SHAFT CONFIGURATION AND BEARING CAPACITY OF PILE FOUNDATION

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ABSTRACT

This paper presents the results of recent research on shaft configuration and bearing capacity of pile foundation from both laboratory as well as field experimental investigations. Prototype piles of cylindrical, prismatic and conical sections were tested in the laboratory, with piles of corresponding (chosen) configurations/cross sections used as test piles on the field. Using experimental models and load tests, the study compares the values of bearing capacities of pile of various shape tested on weak soil in Minsk area of Belarus. Prismatic piles yielded lower strength at the early loading than both conical and cylindrical piles. But as the loading increases, it showed higher resistance to load than cylindrical, but still lower than conical piles. The results of test piles in a close test point proximity area, showed that conical piles have the highest bearing capacity, 1.5 – 2 times higher than prismatic piles, and 2 - 3 times higher than cylindrical piles. It further revealed that, for non-homogenous (layered) soil, mostly encountered in construction sites, pile installed by driven or boring have bearing capacity increment of 10 - 14% in bored piles, 18 - 24% hammer driven piles, and 20-30% in vibrated driven piles. For the investigated prototype modeled piles, as well as test piles, the tapering and wedging effects are responsible for increase in normalized skin friction and normalized lateral stresses of tapered conical piles. In all, tapered conical pile offers larger resistance than the cylindrical piles and prismatic piles, and is therefore recommended for use, with other factors being considered.

Keywords: *Shape factor, Pile foundation, Bearing capacity, Settlement*

1. INTRODUCTION

In foundation engineering practice, the main point of concern is the bearing capacity of soil. Pile foundation is a type of foundation in which pile is usually used as the source to transfer the load to deeper soil levels. Piles are long and slender structural members that transfer the load to stronger soil ignoring or through the soil of low bearing capacity. Piles foundations are therefore, recommended to provide a safe carrying capacity to support a structure when the bearing capacity of the soil is insufficient to do so. 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 [1].

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 [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, 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 [3]. According to De Beer, the base resistance of bored and cast-in-situ pile is about one third of that of driven pile [4]. Sitnikov *et al.*, 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].

Meyerhof concluded 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 [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]. 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 [10]. Kishida proposed from model and field tests, 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 [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]. Adejumo, through experimental investigations, confirmed that, among other determinants, the bearing capacity of piles is a function of method of installation of the piles, especially in layered soil [15, 16].

A comparative study of the observed base resistances of piles by Nurdlund, 1963 [17] and Vesic, 1964 [18], presented by Tomlinson, 1986 [19], showed that, the bearing capacity factor Nq values established by Berezantsev *et al*. 1961 [20], which take into account the depth to width ratio 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 [21].

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 [22]. 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 [23]. 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 [24] and [25].

This paper therefore, presents the results of a series of modeled pile tests as well as field tests on the effects of pile shaft configuration on the bearing capacity of pile foundations in layered soil. The investigation was conducted with piles of cylindrical, prismatic and tapered conical cross sections in the research laboratory, Geotechnical and Environmental Engineering Department, Belarusian National Technical University, Minsk and construction site, also in Minsk region of Belarus. This study is useful in the understanding of the analytical techniques of pile design in relation to determination of the bearing capacity, especially in multi-layered soil.

2. MATERIALS AND METHODS

A detailed research plan was developed for the two-pronged laboratory and field investigations. Laboratory tests 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, (Figure 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 Plexiglas (plasto-fiber material), which is strong enough to withstand consolidation induced pressure and strikes. The transparent strong Plexiglas 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 (Figures 1 - 3). Loading was introduced through the centerline of the pile which is connected to a Pile Design Analyser (PDA) for monitoring and analysis.

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)

The field investigations were performed on 13 No instrumental piles of cylindrical, prismatic and tapered conical sections, (5 cylindrical, 4 prismatic and 4 conical cross sectional piles respectively) at a construction site for high-rise residential buildings in Partisankaya 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 (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 2 dial gauges. Displacement/settlement of soils around the piles measurements were made in reference to the pile cap using 5 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 [26 - 27] as well as Europe code 7 [28, 29]. The settlement was taken with time until the time when the settlement change was insignificant.

