Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-615

Numerical analysis of monopiles supporting offshore wind turbines exposed to scour and cyclic loading

Analyse numérique des monopieux supportant des éoliennes offshores exposées à l'affouillement et aux charges cycliques

C. Menéndez-Vicente*, S. López-Querol
University College London, London, United Kingdom

**carlos.vicente.19@ucl.ac.uk*

ABSTRACT: Offshore wind turbines founded on monopiles are exposed to geohazards such as scour that threaten their long-term stability and serviceability. An active seabed changes the foundation conditions of these structures, which directly affects the soil-structure stiffness and its performance under environmental (cyclic) loading composed of wind and sea waves. This study aims to investigate the effects of scour under cyclic loading. A numerical approach with finite element analysis in Abaqus was applied. To simulate the long-term strain accumulation with load cycles, a hypoplastic constitutive model to reproduce the sand behaviour was implemented. Through these simulations, the ratcheting phenomenon based on increasing deformations with the number of cycles, has been simulated for sandy soils. The results quantify the effect of higher scour depths causing an increase of the displacement incremental rate per load cycle, which leads to larger maximum and residual displacements. This evidences the long-term risk for monopiles exposed to scour and cyclic loading in terms of serviceability and economic viability, due to a potential lifetime reduction given their vulnerability to excessive tilt. This study intends to raise awareness about the importance of considering scour during the design and operation of offshore wind turbines exposed to an active seabed.

RÉSUMÉ: Les éoliennes offshore fondées sur des monopieux sont exposées à des géorisques tels que l'affouillement, qui menacent leur stabilité et leur fonctionnalité à long terme. Un fond marin actif modifie les conditions de fondation de ces structures, ce qui affecte directement la rigidité du système sol-structure et son comportement sous une charge environnementale (cyclique) composée de vent et de vagues. Cette étude vise à examiner les effets de l'affouillement sur un monopieu soumis à une charge cyclique. Une approche numérique avec une analyse par éléments finis dans Abaqus a été appliquée. Pour simuler l'accumulation de déformations à long terme avec cycles de charge, un modèle constitutif hypoplastique simulant le comportement du sable a été implémenté. Ainsi, le phénomène de ratcheting de sols sableux, qui est basé sur l'augmentation des déformations avec l'augmentation du nombre de cycles, a été simulé. Les résultats quantifient l'effet que des profondeurs d'affouillement plus importantes entraînent une augmentation du taux de déplacements incrémentiels par cycle de charge, ce qui conduit à des déplacements maximaux et résiduels plus importants. Ceci met en évidence le risque à long terme pour les monopieux exposés à l'affouillement et aux charges cycliques en termes d'aptitude au service et de viabilité économique, en tenant compte d'une réduction potentielle de la durée de vie en raison de leur vulnérabilité à un basculement excessif. Cette étude vise à sensibiliser à l'importance de la considération de l'affouillement lors de la conception et de l'exploitation d'éoliennes offshore exposées à un fond marin actif.

Keywords: Offshore wind turbines; scour; monopiles; soil-structure interaction; finite elements analysis.

1 INTRODUCTION

Offshore Wind Turbines (OWT) are rapidly being installed worldwide due to the high demand for clean and renewable energy. These structures are exposed to waves and currents, which cause scour around piled foundations. Normally, scour protection such as rock armour is installed to prevent erosion. Nonetheless, non-protected foundations may develop scour holes, which reduce the embedment length and weaken the lateral capacity of monopiles. Cyclic loading caused by wind-wave loads leads to a degradation of the foundation material (often sands), which produces long-term strain accumulation and ultimately irreversible tilting (i.e. serviceability and structural damage). Moreover, this stiffness reduction may lead to a shift in the natural frequency towards the forcing frequencies and an increase in fatigue damage.

