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Research Article

One-Dimensional Consolidation and Settlement Analysis of Soils under Pile Cap of Tapered Piles in Compressible Clay

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Abstract: Analysis and computation of settlements of soils, especially clay is an essential component of geotechnical design for any structure intended to be constructed on it. Consolidation and settlement, especially in clay soil affect the essential criteria of durability, serviceability, as well as functionality and safety of the structure and therefore must be carefully considered in the design of any structured to be cited on it. This research paper presents the results of comprehensive investigations on One-dimensional consolidation and analysis of settlement in soils under pile cap of tapered piles in compressible clay. Compressible clay from Lebiaji, area of Minsk Region was investigated in this work. Settlement of soils underneath pile cap and pile settlement were carried out using Terzaghi's one-dimensional consolidation theory and load-transfer mechanism from pile load tests. The results, in comparison with field measurements showed a wide variance of field/calculated settlement with an average empirical correlation ratio of 0.22 and an empirical coefficient (C_p) of 0.042.Time-constraint (Δt), and a dimensionless ratio (T_v), a time factor, which play a significant role in the consolidation of clay, contribute to this variation. The convergence factor is 0.95 for the four piles, which provides for acceptable simulation, considering site, material, installation method, mechanical and other determinant constraints.
Keywords: One-dimensional consolidation, Tapered Pile, Settlement, Deformation, Pile cap, Compressive clay.

INTRODUCTION

Settlement in soil is defined as the compression of a soil layer due to the loading applied at or near its top surface. Soil under loading, does not assume an instantaneous deflection under that load, but settles gradually at a variable rate. The settlement, caused by gradual adaptation of the soil to load variation, is very apparent in clays and sands saturated with water [1]. Settlement calculation using Terzaghi's 1-D (one-dimensional) consolidation theory [2], which simulates the visco-elastic behaviour of soils under loading has been widely used in spite of the uncertainty of its coefficient. Many methods have since evolved, which seem to address this uncertainties and give more credence to Terzaghi's pioneer equations.

The process of consolidation is often confused with the process of compaction. While compaction increases the density of an unsaturated soil by reducing the volume of air in the voids, consolidation is a time-related process of increasing the density of a saturated soil by draining some of the water out of the voids. Consolidation theory is required for the prediction of both the magnitude and the rate of consolidation settlements to ensure the serviceability of structures founded on a compressible soil layer. Differential settlements, which can lead to structural failures due to tilting, must be taking into consideration during the geotechnical design.

A soil that has never experienced a vertical effective stress (preconsolidation pressure) that was greater than its present vertical effective stress is called normally consolidated(**NC**) soil. The **OCR** for an **NC** soil is equal to 1 and most **NC** soils have fairly lows hear strength. A soil that has experienced a vertical effective stress (preconsolidation pressure) that was greater than its present vertical effective stress is called an over consolidated (**OC**) soil. The **OCR** for an **OC** soil is greater than 1, and most **OC** soils have fairly high shear strength. The **OCR** cannot have a value less than unity (i.e. 1) [3]-[5]. Based on the strength of their digenetic bonds, clay and clay-shale have been grouped into 3: i) over consolidated plastic clay with weak or no bond; ii) over consolidated plastic clay with well-developed digenetic bonds and iii) over consolidated plastic clay with strongly-developed digenetic bonds

[6]. Clay found on the test sites around Minsk region falls into the third category [7].

The flexibility of the pile cap affects individual pile head forces significantly and affects the bending moments and shear forces in individual piles as well, even though the displacement of the pile cap does not vary much [8]. When the pile cap distributes an equal magnitude of load on each pile, the following assumption must be satisfied according to Bowles; (a) the pile cap is in contact with the ground, (b) the piles are all vertical, (c) a load is applied at center of pile group, and (d) the pile group is symmetrical [9].

Measurements have shown that the sudden application of load generates water pressures and that these water pressures dissipate as a time dependent settlement occurs. It has also been shown that, when the pore water pressures decreased back to zero, the rate of settlement diminishes to a relatively small value, i.e., the soil essentially comes to equilibrium [8].The application of areal fills to compressible soils typically generates pore water pressures and some of the pore water flows out of the soils leading to time-dependent volume change. Water flow and deformations are along only a vertical axis, so we can refer to the process of time dependent volume change as one-dimensional consolidation [10].

