Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Behaviour of soil in OWT monopile foundation subjected to torsion

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Abstract. Wind energy is one of the most promising renewable energy sources. Offshore wind turbines (OWT) are now used in many countries. Most OWT farms use driven monopiles as their foundation. The purpose of this study was to investigate the behaviour of monopile under torsional load. Quasi-static analysis using finite element analysis is performed in PLAXIS3D. The performed study is used to evaluate the deformation and frictional mobilization of the surrounding soil. The rotor axis of an OWT rotor is usually not aligned with the wind since the wind is continuously changing its direction. The yaw mechanism, which rotates the nacelle around the tower axis, can help increase energy capture. Any failure in the power control units, torsional loading is added to the monopile foundation. It initiates a twist(ɵ) at the pile head, reduces its axial capacity, and increases the settlement of the foundation. This study includes the torsional effect caused by the failure of the yaw and bearing system and thus, the corresponding strength mobilization of soil is being done. The experimental investigation was done by varying the relative density of the sandy soil. Parametric studies also done by changing the embedded length of the monopile and varying the soil stratum. Through the numerical studies, the effect of cyclic loads on the rate of accumulated displacements, shear stress variation with respect to the depth and changes in soil-pile stiffness were discussed.

Keywords: Offshore Wind Turbine, Monopile Foundation, Torsional Effect, PLAXIS 3D.

1 Introduction

India's need for energy has increased significantly as a result of its consistently strong and rapid economic growth. The offshore wind industry has been growing as a result of the large coastline and adherence to international climate agreements. As a renewable energy source, wind energy is growing in popularity and has a wide range of possible applications across the globe. The estimated lifespan of an offshore wind turbine is 20 to 30 years, whereas foundations are typically built for a longer design life. One of the most popular offshore foundations for wind turbines is the monopile. It is difficult to design foundations for OWTs because these are dynamically delicate structures. The basic goal of a foundation is to safely and within permissible deformations transfer all of the loads from the wind turbine structure to the ground. The main tower, three blades, and nacelle are the components of a wind turbine. The many electrical and electronic components required for the effective and secure conversion of wind power to electrical energy were housed inside the nacelle and the tower. If the yaw system fails, the OWT monopile foundation experiences a torsional effect. The resulting torsional effects then have an impact on the nearby soil. to investigate the response of the surrounding soil (sandy) in the offshore wind turbine monopile foundation when it is impacted torsional owing to the nacelle's yaw mechanism failing. This study will help to understand how the OWT's sandy soils degrade when subjected to torsion.

Numerical study

This study used a finite element application to understand the response of rigid piles embedded in dry homogeneous sand under torsional loading. The Finite Element software PLAXIS 3D have been to analyze the behavior of monopile. Tamil Nadu was the place selected for this investigation (8.500 ^{0}N,78.300 ^{0}E). The Ministry of New and Renewable Energy provided the geotechnical, wind, wave, pile, turbine, and tower data. Based on the reference [2] and [4] various loads acting on the OWT were calculated. From the reference [1], numerical input parameters were collected. With the exception of near the top of the pile, the earth deforms little as it interacts with the pile under lateral loading. Therefore, in this case, the HS small strain model (HS-Small) is the chosen model. Based on Mindlin's theory, the monopile and tower in sandy soil were simulated in PLAXIS 3D using a linear elastic plate element as a hollow steel pipe. A very fine stage of mesh generation was used to divide the geometry into plate elements and volume elements.

2 Results

When sandy soil was subjected to environmental loading and static torsion, the variation of deformation with respect to dynamic time showed that the cyclic loading increased the structure's deformation. Cyclic secant stiffness was estimated using the load variation vs deformation graph.

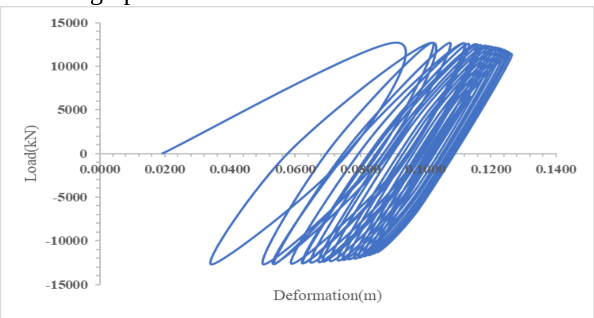

Fig. 1. Load vs Deformation Curve.

