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Effect of Vertical Cross-Sectional Shape of Foundation on Settlement and Bearing Capacity of Soils

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Abstract

Load-settlement relationships of shallow foundation models with different vertical cross-sectional shapes on different modeled subsoil conditions are presented. Model of shallow foundations with rectangular, wedge and T-shape vertical cross-sections were studied. The study generally shows that bulk of the load resistance of subsoil bases at the instance of shallow foundations with rectangular vertical cross-sectional shapes is mostly associated with the soil beneath the foundation base, while at the instances of those with wedge and T-shape vertical cross-sectional shape, both soil beneath the foundations' bases and along their vertical stems, is actively involved in the resistance of structural loads.

Keywords: Bearing capacity; Foundation model; Foundation shape; Settlement; Subsoil condition; Stiff soil; Weak soil.

1. Introduction

Foundation is an integral part of a building whose stability determines the stability of the entire structure, as it acts as a medium through which loads are transmitted to the soil or rock below. Settlement and bearing capacity of soil under a foundation are both function of the latter's dimension and shape, embedment depth, physico-mechanical properties of soil and load geometry. Foundations are generally classified into shallow and deep foundations. Shallow foundations are considered those types that transmit structural loads to the soil strata at a relatively small depth. Terzaghi in 1943 defines shallow foundation as that which is laid at a depth not exceeding the width B of the foundation, that is $D_f / B \leq 1$. However, research studies conducted since then have shown that, for shallow foundations, D_f / B can be as large as 3 to 4 [1–3]. EAG [4] states that, foundation elements are considered to be shallow when the depth to breadth ratio is less than 5 ($D_f / B < 5$).

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. This makes 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. Many studies [5–15, etc] have been conducted on the effect of foundation shape on settlement and bearing capacity of soils. These past studies mostly considered the shape of the foundations plan-wise. The interaction of these shapes of foundations with the soil bases is such that the soil above their bases contributes to the resistance of the structural loads mostly by surcharging the soil below the base of the foundation. Therefore the study of other shallow foundations' shapes (especially vertical cross-sectional shapes), which can both partly distribute/resist structural loads vertically along their trunks and bases, is presented. V and T-shape

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foundations were considered along with the conventional rectangular shape foundations. The study presents pattern of load-settlement relationship of soil under foundations with these shapes. This study is anchored on the fact that, it is commonly believed that the settlement (deformation) criterion is more critical than the bearing capacity one in the designs of shallow foundations [16]. Generally the settlements of shallow foundations such as pad or strip footings are limited to 25 mm [17]. Recent studies on (especially small scale) shallow foundations have shown that allowable bearing capacity occur at settlement of between 5 to 10% of foundation width. For this study, bearing capacity at settlement of 10% of foundation width (i.e., $s/B = 0.1$) was adopted as allowable. This is in line with the reasons advanced by Cerato and Lutenegger [10].

2. Experimental Methodology

Four wooden prototypes of shallow foundations were used for the study: the first prototype was a rectangular shaped block (marked rectangular shape 1) with dimension of 30×60×60 mm for width, length and height respectively; the second prototype was a rectangular shaped block (marked rectangular shape 2) with dimension of 50×60×60 mm for width, length and height respectively; the third prototype was a wedge-shaped block of 60 mm height with width and length for top and lower sides as 60×60 mm and 30×60 mm respectively; and the fourth prototype was a T-shaped block of 60 mm height with width and length for top and lower parts as 60×60 mm and 30×60 mm respectively (Fig. 1). The dimensions of the prototypes were chosen so as to be within $D_f / B \leq 2$ (D_f and B are depth of foundation embedment and width respectively). In accordance with the physico-mechanical properties of Nigerian soils [18] and the classification of Nigerian subsoil bases by Alhassan *et al.* [19], four subsoil conditions were 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 1100×600×250 mm for length, height and width respectively, with a transparent front side.

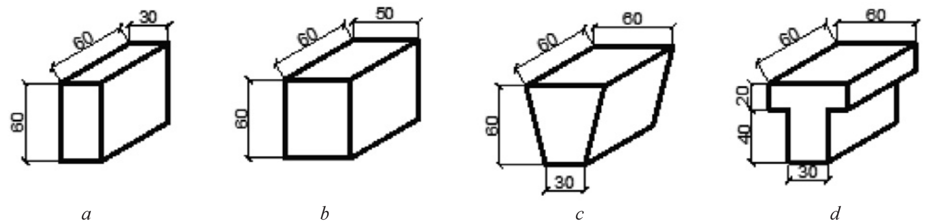

Fig. 1. Foundation prototypes: a & b- rectangular shapes; c- wedge-shape; d- T-shape

