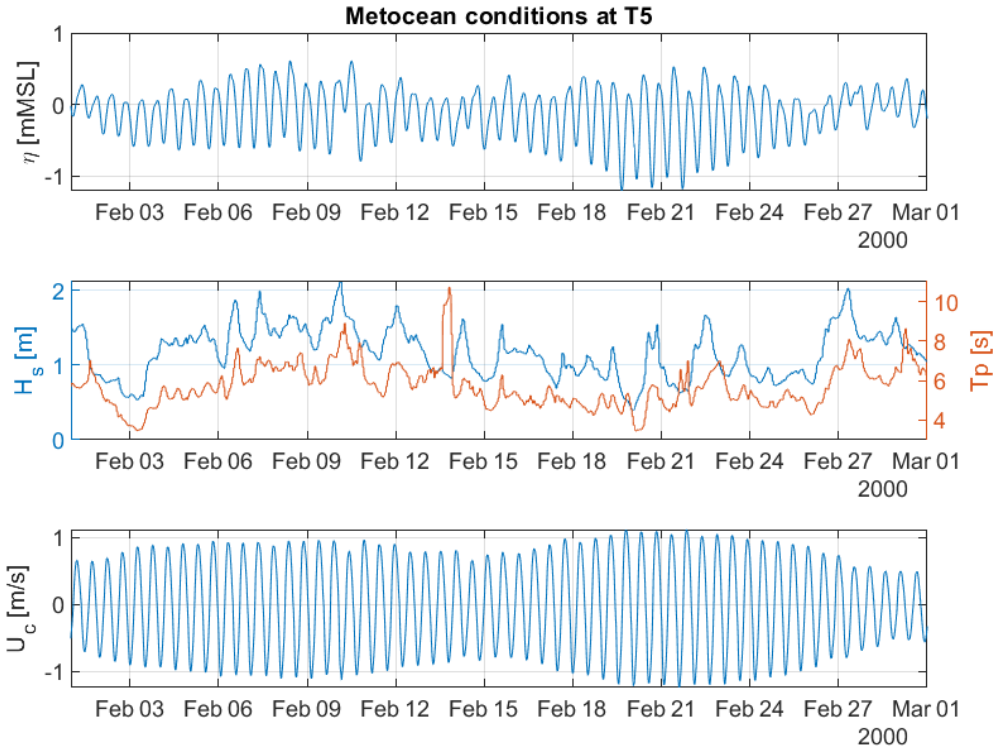


Figure A.6 One month of metocean conditions at T5

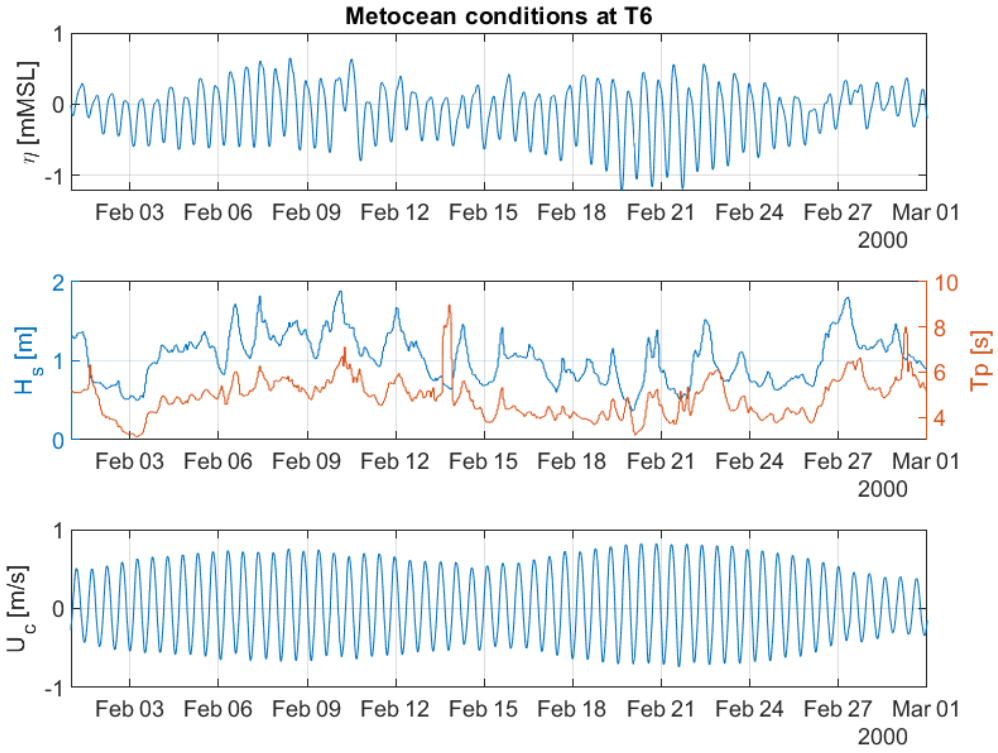


Figure A.7 One month of metocean conditions at T6

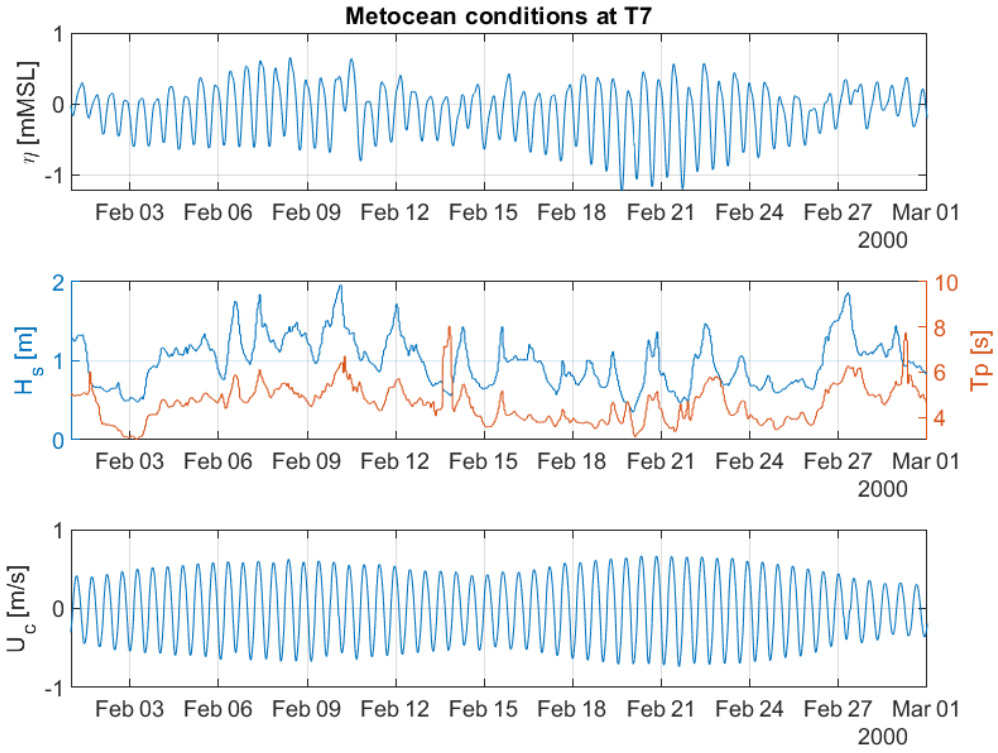


