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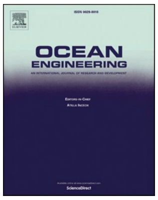

Influence of scour protection layers on the lateral response of monopile in dense sand

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A R T I C L E I N F O

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A B S T R A C T

The scour protection layers are usually installed around the monopiles to prevent the formation of scour hole. While extensive studies have been performed on the effectiveness of scour protection layer as mitigation measure, no study to date has been found to quantify the influence of scour protection layer on the lateral response of monopiles. In this study, centrifuge tests and numerical analyses were performed to examine explicitly the influence of the scour protection layer on the monopile response under lateral load in sand. It was found that a scour protection layer with a diameter of 5 times the diameter of the monopile (5*D*) and equivalent surcharge pressure of 15 kPa can increase the foundation lateral capacity by more than 30% and significantly decrease the accumulation of deflection by more than 100% in dense sand. Numerical analyses suggested that the beneficial contribution is attributed to the densification of sand and the increase of effective stress around the pile, which increased the stiffness and ultimate resistance of the soil reaction curve (i.e., *p-y* curve). Numerical parametric studies suggested that the beneficial effect of scour protection layer is also applicable to monopile in loose sand and by considering the contribution of the scour protection layer, the embedment length of the monopile can be reduced by 10%.

1. Introduction

Monopiles with an aspect ratio (L/D, where L is embedded length and D is pile diameter) less than 6 are the most widely used foundation type for offshore wind turbines. Up to 2020, more than 80% of the total 5476 offshore wind turbines in Europe are founded on monopile foundations (Negro et al., 2017, Wind, 2020). Design of monopile is mostly governed by the lateral response under loads from wind, wave and current (Doherty and Gavin, 2012; Suryasentana and Lehane, 2014).

The scour erosion will reduce the foundation embedment and effective stress along the pile, compromising the lateral response of monopile (Lin et al., 2010, 2014; Qi et al., 2016; Li et al., 2020). Existing experimental studies and field monitoring data suggested that the depth of scour could be up to 1.5*D* or even larger (Qi and Gao, 2014; Matutano et al., 2013). Therefore, rock armour, rubble filter layers and other materials are usually installed around the monopile as scour protection layers (Heibaum, 1999, 2000; Lengkeek et al., 2017). Extensive studies have been performed to investigate the effectiveness of different protection layers against scour erosion (Whitehouse et al., 2011; Nielsen et al., 2013; Petersen et al., 2015). However, no research to date is performed to quantify the influence of scour protection layer on the lateral response of monopile.

In light of these discussions, this paper aims to examine explicitly the influence of scour protection layers on the lateral response of monopile. A series of centrifuge tests were carried out first in dense sand to quantify the effect of scour protection layer on the monotonic and cyclic lateral response of the monopile. Numerical analyses calibrated using the centrifuge test data were also performed to reveal the mechanisms and provide additional insights.

2. Centrifuge modelling

All of the centrifuge model tests in this study were carried out at the Geo-engineering Section of TU Delft using the beam centrifuge with a nominal diameter of the rotating arm of 2.5 m. The centrifuge is capable of performing tests at a maximum acceleration of 300*g* with the maximum carrying capacity of 30 kg (Zhang and Askarinejad, 2019). All the tests in this study were performed at 100 g. The related scaling

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factors to this study are summarized in Table 1 (Taylor, 1995).

All the centrifuge tests in this study were carried out in dry sand to simulate the drained condition. The experimental study performed by Klinkvort (2012) proved that the centrifuge test in dry sand can be used to study the lateral response of monopiles under drained condition. It should be noted that the numerical analyses in Li et al. (2019) suggested that the monopiles will experience partially drained condition under short-term storm loading (e.g. when the rotation of monopile is larger than 0.5°). Considering that the design of monopile requires that the maximum rotation should be less than 0.25° (DNV GL 2018), it is believed that the influence of drainage condition on the lateral response of monopile at load levels relevant for monopile design is negligible. However, to assure the resilience of the foundation design, it is necessary to study the cyclic response of monopile foundation under partially drained condition through physical modelling (e.g., centrifuge tests). According to the scaling law for the permeability, the dissipation of excess pore-pressure will be N^2 (N is the centrifuge acceleration at which the test is conducted) times faster than the prototype in the centrifuge test using sand sample saturated with water (Garnier et al., 2007). For example, if the test was performed at 100 g, then the excess pore water pressure around the model pile will dissipate 10000 times faster than that of the prototype monopile. Therefore, to model the pile response under undrained or partially drained condition, it is recommended to use the high viscosity fluid instead of the water to saturate the sand sample, which can decrease significantly the permeability of seabed and slow down the dissipation of excess pore water pressure without changing sand's mechanical behaviour (Zhang and Askarinejad, 2019, 2021; Roy et al., 2021).

As shown in Table 2, a total of five centrifuge tests were performed in this study. Three monotonic tests were performed first to identify the beneficial contribution from the scour protection layer and quantify the influence of scour protection range on the lateral response of monopile. By referring to existing offshore wind farms, two different diameters of scour protection layer, namely 5D and 7D, with an equivalent effective surcharge pressure of 15 kPa were selected in this study (Matutano et al., 2013). Following the monotonic tests, two additional load-controlled "one-way" cyclic loading tests with an amplitude of 25% F_u (F_u is the pile capacity at 10%D ground surface deflection) were performed to investigate the cyclic response of monopile with and without scour protection layer.

