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Bearing capacity of monotonically installed tapered piles in medium-dense Fontainebleau sand

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ABSTRACT: A series of installation of tapered piles in medium-dense Fontainebleau sand were performed in the geotechnical centrifuge at Gustave Eiffel University. The models of piles with three different shapes - straight profile (S), and with taper angle of 0.70 degrees (T1), and 1.4 degrees (T2) were used. The piles were instrumented with fiber optic wires on the shaft and load cell at the base. After monotonic installation, the models were subjected to static load tests in compression and then in tension. The lowest head load at the end of installation was found for the T2 pile. While the average shaft friction mobilized during penetration of the S pile was almost constant, a considerable increase of friction resistance during installation was observed for T1 and T2 piles. At the end of the installation, the maximum average shaft friction was about 4.5 and 7 times higher as compared to the straight pile for the T1 and T2 models, respectively. These values slightly increase during the static compression test. The ratio of the maximum average shaft friction in tension and compression is close to 1 for the cylindrical pile and decreases to about 0.5 and 0.2 for T1 and T2, respectively.

1 INTRODUCTION

The bearing capacity of piles is an essential component in various infrastructures like buildings, bridges, and offshore platforms, and has been a crucial topic in numerous studies in the field of geotechnical engineering. These studies have explored diverse factors that influence pile behavior including the pile shape, type of soil, and the method of installation.

Pile shape has been identified as a significant factor influencing the bearing capacity, and tapered piles, characterized by a gradual change in cross-sectional area along their length, have emerged as a promising alternative to traditional cylindrical piles. Various studies, including those by Ghazavi and Kalantari (2008), Lee et al. (2009), Manandhar and Yasufuku (2013), Paik et al. (2011), Shabanpour and Ghazavi (2022), and Wei and El Naggar (1998), have consistently highlighted that the tapered shape enhances shaft friction, leading to increased axial capacity of piles. Research by Manandhar et al. (2009) and Manandhar and Yasufuku (2013) in small calibration chamber demonstrated that even a slight increase in the tapering angle significantly boosts skin friction and end-bearing resistance compared to conventional straight piles in various sands and relative densities. Investigations by El Naggar and Sakr (2000) and Suits et al. (2003) using a geotechnical centrifuge explored the behavior of tapered piles driven into sand. Additional studies by El Naggar and Wei (1999), Paik et al. (2013), and Suits et al. (2011) confirmed higher bearing capacity of tapered piles under specific soil conditions. Singh and Patra (2020) observed that the load-carrying capacity increases 1.08 to 1.21 times for taper angles of 1 to 2 degrees. Khan et al. (2008) demonstrated that drilled concrete tapered piles exhibited up to 50% higher load carrying capacity compared to straight-sided piles of equal volume.

Despite their advantages, tapered piles have received limited attention in civil engineering, primarily due to a lack of design procedures that consider their behavior during the installation and loading. In the previous studies the non-displacement tapered piles were considered in calibration chamber tests (Paik et al. 2013). The displacement tapered piles were also analyzed in centrifuge tests as demonstrated in studies by Suits et al. (2003), El Naggar and Sakr (2000), Sakr and El Naggar (2003), and Shabanpour and Ghazavi (2022). They were however installed in

1g conditions, which does not permit the correct physical modelling of stress state and stress/strain changes during the penetration and static loading of such models. This study aims to fill this gap by investigating and enhancing our understanding of the behavior of tapered piles throughout in-flight installation process with monotonic pushing and under axial static loading in both compression and tension modes.

2 METHODOLOGY

A series of centrifuge tests of tapered piles in medium-dense Fontainebleau sand were performed in the geotechnical centrifuge at Gustave Eiffel University (Nantes, France) in the GERS-CG lab (Gers-CG, 2023) within the Geolab (2021) European project. The geo-centrifuge (Thorel, 2022) has a radius of 5.5m and a total mass of 2 tons can be embarked in the swinging basket.

2.1 Model piles

The models of piles with three different shapes- straight profile (S), 0.70 degrees (T1), and 1.4 degrees (T2) of taper angle and having almost the same volume at the embedment of 224mm were prepared (Figure 1). The constant-diameter pile of 16mm was set with an embedment length of 224 mm and slenderness ratio of L/D=14. The piles were instrumented with three optic fibers having five Bragg gratings along the shaft and with axial load sensors at the top and base. The base load cell and fiber optic strain sensors were calibrated before the tests execution (Figure 2a).