Figure A.8 One month of metocean conditions at T7

B Timeseries of scour development full-length monopiles

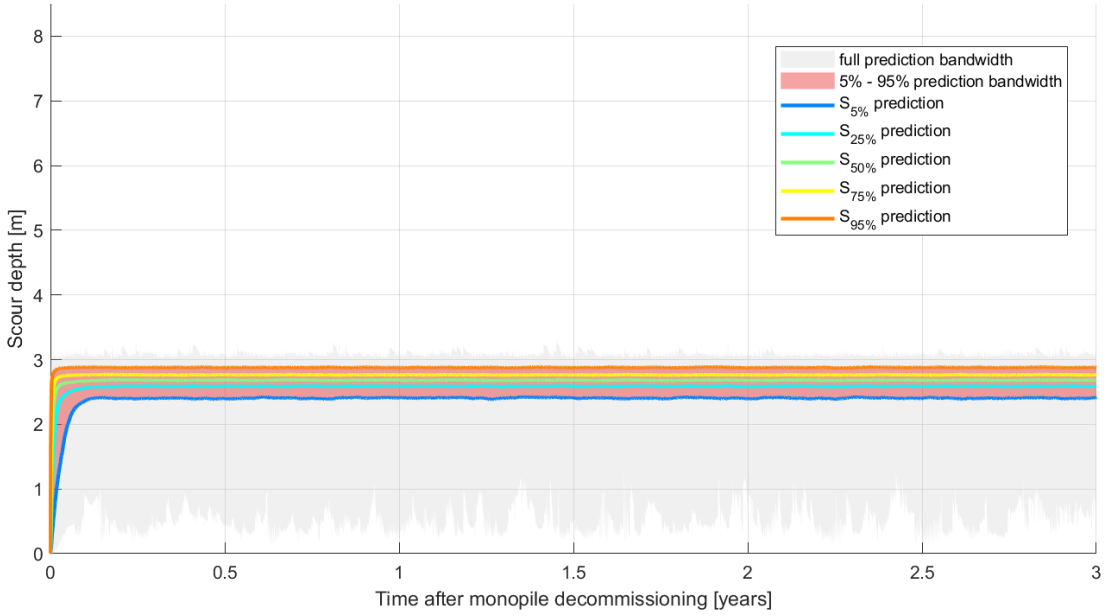


Figure B.1 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for met mast.

