Time Evolution of Scour: The Importance of Event Duration

John M. Harris,[1] Amelia Couldrey,[2] Richard J.S. Whitehouse[3] and Nicholas S. Tavouktsoglou[4]

[1]HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK; e-mail: j.harris@hrwallingford.com Corresponding author.
[2]HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK; e-mail: a.couldrey@hrwallingford.com
[3]HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK; e-mail: r.whitehouse@hrwallingford.com
[4]HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK; e-mail: n.tavouktsoglou@hrwallingford.com

ABSTRACT

The assessment of scour risk at offshore foundations is dependent on a number of different factors including metocean conditions, water depth, soil conditions and structure dimensions and layout. At foundations where the soils are dominated by non-cohesive soils the scour risk is potentially greater than for clay dominated sites. However, even in those locations where sand overlies less erodible soils, it is important to understand the possible time-scale for the loss of this material. Further, as the location of foundation structures moves further offshore into deeper water, not only does the scour process change, the scour development is likely to become event duration limited. However, this latter effect may not only be confined to deeper water sites, but to sites where the metocean conditions are constrained (e.g. weak tidal currents, limited fetch lengths etc). This paper explores the importance of this effect through the use of a time-evolution model of scour.

INTRODUCTION

Over the last two decades offshore wind has developed rapidly from relatively small scale projects in shallow coastal waters such as Horns Rev 1 and Rødsand 1 with a capacity of 160 MW and 166 MW, respectively, to projects such as Hornsea 3 with a capacity of at least 2,400 MW, 120 – 140 km from the coast and in water depths typically in the range -35 to -45 m LAT. Therefore, as the location of a foundation structure moves further offshore into deeper water the processes responsible for scour also change. In shallow water, the part of the total energy at the front of the pile that is due to the hydrostatic component is small relative to the kinetic part. This gives a stagnation point close to the water surface and a significant down-flow down the face of the pile and the generation of larger horseshoe vortices. In deeper water, the hydrostatic component is larger, which combined with the kinetic component, leads to a more even pressure field at the face of the pile, typically, and the stagnation point is located closer to the seabed with corresponding weaker down-flows and smaller horseshoe vortices. Therefore, the magnitude of the scour depth reduces as the water depth increases except in the presence of oceanic currents. Further, the duration of a hydrodynamic event becomes more important in deeper water depths with respect to the scour potential.

In such cases it is important to understand the impact of this on foundation design to avoid being overly conservative when it comes to the likely magnitude of scour over the design life of the structure(s) and any requirement to mitigate scour over this period.

An approach for assessing this effect is to apply a scour evolution model such as that proposed by Harris et al. (2010). For a given project use could be made of a hindcast metocean dataset combining current speed, water surface elevation, significant wave height and peak period as input conditions for the model.

For the purpose of this paper an assessment of the time evolution of scour at a monopile foundation is presented as an example of how this approach could be applied. A comparison of the results from applying a time-evolution model against the results from applying an equilibrium scour model without consideration of time-scale are presented. To assess the time-scale of scouring at the monopile foundation HR Wallingford's STEP model, was applied. The STEP model is an engineering model developed to predict the evolution of scour through time (Harris et al., 2010; 2013).

TIME EVOLUTION OF SCOUR

The time-scale of the scour process can be described in different ways. Typically, the scour depth develops to equilibrium conditions through a transitional period, which is generally asymptotic in form. In the case of live-bed scour the equilibrium scour depth is achieved more rapidly than for the clearwater case. Gosselin and Sheppard (1999) present a review of the time-scale of scour development.

Under steady, uniform flow conditions the scour process will take some time to develop a scour hole and the development of the depth of scour with time, $S(t)$, can be defined by Eqn. (1) (Whitehouse, 1998):

$$S(t) = S_e\left[1 - exp\left(-\frac{t}{T_s}\right)^n\right] \quad (1)$$

Where T_s is the time-scale of the scour process, S_e is the equilibrium scour depth and n is a power, which in the present model takes the value of 0.5. The present version of the STEP model, has been developed to run with a range of different empirical scour formulae including using the formulations of both Sheppard et al. (2011) and Tavouktsoglou et al. (2017). Both methods provide similar results as demonstrated in Figure 1.

