Canadian Geotechnical Journal

The impact of scour on the lateral resistance of wind turbine monopiles: an experimental study

Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2020-0219.R2
Manuscript Type:	Article
Date Submitted by the Author:	18-Nov-2020
Complete List of Authors:	Li, Qiang; Delft University of Technology Faculty of Civil Engineering and Geosciences Askarinejad, Amin; Delft University of Technology Faculty of Civil Engineering and Geosciences Gavin, Kenneth; Delft University of Technology, Faculty of Civil Engineering and Geosciences
Keyword:	Offshore Wind Monopiles, Scour, Centrifuge modelling, Scour-hole shapes, p-y curves
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

The impact of scour on the lateral resistance of wind turbine monopiles: an experimental study

Li, Q.¹, Askarinejad, A.^{2*}, Gavin, K.³

Faculty of Civil Engineering and Geosciences,
Delft University of Technology,
Building 23,
Stevinweg 1 / PO-box 5048,
2628 CN Delft / 2600 GA Delft,
The Netherlands

*Corresponding author

Email: ¹Q.Li-3@tudelft.nl, ²A.Askarinejad@tudelft.nl, ³k.g.gavin@tudelft.nl

Abstract

The majority of offshore wind structures are supported on large-diameter, rigid monopile foundations. These piles may be subjected to scour due to the waves and currents that causes a loss of soil support and consequently decreases the pile capacity and system stiffness. The results of numerical models suggest that the shape of the scour-hole affects the magnitude of pile capacity loss, however, there is a dearth of experimental test data that quantify this effect. This paper presents a series of centrifuge model tests on an instrumented model pile that investigates the effects of scour-hole geometry on the response of a laterally loaded pile embedded in sand. The pile instrumentation allowed load-displacement and p - y (soil reaction-displacement) curves to be derived. Three scour geometries (global, local wide and local narrow) and three scour depths ($1D$, $1.5D$ and $2D$; where D is pile diameter) were modelled. For all three scour types, pile moment capacity decreased almost linearly with increase of scour depth. Simple empirical relations were proposed to evaluate the detrimental influence of scour on the pile moment capacity. A new method has been developed to allow designers to quantify the effect of scour-hole shape and severity of scour on the pile response.

Keywords: Offshore Wind Monopiles; Scour, Moment capacity; Centrifuge modelling; Scour-hole shapes; p - y curves

Notations

C_1, C_2	integration constants	$\tilde{M}$	normalized moment
C_U	uniformity coefficient	NS	no scour
D	pile diameter	p	soil reaction
D_{50}	medium particle size	p_a	atmospheric pressure
D_s	scour depth	r	nondimensional fitting parameter
e	loading eccentricity	W_b	scour base width
e_{max}	maximum void ratio	W_t	top scour width
e_{min}	minimum void ratio	y	pile displacement
E	elasticity modulus	z	depth below original mudline
f	nondimensional fitting parameter	z_{add}	additional soil depth
GL	global scour	$z_{add, LN}$	additional soil depth to account for local narrow scour
G_s	specific gravity	$z_{add, LW}$	additional soil depth to account for local wide scour
I	moment of inertia	z_{equ}	equivalent scour depth
L	pile length	ω	scour slope angle
LN	local narrow scour	ϕ_{cr}	critical friction angle of sand
LW	local wide scour	θ	pile rotation
M	bending moment	$\tilde{\theta}$	normalized pile rotation
M_R	moment capacity	$\tilde{\theta}_{AAR}$	normalized allowable accumulated rotation
$M_{R, reduction}$	moment reduction factor	δ	additional soil depth factor
$M_{R, no scour}$	moment capacity under no scour condition	γ	unit weight of sand
$M_{R, with scour}$	moment capacity under scour condition		

1 Introduction

Monopiles are the most economical foundation system for Offshore Wind Turbines (OWTs) installed in shallow coastal waters (Byrne et al. 2019). The typical slenderness ratio (L/D , L : embedded length, D : diameter) for OWT monopiles is between 3 and 6 (Doherty and Gavin 2012; Wu et al. 2019). Cylindrical structures such as OWT monopiles are prone to loss of soil support due to sand erosion, i.e. scour. As a consequence, the pile lateral capacity and stiffness could be decreased, potentially resulting in large lateral displacement and rotation. Such effects can put the superstructure at risk through the generation of excessive fatigue loading as well as operational issues (Li et al. 2018). The shapes of various types of scour holes are illustrated in Figure 1. Typically, scour holes are formed in a shape approximating an inverted frustum. The slope angle (ω) is roughly equal to the angle of repose of sand, generally in the range 30 to 44° (Richardson and Davis 2001) and the top scour width (W_t) is often assumed to be twice the scour depth (D_s) depends on the diameter of the pile (D), Froude number of the water flow, shear stress applied to the sand surface due to the flow and soil strength (Jones et al. 1992; Sørensen and Ibsen 2013). DNV (2014) suggests the adoption of an extreme scour depth of $2D$. However, Sørensen and Ibsen (2013) illustrated that this assumption ($D_s = 2D$) might be too conservative for wave induced scour holes.