The bearing capacity of prototyped 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 shaft configuration on the bearing capacity of the pile were made thereafter.

Figure 1: Testing Tank for Laboratory Work

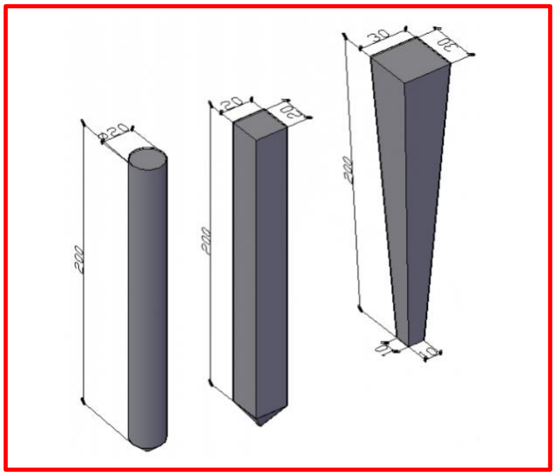

Figure 2: Modeled Pile Shaft Configurations

Figure 3: Modeled Test Piles Bored into the Soil

Figure 4: 2000T HJ as Loading Device

Figure 5: Dial gauges for Settlement Reading

Figure 6: Load Test Modeled Test Piles

3. RESULTS AND DISCUSSIONS

Table 1 shows the summary of geotechnical properties of the dominant soil in the profiles of the investigated samples. The silty-clay soil has high void ration (e) and cohesion, which indicated the compressibility of the soil. The results classified the main or dominant soils to range between, Clayed Gravel – GC (USCS), A-6 (AASHTO); Silty/clayed Gravel sand – GC (USCS), A-2-4 (AASHTO); Sandy clay – SC (USCS), A-4 (AASHTO).

Table 1: Index Properties of Samples from Test Points

Test point/ Pile No	LL (%)	PL (%)	PI (%)	GS	OMC (%)	MDD (kg/cm^3)
P1	32	20	12	2.49	13.2	1842
P2	35	22	13	2.44	18.7	1593
P3	37	20	17	2.51	17.6	1624
P5	38	23	15	2.46	15.6	1769
P6	36	24	12	2.57	16.2	1664
P7	28	21	7	2.46	20.0	1617
P8	29	22	7	2.45	19.1	1614
P10	36	22	14	2.57	16.2	1664
P12	35	21	14	2.56	16.3	1666
P13	34	23	11	2.55	16.2	1663
P20	39	24	15	2.44	18.7	1598
P22	37	20	17	2.51	17.6	1627
P23	33	20	13	2.49	13.3	1848

Using static bearing capacity equations and field load tests method, the increment in bearing capacity for a 5mm design settlement, (for a 2.5D critical state design, where D is pile diameter), for modeled single piles in the 7-modeled soil/loading (cases), were analyzed and shown in Figures. 7 - 13.

