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EFFECT OF VERTICAL CROSS-SECTIONAL SHAPE OF FOUNDATION AND SOIL REINFORCEMENT ON SETTLEMENT AND BEARING CAPACITY OF SOILS

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ABSTRACT

Bearing capacity and settlement of soils are both function of dimension and shape of foundation, embedment depth, physico-mechanical properties of soil and load geometry. Soil reinforcement is one of the methods of improving the engineering properties of soils that has gained acceptance in geotechnical engineering practices. In this paper, patterns of load-settlement characteristic of statically loaded shallow foundation models with different vertical cross-sectional shapes on both unreinforced and reinforced soft clay soils are presented. Models of shallow foundations with rectangular, wedge and T-shape vertical cross-sections were studied. The study generally shows that reinforcement of soil under shallow foundations with deferent vertical cross-sectional shapes increases bearing capacity and reduces settlement of the subsoil base. Evaluation of Bearing Capacity Ratio (BCR) shows that foundations with rectangular vertical cross-sectional shapes have higher BCR values than those foundations with T and wedge vertical cross-sectional shapes.

Keywords: Bearing capacity, Bearing capacity ratio, Foundation shape, Settlement, Soil reinforcement.

I. INTRODUCTION

The stability of civil engineering structures founded on soils depends on the ability of their foundations to effectively and safely transmit the resulting loads to the soil or rock below. By inference, it means that the stability of these structures depends on the ability of the foundation soil to safely carry the structural loads without failure due to shear or excessive settlement. The ability of soil to effectively perform this function under a foundation is a function of dimension and shape of the foundation, embedment depth, physico-mechanical properties of the soil and load geometry. Foundations are generally classified into shallow and deep foundations. Shallow foundations are considered those types of foundations that transmit structural loads to the soil strata at a relatively small depth. However, research studies have shown that, for shallow foundations, D_f/B can be as large as 3 to 4[1-3].

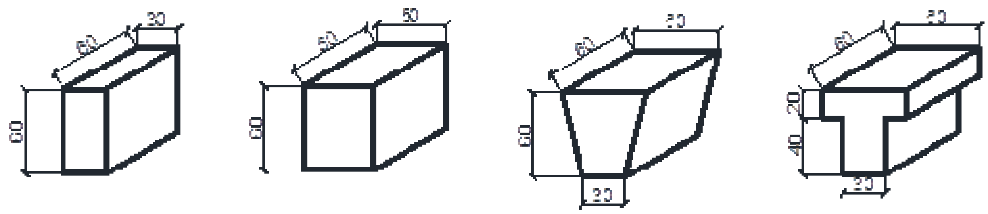
Various types (shapes) of shallow foundations are known, with strip, square, rectangular and circular being the most widely used. These types of shallow foundations have different shapes which only vary from each other plan-wise or by horizontal cross-section. The vertical cross-sections (depending on the design thickness) of these foundations are basically the same. Their (mostly) rectangular vertical cross-sectional shapes make their mode of interaction with the soil bases trunk-wise (vertically) basically the same. The interaction of foundations with soil bases is mostly studied using load-settlement relationship. Recent studies by Alhassan and Boiko [4,5], on shallow foundations with different vertical cross-sectional shapes, have shown that soil above the bases (i.e. along the vertical trunk) of foundations with T and wedge vertical cross-sectional shapes, is usually mobilized to function not only as surcharge to the soil below, but also in actively and vertically resisting structural loads.

Soil reinforcement is one of the methods of improving the engineering properties of soils that has gained acceptance in geotechnical engineering practices. A lot of studies have been carried out over the years on the interaction of foundations with reinforced subsoil bases [6-26]. Effect of vertical cross-sectional shape of foundations on the settlement and bearing capacity of reinforced soil has not been given attention in these past studies. The present study experimentally investigates the effect of vertical cross-sectional shape of foundation and soil reinforcement on load-settlement characteristic of soils. The study presents pattern of load-settlement relationship of foundations with rectangular, T and wedge vertical cross-sectional shapes on unreinforced and reinforced clay subsoil bases. This study is based on the fact that, it is commonly believed that, for design of shallow foundations, settlement criterion is more critical than the bearing capacity one [27]. Generally the settlements of shallow foundations such as pad or strip footings are limited to 25 mm [28]. Studies on (especially small scale) shallow foundations have shown that allowable bearing capacity occurs at settlement of between 5 to 10 % of foundation width. In line with the reasons advanced by Cerato and Lutenegger [29], for this study, bearing capacity at settlement of 10 % of foundation width (i.e., s/B=0.1) was adopted as allowable.