2.2 Experimental setup

The strong box container with dimensions 1200 × 800 × 670 mm was filled with Fontainebleau NE 34 sand characterized by the parameters shown in Table 1. Sand-raining technique was used to prepare homogeneous soil mass with relative density of 0.56. Before the test the model was placed in the loading frame in such a way that the pile base was close to the soil surface (Figure 2b). The 3 piles have been tested in the same strong box in the locations separated from each other and the strong box boundary of at least 8 diameters. Each pile is considered as an isolated one.

Table 1. Fontainebleau sand (NE34) parameters (Andria-Ntoanina et al., 2010; Beroya-Eitner et al., 2022).

	Property	Value	Units
Specific gravity	G_s	2.65	-
Dry density	γ_d	15.52	kN/m^3
Relative density	D_r	0.56	-
Void ratio	e_0	0.674	-
Minimum void ratio	e_{min}	0.510	-
Maximum void ratio	e_{max}	0.882	-

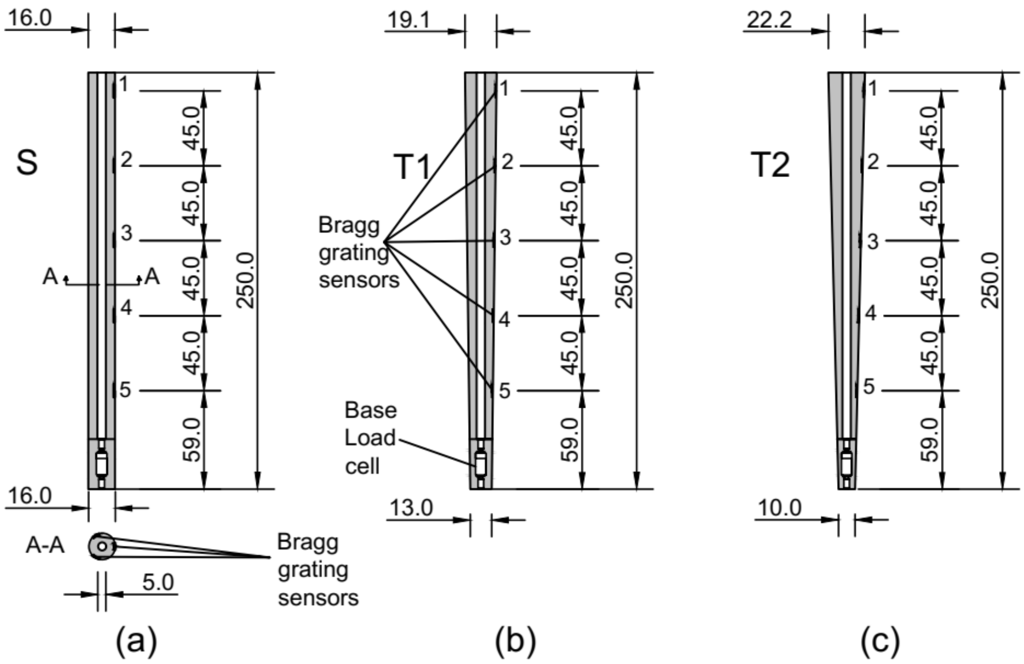

Figure 1. Pile models: (a) Straight pile, S (α=0˚), (b) Tapered pile, T1 (α=0.70˚), and (c) Tapered pile, T2 (α=1.4˚). All dimensions are in mm

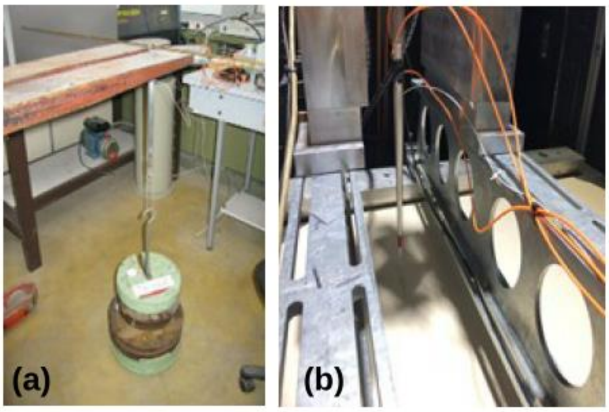

Figure 2. (a) Pile calibration, and b) experimental setup.

2.3 Test procedures

The piles were monotonically installed in the subsoil and then subjected to static axial load tests in compression followed by tension. The centrifuge operated at an acceleration level of 25g. Data acquisition of pile head load, base load, and deformations distribution along the optic wires on the shaft was conducted at 0.01-second intervals.

