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Research Article

Influence of Shaft Configuration and Method of Installation on Load Carrying Capacity of Pile Foundations

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Abstract: The load carrying capacity, otherwise known as the bearing capacity of pile foundations has been reported to be influenced by many factors. Theoretically and from empirical pile baring capacity equations, the shape or configuration of the piles as well as method of installation employed during construction affect its bearing capacity. This article presents the results of laboratory and field investigations on the influence of shaft configuration and method of installation on the bearing capacity of modeled piles carried out on soils in the metropolis of Minsk, Belarus. Conical piles, with tapered cross section have higher bearing capacity in fairly homogenous soils, (either soft or stiff). In sandy and silty sand soils, especially where fine sand overlaid a stronger coarse sand layers, driven piles (installed by hammer or vibrator) have higher bearing capacity than bored piles, whereas the latter have higher bearing capacity where soft soil layers sandwiched between stronger strata. Cylindrical piles installed by boring method have higher bearing capacity in sandy soils than prismatic pile installed by driven, but the latter gave higher bearing values in layered soil with thicker stiff silty clay above sandy layers. In addition to this, the results, show bearing capacity increments of 10% in bored piles, 21% in hammered driven piles, and 26% in vibrated driven piles. The bearing capacity of conical piles with tapered cross section is 2-3 times higher than cylindrical piles and 1.5 – 2 times higher than prismatic piles respectively. Pile driving (by hammer or vibrator) yielded higher result in sandy soils, boring is better in cohesive clay and silty clay soil.

Keywords: Shaft configuration, Pile foundation, Shape factor, Bearing capacity, Pile installation, Settlement, Soil.

INTRODUCTION

Piles are long slender columns, either driven, bored or cast-in-situ. The compaction of the soil mass around a driven pile increase its bearing capacity. The pile end-bearing capacity in sand is not only affected by its compressibility, shear stiffness, and strength, but also by the angle of tapering of the pile. Not many researchers have noticed the effects of tapering angle in end-bearing resistance when penetrated downward in a frictional mode[1]. Piles are primarily used to carry vertical compression loads, as well as resist uplift loads, horizontal and inclined loads, and transfer them through relatively weak soil to stronger strata at depth to minimize settlement. Piles foundations are recommended to provide a safe carrying capacity to support a structure when the bearing capacity of the soil is insufficient to do so[2].

According to Murthy[2], the determination of the ultimate bearing capacity, Qu, of a deep foundation based on most theories is a very complex one, since there are many factors that are not taking into consideration in most of them. Most theories assume that the soil is homogenous and isotropic, which is normally not the case. All the theoretical equations are obtained based on plain strain conditions. Only shape factors are applied to take care of the three-dimensional nature of the problem. Compressibility characteristics of the soil even complicate the problem further. De Beer[3] opined that, the base resistance of bored and cast-in-situ pile is about one third of that of driven pile. Sitnikov *et al.*[4], who investigated on soils in Belarus, established that the shape of the longitudinal section of the pile affects the unit bearing capacity, and concluded that, the unit bearing capacity of square piles varies significantly with their cross-sectional dimensions, and increases with a reduction in their sectional dimensions. The method of installation of a pile at a site and the equipment chosen depends on the type of pile selected. Pile driving is achieved by hammering or by vibration. Boring could be done either by auguring or by percussion drilling. Water jetting may be used to aid pile penetration into dense sand or dense sandy gravel. Jetting is ineffective in firm to stiff clay or any soil containing much coarse to stiff cobbles or boulders[2].

Meyerhof[5, 6] stated that when a pile is driven into loose sand, its density is increased, and the horizontal extent of the compacted zone has a width of 6-8 times pile diameter. However, Kerisel[7, 8] opined that, in dense sand, pile driving decreases the relative density because of the dilatancy of the sand and loosened sand along the shaft has a width of 5 times pile diameter. Kishida[9] concluded from model and field test, that the angle of internal friction decreases linearly from a maximum value φ2 at the tip of the pile to a lower value φ1 at a distance 3.5 times pile diameter; φ1 and φ2 being pre-installation and post-installation angle of internal friction respectively. Vesic[10] opined that, only punching shear failure occurs in deep foundation irrespective of the density of the soil, provided the depth to width ratio is greater than four. Based on theoretical relations to plastic equilibrium, other researchers [11-13] have derived a strength parameter (φ'_{cv}) a critical state frictional angle, which is effective and has rational practical application. According to Meyerhof[6, 14] the ultimate unit skin friction of piles in a given sand or clay is practically independent of the pile diameter. Tomlinson[15] compared base resistance of piles suggested by Nurdlund[16] and that of Vesic[17], and showed that the bearing capacity factor Nq values established by Berezantsev *et al.*[18], which take into account the depth to width ratio of the pile, most nearly conform to practical criteria of pile failure. Adejumo[19] established that the lateral deformation of piles decreases with increase in distance from the pile centerline, while outward radial deformations recorded around the pile decreases downwards along the length. The 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[20, 21].