Figure 1 Symbols and definitions of scour-hole, modified after Li et al. (2020)

One approach, and perhaps the simplest, to model the effect of scour on the lateral behaviour of monopile is to remove the affected soil layer completely. This approach simulates a so-called global scour condition (schematised on the left-hand side of Figure 1). Based on various numerical analyses, Li et al. (2013), Lin et al. (2010), Mostafa (2012), Qi et al. (2016) and Zhang et al. (2017) suggested

that the assumption of a global scour can be highly conservative. Similarly, centrifuge tests on piles with $L/D = 12.7$ conducted by Qi et al. (2016) indicated that removing the entire soil layer to the scour depth can result in a 49-68% increase in lateral displacement of the pile at a fixed load, when compared to a model that three dimensional scour-hole dimensions were incorporated. A more realistic approach is to consider a three dimensional shape for a scour hole. In an attempt to follow the second modelling approach, Lin et al. (2014) developed simplified stiffness models for soil reaction based on Winkler model (p - y curves) assuming a wedge failure mechanism for a slender laterally loaded pile ($L/D = 35$) subjected to scour. Their model was verified with a three dimensional finite element model. The pile response accounted both the scour-hole geometry and the over-consolidation effects of the removed soil on the remaining soil. It was found that for global scour, the p - y curves at given depths were essentially identical when compared between those below the post-scour surface and those at the same depths without scour. In contrast, for local scour, the p - y response at a given depth was found to be much stiffer below the scour-hole base than at the same depth below the original soil surface. The authors concluded that the difference in the effects of global and local scour is attributed to the beneficial influence of the remaining overburden soil surrounding the pile in the latter case.

To address the dearth in experimental data concerning the impact of scour-hole geometry on the response of rigid monopiles, this paper presents the results of a series of centrifuge model tests conducted considering different parameters, such as scour depth and scour hole dimension as well as the magnitude of applied lateral and moment loading. Based on the measured bending moment distributions, p - y curves were derived and analysed to evaluate the impact of scour type on the tested piles. Based on the analysis of experimental data, a new design method has been developed to take the three dimensional shape of the scour hole into account. An example of the design method is presented in the last section of the paper.

2 Experimental set-up

2.1 Model pile and soil characterisation

The model pile was open-ended and fabricated from a hollow, circular, aluminium tube with an outer diameter (D) of 18 mm and an embedment length (L) of 90 mm. Therefore, an L/D ratio of 5 was achieved which is in good accordance with those typically used in the offshore environment. The pile diameter is selected so as to minimise boundary effects associated with the centrifuge strongbox, which houses the pile, and also to satisfy constraints associated with the mean grain particle size. Certainly, the pile in this research has a small diameter with respect to those typically used in the offshore

environment (Arany et al. 2017; Prendergast et al. 2018). However, the pile L/D ratio was closely simulated between offshore monopile applications and model pile in this study.

The pile wall thickness (t) was derived based on the calculations for minimum wall thickness for monopiles (API 2007; Arany et al. 2017; Li et al. 2020). Byrne et al. (2015) has produced a database of piles and presented that the pile diameters normalised to pile wall thickness varied from 39 to 80. In the present analysis, the D/t value is 60, suggesting this pile has a good rigidity (in line with present developments for offshore wind monopile foundations). Aluminium was selected as the material to fabricate the pile, therefore the pile wall thickness could be enlarged while the flexural rigidity was kept the same to satisfy the scaling laws. The primary dimensions and material properties of the pile can be found in Table 1. The scaling factor in length is set as 0.01. The pile was instrumented with ten levels of strain gauges calibrated for measuring bending moment (see Figure 2). The model pile was jacked into the sand sample prior to spinning up the sample (i.e. installation at 1g) with the result that installation effects were not fully modelled. However, the same preparation method and testing procedure was followed for all of the tests.

Table 1. Model and corresponding prototype pile dimensions and properties (centrifuge tests were performed at 100g)

Property	Model pile	Prototype pile*
Length (embedded + load eccentricity)	90 + 144 mm	9 + 14.4 m
Diameter, outer	18 mm	1.8 m
Wall thickness	1 mm	30 mm *
Elasticity modulus (E)	70 GPa	210 GPa *
Moment of inertia (I)	1936 mm ⁴	0.065 m ⁴
Bending stiffness (EI)	0.137 kPa.m ⁴	13.7 GPa.m ⁴

*Assuming prototype pile is fabricated from steel

Figure 2 Model pile schematic diagram with strain gauge layout (dimensions in mm)

The experiments were conducted using dry Geba silica sand. The mechanical parameters for Geba sand has been determined by Charles University (CU) in Prague as a request from Royal IHC (Masin 2017). The drained triaxial tests have been performed on sand with $D_r = 80\%$ up to the axial strain at least 20% ($\sim 17.7\%$ shear strain) under confining pressure of 50, 100, and 150 kPa. The critical (post-rupture) shear strength was measured as $\phi_{cr} = 35^\circ$. The geotechnical characteristics of the sand are summarised in Table 2. The relative density (D_r) of the prepared sand specimens in tests was 80%.

Table 2. Soil properties of Geba sand (De Jager et al. 2017; Maghsoudloo et al. 2018)

e_{min}	e_{max}	G_s	$D_{50} (mm)$	C_U	ϕ_{cr}
0.64	1.07	2.67	0.11	1.55	35°

2.2 Centrifuge loading actuator

The experiments were performed using the beam centrifuge in the Geo-engineering Section of TU Delft (Allersma 1994; Zhang and Askarinejad 2019). A two-dimensional actuator which is shown in Figure 3 was used to impose lateral load (H) at the pile head. Applied lateral load was measured by

parallel beam load cell (HTC-SENSORS; TAL220; measuring range 100 N; sensitivity 0.05%). Pile lateral displacements were measured at two locations: pile top using the signal encoder of the actuator; and $1.7D$ above the sand surface using a potentiometer (ETI SYSTEMS; LCP8S-10; measuring range 0-14 mm; sensitivity 0.2%). These two measurements facilitate the calculation of both lateral translation and rotation of the model pile. A specially-designed friction-reducing ball connection was constructed to transfer the lateral loading with application of minimal rotational constraint at the pile top. Details of this ball connection are described by Li et al. (2020) and Chortis et al. (2020).