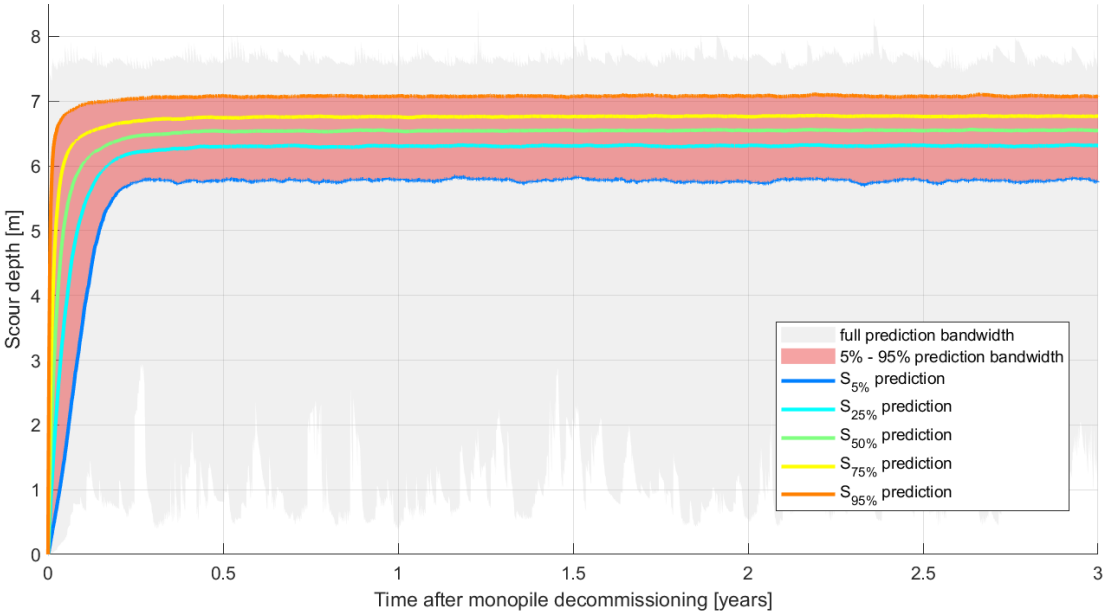


Figure B.2 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T1.

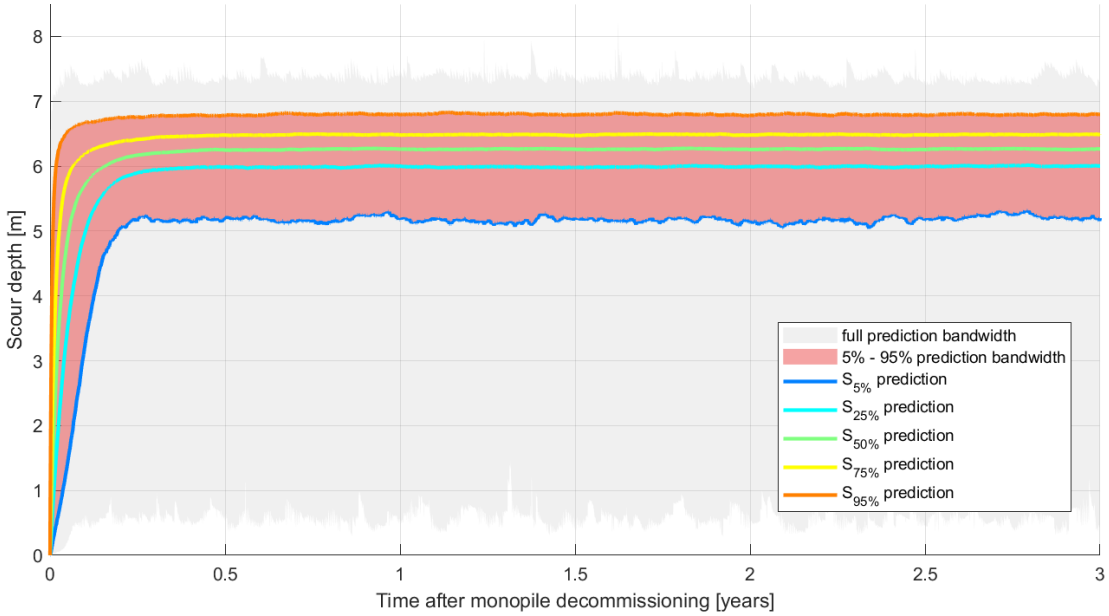


Figure B.3 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T2.

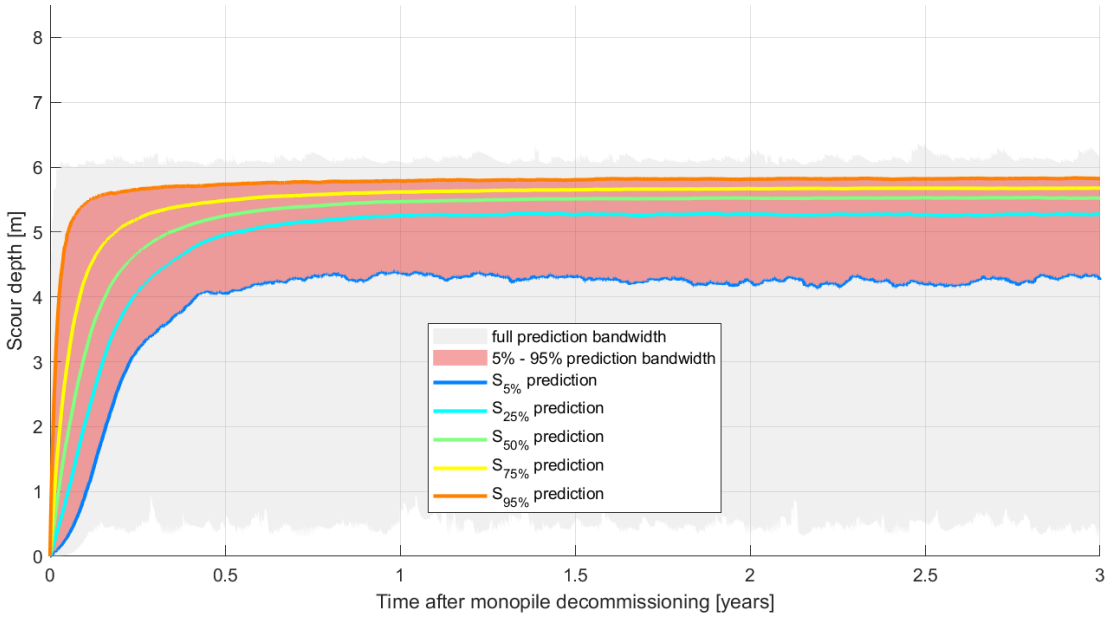


Figure B.4 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T3.