All the tests were performed in Geba sand with a relative density of 80%. The sand is sub-angular to sub-rounded, with a median grain size (d_{50}) of 0.11 mm. The maximum and minimum void ratios are 1.07 and 0.64, respectively. More properties of Geba sand are summarized in Table 3. The sample seabed was prepared by "raining" the sand from a sand bucket with holes at a pre-calibrated height. For the tests with scour protection layer, a cardboard ring was placed at the flat surface of prepared sample and filled with Geba sand. The cardboard ring was then softly removed to achieve a scour protection layer with a thickness of 10 mm and unit weight of 15 kN/m^3 (an equivalent surcharge pressure of 15 kPa at 100 g). It is of importance to note that rocks instead of sand are usually used for scour protection for its better performance to resist the scouring process due to the weight. However, this paper aims to investigate the influence of scour protection from the geotechnical consideration, i.e. the application of additional local surcharge on the lateral monopile response. Therefore, it is believed that using the sand to simulate the scour protection layer will not affect the generality of the conclusions from this study. A close look of the scour protection layer is presented in Fig. 1.

Table 1
Scaling factors relevant to centrifuge tests in this study (Taylor, 1995).

Physical quantity	Scaling factor (Model/Prototype)
Gravitational acceleration	N
Length	$1/N$
Area	$1/N^2$
Volume	$1/N^3$
Settlement	N
Stress	1
Strain	1
Force	$1/N^2$
Density	1
Mass	$1/N^3$
Flexural rigidity	$1/N^4$
Bending moment	$1/N^3$

Table 2
Centrifuge test objectives and program.

Test ID	Soil	Pile Geometry	Scour protection length	Scour protection pressure	Loading condition
TM1	Geba sand (D_r = 80%)	$D = 1.8$ m, $L = 5D$	–	–	Monotonic
TM2			5.0D	15 kPa	
TM3			7.0D	15 kPa	
TC1			–	–	Cyclic[a]
TC2			5.0D	15 kPa	

Note.
*F_u denotes the lateral capacity of the pile at 10%D ground surface deflection.
[a] For each cyclic test, 10 cycles of repeated loading with an amplitude of 25% F_u were applied.

Table 3
Basic properties of Geba sand (De Jager et al., 2017; Chortis et al., 2020).

Property	Sand
Group symbol based on USCS[#]	SP
Median grain size, d_{50} (mm)	0.11
Curvature coefficient, Cc	1.24
Uniformity coefficient, C_U	1.55
Specific gravity, G_s	2.67
Maximum void ratio, $e_{\max}$	1.07
Minimum void ratio, $e_{\min}$	0.64
Critical friction angle, φ (°)	34

Note: [#] Unified Soil Classification System (USCS) (ASTM D2487).

An aluminum pile with a diameter (D) of 18 mm (1.8 m at prototype), a wall thickness (t) of 1 mm (0.031 m at prototype for steel pipe with the same cross section bending stiffness) and an aspect ratio (L/D) of 5 was used in this study. The model pile has an elastic modulus and a poison's ratio of 71.7 GPa and 0.33, respectively. A dead weight of 0.3 kg (3.0 MN at prototype) was applied at pile head to simulate the self-weight of a typical offshore wind turbine. Field tests performed by Anusic et al. (2019) suggested that the influence of installation method on the lateral response of single pile is limited, while centrifuge tests and numerical analysis by Fan et al. (2021) observed a higher bearing capacity of driving pile than the jacking pile at large pile deflection. However, numerical parametric studies by Fan et al. (2021) also proved that the influence of installation effect decrease significantly with the increase of the diameter of monopile. Moreover, Li (2020) performed a series of tests to study the installation effects on the lateral behaviour of the monopile using the same setup of this paper, and concluded that the normalized lateral response of the pile changed by less than 10%. However, since the installation effect is not the focus of this study, the model pile was installed by jacking at 1 g in all tests. Although the soil state around monopile may be slightly different, the general applicability of the results concerning the relative influence of scour protection layer on the lateral behaviour of the monopile is not expected to be affected by the installation effects majorly.

A 2D actuator was used to apply the monotonic and cyclic lateral loading in all tests. For a typical offshore wind turbine, the loading eccentricity of loads from wind, waves and current is in the range of 1–2L. In this study, a loading eccentricity of 7.7D (1.54L) was adopted in all tests. Load cell and displacement sensors were installed at pile head to

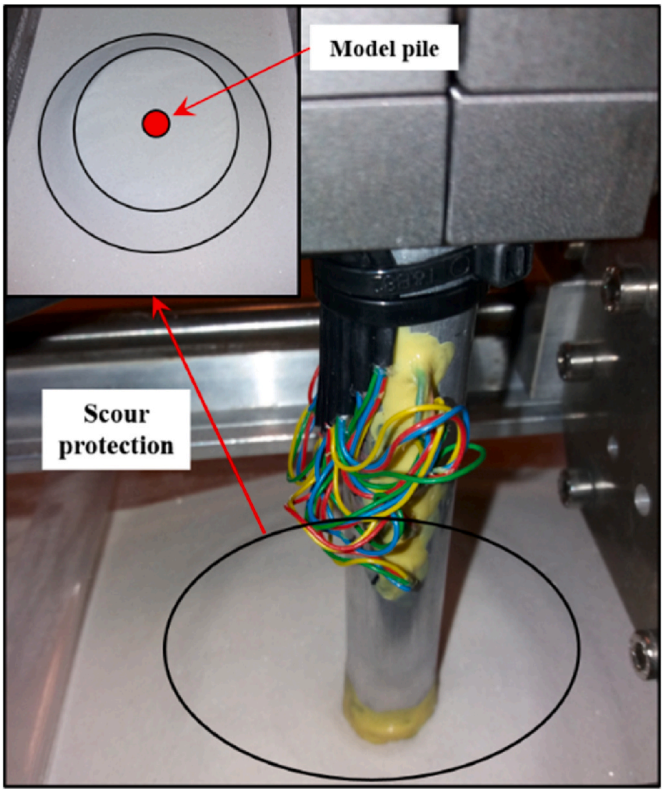


Fig. 1. Scour protection layer.

monitor the lateral load and displacement during the tests. The schematic diagram of a typical model setup is presented in Fig. 2.