Figure 3 Two dimensional loading actuator and pile testing set-up: (a) Schematic diagram and (b) Photo

In the following, the experimental data is expressed in prototype scale. For all tests performed in this study, the centrifuge acceleration level was 100g. Lateral loading was applied at a predetermined height $e = 8D$ above the original sand surface, to mimic the lateral loading and significant overturning moment resulting from combinations of wind, wave and current actions. The pile diameter was 1.8 m and original embedment depth was 9 m ($L/D = 5$).

2.3 Scour-hole formation

A certain scour-hole could be determined by scour shape, scour depth, and scour-hole slope angle. Regarding the scour bottom width (W_b) for differentiating local narrow scour and local wide scour, the value of 0 and D was chosen in accordance with Mostafa (2012). It has been documented that local scour depth in sandy soils (D_s) is 1.3 times pile diameter (D) with a mean of 0.7 (Sumer et al. 1992). Moreover, the maximum scour depth is reported to be about 2 times the pile diameter (i.e., $D_s/D = 2$). Global scour exposing piles due to storm surge events has been reported in the literature (Robertson et al. 2007) with the ultimate scour depth ratio D_s/D is 0.75 to 1. In the current research scour depths from $1D$ to $2D$ were concentrated on, which covers the common scour depth range and more importantly, the critical value of scour depth that a wind turbine most probably will face. Scour-hole slope angle was found to be the least important factor among the three scour hole geometry parameters (scour type, scour depth and scour-hole slope angle) influencing the responses of laterally loaded piles (Li et al. 2013). Zhang et al. (2017) indicated that an increase of the scour-hole slope angle from 20 to 60 degree only results in a decrease of the pile-head deflection and maximum bending moment by approximately 5% and 2.5%, respectively, when $D_s = 4D$ and $W_b = 0$. Lin et al. (2016) observed that for a case with $D_s = 3D$ and $W_b = 0$, changing the slope angle from 0 to 60 degrees reduced the maximum bending moment only by 6-8%. Li et al. (2013) investigated the influence of scour slope angle on the pile head lateral load versus lateral deflection relationship. It found that when the slope angle was larger than 13 degrees, the pile head lateral load versus lateral deflection curves at different scour slope angles (13, 24, 33, 45, 90 degrees) overlap with each other. This suggests that the effect of the scour hole slope angle on the lateral response of the pile is not so significant in the case when the slope angle is larger than 13 degrees.

Therefore, to cover the main range of expected scour hole geometries, three scour depths, 1.8 m ($1D$), 2.7 m ($1.5D$) and 3.6 m ($2D$), and three scour shapes, local narrow scour, local wide scour and global scour, were modelled (Li et al. 2020) (schematically shown in Figure 4). Global scour was modelled by removing the soil layer of thickness equal to different scour depths. For the tests with local scour, scour-holes were created in the shape of inverted circular cones. To compare the influence of scour-hole shape, the scour-hole base extended around the pile at a distance varying between 0 and D (shown as W_b in Figure 1). Local narrow scour was defined when the scour-hole base has a dimension $W_b = 0$. When the scour-hole base had a dimension $W_b = D$, this was named local wide scour. The scour-hole slope angle was kept constant at 30° , which is in line with experimental investigation of Roulund et al. (2005) and recommendation of Hoffmans and Verheij (1997). The scour-holes were formed after sand

specimen preparation using a grab bucket and each hole was checked using specifically fabricated moulds.

2.4 Testing programme

Following the creation of a scour-hole (when relevant), each pile was pushed into the given soil location at $1g$ using the vertical actuator operating at a rate of 0.1 mm/s to the target depth of $L = 5D$. Subsequently, the model was subjected to an enhanced acceleration field of $100g$. The lateral load was applied to the pile head by the lateral movement of actuator at a constant rate of 0.02 mm/s .

The testing programme comprises 10 tests: one monotonic load test with no scour (reference test) and nine monotonic load tests with three scour types and three scour depths, see Table 3. The effects of global scour, local narrow scour and local wide scour were assessed at scour depths of $1D$, $1.5D$ and $2D$.

Table 3. Programme of centrifuge test

Test name	Dr (%)	Scour type	Scour depth
S-NS	80	No Scour (NS)	-
S-LN-1D	80	Local Narrow (LN)	1D
S-LN-1.5D	80	Local Narrow (LN)	1.5D
S-LN-2D	80	Local Narrow (LN)	2D
S-LW-1D	80	Local Wide (LW)	1D
S-LW-1.5D	80	Local Wide (LW)	1.5D
S-LW-2D	80	Local Wide (LW)	2D
S-GL-1D	80	Global (GL)	1D
S-GL-1.5D	80	Global (GL)	1.5D
S-GL-2D	80	Global (GL)	2D

Figure 4 Schematic illustration of (a) local narrow scour, (b) local wide scour and (c) global scour (dimensions in m)

3 Centrifuge test results

The results of the laboratory tests were investigated by plotting the angular rotation of the pile θ in response to the applied moment M , all measured at sand surface. Normalising these parameters enables comparison of results across scales. In this study, M and θ were normalized according to the equations suggested by LeBlanc et al. (2010):

$$\tilde{M} = \frac{M}{L^3 D \gamma} \quad \text{Equation 1}$$

$$\tilde{\theta} = \theta \sqrt{\frac{p_a}{L \gamma}} \quad \text{Equation 2}$$

in which, $\tilde{M}$ is the normalized moment, γ is the sand unit weight, $\tilde{\theta}$ is the normalized pile rotation, p_a is the atmospheric pressure.