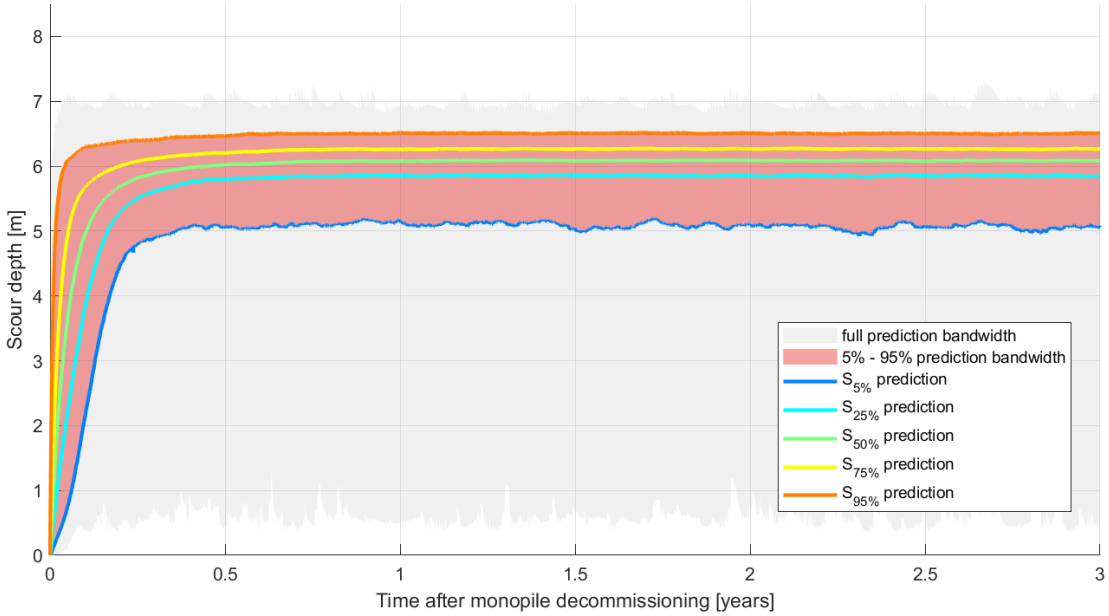


Figure B.5 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T4.

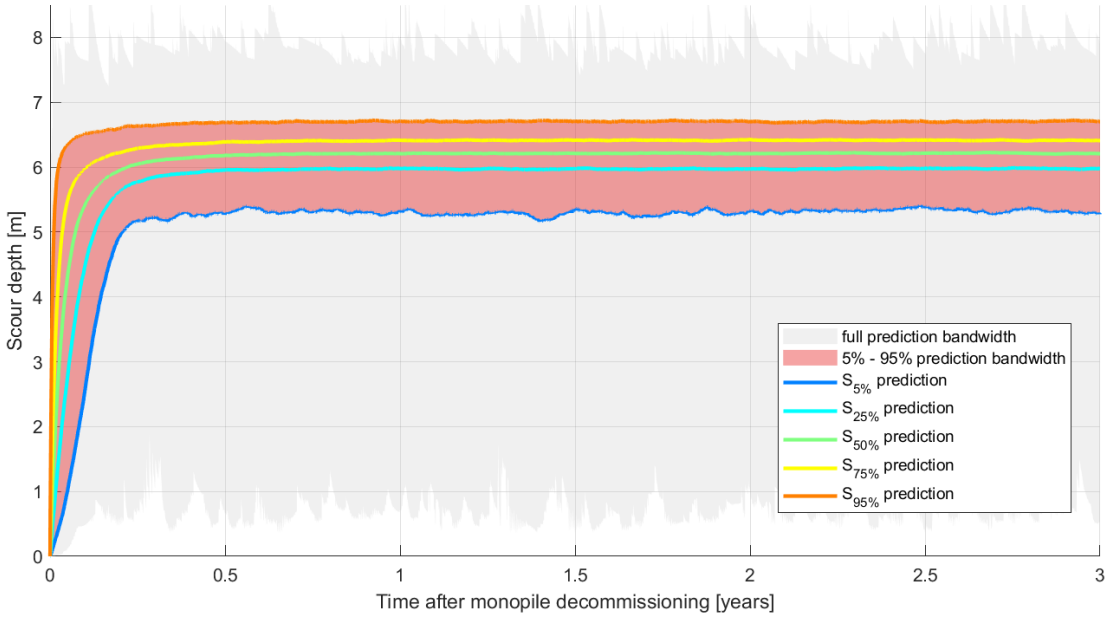


Figure B.6 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T5.