Figure 1, shows the curve with more cycles, the total displacement decreases. For the first few cycles, the displacement amplification grew more quickly before slowing down. This is a result of the sand around the pile becoming denser. The grains close to the pile are rearranged by the accumulated displacement. With each loading cycle, the hysteresis loop's shape flattened. It exhibits a reduction in loop area, indicating that the behavior is hardening.

Variation of cyclic secant stiffness with increasing number of cycles

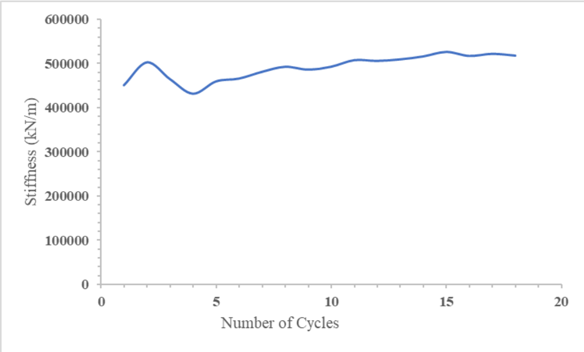

Fig. 2. Stiffness vs Number of cycles Curve.

The fluctuation in cyclic secant stiffness with respect to the number of cycles for sandy soil subjected to external loading and static torsion is shown in Figure 2. The active and passive zones in the sand were created by the lateral load on the monopile. Under each cycle of loading, the sand mass develops resistance to applied lateral load with some permanent displacement on the soil monopile system. With more load cycles, the cyclic secant stiffness gradually increases. The decrease in intergranular voids is too responsible for this. Sand surrounding the pile densifies as a result of repetitive loading, raising the sand's shear modulus.

Variation of shear stress due to the application of lateral loads in sand

We can see from the figure 3, the shear stress rises as the depth increases. In the initial cycle of cyclic lateral loading in the sand, the monopile creates irrecoverable displacement because it minimizes friction between the pile and soil. The void will decrease as the number of cycles increases, causing friction that raises the shear strength and goes along with the reduction of the rate of increasing displacement.

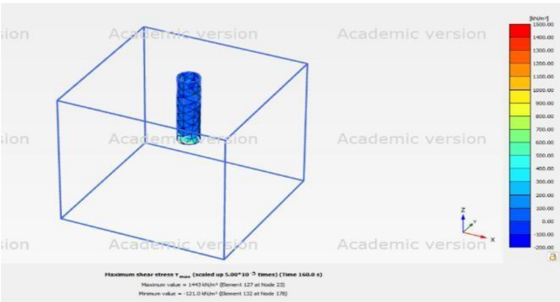

Fig. 3. Shear Stress Variation Due to the Torsion and Environmental Loading

Variation of shear stress due to the application of pure static torsion in sand

Figure 4, shows the fluctuation in shear stress brought on by using static torsion solely. The shear stress contours surrounding the pile under pure static torsion are also used to study the rise in shear stresses over the frictional face of the pile. We can see from the graphs that the torsional load distribution diminishes along the monopile's depth and the shear stress increases with regard to the monopile's embedded length.

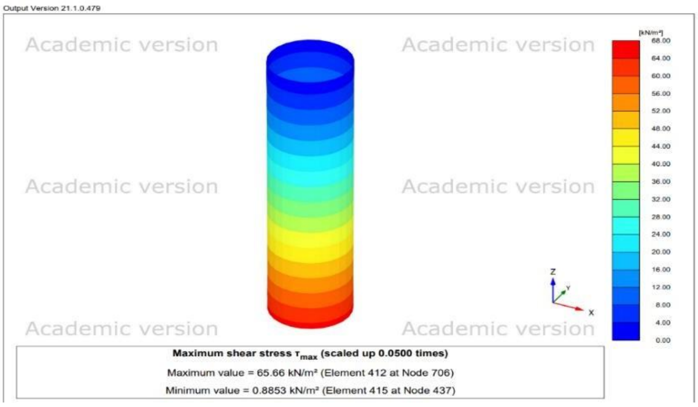

Fig. 4. Maximum Shear Stress Variation Contour for Sandy Soil Stratum Subjected to the Static Torsion

