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ABSTRACT: Pile foundations used for offshore wind structures are subjected to large lateral loading from wind and waves while in service as well as significant vertical loading from the top structure. Erosion of soil from around these structures, termed scour, poses a significant problem for the structural stability. In order to better understand the performance of piles facing scour problems, the effect of local scour on the behavior of monopiles installed in sand under combined lateral and vertical loading has been investigated using the Finite Element Method (FEM) using PLAXIS in this paper. The simulation results showed that vertical loading can decrease pile lateral displacement and improve the lateral capacity of piles in the absence of scour and under scour. The increase of scour depth will largely reduce lateral capacity of piles.

1 INTRODUCTION

Offshore wind energy is being generated at a tremendous pace, with the EU capacity predicted to be 150 GW by 2030. In addition to reducing carbon dioxide emissions by 315 million tons, this growth would satisfy 14 % of the EU electricity demand (Zervos & Kjaer, 2006). Together with the EU, Governments of other countries with major economies such as the US, South Korea and China have earmarked significant investment, to the tune of $38 billion USD, for offshore wind and other renewable sources of energy (Green & Vasilakos, 2011). Owing to its economy, simple manufacture and installation procedures, monopiles account for approximately 75% of offshore wind foundations (Gavin et al., 2011). Vertical loading transferred from the self-weight of the structure and lateral loading due to wind and wave actions are imposed on piles. However, in view of the complexity involved in analyzing the piles under combined loading, the current practice tends to ignore the interaction effects in combined loaded piles. Instead, these are broadly analyzed independently, i.e. for vertical loading to determine their bearing capacity and settlement and for the lateral loading to determine their flexural behavior (Karthigeyan et al. 2006 and Anagnostopoulos & Georgiadis 1993).

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 (Prendergast et al. 2018, Prendergast et al. 2015 and Sørensen & Ibsen 2013). This can pose problems for the superstructure through the generation of excessive fatigue stress as well as operational issues with the turbine. Therefore, effects of scour must be considered during the analysis and design of combined loaded pile foundations unprotected against scour.

The lateral resistance of piles under combined loading has been numerically studied by a number of researchers. With an increase in the vertical load, Karthigeyan et al. (2006), Achmus & Thieken (2010b) and Taheri et al. (2015) observed an increase in the lateral capacity while Madhav & Sarma (1982) and Meera et al. (2007) observed a decrease. Moreover, Klein & Karavaev (1979) and Karthigeyan et al. (2007) obtained a result of both increase and decrease depending on the pile and soil properties. Furthermore, Trochanis et al. (1991) and Abdel-Rahman & Achmus (2006) found the effect of vertical load on the lateral capacity of piles to be negligible, which implies that the combined action can be ignored in design. The findings of previous studies on the influence of vertical load on the lateral capacity of a pile subjected to combined loading is summarized in Table 1. Considering the contradictory conclusions discussed above, there is recognized ambiguity in the results of previous works describing whether vertical load combined with lateral load increases or decreases the lateral resistance properties of piles.

Offshore monopiles can fail due to severe scour caused by currents and waves. Because of the formation of the scour hole around the pile, the depth of embedment of the pile reduces, and consequently there is a reduction in load carrying capacity of piles (Kishore et al., 2009). Experiments have determined that local scour depth (*ds*) in sandy soils equates to