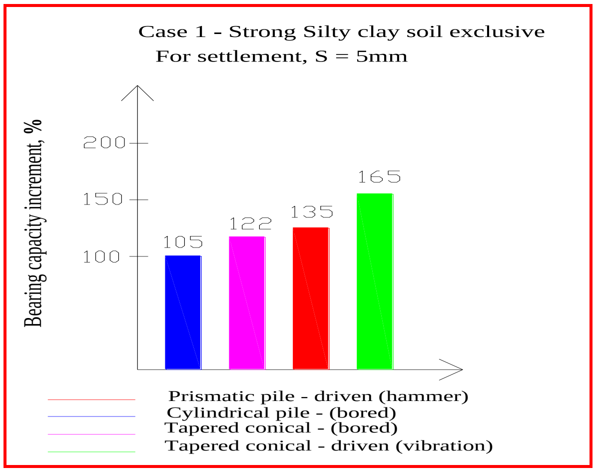

Figure 7: Bearing capacity of piles - case 1

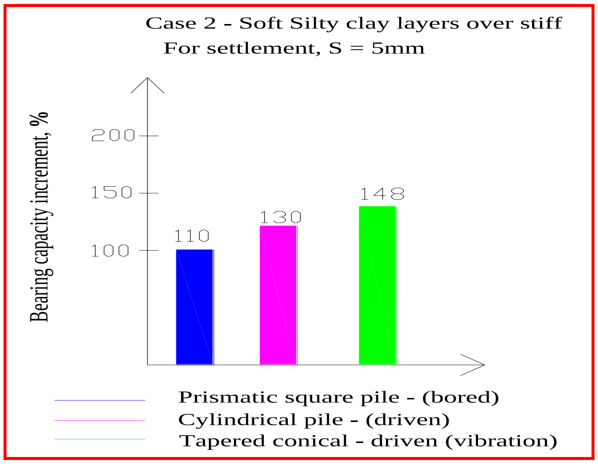

Figure 8: Bearing capacity of piles - case 2

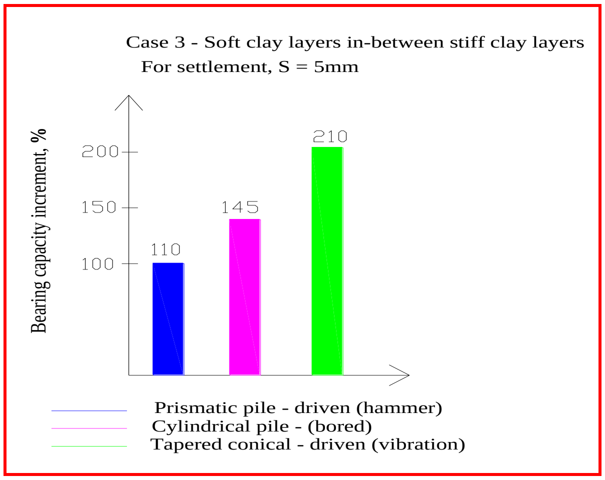

Figure 9: Bearing capacity of piles - case 3

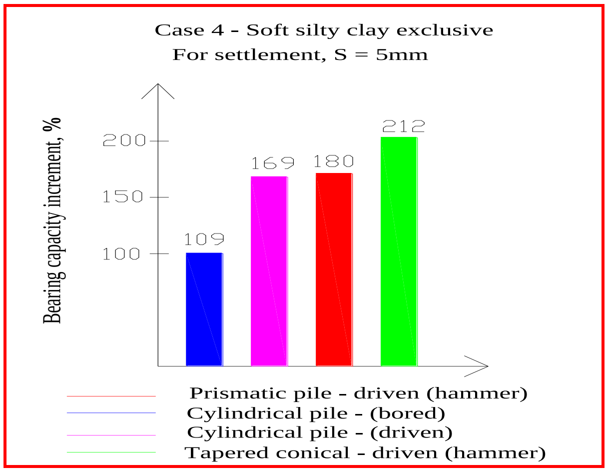

Figure 10: Bearing capacity of piles - case 4