This article therefore, presents the results of a series of modeled pile tests as well as field tests on the influence of shaft configuration (shape) and the method of installation on the bearing capacity of pile foundations. The investigation was conducted with piles of conical (tapered), cylindrical, and prismatic sections in the research laboratory, Geotechnical and Environmental Engineering department, Belarusian National Technical University, Minsk and construction sites, also in Minsk region of Belarus. The results of the investigation is essential in the understanding of the analytical techniques of pile design in relation to determination of the bearing capacity, especially to ensure a rational choice of configuration of the pile shaft and optimized method of installation during pile construction.

MATERIALS & METHODS

Laboratory investigations were carried with piles of different shaft configurations (cylindrical, prismatic and conical cross section) on soil samples obtained from sites around Minsk province of Belarus, where field tests were also carried out. Consolidated in a specially constructed multipurpose test tank, shown in **Figure-1**, the soil samples were properly pulverized and mixed to the desired water content and bulk densities as shown in **Table-1**. The testing tank has a relatively rigid steel framework support, with a one sided steel panel having open and close apertures for drained and undrained tests. The frontal panel is made with transparent plastic fiber, which is strong enough to withstand consolidation induced pressure and strikes. The transparent strong plastic allows proper monitoring of sample's state during the test as well as ensures visual observation of failures in the tested soils in terms of depression, heaving or wobbles. The weights of the soil required to obtain designed unit weight were packed into the test tank in lifts, with the interface between the lifts being made uneven, to reduce the bedding effects, and clearly marked to give room for proper monitoring during loading and unloading. The testing tank was then made rigid and ready for pile installation by driving (hammering and by vibration), as well as by boring as shown in **Figures-1 - 3**. After the predetermined densities (field-laboratory conditioned density) was achieved, axial compressive load was applied through the upper surface layer. Detailed procedures of laboratory investigations are contained in my earlier works including Adejumo[22-24].

Figure-1: Testing Tank for laboratory work

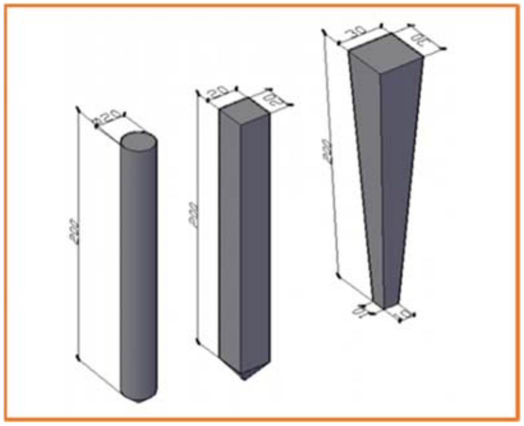


Figure-2: Modeled pile of 3 configurations

Table-1: Geotechnical properties of the investigated soil sample

Parameters	**Type of Soil**			
	Silty clay		**Sand**	
	Stiff	Soft	Coarse	Medium
Specific gravity of solids γ_s, ($кН/м^3$)	26,6	26,6	27,4	27,0
Density γ, ($кН/м^3$)	18	17	17 и 18	19
Moisture content W, (%)	10	20	8	6
Liquid Limit L_L, (%)	24	24	-	-
Plastic Limit P_L, (%)	18	18	-	-
Plasticity Index I_p, (%)	6	6	-	-
Liquidity Index (I_L)	$I_L < 0$	$I_L = 0,3$	-	-
Void ratio (e)	0,60	0,84	0,61	0,47
Angle of internal friction φ, (degree)	25	33	-	-
Cohesion C, (kPa)	20	0	-	-

The field investigations were performed on 18 No instrumental piles of cylindrical, prismatic and conical sections, (6 for each of the 3 chosen configurations were installed by boring, while 6 were driven, with 3 driven by hammering and 3 driven by vibration). The test was conducted at a construction site for high-rise residential buildings in Lebiadji district of Minsk, Belarus. Static loads were applied and maintained using a hydraulic jack (of 200T capacity) and were measured with a load cell attached to the fulcrum of the pile cap as shown in **Figure-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 two dial gauges. Displacement/settlement of soils around the piles measurements were made in reference to the pile cap using five dial gauges, **Figure-5**. The piles were subjected to axial compressive loads until the allowable pile settlement of 0.1d (10% of pile diameter) is reached or exceeded in line with the submission of Poulos[25] and Al–Saoudi and Salim[26] as well as Europe code 7[27] and Bauduin[28]. The settlement was taken with time until the time when the settlement change was insignificant. Section of tapered of one of the six conical configured shaft pile is shown in **Figure-6**.