3 Parametric study

Effect of embedded length of the monopile in sandy soil

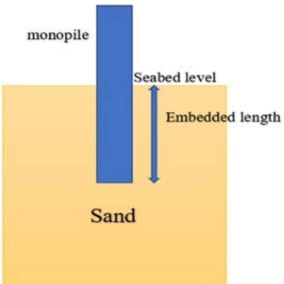

Fig. 5. Schematic Diagram of the OWT in the Field

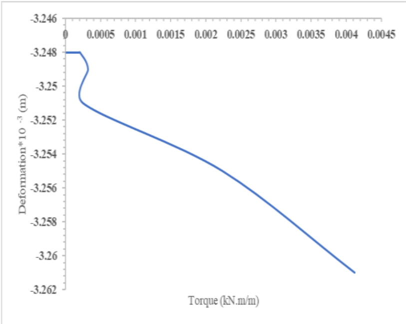

Fig. 6. (a)

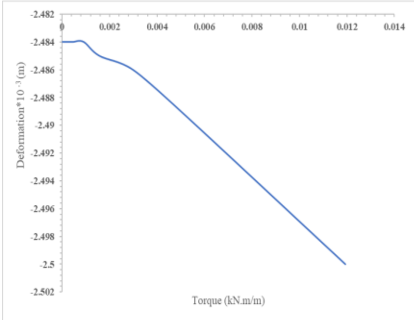

Fig. 6. (b)

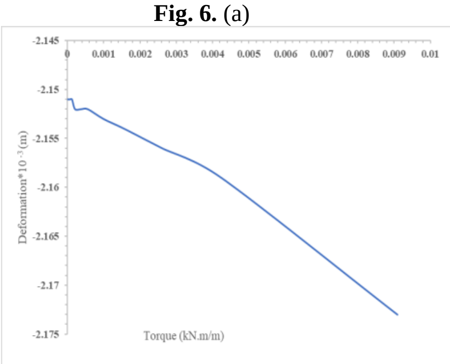

Fig. 6. (c)

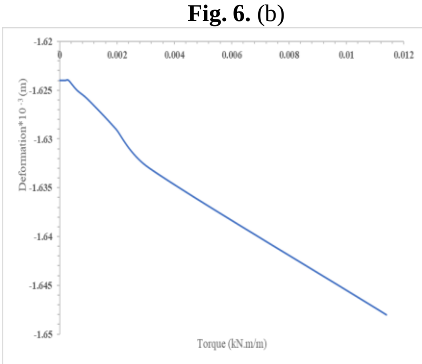

Fig. 6. (d)

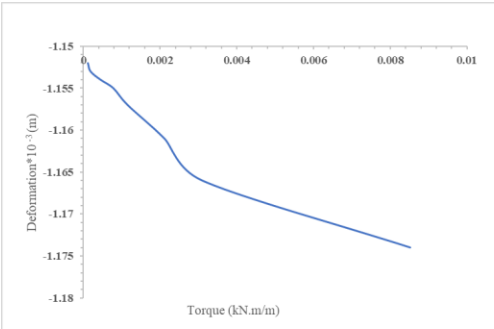

Fig.6. (e)

Fig. 6 (a), (b), (c), (d), (e) Torque vs Torsional Deformation for Embedded Length of (a) 20 m, (b) 25 m, (c) 30 m, (d) 35 m, (e) 40 m.

