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ESTIMATION OF DEFORMATION OF SOILS AROUND TAPERED AND NON-TAPERED PILES IN MULTI-LAYERED SOILS

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Abstract

The result of a comprehensive study on the estimation of deformation of soils around tapered and non-tapered piles in multi-layered soil is presented in this study. These results show the pile-soil interaction when tapered and non-tapered piles were driven through layers of inter-bedded sandy clay soil. The investigation was carried out to study the influence of tapering on the behavior of the soils around the 20 mm diameter and 200 mm long modeled circular piles, driven through specially conditioned layered sandy clay soil in a specially designed multi-purpose testing device (laboratory), and modeled reinforced concrete instrumental test piles of diameters 200mm, 250mm in a corresponding fairly modeled field condition at a construction site. The piles were subjected to axial compressive load on incremental basis till failure. The effects of the pile tapered on its side response to axial compressive loads were examined. The distribution and stress pattern around the two configurations of piles were also examined. The results of the study confirmed the efficiency of tapered piles over cylindrical piles of straight-sided (uniform section) of the same material and under the same loading conditions considered in this study. From settlement analysis and shaft resistance consideration, the shaft resistance of non-tapered cylindrical piles was about 42% less than that of the tapered piles. It is concluded that, for structural and material optimization, the tapered piles offer a larger (better) resistance than the cylindrical non-tapered piles.

Keywords — Deformation; Tapered piles; Non-tapered piles; Multi-layered soil; Settlement.

INTRODUCTION

Soil exhibits non-linear stress-strain properties at relatively small shear strains. Tapered piles otherwise known as non-uniform section piles are piles with the diameter of the trunk narrows from the top (its head) downwards to its tip. It generally has greater top cross-sections than bottom ones, and has the potential for substantial cost advantages for static loading conditions. However, tapered piles have not often been considered a design option because of the lack of design tools and knowledge about their behavior Wei and El Naggar [35].

The shaft resistance of tapered piles stems from two mechanisms: 1) the frictional resistance (i.e. shear resistance along the pile skin) and 2) the wedging effect due to the pile taper (i.e. direct bearing on the projected area of the pile shaft), El Naggar and Wei [9].

When pile is penetrated in a downward frictional mode, a failure zone is developed along the soil-pile interface which partly upheaves laterally and disturbs the soil below the pile tip. Partly consolidation develops around soil-pile interface when soil compresses elastically below the critical depth Manandhar and Yasufuku [14]. In medium dense sand, dragging of thin layer of soil particle compresses laterally such that the displacements decrease according to parabolic law with increasing the diameter of the disturbed zone around the pile approximately six times the diameter of the pile Kézdi [11].

Several attempts have been made to investigate the change in the soil state in domains around the piles. Rational analyses of pile group displacements were pioneered by Poulos [22]. 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. Previous studies of tapered pile subjected to axial compressive load include full-scale field testing, laboratory testing and analytical procedures. Field testing results on tapered piles were reported by Norlund [20], Appolonia and Haribar [5] and Rybnikov [29]. Laboratory testing observations on non-uniform section piles include those reported by Robinsky et al. [28], Bakholdin [7], Ladanyi and Guichaoua [13]. Kodikara and Moore [12] suggested analytical solutions for tapered pile response. Poulos [23] investigated the behavior of laterally loaded single pile, while Poulos and Sim [25] conducted a theoretical analysis with five types of pile to assess their cyclic load capacity, Wei [34].