To numerically simulate OWT monopiles exposed to cyclic loading, complex constitutive models to replicate the long-term stress-path dependent strain accumulation of granular materials such as sands are needed. Hypoplasticity (von Wolfersdorff, 1996;

Niemunis and Herle, 1997) was implemented successfully by Askarinejad et al. (2022) for sands to reproduce their results obtained through centrifuge testing for a monopile with scour protection. The present paper intends to analyse the opposite: the effect of scour on monopiles exposed to cyclic loading. With a series of simulations for different scour depths *S*, the impact of cyclic loading is analysed through a hypoplastic constitutive law of the sand surrounding the scoured piled foundation.

2 METHODOLOGY

2.1 Numerical model

A finite element (FE) model based on the study of Askarinejad et al. (2022) was developed in Abaqus. The domain consists of a symmetric half soil-pile system with a pile diameter of $D = 1.8$ m (Figure 1). For comparison purposes, a further FE model with a large-diameter monopile ($D = 7.5$ m) was also modelled. Regarding the boundary conditions, the lateral faces were constrained in normal direction, whereas the bottom plane was fixed in all directions. The pile was modelled for simplicity with an elastic constitutive behaviour using solid bodies (instead of tubular structures) with equivalent masses and flexural stiffnesses (López-Querol et al., 2020). Table 1 shows the material properties, where *D* is the diameter of the pile, *t* is the thickness of the tubular profile, ρ is the density, ν is the Poisson's ratio, *E* is the Young's modulus, and *I* is the moment of inertia. For the pile embedded in the soil, a sand fill of the tubular section was considered, whereas the upper part was modelled as a hollow cylinder. Dry densities were considered in analogy to Askarinejad et al. (2022); nonetheless, the findings are also applicable to submerged conditions. For the soil-pile interface, a fully rough condition was applied. The scour hole was modelled for simplicity as an inverted cone with a range of scour depths $S = \{0; 0.5D; 1.0D\}$ that may be found on the field (Whitehouse et al., 2011) and a slope angle equivalent to the soil's friction angle.

Table 1. Pile elastic properties.

Type	*D* [m]	*t* [m]	ρ [t/m^3]	ν [-]	*E* [GPa]	*I* [m^4]
			pile filled with sand			
tubular	1.8	0.031	7.86	0.2	210	0.0674
solid	1.8	-	2.397	0.2	27.51	0.5153
			hollow structure			
tubular	1.8	0.031	7.86	0.2	210	0.0674
solid	1.8	-	0.532	0.2	27.47	0.5153

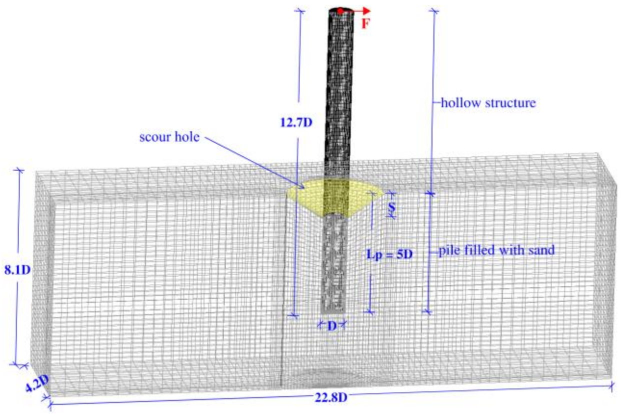

Figure 1. Mesh of the scoured soil-pile system used for FE analysis in Abaqus (adapted from Askarinejad et al., 2022).

2.2 Constitutive model

To reproduce the cyclic soil response, a hypoplastic constitutive model was implemented. This allows a strain and stress-path dependent stiffness adaptation for the simulation of strain accumulation under loading, unloading and reloading stress paths (von Wolfersdorff, 1996; Niemunis and Herle, 1997). With the hypoplastic model, the ratcheting phenomenon (i.e. cumulative plastic deformation, with a constant increment per cycle; Cuéllar, 2011) in sand was simulated. Readers are referred to Askarinejad et al. (2022) for further details about the implementation of hypoplasticity. A drained Geba sand was used with the parameters shown in Table 2 (Azúa-González et al., 2019). These parameters correspond to a fine sand with a d_{50} of 0.12 mm and a relative density of 0.63.