In a one-dimensional case, having a stress-strain curve and knowing the initial and final stresses, the settlement can be calculated even from the vertical stresses alone. One-dimensional consolidation equationdescribes the hydraulic behaviour of soils in transient conditions by making it possible to simulate the variation in time of interstitial overpressures (u). The pressures are generated by the load induced on the foundation or by a road embankment, with consequent visco-elastic settlements to which corresponds a structural reorganization of the solid skeleton, with reduction of porosity and, concurrently, of the degrees of freedom [11]. Hussein and Jianlin have observed a wide range in the values of settlement calculated and that measured on the field [12].

Generalized Terzaghi's 1-D (one-dimensional) consolidation theory (elastic theory) extension and load-transfer mechanism were employed to analyze the settlements of soils under the piles cap of tapered piles in compressible clay. Settlements were theoretically calculated and experimental measured on the field. The results and findings are presented in this article.

MATERIAL AND METHODS

Laboratory investigations were conducted on clay samples taken from sites around Lebiaji, an outskirt of Minsk province of Belarus. The clay soils were conditioned in order to determine its settlement under axial compressive load when modeled reinforced concretetapered piles were bored in to it. Detailed procedure of the laboratory test has been widely covered in my earlier work [13].

The field tests were performed on four (4) tapered piles with diameters of 500mmand250mm at the head and tail end of the piles respectively. Static loads were applied and maintained using a hydraulic jack (of 200T capacity) and were measured with a load cell as shown in (Figs. 2 and 4). 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 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. 4).

The modeled tapered 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 soil below the pile cap at depths 0.2m, 0.5m, 1.0m 1.5m, and the 5^{th}one at 0.2m outside the pile cap.

The settlements of the clay were measured by means of a dial gauge, which was connected to the upper plate as shown in (Fig 1) for laboratory test. The settings in (Figs.2 - 4)are for the field tests. The settlement were taken at the interval of quarter-hour with load increment until the time when the settlement change was insignificant or refusal according to the submission of [14- 6].

Fig.1: Testing tank for the laboratory work

Fig.2: Loading device for the field test

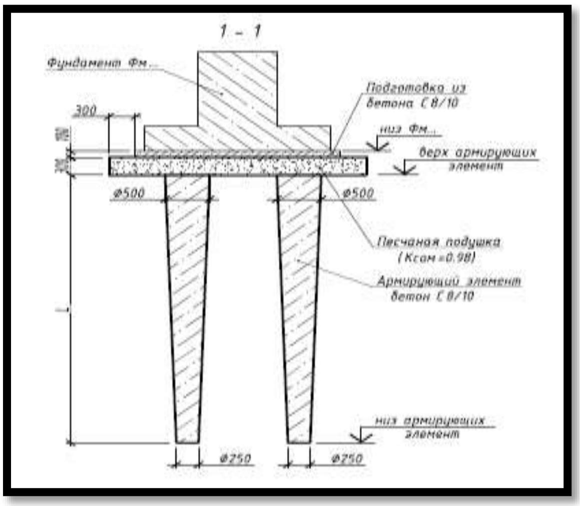

Fig.3:Tapered Piles section on the field

Fig.4: Taking Settlement Reading on Dial gauges

RESULTS AND DISCUSSION

Table 1 shows the summary of laboratory results for the geotechnical properties of the compressive clay soil investigated. It shows a high void ration (e) and cohesion with maximum values of 1.82 and 35 kPa respectively, which indicated the compressibility of the sample. It does not drain readily and may absorb water by capillary action with resulting loss in strength.

Table 1: Geotechnical properties of the investigated clay sample

Parameters	Values for the Sample
Densityγ (kN/m^3)	19.2
Moisture content (***w***)	15
Specific gravity of solids	2.68
Liquid Limit (%)	22 – 31
Plastic Limit (%)	16 – 20
Plasticity index (%)	6 - 11
Liquidity Index (%)	0.1 – 0.3
Void ratio (***e***)	0.69 - 1.82
Cohesion (*kPa*)	19 - 35
Angle of internal friction (φ^o)	7 - 18
Modulus of Deformation ***E*** (*kPa*)	7.5 - 13
High void ratio (e) and cohesion indicate the compressibility of the clay sample	

Presented in Table 2are the results including calculated and measured settlements of the four piles investigated on the field. The empirical correlation coefficient of measured and calculated settlement, shown in the last column of the table shows a varied convergence, a trend similar to the findings of Hussein and Jianlin [12].