The method for data extraction is outlined in Figure 5 based on the test data of no scour case (S-NS). The results indicate that the pile rotation increases continuously as the applied moment increases, thus there is no distinct point which can be used to define failure. Following the recommendation of LeBlanc et al. (2010), failure was defined by $\tilde{\theta} = 4^\circ = 0.0698$ rad. The moment capacity (M_R) for the pile under no scour case was determined to be 0.84.

Figure 5 Determine of moment capacity (test S-NS)

3.1 p - y reaction curve construction

Using the strain gauge data, the measured distribution of bending moment $M(z)$, with depth z , was used to derive the soil reaction $p(z)$, by double differentiation, and the displacement profile $y(z)$, by double integration, according to the following equations:

$$p(z) = \frac{d^2 M(z)}{dz^2} \quad \text{Equation 3}$$

$$y(z) = \iint \frac{M(z)}{EI} dz dz \quad \text{Equation 4}$$

where $M(z)$ is the bending moment at soil depth z , EI denotes the pile bending stiffness.

The sixth-order polynomial curve-fitting method was adopted to fit the moment data points. It was then differentiated twice and the soil response $p(z)$ was evaluated.

When determining displacement at any depth, $y(z)$, two integration constants C_1 and C_2 were determined from: 1) the measured displacement at the loading position and 2) an assumed zero displacement condition at the point with zero lateral soil resistance (Wang and Qi 2008).

The measured bending moment (M) distributions, corresponding deduced distributions of soil resistance (p) and lateral pile displacement (y) for test S-NS are shown in Figure 6. It can be seen that, with increase of lateral load, the bending moment, soil resistance and pile lateral displacement all increase. The results generally suggest rigid pile behaviour, with significant displacement of the pile tip developed opposite to the loading direction.

Figure 6 Distributions of: (a) measured bending moment; (b) lateral soil resistance; (c) lateral pile displacement under different values of applied moment (test S-NS)

The p - y curves were obtained by combining the soil resistance (p) and lateral displacement (y) at discrete intervals to produce curves at each depth, as shown in Figure 7. Absolute values are plotted, noting that the curves at depths of 7, 8.5 and 9 m correspond to passive soil pressures (negative values of displacement). The stiffness of the p - y curves increases rapidly with soil depths for $z \leq 4$ m, whereas the difference between the p - y curves on the passive side also appears quite significant ($z \geq 7$ m).

Figure 7 Experimental p - y curves at different soil depths (test S-NS)

3.2 Effect of scour type on the lateral pile behaviour

The effect of the scour type, i.e. global, local wide and local narrow scour around the monopile, on the lateral behaviour of the foundation are discussed from three aspects of: (i). Moment-rotation at the sand surface, (ii). Distribution of bending moment along the pile, and (iii). Soil reaction curves (p - y curves)

i. Moment-rotation behaviour

Figure 8 shows the moment-rotation curves from centrifuge tests considering different scour types and scour depths. In all figures, the pile with no scour shows the highest initial stiffness and capacity, followed by local narrow scour, then local wide scour, and with global scour showing the lowest results. Comparing the measurements from the local wide and global scour cases, results suggest that the remaining soil above scour base line can have considerable effect on the confining stresses and hence on the lateral stiffness of the foundation system. The difference of pile stiffness and capacity between local narrow and local wide scour maybe due to the difference in the amount of the soil above scour base line.

Figure 8 Influence of scour type on the moment-rotation response of piles: (a) scour depth $1D$, (b) scour depth $1.5D$ and (c) scour depth $2D$

As suggested by DNV (DNV 2016), the typical limiting rotation is 0.5° at the soil surface, whereas a 0.25° construction tolerance should be taken into account. Therefore it gives an allowable accumulated rotation of 0.25° due to various kinds of loading during the life time of OWTs (Truong et al. 2019), which corresponds to $\tilde{\theta}_{AAR} = 0.00375$ rad (in $\tilde{\theta}_{AAR}$, the subscript “AAR” signifies “Allowable Accumulated Rotation”). From Figure 8 it can be seen that, at scour depths of $1D$ and $1.5D$, scour type has minimal effect on the initial stiffness of pile lateral bearing behaviour. It suggests that when carrying out pile dynamic analysis within small strain range, scour type can be regarded as no effect especially at shallow scour depths ($D_s < 1.5D$). While at very large scour depths ($2D$ for example),

effect of scour type should certainly be taken into consideration, as the initial stiffness of pile is significantly influenced by scour type.

Moment reduction factor, $M_{R, reduction}$, is used to describe the influence of scour on the moment capacity, which is defined in the following equation:

$$M_{R, reduction} = \frac{M_{R, no scour} - M_{R, with scour}}{M_{R, no scour}} \quad \text{Equation 5}$$

where, $M_{R, reduction}$ denotes the reduction of M_R as a result of scour, $M_{R, no scour}$ is the moment capacity under no scour condition, and $M_{R, with scour}$ is the moment capacity under scour condition. The reduction of moment capacity compared with the reference case, increased with scour depth, can be seen in Table 4, which shows reduction of 13-39% for a scour depth of $1D$, increasing to 46-69% for a scour depth of $2D$.