1.3 times pile diameter (D) with a mean of 0.7 (Sumer et al., 1992). In other words, the maximum scour depth is about 2 times the pile diameter (*i.e.*, ds/D = 2). Several investigators numerically studied the scour depth and scour pattern around piles in cohesive and cohesionless soils. Lin et al. (2010) modified lateral load–displacement (p–y) curve for a pile in sand and input into the computer software, LPILE Plus V 5.0. It is indicated that by considering the stress history effect on the behavior of piles in sand under scour, ignoring the stress history could result in a conservative estimate. Achmus & Thieken (2010a) developed a 3D FE model using the finite element program ABAQUS to study the lateral deformation response of monopile foundations with scour under monotonic and one-way cyclic loading. With this model, a case study on a planned wind turbine in Taiwan Strait was analyzed and the economic considerations of different design options were discussed. Mostafa (2012) investigated the effect of local and global scour on the behavior of laterally loaded piles installed in different soil conditions using the software program PLAXIS. Various parameters were analyzed such as soil type, scour depth, scour hole dimension, pile material, magnitude of lateral load and load eccentricity. The results showed that scour has a significant impact on piles installed in sand and a less significant impact on piles installed in clay, and global 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. Effect of scour of stiff clayey soils on piles is more pronounced than that of soft clayey soils. Based on the FLAC 3D, Li et al. (2013) calibrated the numerical model of a single pile in soft marine clay against field test data without scour and analyzed several key factors of scour, such as the depth, width and slope of the scour hole and the diameter and head fixity of the pile. The relationships of the ultimate lateral capacity of a single pile with depth, width and slope angle of the scour hole were obtained. The numerical results show that the scour depth had more significant influence on the pile lateral capacity than the scour width. In addition, the pile with a free head was more sensitive to scour than the pile with a fixed head condition.

From the literature, it is evident that not much work has been carried out on the combination of scour with combined loading on piles. Hence, in this investigation, numerical studies were carried out to explore the effect of scour on the lateral capacity of a monopile under combined loading conditions. Different parameters were considered such as vertical load magnitude and scour depth. In all cases considered, the pile was embedded in homogeneous sand with a unit weight of $\gamma = 20$ kN/m^3.

Table 1 Summary of the effect of vertical load on the lateral response of piles using FEM

Literature	Effect of vertical load on the lateral response of pile	Soil type
Klein & Karavaev (1979)	Increased capacity	Dense soil
	Decreased capacity	Weak soil
Madhav & Sarma (1982)	Decreased capacity and bending moment	Clay
Trochanis et al. (1991)	Unaffected	Multilayer soil
Abdel-Rahman & Achmus (2006)	Unaffected	Sand
Karthigeyan et al. (2006, 2007)	Increased capacity	Sand
Meera et al. (2007)	Decreased capacity and bending moment	Loose sand
Achmus & Thieken (2010a, b)	Both increased and decreased capacity	Sandy soil
Taheri et al. (2015)	Increased capacity	Silty sand

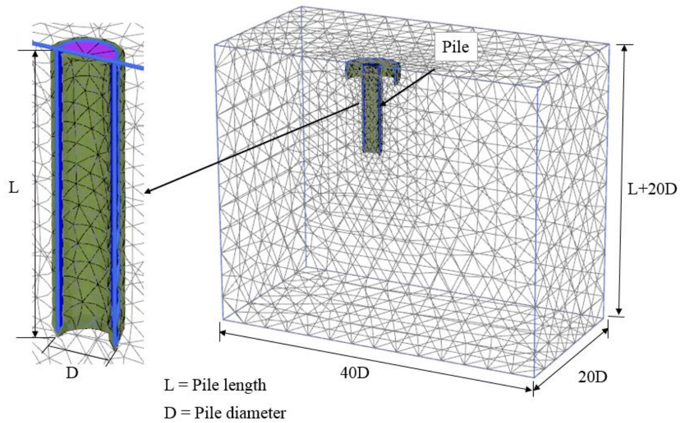

Figure 1. Typical mesh for three-dimensional finite element analyses

2 MODEL FEATURES

The finite element method is used to simulate the behavior of a vertical pile under combined vertical and lateral loading under the effect of scour. The computations were carried out using the finite element program system PLAXIS (Brinkgreve et al., 2015). A three dimensional model of the pile-soil system was generated in Figure 1.

Figure 2 shows schematic of local scour and the simplification in the modelling. D denotes the pile diameter, W_t denotes the top width of scour hole, ds denotes scour depth. Scour hole depths equivalent to 0.5 and 1.5 times the pile diameter were considered (i.e., ds/D = 0.5, 1.5).

