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Research Article

Effects of Shape and Technology of Installation on the Bearing Capacity of Pile Foundations in Layered Soil

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Abstract: Among other factors, which influence the bearing capacity of piles, the shape of its external configuration, as well the installation technique employed during construction, also play major roles. This paper presents the results of recent experimental investigation on effects of shape and technology of installation on the bearing capacity of pile foundations. The results from both laboratory and field investigations conducted on modeled prototype test piles of cylindrical, prismatic (square) and tapered conical sections are presented in this study. The piles were installed by driving (hammering and vibration) and boring techniques. The results of influence of installation methods, show bearing capacity increments of 10% in bored piles, 20-22% in hammered driven piles, and 20-30% in vibrated driven piles. The bearing capacity of tapered conical piles is 1.5 – 2 times higher than prismatic (square) piles and 2-3 times higher than cylindrical piles respectively. Tapered conical piles have higher bearing capacity in fairly homogenous soils, (whether soft or stronger). In sandy and silty sand soils, especially where fine sand overlaid a stronger coarse sand layers, driven piles (hammer or vibration) have higher bearing capacity than bored piles, whereas the latter have higher bearing capacity where soft fine sand sandwiched between stronger coarse sand layers. 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.
Keywords: Shape factor; Bearing capacity; Settlement; Pile foundation; Installation technology, Layered soil.

INTRODUCTION

Piles are primarily used to carry vertical compression loads (compression piles), as well as resist uplift loads (tension or anchor piles), horizontal and inclined loads (batter piles),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. According to Murthy, 2007, structural loads may be transferred to deeper firm strata by means of piles [1].A modified form of the general bearing capacity equation may be used to account for the effects of footing shape, ground surface slope, base inclination, and inclined loading [2]. The compaction of the soil mass around a driven pile (compression 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 [3].

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 is 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 [1].

The determination of the ultimate bearing capacity, Q_u, of a deep foundation based on most theories is a very complex one, since there are many factors, which 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 [1]. According to De Beer, 1965, the base resistance of bored and cast-in-situ pile is about one third of that of driven pile [4].Sitnikov *et al.* 1980, 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 [5].

According to Meyerhof, 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 [6, 7]. However, Kerisel 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 [8, 9]. Kishida proposed from model and field test, that the angle of internal friction decreases linearly from a maximum value φ_2 at the tip of the pile to a lower value φ_1 at a distance 3.5 times pile diameter; φ_1 and φ_2 being pre-installation and post-installation angle of internal friction respectively [10].Vesic 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 [11]. Based on theoretical relations to plastic equilibrium, a critical state frictional angle (φ'_{cv}), which is effective and a rational practical application as a strength parameter has been derived by researchers [12-14]

Comparison of observed base resistances of piles by Nurdlund, 1963 [15] and Vesic, 1964 [16], have shown by Tomlinson, 1986 [17] that bearing capacity factor Nq values established by Berezantsev *et al*. 1961 [18], which take into account the depth to width ration of the pile, most nearly conform to practical criteria of pile failure. The ultimate unit skin friction of piles in a given sand or clay is practically independent of the pile diameter [7] and [19].The collapsibility properties of a highly porous layered soil diminish with depth, from 2-3% to 1 - 1.5%, while the unit bearing capacity of bored piles reduces 2-3 times on the average [20].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 [21].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 [22] and [23].

In practice, absolute homogenous soil, especially over several meters through which piles usually penetrate, rarely exit, if at all they do. Soil of varied types usually interwoven in beds and layers in real life occurrence. This paper therefore, presents the results of a series of modeled pile tests as well as field tests on the effects of shape and technology of installation on the bearing capacity of pile foundations in layered soil. The investigation was conducted with piles of cylindrical, prismatic (square) and tapered conical sections in the research laboratory, Geotechnical and Environmental Engineering department, Belarusian National Technical University, Minsk and construction sites, also in Minsk region of Belarus. This investigation is essential in the understanding of the analytical techniques of pile design in relation to determination of the bearing capacity, especially in multi-layered soil situations to ensure a rational choice of shape and method of installation during pile construction.

MATERIAL AND METHODS

Detailed laboratory investigations were conducted on soil samples taken from sites around Minsk province of Belarus, where field tests were also carried out. Consolidated in a specially constructed multipurpose test tank, (Fig. 1), the soil samples were properly pulverized and mixed to the desired water content and bulk densities (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.