Table 2. Hypoplastic model for Geba sand (Azúa-González et al., 2019).

von Wolffersdorff´s model parameters							
φ'	h_s	n	α	β	e_{i0}	e_{c0}	e_{d0}
[º]	[MPa]	[-]	[-]	[-]	[-]	[-]	[-]
34	2500	0.3	0.11	2	1.28	1.07	0.64

IS model parameters				
m_R	m_T	R	β_R	χ
[-]	[-]	[-]	[-]	[-]
5.5	3.9	10^{-4}	0.3	0.7

2.3 Validation

The results obtained through centrifuge testing in Askarinejad et al. (2022) were used for validation. The numerical model described previously was subjected to a horizontal cyclic load applied on the top of the structure with a magnitude of 100 kN and a load frequency of 1 Hz with $N = 10$ load cycles.

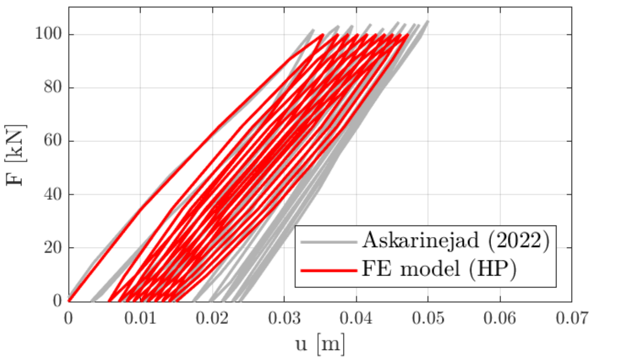

Figure 2. Validation results with hypoplasticity vs. centrifuge results from Askarinejad et al. (2022).

The FE model with hypoplasticity yielded similar results compared to those presented by Askarinejad et al. (2022). Figure 2 shows the horizontal displacements u at the top of the structure (loading point) plotted against the loading force F. A good agreement of the results with the centrifuge data is found, especially for the first load cycles. Hence, the hypoplastic model was considered validated and applied for further investigations of scour affecting the lateral soil-pile response under cyclic loading.

3 RESULTS AND DISCUSSION

The FE model described previously was subjected to a cyclic load with an amplitude of F = 50 kN at the top of the structure and a frequency of f = 1 Hz during N = 10 cycles as a simplified horizontal load representing a wind-wave resultant. For simplicity, only one-way load cycles were considered. Figure 3 and Figure 4 show the dimensionless load-displacement curve for different scour depths S = {0; 0.5D; 1.0D} for the small and the large diameter monopiles respectively. A similar behaviour is observed for both models. In Figure 4 it is seen that the higher scour depth (S = 1.0D) moves away from the cases with S = {0; 0.5D}, evidencing the (large diameter) monopile vulnerability to scour compared to the small diameter monopile. The scour depth is linked with D, i.e. a higher D causes a higher absolute S. The displacements were recorded at the loading point (i.e. the top of the structure). The load was normalized by the dead load of the tubular pile ($V = m_{pile}\, g$) and the displacement was normalized by D. Figure 6 shows the soil horizontal stresses (σ_{11}) and the horizontal displacements (u_1) for S = 0.5D. Figure 5 shows the evolution of the maximum displacements with N. As expected, the accumulated displacements increase with increasing scour depth due to the loss of lateral bearing capacity given the shorter embedment length and the material degradation with increasing cycling.

It is seen from Figure 5 that the displacement accumulation increases at a higher rate with increasing scour depth. The incremental rate $(u_{N=10} - u_{N=1})/u_{N=1}$ increases from 13% (for S = 0) to 19% (for S = 1.0D) in the first ten cycles. This confirms that scoured monopiles are more vulnerable to cyclic loading compared to non-scoured monopiles or those with scour protection. Figure 6 (u_1) shows that plastic displacements remain after a series of cycles at the top and bottom of the pile, suggesting a permanent tilt for a combined action of scour and cyclic loading. The simulations are limited by the computational power required, which restricts the number of cycles that can be simulated in a reasonable amount of time.