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 Belyaev and Rud [8]. The lateral deformation of piles decreases with increase in distance from the pile center line, while outward radial deformations recorded around the pile decreases downwards along the length, Adejumo [1], [2]. The piles penetration depth depends on the magnitude of the applied load and type of soil. The rate of application of external load affects the strength of cohesive soils, Al-Mhaidib [3]. For a group of piles, it would be expected that the strain level will increase as the pile-soil interface is approached, and thus, the stiffness of the soil at the pile-soil interface is smaller than that between the piles at some distance from the pile shafts. Simplified distributions of the soil modulus with distance from the pile shafts may be assumed, especially with a steady rate of load application. It has been demonstrated that the presence of the stiffer soil between the piles can lead to a significant reduction in the interaction factor between two piles, Poulos [24]. The result has been viewed to be in agreement with the results of field tests on pile group in clay, Poulos and Sim, [25]. Soil within a few pile diameters can undergo large shear deformations. The pile driving process can potentially generate large stresses and deformations in the nearby soils, Swan [30]. For many cohesive clay soils which tend to be highly sensitive to remolding, this leads to significant loss of strength in the short term. Observations of settlement and deformation of piles under load do not only present scientific interest for the geotechnical engineer, but also an indication of the long term behavior of the construction and the overall functionality of the project, Badellas and Savvaidis, [6]. One of the common mean of analyzing pile group behavior is by use of interaction factor method which was described by Poulos and Davis, [26], otherwise known as the principle of superposition. A simplified expression for the interaction factor, which enables easier computational analysis of group settlement of piles, was later developed by Mandolini and Viggiani, [18].

Recent investigations concluded that, skin friction and radial stress are highly influenced by tapered piles compared with conventional piles. The tapering and wedging effects are responsible for increase in normalized skin friction and normalized lateral stresses. Taper-shaped piles offer a larger resistance than the cylindrical piles, Manandhar et al. [14] and Manandhar et al. [15]. The mobilized mechanism of skin friction shows that the effective radius of the influence zone around the pile shaft increases with increases in line with increase in tapering angle Manandhar et al. [16].

However, the shape and pattern of displacement around the piles under loading is still being investigated. In this study therefore, several investigations including laboratory and field tests, were conducted to estimate the deformation of soils around piles with uniform periphery and the ones with non-uniform periphery in relations with diameter and length, to further understand the behavior of tapered and non-tapered piles, as a guide to towards greater efficiency in their application and optimizations.

MATERIALS AND METHODS

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 Figs. 1 and 2. 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. 3. 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 Vesic, [33], Jahanadish et al. [10] and Al-Saoudi and Salim, [4], also commented upon by Swan, [31], Poulos et al. [27], and Tomlinson, [32]. 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 laboratory component of this study was carried out in a specially designed multi-purpose steel tank, with dimensions 110 X 250 X 60cm for length, width and depth respectively as shown in Fig. 3, in the post graduate laboratory, Geotechnical and Environmental Engineering Department, Belorussian National Technical University, Minsk with a 20mm diameter, 200mm long modeled tapered and non-tapered wooden piles.

The procedure for the detailed comprehensive laboratory investigations is given in my earlier work, Adejumo [2] only that it was for circular tapered and non-tapered piles in this case. The effects of the pile tapered on its side response to axial compressive loads were examined. The influence of tapering on the pile-soil interface and the state of soil around the tested piles were recorded and discussed in this study.

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

Fig. 2 Full loading assemblage Hydraulic Jack

Fig. 3 Dial gauges Connected for Settlement Reading

Fig. 4 Multi-purpose Testing Tank in the Laboratory

DISCUSSION OF TEST RESULTS

Modeled 20 mm diameter and 200 mm long wooden piles used for the laboratory investigation on the sandy and peaty-clay soils obtained from the site were tested as single pile and 2x2 (4piles group). Group efficiency of 0.85 was adopted for the 2x2 piles group with 4d spacing for both cylindrical non-tapered and tapered piles, while the tapering angle (α) of 1.43^o was adopted for the latter.

The result of some of the geotechnical 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

Visual inspection and measurements of dimensions of disturbed soil particle (failure zone) below the pile tip, with its effective length measured from the tip of the pile to the point of maximum curvature below its tip increases relatively, although it is less radially outward from the pile centerline in tapered piles than in non-tapered ones, Figs. 5 - 7, similar to the earlier findings of Manandhar and Yasufuku, [16].

As shown in these figures, the soils at the upper layers provided lesser resistance to stress in tapered piles than in the circular ones, but as the load increases, tapered piles with greater pile-soil interface bonding and higher skin friction than the circular counterparts provided greater resistance with lesser settlement altogether.