Table 4. Reduction of moment capacity ($M_{R, reduction}$) as a result of scour

Scour type	$D_s = 1D$	$D_s = 1.5D$	$D_s = 2D$
Local narrow scour	0.13	0.30	0.46
Local wide scour	0.20	0.45	0.58
Global scour	0.39	0.56	0.69

ii. *Bending moment distributions*

The normalised bending moment profiles of piles subjected to an external normalised bending moment of $\tilde{M} = 0.2$ under various types and depths of scour are shown in Figure 9. For all scour types and depths considered, the bending moment along the pile increased significantly compared to the non-scour case. This would suggest in practice that an increase of pile diameter and/or wall thickness might be required during design of a monopile installed in an area with potential of scour (Arany et al. 2017). For scour depths of $1D$ and $1.5D$, the moment profiles developed for local wide scour and global scour are very similar, and those for the case of local narrow scour are slightly smaller. Therefore, it can be concluded that scour shape has non-significant effect on the bending moment profile along the embedded length of the pile at shallow scour depth ($D_s \leq 1.5D$). However, there is a clear distinction between results of scour types as scour depth increased to $2D$, due to the enlarged difference in the overburden pressure above scour base line. Local narrow scour owns the highest amount of overburden pressure, followed by local wide scour, then global scour. The decrease in the overburden pressure caused a decrease in the vertical and lateral effect stresses in the soil below the scour base line. As a result, the soil resistance and pile capacity were decreased and pile bending moment was increased.

Figure 9 Profiles of bending moment along the pile at various scour types ($\tilde{M} = 0.2$): (a) scour depth $1D$, (b) scour depth $1.5D$ and (c) scour depth $2D$

iii. *p-y reaction curves*

The *p-y* curves at a soil depth of $z = 3$ m are compared for different shapes of scour with depth of $1D$ in Figure 10. The results indicate that, the no-scour case shows the highest soil reaction at this depth for any level of pile lateral displacement. Moreover, it can be observed that the soil elements around the piles suffering from a $1D$ scour condition show much lower stiffness comparing to the intact soil surface situation. The difference in the *p-y* curves between the cases of local wide and global scour conditions is not that significant compared with no scour and local narrow scour conditions.

Figure 10 p - y curves at $z = 3$ m in the cases of no scour, $1D$ local narrow scour, $1D$ local wide scour and $1D$ global scour

The effects of scour shape and depth on the p - y curves for various depths below the original mudline level are illustrated in Figure 11. It can be concluded that at scour depths of $1D$ and $1.5D$ the p - y curves are less sensitive to the scour shape. Similarly, for a scour depth of $2D$ the initial response ($y/D < 0.005$) of p - y curves is not significantly affected. This observation implies that the dynamic behaviour of the pile at small strains might not be affected by the scour shape. However, at larger strains the pile under local narrow scour mobilizes the highest amount of soil resistance, followed by local wide scour, then global scour. This observation might be due to the fact that the major consequential difference between local narrow scour and local wide scour is the amount of overburden pressure and resistance provided by the sand slope near to the pile. While the difference between local wide scour and global scour lies in the overburden pressure provided by the soil above the scour base mudline.

Figure 11 p - y curves at $z = 4$ m for different scour types: (a) scour depth $1D$, (b) scour depth $1.5D$ and (c) scour depth $2D$

3.3 Effect of scour depth on the moment-rotation behaviour of the monopile

Figure 12 shows the influence of scour depth on the rotation of monopiles subjected to a certain external bending moment of $\tilde{M} = 0.2$. The results indicate that for all three scour types, $\tilde{\theta}$ increases significantly with the increase of scour depth. For example, it can be seen that the rotation of the pile can be increased by a factor of 3.48 in case of a global scour condition with a depth of $2D$. By interpolating data when scour depth $D_s \in [0, 1D)$, the difference of normalized pile rotation among scour types of local narrow, local wide and global at the scour depth $D_s/D = 0.5$ is not significant.

Figure 12 Influence of scour depth on the normalized pile rotation ($\tilde{M} = 0.2$)

The effects of scour depth on the moment capacity of laterally loaded piles subjected to various types of scour are shown in Figure 13. The results indicate that for all three scour types, $\tilde{M}$ decreases almost linearly with the increase of scour depth. The rate of this increase has a direct relationship with the amount of pile normalized rotation, $\tilde{\theta}$.

Under various kinds of scour types, the decrease of pile capacity due to the increase of scour depth could be directly related to the loss of overburden pressure. As mentioned in the previous section, a decrease in the overburden pressure leads to a decrease in the vertical and lateral effect stresses in the soil underneath. Therefore, the soil resistance and pile capacity were decreased, while the pile bending moment was increased.

Figure 13 Influence of scour depth on the moment bearing: (a) local narrow scour, (b) local wide scour and (c) global scour

4. Discussion and new design method

Based on the centrifuge tests results a new design method is developed to consider the three dimensional shape of the local scour holes around the monopile. The first part of this section will discuss the basics of the method by introduction of an equivalent scour depth according on the shape of the local scour. The steps of the proposed method are presented for a case study in the second part.

4.1. Equivalent scour depth z_{equ}

The results from the centrifuge tests indicate that the detrimental effects of scour are generally less in case of local scour compared with those of global scour. Therefore, as a practical approach to account for the effect of local scour types compared with global scour on the pile moment capacity, the term “additional soil depth (z_{add})” is introduced and is defined in Equation 6. In this approach, the beneficial effect of local scour types is deemed as an additional soil layer lying above assumed global scour, which leads to a larger pile embedment length after local scour (L) and a smaller loading eccentricity (e), as illustrated in Figure 14. In this figure, the terms $z_{add, LN}$ and $z_{add, LW}$ denote additional soil depth to account for local narrow scour (LN) and local wide scour (LW) scour types respectively. Another term “equivalent scour depth (z_{equ})” is introduced hereafter, which signifies the effective scour depth after taking into account the compensation effect by local scour types compared with global scour, which is defined by Equation 7.

$$z_{add} = \delta \cdot D_s \quad \text{Equation 6}$$

$$z_{equ} = D_s - z_{add} = D_s \cdot (1 - \delta) \quad \text{Equation 7}$$

Compared with global scour, the improvement in moment capacity by local scour types is quantified by “additional soil depth factor” δ . Therefore, the condition of global scour is set as the base level for δ , i.e. no compensation effect is introduced which corresponds to $\delta = 0$. Consequently, the condition of no scour can be set as the upper boundary for δ and it can be considered as “full compensation”, which corresponds to $\delta = 1$. Thus δ for the local scour types ranges between 0 and 1.