Figure-3: Modeled test piles prepared for loading

Figure-4: Loading device of 200T capacity

Figure-5: Dial gauges for Settlement Reading

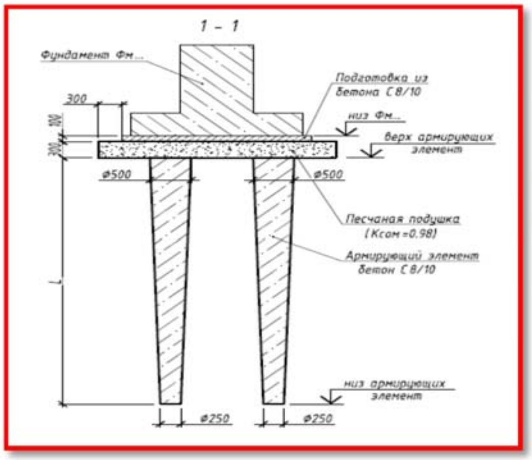


Figure-6: Section of Conical shaft pile

The bearing capacity of modeled piles of cylindrical, prismatic and conical section were determined using the established methods of static bearing capacity equations and field load test method. The results were analyzed, and inferences were drawn on the influence of pile shaft configuration and installation method on the bearing capacity of pile foundations.

RESULTS & DISCUSSIONS

The results of the various tests conducted in the laboratory and on the field are presented in the **Tables** and **Figures** below. **Table-1** shows the summary of geotechnical properties of the silty-clay and sandy soils investigated in the laboratory. It shows a high void ration (e) and cohesion, which indicated the compressibility of the stiff and soft silty-clay samples of ML index classification. The void ratios of the sandy soil samples indicated MS, MSa or Песок according to ASTM D 2487-2006, ISO 14688-2:2004 and ГОСТ 25100–2011 classifications respectively[29-31]. Seven soil condition scenarios were modeled with the three chosen shaft configuration sections of piles for the laboratory investigations in the testing tank. They are: I) Strong Silty clay soil exclusive; II) Soft Silty clay layers over stiff; III) Soft clay layers in-between stiff clay layers; IV) Soft silty clay exclusive; V) Coarse sand exclusive VI) Medium sand layers in-between coarse sand layers; VII) Medium sand layers over coarse sand layers.

Plot of load-settlement curve for the 18 tested piles in the field is shown in **Figure-7**. As shown in **Figure-7** as well as **Table-2**, piles N124 and N259 haven the highest bearing capacity of 1000 KN, without extrapolation, while pile N8 has the lowest bearing capacity of 228 kN. The normalized load-settlement for the ultimate load ratio is shown in **Figure-8**.

Using static bearing capacity equations and field load tests method, the bearing capacity of the piles tested on the field is shown in **Table-2**. The increment in bearing capacity for a uniform design 5mm settlement, (for a 2.5D critical state design, where D is pile diameter), for static load test in the laboratory which corresponds to 40 mm settlement on the field, for modeled single piles in the 7-modeled soil conditions (cases), were analyzed and shown in **Figures-9 - 15**.

