Centrifuge modelling of laterally loaded piles in silty sand

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ABSTRACT: Monopiles have been the preferred foundation solution for bottom-fixed offshore wind turbines in the past decades. Already at the early stages of implementation, the traditional API design methodology was found inadequate to capture the responses of large diameter piles to lateral loading. This triggered enormous research efforts, including the development of field tests and numerical modelling to introduce new design methods for lateral pile response embedded in sand or clay. Moreover, centrifuge testing has also been central in establishing a better understanding of the underlying mechanisms of soil-pile interaction for monotonic but also cyclic loading. In the present study, the response of rigid piles embedded in silty sand and subjected to lateral loads of high eccentricity is examined. A series of centrifuge tests were carried out for silty sands with different fine content. The reconstituted samples were prepared with the moist tamping method. For every sample, cone penetration tests with pore pressure measurements (CPTU) and laterally loaded pile tests were performed. Hereafter, a correlation between the lateral response of the pile and CPTU measurements is investigated. The homogeneity of the samples and the repeatability of the results are examined. It is shown that both stiffness and ultimate lateral soil resistance of experimentally derived p-y curves are well correlated with the measured cone tip resistance.

1 INTRODUCTION

Monopiles have been the most commonly used foundation type for fixed-base offshore wind turbines over the past few decades, accounting for approximately 80% of the installed capacity and remaining the preferred solution for shallow waters. Their performance is dominated by the experienced lateral loads, and it was early recognised that the well-established p-y method, recommended by the American Petroleum Institute (API, 2000), would be marginally applicable, as it is based on field experiments carried out in slender piles. Enormous research efforts were placed on highlighting the limitations of the p-y method by conducting experiments in the geotechnical centrifuge (e.g. Choo and Kim, 2015; Klinkvort and Hededal, 2013; Klinkvort et al., 2016; Jeanjean et al., 2017), performing numerical analyses (e.g. Sørensen et al., 2010; Wang et al., 2020) and interpreting field observations (Kallehave et al.,2015). A highlight of this quest has been the PISA project, where extensive field testing and numerical modelling were performed (Byrne et al., 2020a, 2020b; Taborda et al., 2019; Zdravkovic et al., 2019b). Meanwhile, a new design model, the so-called PISA design model (Byrne et al., 2020c), has been proposed based on fundamental observations to narrow the knowledge gap regarding the response of short rigid piles under monotonic lateral loading.

Furthermore, centrifuge testing has been extensively employed to investigate various aspects of monopile behaviour that are quite cumbersome to realize in field testing. The ongoing research efforts have been investigating, among others, the effects of embedding depth and eccentricity (Zania et al., 2015; Maatouk et al., 2022a), pile installation (Fan et al., 2021; Maatouk et al., 2022b), and vertical load (Li et al., 2022). The majority of the studies have been on piles embedded in sand. The pile response in intermediate soils has, to the authors' knowledge, received no attention so far. Few studies have performed cone penetration tests in clayey sands, silts, and silt-clay mixtures (Suzuki, 2014, Price et al., 2019, Zania et al., 2020). The authors have used either the slurry deposition method or the undercompaction method. The rate dependency to the cone resistance in clayey sands was also investigated and it was found that the transition from undrained to partially drained occurred at a velocity of 10mm/s while from drained to partially drained at a velocity of 0.1mm/s.

In the present study, the response of rigid piles embedded in silty sand and subjected to lateral loads of high eccentricity is examined by centrifuge testing. Hereafter, a correlation between the response of the pile and CPTU measurements is investigated. To do so, reconstituted silty sand samples have been prepared at different fine contents and cone penetration tests with pore pressure measurements (CPTU) and pile testing were performed at the centrifuge facilities of the Technical University of Denmark.