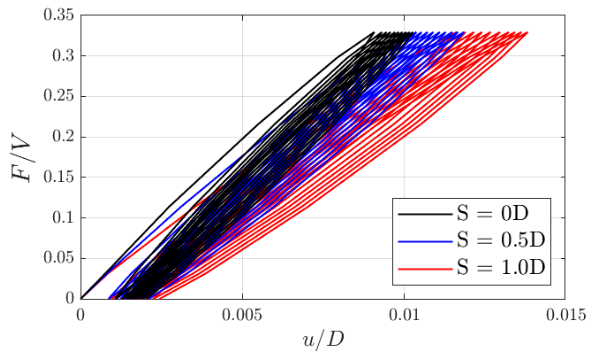

Figure 3. Load-displacement curve for S = {0; 0.5D; 1.0D} with D = 1.8 m.

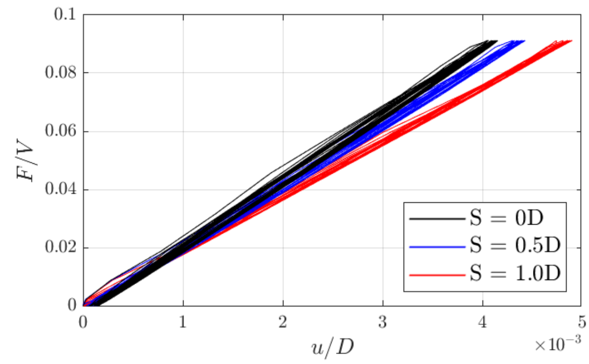

Figure 4. Load-displacement curve for S = {0; 0.5D; 1.0D} with D = 7.5 m.

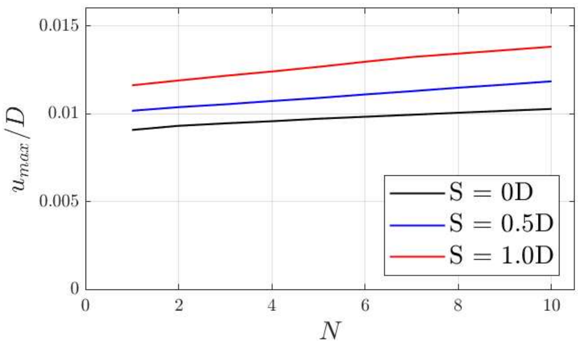

Figure 5. Evolution of maximum displacements with load cycles N for S = {0; 0.5D; 1.0D} with D = 1.8 m.

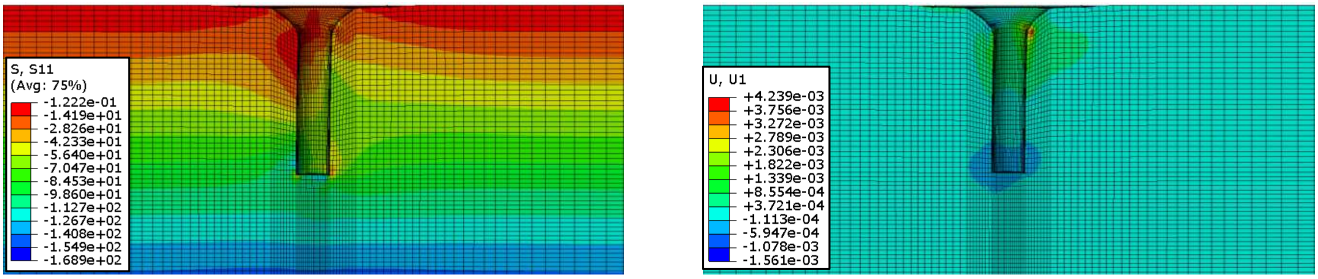

Figure 6. (l) Horizontal stresses (σ_{11}) in kPa; and (r) displacements (u_1) in m for S = 0.5D (scale factor: 50).