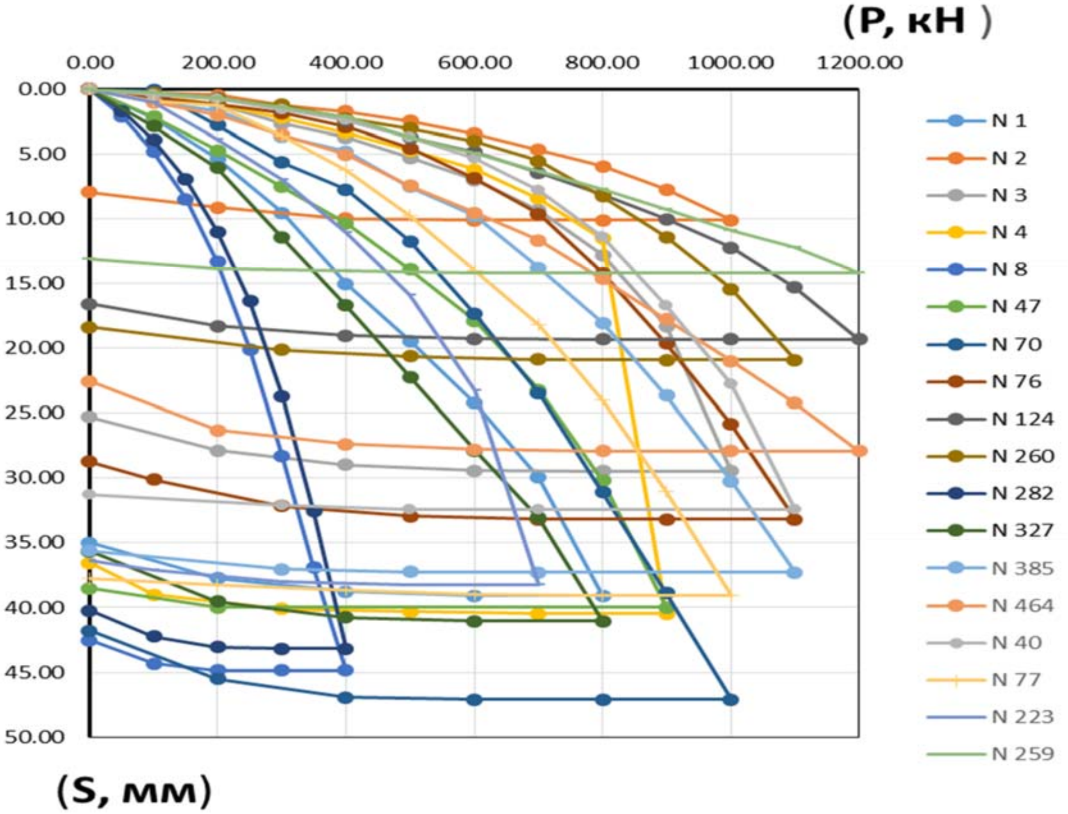


Figure-7: Load-settlement curve S=f (P), for the 18 test piles

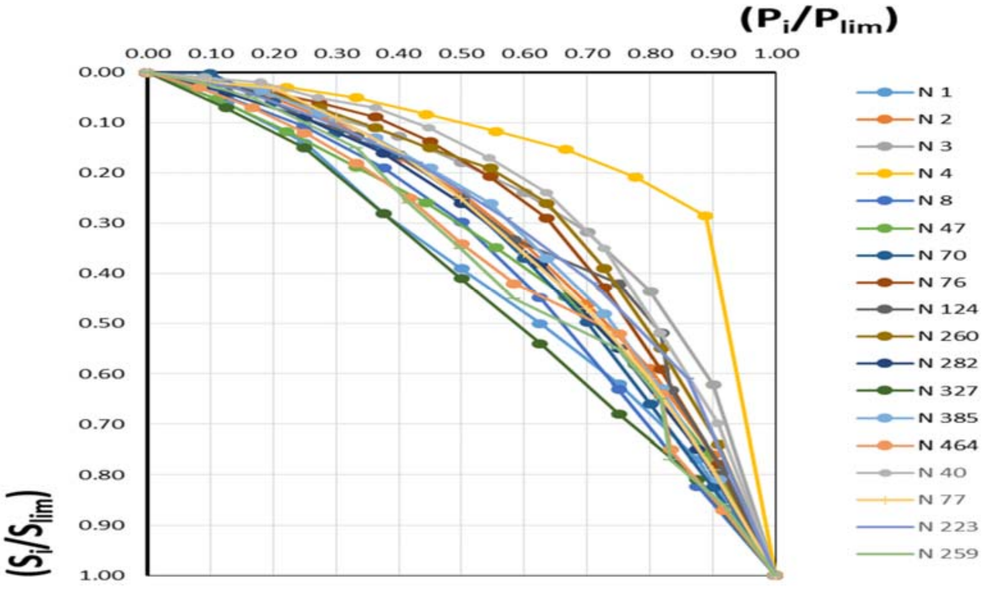


Figure-8: Normalized Load-settlement curve S_{lim}=f (P_{lim}), for the 18 test piles