Fig.5 Visual observation of soil displacement under load

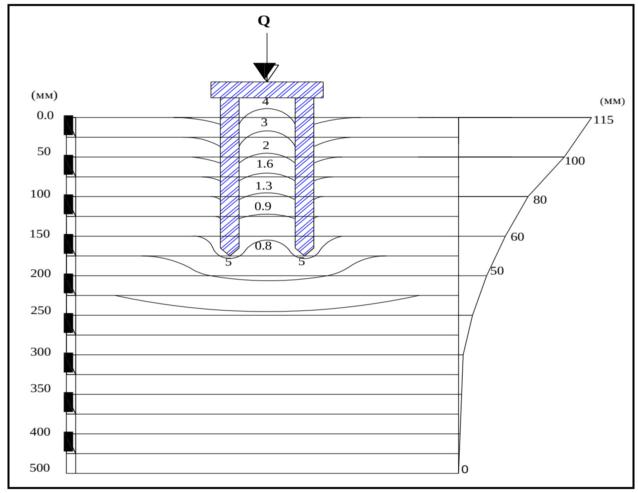

Fig. 6 Vertical and Horizontal displacement (non-tapered piles)

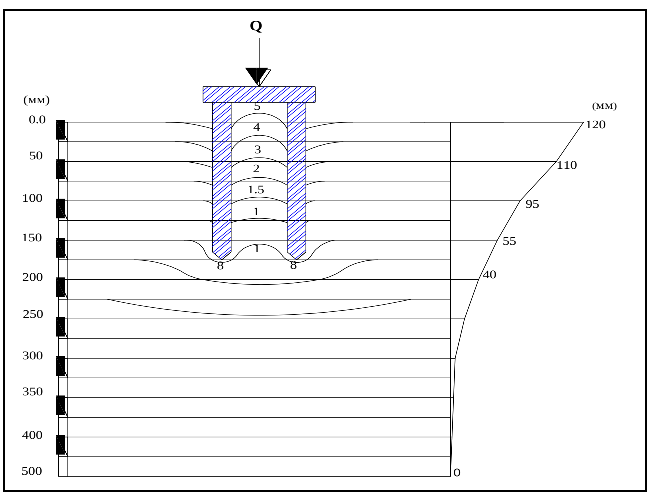

Fig. 7 Vertical and Horizontal displacement (tapered piles)

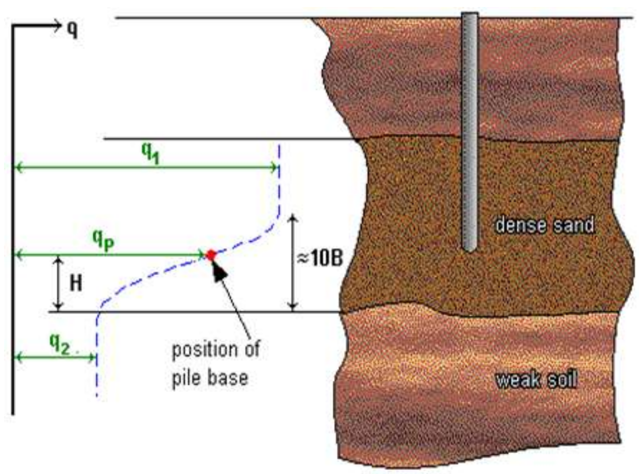

Fig. 8 Pile penetrating multi-layered soil strata

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 [36] and shown in Fig. 8 above. The base resistance at the pile toe is calculated using the Meyerhof's equation [19];

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

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 modeled piles tested in the laboratory is shown in Fig. 9. Soils around non-tapered piles show less settlement at the initial period of loading, but at higher loading, tapered piles reacted better to load as it produce a generally lower settlement and deformations than the corresponding non-tapered piles