2 METHODOLOGY

The moist tamping method with under compaction was used for the sample preparation as previous research projects have demonstrated satisfactory homogeneity of the sample (Zania et al., 2020). Initially, a Leighton buzzard sand layer was placed at the bottom of the strongbox with a thickness of 6.2cm, followed by the positioning of a geotextile on the top of the sand layer to ensure free and uniform water flow during saturation. The soil samples were prepared in 4 equivalent layers, each consisting of a mixture of Fontainebleau sand and silica powder, with fine contents of 2% and 84% (nonplastic fines), respectively. The materials were initially mixed in a dry condition and then with water until a homogeneous mixture was achieved. Eventually, each layer was compacted by placing a circular steel plate on the soil surface and using a proctor hammer, with a mass of the hammer equal to 2.5kg and a fall height of 30cm. After the compaction of each layer, the layer surface was scarified with a screwdriver to ensure continuity between the layers. The samples were saturated by inducing a hydraulic gradient below the critical value via a controlled, deaired water supply at the bottom of the strongbox. The duration of the saturation phase varied from a few hours to a day, depending on the fine content of the sample. A water level of 1-1.5cm was maintained above the soil surface throughout the centrifuge testing, to avoid water evaporation during the spinning.

A total of four centrifuge monotonic tests have been performed. The prepared silty sand samples had fine content of 20%, 30%, 40%, and 50%. The properties of the silty sand samples prepared at centrifuge facilities are presented in Table 1. For all the tests the void ratio was found to vary in the range of 0.62-0.81 and the bulk unit weight in the range of 19.5-19.9 [kN/m^3].

Cylindrical soil samples were retrieved after the completion of the centrifuge tests for sieve analysis and triaxial testing. Particle size distribution curves and fine content were estimated according to both ISO 17892-4 (2016) and ASTM D2487 (2011) and the results indicate that the soil samples were homogeneous (Table 1). It should be highlighted that a change in the thickness of the samples in the range of 5 – 10 mm was captured after the completion of the test increasing with the fine content. The consolidation was not monitored during the tests; therefore, it was assumed that this occurred until the centrifuge reached the targeted g-level and not during the test.

Table 1. Properties of the samples prepared for the centrifuge testing.

Properties	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
Saturated unit weight, γ (kN/m^3)	19.9	19.5	18.6	19.8
Void ratio, e_o (-)	0.63	0.63	0.81	0.62
Fine content (ISO 17892-4)	18.3	28.1	39.8	49.9
Fine content (ASTM D2487)	19.4	28.7	39.8	50.1
Layer thickness (mm)	165	172	197	205

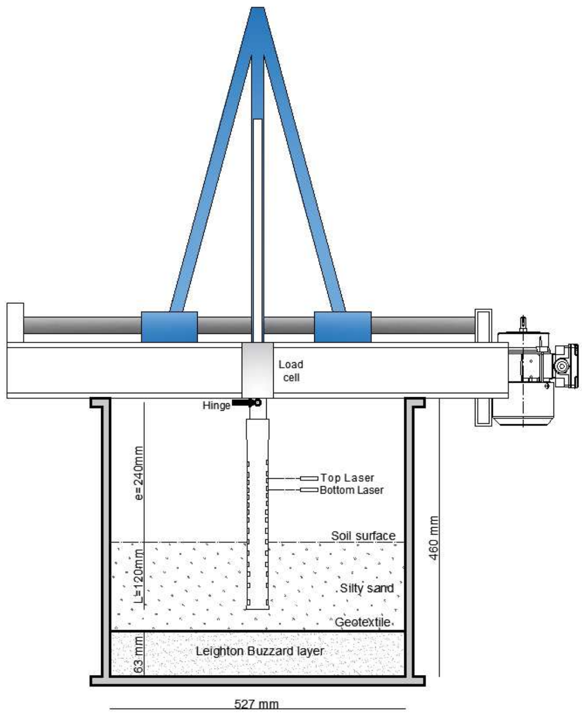

Figure 1. Experimental setup in the geotechnical centrifuge at DTU.

After the positioning of the soil sample, the centrifuge was accelerated gradually until the rotational speed achieved an equivalent acceleration of 50g. Initially, in-flight CPTU was performed by using a mini penetrometer of a diameter (d) of 11.3mm and a net area ratio (α) of 0.55. The cone penetration test was conducted at a distance greater than 150mm from the strongbox boundaries and 60mm from the location where the pile would be installed. The cone penetration depth varies from 120 to 140 mm to avoid boundary effects introduced by proximity to the geotextile. Afterwards, the spinning was halted, and the pile was mounted into the load frame. The test procedure consisted of two phases: first, the pile was driven into the silty sand in flight, and then the lateral load test was carried out by controlling deformation at the pile head. Like for the CPTUs, the centrifuge accelerated until 50g, then the pile was driven inflight until an embedment length of 120mm. The pile used for the laterally loaded pile tests was a hollow aluminium pile of outer diameter of 40mm and wall thickness of 1.5mm, bending stiffness (EI) equal to 2.06kNm^2. It was instrumented by 15 pairs of strain gauges, which were covered by an epoxy layer of 1mm thickness. An illustration of the test configuration with the corresponding attached instrumentation is shown in Figure 1.

