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Physical and numerical modelling of the effect of scouring on the lateral behaviour of monopiles

Modélisation physique et numérique de l'effet de l'affouillement sur le comportement latéral des monopiles

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ABSTRACT: The effect of scour hole shape on the lateral capacity of monopiles, as the foundation of offshore wind turbines, in a sand layer has been investigated both experimentally and numerically. The experimental programme consists of 4 centrifuge tests at 100g on a 1.8 m rigid monopile with original embedment of 5 time the pile diameter (5D). Three types of scour were tested; local narrow, local wide and global. The scour depth in all cases was set to 2D. Hypo-plastic constitutive model in drained condition was used for the numerical simulations. The results of the centrifuge tests and the numerical analyses are presented. The effect of scour shape on the lateral capacity of the piles is investigated.

RÉSUMÉ: L'effet de la forme du trou d'affouillement sur la rigidité latérale des monopiles, en passant par les éoliennes au large, dans une couche de sable dense. Le travail expérimental consiste en 4 tests de centrifugation à 100g. Ces tests ont été utilisés pour calibrer le modèle numérique avec la méthode des éléments finis. Trois types d'affouillement ont été testés; étroit, large et global. Dans tous les cas, la profondeur d'affouillement était fixée à 2 fois le diamètre du pieu. Un modèle constitutif d'hypo-plastique à l'état drainé a été utilisé pour les simulations numériques. Les résultats des tests de centrifugation et de l'analyse numérique sont déterminés dans cet article.

Keywords: Monopiles, Offshore Wind, Scouring, Geotechnical Centrifuge, Finite Element Method

1 INTRODUCTION

The offshore wind industry has developed rapidly in the past few years, as this sector offers a viable and eco-friendly renewable energy with the EU capacity predicted to be 150 GW by 2030. Owing to its economy, simple manufacture and installation procedures, monopiles account for more than 80% of offshore wind foundations (Wind Europe, 2018). Vertical loading transferred from the self-weight of the structure and lateral loading due to wind and wave actions are imposed on monopiles while in service. However, despite their market dominance, there are certain mechanisms such as scour formation, that affect the stability and functionality of monopiles during their lifetime. Cylindrical structures such as monopiles are prone to scour, which induces loss of soil support around the piles, reducing the lateral capacity and changing the structural stiffness and natural frequency of the whole structure (Prendergast et al., 2018, Prendergast et al., 2015, Sørensen and Ibsen, 2013, Li et al., 2018). This can pose problems for the superstructure through the generation of excessive fatigue stresses as well as operational issues with the turbine. Therefore, effects of scour must be considered during the analysis and design of unprotected pile foundations. Experiments have determined that local scour depth in sandy soils can reach 1.3*D* to 2D, (D: pile diameter) (Sumer et al., 1992).

Several investigators numerically studied the scour depth and scour pattern around piles in fine and coarse grained soils. Mostafa (2012) concluded that scour has a significant impact on pile lateral displacement and bending stresses. The effect of scour is more significant if piles are subjected to large lateral loads due to the nonlinear response of the pile-soil system. Li et al. (2013) calibrated the numerical model of a single pile in soft marine sediments against field test data without scour and analyzed several key factors of scour, such as the depth, width and slope of the scour hole as well as the diameter and head fixity of the pile. Their numerical results show that the scour depth had more significant influence on the pile lateral capacity than the scour width.

Hence, in this investigation, advanced physcal and numerical modelling methods have been utilised to explore the effect of scour shape on the lateral capacity of a monopile under combined loading conditions. Different shapes of scour around the monopile were considered.

2 SOIL CHARACTERISATION

Fine uniform Geba sand (SibelcoEurope, 2016) was used in this study. It is mainly comprised of silica (99% SiO_2) and 84.2% of the grains have a diameter between 0.1 mm and 0.2 mm. The ratio of pile diameter to average grain size of the sands (D/D_{50}) for the tests is approximately 164, which is larger than the value of 20 and 60 suggested by Gui *et al.* (1998) and Remaud (1999). Table 1 summarizes the geotechnical properties of the sand.