Medium size grain sand of 0.59 void ratio and two types of clay soils were used in modeling the subsoil bases. The first clay was a stiff clay soil having *relative consistency* of 2.33 and *liquidity index* of less than 0, cohesion c and angle of internal friction ϕ of the soil, at unit weight and 10% moisture content, was 20 kN/m^2 and 24° respectively, while the second was a 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. The properties of the soft clay are typical for soft clay soil found in Sokoto (Northwestern) region of Nigeria, as reported by Ola [20]. The first subsoil condition was modeled with the sandy soil at unit weight of 17 and 18 kN/m^3 and moisture content of 6% (Fig. 2). The other modeled subsoil condition included: a homogeneous stiff clay soil (Fig. 3); the second was soft clay overlaying stiff clay (Fig. 4); while the third modeled condition was soft clay in between layers of stiff clay at top and below (Fig. 5).

The experimental stand was filled with the soils in layers of 25 and 50 mm, with each layer compacted to unit weight of 18 kN/m^3, 18 kN/m^3 and 17 kN/m^3 at moisture contents of 8%, 10% and 20% for sand, stiff and soft clay soils respectively. The foundation prototypes were placed during placement and compaction of the last two upper layers as shown in Fig. 2–5. Using 1:10 loading lever, loads were 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.

The results are presented graphically as load-settlement curves for the respective foundations under respective modeled subsoil conditions in Figs 6–8.

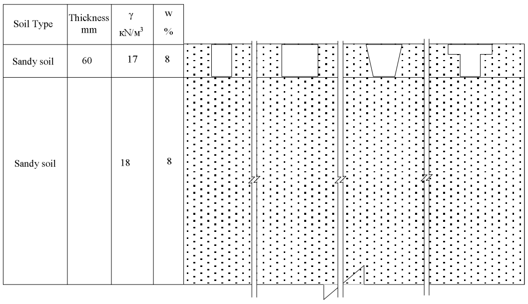

Fig. 2. First modeled soil condition (sand)

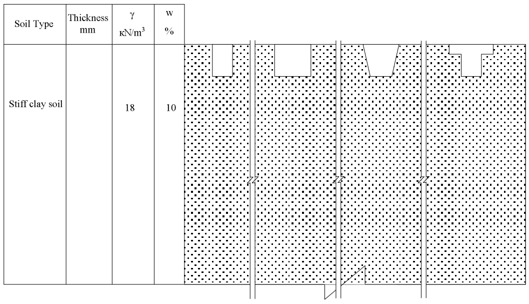

Fig. 3. Second modeled soil condition (clay soil)

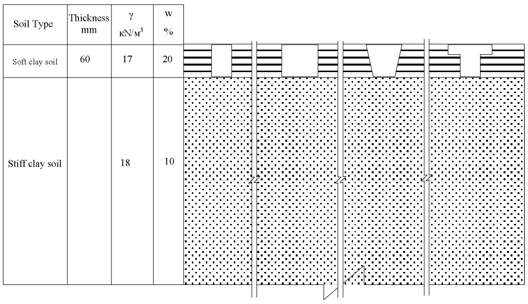

Fig. 4. Third modeled soil condition (clay soil)

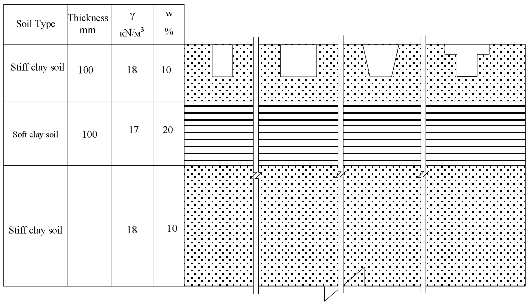

Fig. 5. Fourth modeled soil condition (clay soil)

3. Results and Discussion

Results of load-settlement relationship of foundations prototypes on the first, second and third modeled subsoil conditions are shown in Figs 6, 7 and 8. From the figures, it is observed that the bearing capacities of rectangular shape foundations are generally higher than those of wedge and T-shape foundations. The highest bearing capacity was observed with rectangular-1 shape. This can be attributed to its smaller width. The results for rectangular shape 1 and 2 on the first subsoil condition (sand) are similar to those obtained by Cerato and Lutenegger [10], Al-Khuzaei [14] and Nareeman [15]. The lower bearing capacity generally observed with wedge and T-shaped foundations can be attributed to the shape of their lower parts, which caused high settlement under the same loads magnitudes, in comparison with rectangular shapes. The width of the lower parts of wedge and T-shapes are smaller, compared to the width of their upper parts. On the first modeled subsoil condition, which was modeled with sand, the least bearing capacity was observed with wedge-shape foundation.

