Evaluation of Load Bearing Capacity of Foundations with Different Vertical Cross-sectional Shapes

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ABSTRACT: The paper presents results of experimental and theoreticalevaluation of load bearing capacity of shallow foundations with different vertical cross-sectional shapes. Load-settlement relationships ofmodels of shallow foundations with rectangular, wedge and T shape vertical cross-sections were studied through experimentation, and theoretically using Terzaghi bearing capacity equation.The experimental and theoretical evaluations show the load bearing capacity increasing in the order: T shape > wedge shape >rectangular shape. The study indicate that the soil above the bases of shallow foundations with wedge and T vertical cross-sectional shapes, function not only as surcharge to the soil below the bases (as is the case of rectangular shape), but also offers additional resistance to structural loads, and thereby increasing the load bearing capacity of the foundations. The economicbenefit of using wedge and T shapes shallow foundations is also demonstrated.

KEYWORDS: Foundation shape; Load bearing capacity; Settlement; Soil base.

I.   INTRODUCTION

Load bearing capacity of foundationis a function of its dimension and shape, its embedment depth, physico-mechanical properties of the soil base and load geometry. Foundations are generally classified into shallow foundations and deep foundations. Shallow foundations are those types of foundations that transmit structural loads to the soil strata at a relatively small depth. Terzaghi [1] defines shallow foundation as that which is laid at a depth D_f not exceeding the width B of the foundation, that is $D_f/B \leq 1$. However, other research studies have shown thatD_f/B can be as large as 3 to 4 for shallow foundations [2-4].

It is a conventional believes that in orderto increase the load bearing capacity of shallow foundation and reduce stresses on the soil base, the base area (width) is increased.Many studies conducted over the years, on scale effect of shallow foundation on load bearing capacity, have shown that increase base width of shallow foundation does not necessarily (always) translate to increase in the load bearing capacity [5-13].

Shallow foundations of various types/shapes are known, with strip, square, rectangular and circular shapes being the most widely used. These conventionaltypes of shallow foundations have different shapes which only vary from each other plan-wise or by horizontal cross-section. Theirvertical cross-sectional shapes(depending on the design thickness) arebasically the same. This makes the mode of their interaction with the soil bases vertically, basically the same. Moststudies on the interaction of foundations with soil bases are carried out using load-settlement approach. Many studies[14-18], havebeen conducted on the effect of foundation shape on settlement and load bearing capacity of soils.Vast of these past studies 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, which can both partly distribute/resist structural loads vertically along their trunks and bases, is presented. V and T-shape foundations were considered along with the conventional rectangular shape foundations. The study presents 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 [19]. Generally the settlements of shallow foundations such as pad or strip footings

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are limited to 25 mm [20]. Studies on (especially small scale) shallow foundations have suggested that ultimate bearing capacity can be estimated at settlement of 10% of foundation width [7, 8].

II.   MATERIALS AND METHODS

Three wooden models of shallow foundationswere used for the study: the first model was a rectangular shaped block with dimension of *30x60x60* mm for width, length and height respectively; the second 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 third was a Tshape 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 chosen so as to be within $D_f/B \leq 2$ (D_f and *B* are depth of foundation embedment and width respectively).
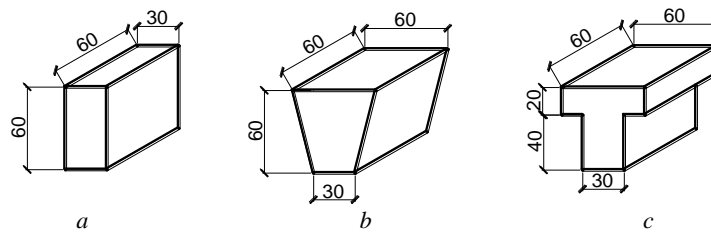

Fig. 1: Foundation models: a rectangular shape; b- wedge-shape; c- T-shape

Three subsoil conditions were modeled in a rectangular container with dimension *1100x600x250* mmforlength, height and width respectively. One of the soil conditions was modeled using sand, while the other two were modeled using clay soils.