II. EXPERIMENTAL METHODOLOGY

Four wooden models of shallow foundations were used for the study: the first model was a rectangular shaped block (marked rectangular shape 1) with dimension of *30x60x60* mm for width, length and height respectively; the second model was a rectangular shaped block (marked rectangular shape 2) with dimension of *50x60x60* mm for width, length and height respectively; the third model was a wedge-shaped block of *60* mm height with width and length for top and lower sides as *60x60* mm and *30x60* mm respectively; and the fourth model was a T-shaped block of *60* mm height with width and length for top and lower parts as *60x60* mm and *30x60* mm respectively (fig. 1). The dimensions of the models were so chosen so as to be within $D_f/B \leq 2$ (D_f and B are depth of foundation embedment and width respectively). Two subsoil conditions were also modeled in the geotechnical laboratory of the Department of Geotechnics and Ecology in Civil Engineering of Belorussian National

Technical University, Minsk, Belarus. The experimental stand used for the study was a rectangular container of dimension *1100x600x250* mmforlength, height and width respectively, with a transparent front side.



a **b** **c** **d**

Fig. 1: Foundation models: **a** & **b**- rectangular shapes; **c**- wedge-shape; **d**- T-shape.

Soft clay soil having *relative consistency* of 0.67 and *liquidity index* of 0.33, with cohesion c and angle of internal friction φ, at 17 kN/m^3 unit weight and 20 % moisture content as 0 and 33° respectively, was used in modeling the subsoil bases. The properties of the soft clay are typical for normally consolidated (soft) clay soil found in Sokoto (Northwestern) region of Nigeria, as reported by Ola [30]. The modeled subsoil conditions were homogeneous unreinforced soft clay soil (fig. 2) and reinforced clay soil (fig. 3). The reinforcement material used was galvanized steel pipes of relatively small diameters. In accordance with the works by Binquet and Lee [6], Guido *et al.*[8], Khing*et al.*[11] and Puri*et al*. [19], u/B and h/B (u is depth of the first layer of reinforcement from the foundation base, h is the vertical spacing of the reinforcement layers and B is the foundation width) were both kept below 0.65 for the arrangement of reinforcement layers under all the respective foundation models, and three (N=3) layers of reinforcement were used in accordance with Akinmusuru and Akinbolade[7] and Demiröz and Tan [20]. For the T and wedge shape foundation models, the top widths of the foundations were used for the determination of u/B and h/B.

The experimental stand was filled with the soil in layers of 25 and 50 mm, with each layer compacted to unit weight of 17 kN/m^{3}at moisture content of 20 %. To easily achieve this, the weights of the wet soil, required to fill the resulting (from 25 and 50mm layers) volumes were measured and compacted to fit into the respective layers. The foundation models were placed during placement and compaction of the last two upper layers as shown in figs. 2 and 3. Using 1:10 loading lever, loads were statically, vertically, centrally and uniaxially applied to the foundations in an incremental manner, recording corresponding settlement for each load increment, using dial gauges of 1/100 mm division. Subsequent load increments were done when the rate of settlement from the previous loads becomes less than 0.02 mm/min.

On the first modeled subsoil condition i.e unreinforced soil, static loads were applied incrementally to maximum loads of 201, 170, 168 and 168 kN/m^2 to rectangular-1, rectangular-2, wedge and T-shaped foundation models respectively. While on the second subsoil condition i.e reinforced soil, maximum loads of 450, 400, 278 and 278 kN/m^2 were applied to rectangular-1, rectangular-2, wedge and T-shaped foundation models respectively.

The results for the foundation models on unreinforced and reinforced subsoil conditions are graphically presented as load-settlement curves in figs 4 and 5 respectively.