3. Finite element analysis

Numerical analyses using the finite element (FE) software PLAXIS 3D were performed to reveal the mechanism of the beneficial contribution from the scour protection layer (Brinkgreve et al., 2016). Considering that the centrifuge tests were performed in dry sand, fully drained analysis was performed. It should be noted that excess pore pressure might be generated during the storm loading around monopile foundation of the offshore wind turbine. However, simulation of storm loading is out of the scope of this study.

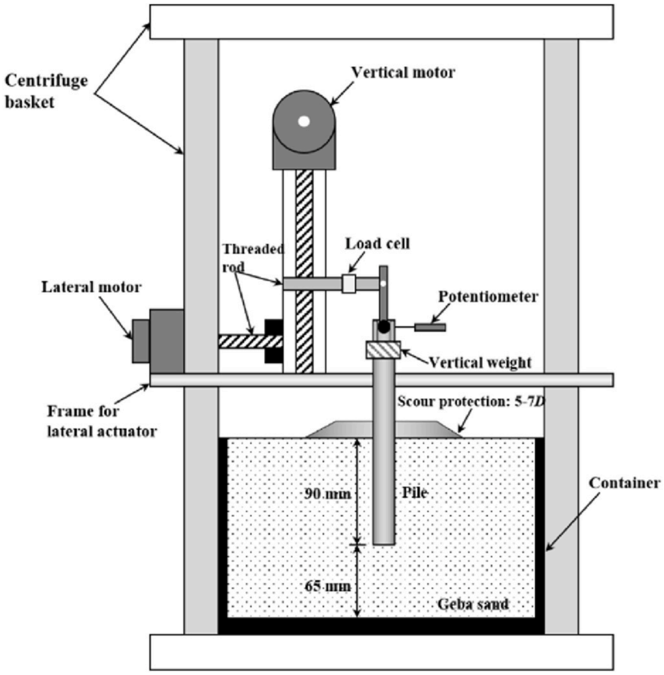


Fig. 2. Schematic of the model setup.

Fig. 3 shows the typical finite element model used in this study. By taking advantage of the symmetry of the problem, only half of the pile-soil system was modelled to save the computation time. The soil domain was chosen as 22.8*D* in length, 4.2*D* in width and 3.1*D* beneath the tip of pile, which is identical to the centrifuge tests. The lateral boundaries were supported by a roller while the bottom boundary was fully fixed. The soil and model pile were simulated using ten-node tetrahedral elements and six-node plate elements, respectively. Fully rough interface behaviour between model pile and sand was adopted with fully soil plug assumed. Parametric studies suggested that the interface roughness and soil plug had little influence on the results and will not affect the overall conclusions of this study. For the modelling of scour protection layer, considering that this study is mainly focused on its geotechnical contribution, i.e. the enhancement of the overburden pressure in the vicinity of the pile. Therefore, a uniformly distributed pressure of 15 kPa was applied in a half-circular area around monopile to model the scour protection layer. However, parallel simulation with scour protection layer explicitly modelled was also performed to quantify the influence of this simplification. As shown in Fig. 4, although the simplified modelling method ignored the soil flow mechanics in the scour protection layer, the computed results suggested that the difference between the two modelling strategies is negligible at small pile deflection related to the offshore wind turbine design. In addition, for the cyclic loaded monopile in sand, the soil around the pile will get densified (Staubach et al., 2021; Staubach and Wichtmann, 2020), preventing the formation of gap between the pile and scour protection layer. However, it should be noted that the existence of scour protection layer and the type of scour protection material will also affect the flow field around the pile and the hydraulic force on the pile. However, this is beyond the scope of this paper.

The hypo-plastic model incorporating strain dependence and stress-path dependence of stiffness was adopted in this study to model the behaviour of drained Geba sand (Von Wolffersdorff, 1996; Niemunis and Herle, 1997). The original concept of the hypoplastic constitutive law was proposed by Kolymbas (1991) using the rational mechanics. Instead of using the yield surface and plastic potential in traditional plastic theory, the hypoplastic theory directly establish the incremental relationship between the stress and strain rate using its tensor invariants. Following the original concept of Kolymbas (1991), Wu and Bauer (1994) improved the tensor invariant combinations in the model to better replicate the soil response. However, the models proposed by Kolymbas (1991) and Wu and Bauer (1994) only use the current stress as the state variable. The model is limited to small strain problem and its parameters have to be calibrated for different density sand. Gudehus (1996) and Bauer (1996) incorporated the critical state theory into the hypo-plastic model, accounting for both stress and state dependent characteristics of sand. Von Wolffersdorff (1996) further incorporated the Matsuoka-Nakai failure criterion into hypo-plastic model to better model the soil strength at different shearing modes. Niemunis and Herle (1997) further improved the hypoplastic model proposed by Von Wolffersdorff (1996) for sand to account for strain- and path-dependent stiffness at small strains by introducing an intergranular strain concept. The improved version of the hypoplastic model by Niemunis and Herle (1997) can account for the nonlinear degradation of shear modulus at small strain and the dependency of shear modulus on the stress path (i.e. increase of stiffness for load reversal). Considering that there is load reversal for the monopile under cyclic loading, the hypoplastic model improved by Niemunis and Herle (1997) is used in this study.