After layer by layer densities were achieved, axial compressive load was applied through the upper surface layer. The testing tank was then made rigid and ready for pile installation by driving (hammering and by vibration), as well as by boring (Fig. 1- 3). Detailed procedures of laboratory investigations are contained in my earlier works including [24 - 26].

The field investigations were performed on 18 No instrumental piles of cylindrical, prismatic and tapered conical sections, (3 for each shape) 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 as shown in (Fig. 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. 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 [27 - 30] as well as Europe code 7 [31, 32]. The settlement was taken with time until the time when the settlement change was insignificant. Section of tapered conical shaped pile is shown in (Fig. 6).

Bearing capacity of modeled piles of different shapes were determined using the established methods of static bearing capacity equations and field load test method. The results were analyzed, and inferences on the effects of shape and installation technology on the bearing capacity of pile foundations in layered soilwere made thereafter.

Fig.1: Testing device for laboratory work

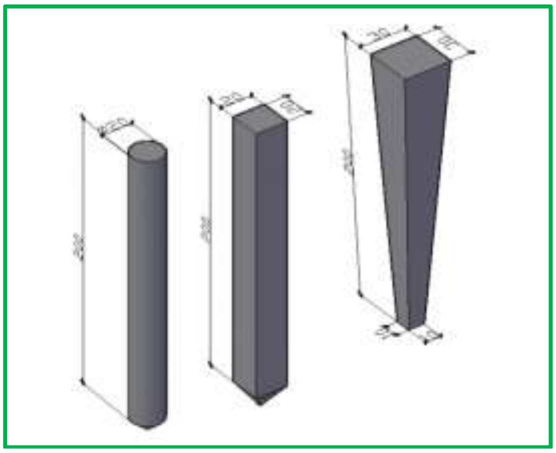

Fig.2: Modeled pile configurations (shape)

Fig.3: Modeled test piles bored into the soil

Fig.4: Loading device of 200T capacity HJ

Fig.5: Dial gauges for Settlement Reading

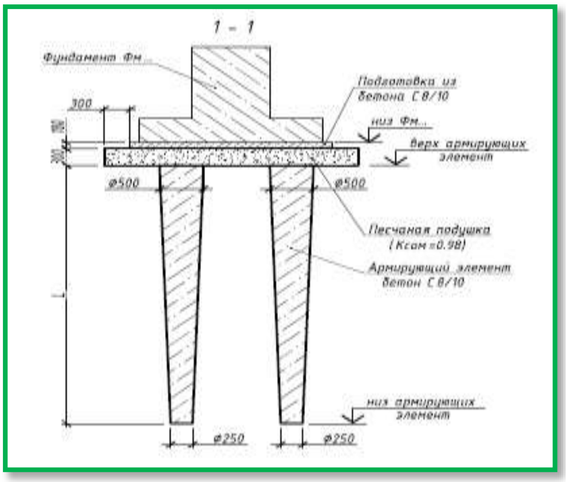

Fig.6: Section of conical shaped pile

RESULTS AND DISCUSSION

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 [33 - 35].

Table 1: Summary of Geotechnical properties of the investigated clay 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
Densityγ, (*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	-	-

Seven soil condition cases were modeled with the three chosen shapes of piles for the laboratory investigations in the testing tank. They are: *1*) Strong Silty clay soil exclusive; *2*) Soft Silty clay layers over stiff; *3*) Soft clay layers in-between stiff clay layers; *4*) Soft silty clay exclusive; *5*) Coarse sand exclusive*6*) Medium sand layers in-between coarse sand layers;*7*) Medium sand layers over coarse sand layers. Deformation of 2x2-pile group is shown in (Fig. 7).