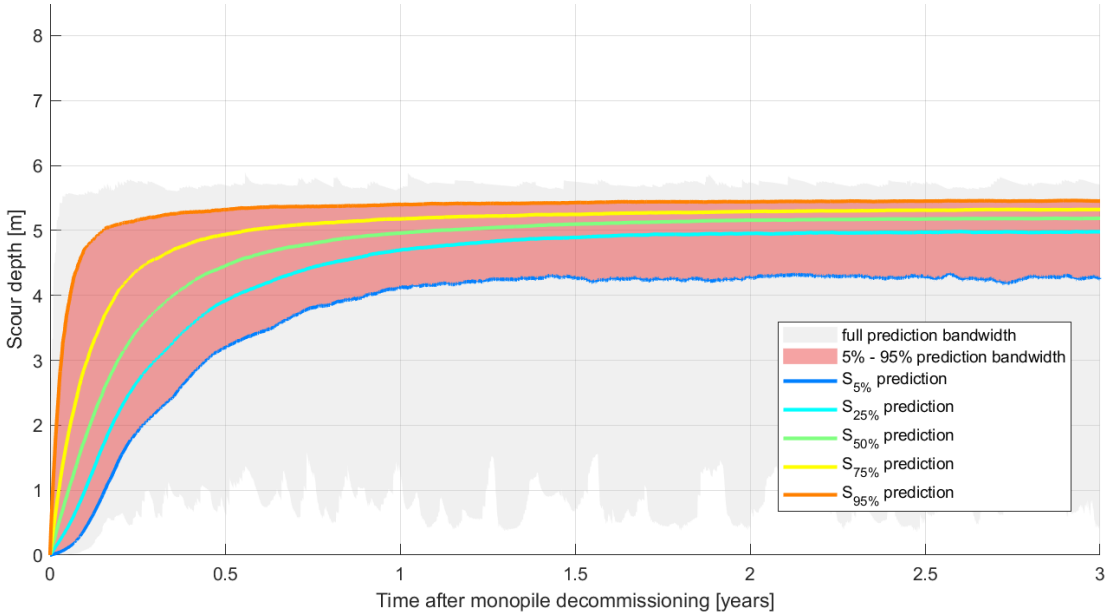


Figure B.7 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T6.

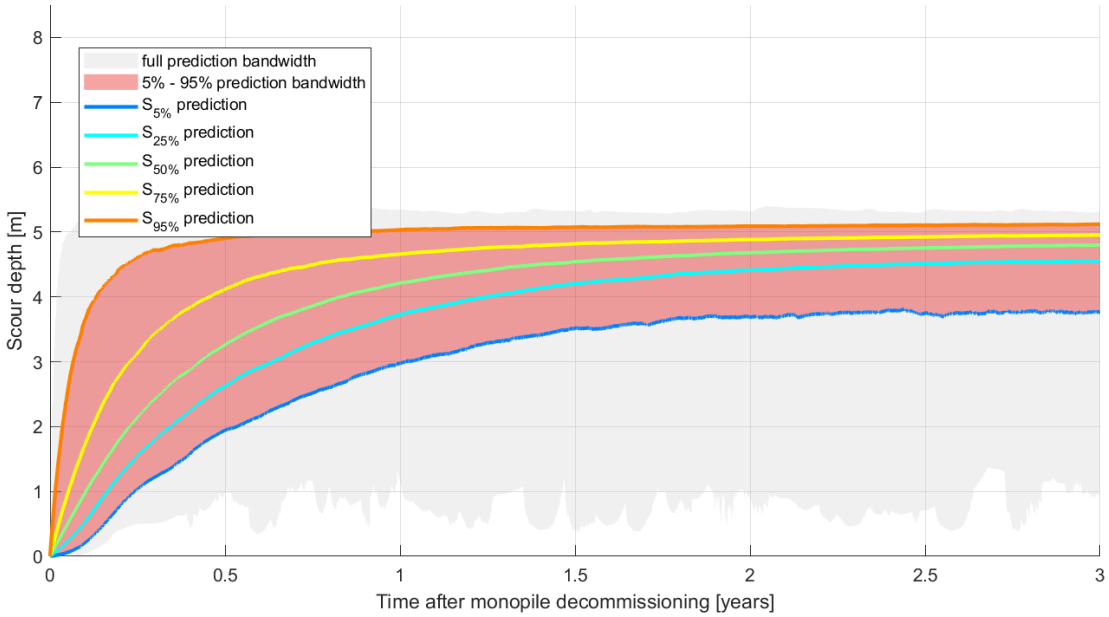


Figure B.8 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T7.

C Timeseries of scour development around exposed residual monopiles

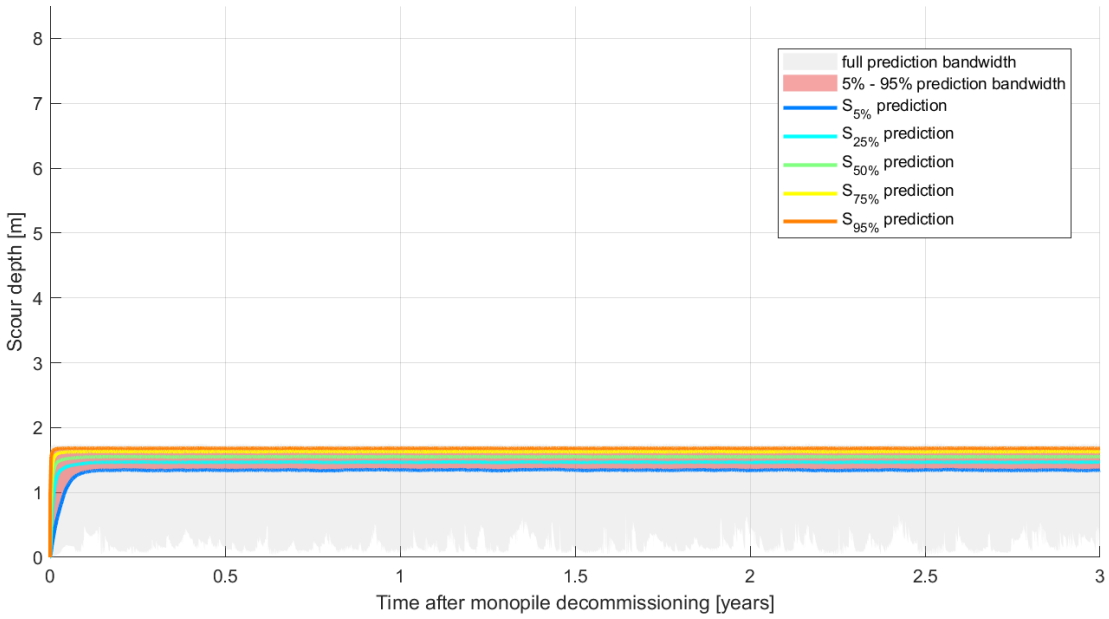


Figure C.1 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for met mast.

