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Effect of Installation Techniques on the Allowable Bearing Capacity of Modeled Circular Piles in Layered Soil

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***Abstract*—The results of a comprehensive study on the effect of installation techniques on the allowable bearing capacity of modeled circular piles in layered sandy clay soil are presented. These results show the influence of driving by hammering and drop weights as well as boring techniques on load carrying capacity of modeled wooden piles driven or bored through layers of inter-bedded sandy clay soil. The investigation was carried out to study the influence of both driving and boring techniques on 20 mm diameter and 200 mm long modeled circular piles, driven/bored through specially conditioned layered sandy clay soil in a specially designed multi-purpose testing device in the laboratory. The piles were subjected to axial compressive load on incremental basis till failure. Modeled reinforced concrete instrumental test piles of diameters 200mm, 250mm, and 300mm were driven and bored through layered soil at a construction site. The effect of driving and boring on the pile-soil interaction and behavior as well as bearing capacity of these piles were also studied. Under similar conditions, driven piles have lower bearing capacity than identical bored piles. In addition, the overall settlement of bored piles is lesser than the corresponding driven piles, but the latter recorded a lesser settlement at lower depth beneath the pile cap than the former. In all, driven piles recorded less bearing capacity than the corresponding bored piles by approximately 12 - 18 % but are more easily handled and effective especially in a more cohesive soils**

***Index Terms*—Bearing capacity, Circular piles, Installation techniques, Normally consolidated clay.**

I. Introduction

In principle, the ultimate capacity of a pile is the load at which the load-displacement curve shows a sharp plunge, and beyond which the pile undergoes dramatic settlement. Practically speaking, however, the allowable capacity of a pile as determined from a full-scale field test is that load Q at which the settlement S equals or exceeds the allowable settlement for the desired application [1]. The ultimate load which a foundation can support may be calculated using bearing capacity theory. Estimation of the axial capacity of piles driven into sand involves considerable uncertainties, and design rules are generally not consistent with the physical processes involved [2] and [3]. Estimating the bearing capacity of a pile, usually considered as the resistance offered by the pile shaft plus the one offered by the base is an important consideration in pile design and Geotechnical engineering [4].

The bearing capacity of a pile depends on the soil properties and the stress state it is surrounded with. This is because the behavior of granular material is governed by the packing of the grains and the contact stresses in between. The mean stress and the density can be described as the soil state, and the soil behavior is determined on the basis of this state and the loading conditions [5].

However, in case of displacement piles, the installation process causes a considerable amount of soil displacement and high levels of (reaction) stresses. These effects of pile installation are transmitted to soil through the interaction between sand grains and the pile, resulting in an altered soil state and properties. The parameters that affect pile behavior have been conveniently divided into four categories: (i) Soil characteristics; (ii) pile characteristics; (iii) method of pile installation; and (iv) type of loading [6].

Several attempts have been made to investigate the change in the soil state in domains around the piles. However, the behavior of piles during installation, the interaction with the surrounding soil and the resulting alteration of soil properties during installation are still being investigated till date. Varied opinions with contradictory conclusions have been postulated by many researchers on this subject. In a highly porous layered soil with collapsibility properties diminishing with depth, from 2-3% to 1 - 1.5%, the unit bearing capacity of bored piles reduces 2-3 times on the average, while driven piles reduces to only 30%. They went further to reveal that the unit bearing capacity of bored piles is 1.5 - 2 times less than that of driven piles of identical properties under the same conditions [7].

For piles in stiff fissured clay, an empirical reduction factor of the undrained shear strength has been established to decrease with greater pile base diameter and is greater for driven than for bored piles. The ultimate unit skin friction of piles in a given sand or clay is practically independent of the pile diameter [8] and [9]. A circumferential arching mechanism develops during pile driving in marine sand, which produces creep resulting in an increase in radial stress leading to a gain in shaft capacity [10]. When a pile is driven into soil, it initially displaces a volume of soil equal to its volume, with eaves of up to 5 times the pile diameter occurring with a small penetration [11]. The outward radial displacement of soil at greater depth has made pile installation process to be modeled as expansion of cylindrical cavity with the final resonance radius i.e. radius of the displacement bulb equal to that of the pile [12] - [15]. The shear stress distribution in the soil around a vertically loaded pile may be deduced by considering vertical equilibrium, in which the shear stress decreases inversely with the radius from the pile center- line. The decrease is less rapid in driven piles than in bored ones [16] - [19].