Settlements of the disturbed soil particles (failure zone) around the pile stem, with its effective length measured from the tip of the pile to the point of maximum curvature below its tip, increases radially outward from the pile centerline, are shown in a reduced scale in(Figs. 5 -8).

Table 2: Experimental results of design loads and pile settlements

Pile No	Design/Maximum Load (kN)		Settlement (S, mm)		Empirical settlement correlation (Measured/Calculated)
	Design Load	Maximum Load	Measured	Calculated	
PN-1	496	800	39.08	217.11	0.18
PN-2	833	1000	10.12	42.16	0.24
PN-3	792	1000	29.47	113.34	0.26
PN-4	667	900	40.47	192.71	0.21

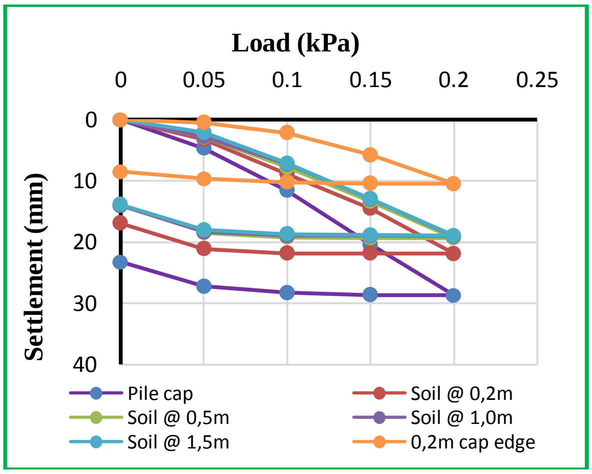

Fig.5: Settlement of soils under cap of PN-1

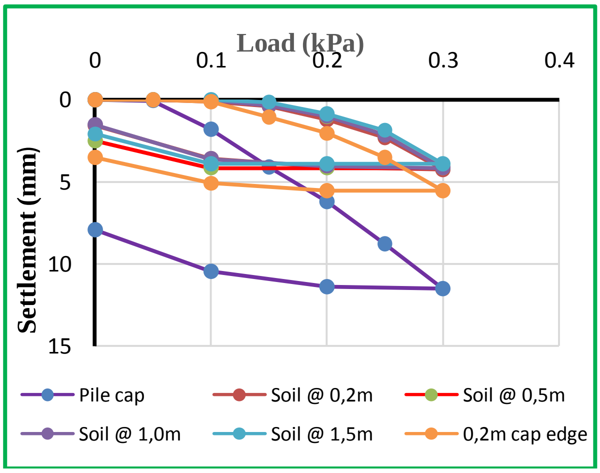

Fig.6: Settlement of soils under cap of PN-2

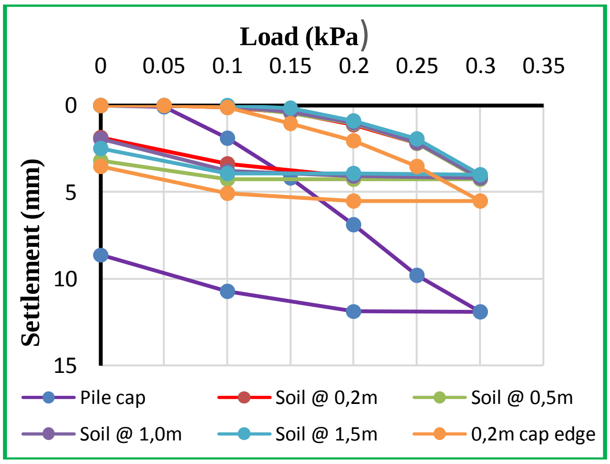

Fig.7:Settlement of soils under cap of PN-3

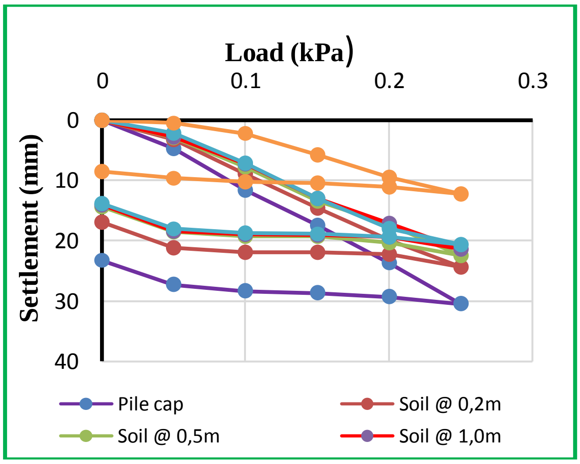

Fig.8: Settlement of soils under cap of PN-4

The Load-settlement curves for modeled tapered piles from field results are shown in (Figs. 9 and 10).Fig. 9 shows the load-settlement curves for the piles, while the empirical relationship of limit load/limit settlement is shown in (Fig. 10), which is similar to the empirical methods of Vesic, Meyerhof and Li [15], [17] and [18].The deformation/displacement pattern of the pile cap-soil interface for the field investigation is shown in (Figs. 9 – 12).Since the shape and pattern are similar in the four-pile cases, representative vertical and horizontal sections have been considered and shown for each of the four piles.