A 5th order polynomial fitting was carried out so as to obtain the bending moment curve along the pile length. Hereafter, shear force and soil resistance were estimated by differentiating the bending moment distribution and setting the soil resistance equal to zero at the soil surface. The determination of the p-y curves requires the estimation of the pile deflection. To do so, the rotation and deflection along the pile were obtained by the integration of the polynomial functions defined based on the moment measurements. The integration of the bending moment curve requires boundary conditions; the rotation and the displacement at the soil surface were predicted and used as boundary conditions, based on the three available displacement measurements, one provided by an LVDT transducer, measuring the displacement at the head of the pile during the test and two by lasers, located at a measured distance from the soil surface. The boundary conditions were initially estimated under the assumption that the pile behaviour is rigid, allowing rotation and displacement to be easily determined. Hereafter, Castigliano's method was applied to account for the pile's bending stiffness. The results from both methods are in good agreement; therefore, the predicted boundary conditions can be considered highly accurate.

The lateral force applied to the head of the pile is evaluated by the moment distribution above the soil surface (available through the 9 pairs of strain gauges positioned above the soil surface), which should be in linear relationship with depth. A linear fitting of moment data above soil surface is carried out and the lateral force is determined by the derivation of the linear fitting moment curve.

3 RESULTS

The tip resistance for the four samples is illustrated in Figure 2, and for the samples of higher fine content, the distribution with depth indicates that the samples are homogeneous since no variations were recorded. The tip resistance of the sample with the lowest fine content increased with depth, except for a change in slope at a penetration depth of 120mm. It should be stressed that the fine content does not affect the tip resistance measurements in a particular way.

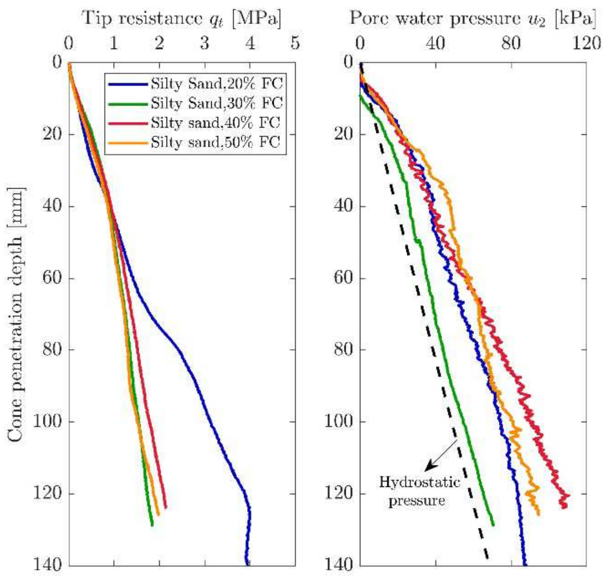

Figure 2. Tip resistance (left) and pore pressure (right) distributions from CPTU tests at 50g.

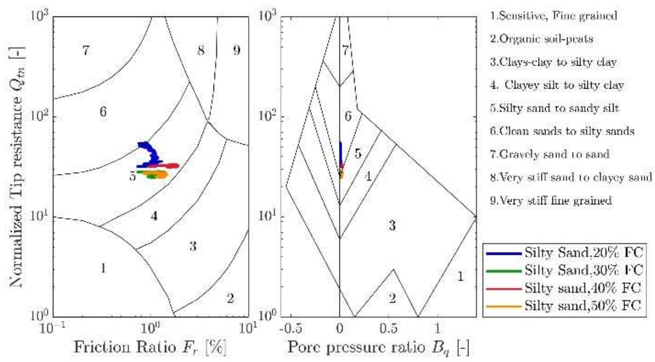

Figure 3. Normalised tip resistance with respect to friction ratio (left) and Normalised tip resistance with respect to pore pressure ratio (right) for the silty sand samples of

varying fine content, 20-50%. Classification scheme with soil behavior type zones based on Robertson 2009.