In each test, the pile was continuously pushed into the sand at a controlled rate of 0.1mm/s until it reached a depth of 224mm. After unloading, a static compression loading equivalent to the pile diameter of 16mm was applied. The pile head was then unloaded to zero before final tension test.

3 EXPERIMENTAL RESULTS

3.1 Load-settlement curves

Load-settlement curves of piles are shown in Figure 3. It was found that the installation of tapered piles requires lower force during penetration (Figure 3a). However, at the end of penetration the head load becomes similar for all models. The head load at the end of penetration for the pile T1 exceeds that corresponding to the straight pile S, while it remains the lowest for T2. During static loading tests, the tapered pile (T1) consistently exhibited higher load resistance compared to the cylindrical one (Figure 3b). Such behavior may suggest the existence of an optimal taper angle corresponding to the maximal pile bearing capacity, as it results from the tests performed by Ghazavi and Kalantari (2008) and Lee et al. (2009). More experiments are, however, necessary to confirm this finding. It was also found that the maximum tension load constitutes only about 0.15-0.2 of the corresponding force in compression (Figure 3b). The installation effort for tapered piles (Figure 4) is significantly lower than for the cylindrical one. The difference reaches about 7% for T1 and even 30% for T2.

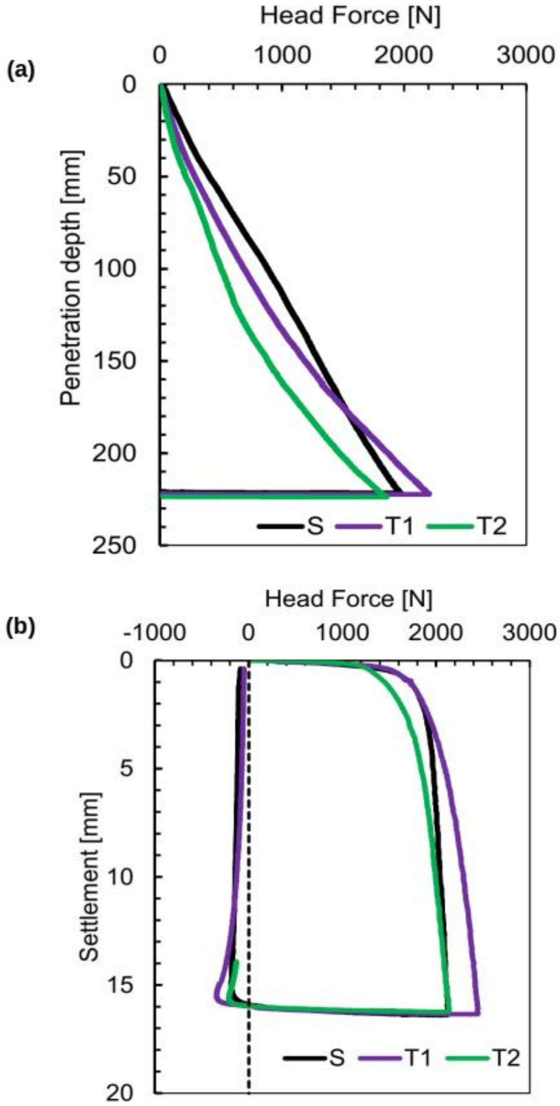

Figure 3. Head load – settlement curves during (a) installation, and (b) static load test (model scale).

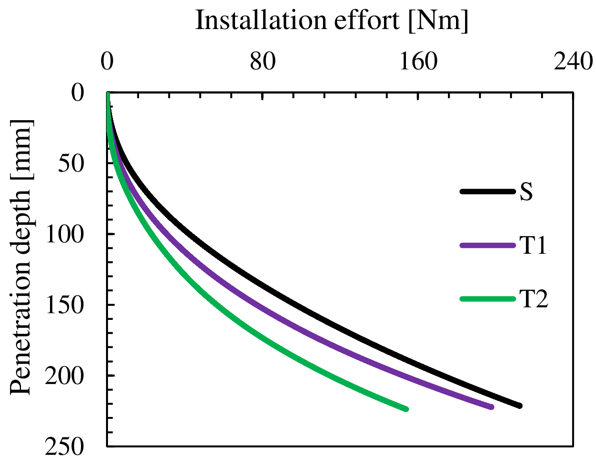

Figure 4. Installation effort during pile installation.