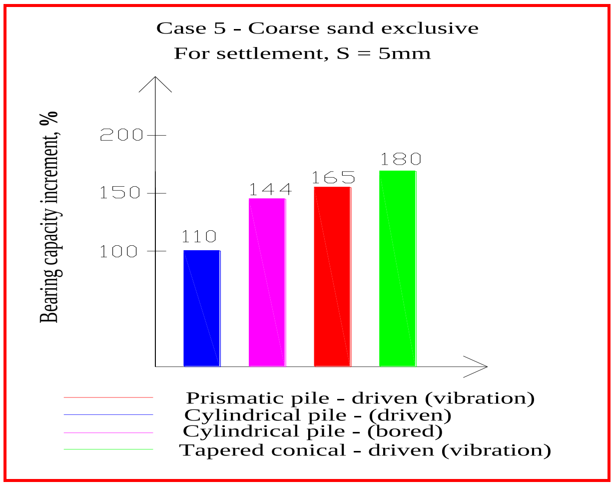

Figure 11: Bearing capacity of piles - case 5

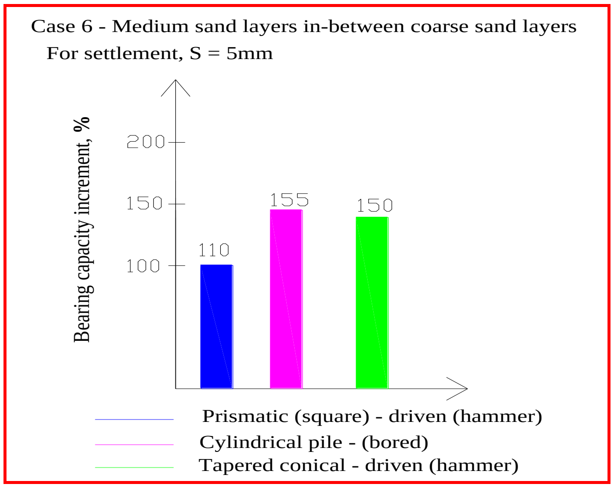

Figure 12: Bearing capacity of piles - case 6

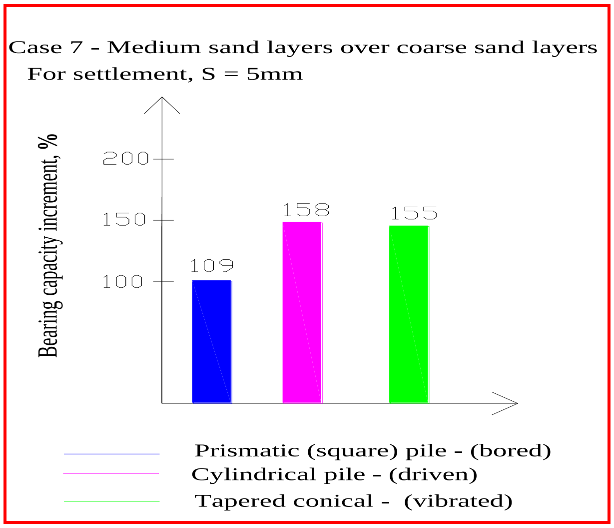

Figure 13: Bearing capacity of piles - case 7

The Load-settlement for a limiting 5mm design 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 14 - 20.