The hypoplastic constitutive model is characterized by the following formulation, which established the relationship between the stress rate

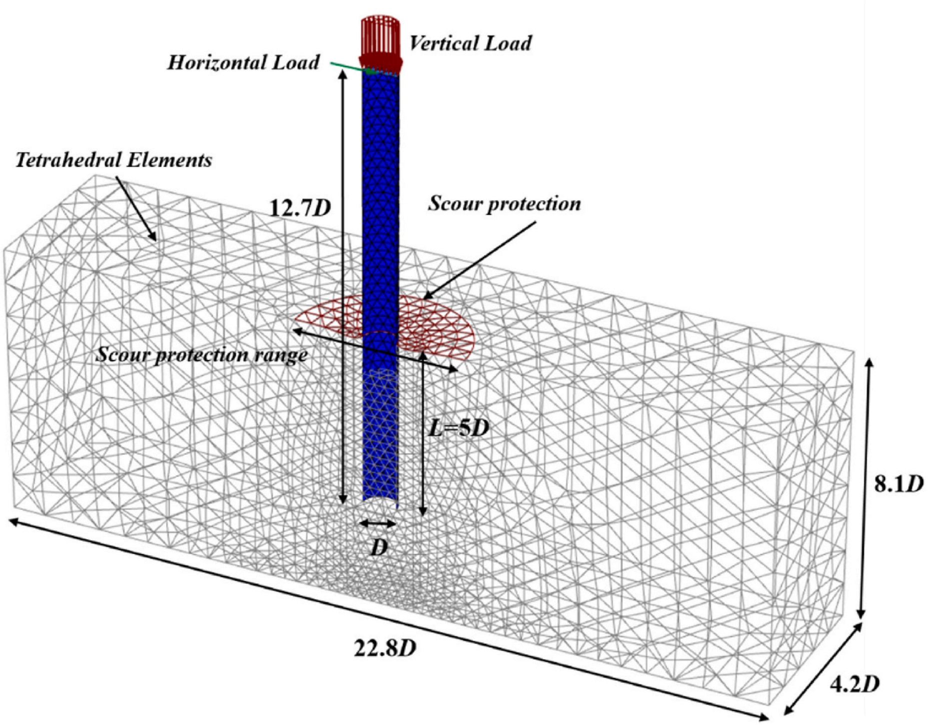


Fig. 3. The finite element model of the monopile protected against scouring and subjected to combined vertical and lateral loads.

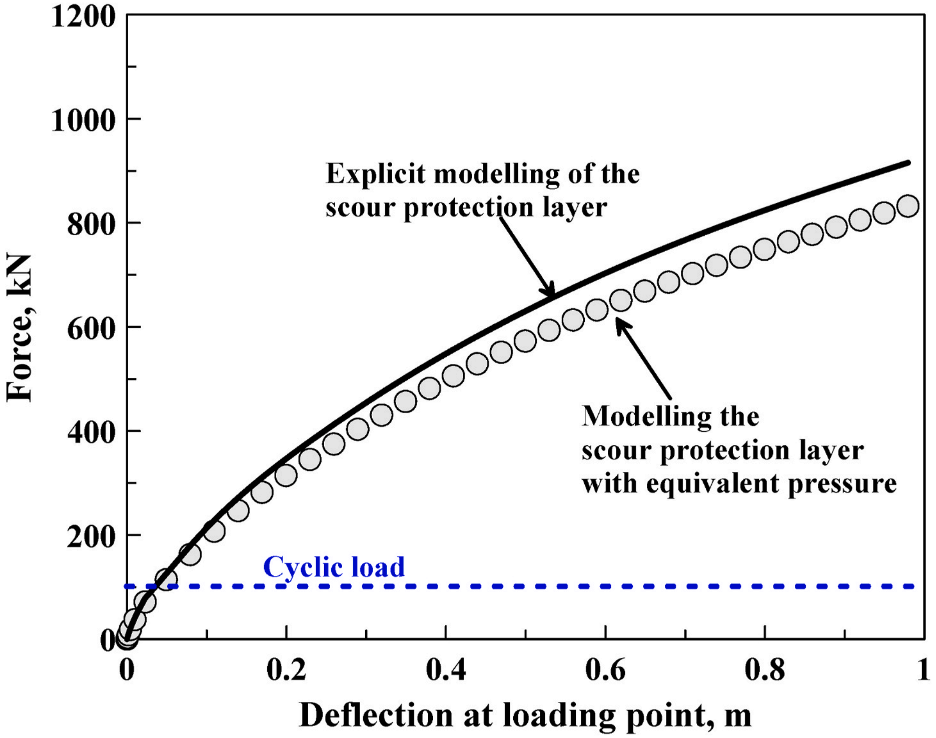


Fig. 4. The influence of modelling strategy on the pile response.

and the strain rate:

$$\dot{\boldsymbol{T}} = f_b f_e [\boldsymbol{L}(\boldsymbol{T}, e) : \dot{\boldsymbol{D}} + f_d \boldsymbol{N}(\boldsymbol{T}, e) f \dot{\boldsymbol{D}} f] \tag{1}$$

where ***T*** is a stress rate tensor, $\dot{\boldsymbol{D}}$ is a strain rate tensor, ***L*** is a fourth order tensor, ***N*** is a second-order tensor, f_b is barotropy factor considering the influence of soil state, f_d and f_e are pyknotropy factors considering the influence of relative density. The model has thirteen material parameters, including eight basic material parameters (i.e. φ_c', h_s, n, e_{d0}, e_{i0}, e_{c0}, α, β) and additional five parameters (i.e. m_R, m_T, R, β_r, χ) controlling strain- and stress-dependent stiffness at small strains More details about the model equations and parameters can be found in the Von Wolffersdorff (1996) and Niemunis and Herle (1997). The model has been implemented into the software package Abaqus as a user-defined material using the subroutine, UMAT, written in FORTRAN (Gudehus et al., 2008). The material parameters of the hypoplastic model for the Geba sand were calibrated using the oedometer and triaxial tests. The detailed procedure presented by Herle and Gudehus (1999) was followed to calibrate the model. In addition, the good agreement of computed monotonic and cyclic monopile response with the measured from centrifuge tests proves the reliability of the calibrated model parameters. The calibrated mode parameters for the sand are summarized in Table 3. For the model pile, an elastic behaviour was assumed with a Young's modulus of 210 GPa and a Poisson's ratio of 0.2.

