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The effect of scour on lateral behavior of monopiles in calcareous sand

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ABSTRACT: Monopiles with large diameters and low L/D ratios are frequently used as the foundations of offshore wind turbines. In the case of unprotected soil surface, the wave and tidal currents wash away the surrounding soil, creating an inverted-frustum-like ditch, local scour, with depths ranged between 0.5D through 2D. Also, the erosion of sand over the entire field is called global scouring. To evaluate the effect of scouring over lateral capacity of monopiles, a series of centrifuge tests were conducted at 40g acceleration level to model a 2.08-meter diameter monopile with embedment depth to diameter ratio (L/D) of 5. The Hormuz calcareous sand was utilized in dry condition and rained via a devised sand pluviation setup. A set of tests were performed for simulating 1D-global-scouring, 1D-local-scouring, and a test with no scouring for comparison. The monotonic lateral load was generated by an actuator and transferred through an articulated joint, which allows unrestricted rotation of the loading point. Based on the results, scouring could significantly reduce the lateral load capacity of monopiles. A 1D local scouring decreased the lateral load capacity by 30%. This reduction was more considerable in global scour due to less overburden pressure on the remaining adjacent soil. Finally, p-y diagram revealed an insignificant reduction of moment capacity in depths beyond 1D beneath the scouring bottom.

Keywords: Centrifuge Modelling, Offshore Wind Turbine, Scour, Monopile Lateral Capacity

1 INTRODUCTION

Installing wind turbines in offshore environments is highly efficient due to the consistency of high-velocity winds (Bhattacharya, 2019). Monopiles are hollow tubes with diameters ranging between 3 to 11 meters. High-intensity lateral loads due to wind and wave loads and low magnitude vertical loads stemming from rotor-nacelle assembly and tower self-weight led to the implementation of piles with small embedment to diameter ratio (Li et al., 2021). Scouring is the erosion of sand which leads to the reduced embedment depths and effective stress of the foundation and subsequent change in pile response to excitation loads. There are generally two types of scouring. First, global scour, which is the removal of sand over the entire field, and second, local scour, which leads to the formation of an inverted frustum-like ditch around the monopiles (Mostafa, 2012). Studies by Robertson et al. (2007) revealed that when the storm surge waves cross the field, global scour with 1D depths are frequent. Design codes also propose a local scouring depth of 1.3 times the pile diameter. Mostafa (2012) performed numerical modelling and concluded that the global scouring has more significant effects on the lateral load capacity and displacement of piles compared with local scour. Qi et al. (2016) modelled slender monopiles with L/D 9.5 to 12.5 to investigate scouring effects over p-y curves in sandy soils. Their results showed that the remaining over-consolidated soil below the new mudline level in the global scouring case performs similar to the normally consolidated sand at the same depth below the original mudline level; this finding contradicts the results of previous studies. Choo and Kim (2016) performed centrifugal modelling on a 6-meter diameter monopile and showed that the API model results in stiffer response compared to experimental data. Bayton and Black (2019) used a model pile with embedment depth to diameter ratio of 5 in different local and global scouring depths under lateral loading. Comparing the results of 1D local and 1D global scouring, they showed a 50% difference in lateral response, which reveals conservatism for current design practices. Liang et al. (2018), considering the geometry of the scouring hole and stress history of soil in an analytical model, revealed that by increasing the scouring depth as the most effective parameter among scour hole geometry, the lateral load-bearing greatly decreases. Li et al. (2018) investigated the response of monopiles under simultaneous lateral and vertical loading with different scouring conditions. They revealed that the lateral capacity of piles decreases linearly with increasing scouring depth. Chortis et al. (2020) using centrifuge and numerical modelling showed that increasing the scouring depths results in lower pile lateral capacity and the scouring geometry has significant effects on the lateral response of monopiles. They also concluded that using the API curves results in stiffer responses with higher capacities. The current study focuses on an investigation on the lateral response of monopiles under globally and locally scoured calcareous sand.

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2 EXPERIMENTAL SETUP

The tests were performed at 40g acceleration level using C-67-2 swinging platform ACTIDYN SYSTEMS centrifuge at the soil dynamics laboratory of the University of Tehran. The model pile is an open-ended steel tube with an outside diameter of 5.2cm and the wall thickness of 1mm plus 0.6mm protection coating over 9 levels of strain gauges. The wall thickness is greater than the minimum suggested by API (2007). The pile was hammered at 1g to the embedment depth of 26 cm to reach the L/D of 5, which is compatible with previous studies (Li et al., 2020, Peder Hyldal Sørensen and Bo Ibsen, 2013, Doherty and Gavin, 2012, LeBlanc et al., 2010). The wall thickness to pile diameter ratio (D/t) is 52, which is compatible with the monopile database (Byrne et al., 2015), suggesting D/t between 39 and 80 for L/D of 5.