In modeling the first soil condition, medium and coarse grained sands were compacted in layers of 25 and 50 mm, with each layer compacted to unit weight of 19 kN/m^3 and 18 kN/m^3 at moisture contents of 6 % and 8 % for medium and coarse grained sand respectively (fig. 3). The 19 kN/m^3 medium grained sand was compacted to 60 mm layer thickness on the 18 kN/m^{3}coarse grained sand as shown in fig. 2.
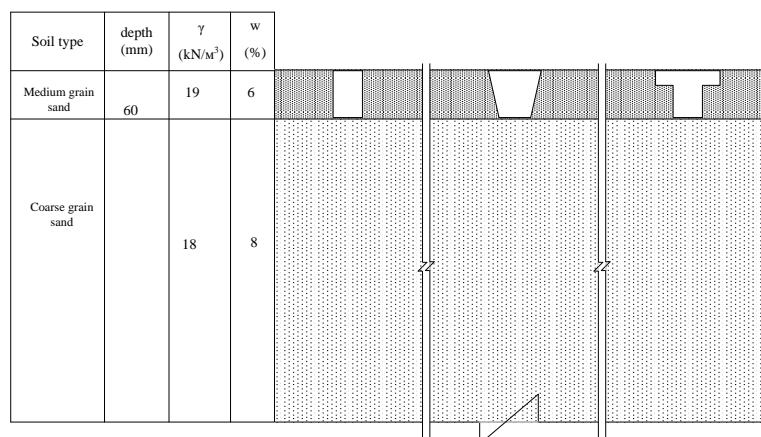

Fig. 2: Third modeled soil condition with sand

In modeling the second and third soil conditions, 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 and 17 kN/m^3 at moisture contents of 10 % and 20 % for stiff and soft soil respectively as shown in figs. 3-4. In the case of the second soil condition, clay soil with moisture content of 10 % wascompacted to unit weight of 18 kN/m^{3}into the whole test tank, as shown in fig.3.

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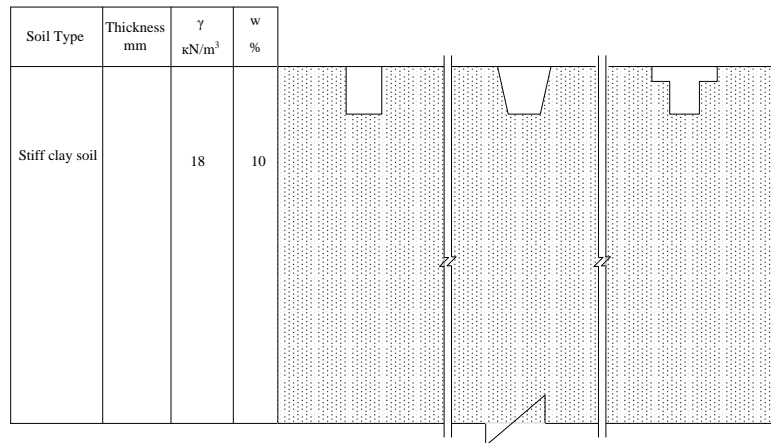| Soil Type	Thickness mm	γ kN/m^3	w %
Stiff clay soil		18	10

Fig. 3: First modeled soil condition with clay soil

In modeling the third soil condition, the stiff clay soil of 10 %moisture content, was compacted to unit weight of 18 kN/m^3, up to 60 mm below the top of the test tank. The remaining 60 mm depth was then filled with the soft clay soil ot 20 % moisture content and17kN/m^{3}unit weight, as shown in fig. 4.

The foundation models were placed during placement and compaction of the last two upper layers as shown in figs. 2-4. 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 soil conditions in figs 5-7.
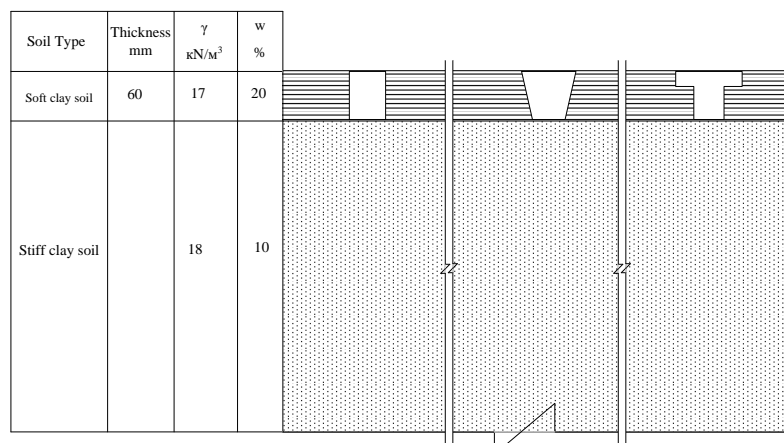
Soil Type	Thickness mm	γ kN/m^3	w %
Soft clay soil	60	17	20
Stiff clay soil		18	10

Fig. 4: Second modeled soil condition with clay soils

III.   EXPERIMENTAL RESULTS AND DISCUSSION

From the figures, it is observed that the load bearingcapacity of T shape foundation is generally higher than those of rectangular and wedge shapes. The lowest load bearing capacity was observed with rectangular shape. The relatively higher load bearing capacity recorded with T and wedge shapes is attributed to additional resistance offered by the soil above their bases from the compression by their flanges.