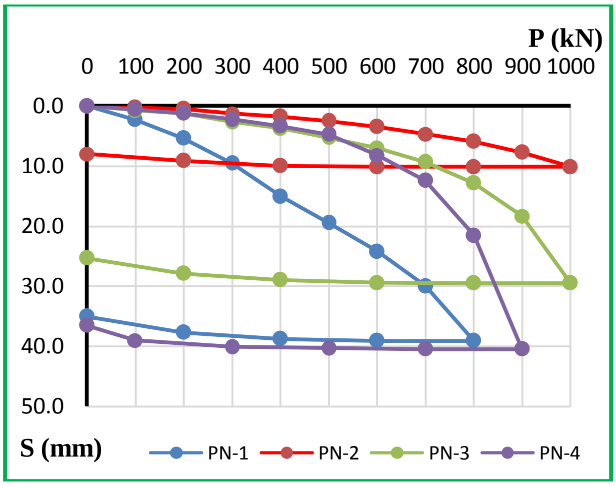

Fig.7: Load-settlement of four tested piles

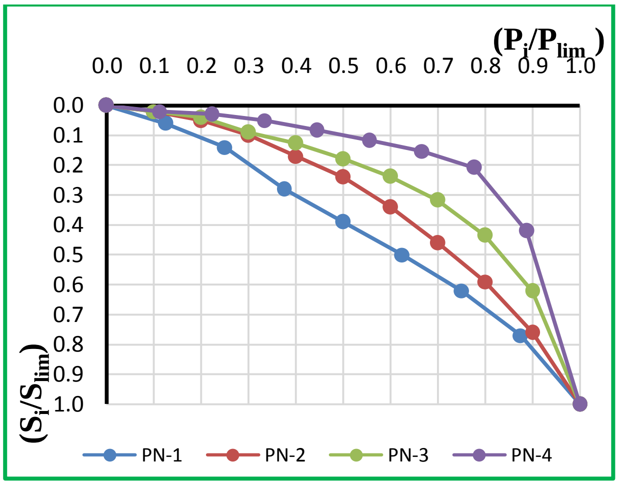

Fig.8:Empirical relationship of P_{lim}/S_{lim}

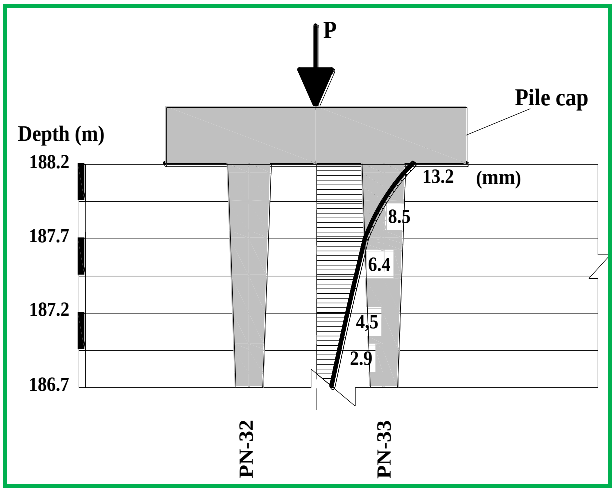

Fig.9: Vertical Settlement of pilePN-1

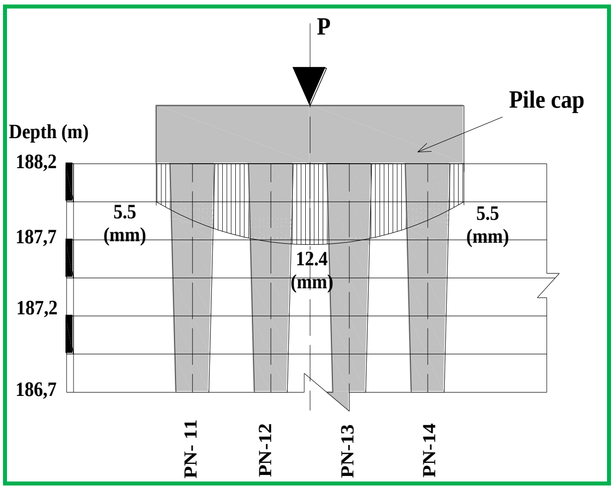

Fig.10: Horizontal Settlement of pile PN-2

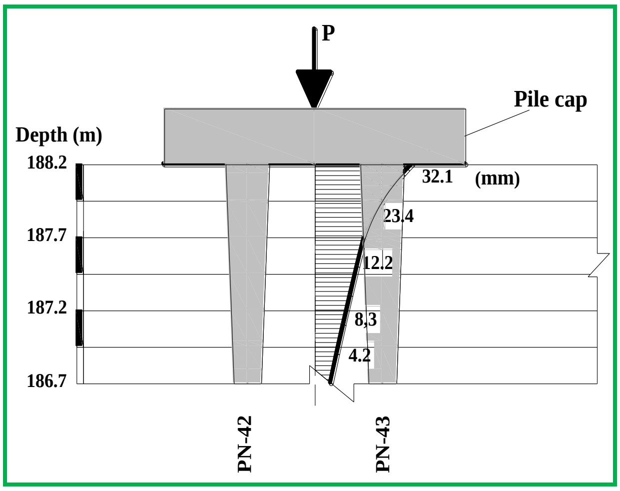

Fig.11: Vertical Settlement of pile PN-3

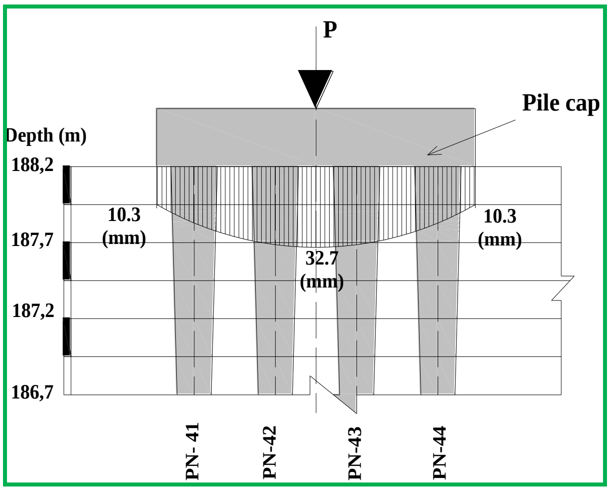

Fig.12: Horizontal Settlement of pile PN-4

CONCLUSION

Settlement analysis of soils around and underneath tapered piles bored into compressive clay soils of Lebiaji area, Minsk region, when subjected to compressive axial loads has been investigated using one-dimensional consolidation elastic theory and load-transfer mechanism. The results of the investigations showed that in compressive clay, measured settlement of tapered piles as well as that of soils immediately underneath pile cap varied widely with the calculated values. However, the shape and patterns of the settlement/deformation are the same. The convergence factor for the four piles is **0.95**, which is within the acceptable range. The empirical ratio of measured/calculated settlement correlation of **0.18-0.26**, with an average of **0.22**, and an empirical coefficient (C_p) of **0.042** is also within acceptable values for piles bored in clay soil. Notwithstanding the variation, the field (measured/experimental), as well as the calculated settlements are within the acceptable limit. The variation in both field and calculated settlements may also be premised on time-constraint(Δt), which play significant role in the consolidation of clay. Care must be taking by geotechnical engineers to correlate calculated settlements with measured ones, especially at the commencement of or during construction for proper simulation of theoretical and experimental settlement, in order to achieve safe, durable and functionally designed/actualized projects.

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