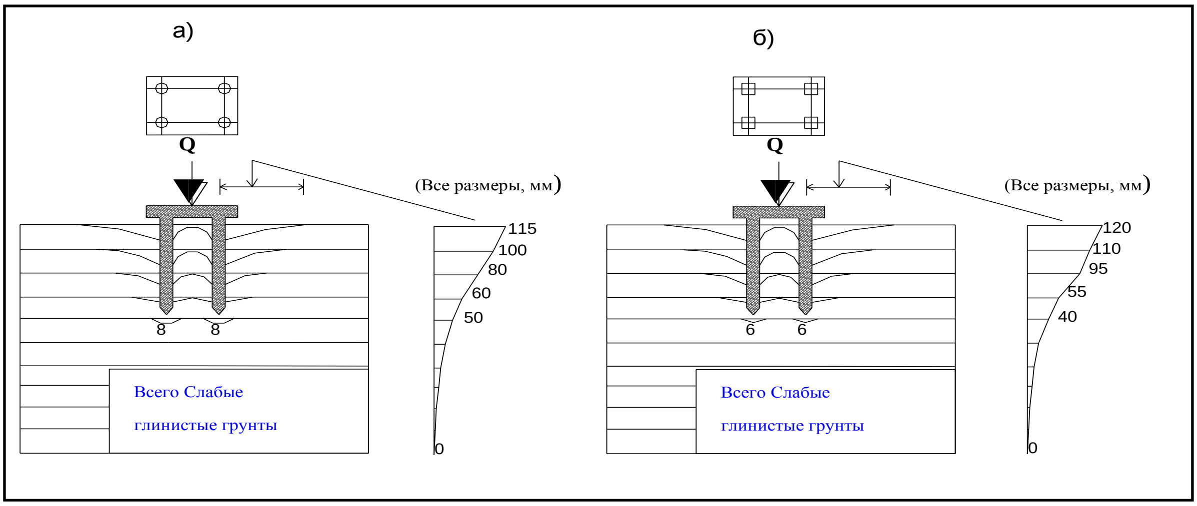

Fig.7: Deformationof2x2-pilegroup for Case-4soil condition:(a) - cylindrical shaped piles (б) tapered conical section.

Using static bearing capacity equations and field load tests method, the increment in bearing capacity for a uniform design 5mm settlement, (for a 2.5D critical state design, where D is pile diameter), for modeled single piles in the 7-modeled soil conditions (cases), were analyzed and shown in (Figs. 8 -14).