For this investigation, the embedding length was 20 m, 25 m, 30 m, 35 m, and 40 m. the sandy ground beneath the pile. The pile was rotated strictly in static motion. The above graph (figure 6 (a), (b), (c), (d), (e)) illustrates the relationship between torque and torsional deformation for various embedded lengths in sandy soil layer. As the mono-pile's depth increased, the torsional load's magnitude reduced. because of the frictional resistance provided by the surrounding soil. Due to the impact of overburden soil, the frictional resistance provided by the soil increased with respect to depth. As a result, both the torsional load's magnitude and the deformation it induced along the monopile's depth decreased.

Effect of various soil stratum

Figure 7 (a), (b), (c), (d) shows the variance in shear stress as well as the monopile's depth of embedment in various soil strata. We can see from the curve that the shear stress variation follows a linear pattern. With respect to the monopile's depth, the shear stress was rising linearly. The depth of the soil layer that affects shear resistance is the key factor in the variance. When fine-grained soil (clay) and a layer of coarse-grained soil (sand) are combined, the angle of friction and cohesiveness both rise. Shear-stress profiles for piles in clay and sand typically show that the stress rises linearly to a peak value and then sharply declines curvilinearly. For layered soil, the layering was the source of segmental variation in shear stress

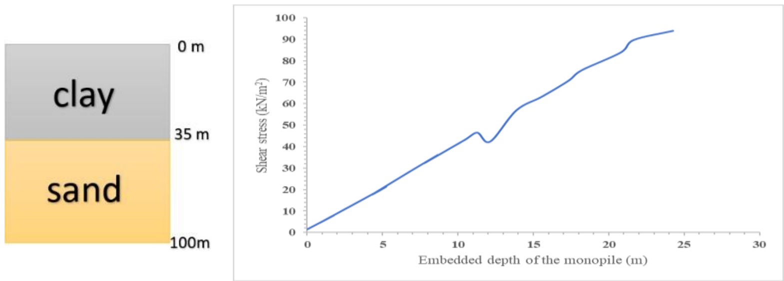

Fig. 7. (a)

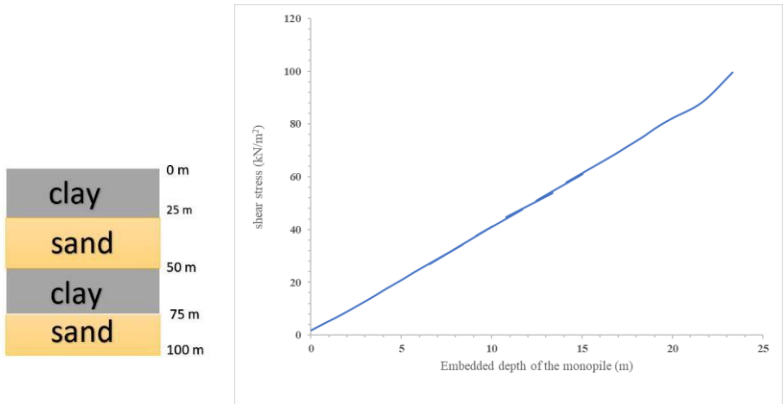

Fig. 7. (b)

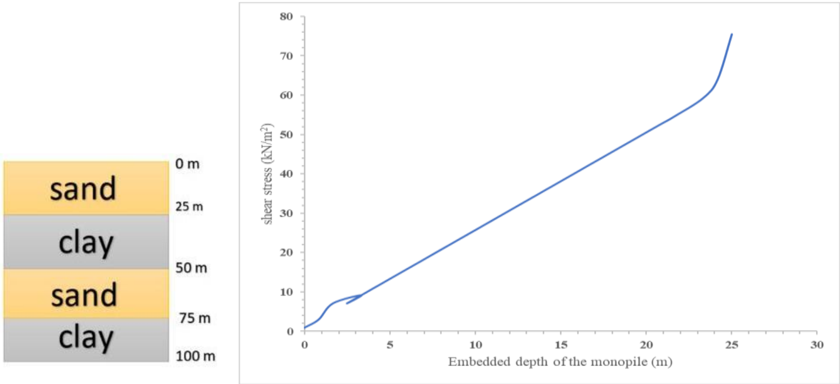

Fig. 7. (C)