Observation of results on the second (Fig. 7) and third (Fig. 8) modeled subsoil conditions, shows that no significant difference in load-settlement relationship was recorded in the case of foundations with rectangular shape. But in the case of wedge and T-shape foundations, higher settlement values were recorded at corresponding loads on the third model subsoil conditions (Fig. 8). This is attributed to the presence of weaker (soft) soil above the foundations' bases. This indicates that at the instance of wedge and T-shape foundations, soil layer above the bases of the foundations, i.e. along the vertical trunk of the foundations, significantly contributes in resisting loads. The small difference recorded between second (Fig. 7) and third (Fig. 8) model subsoil conditions, in the load-settlement relationship, in the case of rectangular shape foundations, is attributed to only the surcharge contribution of the soil above the bases of the foundations.

Results of load-settlement relationship of foundations prototypes on the fourth modeled subsoil condition is shown in Fig. 9. From the figure, it is observed that at first the bearing capacities of rectangular shape foundations are higher than those of wedge and T-shape foundations. This trend is attributed to already advanced reasons in the case of the second modeled subsoil condition. With higher loads, rectangular-2 loses its bearing capacity, i.e. higher settlement values were recorded than with rectangular-1. This is attributed to the relatively wider width of the foundation, which causes formation of stressed zone (pressure bulb) spreading beyond the stiff soil lying directly beneath the foundation base. In the case of the rectangular-1, the smaller width of the foundation causes formation of stressed zone (pressure bulb) not spreading beyond the stiff soil lying directly beneath the foundation base [1, 21–24], and hence lower settlement values at corresponding pressures (Fig. 9). Under this condition, it was observed that the bearing capacity of wedge and T-shaped foundations continues to increase. This can be explained by the mobilization of the stiff soil along their vertical trunks in load resistance.

A comparison of the test results shown in Figs 7, 8 and 9 shows that the bearing capacity of foundations on the fourth modeled subsoil condition is generally smaller than in the second and third modeled subsoil conditions.

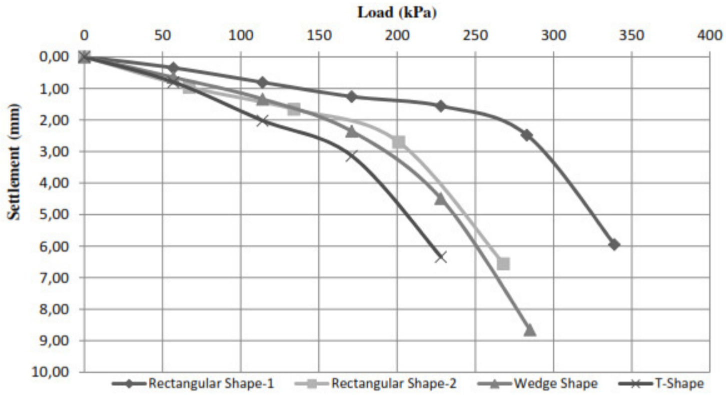

Fig. 6. Load-settlement curves for foundation prototypes on first modeled sandy subsoil condition

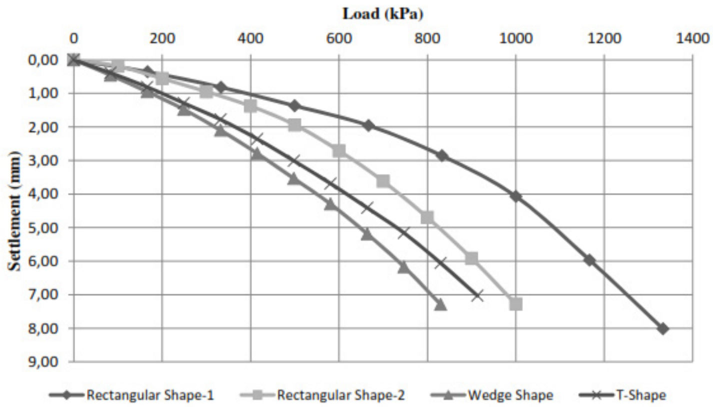

Fig. 7. Load-settlement curves for foundation prototypes on second modeled clay subsoil condition

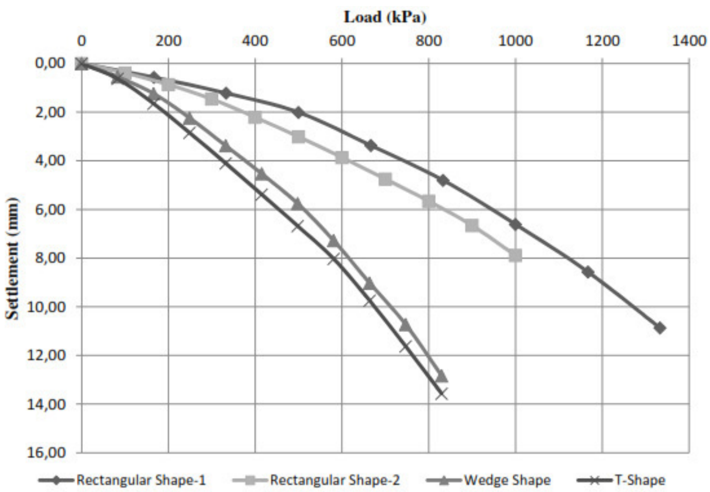

Fig. 8. Load-settlement curves for foundation prototypes on third modeled clay subsoil condition