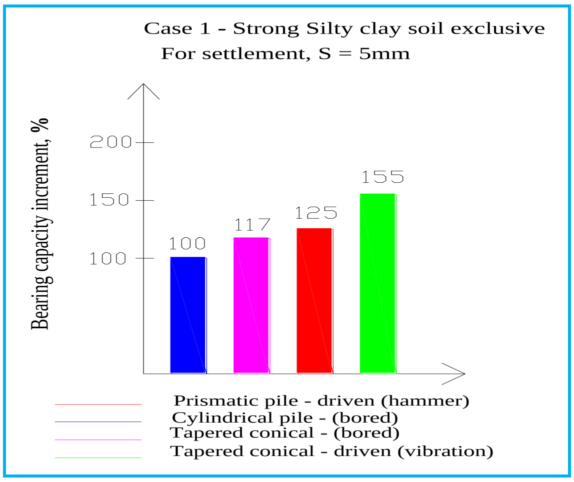

Fig.8: Bearing capacity of piles - case 1

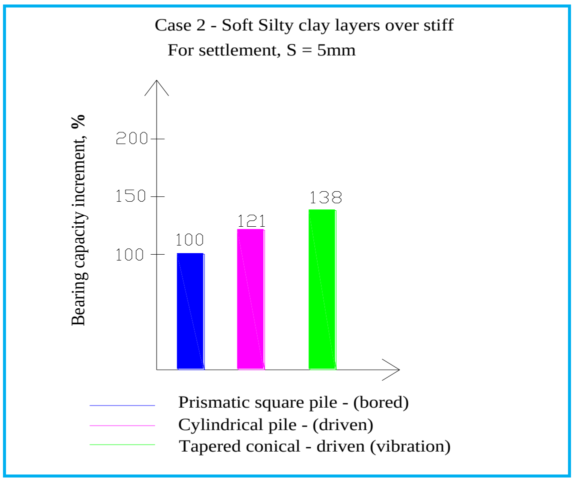

Fig.9:Bearing capacity of piles - case 2

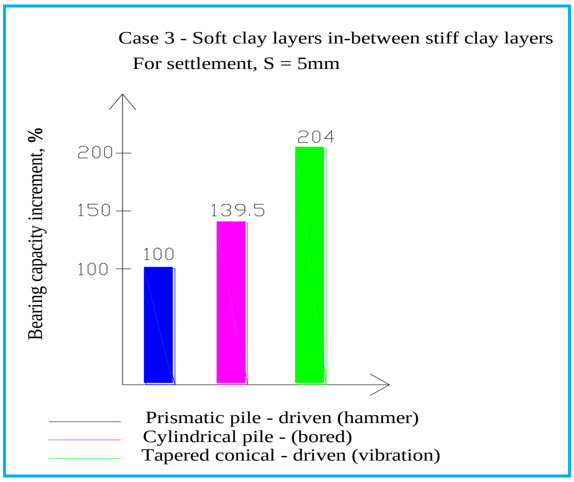

Fig.10: Bearing capacity of piles - case 3

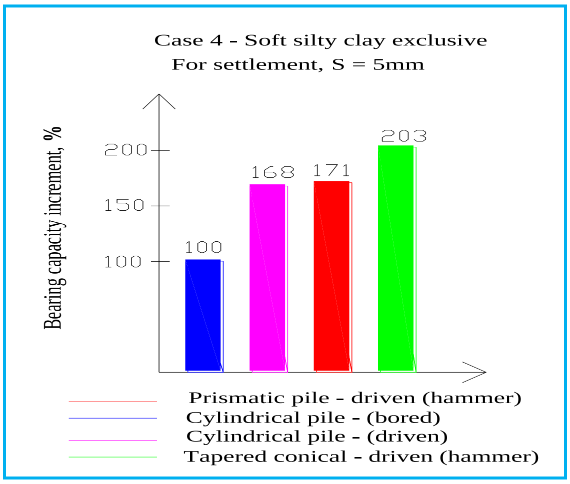

Fig.11: Bearing capacity of piles - case 4

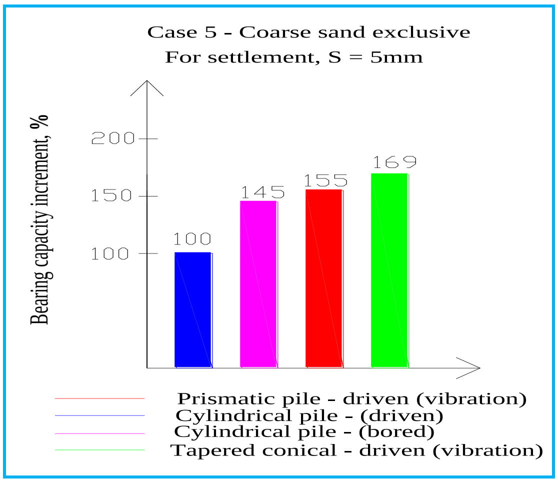

Fig.12: Bearing capacity of piles - case 5

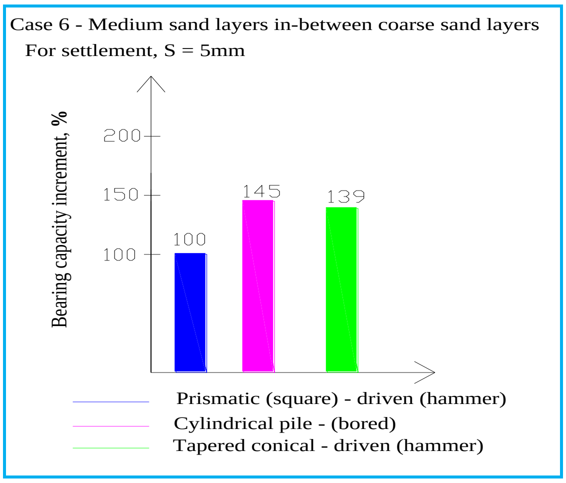

Fig.13: Bearing capacity of piles - case 6

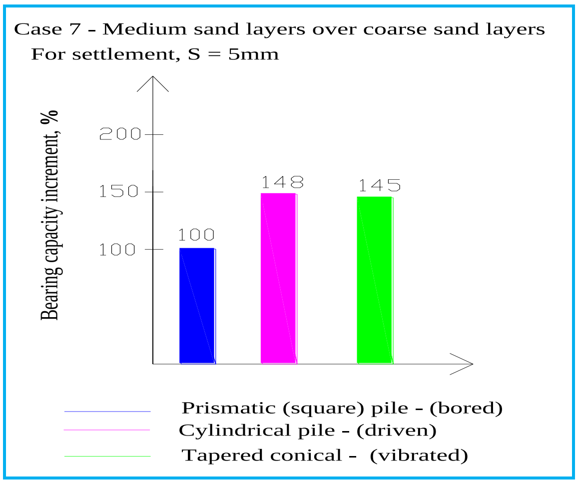

Fig.14: Bearing capacity of piles - case 7

The bearing capacities development of the piles were also analyzed and compared using Pile-pile cap mechanism of pile cap-soil contact, i.e. contact