Table 1. Geotechnical properties of the soil (De Jager et al., 2017)

Parameter	**Values**
D_{50} (mm)	0.11
$\varphi'_{residual}$ (Deg)	36
Permeability (m/s)	4.2E-5
Min-Max void ratio	0.64-1.07
Particle shape	Sub-rounded

Figure 1 illustrates the grain size distribution of the nine samples that were collected from nine different locations of the sand batch.

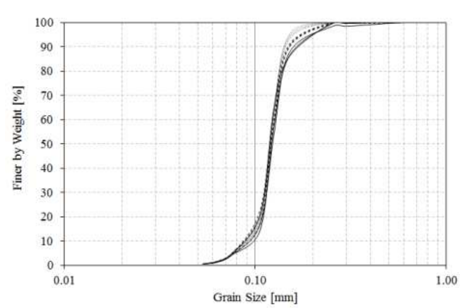

Figure 1. Grain size distribution curves of nine silica sand samples (Maghsoudloo et al., 2018).

3 CENTRIFUGE TESTS

The TU Delft geotechnical centrifuge was used to conduct the physcial modelling of the monopiles. This centrifuge is a 2m diameter beam-type apparatus (Askarinejad et al., 2017, Allersma, 1994, Zhang and Askarinejad, 2018). The device enables test models with dimensions up to 300 mm × 400 mm × 450 mm be tested up to a maximum of 300 times the gravitational acceleration (300g).

Three different scour hole shapes (one for global scour and two for local scour) were considered to cover the main range of expected scour hole geometries around a monopile. Figure 2 shows a schematic of simplified global and two types of local scour patterns. In the models, D denotes pile diameter, W_t denotes top width of scour hole, W_b denotes bottom width of scour hole, D_s denotes scour depth and α denotes slope angle of the scour hole.

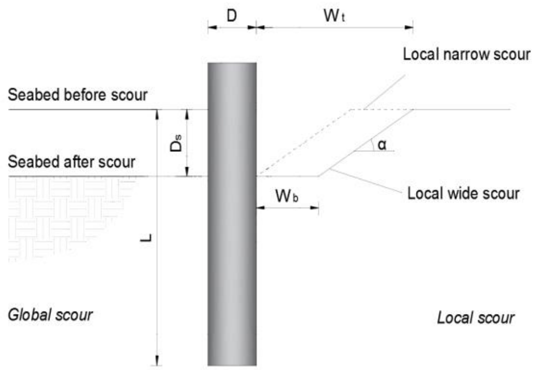

Figure 2. Schematic showing scour hole shape in centrifuge test.

Global scour was modelled through the complete removal of a given soil layer, and typically occurs due to natural sea bed migration. Local scour represents the case of a scour hole forming in the direct vicinity of a monopile. To model local scour, a scour hole was created in the shape of an inverted frustum. To investigate the influence of scour hole shape, the scour hole base extends around the pile at a distance (W_b) varying between 0 and D. A scour hole with a base width W_b = 0 is termed *local narrow scour* while a scour hole with a base width W_b = D is termed *local wide scour* in subsequent analyses. A scour hole side slope of 30° was assumed for all cases, which is in line with previous experiments (Hoffmans and Pilarczyk, 1995, Guan et al., 2018). Each scour hole was created immediately prior to installing the pile at 1*g* and just before spinning the centrifuge up to 100*g*.

An open-ended aluminum pile has been used in the centrifuge experiments. At the top of the pile a dead load of 300 grams has been attached. This dead load is equivalent to 3.0 MN vertical load at the prototype scale, which is in the range of typical loads expected from the nacelle weight of a wind turbine.