Table-2: Bearing capacity of pile from static load tests

Pile No	Volume of displaced soil/concrete mix (m^3)	Bearing capacity of piles calculated from results of tests (kN)	Settlement at which Bearing capacity is determined (mm)	Remarks
1	0.3	496	24	—
2	0.1	833 (1562)[1]	10 (24)[1]	Less than 40 mm settlement
3	0.3	792	24	Less than 40 mm settlement
4	0.3	667	24	—
8	0.4	228	24	—
40	0.3	844	24	Less than 40 mm settlement
47	0.4	592	24	—
70	0.1	590	24	—
76	0.2	808	24	Less than 40 mm settlement
77	0.1	643	24	—
124	0.1	1200 (1310)[1]	19,2 (24)[1]	Less than 40 mm settlement
223	0.1	505	24	—
259	0.2	1200 (1770)[1]	14 (24)[1]	Less than 40 mm settlement
260	0.3	1100 (1152)[1]	20,9 (24)[1]	Less than 40 mm settlement
282	0.3	252	24	—
327	0.2	442	24	—
385	0.1	754	24	—
464	0.3	908	24	—

[1] **– In brackets is bearing capacity of piles on nonlinear extrapolation**

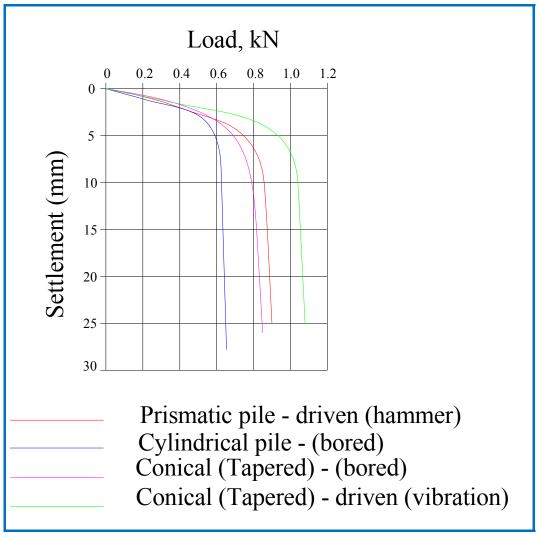