From fig. 5, it is observed that for rectangular shape foundation, the load-settlement curve is linear up to 0.5 kN load, after which the settlement begins rapid increase with subsequent load increments. But for wedge and T shape

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foundations,rapid increase in settlement with subsequent load applications begin after 0.62 kN load. This observation is attributed to additional resistance offered by the soil above the bases of T and wedge shapes from the compression by their flanges. Note that the difference in the patterns of the curves becomes more defined after these defined loads.
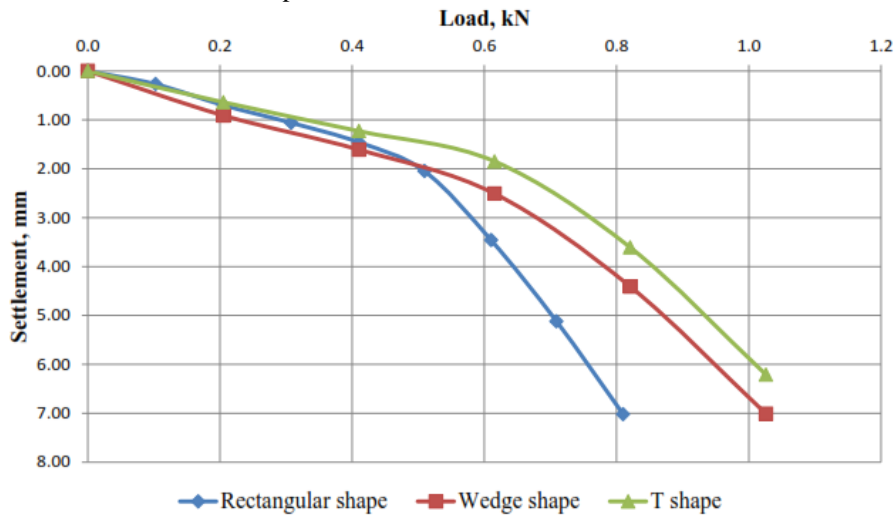

Fig. 5: Load-settlement curves on second modeled subsoil condition with sand

Observation of fig. 6 showed that for rectangular shape foundation, load-settlement curve remains linear up to 1.5 kN load, after which the settlement begins relatively rapid increase with subsequent load application. But for wedge and T shape foundations,because of the additional resistance offered by the soil above their bases, from the compression by their flanges, the linearity of the curves remains, almost to the maximum tested load.
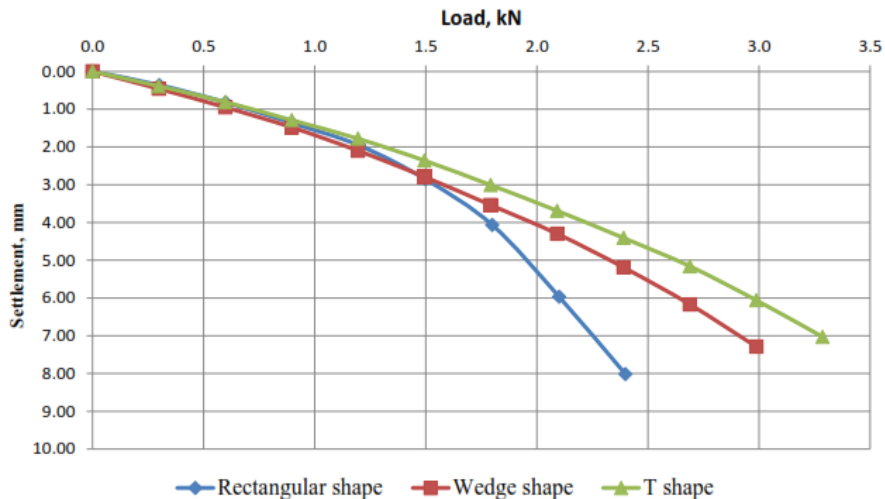