Local scour represents the case of scour hole occurring in the direct vicinity of a pile which results in a localised reduction in effective stress. Normally the local scour hole is conical in shape with a trapezoidal cross section. For simplify, the scour hole was modelled as a foundation pit with circular shape cross section, assuming the scour hole base extends around the pile at a distance of D, see the schematic in Figure 2. This was necessary as the implementation of a conical shaped hole to represent the scour hole resulted in numerical instabilities related to the slope. According to Askarinejad et al. (2017) the effective zone of influence around a lateral loaded pile is within one pile diameter, thus it was considered that outside the 1*D* region from the pile outer surface the small change of the scour shape will have negligible influence on the pile load behaviour. Li et al. (2013) indicated that when the scour hole bottom width is larger than 1*D*, the influence of the slope angle on the pile lateral displacement is negligible. The scour hole side slope angle was assumed to be 45˚ in the physical situation, therefore the modelling of the scour slope was simplified by adding an additional length of scour hole base of 0.5*ds* in the analysis and maintaining the side slope angle at 90˚. At a scour depth of more than 1*D*, the impact of scour hole shape on the effective soil pressure diminishes (Zaaijer and Van der Tempel, 2004). To account for scour around the pile, before the application of a horizontal load, soil elements located inside the scour hole to be modelled were removed.

The sand properties considered in these analyses are reported in Table 2. For the steel pipe pile, the diameter is 1.8 m, the length is 9 m, the wall thickness is 25 mm, the elastic modulus (*E*) is 210 GPa and the unit weight (γ) is 78.5 kN/m^3. The pile was modelled as a non-yielding elastic continuum medium and the soil was modelled as a linearly elastic-perfectly plastic material with the Mohr-Coulomb failure criteria.

The response of the piles under pure lateral load was analysed in the first instance. With regard to studying the response of piles under combined loads, the influence of vertical loads of $0.4V_{ult}$ and $0.8V_{ult}$ were considered. In this context. V_{ult} is determined as the vertical load which causes a vertical displacement equating to 0.1*D*, obtained through analysis of a single pile subjected to a pure vertical load. The analysis in the lateral direction was performed using load control and the lateral displacement developed at various lateral load magnitudes could be evaluated.

The FE calculations were executed in several phases. Firstly, the initial stress state in the system due to the self-weight of the soil was generated using soil elements only. Subsequently, the pile was generated and 'wished in place', i.e. the installation of the pile was not modelled. The soil elements in the scour hole were then removed. The various load stages were specified in the model, more details are provided in the following section.

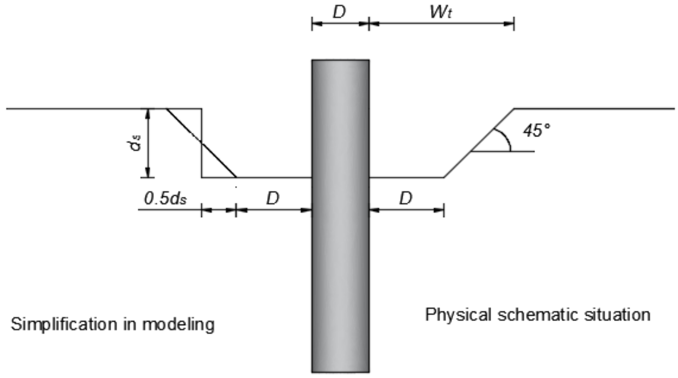

Figure 2. Local scour hole and simplification in the modelling

Table 2. Sand characteristics used in the analysis

Material	Sand
Initial Elastic Modules/E [MPa]	20
γ_{sat} [kN/m^3]	20
Poisson Ratio/v	0.25
Friction angle/φ'	37.5°
Dilation Angle/ψ	7.5°
E_{inc} [MPa/m]	0.5
Cohesion/c [kPa]	0
Soil Model	Mohr-Coulomb (Drained)

3 ANALYSIS AND RESULTS

In the simulation of influence of combined vertical and lateral load, the vertical load is applied prior to lateral load.

3.1 *Pile lateral load-displacement curve*

The ultimate vertical load (V_{ult}) capacity of a single pile was evaluated a priori in a separate numerical analysis, whereby loading was incrementally applied to the pile until a vertical displacement of 0.1*D* = 180 mm was mobilized. V_{ult} was found to be 4.4 MN. Once a datum ultimate capacity was obtained, the response of piles under combined loading were subsequently analysed separately with the vertical load applied in separate cases as follows: v = 0, v = $0.4V_{ult}$ and v = $0.8V_{ult}$.