Figure 14 Illustration of the additional soil depth (z_{add})

Figure 15 shows the influence of scour type on the normalised external moment at various scour depths, along with the strategy to determine the “additional soil depth factor” δ experimentally. For example, for 1D local narrow and 2D local wide scour conditions, δ would be equal to 0.66 and 0.17, respectively. This means that the equivalent scour depth for these two cases will be $0.34D$ and $1.66D$, respectively. The equivalent scour depths for various conditions are summarised in Table 5.

Figure 15 Determination of the additional soil depth factor (δ): (a) scour depth $1D$, (b) scour depth $1.5D$, and (c) scour depth $2D$

Table 5. Equivalent scour depth (z_{equ})

Scour type	$D_s = 1D$	$D_s = 1.5D$	$D_s = 2D$
Local narrow scour	$0.34D$	$0.87D$	$1.3D$
Local wide scour	$0.67D$	$1.215D$	$1.66D$
Global scour ($= D_s$)	$1D$	$1.5D$	$2D$

As a practical approach to incorporate effects of scour type on equivalent scour depth (z_{equ}), the data from Table 5 were used to plot the relationship between z_{equ}/D and D_s/D considering different scour types, as shown in Figure 16. When the scour depth $D_s \in [1D, 2D]$, linear fits between z_{equ}/D and D_s/D were found and the following empirical equation was generated:

$$\frac{z_{equ}}{D} = \frac{D_s}{D} - f \quad \text{Equation 8}$$

in this equation, $f = 0$, for global scour; $f = 0.4$, for local wide scour; $f = 0.7$, for local narrow scour.

However, when the scour depth $D_s \in [0, 1D]$, the effect of scour type is not significant on the pile rotation (Figure 12). Therefore, as a preliminary attempt linear interpolation technique could be applied which leads to the following empirical equation:

$$\frac{z_{equ}}{D} = \frac{D_s}{D}(1 - f) \quad \text{Equation 9}$$

In this way, the beneficial effect of local scour shapes can be practically considered as shallower global scours, when design pile foundation from moment capacity perspective. The derived empirical equation offers a straightforward approach to calculate the equivalent scour depth (z_{equ}).

Figure 16 Influence of scour type on the equivalent scour depth (z_{equ})

4.2 Reduction of pile moment capacity caused by scour

The data from Table 4 was used to plot the relationship between $M_{R, reduction}$ and scour depth (D_s) considering different scour types, which is shown in Figure 17. When the scour depth $D_s \in [1D, 2D]$ a linear equation has been used to fit the data, resulting in the following general equation:

$$M_{R, reduction} = 0.35 \frac{D_s}{D} + r \quad \text{Equation 10}$$

in this equation, r is a fitting parameter and is equal to 0.05, -0.16 and -0.2 for global scour, local wide scour and local narrow scour, respectively.

Similar with the technique in the derivation of equivalent scour depth (z_{equ}) when the scour depth $D_s \in [0, 1D)$, linear interpolation technique could be applied which leads to the following empirical equation:

$$M_{R, reduction} = \frac{D_s}{D} (0.35 + r) \quad \text{Equation 11}$$

Using this method, the detrimental influence of scour on the moment capacity can be directly related to the scour depth and scour type. In the practical application, depending on the formation of the scour-hole, as long as the scour type and scour depth are primarily estimated, the moment capacity reduction factor $M_{R, reduction}$ can be estimated from Figure 17, and then be employed by the following equation to determine the “design pile moment capacity under scour condition ($M_{R, with scour}$)”:

$$M_{R, \text{ with scour}} = M_{R, \text{ no scour}} \times (1 - M_{R, \text{ reduction}}) \quad \text{Equation 12}$$

in this equation, $M_{R, \text{ with scour}}$ is the design pile moment capacity considering the influence of scour, and $M_{R, \text{ no scour}}$ is the design pile moment capacity when no scour erosion is considered.

Figure 17 $M_{R, \text{ reduction}}$ vs. D_s/D

4.3 Example

An example is given to demonstrate the use of the proposed equivalent scour depth method in this part. Consider a rigid monopile, with $L/D = 5$, driven into sand with a relative density of 80%. The task is to determine the equivalent scour depth (z_{equ}) and the design pile moment capacity under scour condition ($M_{R, \text{ with scour}}$) from the equivalent moment capacity point of view, when the pile is subjected to local wide scour with a scour depth of $1.2D$. The design pile moment capacity when there is no scour erosion is signified by $M_{R, \text{ no scour}}$.

According to Figure 16, the non-dimensional coefficient f under local wide scour condition is 0.4. Therefore, z_{equ} can be calculated using Equation 8:

$$\frac{z_{equ}}{D} = \frac{D_s}{D} - f = \frac{1.2D}{D} - 0.4 = 0.8 \quad \text{Equation 13}$$

This result indicates that local wide scour with a scour depth of $1.2D$ equivalents to global scour with a scour depth of $0.8D$.

According to Figure 17, the non-dimensional coefficient r under local wide scour condition is -0.16. Therefore, the moment capacity reduction factor ($M_{R, reduction}$) can be calculated from Equation 10:

$$M_{R, reduction} = 0.35 \frac{D_s}{D} + r = 0.35 \times 1.2 - 0.16 = 0.26 \quad \text{Equation 14}$$

Accordingly, the design pile moment capacity under this specific scour condition ($M_{R, with scour}$) can be calculated according to Equation 12:

$$M_{R, with scour} = M_{R, no scour} \times (1 - M_{R, reduction}) = 0.74 M_{R, no scour} \quad \text{Equation 15}$$

In summary, the equivalent scour depth is $0.8D$ and the moment capacity of the pile would decrease by 26% in case of a local wide scour to a depth of $1.2D$.