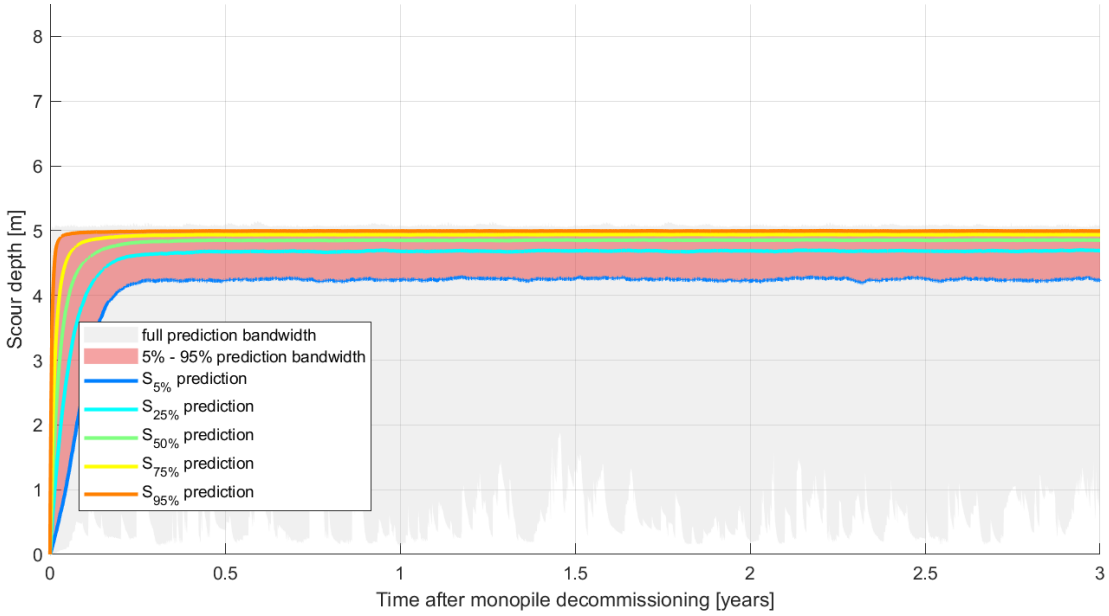


Figure C.2 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T1.

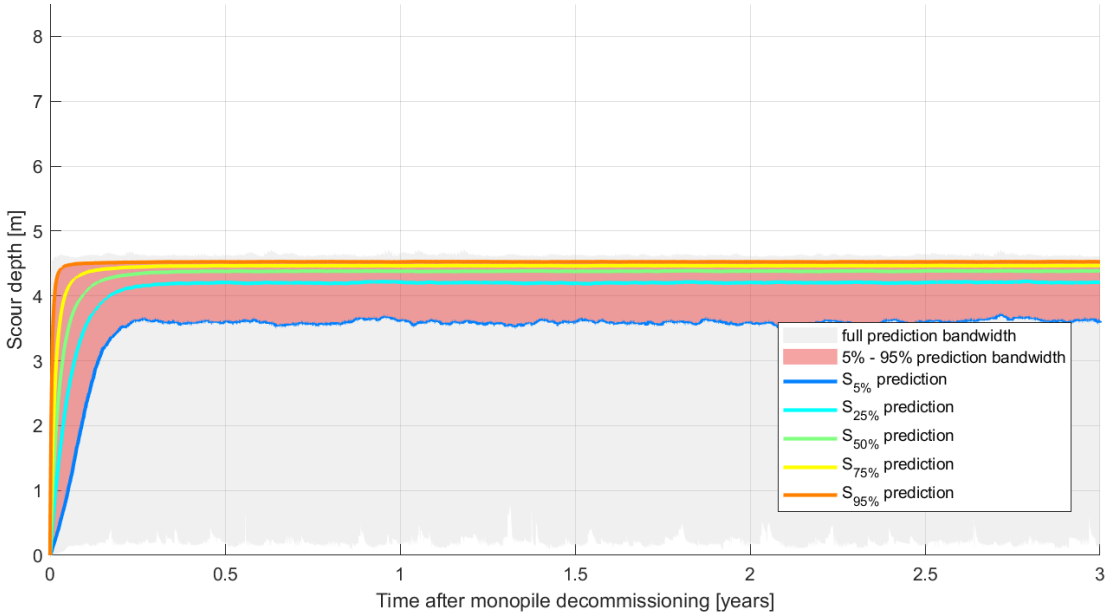


Figure C.3 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T2.