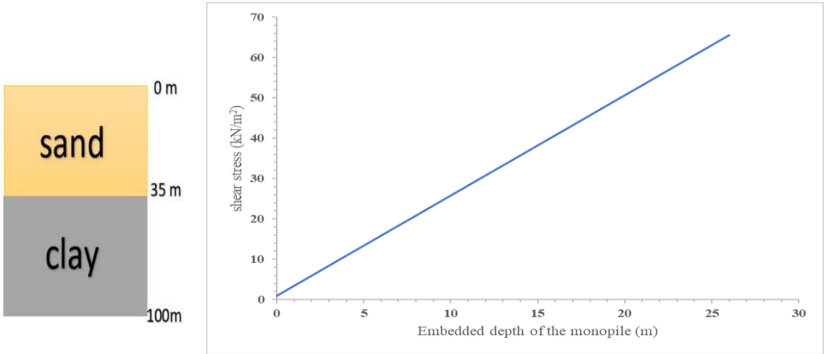

Fig. 7. (d)

Fig. 7. (a), (b), (c), (d) Shear stress Variation along the Embedded Depth of the Monopile

4 Experimental investigation

The precise result can be controlled by doing a field test on a prototype pile, but due to the restricted field test setup facilities and high costs, it is difficult to implement precise loading on a monopile with a large diameter. Because of these difficulties, which are also quite easy to arrange in the experimental setup. A Model pile placed in a soil profile that has been artificially prepared can undergo a scaled test.

Soil

The sand used in the model tests was extracted from the Cauvery Riverbed, Tiruchirappalli. The sieve analysis was done as per IS 2720-part 4 (1985). From the curve, the sand is found to be poorly graded sand (SP).

Test tank

A small-scale model monopile was used as the subject of laboratory experiments. In a rectangular steel tank, various tests on the small-scale monopile were conducted. The test tank is 1.5 meters in length, 1 meter in width, and 1 meter in height. The test tank's wall has a significant influence on the boundary effect in this model test. In order to prevent the bottom boundary effect in all tests, a minimum soil cushion at the bottom of the pile toe was maintained at 3 times the pile diameter. In order to reduce the possibility of friction between the sidewalls and sand, the tank was polished and smoothed.

Sand raining device

To execute the test in dry sand circumstances, the sand must be deposited at a specific density. The Pluviation technique can be used to achieve this. The uniform sand bed was created using the sand draining apparatus. To achieve consistent density, the sand was poured into the test tank through the sand raining equipment. To ensure proper sand dispersion, the sand was pluviated in layers, with the vertical pipe being straight. In numerous tests, the device's configuration was calibrated by adjusting the height of the fall in order to obtain a good, consistent soil density. With the aid of a reference steel rod, the height of the fall was kept constant by making sure that, during the pluviation process, the bottom tip of the reference rod only contacts the surface of the sand bed. The photographic image of sand filling in the necessary density is shown in Figure 8.

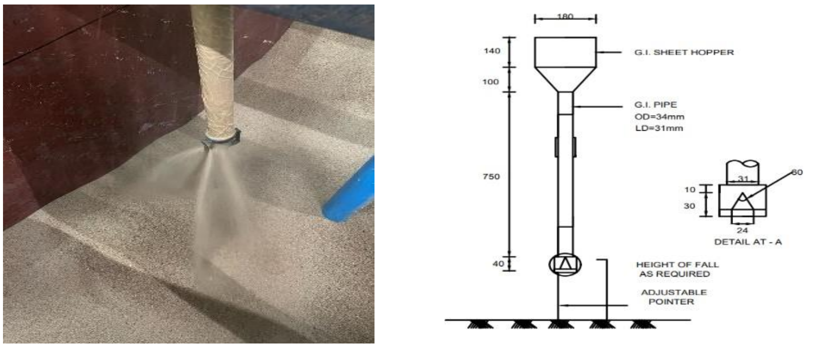

Fig. 8. Sand raining device

Begum and Muthukkumaran (2009) and Gandhi and Selvam (2010) varied the free fall height of the sand particles to generate various sand densities (1997). A relationship between the height of fall and relative density for various heights of fall was discovered. From that work, to keep the height of fall constant during the pluviation process, the device was risen in respect to the reference rod. For the relative densities of loose conditions (Id = 30%), medium dense conditions (Id = 50%), and dense conditions (Id = 70%), the height of fall was selected as 4.7 cm, 31 cm, and 72 cm.