3.2 Base Resistance

Due to considerably smaller base area of tapered piles the load transmitted by their base is significantly lower than for the cylindrical one during the installation and static loading (Figure 5). The lowest base load was found for the T2 pile. During the penetration phase the unit base resistance of tapered piles (Figure 6) is getting higher than that corresponding to the cylindrical one. This tendency is confirmed in static loading being in agreement with the works of Lee et al. (2009) and Suits et al. (2011) which show that in calibration chamber tests the ultimate unit base resistance of non-displacement piles in medium dense sand increases with taper angle. One should notice that the stress state in the vicinity of tapered pile base during the penetration is quite different as compared to the cylindrical one. Additional vertical stress component is imposed above the pile base level due to insertion of tapered shape model. Another factor is the inclination of friction force on the tapered pile shaft. The larger unit base resistance of tapered piles in static loading can be also explained by higher relative penetration of the base of tapered piles compared to the cylindrical one (Lee et al., 2009).

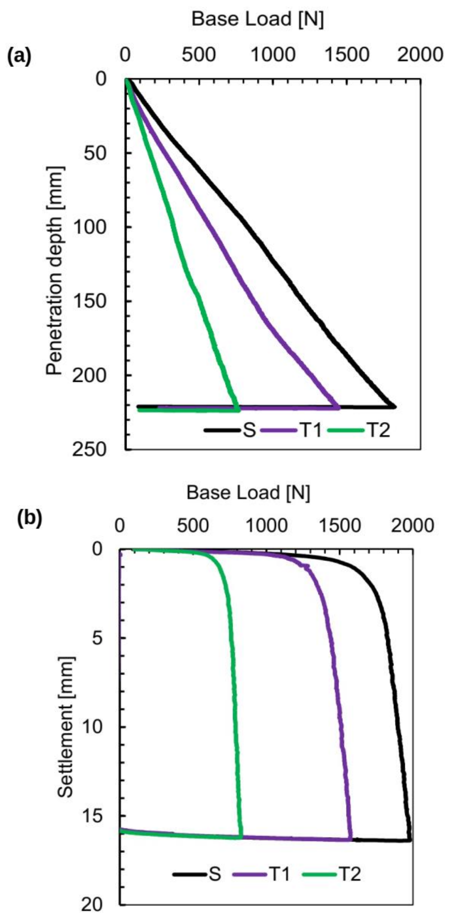

Figure 5. Base load – settlement curves during (a) installation, and (b) static load test (model scale).

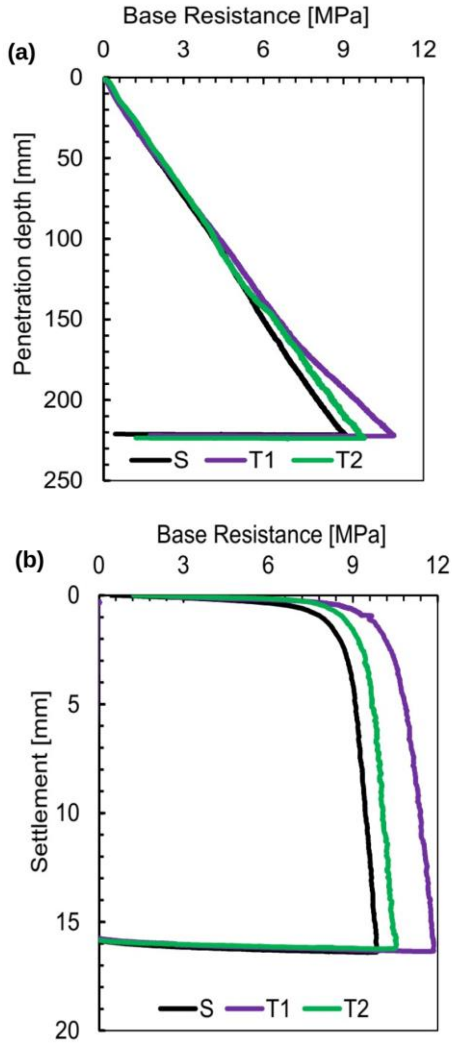

Figure 6. Unit base resistance during (a) installation, and (b) static load test.

3.3 Shaft resistance

The average friction force along piles during installation and static load testing is given in Figures 7a and 7b. While almost linear grow of friction force during the penetration of the cylindrical pile is observed this evolution is clearly non-linear in case of tapered ones. During installation process and compression static loading the friction force is considerably smaller for tapered than for cylindrical piles.