Figure-9: Load-settlement for test piles - case 1

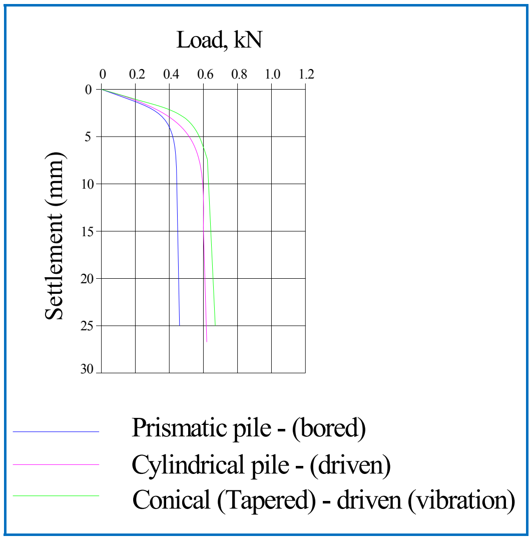


Figure-10: Load-settlement for test piles - case 2

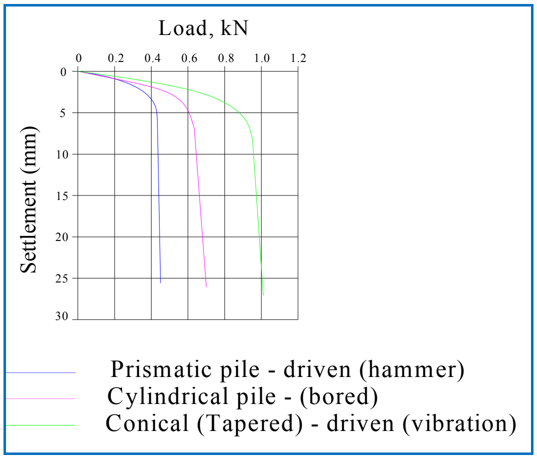


Figure-11: Load-settlement for test piles - case 3

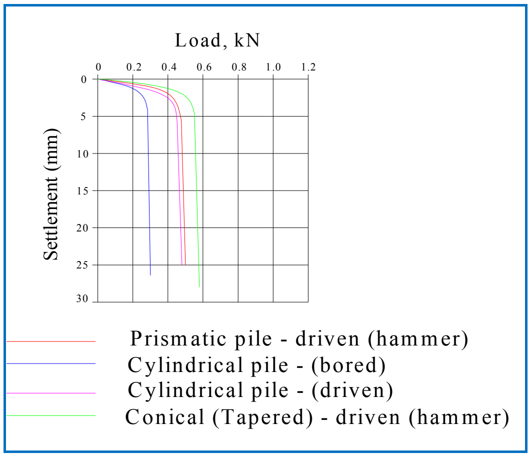


Figure-12: Load-settlement for test piles - case 4

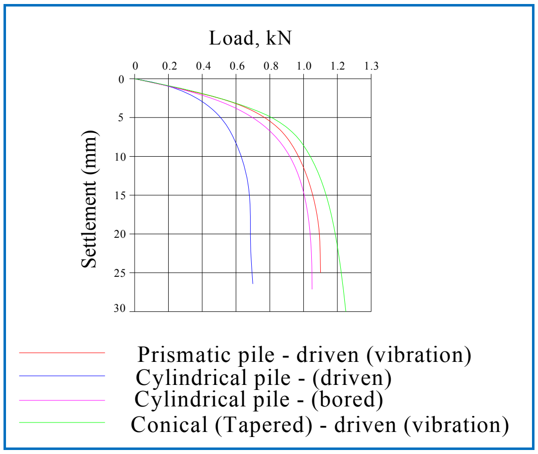


Figure-13: Load-settlement for test piles - case 5

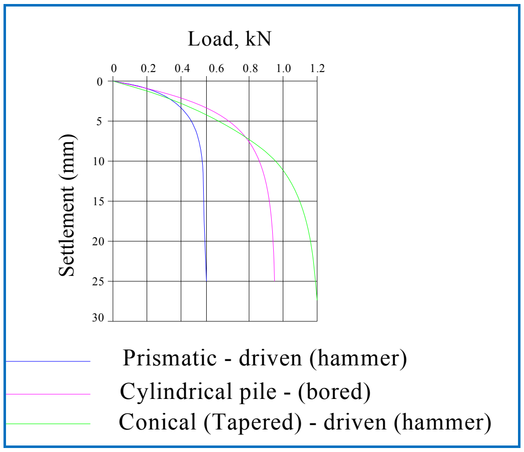


Figure-14: Load-settlement for test piles - case 6

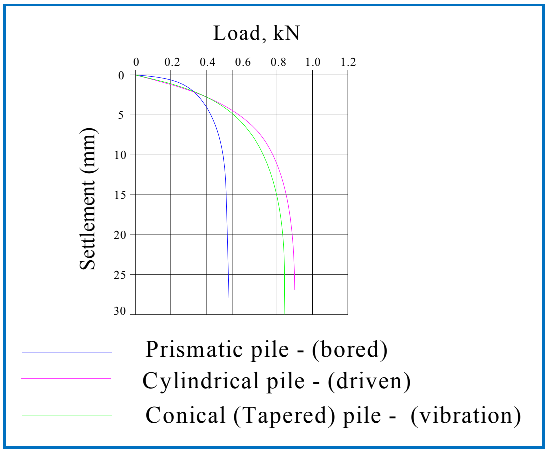
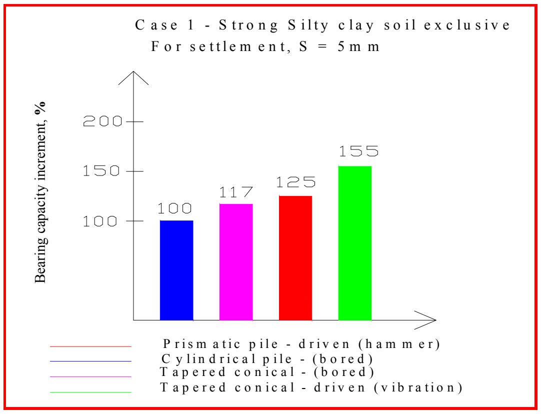


Figure-15: Load-settlement for test piles - case 7

The increment in bearing capacity for a uniform design 5mm settlement, for the laboratory test, which corresponds to 40 mm settlement on the field, for modeled single piles in the 7-modeled soil conditions (cases), was further analyzed and presented in **Figures-16 - 22**.