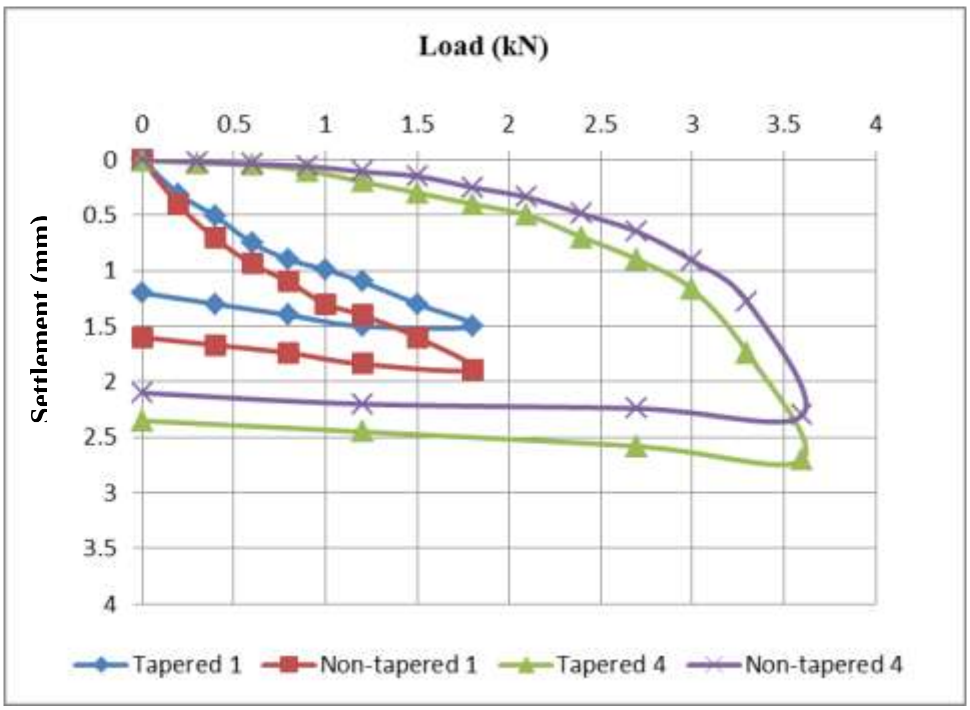

Fig. 9 Load-Settlement curve for Laboratory Test

The stress distribution and deformation pattern of the pile cap-soil interface during loading and unloading on the field is shown in Figs. 10 – 13. While Figs. 10 and 11 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 non tapered pile cap line, the settlement variations for the corresponding tapered piles are shown in Figs. 12 and 13 below.

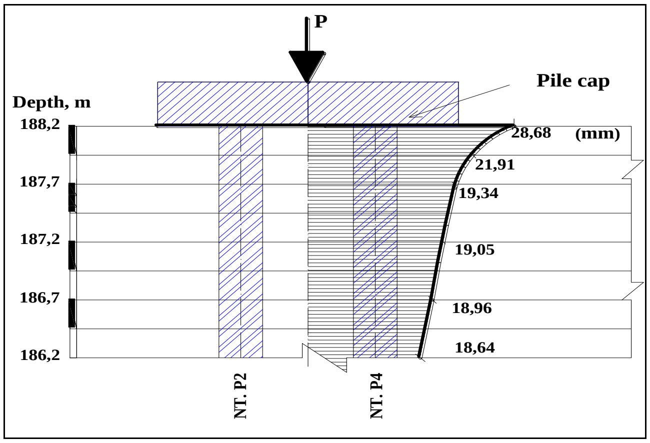

Fig. 10 Vertical settlement variation (Non-tapered)

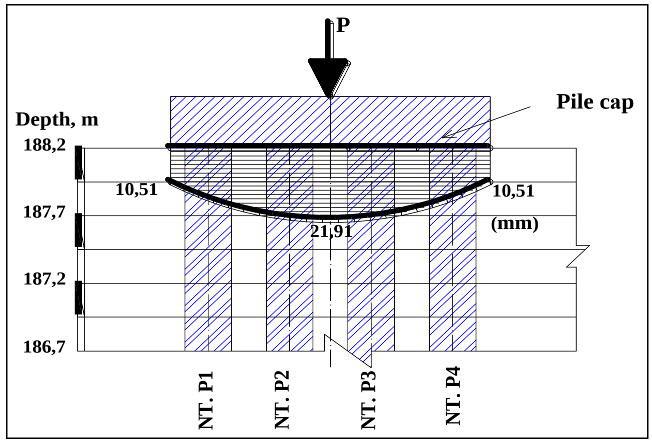

Fig. 11 Horizontal settlement variation (Non-tapered)