At the time of the original study of Harris et al. (2010) there was adequate information to reconstruct the scour process within the model, but very few studies had been carried out on the backfilling process and this remains the case. Hartvig et al. (2010) presented results from a study of wave-induced backfilling at a circular pile, but the study was limited due to the chosen time intervals for the scour and backfilling processes measurements being too coarse. This meant the results were not sufficiently accurate and the time-scale results were inadequate for model proving. Sørensen et al. (2011) conducted a wave backfill test of a simulated current generated scour pit at larger physical scale than Hartvig et al. and showed the backfill time-scale may have a scale dependency. Sumer et al. (2013) presented results of an experimental investigation of the wave-induced backfilling of scour holes around circular piles. They demonstrated that the time-scale of the backfilling process is different from that of scouring. The backfilling process is faster than that during scouring when the Keulegan-Carpenter number, KC, is less than 10 and slower when KC is much greater than 10.

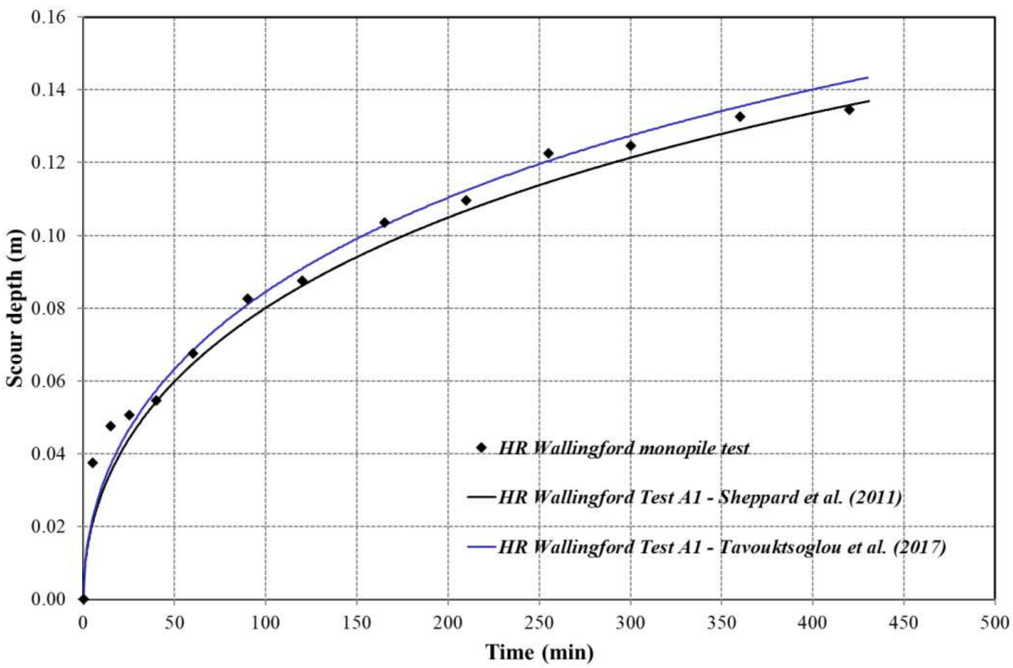

Figure 1: Comparison of the Sheppard *et al.* (2011) and Tavouktsoglou *et al.* (2017) scour predictors

In tidal flows there is an element of infilling of the scour hole taking place due to flow reversal (Figure 2) and due to changes in the magnitude of the tidal current over a spring-neap cycle. It can be observed that infill of the scour hole takes place on the reversing tide which needs to be removed before further deepening of the scour hole can take place (Whitehouse and Stroescu, 2023). This infilling is different to that due to waves as investigated by Hartvig et al. (2010) and Sumer et al. (2013), which may occur during storm events, but is equally important in understanding the time evolution of scour. Given that the time-scale of scour development is, generally, longer under tidal flows than wave dominated flows, errors in this parameter will be most important in tidally dominated situations.

Infilling due to flow reversal in the tidal cycle, whilst important, is still part of a research version of the STEP model and requires further calibration before being applied generally within the model. However, the model does allow for infilling due to the sediment flux balance between flow amplification and ambient sediment transport within the existing STEP model over a tidal cycle. Neglecting the infilling component due to the flow reversal in the tidal process will give a more conservative result (i.e. increased scour depth), and in the present paper this effect is not included in the results presented.