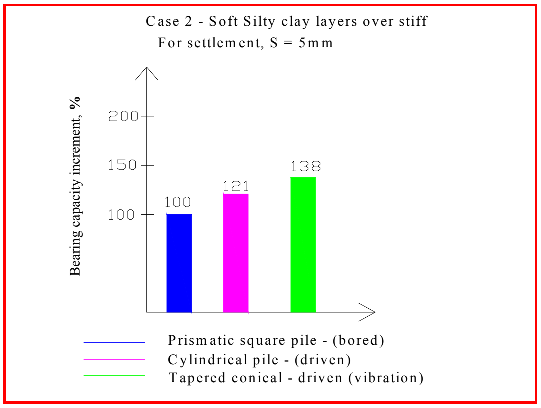
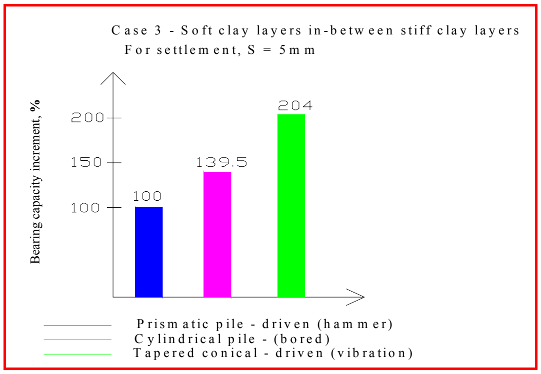


Figure-16: Bearing capacity of piles - case 1

Figure-17: Bearing capacity of piles - case 2



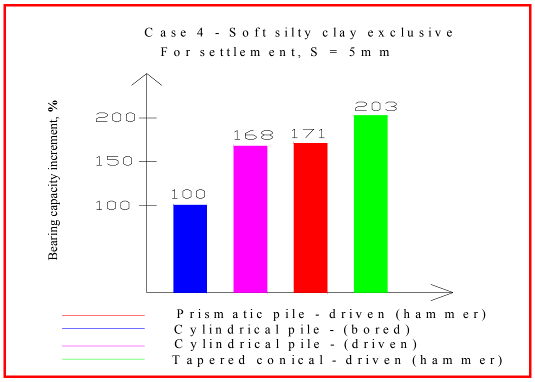


Figure-18: Bearing capacity of piles - case 3

Figure-19: Bearing capacity of piles - case 4

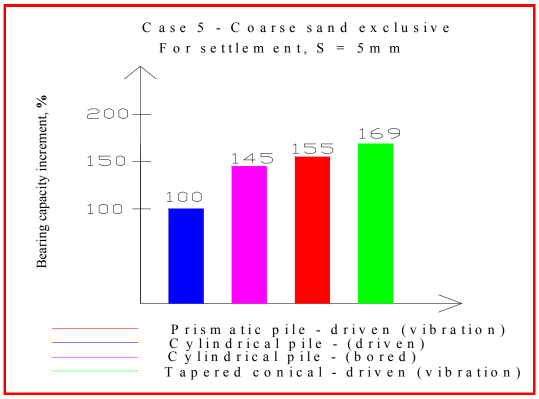


Figure-20: Bearing capacity of piles - case 5

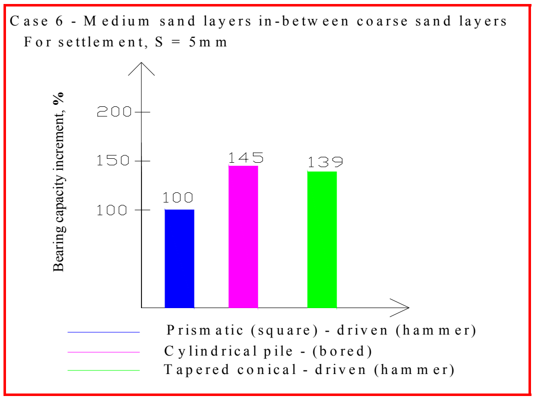


Figure-21: Bearing capacity of piles - case 6

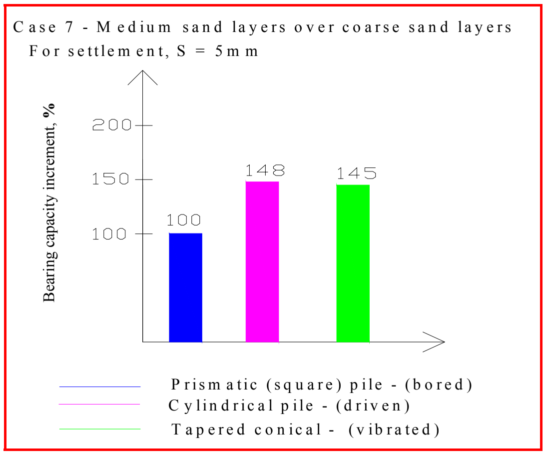


Figure-22: Bearing capacity of piles - case 7

Using the mechanism of pile cap-soil (i.e. pile cap-soil contact also known as lowered pile cap system), the bearing capacities of cylindrical, prismatic and conical cross section shaft piles were also analyzed and compared. Selected representative critical soil condition scenarios are shown in shown in **Figures 23** – **26** below.