Future work will focus on investigating the long-term tendency of cycling and scour. To this end, Niemunis et al. (2005) proposed the high-cycle accumulation (HCA) model for number of cycles $>10^3$ and moderate or small strains, which may also be appropriate for offshore applications.

4 CONCLUSIONS

This paper studied the combined action of scour and cyclic loads obtaining the following conclusions:

- Hypoplasticity has shown to be an appropriate constitutive law to simulate cyclic loading in sands, including cycle-dependent permanent displacements and the ratcheting phenomenon for the explored cyclic loading conditions.
- As expected, the maximum and residual displacements increase with increasing *S*. However, this study demonstrates that also the displacement incremental rate increases with *S*. For the analysed monopile (*S* = 1.0D), during the first cycles the displacement incremental rate $(u_{N=10} - u_{N=1})/u_{N=1}$ reaches 19%, compared to only 13% for the *S* = 0 case.
- This study shows the vulnerability of scoured monopiles in terms of serviceability and economic viability. Hence, it is concluded that scour requires substantial consideration during design and, particularly, close monitoring of scour development and corresponding structural performance during operation.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the expertise provided by Prof R. Simons (UCL), Dr J. Harris, and Dr N. Tavouktsoglou (HR Wallingford).

REFERENCES

Askarinejad, A., Wang, H., Chortis, G., Gavin, K. (2022) Influence of scour protection layers on the lateral response of monopile in dense sand, *Ocean Engineering*, 244(110377), https://doi.org/10.1016/j.oceaneng.2021.110377.

Azúa-González, C. X., van Zeben, J. C. B., Álvarez-Grima, M., van't Hof, C., Askarinejad, A. (2019). Dynamic FE analysis of Soft Boundary (SB) effects on impact pile driving response in centrifuge tests, In: *Proceedings of the XVII EXSMGE-2019*, Reykjavik, Iceland, https://doi.org/10.32075/17ECSMGE-2019-0821.

Cuéllar, P. (2011). *Pile foundations for Offshore Wind Turbines: Numerical and experimental investigations on the behaviour under short-term and long-term cyclic loading*, Doctoral thesis, TU Berlin. Available at: https://depositonce.tu-berlin.de/items/baebdda2-4a78-4db7-8986-ed6c9149d747/full, accessed: 29/08/2023.

López-Querol, S., Spyridis, M., Moreta, P. J. M., Arias-Trujillo, J. (2020) Simplified numerical models to simulate hollow monopile wind turbine foundations, *Journal of Marine Science and Engineering*, 8(11), pp. 1-25, https://doi.org/%20doi:10.3390/jmse8110837.

Niemunis, A., Herle, I. (1997) Hypoplastic model for cohesionless soils with elastic strain range, *Mechanics of cohesive-frictional materials*, 2(4), pp. 279-299, https://doi.org/10.1002/(SICI)1099-1484(199710)2:4%3C279::AID-CFM29%3E3.0.CO;2-8.

Niemunis, A., Wichtmann T., Triantafyllidis, Th. (2005) A high-cycle accumulation model for sand, *Computers and Geotechnics*, 32(4), pp. 245-263, https://doi.org/10.1016/j.compgeo.2005.03.002.

von Wolffersdorff, P.-A. (1996) A hypoplastic relation for granular materials with a predefined limit state surface, *Mechanics of cohesive-frictional materials*, 1(3), pp. 251-271, https://doi.org/10.1002/(SICI)1099-1484(199607)1:3<251::AID-CFM13>3.0.CO;2-3.

Whitehouse, R.J., Harris, J.M., Sutherland, J., Rees, J. (2011) The nature of scour development and scour protection at offshore windfarm foundations, *Marine Pollution Bulletin*, 62(1), pp. 73-88, https://doi.org/10.1016/j.marpolbul.2010.09.007.