Modeled circular piles were tested in a layered soil consolidated in a multi-purpose device in the Post graduate research laboratory, Geotechnical and Environmental Engineering Department, Belorussian National Technical University, Minsk, Belarus. The field test was carried out with 300mm diameter circular piles on a site around Mogilev Train station, an area on the outskirt of Minsk, Belarus. The information from the study which was focused on the influence of installation techniques of driving and boring on pile capacity, is therefore essential, not only to make accurate or near accurate prediction of the pile bearing capacity under different loading conditions, but also to be able to make better judgment on the effects of pile installation process/techniques on the overall performance of the piles and the structure for which it was designed.

II. EXPERIMENTAL INVESTIGATIONS

Since the driving and boring operations can be considered as quasi-static loading, with little lateral movement compare to the vertical, the dynamic effects are not considered in the analyses. For the same reason, drained conditions are assumed such that the pore pressures are only taken into account as a reduction of total stress (giving the effective stresses) [5] and [20].

The location of the field test for this study was a site being prepared for the Multi-purpose Business Centre with Underground Parking, near Mogilev Train station, an outskirt of Minsk Province, Belarus. The tests were conducted between November 2012 and May, 2013.

In this study, the installation effects are taken into account by some empirical design methods in order to estimate the bearing capacity of foundation piles similar to the one explained by [1] and [20].

The Reaction Beam Load Test method of Static Pile Load Test (SPLT), which involved direct measurement of pile head/cap displacement as well as that of the soils around the piles and beneath the piles cap was adopted for the field tests carried out.

Static loads were applied and maintained using a hydraulic jack (of 200T capacity) and were measured with a load cell as shown in Fig. 1. Reaction to the jack load is provided by a steel frame that is attached to an array of steel H-piles located at least 1.5m away from the test piles. Pile cap/testing plate settlements were measured relative to a fixed reference beam using 2 dial gauges. Displacement/settlement of soils around the piles measurements were made in reference to the pile cap using 5 dial gauges, Fig. 2. The settlements were recorded for each loading increment at an interval of 15 minutes or the time when the movement of the indicator on the dial gauges becomes insignificant.

The modeled test piles were instrumented with strain gauges connected to the stylishly perforated steel cone-heads by string-pulley (for static resistance) with censors to the pile centerline. The steel cone-heads with series of springs connected to the indicators were installed in the soils around the piles at depths 0.2m, 0.5m, 1.0m 1.5m, and the 5th one at 0.2m outside the pile cap.

Load-controlled tests were performed by applying vertical compressive loads to the piles and observing/measuring the vertical pile and soil displacements using failure criteria, which establishes the allowable design capacity as "50 percent of the applied test load which results in a net settlement of the top of the pile of up to 1.3 cm, after rebound, for a minimum of one hour at zero load," which in this case is a displacement of 0.1d (10% of pile diameter) or until excessive pile displacement (at failure), whichever of them is less in line with the submission of [21], [22] and [23], also commented on by [1], [24], and [25]. The piles were loaded up to 200 kPa in four stages (25% incremental loading rate) at Test point one, and 300 kPa in six stages (16.66% incremental loading rate) at Test point 2. The unloading was done at equal/corresponding load decrement, allowing 15mins between decrements. The driving was conducted using hydraulic squirt boom vibratory hammer JSC-D180-42, Fig. 3, while the boring was done with Rig UGB-1VS GA-Z66 with D130-34 meters Auger and Bailer D127, as shown in action at the test site in Fig. 4.

The laboratory component of this study was carried out in a specially designed multi-purpose testing device (Testing Tank) Fig. 5, in the post graduate laboratory, Geotechnical and Environmental Engineering Department, Belorussian National Technical University, Minsk with a 20mm diameter, 200mm long modeled wooden piles.

The procedure for the detailed comprehensive laboratory investigations is given in my earlier work [26], only that it was repeated for the driving and boring techniques separately in this case.

The required ultimate capacities were determined by multiplying the allowable designed capacities by a factor of safety of 2.5 (conservative) as recommended by [1], [4], [27] and [28] as earlier discussed by [29]. The influence of driving and boring techniques on the bearing capacity of the tested piles were recorded and discussed in this study.