5 Conclusions

As a process of soil erosion, scour broadly occurs around offshore wind turbine monopiles, which decreases the pile capacity and stiffness and might potentially lead to failure of the structure. A series of centrifuge tests was carried out at 100g on a model monopile installed in dense sand with embedment ratio of 5 to investigate the effect of scour on the foundation lateral response. Three scour types (local narrow, local wide and global) and three scour depths ($1D$, $1.5D$ and $2D$) were considered in this investigation, which represent a range of common scour shapes in real engineering applications. Empirical equations were derived to evaluate the beneficial effect of local scour types compared with the assumption of global scour condition, and to assess the detrimental effect of increased scour depth on pile moment capacity. The following conclusions can be drawn from this study:

(1) Scour type has significant influence on the pile moment-rotation behaviour. Piles under local narrow scour show the highest moment capacity, followed by local wide scour, and then by global scour condition. At scour depths of $1D$ and $1.5D$, scour type has minimal effect on the stiffness of the pile at small rotations, which signifies that in pile dynamic analysis within small strain range the effect of scour type could be ignored. However, the results indicate that in case of a global scour condition to a depth of $2D$, negative effect of scour on the stiffness of pile should certainly be taken into consideration.

At the same soil depth (z) and lateral displacement (y), pile under local narrow scour mobilizes the highest amount of soil resistance (p), followed by local wide scour, then global scour. The major consequential difference between local narrow scour and local wide scour was speculated as the

amount of overburden pressure and resistance provided by the sand slope near to the pile. While the difference between local wide scour and global scour was suspected to be due to the overburden pressure provided by the soil above the scour base. According on this hypothesis, the beneficial effect of local scour types could be regarded as additional soil layers lying above global scour. Empirical equations were derived to calculate the equivalent scour depth (z_{equ}), which can be implemented in the current monopile foundation design methodology.

(2) The pile moment capacity was found to decrease almost linearly with the increase of scour depth, in all the three scour types (local narrow scour, local wide scour and global scour). The pile initial stiffness decreases with increasing scour depth as well. Increasing scour depth leads to increase in the peak bending moment and moves the location of the peak moment into deeper soil.

The detrimental effect of scour on the moment capacity considering influence of scour depth and scour type was described by empirical equations for a monopile with $L/D = 5$ installed in dense sand. In the practical application, depending on the marine hydraulic environment, as long as the type and depth of the scour-hole are estimated, the moment capacity reduction factor $M_{R, reduction}$ could be calculated and employed to determine the “design pile moment capacity under scour condition ($M_{R, with scour}$)”. In this way, the traditional design method which neither fully considers the effect of scour shape nor properly addresses the effect of scour depth could be improved.

Acknowledgement

This work is partly funded by the Section of Geo-Engineering, Delft University of Technology. The first author is grateful for the support by the China Scholarship Council (CSC).

References

- Allersma, H. 1994. The University of Delft geotechnical centrifuge. Proc. Int. Conf. Centrifuge, 47-52.
- API. 2007. “RP2A: Recommended Practice for Planning, Designing and Constructing Offshore Platforms - Working Stress Design.” Washington, DC.
- Arany, L., Bhattacharya, S., MacDonald, J. and Hogan, S. 2017. Design of monopiles for offshore wind turbines in 10 steps. *Soil Dynamics and Earthquake Engineering*, 92, 126-152.
- Byrne, B. W., McAdam, R., Burd, H. J., Houlsby, G. T., Martin, C. M., Gavin, K., Doherty, P., Igoe, D., Zdravkovic, L., Taborda, D. M. G., Potts, D. M., Jardine, R. J., Sideri, M., Schroeder, R. F. C., Muir Wood, A., Kallehave, D., and Skov Gretlund, J. 2015. Field testing of large diameter piles under lateral