3 SAND

Calcareous material is abundant between latitudes -30 and +30 degrees. Working properties of calcareous materials are different from silica sands as they are angular with high porosity ratio and have internal friction angles of more than 35 degrees. The specific gravity of calcareous sands is between 2.75 and 2.85 (Murff, 1987). Due to the high porosity ratio, they are highly crushable under high stresses (Dyson and Randolph, 2001). The calcareous sand utilized in the current study was retrieved from Hormuz island located north of the Hormuz strait. The physical properties of the Hormuz calcareous sand were investigated by Rasouli et al. (2020) and are presented in Table 1. Based on the sieve analysis suggested by ASTM D2487 this sand is classifies as poorly graded.

Table 1. physical properties of Hormuz Calcareous Sand.

C_u	C_c	D_{50} (mm)	G_s	γ_{dmin} (kN/m^3)	γ_{dmax} (kN/m^3)	e_{max}	e_{min}
1.8	0.87	0.31	2.73	14.245	17.167	0.88	0.56

The pile diameter to mean particle size is 167.7, which is greater than the minimums suggested by many researchers (Zhang and Askarinejad, 2019, Klinkvort et al., 2013, Dyson and Randolph, 2001), so the effect of particle size scale was ignored.

4 MODEL PREPARATION

Calcareous sand was dry pluviated using a devised hooper that allows drop elevation and slot width adjustments (Malakshah et al., 2021). In each test, the total weight of the dropped sand and the total occupied volume of the box were known. Therefore, the final relative density was calculated to reach about 70%. The model pile was wished in place by hammering at 1g. Installing the model pile at 1g is not a perfect representation of shear stresses created during prototype installation (Bayton and Black, 2019), and in some cases, sand dilation was observed due to lower confining stresses (Li et al., 2020). Installing at prototype acceleration will result in greater moment capacity (Murphy et al., 2018) but jacking at 40g and adjusting lateral loading instruments during the flight was not applicable. Global scouring was created by raining less sand, and the local scour hole was hand excavated by placing a wedge with a slope angle of 30 degrees and the bottom depth of 1D. It is noteworthy that the scouring slope angle has little effect on the response of piles under lateral loading (Zhang et al., 2017, Li et al., 2013). The method utilized to create scouring at 1g is conservative because excavating sand at 1g eliminates the over-consolidation ratio due to the presence of less overburden pressure (Bayton and Black, 2019). The monotonic lateral loading was exerted to the model pile at the eccentricity of e/D=5.75 using a servo-motor at the rate of 0.1mm/s. The motor-pile connection was a fully articulated joint with little friction as the load-displacement response of the pile is highly dependent on the head boundary conditions (Han and Frost, 2000). The tests program is provided in Table 2. Also, the test configurations for the local and global scouring scenarios are provided in Fig. 1.

Table 2. Tests program.

Test No.	Scouring Type	Embedment Depth
1	No Scouring	5D (26 cm)
2	Local 1D	4D (20.8 cm)
3	Global 1D	4D (20.8 cm)

a

b C

Fig. 1. a) overall configuration of test 2. b) local scouring of test 2. c) global scouring of test 3.

5 RESULTS

5.1 Monopile behavior

The results are presented in model scale with reference point being the original mudline level.
Fig. 2 represents the load-displacement response of monopile under no-scour, 1D local scour and 1D global scour conditions. It is evident that scouring reduces both the stiffness and ultimate lateral capacity. For example, at the head displacement of 0.1D, the lateral capacity decreased up to 30% in the case of local scour in comparison with no scour condition. This reduction was 40% in the case of global scouring as less overburden pressure was supporting the pile.