Fig. 1Hydraulic Jack (200T capacity) for loading

Fig. 2 Dial gauges Connected for Settlement Reading

Fig. 3 Vibratory Pile Hammer during Field Test

Fig. 4 Boring during the Field Test

Fig. 5 Multi-purpose Testing Tank in the Laboratory

III. DISCUSSION OF TEST RESULTS

The 20 mm diameter and 200 mm long modeled wooden piles used for the laboratory investigation on the sandy and peaty-clay soils obtained from the site were tested as single pile, 2x2 (4piles group), and 3x3 (9 piles group). Group efficiency of 0.85 and 0.95 were adopted for the 2x2 piles group with 4d spacing, and 3x3 piles group with 3d spacing respectively.

The result of some of the physico-mechanical properties of the soil samples tested is presented in Table 1. The values to the left of the hyphens are laboratory figures, while the ones to the right are figures from the field tests. As shown in Table 1, the slight variations between laboratory and field tests are within acceptable range owing to modeling and controlled conditions in the former than the later.

Table 1 Geotechnical Properties of the Tested Soil Samples

Parameters	**Sandy Soil**	**Peaty-clay Soil**
Density γ (kN/m^3)	18.1 – 19.2	17 – 18.4
Moisture content (w)	10	10
Specific gravity of solids	2.75	2.64
Liquid Limit (%)	22 - 42	23 - 29
Plastic Limit (%)	15 - 30	17 - 19
Plasticity index (%)	07 - 12	05 - 10
Liquidity Index (%)	$I_L < 0$	0.1 – 0.3
Void ratio (e)	0.55 – 0.87	0.70 - 0.91
Cohesion (kPa)	0.7 - 11	25 - 30
Angle of internal friction (φ^o)	32 - 39	7 - 18
Modulus of Deformation E (kPa)	17 - 37	7.6 - 14

The Load-settlement curve for modeled piles tested in the laboratory is shown in Fig. 6. The driving process seems to displace more soils around the piles leading to higher settlement than the corresponding identical bores piles.

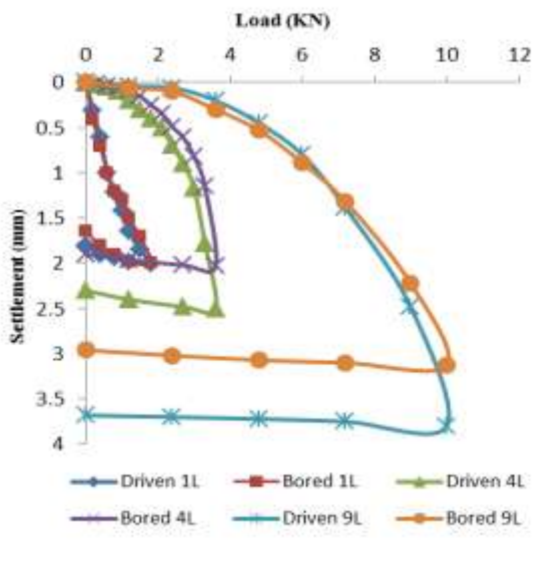

Fig. 6 Load-Settlement curve for Laboratory Test

The result of computed bearing capacity of the instrumented driven and bored piles of diameters 200 mm for DR-1 and BO-1; 250 mm for DR-4 and BO-4; and 300 mm for DR-9 and BO-9 is shown in Table 2 below. The Ultimate capacity of piles installed by driven is less than those of piles installed by boring with 12 – 18%.

Table 2 Summary of Bearing Capacity for the Tested Piles

Pile Name	Static Load (kPa)	Factor of Safety	Ultimate Capacity (kPa)
DR-1	337.5	2.5	135
BO-1	375.0	2.5	150
DR-4	470.0	2.5	188
BO-4	500.0	2.5	200
DR-9	707.5	2.5	283
BO-9	752.5	2.5	301

DR – Driven Pile; BO – Bored Pile

Since the piles extended through layers of soil with different properties, the scenario was taken into account when calculating the ultimate carrying capacity of the piles. The skin friction capacity was calculated by simply summing the amount of resistance each layer exerts on the piles. The end bearing capacity is calculated just in the layer where the pile toe terminates as recommended by [30] and shown in Fig. 7 below.