The average shaft friction was calculated with readings of the force at the head and the pile toe. While the average shaft friction mobilized during penetration of the S pile (Figure 7c) is almost constant, a continuous increase of this friction is observed for tapered models. At the end of penetration the shaft resistance of tapered piles is even about 4.5 and 7 times higher as compared to the standard one for T1 and T2, respectively. The same tendency is confirmed in static loading (Figure 7d). Different schemes of shaft friction mobilization in case of tapered piles and the cylindrical one could be explained by the evolution of the horizontal stress in the vicinity of the pile shaft during penetration, which should be qualitatively very similar to the observation of the horizontal stress changes in the vicinity of monotonically installed tapered walls in centrifuge (Bałachowski et al. 2024). Once the wall base has moved below the position of the stress cells, a continuous decrease of the horizontal stress at a given altitude was observed for the straight wall model. In contrast, for tapered walls the stress cells in the soil mass exhibit further slight re-mobilization of horizontal stress, especially for the model with higher taper angle. As a result a considerable increase of the horizontal stress near the plane-strain tapered walls is noticed at the final stage of penetration. One can expect similar phenomena in case of tapered piles. Additionally, in case of pushed-in small diameter cylindrical pile the arching phenomena could appear and hamper the proper transmission of the normal stress to the pile shaft.

While, a similar maximum average shaft resistance in tension and compression during static loading was found for the cylindrical pile these values were very different in case of tapered models (Figure 7d). The maximum average shaft friction in tension constitutes only about 50% and 20% of the corresponding value in compression for T1 and T2, respectively. Thus the ratio of tension to compression shaft friction highly reduces with taper angle. Moreover, a distinct peak value of shaft friction was observed for tapered piles at the beginning of tension test, as it was also recorded by Shabanpour and Ghazavi (2022) in centrifuge tests.

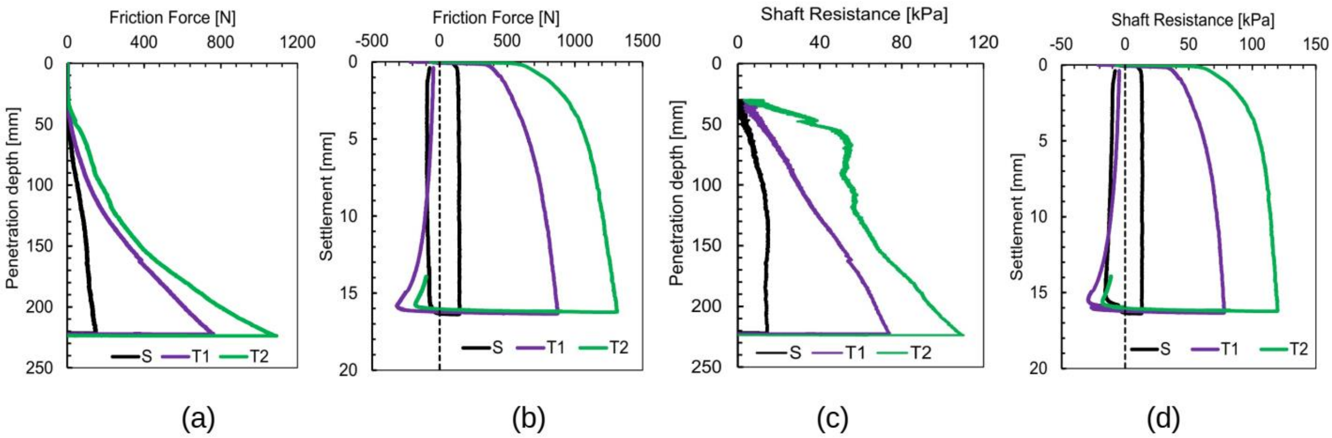

Figure 7. Friction force during (a) installation,(b) static loading test, and unit shaft resistance during (c) installation and (d) static loading test.

4 CONCLUSIONS

The bearing capacity of monotonically installed tapered piles within medium-dense Fontainebleau sand was evaluated. Three distinct pile models - straight profile (S), 0.70-degree taper angle (T1), and 1.4-degree taper angle (T2) were installed in-flight at 25g in the geotechnical centrifuge at Gustave Eiffel University. During the model penetration the installation effort is generally lower for tapered than for cylindrical piles. The difference grows with taper angle. While quite similar bearing capacity in compression was obtained for all models the tension capacity was slightly higher in case of tapered piles. The unit shaft friction during the penetration of the cylindrical pile was almost constant A considerable increase of this parameter was, however, noticed for the tapered models. It means that the monotonically installed tapered piles can be efficient only at higher penetration depth. The tests confirmed the high contribution of shaft resistance to overall capacity of tapered piles. As the friction force at the end of penetration constitutes only about 8% of total load in case of cylindrical pile, it makes up to 35% and 58% for T1 and T2, respectively. The same value of unit shaft friction in compression and tension is measured for the cylindrical pile. In contrast, the ratio of shaft friction in tension and compression considerably decreases with taper angle.

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