4. Interpretation of measured and computed results

All results (measured and computed) reported in the following sections are in prototype scale unless stated otherwise.

4.1. Influence of scour protection layer on the lateral response of monopile

Fig. 5 shows the measured and computed monotonic load-deflection response at the loading point. As shown in the figure, the load-deflection response of monopile in sand exhibits a continuously hardening response with increase of pile deflection. As shown in the figure, beneficial contribution from the scour protection layer could be clearly identified. Comparing the load-deflection response of tests without and with a scour protection layer of 5*D* in diameter, it was found that the increase of lateral resistance of pile foundation can be more than 30% for large deflection. However, it should be noted that when increasing the diameter of scour protection layer from 5*D* to 7*D*, the change of overall load-deflection curve was less than 5%. This suggests that there is an "optimum" scour protection range of around 5*D*, beyond which the beneficial contribution on lateral response of the monopile is negligible. In the same figure, the computed load-deflection response using the *p-y* method in API design code is also presented for the case without scour protection layer. As shown in the figure, the API code predicts a much stiffer response of monopile with higher lateral capacity. The monopile reached a capacity of 1836 kN at a deflection of 1 m, compared with the 660 kN at the same deflection from the centrifuge test. More importantly, the lateral resistance of monopile in centrifuge test tends to keep increasing after a pile head deflection of 1 m. Same observation was also reported in previous centrifuge tests on monopile in sand (Georgiadis et al., 1992; Choo and Kim, 2016). For all three monotonic centrifuge tests, 3D FEM simulations were performed using the calibrated model parameters of hypoplastic model. The computed results are also presented in Fig. 5. It can be seen that the FE model captures well the overall development of lateral force with pile deflection for cases with and without scour protection layer. The critical threshold value of scour protection range was also accurately captured by the FE model. The good agreement between the measured and computed results further proves the reliability of the calibrated material parameters of the hypoplastic model.

Fig. 6 presents the measured cyclic load-deflection response of piles with and without scour protection. Considering the limited enhancement of pile response when increasing the diameter of scour protection layer after 5*D*, only the case with a scour protection range of 5*D* is investigated in the cyclic tests. As shown in the figure, the cyclic deflection increased with loading cycles in both cases. However, the monopile with the scour protection layer exhibits a higher stiffness and less accumulation of deflection. After ten cycles of loading, the accumulated deflection of the monopile with the scour protection layer was less than half of that in the test without the scour protection layer. The cyclic load-deflection response computed by the FE model are also presented in Fig. 6. It can be seen that the overall cyclic response of the monopile was well predicted by the FE model, although there is a slight overestimation of stiffness in the initial cyclic loading phase. This mismatch should be caused by the installation method used in this study, i.e. jacking at 1 g. Due to the low stress level at 1 g, dilatation of sand around the model pile will happen during jacking at 1 g. However, the relative difference between the tests with and without scour protection layer from the centrifuge tests and the 3D FEM simulations is consistent. The comparison of the computed and measured results in Figs. 5 and 6

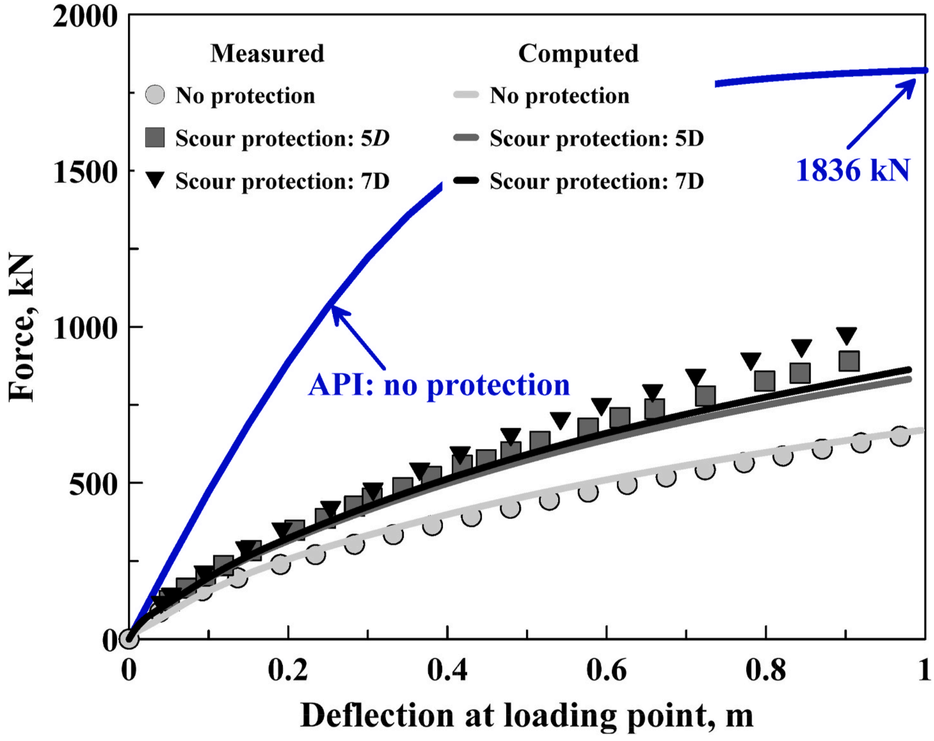
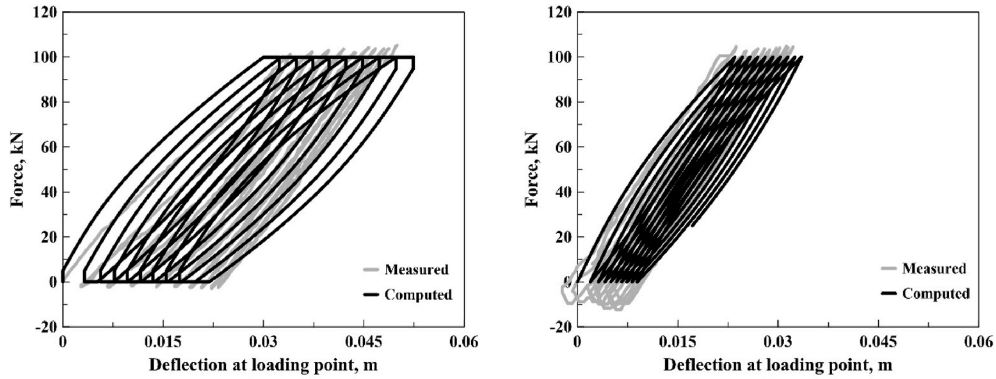