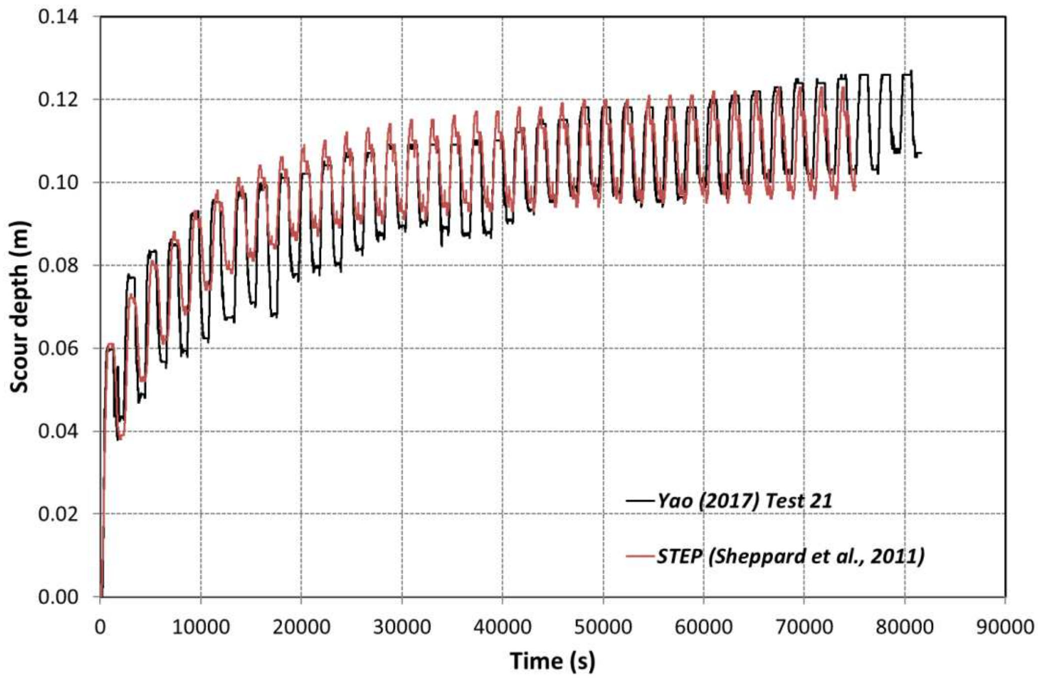

Figure 2: Comparison of the modified STEP model against experimental data for scour development under tidal flow conditions. The experimental scour depth data is measured at the same point on the pile

CASE EXAMPLES

Introduction

In order to apply the time evolution model to assess the scour development over the design life of a project it is necessary to have a metocean time-series that represents the hydrodynamic design conditions (wave, current water level variations). For example, if the foundation has a 25 year operational life, then for design purposes 50 year conditions would normally be applied for design unless the foundation is part of some critical infrastructure, in which case a longer design life may be applicable.

In the present paper synthetic metocean time-series data has been generated based on conditions typical of the North Sea and more sheltered conditions such as the Baltic Sea.

Example 1: Deeper water scenario

If we assume a monopile location with the following input information:

- water depth is 50 m Mean Sea Level (MSL);
- median seabed sediment size (d_{50}) is 0.2 mm and 84th percentile (d_{84}) is 0.26 mm;

- the sediment density is 2650 kg/m^3;
- monopile diameter is 11 m;
- the water density is 1027 kg/m^3;
- 50 year design depth-averaged current is 1 m/s; and,
- 50 year design significant wave height and peak wave period are 8.6 m and 12.8 s, respectively.

Figure 3 shows the synthetic metocean data for the -50 m MSL location.