Pore water pressure measurements measured during the CPTUs with depth are compared with the hydrostatic pressure distribution and illustrated in Figure 2. It can be seen that small excess pore pressure were measured during all tests, with the CPTu carried out at silty sand sample of 30% FC to show a drained behaviour. The results from the CPTUs are assessed according to soil classification, and for this purpose, the soil classification scheme proposed by Robertson (2009) is used. The results are shown in Figure 3, and they lie within Zone 5, which corresponds to Silty sand to sandy silt, in agreement with the sample composition.

Figure 4 illustrates the pile installation force for all experiments as a function of penetration depth. This indicates that the soil samples are homogeneous, as no variations or contrasts are observed across the layer. It is hardly noticed that any effect of the fine content on the installation forces at the shallow penetration, while beyond that point, installation forces increase with depth. It is essential to highlight that a change in the slope was captured during all the tests at a penetration depth ranging from 60 to 75 [mm], indicating soil plugging, which is in agreement with what was observed after the completion of the test through visual inspection of the top of the soil column at the inner part of the pile.

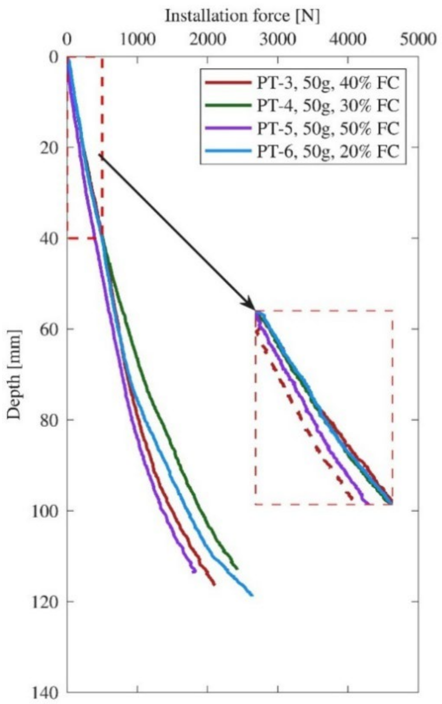

Figure 4. Installation forces with respect to the depth of penetration for the silty sand samples with varying fine content.

The bending moment distributions along the pile for three load conditions (P=30 N, 60 N and Pult) are illustrated in Figure 5. The maximum bending moment for all the experiments occurred at a depth equal to 40 [mm] (1D), while the bending moment is not zero at the tip of the pile, which may be related to the response of the last strain gauge of the pile. The recording at the pile tip may be related to the base-moment resistance as depicted in the PISA model. However, this should be confirmed with more refined measurements around the pile tip.

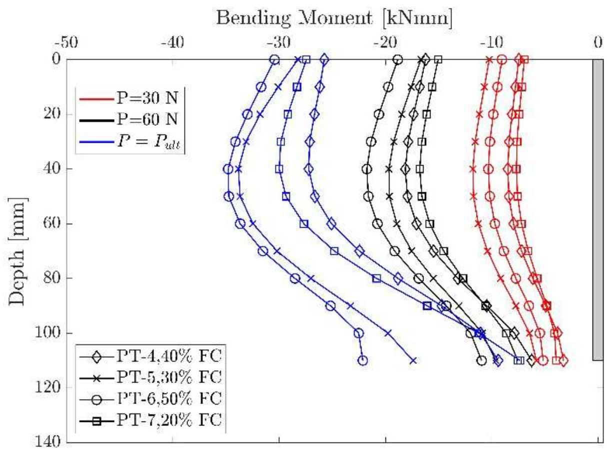

Figure 5. Bending moment versus depth for three different load conditions (P=30 N, P=60 N and P=P_{ult}).

The normalized load deflection curves at the soil surface are illustrated in Figure 6. The capacity curves indicate that the ultimate capacity is reached at a deflection equal to 5% of the pile diameters at the soil surface. Moreover, the increasing fine content has a consistent effect on the soil-pile stiffness and the ultimate load. Both the ultimate lateral load and the stiffness of the capacity curve are observed to decrease at higher fine content. The former is further illustrated in Figure 7, where the normalised ultimate load obtained from the capacity curves is plotted with respect to the fine content. A linear trend is obtained with a high coefficient of determination.