Model pile

In this work, the behavior of a monopile was determined using a smooth aluminum model pile. An almost rigid pile was modelled using an open-ended aluminum pipe with a wall thickness of 2.5 mm and a diameter of 63.5 mm. The pile's embedded length was 533 mm and its overall length was 1000 mm. The pile was placed vertically on the sand bed in the Centre of the testing tank, and the sand cushion was created at the bottom for a depth of 3B. During the sand filling, the preinstalled model pile temporarily gets support from the field vane shear instrument. The layers of sand were filled in until the necessary embedment length was reached. In this experiment, the impact of driving a model monopile was disregarded.

Experimental program

A total of nine small-scale torsional load tests are performed to investigate and formulate the effect on piles. Nine tests are carried out on a model pile with an embedded length of 533 mm in the sand with varying relative density (30%,50%,70%). then field vane shear instrument was used for the torsional load application. The model pile of length 1m was placed at the required position in the tank. The vane shear apparatus and model pile were connected by the holder arrangement. The sand was poured into the tank to attain a required relative density of 30%,50%, and 70% with the help of the sand raining device developed on basis of the air pluviation technique. The torsional load was applied at the pile head using the field vane shear instrument. The experimental setup is shown in figure 9. The torsional deformation of soil was measured using a dial gauge attached to the field vane shear instrument. After the failure of the pile, it will rotate freely. The dial gauge readings are reduced because there is no resistance offered by the surrounding soil. The applied torque was calculated by using spring stiffness and angular movement.

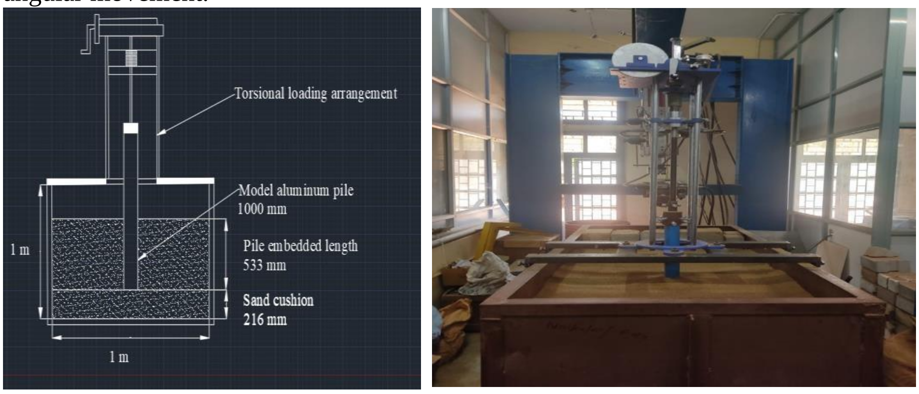

Fig. 9. Detailed Test Setup and photographic view of the Arrangement for Torsional Loading

Experimental results and validation Shear

strength calculation

Field vane shear equations were modified based on the pile and soil conditions. In the field vane shear, Total torque (T) is the summation of resisting torque at the sides(T_1) and resisting torque at the top and bottom(T_2). But here the pile is an open-ended hollow pile. so, there is no contribution in the bottom for resisting torque. Here the pile is not fully embedded in the soil.so the top of the pile also does not contribute to resisting torque.

The total torque (T) = resisting torque at the top and bottom(T_2)

- $T = T_2 = \int_0^{D/2} S * 2\pi r \, dr * r$ (1)
- From the integration, $T = \frac{\pi D^3 S}{12}$ (2)

The applied torque(T) and diameter of the pile(D) is known parameter. From that data, the shear strength was back-calculated.

- Shear strength, $S = \frac{12\,T}{\pi D^3}$ (3)

The experimental values were checked with the theoretical calculation.