Fig. 5. Measured and computed monotonic load-deflection response at the loading point.



(a) (b)

Fig. 6. Cyclic load-deflection response at the loading point for the case: (a) no scour protection, (b) scour protection range of 5*D*.

indicates that the FE model can capture the influence of scour protection on pile-soil interaction under lateral loading in Geba sand.

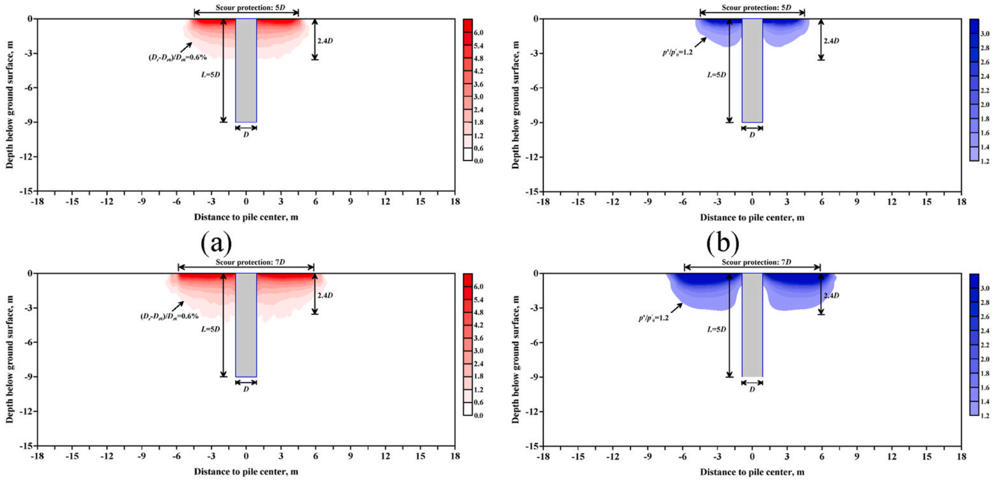
4.2. Pile-soil interaction mechanism under scour protection

The validated FE model is used to reveal the mechanism of the beneficial contribution from scour protection layer on lateral response of monopile. Fig. 7 presents the densification contour in terms of change in the relative density and mean effective stress after the application of scour protection layer. As shown in Fig. 7(a) and (c), the sand until the depth of 2.4*D* is densified by more than 3%. This is consistent with the increase of mean effective stress around the monopile, as shown in Fig. 7 (b) and (d). However, by comparing Fig. 7(a) and (c), it can be seen that further increasing the diameter of scour protection layer has little influence on the maximum depth of the densified zone. This explains the measured and computed load-deflection response in Fig. 5.

To further study the influence of scour protection layer on the pile-soil interaction, the *p-y* curve at different depths derived from the numerical simulations are compared in Fig. 8. As shown in the figure, due to the densification of soil and increase of effective stress around monopile, the *p-y* curves of the piles with scour protection layers exhibit much larger soil resistance at the same deflection. The corresponding ultimate soil resistance at 0.5*D* below ground surface is more than 100% larger than that of the pile without scour protection layer. However, the influence of scour protection layer is mainly concentrated at shallow depths. The *p-y* curves of three cases almost converged into a single line at a depth of 2*D*. In addition, same as the response of the load-deflection and the densification contour, the difference between the cases with a scour protection layer range of 5*D* and 7*D* is less pronounced.

4.3. Case study of the beneficial contribution from scour protection layer

The preceding discussion on the experimental and numerical results have proved the beneficial effect of scour protection layer on monopiles in dense sand. To further validate the general applicability of the conclusion, additional simulations on the monopiles with two aspect ratios of 4.5 and 5 in loose sand ($D_r = 40\%$) were also performed. The computed results using the 3D FE model are presented in Fig. 9, together with the computed results from the *p-y* method in API code. Same as the observation in centrifuge tests, the API code will also highly overestimate the pile response in loose sand. Therefore, based on the experimental and numerical results from this study and existing studies (Georgiadis et al., 1992; Choo and Kim, 2016), it can be concluded that the *p-y* model in API is not applicable to monopile in sand and requires further improvement. In the same figure, the response of monopile with an aspect ratio of 5, without scour protection and the monopile with an aspect ratio of 4.5 and different scour protection layers are also presented. As expected, the longer pile exhibits higher lateral resistance at the same deflection. However, after the application of scour protection, clear increase of pile resistance can be observed. For a protection range of 5*D*, the monopile with an aspect ratio of 4.5 exhibits comparable response with that of the monopile with an aspect ratio of 5.0. As the



(a) (b)

(c) (d)

Fig. 7. Densification and stress level change of sand around monopile for different scour protection ranges: (a) densification-5*D*, (b) stress level change -7*D*, (c) densification-5*D*, (d) stress level change -7*D*.