This trend indicates that the soil strength decreases for silty sand samples with higher fine content. The pile installation forces didn't show a clear linear relationship with the fine content, particularly due to the results of the sample with 30% FC. This may be related to phenomena such as soil plugging and the magnitude of excess pore pressure developed during pile driving. Note that the 30% FC sample didn't display excess pore pressures in the CPTU (Figure 2).

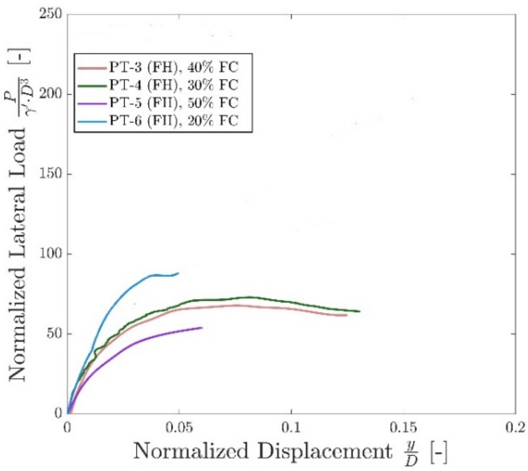

Figure 6. Normalized lateral load with respect to the normalized displacement measured at soil surface.

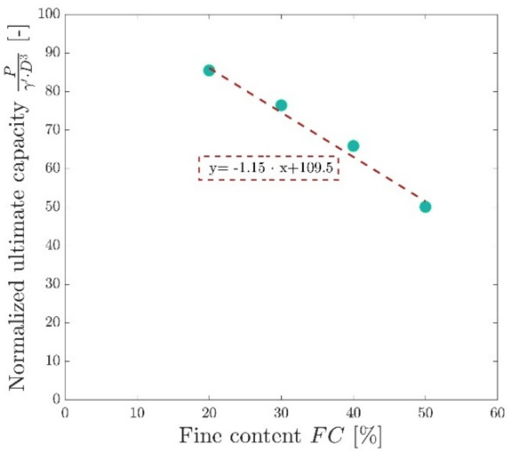

Figure 7. Normalized ultimate lateral load with respect to the fine content.

The pressure distribution with depth was estimated, and the maximum soil resistance for all tests occurred at approximately 60 mm (1.5D). The pile shows a whole rotation but remains straight which is an indication of a rigid pile behaviour. It should be noticed that the pressure centre depth is relatively close to the rotation centre, which ensures precision and quality of the fitting operation. The rotation point is located at a distance of 0.64-0.72 D from the pile tip for all the free headed pile tests.

The p-y curves from the four centrifuge tests were calculated at different depths. Figure 8 presents the soil pressure with respect to the lateral pile deflection at two reference depths 0.75D and 1.25D. The mobilised soil resistance and the stiffness of the soil-pile interaction increases with depth as expected. Moreover a consistent effect of the fine content is observed for both sets of p-y curves. The ultimate lateral soil resistance decreases with increasing fine content. Similarly, the p-y modulus also decreases with increasing fine content.

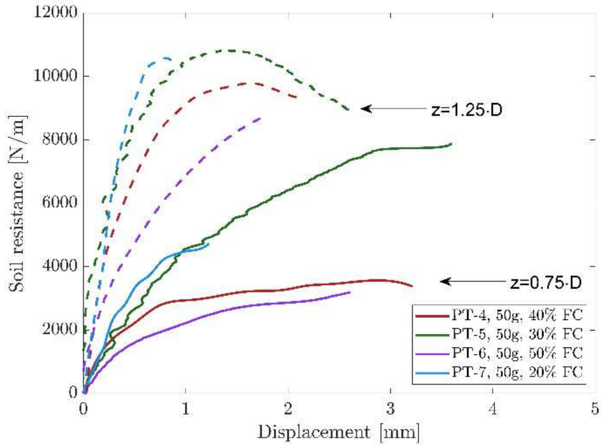

Figure 8. Experimentally established p-y curves at depth equal to 0.75D and 1.25D for the silty sand samples with varying fine content from 20-50%.

4 CONCLUSIONS

This study presents a series of centrifuge tests of laterally loaded piles embedded in silty sand. The results demonstrate a clear and consistent effect of the fine content on the pile response. The ultimate lateral pile capacity was found linearly related to the fine content. The effect of the fine content was further demonstrated by the estimated p-y curves. The increasing fine content is shown to result in a decrease of the ultimate lateral resistance and the corresponding modulus of subgrade reaction.

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