soil pile cap system. Representative critical soil condition scenarios are shown in shown in (Figs. 15 – 18) below.

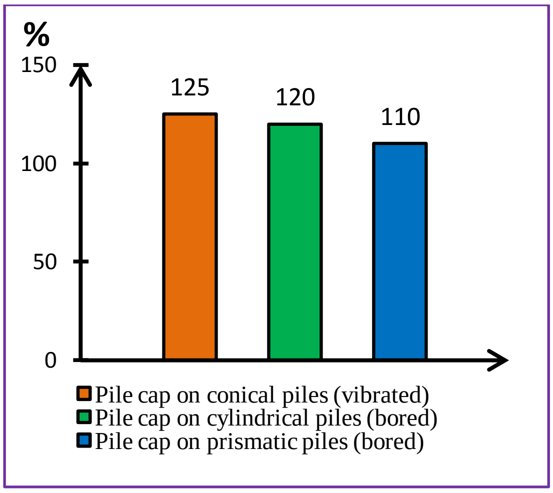

Fig.15: B/Capacity of pile & pile cap - case 1

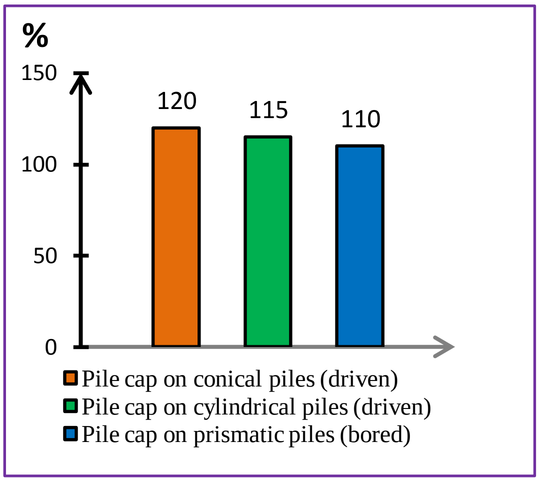

Fig.16: B/Capacity of pile & pile cap - case 2

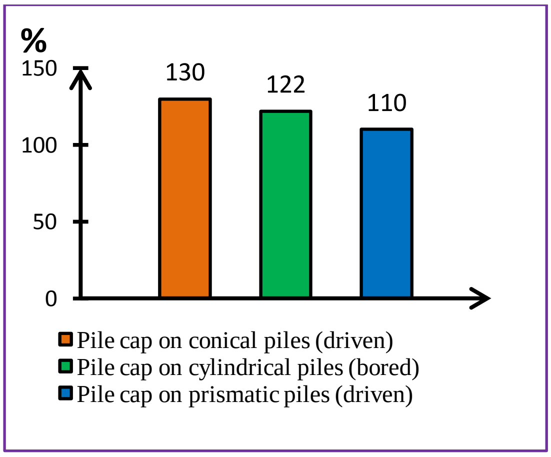

Fig.17: B/Capacity of pile & pile cap - case 5

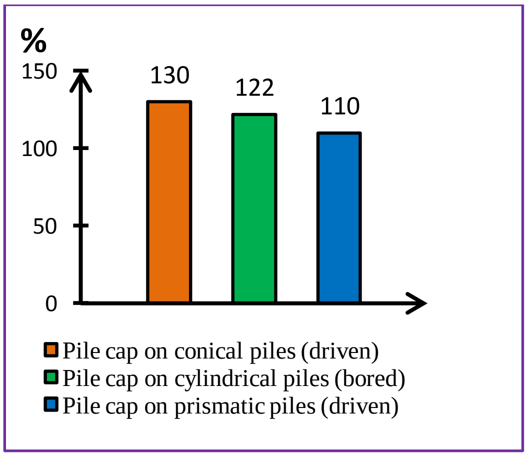

Fig.18: B/Capacity of pile & pile cap - case 7

CONCLUSION

From the analyzed results of the laboratory and field investigations carried out to study the effects of shape and installation technology on the bearing capacity of pile foundations in layered soil, the following deductions can be made;