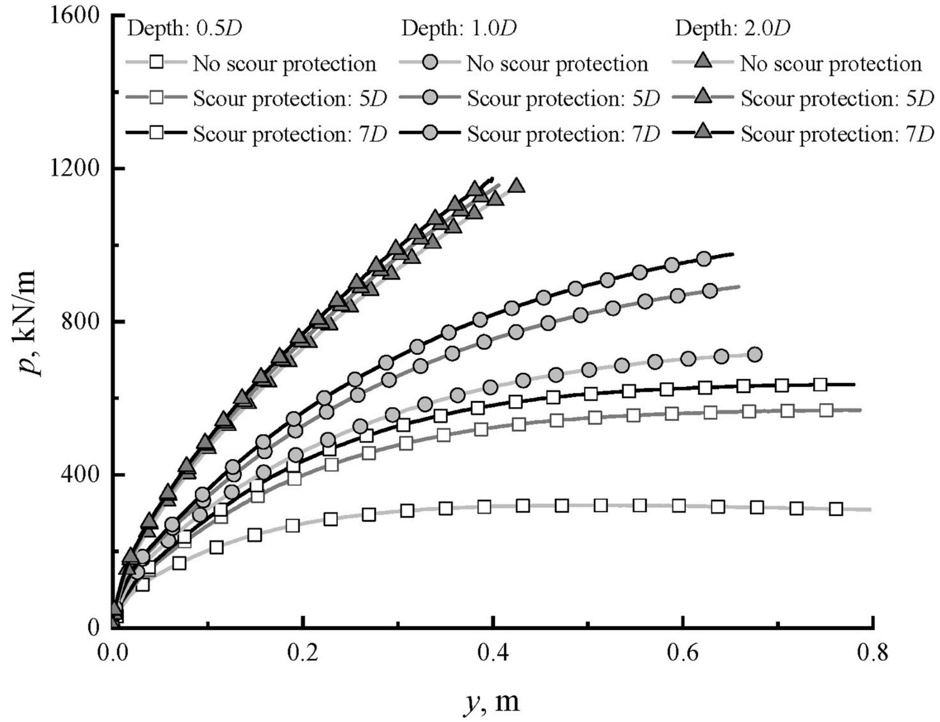


Fig. 8. *p-y* curves at different depths.

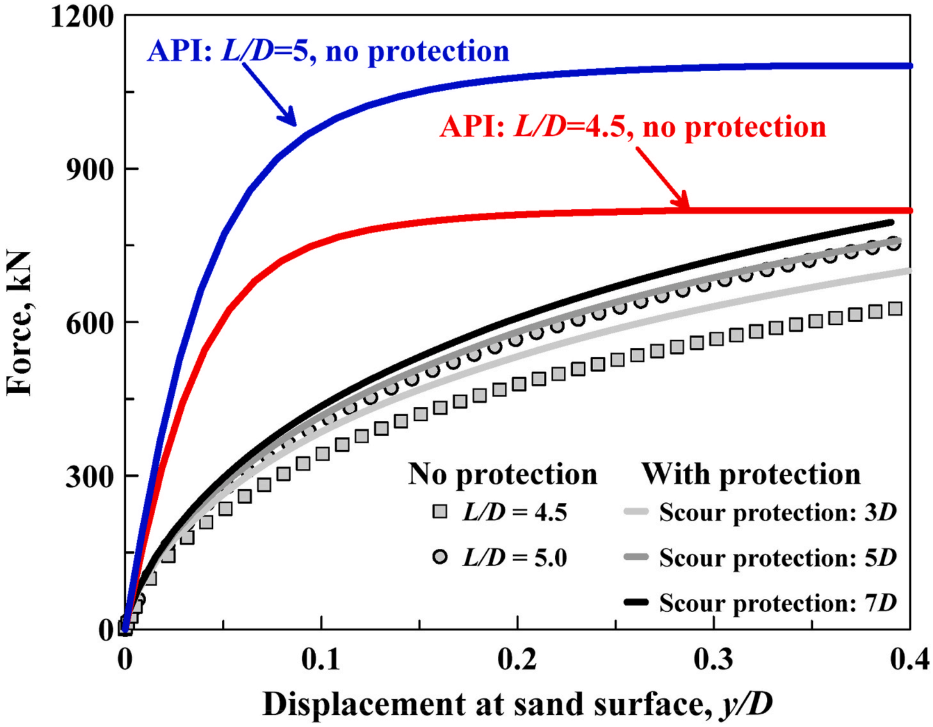
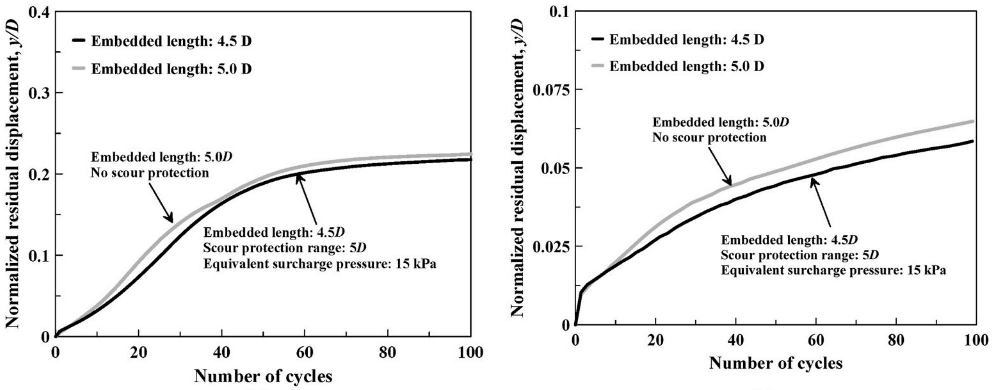