Figure 3 shows the pile lateral load-displacement curve under no scour (presented in dotted line), local scour of 0.5D (presented in full solid line) and local scour of 1.5D (presented in dashed line). The pile under a vertical load of $0.4V_{ult}$ is marked with squares and the pile under a vertical load of $0.8V_{ult}$ is marked with circles. From Figure 3 it can be seen that under the same lateral load pile under higher vertical load has less lateral displacement, for both scour and no scour conditions. For the pile under same vertical load and lateral load, the pile with larger scour depth will have larger lateral displacement. With the increase of lateral load, the lateral displacement of pile under *ds*

= 0, v = 0 and *ds* = 0.5D, v = 0.8V_{ult} are really close to each other, which means, in some case the deleterious effect of scour can be compensated by the reinforcing effect of vertical load.

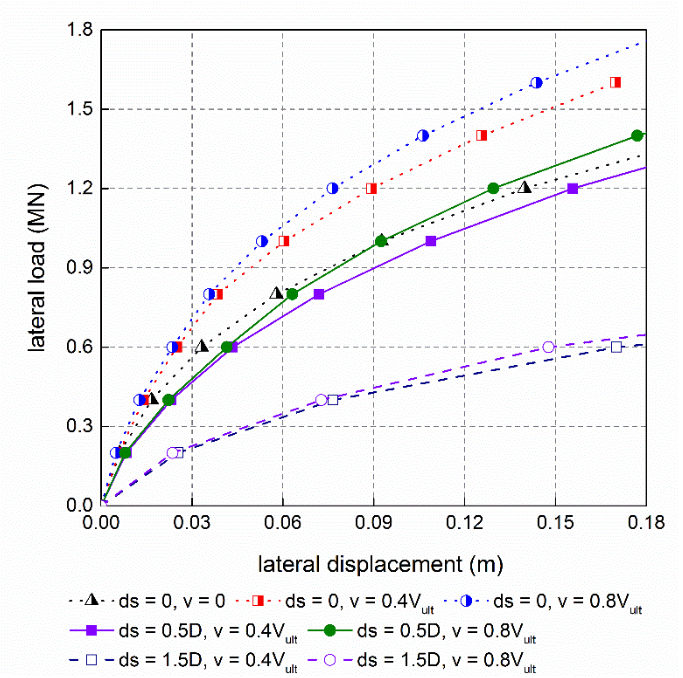

Figure 3. Pile lateral load-displacement curve

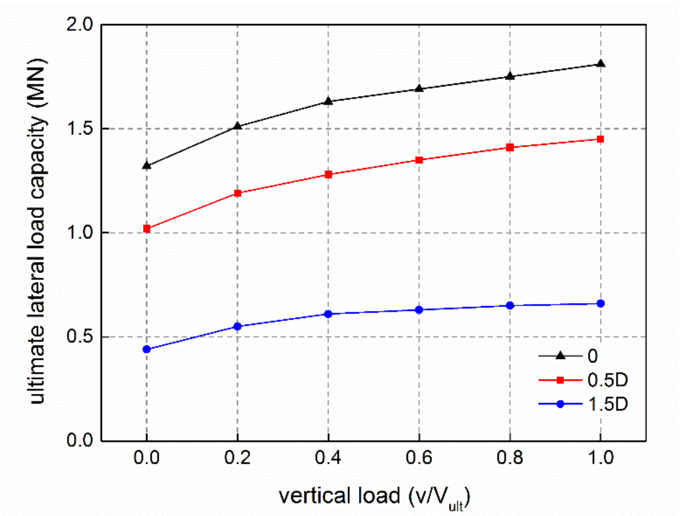

Figure 4. Relationship of pile ultimate lateral load capacity with vertical load level

3.2 *Influence of vertical load on pile lateral capacity*

Figure 4 presents how the ultimate lateral load capacity varies with vertical loading under no scour and local scour. The ultimate lateral load capacity (L_{ult}) is defined as the load corresponding to a lateral displacement equating to 10 % of the pile diameter (0.1*D* = 180 mm). The results indicate that the larger the vertical load is, the higher the ultimate lateral load capacity of the pile. For example, under no scour condition, with vertical load equating to 40% and 80% of the ultimate vertical load (V_{ult}), the pile lateral ultimate capacity (L_{ult}) increased 23% and 33% respectively as compared to the case with no vertical load.