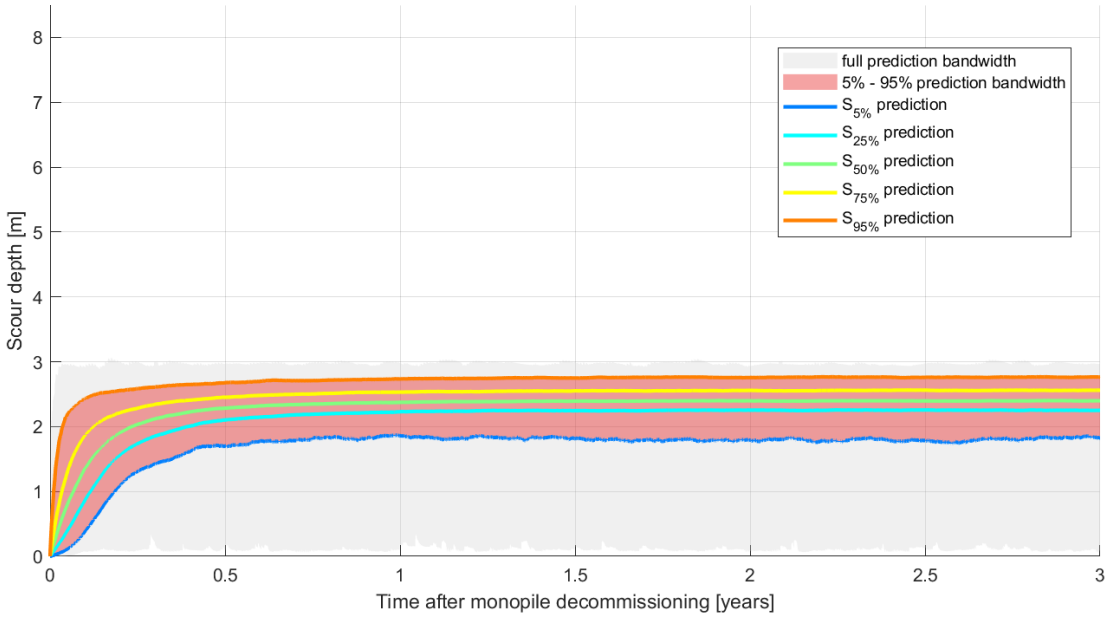


Figure C.4 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T3.

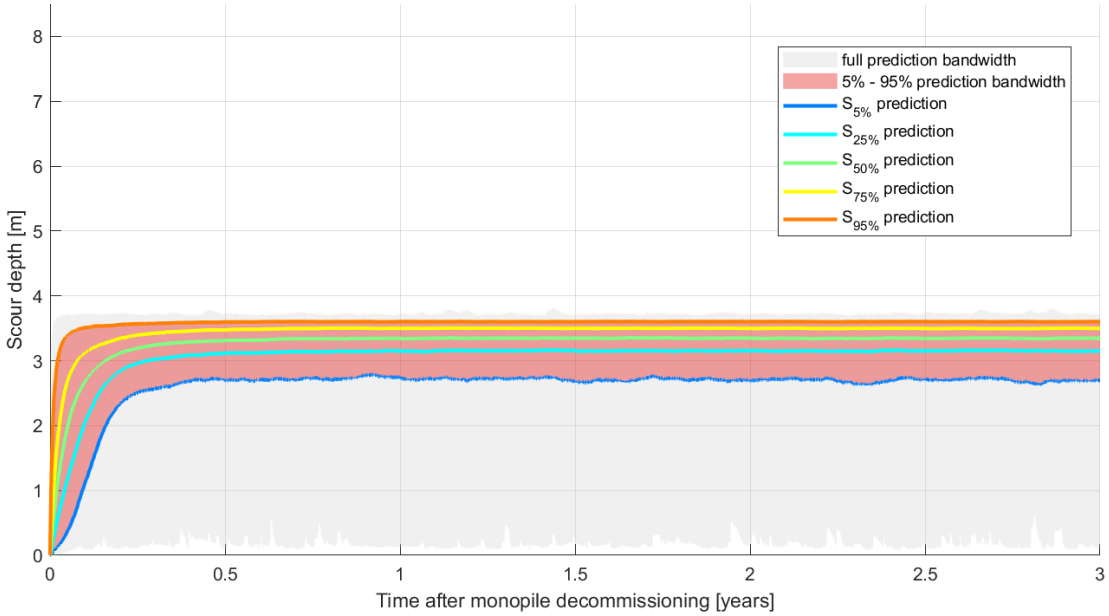


Figure C.5 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T4.

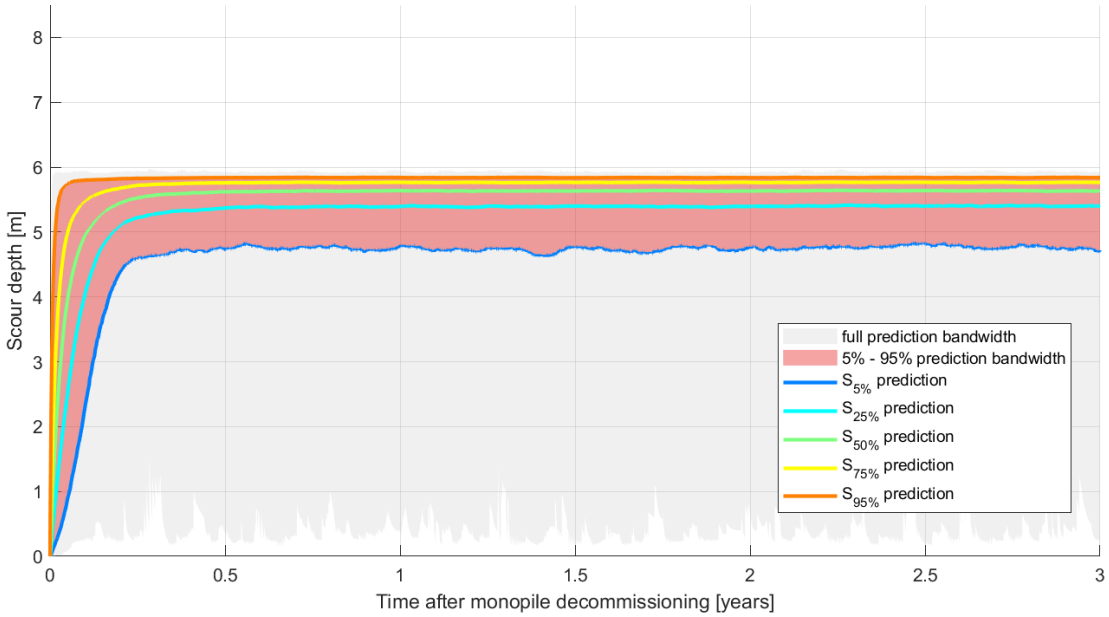


Figure C.6 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T5.