Soil Type	Thickness mm	γ кN/м^3	w %
Weak clay soil		17	20

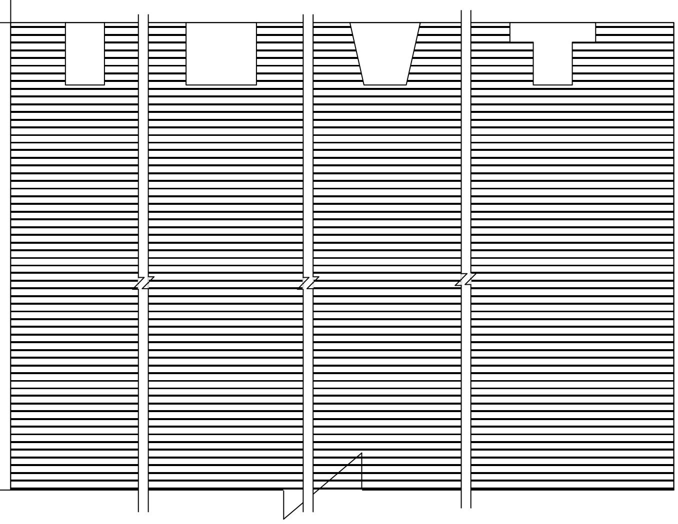


Fig. 2: Unreinforced subsoil condition

Soil Type	Thickness mm	γ кN/м^3	w %
Weak clay soil	60	17	20
Reinforced clay soil	Depends on u/B and h/B		
Weak clay soil		17	20

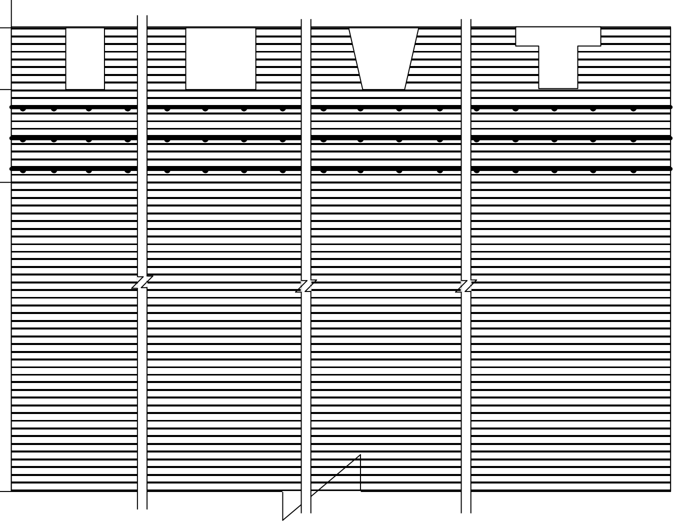


Fig. 3: Reinforced subsoil condition

III. RESULTS AND DISCUSSION

Results of load-settlement relationship of foundations models on the unreinforced and reinforced subsoil conditions are shown in fig. 4 and 5. From fig. 4, it is observed that T-shape foundation recorded the highest bearing capacities at corresponding settlements on the unreinforced soil. This can be attributed to its shape, which gives it a relatively kind of '*floating balance*', on the soft clay base, when compared with the rest shapes. The least bearing capacity was observed with wedge shape foundation. This can be attributed to the width of its lower part, which impact high settlement under the same loads magnitudes, when compare with other shapes.

Observation of results on the unreinforced (fig. 4) and reinforced (fig. 5) subsoil conditions shows that significant difference in load-settlement relationships were recorded with all the foundation models on the reinforced subsoil conditions. Higher bearing capacity values at lower settlements were generally recorded on the reinforced subsoil. The initial sudden settlement exhibited by all the foundation models, on application of the first load, on the reinforced soil, is attributed to the settlement of the soil layer in between the foundation bases and the first layer of the reinforcement. With subsequent load application, the reinforced soil base act as a single unit in resisting the loads. This phenomenon accounts for the pattern of the curves henceforth. On this condition, rectangular shape foundation models recorded the highest bearing capacity, while the least bearing capacity was also recorded from wedge shape foundation model. The higher bearing capacity values recorded from rectangular shape foundation models were as a result of the relatively wider widths of the foundation models on the reinforced soil in comparison with lower parts of T and wedge shape foundation models.