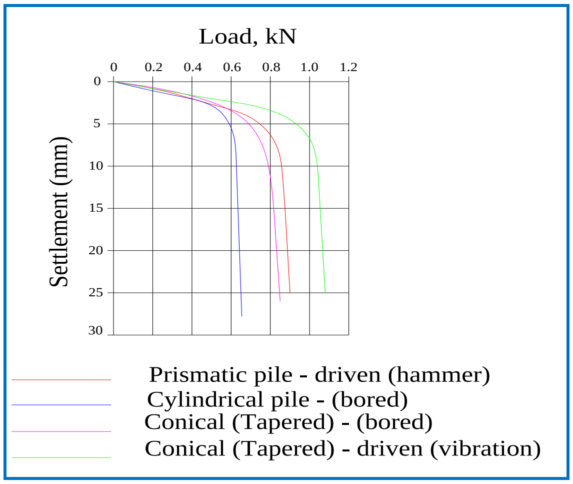

Figure 14: Load-settlement for test piles - case 1

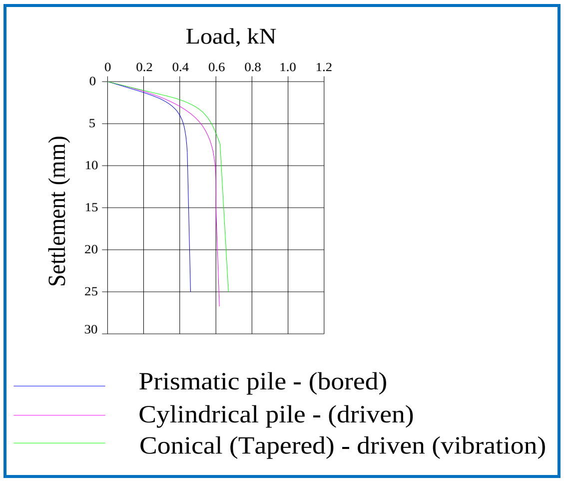

Figure 15: Load-settlement for test piles - case 2

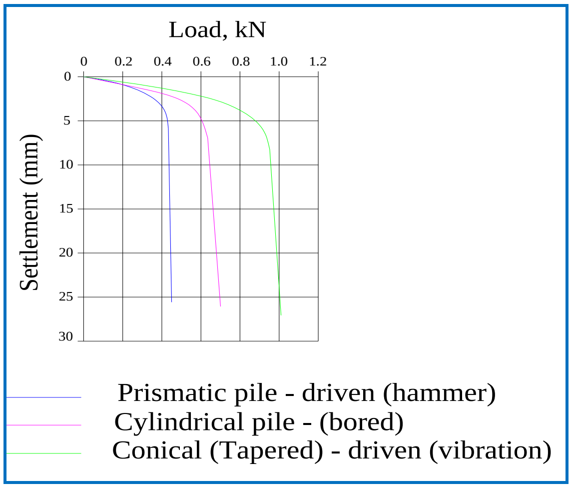

Figure 16: Load-settlement for test piles - case 3

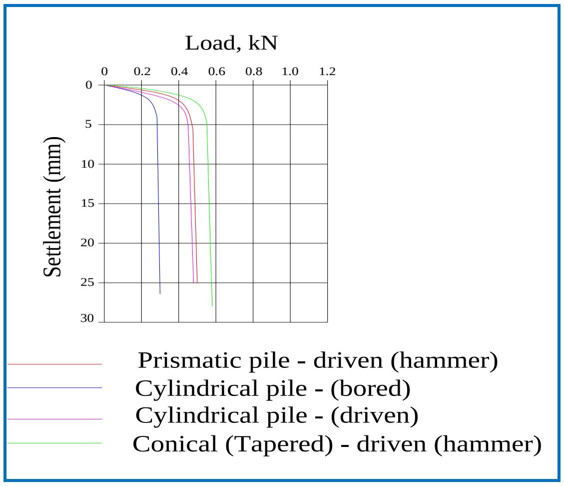

Figure 17: Load-settlement for test piles - case 4

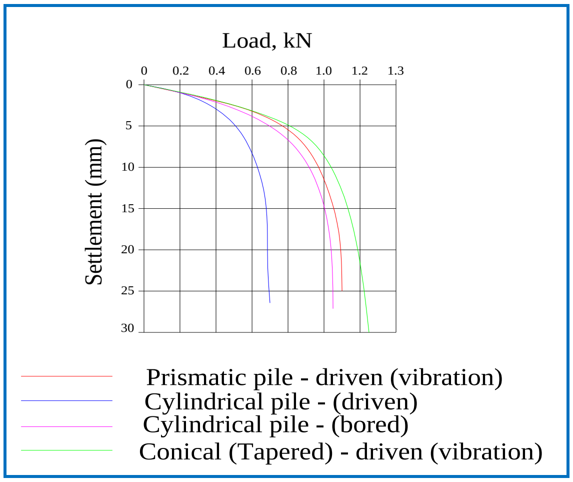

Figure 18: Load-settlement for test piles - case 5

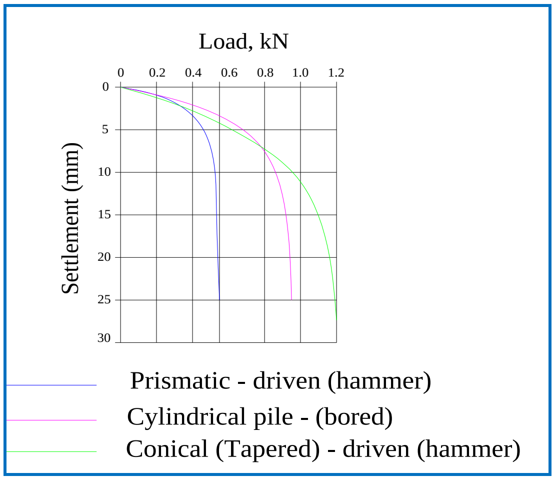

Figure 19: Load-settlement for test piles - case 6

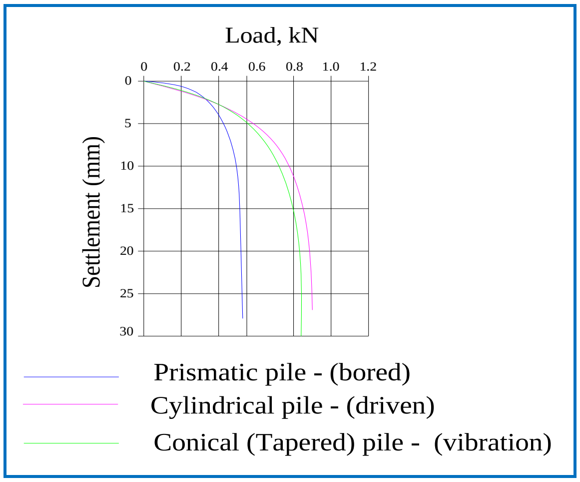

Figure 20: Load-settlement for test piles - case 7

Load-settlement curves for the 13 test piles is shown in Figure 21, while the normalized load-settlement for the ultimate load ratio is shown in Figure 22. Prismatic piles yielded lower strength at the early loading than both conical and cylindrical piles. But as the loading increases, it showed higher resistance to load than cylindrical, but still lower than conical piles.

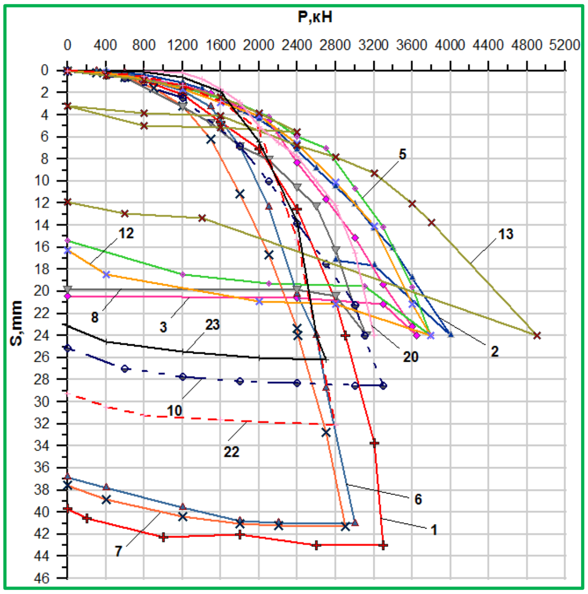

Figure 21: Load-settlement curves for the 13 Test Piles

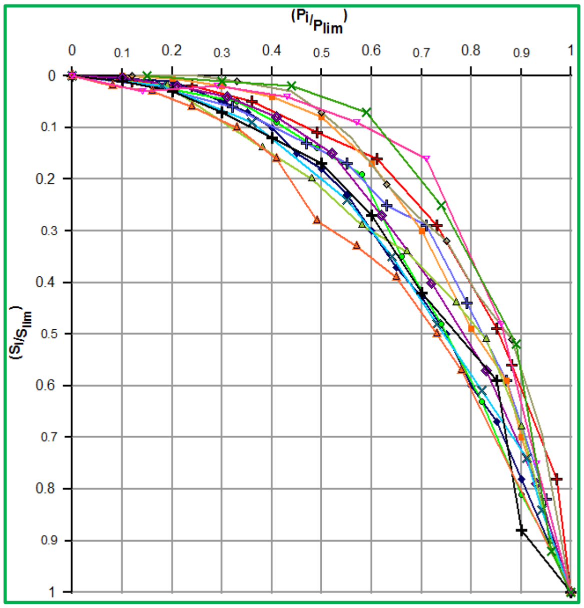

Figure 22: Normalised Load-settlement curves for the 13 Test Piles

4. CONCLUSION

From laboratory and field investigations conducted on shaft configuration and bearing capacity of pile foundation, the following conclusions could be drawn:

1. In silty-clay and clayed gravel soil, tapered conical piles yielded higher bearing capacity than cylindrical and prismatic piles.
2. For a give test area, for a given test areas (close test proximity) conical piles have the highest bearing capacity, 1.5 – 2 times higher than prismatic piles, and 2 - 3 times higher than cylindrical piles
3. For non-homogenous (layered) soil, pile installed by driven or boring have bearing capacity increment of 10 - 14% in bored piles, 18 - 24% hammer driven piles, and 20-30% in vibrated driven piles.
4. Prismatic piles yielded lower strength at the early loading than both conical and cylindrical piles. But as the loading increases, it showed higher resistance to load than cylindrical, but still lower than conical piles.
5. The results of field investigations and laboratory tests for modeled piles have an 85% agreement, which is within acceptable limits of correlation.
6. Where applicable therefore, conical piles of tapered cross section is recommended for use in weak layered soil.

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