- loading for offshore wind applications, in: Proceedings of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. pp. 1255–1260.
- Byrne, B. W., Burd, H. J., Zdravkovic, L., McAdam, R. A., Taborda, D. M., Houlsby, G. T., Jardine, R. J., Martin, C. M., Potts, D. M., and Gavin, K. G. 2019. PISA: new design methods for offshore wind turbine monopiles. *Revue Française de Géotechnique*, 158, 3.
- Chortis, G., Askarinejad, A., Prendergast, L., Li, Q., and Gavin, K. 2020. Influence of scour depth and type on p–y curves for monopiles in sand under monotonic lateral loading in a geotechnical centrifuge. *Ocean Engineering*, 106838.
- De Jager, R. R., Machsoudloo, A., Askarinejad, A., and Molenkamp, F. 2017. Preliminary results of instrumented laboratory flow slides. In: ROHE, A., SOGA, K., TEUNISSEN, H. and COELHO, B. Z. (eds.) *Proceedings of the 1st International Conference on the Material Point Method (MPM 2017)*. Delt, The Netherlands: Elsevier.
- DNV, G. 2014. Design of Offshore Wind Turbine Structures (DNV-OS-J101). *Det Norske Veritas AS, Oslo*.
- DNV, G. 2016. DNVGL-ST-0126: Support structures for wind turbines. *Oslo, Norway: DNV*.
- Doherty, P. and Gavin, K. 2012. Laterally loaded monopile design for offshore wind farms. *Proceedings of the Institution of Civil Engineers-Energy*, 165, 1, 7-17.
- Hoffmans, G. J., and Verheij, H. J. 1997. *Scour manual*, CRC press.
- Jones, J. S., Kilgore, R. T., and Mistichelli, M. P. 1992. Effects of footing location on bridge pier scour. *Journal of Hydraulic Engineering*, 118, 2, 280-290.
- Khari, M., Kassim, K. A., and Adnan, A. 2014. Development of Curves of Laterally Loaded Piles in Cohesionless Soil. *The Scientific World Journal*, 2014.
- Leblanc, C., Houlsby, G., and Byrne, B. 2010. Response of stiff piles in sand to long-term cyclic lateral loading. *Geotechnique*, 60, 2, 79-90.
- Li, F., Han, J., and Lin, C. 2013. Effect of scour on the behavior of laterally loaded single piles in marine clay. *Marine Georesources & Geotechnology*, 31, 3, 271-289.
- Li, Q., Prendergast, L., Askarinejad, A., Chortis, G. and Gavin, K. 2020. Centrifuge Modeling of the Impact of Local and Global Scour Erosion on the Monotonic Lateral Response of a Monopile in Sand. *Geotechnical Testing Journal*, 43, 5.
- Li, Q., Prendergast, L., Askarinejad, A. and Gavin, K. Effect of scour on the behavior of a combined loaded monopile in sand. *Proc. 9th European Conf. on Numerical Methods in Geotechnical Engineering (NUMGE 2018)*, 2018. 25-27.
- Lin, C., Bennett, C., Han, J. and Parsons, R. L. 2010. Scour effects on the response of laterally loaded piles considering stress history of sand. *Computers and Geotechnics*, 37, 7-8, 1008-1014.
- Lin, C., Han, J., Bennett, C. and Parsons, R. L. 2014. Analysis of laterally loaded piles in sand considering scour hole dimensions. *Journal of Geotechnical and Geoenvironmental Engineering*, 140, 6, 04014024.
- Lin, C., Han, J., Bennett, C. and Parsons, R. L. 2016. “Analysis of Laterally Loaded Piles in Soft Clay Considering Scour-Hole Dimensions.” *Ocean Engineering* 111: 461–70. <https://doi.org/10.1016/j.oceaneng.2015.11.029>.
- Maghsoudloo, A., Askarinejad, A., R.R., D. J., Molenkamp, F. and Hicks, M. 2018. Experimental investigation of pore pressure and acceleration development in static liquefaction induced failures in submerged slopes. *9th International Conference of Physical Modelling in Geotechnics*. London: Accepted.
- Masin, D. 2017. Calibration of sand hypoplastic model on Geba sand data, Internal report issued for Royal IHC, Netherlands (Charles University in Prague)

- Mostafa, Y. E. 2012. Effect of local and global scour on lateral response of single piles in different soil conditions. *Engineering*, 4, 06, 297.
- Prendergast, L. J., Reale, C. and Gavin, K. 2018. "Probabilistic Examination of the Change in Eigenfrequencies of an Offshore Wind Turbine under Progressive Scour Incorporating Soil Spatial Variability." *Marine Structures* 57 (January): 87–104.
- Qi, W., Gao, F., Randolph, M. and Lehane, B. 2016. Scour effects on p–y curves for shallowly embedded piles in sand. *Géotechnique*, 66, 8, 648–660.
- Richardson, E. and Davis, S. 2001. Evaluating scour at bridges (HEC-18). *US Department of Transportation, Federal Highway Administration, Colorado, 4th edn. FHWA NHI, 01-001*.
- Robertson, I. N., Riggs, H. R., Yim, S. C., and Young, Y. L. 2007. "Lessons from Hurricane Katrina Storm Surge on Bridges and Buildings." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 133 (6): 463–83.
- Roulund, A., Sumer, B. M., Fredsøe, J. and Michelsen, J. 2005. Numerical and experimental investigation of flow and scour around a circular pile. *Journal of Fluid Mechanics*, 534, 351–401.
- Sørensen, S. P. H. and Ibsen, L. B. 2013. Assessment of foundation design for offshore monopiles unprotected against scour. *Ocean Engineering*, 63, 17–25.
- Sumer, B. M., Fredsøe, J., and Christiansen, N. 1992. "Scour Around Vertical Pile in Waves." *Journal of Waterway, Port, Coastal and Ocean Engineering* 118 (1): 15–31.
- Ttrong, P., Lehane, B., Zania, V., and Klinkvort, R. T. 2019. Empirical approach based on centrifuge testing for cyclic deformations of laterally loaded piles in sand. *Géotechnique*, 69, 2, 133–145.
- Wang, J. and Qi, C. Py Curves of Piles in Saturated Degradation Sands with Residual Pore Water Pressures. The Eighteenth International Offshore and Polar Engineering Conference, 2008. International Society of Offshore and Polar Engineers.
- Wu, X., Hu, Y., Li, Y., Yang, J., Duan, L., Wang, T., Adcock, T., Jiang, Z., Gao, Z. and Lin, Z. 2019. Foundations of offshore wind turbines: A review. *Renewable and Sustainable Energy Reviews*, 104, 379–393.
- Yang, K., and Liang, R. 2006. Methods for deriving py curves from instrumented lateral load tests. *Geotechnical testing journal*, 30, 1, 31–38.
- Zhang, H., Chen, S. and Liang, F. 2017. Effects of scour-hole dimensions and soil stress history on the behavior of laterally loaded piles in soft clay under scour conditions. *Computers and Geotechnics*, 84, 198–209.
- Zhang, W., and Askarinejad, A. 2019. Centrifuge modelling of submarine landslides due to static liquefaction. *Landslides*, 10.1007/s10346-019-01200-z.