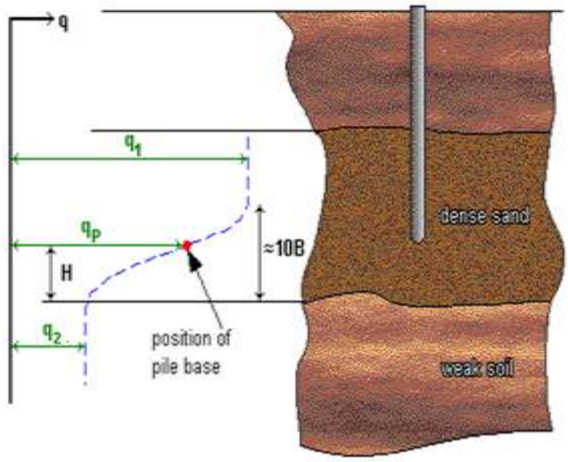

Fig. 7 Pile penetrating different soil layers

The Piles BO-1, BO-4, and DR-9 especially at Test point 1 terminated in a layer of loose sand, therefore, to compensate for the punching shear, the base resistance at the pile toe just like shown in Fig. 7 above is calculated using the Meyerhof's equation [9];

$$Q_b = q_2 + \frac{(q_1 - q_2)H}{10B}$$

where B is the diameter of the pile, H is the thickness between the base of the pile and the top of the weaker layer, q_2 is the ultimate base resistance in the weak layer, q_1 is the ultimate base resistance in the strong layer.

The Load-settlement curve for the modeled instrumented piles tested in the field is shown in Figs. 8 and 9. Test point 1 has weak layers of peaty-clay and loose sand and therefore gave higher settlement which is especially more pronounced in piles installed by driving with less compressive load compare to Test point 2.

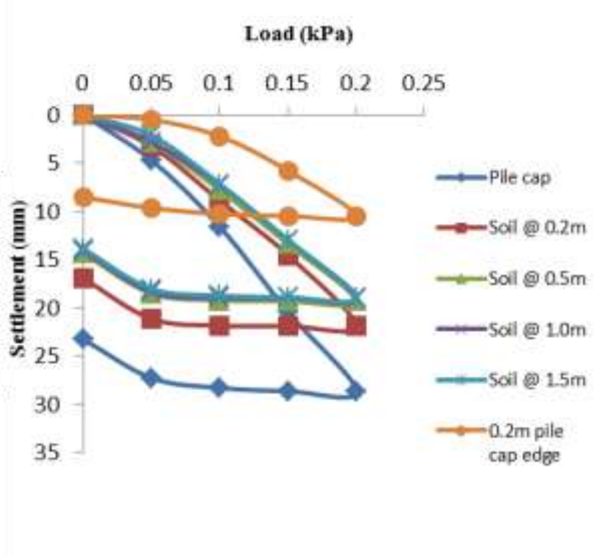

Fig. 8 Load-Settlement curve for Test Point 1

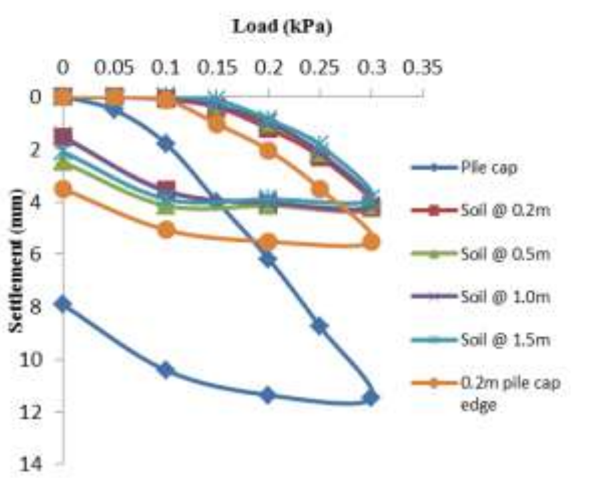

Fig. 9 Load-Settlement curve for Test Point 2

The stress distribution and deformation pattern of the pile cap-soil contact surface during loading and unloading on the field is shown in Figs. 10 – 13. While Fig. 10 shows the horizontal displacement and settlement variation at a depth of 0.2m below the pile cap, the vertical variation of displacement of soil under pile cap line at Test point 1 is shown in Fig. 11. Figs. 12 and 13 show the settlement variations for Test point 2.