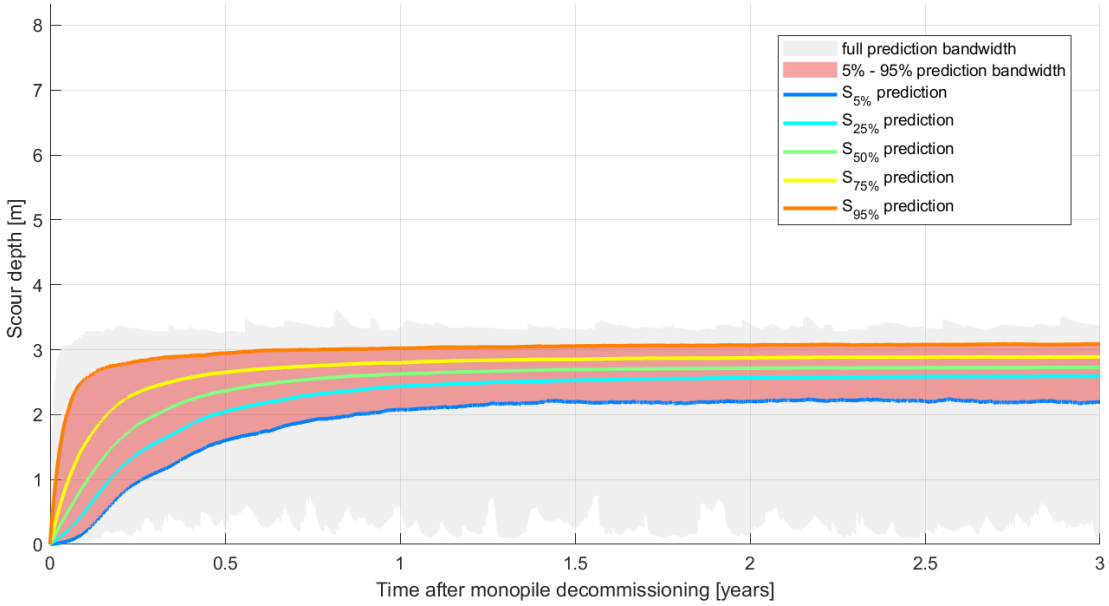


Figure C.7 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T6.

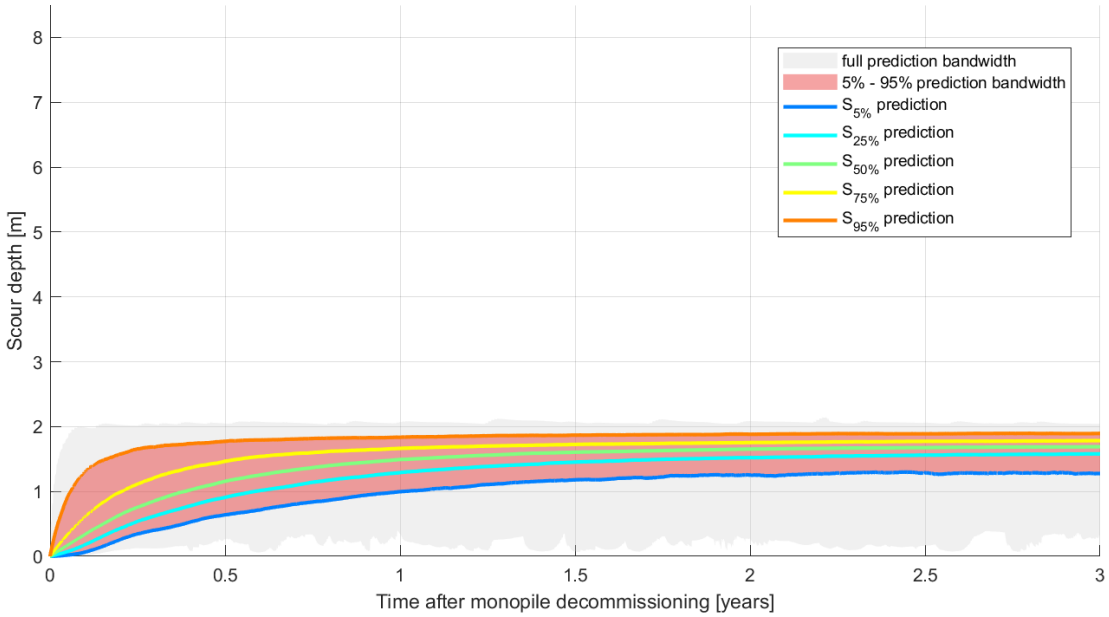


Figure C.8 Time-varying synthetic local scour development for 5000 simulations of varied input parameters within the chosen sensitivity ranges and distributions for T7.

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares

www.deltares.nl