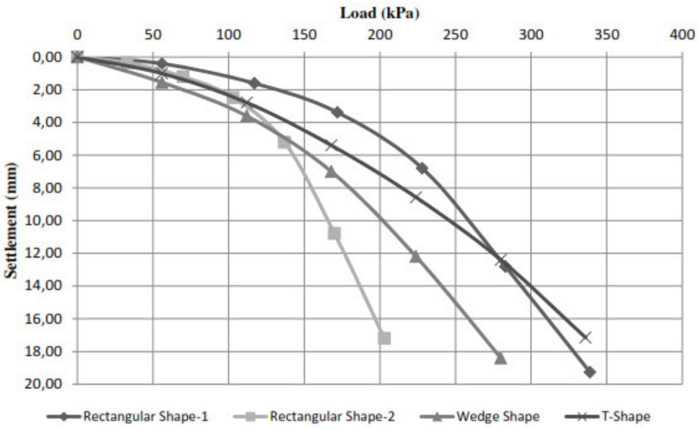

Fig. 9. Load-settlement curves for foundation prototypes on fourth modeled clay subsoil condition

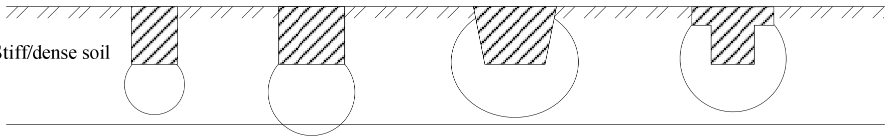

Fig. 10. Development of pressure bulbs under foundations of different widths and shapes

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 [6], [10], [13], [25], [26] or 25 mm, whichever of them is less. Thus, the maximum permissible settlement of our foundation models is taken as 10% of the width of foundations prototypes, 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 (Fig. 6–9), the allowable bearing capacity of each foundation prototype at the given settlement is presented in Table 1.

Table 1. Bearing capacity of tested foundation prototypes

Foundation type	Bearing capacity (kPa)			
	First modeled soil condition (sand)	Second modeled soil condition (clay soil)	Third modeled soil condition (clay soil)	Fourth modeled soil condition (clay soil)
Rectangular shape –1	295	863	640	165
Rectangular shape –2	260	831	720	145
wedge-shape	250	732	461	153
T-shape	243	829	521	165

From Table 1, it can be seen that on the first modeled subsoil condition, the highest allowable bearing capacity was recorded with the rectangular shaped foundation prototypes. The lowest allowable bearing capacity of 243 kPa was recorded from T-shape foundation. On the second modeled subsoil condition, the highest bearing capacity was recorded with the rectangular shaped foundation prototypes. The bearing capacity of rectangular-1 was higher than that of rectangular-2 and T-shape by 4%. The lowest bearing capacity of 732 kPa was recorded from wedge-shape foundation prototype. On the third modeled subsoil condition, the highest allowable bearing capacity was observed with the rectangular-2, while the lowest was with wedge-shape foundation prototype. This can be attributed to the wider width of the rectangular-2 on stiff soil in comparison with the rest of the foundation prototypes. On the fourth modeled subsoil condition, the lowest bearing capacity of 145 kPa was recorded with rectangular-2, and the highest of 165 kPa with rectangular-1 and T-shaped foundation prototypes. The low bearing capacity, recorded from the rectangular-2 can be attributed to its relatively larger width, which caused the formation of stressed zone (pressure bulb) within the soil beneath its base, extending beyond the stiff soil lying directly below the base of the foundation to soft or weaker soil at dipper depth (Fig. 9). The high bearing capacity recorded from T-shape foundation, is as a result of the mobilization of the stiff soil above the foundation base in the resistance of load.

4. Conclusion

The study generally showed 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. This indicates that using foundations with wedge and T-shape vertical cross-sections can help in mobilizing substantial mass of soil above the foundation base, to function not only as surcharge to the soil below the foundation base, but also in resisting load, and therefore assisting in the distribution of structural load to less dipper soil strata, especially when stronger, Denser or stiffer soil layers is underlain by weaker ones.

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