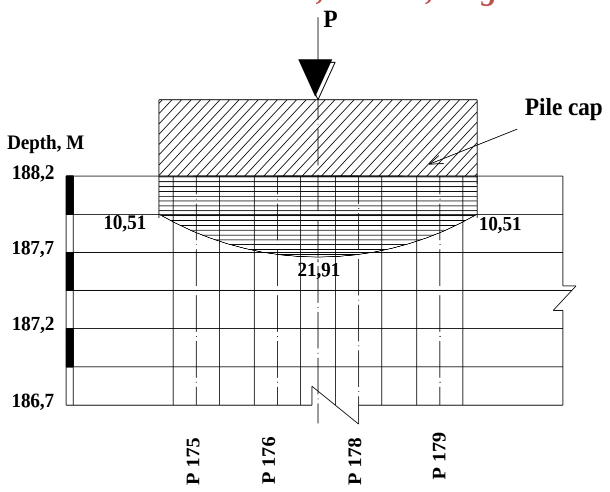

Fig. 10 Horizontal settlement variation for Test Point 1

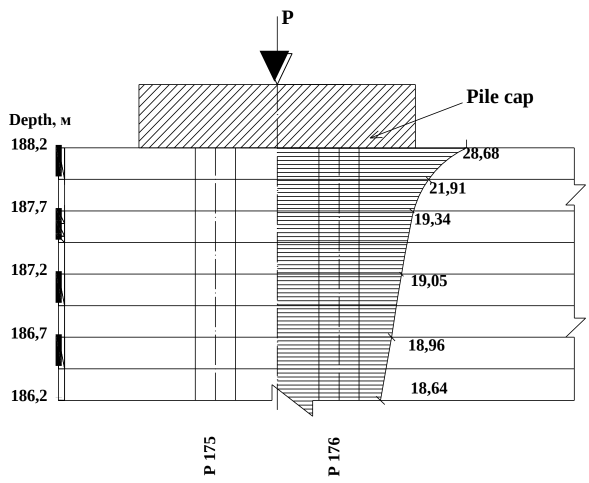

Fig. 11 Vertical settlement variation for Test Point 1

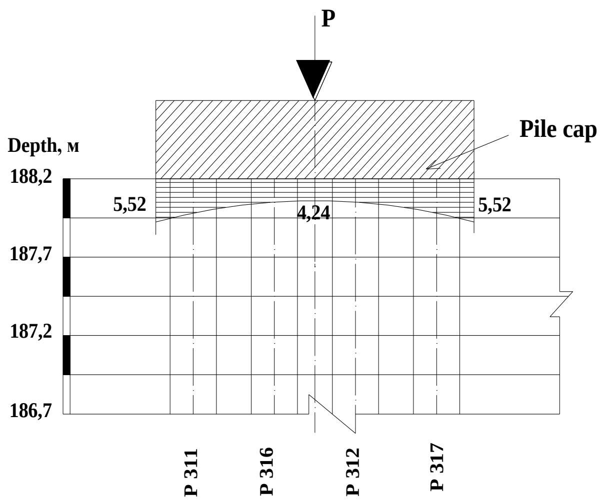

Fig. 12 Horizontal settlement variation for Test Point 2

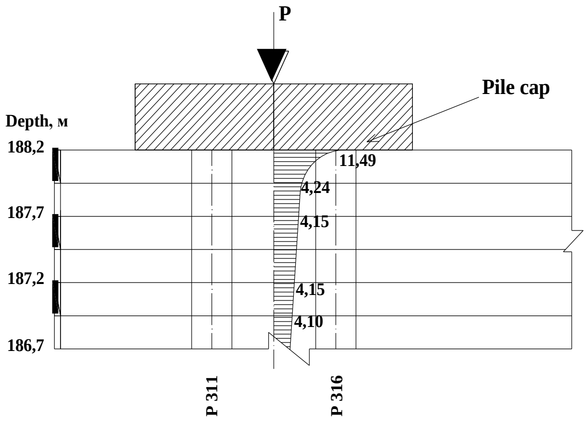

Fig. 13 Vertical settlement variation for Test Point 2

IV. Conclusion

More of the applied loads are being distributed to the toe of the piles at test point 1 with layered loose sand, sandy loam and peaty soils with less relative contribution of shaft friction around bored piles than in the driven case.

Driving installation techniques seems to cause wider pulverization/loosening, as a result of higher settlement of the soils around the piles and therefore results in lesser capacity for the piles than in bored installation.

The unsuitability of vibratory hammer for driven or displacement piles could be responsible for the low resistance and hence bearing capacity of the piles than the piles installed by boring during the field tests.

Boring installation technique displaces less soil in comparison with driving installation. A radial displacement of 2d and 3.5d from pile centerline were recorded for boring technique and driving technique respectively; where d is the pile diameter in millimeter.

The settlement at the middle of the instrumental piles was less for the driven installation, i.e. displaces more soils than boring installation which seems to mobilize less soil along the pile stems.

Driving installation displaces more soils around the piles and therefore reduces the bearing capacity of the piles (by approximately 12 - 18%) in comparison with boring installation in a fully mobilized soil resistance and loading case.

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