- Theoretical torque = skin friction *perimeter *diameter/2 (4)

Skin friction = K σ tan δ

Perimeter = πdl,

K = earth pressure coefficient, σ = vertical stress, D = diameter of the pile, L = length of the pile.

Experimental calculation

The torsional deformation was calculated based on the dial gauge reading. The torque was calculated based on the stiffness of the spring attached to the field vane shear test apparatus and the angular movement. The shear strength was back-calculated by using equation (3). The calculated value tabulated in the below table,

Table 1. Shear Strength Calculation Based on the Experiment

Relative density (%)	Torque(kNm)	Shear strength(kN/m^2)
30	0.002739	40.8534
50	0.03423	51.067
70	0.00377	56.1734

Validation

To verify the accuracy of the model developed, comparisons of the FEM solutions are made with available theoretical (analytical) and experimental (laboratory model tests) results. The analysis carried out and the interpretations made are sequentially described herein.

Table 2. Shear Strength Calculation Based on the Theoretical Calculation and FEM

Relative density (%)	Shear strength(kN/m^2) as per theoretical calculation	Shear strength(kN/m^2) as per FEM
30	48.55	47.26
50	66.11	59.95
70	86.89	70.88

The theoretical torque was calculated based on equation (4). Theoretical shear strength was back-calculated by using the theoretical toque. From tables 1 and 2, shear strength calculated from the experimental and numerical calculation falls within the theoretically calculated shear strength.

5 Conclusions

Based on the present work, the following conclusion is drawn.

i. According to the load vs deformation curve, the total displacement decreases as the number of cycles increases. This is a result of the sand around the pile becoming denser.

ii. As the number of cycles increases, the monopile foundation experiences a larger reversal of accumulated displacement at relatively low load amplitude. The monopile was subjected to recoverable displacement with increasing cycles under serviceability and fatigue loading conditions after initial cycles of irrecoverable displacement.

iii. As loading cycles increased, the hysteresis loop's shape became flatter. It exhibits a reduction in loop area, which indicates that hardening behaviour is involved.

iv. As the number of load cycles increases, the stiffness of the cyclic secant increases gradually. This results from the decrease in inter-granular voids. Additionally, the higher stiffness and less displacement that result from the reduced load amplitude. This demonstrates how closely the load amplitude affects the lateral cyclic secant stiffness.

v. The sand surrounding the pile densifies as a result of repetitive loading, increasing the sand's shear modulus.

vi. The performance of the structure may be negatively impacted by an increase in the cyclic secant stiffness of the soil-pile system with an increasing number of load cycles. However, this behaviour increases the soil-pile system's natural frequency, which could result in the resonance phenomena.

vii. As the number of cycles increases, there will be a reduction in the void, which causes friction and increases the shear strength while reducing the rate of increasing displacement.

viii. The variation in shear stress is only caused by the application of static torsion, and it increases with regard to the monopile's embedded length whereas the distribution of the torsional load reduces as the depth of the monopile increases.

ix. The torsional load's magnitude reduced in relation to the depth of the OWT. because of the frictional resistance provided by the surrounding soil. Due to the impact of overburdening the soil, the frictional resistance provided by the soil increases with respect to depth. As a result, both the torsional load magnitude and the deformation it induced decreased, along with the monopile's depth.

x. The shear stress variation follows a linear pattern as the soil layer is changed. With respect to the monopile's depth, the shear stress was increasing linearly. The depth of the soil layer that contributes to shear resistance is the key factor influencing the variation.

xi. The variation of the shear stress is mainly based on the depth of the soil layer contributing to the shear resistance. The addition of the layer of coarse-grained soil(sand) with the fine-grained soil(clay) leads to an increase in the angle of friction and a decrease in cohesion.

xii. The shear-stress profiles for monopile in clay and sand indicate that the stress increases linearly to a peak value followed by a sharp curvilinear decrement. For layered soil, segmental variation of shear stress originated from the layering.

xiii. Torsional load on pile foundations is induced by the action of eccentric horizontal forces on the supporting structures. Such loading not only initiates a twist at the pile head. but also reduces its axial capacity significantly.

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