1. The results of field investigations and laboratory tests for modeled piles have an 88% agreement, which is within acceptable limits of correlation;
2. Infairly homogeneous silty clay and sandy soils, tapered conical piles have higher bearing capacity than cylindrical and prismatic piles in both soft (weak) and strong soil conditions;
3. With stronger silty clay strata over soft silty clay strata, as well as exclusive soft silty clay, conical tapered piles yielded higher maximum load carrying capacity except for driving by vibration method;
4. In the sandy soil (with fine sandy layers over coarse layers) driving by vibration yielded higher load bearing capacity in the piles than boring method. However, bored pile piles have slightly higher bearing capacity in layered soil with soft sand sandwiching between stronger coarse sand layers;
5. In exclusive fine sandy (soft) soils, the tests yielded bearing capacity increments of 10% in bored piles, 20-22% in hammered driven piles, and 20-30% in vibrated driven piles;
6. 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;
7. The bearing capacity of tapered conical piles is 1.5 – 2 times higher than prismatic (square) piles and 2-3 times higher than cylindrical piles respectively;
8. Pile driving (hammering of vibration) yielded a higher result in sandy soils, boring 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.

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REFERENCES

1. Murthy VNS; Advance Foundation Engineering, Geotechnical Engineering Series, 1st edition, CBS Publisher & Distributors, New Delhi, 2007:251–534.
2. General Requirements and Materials, Bridge Design Specification, Section 4–Foundations, Caltrans, November 2003: Part A, 4–1-4–8.
3. Manandhar S, Yasufuku N, Omine K, Kobayashi T; Response of tapered piles in cohesionless soil based on model tests, Journal of Nepal Geological Society, 2010; 40:85–92.
4. De Beer EE; Bearing Capacity and Settlement of Shallow Foundations on Sands, Proceeding, Symposium on the Bearing Capacity and Settlement of Foundations, Duke University, Durham, NC, 1965; 15–34.
5. Sitnikov MA, Shaitarov LD, Lozovik MA; Introduction of rectangular pyramidal piles in Belorussia, Soil Mechanics and Foundation Engineering, 1980; 17(1):5–10.
6. Meyerhof GG; compaction of Sands and Bearing Capacity of Piles, JSFMD, ASCE, 1959; 85: SM 6.
7. Meyerhof GG; Bearing capacity and settlement of pile foundations, 11th Terzaghi Lecture, 5th November 1975, Jour. Geotech. Eng. Div. Am. Sot. Civ. Engr., 1976; 102, GT3:195–228.
8. Kerisel J; Foundation Profoundesen Milieu Sableux, Proc. 5th Intern. Conf. SM and Found. Eng., 1961; 2.
9. Kerisel J; Deep Foundation – Basic experimental facts, Proc. No. Amer. Conf. on Deep Foundations, Mexico City, 1964; 1.
10. Kishida H; Ultimate Bearing Capacity of Piles Driven into Loose Sand, Soil and Foundations, 1967; 7(3).
11. Vesic, AS; A Study of Bearing Capacity of Deep Foundations, Final Report, School of Civil Engineering, Georgia Institute of Technology, Atlanta, U.S.A. 1967.
12. Yasufuku N, Ochiai H and Maeda Y; Geotechnical analysis of skin friction of cast-in-place piles, Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering (SMFE '97), 1997; Hamburg:921–924.
13. Yasufuku N, Ochiai H, Kwag JM and K. Miyazaki; Effectiveness of critical state friction angle of volcanic ash soils in design applications, Proceedings of the International Symposium on Problematic Soils, IS-Tohoku, 1998; 1:189–193.
14. Bolton MD; What are partial factor for, Proceedings of the International on Limit State Design in Geotechnical Engineering, Danish Geotechnical society for ISSMFE TC23, DGF Bulletin, Copenhagen, 1993; Vol. 10: 565–583.
15. Nordlund RL; Bearing Capacity of Piles in Cohesionless Soils, JSMFD, ASCE, 1963; Vol.89: SM 3.