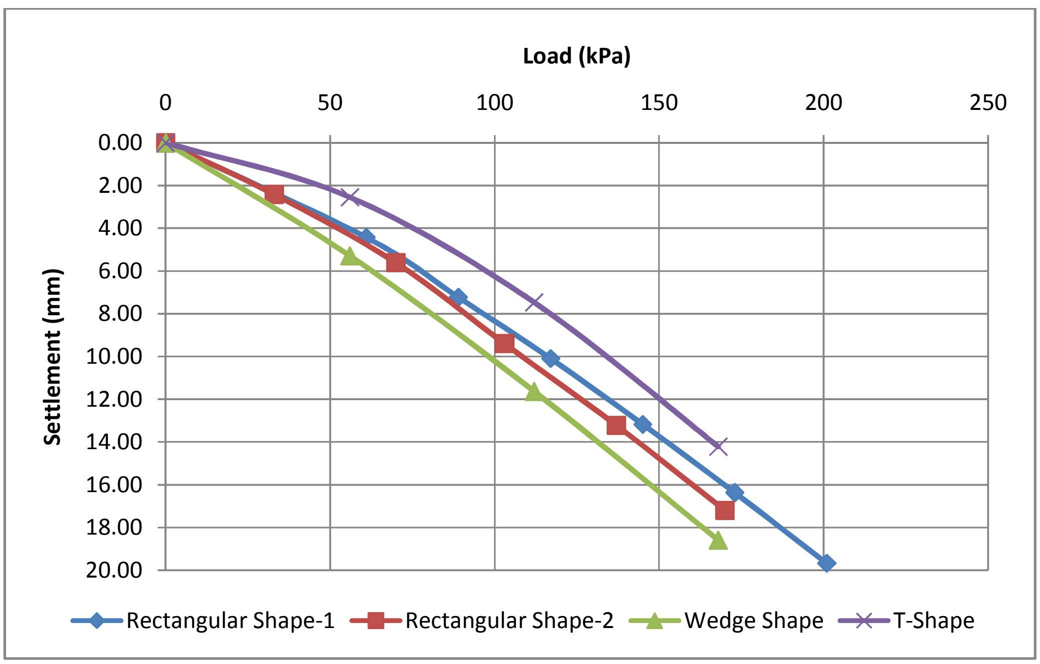


Fig. 4: Load-settlement curves for foundations models on unreinforced soil

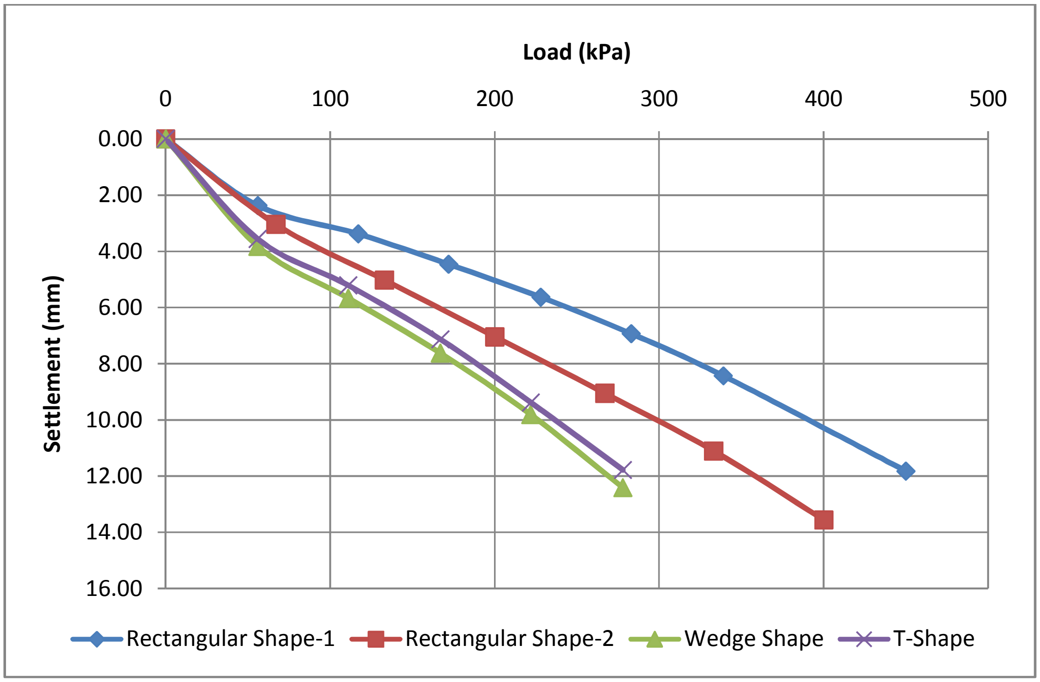


Fig. 5: Load-settlement curves for foundations models on reinforced soil

From the graphs, it is possible to evaluate the effect of the shapes of the foundations on the bearing capacity and settlement of the soils. Studies have shown that for shallow foundations on clay soils, the maximum settlement at which the bearing capacity is considered allowable, is taken as 10 % of foundation width [29, 31-34]or 25 mm, whichever is less from these values. Thus, the maximum permissible settlement of the studied foundation models is taken as 10 % of the width of the foundations models, i.e. 3 mm, 5 mm, 6 mm, and 6 mm for rectangular-1, rectangular-2, wedge and T-shape foundation prototypes respectively. Therefore, from the graphs (figs4 and 5), the allowable bearing capacity and consequently, the bearing capacity ratio of each of the foundation model at the given settlement is presented in Table 1.

Table 1: Bearing capacity of foundation models

Foundation model	Allowable Bearing capacity (kPa)		Bearing capacity ratio
	Unreinforced soil	Reinforced soil	
Rectangular shape –1	45	100	2.2
Rectangular shape –2	58	140	2.4
wedge-shape	56	120	2.1
T-shape	98	135	1.4

From table 1, it can be seen that on the unreinforced subsoil condition, the highest allowable bearing capacity of 98 kPawas recorded with T-shape foundation model. The least allowable bearing capacity of 45kPa was recorded from rectangular-1 foundation model. On the reinforced subsoil condition, the highest allowable bearing capacity was observed with the rectangular-2, while the least was observed with rectangular-1 foundation models. This can be attributed to the wider width of the rectangular-2 on reinforced soil in comparison with the rest of the foundation models. Considering the Bearing Capacity Ratio (BCR), a nondimensional quantity, expressed as:

$$BCR = \frac{q_{allow(R)}}{q_{allow}} \qquad (1)$$

where $q_{allow(R)}$and q_{allow} is the allowable bearing capacities on reinforced and unreinforced soil, respectively, although the highest bearing capacity on the unreinforced soil, was recorded from T-shape foundation, this shape of foundation recorded the least value of 1.4 for BCR, wedge shape has BCR of 2.1. The highest BCR value of 2.4 was recorded from rectangular shape-2, while rectangular shape-1 has 2.2 as BCR value. This implies that the use of foundations with wedge and T-shape vertical cross-sections on reinforced soils, especially when only the soil below the foundation bases is reinforced, will have relatively less positive effect on the bearing capacity when compare with those of rectangular shapes. This results conformed with findings by Alhassan and Boiko [4, 5], that “bulk of the load resistance of subsoil bases at the instance of shallow foundations with rectangular vertical cross-sectional shape is mostly associated with the soil beneath the foundation base, while at the instances of those with wedge and T-shape vertical cross-sectional shapes, both soil beneath the foundations’ bases and along their vertical stems, actively participates in resistance of structural loads”. Since the soil above the foundation bases is unreinforced, this account for the recorded values in the case of wedge and T-shapes foundations.

IV. CONCLUSION

The study generally showed that vertical cross-sectional shape of foundation affects the bearing capacity and settlement of both unreinforced and reinforced soil bases. The use of foundations with wedge and T-shape vertical cross-sections on reinforced soils, especially when only the soil below the foundation bases is reinforced, have relatively less positive effect on the bearing capacity when compare to those of rectangular shapes.

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