Displacement controlled lateral loading is applied to the pile head by the lateral movement of the actuator at a constant displacement rate of 0.01 mm/s. The Ultimate Limit State (ULS) for an offshore monopile is considered to occur at a displacement of 0.1D at the original soil surface, regardless of the possible scour formation. In the centrifuge set-up however, the displacement at the soil surface is not known, as the only available measurement of the pile deflection is close to the pile head (Section 3.1.4). However, due to the high rigidity of the monopile (L/D=5), it can be assumed that the pile rotates as a rigid body around the rotation point, allowing almost negligible deformation along its longitudinal axis. It is then shown by the model geometry that when the pile head reaches a displacement of 0.3D, the pile deflection at the soil surface is 0.1D and hence the conditions for the conventional ULS failure are met. The testing program comprised investigating the effect of scour type on the lateral behaviour of the pile. Zero scour and three scour types, namely local narrow scour, local wide scour and global scour were investigated. The testing program is summarised in Table 3.

Table 2Programme of centrifuge test

Test No.	Scour type	Scour depth	Vertical load (MN)
1	No scour	-	3
2	Global scour	2D	3
3	Local wide scour	2D	3
4	Local narrow scour	2D	3

The normalised lateral load-displacements curves for monopiles with scour depth of 2 times the pile diameter (2D) are shown in Figure 3. The normalised load is derived based on the lateral capacity of the pile in the case of zero scour. The general trend indicates that the wider the scour hole get the less stiff the behaviour of the pile is, global scouring being the most critical case. The wide scour hole is an intermediate state between the two extremes, which may be understood as the most possible state to occur in real conditions.

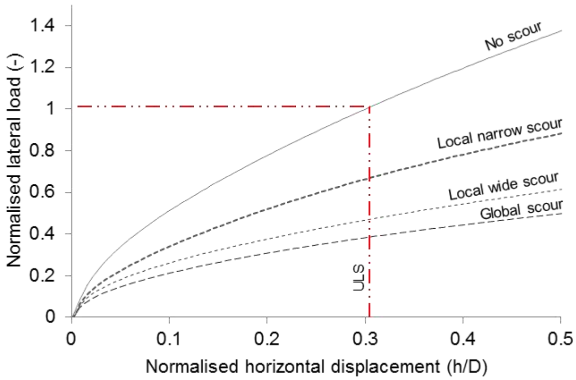

Figure 3. Centrifuge tests rsults of normalised lateral load vs. normalised dispacement at pile head for monopiles experiencing scouring with a depth of 2D.

It can be observed that the effect of the scour type can be crucial to the overall pile response. Furthermore, even in the case of the local scour, the distinction between narrow and wide is important, as it may lead to differences in the responses of the order of 20% at the ULS, suggesting that the term local scour is not sufficient in design, as the erosion geometry highly dictates its influence. On the contrary, in the global scour case the soil layer is uniformly deepened, meaning the overburden and hence the confining pressures are considerably lower, leading to a softer behavior compared to the narrow case.

4 NUMERICAL MODELLING

In this study, numerical analyses have been performed using the Finite Element (FE) software PLAXIS 3D (Brinkgreve et al., 2016). The geometry of the model, the material properties, the load pattern and all the relevant parameters have been determined so as to simulate the physical modelling in the centrifuge as accurately as possible. The simulations have been performed in fully drained conditions.

A finite element mesh with tetrahedral elements was implemented. In the proximity of the pile the mesh was denser, with a minimum element size of about 0.2D, and gradually becomes coarser towards the boundaries of the model (Figure 4).

Table 3 Hypo-plastic model parameters after the calibration of the PLAXIS model

von Wolffersdorff's hypoplastic model parameters							
φ_c	h_s	n	e_{d0}	e_{c0}	e_{i0}	α	β
34	2500 MPa	0.30	0.640	1.070	1.280	0.11	2.0

Intergranular Strain Concept				
m_R	m_T	R_{max}	β_r	χ
5.5	3.9	0.0001	0.3	0.7

Hypo-plastic constitutive model for the sand was adopted (Von Wolffersdorff, 1996, Niemunis and Herle, 1997, Herle and Gudehus, 1999) and the soil parameters were calibrated based on element tests. The parameters for the hypoplastic model that result from the calibration tests of the model are presented in Table 3.