Fig. 9. Load-deflection response of monopile in loose sand.

scour protection layer range further increase from 5*D* to 7*D*, the change of beneficial effect is less pronounced. Therefore, it can be concluded that for monopiles in both loose and dense sand, the existence of scour protection can improve the lateral response.

The monopile foundations for offshore wind turbines are subjected to cyclic lateral loads from wind, wave and current. It is worth of checking the influence of scour protection layer on the cyclic response of monopile in different relative densities sand. Therefore, additional simulations were performed in loose ($D_r = 40\%$) and dense ($D_r = 80\%$) sand on monopiles with different embedded lengths. One hundred cycles of lateral load with an amplitude of $25\%F_u$ (F_u is the pile capacity at 10% *D* ground surface deflection) was applied to the piles. The computed residual deflection of monopiles in loose and dense sand are presented in Fig. 10a and Fig. 10b, respectively. As shown in the figure, for both



(a) (b)

Fig. 10. Evolution of the residual displacements for the pile with an embedment of 5.0*D* and no scour protection and the pile with an embedment of 4.5*D* and a scour protection of length 5.0*D* and added effective pressure 15 kPa: (a) $D_r = 40\%$; (a) $D_r = 80\%$.

relative densities sand, the monopile with an aspect ratio of 4.5 (10% shorted pile) produced even smaller residual deflection due to the contribution from scour protection layer. The beneficial effect of scour protection layer on the cyclic response of monopile can also be explained based on the experimental observation in Cuéllar et al. (2009). By using the colored sand particle to trace the movement, Cuéllar et al. (2009) found the sand around the monopile is governed by two mechanisms: the densification and the convective movement concentrated in shallow depth (less than 2*D*). For the first 100 000 load cycles, the residual displacement of monopile is mainly from the densification of sand. When applying a scour protection layer, Fig. 6a and 6b suggested that the sand at shallow depth of 2.4*D* will be densified due to the increase of mean stress. Wichtmann (2005) and Sturm (2011) further suggested that the strain accumulation of sand under cyclic loading decrease with the densification of sand and the increase of stress level. Therefore, under the same cyclic load, the monopile with scour protection layer can even produce less accumulated deflection, as shown in Fig. 10. It should be noted that decreasing the pile length will also decrease the vertical bearing capacity of monopile. According to existing studies, the vertical load on the monopile from the self-weight is relatively small compared with the vertical capacity of monopile (Arany et al., 2017). Meanwhile, the vertical capacity of monopile is mainly from the base resistance, which is mainly governed by the pile diameter (API, 2014). Therefore, the 10% reduction of pile length from scour protection layer should not affect the vertical stability of monopile. However, it is recommenced to perform the vertical capacity check in real design.

Based on the observation from the experimental and numerical results in the preceding discussion, it can be concluded that a more economical design can be achieved by considering the contribution of scour protection layer. Alternatively, the results in this study also implied that the designer could economically increase the pile capacity by adding some surcharge load around the monopile.

5. Conclusions

A series of centrifuge tests and numerical analyses were performed in this study to investigate the influence of scour protection layer on the lateral response of monopile. The following conclusions can be drawn:

- Both experimental and numerical analyses in dense sand suggest that there is a beneficial contribution of scour protection layer on the lateral response of monopile. The lateral resistance can increase by more than 30%, while the accumulated deflection showed a decrease by 100%, due to the existence of scour protection layer.
- The increase of beneficial contribution from scour protection on the stiffness and lateral capacity of the monopile is limited when the scour protection diameter is larger than 5*D*.
- The enhancement of pile response is mainly caused by the increase of soil density and effective stresses around the monopile at depths of up to about 2.4*D*. The corresponding *p*-*y* curves exhibit much larger resistance, resulting the stiffer lateral response of monopile.
- Numerical case study in loose sand further validate the general applicability of the conclusions and suggests that a 10% reduction of embedded length can be achieved by considering the contribution from the scour protection layer, leading to a more economical design.

6. Limitations

This study identified a beneficial contribution of scour protection layer on the lateral response of monopile in sand through centrifuge tests and numerical analyses. However, it is of importance to note that the conclusions are purely based on geotechnical considerations for a single type of scour protection layer. Different scour protection layers, like rock armour and rubble filter layers, can be used in the offshore wind farms. Existing research works (Nielsen et al., 2013) suggested that the scour protection layer can also affect the flow field around the monopile, leading to a change of hydraulic force. As a result, larger scour protection layers might be required due to the dynamics of the sediment transport and scouring process. An iterative design process is suggested to be implemented in monopile foundation design, which is beyond the scope of this paper.

CRediT authorship contribution statement

Amin Askarinejad: Supervision, Project administration, Conceptualization, Methodology, Writing – review & editing. **Huan Wang:** Writing – original draft, preparation, Software, Visualization. **Giorgos Chortis:** Investigation, Methodology, Software, Writing – review & editing. **Ken Gavin:** Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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