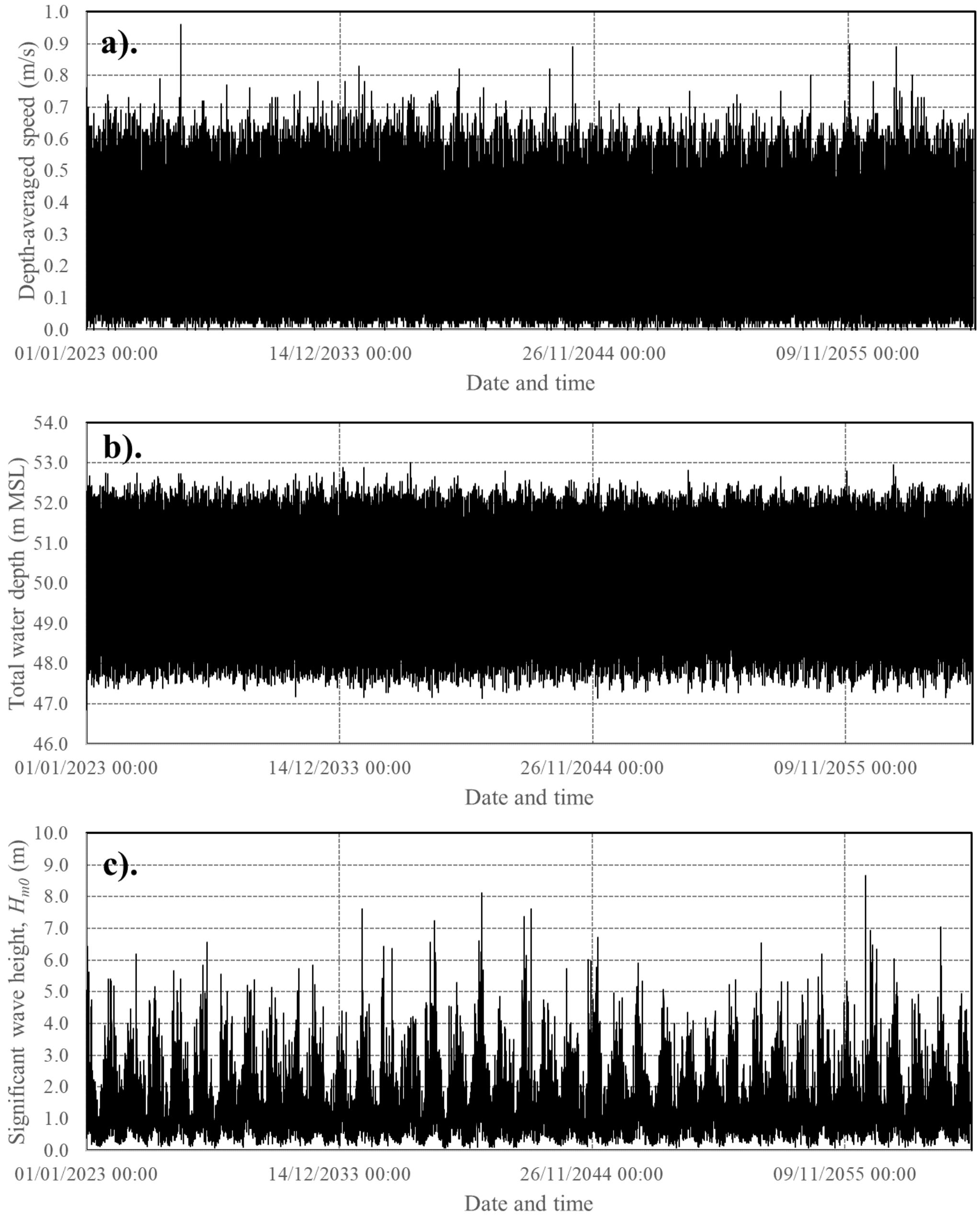

Figure 3: Synthetic time-series simulation for -50 m MSL location showing a). depth-averaged speed; b). total water depth and c). significant wave height. Simulation covers 38 years

Calculating the equilibrium scour depth for current only conditions using the approach of Sheppard et al. (2011) for 50 year return period design conditions gives a value of about 7.9 m. This assumes that the seabed material is comprised sand (d_{50} = 0.2 mm) with unlimited thickness.

Applying the STEP model using the synthetic metocean data to provide the hydrodynamic input data for the model the corresponding estimated scour results for current only and combined wave and current conditions are shown in Figure 4.