A similar trend of vertical load increasing the pile lateral capacity under different scour depth conditions of local scour can also be observed from Figure 4 and the details of improvement is presented in Table 3.

Table 3 shows the improvement in pile ultimate lateral load capacity under increasing vertical load, considering no scour and local scour at various scour depths. From the data presented, it is noteworthy that the lateral load capacity increases considerably with increasing vertical load. The vertical load has a higher influence on pile lateral ultimate capacity for deeper scour compared with shallow scour depths.

Table 3. Improvement in pile ultimate lateral load capacity (L_{ult}) with increasing applied vertical load

Vertical load	Scour type and depth		
		Local scour	
	No scour	0.5D	1.5D
0.4 V_{ult}	0.23	0.25	0.39
0.8 V_{ult}	0.33	0.38	0.48

3.3 *Influence of scour depth on pile lateral capacity*

Figure 5 shows the ultimate lateral load capacity of a single pile under local scour varying with the normalized scour depth. Ultimate lateral load capacity was found to be 1.76 MN when scour was neglected. The ultimate lateral pile capacity under local scour depth equating to *D* and 2*D* were found to be 0.95 MN and 0.42 MN respectively, which are approximately 54% and 24% of the ultimate capacity when there is no scour. This indicates that, when the scour depth reaches 2*D*, the pile ultimate lateral load capacity is reduced by approximately 75%. It is also shown that the ultimate lateral load capacity of the single pile decrease significantly and almost linearly with the scour depth in current research.

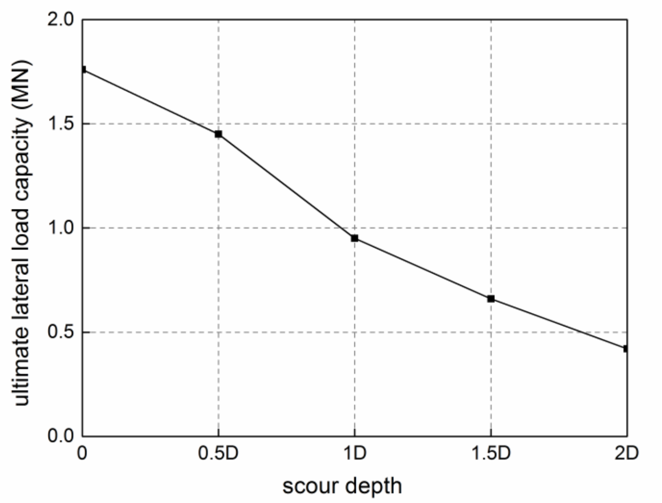

Figure 5. Pile ultimate lateral load capacity with normalized scour depth. (Vertical load = 0.8V_{ult})

4 CONCLUSIONS

The effect of scour on the response of combined loaded monopiles in marine sand is an important subject for the safety of offshore structures. A three dimensional numerical analysis was conducted to investigate this effect. The following conclusions can be drawn from the numerical results:

If the vertical load is applied prior to lateral load, the presence of vertical load will decrease pile lateral displacement and increase the pile lateral capacity. For example, under no scour condition, under vertical load equating to $0.4V_{ult}$ and $0.8V_{ult}$ respectively, the pile lateral ultimate capacity increases by 23% and 33% compared with no vertical load when there is zero scour. At the scour depth of 1.5D, the pile lateral ultimate capacity increases 39% and 48% corresponding to vertical load of $0.4V_{ult}$ and $0.8V_{ult}$ respectively. The vertical load shows a higher effectiveness in improving the pile lateral ultimate capacity under deep scour depth compared with shallow scour depth.

The pile ultimate lateral load capacity decrease almost linearly with the increase of the scour depth. The percentage reduction in the pile lateral load capacity is approximately 50% when the scour depth reaches 1D and 76% when the scour depth reaches 2D.

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