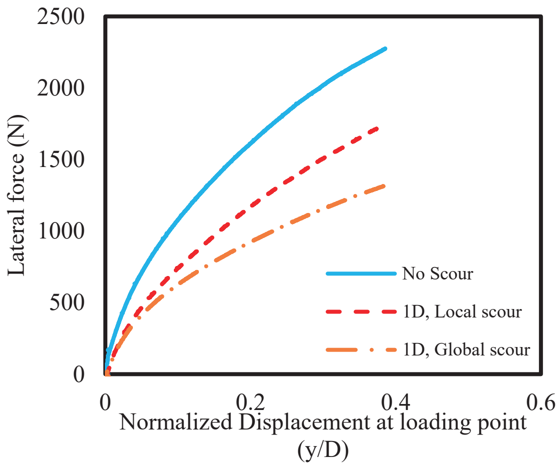

Fig. 2 Normalized load-displacement response.

Furthermore, the profile of bending moments at the lateral head load of 900 N is shown in Fig. 3 a. It is inferred that scouring increased bending moment along the embedded length, and also lowered the point of maximum moment due to the absence of confining soil resistance in the scoured section. Also, the increase of moment profile was higher for the case of global scouring. Fig. 3 b. illustrates the soil resistance as normalized depth of the monopile. It can be seen that the point of zero soil pressure or the point of rotation was located about 65 to 70% of the embedded part and slightly lowered when the confining pressure decreased as in local and global scour conditions. It was also seen that scouring increased the tendency of rigid body rotation and intensified the 'toe kick' phenomenon at the pile tip.

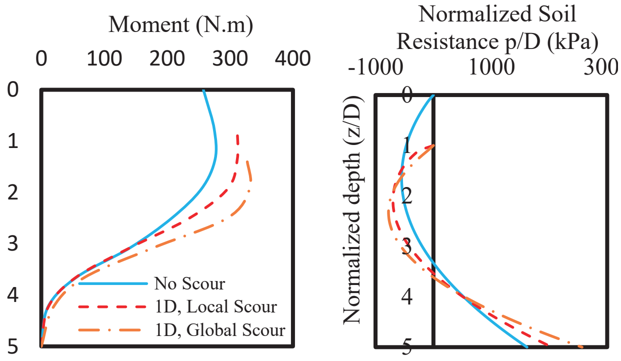

Fig. 3. a) Moment profiles at the lateral load of 900 N. b) Soil resistance vs normalized depth.

5.2 Local p-y curve behavior

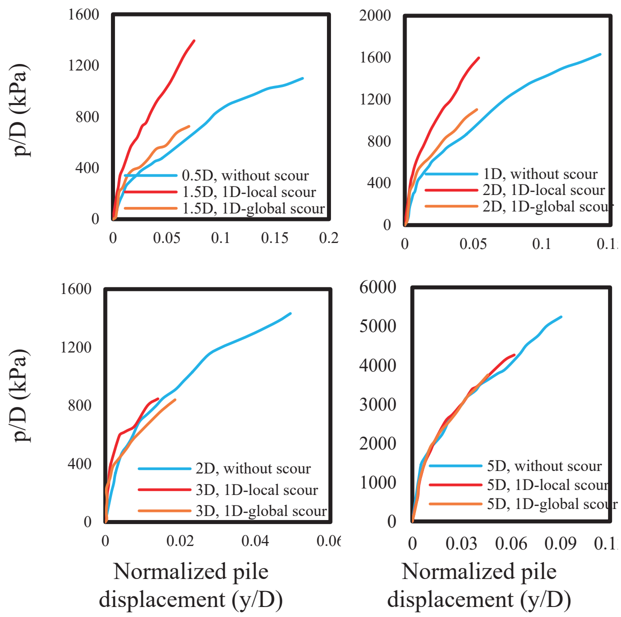

Fig. 4 Local p-y curves with absolute depth, from original mudline level.

The following section evaluates the local p-y curves in different pile depths. Fig. 4 is the illustration of soil pressure changes with the pile displacements in relative depths from the original mudline level. It can be seen that in relatively low depths the local scouring scenario illustrated grater soil stiffness and capacity but at deeper locations the p-y curves for all cases were almost identical. This can be attributed to the confining pressure from the soil surrounding the pile at upper sections.

6 CONCLUSIONS

A series of centrifuge model experiments have been performed to identify the effect of scouring on the lateral behavior of monopile foundations in calcareous sand.

Load-displacement observations show a 30 and 40% reduction of lateral capacity in the case of local and global scouring respectively.

The moment profiles illustrate an increase in bending stress in cases with scouring hole. Also, the soil stress profiles show a tendency towards pure pile rotation under scouring conditions.

Examination of individual p-y curves revealed an increase in the soil stiffness and capacity at lower depths as a result of confining pressure of the remaining soil at the case of 1D local scour. This confining pressure fades at lower sections.

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