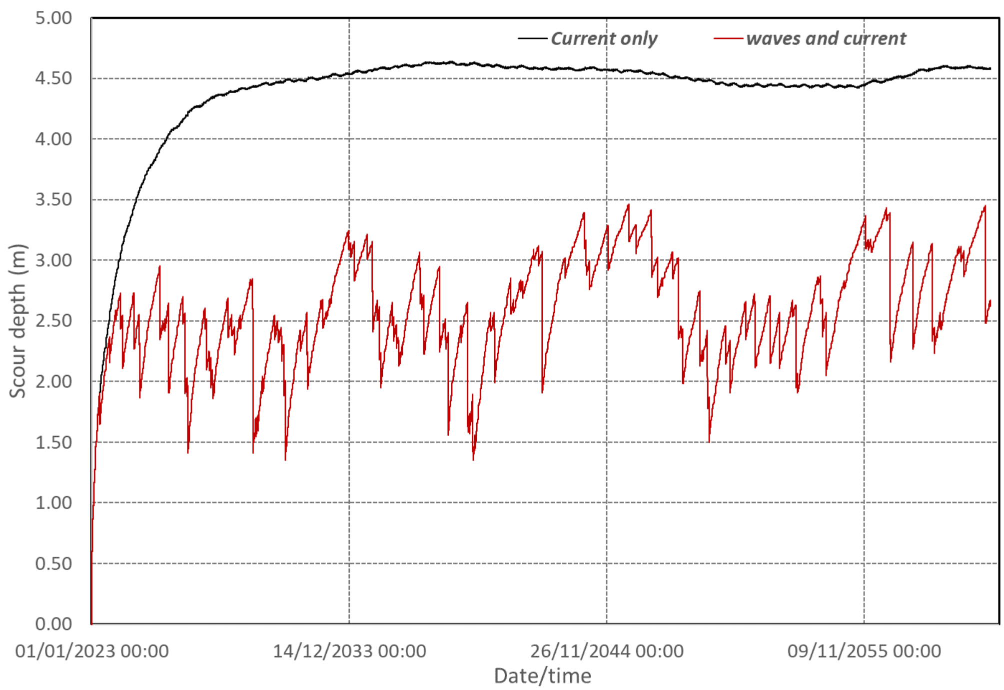

Figure 4: STEP model simulation of scour development at example -50 m MSL water depth with an 11 m diameter monopile for combined wave and current and current only conditions based on the synthetic metocean time-series

From the STEP simulation the peak scour depth over the simulated 38 years is about 4.6 m (3.5 m combined waves and current) rather than the 7.9 m obtained by applying an empirical scour equation, in this case the method of Sheppard et al. (2011).

Example 2: Limited metocean conditions scenario

If we assume a monopile location with the following input information:

- water depth is 25 m Mean Sea Level (MSL);
- median seabed sediment size (d_{50}) is 0.2 mm and 84th percentile (d_{84}) is 0.26 mm;
- the sediment density is 2650 kg/m^3;
- monopile diameter is 8 m;
- the water density is 1006 kg/m^3;
- 50 year design depth-averaged current is 1.1 m/s; and,

- 50 year design significant wave height and peak wave period are 9.0 m and 12.0 s, respectively.

Calculating the equilibrium scour depth for current only conditions using the approach of Sheppard et al. (2011) for 50 year return period design conditions gives a value of about 6.3 m. This assumes that the seabed material is comprised sand (d_{50} = 0.2 mm) with unlimited thickness.

Applying the STEP model and using a different synthetic metocean data applicable to conditions in the Baltic Sea to provide the hydrodynamic input data for the model the corresponding estimated scour results for current only and combined wave and current conditions are shown in Figure 5.