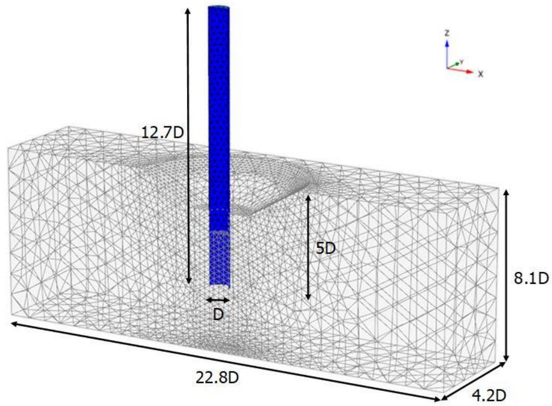

Figure 4. FE model from half of the centrifuge tests geometry.

The normalised lateral load-displacement curves for monopiles with a scour depth of 2D are shown in Figure 5. Similar general trends as those from the centrifuge tests are observed. More specifically, the narrow scour type is the most favorable in terms of lateral soil capacity, while the global scour type is the most critical case. The wide type of local scour is an intermediate state, and depends on the length of the horizontal part of the erosion around the pile to define whether its response is closer to the narrow or the global scour type. In the case chosen in this paper, w_b = 1D, the behavior of the wide type tends to be slightly closer to the global scour scenario.

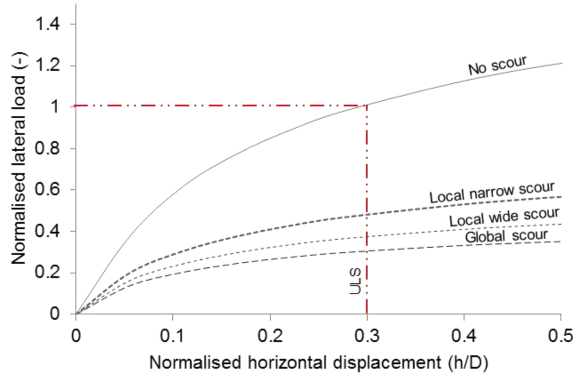

Figure 5. Finite Element simulations rsults in terms of normalised lateral load vs. normalised dispacement at pile head for monopiles experiencing scouring with a depth of 2D.

5 DISCUSSION AND CONCLUSIONS

Advanced experimental and numerical investigations were conducted, to study the impact of scour hole geometry on the monotonic lateral response of a typical offshore monopile. The original embedment of the pile was 5D and it is assumed that it has experienced a scour erosion equating to a depth of 2D. The resuls of estimated normalised lateral capacity based on the centrifuge test and 3 dimensional finite element simulations are summarised in Table 4. The results indicate that the capacity can decrease to about 35% of the original value.

Table 4. Normalised lateral capacity of monopiles experiencing a scour depth of 2D.

	Normalised lateral capacity (-)	
Scour type	Experimental results	Numercial results-
No Scour	1	1
Local narrow	0.68	0.5
Local wide	0.48	0.38
Global	0.39	0.32

The following conclusions can be drawn from the results of the centrifuge monotonic experiments and the numerical modelling:

Soil lateral capacity is significantly reduced by the increase in scour depth and extent. A dual mechanism is responsible for this behavior, as the embedded pile length is reduced due to the scour hole and simultaneously the overburden pressures become lower due to the soil removal, hence the soil strength is reduced and limited to a smaller contact area.

Scour width can highly dictate the scour influence in the soil-pile system capacity, as the local scour type can offer up to 100% larger resistance compared to the global case for the same scour depth. However, the distinction between global and local scour seems to be insufficient, as local narrow and local wide cases can differ by up to 30% in the ultimate limit state. Therefore, it is highly recommended to model at least two different geometries for the local scour case.

Accurate prediction of the scour hole geometry is highly unlikely, as stated in the literature. Therefore, a valid design against scour should include a series of scenarios with different combinations of scour type and depth, within realistic ranges.

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