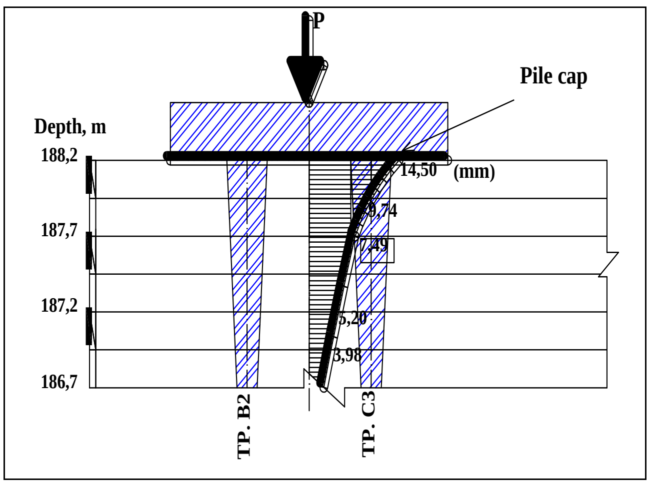

Fig. 12 Vertical settlement variation (Tapered)

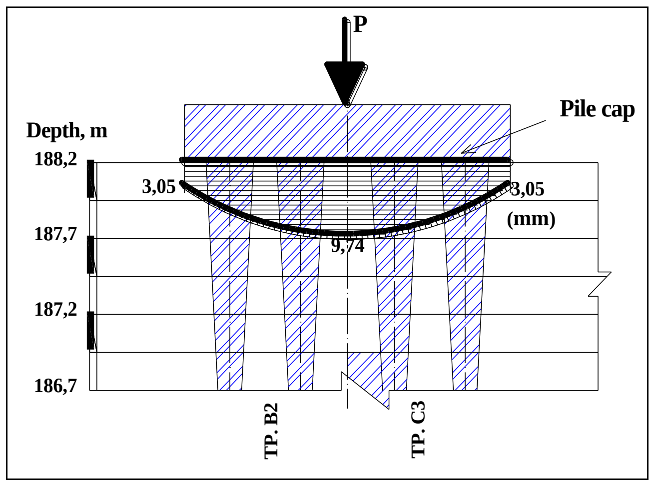

Fig. 13 Horizontal settlement variation (Tapered)

CONCLUSION

The following conclusions could be drawn from the analysis of the results of the investigations conducted in this study:

1. The load-displacement curves for tapered piles represented a much stiffer soil resistance at higher load levels, especially in the topmost soil layers. In addition, the topmost soil layers surface offered greater resistance to lateral pressure around the piles than with the corresponding non-tapered piles.

2. The shaft resistance for uniform section (non-tapered) piles established from the laboratory experimental results compared well with the field results than for tapered piles using the standard testing procedure.
3. Depth of failure zone vertically downward below the tip (toe effect on deformation) of non-tapered piles is relatively lower than that recorded in tapered piles, but the radial deformation about the horizontal axis is greater in non-tapered piles.
4. The response of piles is strongly controlled by the response of the top most soi1 layers, up to a depth corresponding to 7.5-12 times the diameter for tapered piles, and 10-15 times the diameter for non-tapered piles.
5. This type of analyses rarely captures the actual response of soil and the foundation structure in pile-soil interaction mode. However, empirical design methods are mainly based on the correlation of observed results with measured parameters, which makes it a useful guide or in the overall design of foundation, especially where choice can be made on the uniformity or non-uniformity of its peripheral circumference along its length. Besides this, every site and project has its peculiar conditions.
6. From settlement analysis, the shaft resistance of non-tapered cylindrical piles was about 42% less than that of the tapered pile.
7. With proper predetermined confinement, apart from greater efficiency for axial compressive loads, especially where large lateral loading is prevalent, the lateral loading behavior of pile foundations could be improved by using tapered piles instead of non-tapered piles.

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