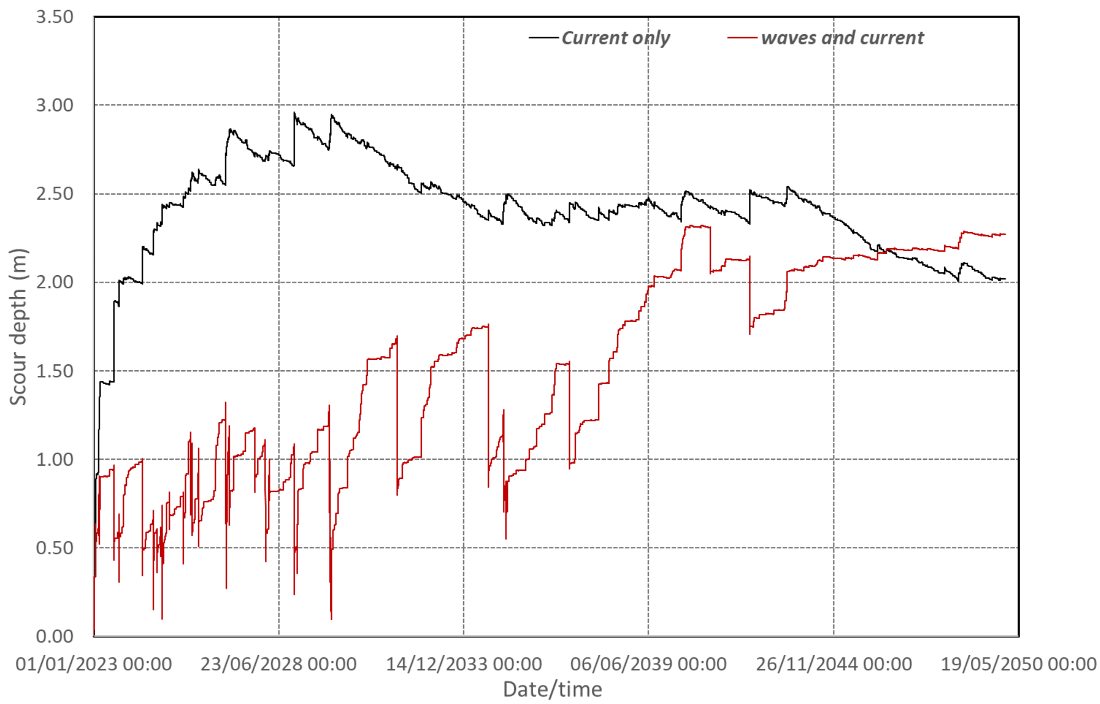

Figure 5: STEP model simulation of scour development at example -25 m MSL water depth with an 8 m diameter monopile for combined wave and current and current only conditions based on the synthetic metocean time-series

From the STEP simulation the peak scour depth over the simulated 26 years is about 3.0 m (2.3 m for combined waves and current) rather than the 6.3 m obtained by applying an empirical scour equation, in this case the method of Sheppard et al. (2011).

DISCUSSION

In both scenarios the STEP simulations utilized the method of Sheppard et al. (2011) to ensure consistency between the equilibrium scour predictions and the time evolution of scour predicted from the engineering model. Clearly, the results show a difference in the estimated scour potential between a standard application of an empirical scour predictor and the application of the same predictor where the duration of the metocean conditions is included. The simulation of the scour development at the two generic sites using the synthetic metocean data show the scour development to be event duration limited. This implies that the scour development is controlled by the duration of the hydrodynamic conditions and this limits the depth to which scour can develop over time. At actual project locations the soil conditions may enhance this effect by slowing the scour development and thereby reducing the longer term local scour development further, albeit there may be a contribution at foundations, particularly related to monopile foundations and offshore wind developments, from the mechanical effect of foundation cyclic loading at the mudline (Harris and Whitehouse, 2017). Where the seabed soils are primarily cohesive then scour can be determined using approaches such as those outlined in Harris et al. (2023).

The implication of the above is that the hindcast metocean time-series often created for projects need to be accurate and representative of the conditions at a site over the design life, ensuring that any time-series captures the design conditions within the simulated period. The simulated period also needs to cover the overall lifespan of the foundations including the installation and decommissioning periods.

The sequence of events can be important and this can be simulated by resequencing the hindcast data to investigate the impact of storm occurrence within the time-series.

Ultimately, the benefit of using models like STEP is that it may enable foundations to be installed without scour protection. If the adopted design philosophy for the foundations involves installing them without scour protection, then it is important to develop a monitoring and contingency plan. In simplified terms the plan can be defined by the following steps:

1. Set and agree critical seabed levels for intervention works.
2. Obtain baseline survey for scour condition monitoring immediately on completion of foundation installation.
3. Undertake first annual survey (after first winter period in the spring) covering all foundations.
4. Undertake second annual survey (after second winter period in the spring) covering all foundations.
5. Thereafter carry out surveys (after winter period in the spring) of all or representative subset group of foundations every 4 years minimum.
6. Carry out event-led monitoring as required.
7. Review and revise monitoring strategy informed by the results of previous surveys.

Remedial works of appropriate design to maintain the seabed level around the foundations may be required to be undertaken after analysis and review of annual/four-year surveys and event-led trigger monitoring.

There are a number of scenarios that exist where there may be a requirement to place scour protection. These scenarios can be summarised as:

- The potential to scour is greater than anticipated or the scour (combined general and local) is greater than expected and exceeds or equals the design level for placement of scour protection; and/or,
- The scour and corresponding scour extents associated with ancillary structures (i.e. cable protection system and cables) is greater than expected and exceeds or equals the design level for placement of scour protection.

In the event of the above applying, then remedial measures can be considered for installation involving the placement of rock scour protection or other appropriate protection measure.