16. Vesic AS; Investigation of Bearing Capacity of Piles in Sand, Proc. No. Amer. Conf. on Deep Foundations, Mexico City, 1964; Vol. 1.
17. Tomlinson MJ; Foundation Design and Construction. 7th Edition, Pearson Education Ltd., England: Prentice Hall, 2001:276–387.
18. Berezantsev VG, Khristoforov V, and Golubkov V; Load Bearing Capacity and Deformation of Pile Foundations, Proc. 5th Int. Conf. of Soil Mech. and Found. Eng., 1961; 2.
19. Meyerhof GG; Scale Effects of Ultimate pile Capacity, Journal of Geotechnical Engineering, 1983; 109 (6):797–806.
20. Belyaev VI and Rud YP; 1979. Effect of boring method on bearing capacity of short cast-in-place piles, Soil Mechanics and Foundation Engineering, 1979; 16(4):194–197.
21. Adejumo TW; Settlement and Deformation Pattern of Modeled Wooden Piles in Clay, International Journal of Advanced Technology and Engineering Research, IJATER, 2013; 3 (3):94–99.
22. Manandhar S and Yasufuku N; Evaluation of skin friction of tapered piles in sands based on Cavity Expansion Theory, Memoirs of the Faculty of Engineering, Kyushu University, 2011; 71(4):101–126.
23. Manandhar S, Yasufuku N and Omine K; Application of cavity expansion theory for evaluation of skin friction of tapered piles in sands, International Journal of Geo-Engineering, 2012; 4(3):5–17.
24. Adejumo TW, Alhassan M and Boiko IL; Laboratory Investigation of Load Incremental Effect on the Deformation of Clay under Axially loaded Modeled Circular Piles, 11th International Conference, Modern Building Materials, Structures and Techniques, Vilnius Gediminas Technical University, Vilnius, Lithuania, May 16 – 17, 2013, Procedia Engineering, Elsevier Journals, 2013; 57:83 – 87.
25. Adejumo TW; Settlement Analysis of Wooden Piles in Clay, International Journal of Science, Engineering and Technology Research, IJSETR, 2013; 2(4):778 – 782.
26. Adejumo TW; Modeling Analysis of Axially loaded Pile Group Settlement in Soft Compressive Clay, International Journal of Remote Sensing and Geosciences, IJRSG, 2013; 2(2):42 – 48.
27. Poulos HG, Carter JP and Small JC; Foundations and Retaining Structures–Research and Practice; State of the Art Lecture, Proc. 15th Int. Conf. Soil Mech., Found. Eng., Istanbul, 2002; (4):2527-2606.
28. Al–Saoudi NKS and Salim HM; The Behavior of groups of reinforced concrete model piles in expansive soil, Proceedings of the 2nd International Conference on Unsaturated Soils, Beijing, 1998; 1:321-326.
29. Manandhar S, Yasufuku N and Omine K; Application of cavity expansion theory for evaluation of skin friction of tapered piles in sands, International Journal of Geo-Engineering, 2012; 4(3):5-17.
30. Phanikanth VS, Choudhury D and Reddy GR; Behavior of Fixed Head Single Pile in Cohesionless Soil under Lateral Loads, Electronic Jour. of Geotech. Eng., EJGE, 2010; 15 (M):1243-1262.
31. ENV 1997-1, 1994. Eurocode 7 – Geotechnical design, part 1: General rules. CEN/TC 250/SC7. Bruxelles: 1994; ComitéEuropéen de Normalisation.
32. Bauduin C; Design procedure according to Eurocode 7 and analysis of the test results. Proceedings of the symposium Screw Piles: Installation and design in stiff clay. Rotterdam, Balkema, 2001:275-303.
33. ASTM D 2487–2006 Standard Test Method for Classification of Soils for Engineering Purposes.
34. ISO 14688-2:2004 Geotechnical Investigation and Testing – Identification and Classification of Soils.
35. ГОСТ 25100–2011. Классификация грунтов. УДК 624.131: 006.354 МКС 93.020 Ж39.