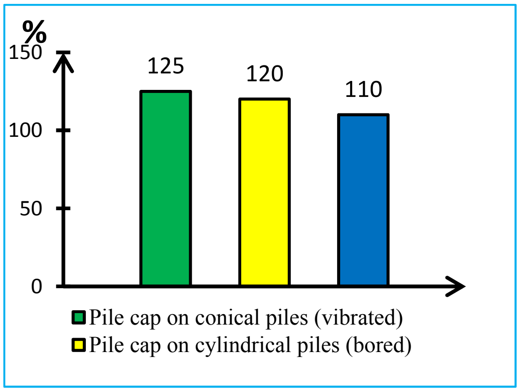


Figure-23: B/Capacity of pile & pile cap - case 1

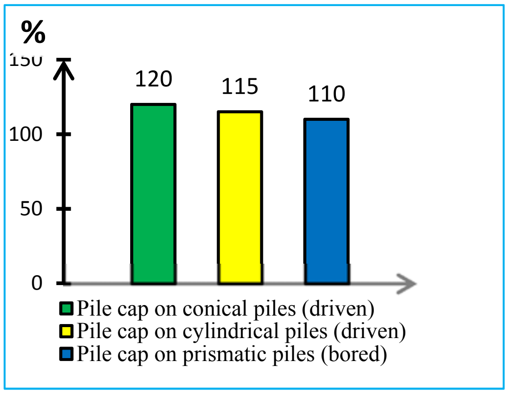


Figure-24: B/Capacity of pile & pile cap - case 2

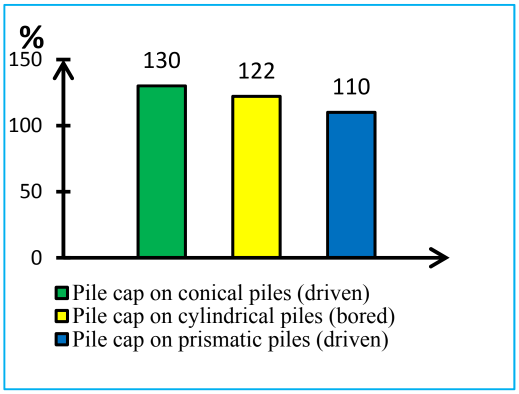


Figure-25: B/Capacity of pile & pile cap - case 5

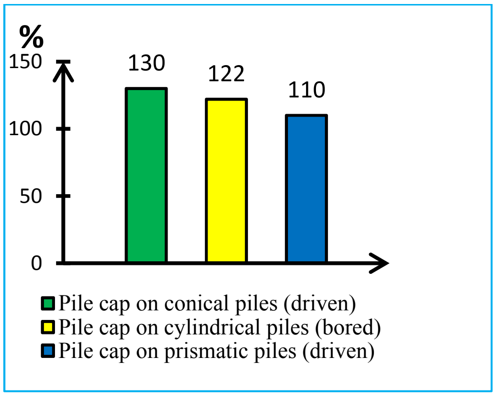


Figure-26: B/Capacity of pile & pile cap - case 7

CONCLUSIONS

From the analysis of results from laboratory and filed investigations on the influence of shaft configuration and method of installation on the load bearing capacity of pile foundations, the following conclusions may be drawn:

- In fairly homogeneous silty clay and sandy soils, tapered conical piles have higher bearing capacity than cylindrical and prismatic piles in both soft (weak) and strong or stiff soil conditions.
- With stronger silty clay layer over soft silty clay layer, as well as exclusive soft silty clay, conical pile with tapered cross section yielded higher maximum load carrying capacity except for driving by vibration method.
- In exclusive fine sandy (soft) soils, the tests yielded bearing capacity increments of 10% in bored piles, 21% in hammered driven piles, and 26% in vibrated driven piles.
- Pile driving (by hammer of vibrator) yielded a higher result in sandy soils, boring installation is better in cohesive clay and silty clay soil. This phenomenon is in agreement with the submissions of most early scholars and researchers in pile foundation constructions.
- The bearing capacity of conical piles with tapered cross section is 2-3 times higher than cylindrical piles and 1.5 – 2 times higher than prismatic piles respectively.
- The correlation between the laboratory modeled test and field investigations results is 88% agreement, which is within acceptable limits, especially giving the divergences, which usually occur between easily controlled modeled tests and difficulties usually experienced during filed operations.

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