CONCLUSION

This paper has explored the concept of scour development being event duration limited through the use of a time-evolution model of scour. Two scenarios have been considered, the case where the foundation(s) is located in deeper water (in this case -50 m MSL), and secondly the situation where a shallower water site (-25 m MSL) where the metocean conditions are constrained (e.g. weak tidal currents, limited fetch lengths etc).

The simulation of the scour development at the two generic sites using the synthetic metocean data show the scour development to be event duration limited. This implies that the scour development is controlled by the duration of the hydrodynamic conditions and this limits the depth to which scour can develop over time. For actual projects where such an approach is applicable the accuracy of the metocean data time-series derived for the project then becomes important.

In the deep water scenario the apparent overprediction between the scour depth determined from applying an empirical scour predictor with the design current, compared to the value determined from using the same predictor in a time evolution model is about 58 %, whilst in the second scenario the difference is about 48 %.

Therefore, for design purposes, consideration of the likely metocean conditions over the lifetime of the project, and using this information in assessing the scour risk through the application of a time evolution scour model such as STEP can yield potential benefits in relation to seabed impacts including ecology and decommissioning costs, and allow for scour mitigation on the basis of developing a monitoring and maintenance plan.

ACKNOWLEDGEMENTS

The authors were funded by HR Wallingford’s strategic scour research programme whilst preparing the paper.

REFERENCES

Gosselin, M.S. and Sheppard, D.M. (1999). "A review of the time rate of local scour research." In: *Stream Stability and Scour at Highway Bridges.* (eds.) Richardson, E.V. and Lagasse, P.F., ASCE, New York, 261 – 279.

Harris, J.M., Whitehouse, R.J.S. and Benson, T. (2010). "The time evolution of scour around off-shore structures." *Proceedings of the Institution of Civil Engineers, Maritime Engineering*, 163, March, Issue MA1, 3 – 17.

Harris, J.M., Whitehouse, R.J.S., Porter, K. and Simons, R.R. (2013). "Scour development through time – modelling scour in layered soils." *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, OMAE2013, June 9-14, Nantes, France, OMAE2013-10720.

Harris, J.M. and Whitehouse, R.J.S. (2017). "A review of scour development around large diameter monopiles in cohesive soils: Evidence from the field." *J. Waterway, Port, Coastal, Ocean Engng.*, 143(5), ASCE.

Harris, J.M., Tavouktsoglou, N., Couldrey, A., Whitehouse, R.J.S., and Klapper, J. (2022). "Scour Prediction in Cohesive Marine Soils: A Hybrid Approach." *International Journal of Geoengineering Case Histories*, Vol. 7, Issue 4, pp. 59-75, doi: 10.4417/IJGCH-07-04-06

Hartvig, P.A., Thomsen, J.M., Frigaard, P. and Andersen, T.L. (2010). "Experimental study of the development of scour and backfilling." *Coastal Engineering Journal*, Vol. 52, No. 2, 157–194.

Sheppard D.M., Demir, H. and Melville, B. (2011). *Scour at Wide Piers and Long Skewed Piers*. Transportation Research Board, Washington, D.C., NCHRP Report 682, 55 p + Appendices.

Sørensen, S.P.H., Ibsen, L.B. and Frigaard, P. (2011). "Experimental evaluation of backfill in scour holes around offshore monopiles." *In: Frontiers in Offshore Geotechnics II – Gouvernec S. and White, D. (eds), 617-622. Taylor & Francis Group, London.*

Sumer, B.M., Petersen, T.U., Locatelli, L., Fredsøe, J., Musumeci, R.E. and Foti, E. (2013). "Backfilling of a scour hole around a pile in waves and current." *J. Waterway, Port, Coastal, and Ocean Engng.*, Vol. 139, No. 1, January 1, 9 -23.

Tavouktsoglou, N.S., Harris, J.M., Simons, R.R. and Whitehouse, R.J.S. (2017). "Equilibrium scour depth prediction around cylindrical structures." *J. Waterway, Port, Coastal, Ocean Engng.*, 143(5), ASCE.

Whitehouse, R.J.S. (1998). *Scour at marine structures: A manual for practical applications*. Thomas Telford, London, 198 p.

Whitehouse, R.J.S. and Stroescu, E.I. (2023). "Scour depth development at piles of different height under the action of cyclic (tidal) flow." *Coastal Engineering*, 179, 104225.

Yao, W. (2017). Personal communication.