Fig. 6: Load-settlement curves on first modeled subsoil condition with clay soil

Observation of results on the first (fig. 5, base of sand) and second (fig. 6, base of clay soil) modeled soil conditions, shows that, higher load bearings, in relation to settlement were generally recorded with all the foundations shapes on the second condition as compared to those recorded on the first condition. The cohesive nature of the clay soils, which enable full mobilization of the shear strength parameters (c and φ) was responsible for the observed trend on the second condition, in comparison with the first. The relatively lower loads bearing recorded on the first condition is as a result of the mobilization for load resistance from frictional component only.

Observation of fig. 7 shows the load-settlement curves of the three shapes taking relatively similar pattern. This can be explained by the presence of the soft soil layer above the bases of the foundations, which offers not much resistance to

the flanges of wedge and T shapes. This resulted in much of the resistance been offered by the stiff soil beneath the base of the foundations, and hence the pattern of the curves.
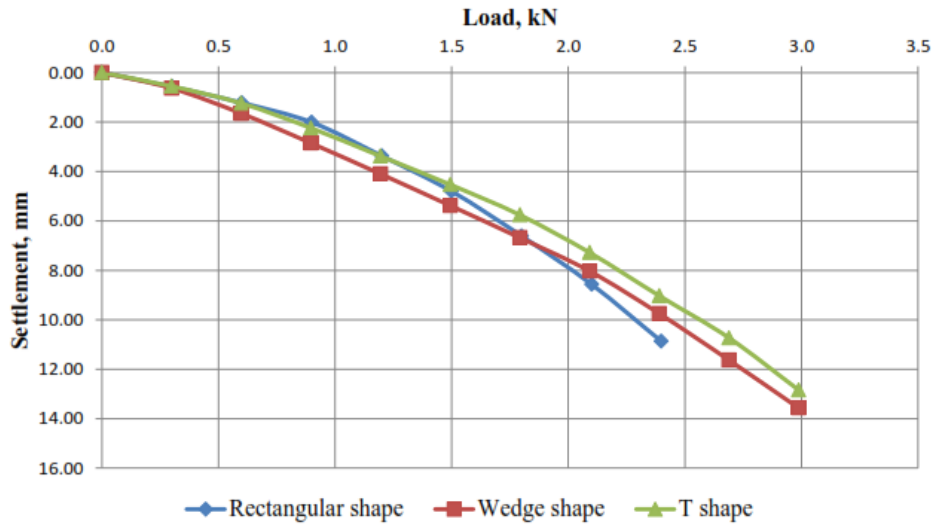

Fig. 7: Load-settlement curves on second modeled subsoil condition with clay soils

IV.   THEORETICAL EVALUATION USING TERZAGHI BEARING CAPACITY EQUATION

In order to theoretically evaluate the load bearing capacity of foundation with wedge and T vertical cross-sectional shapes, Terzaghi general bearing capacity equation for load bearing resistance at the base of foundation of rectangular stripe foundation, for two layered soil, was used,

$$q_{ult} = cN_c + \gamma_2 dN_q + \frac{1}{2}b\gamma_1 N_\gamma, \tag{1}$$

To account for the additional resistance offered by the flanges of the T shape foundation, and in accordance with fig. 8b, we resolve in two parts: the central trunk and the flanges. For the central trunk, equation (1) becomes:

$$q_{ult\,(t)} = c_1 N_{c1} + \gamma_2 d_1 N_{q1} + \frac{1}{2}b_1\gamma_1 N_{\gamma 1}. \tag{2}$$

And for the additional resistance from the two flanges (2F) equation (1) becomes:

$$2q_{ult\,(F)} = 2(c_2 N_{c2} + \gamma_2 d_2 N_{q2} + \frac{1}{2}b_2\gamma_2 N_{\gamma 2}). \tag{3}$$

Summing (2) and (3), we have;

$$q_{ult\,(T)} = q_{ult\,(t)} + 2q_{ult\,(F)}, \tag{4}$$

$$q_{ult\,(T)} = c_1 N_{c1} + \gamma_2 d_1 N_{q1} + \frac{1}{2}b_1\gamma_1 N_{\gamma 1} + 2(c_2 N_{c2} + \gamma_2 d_2 N_{q1} + \frac{1}{2}b_2\gamma_2 N_{\gamma 2}). \tag{5}$$
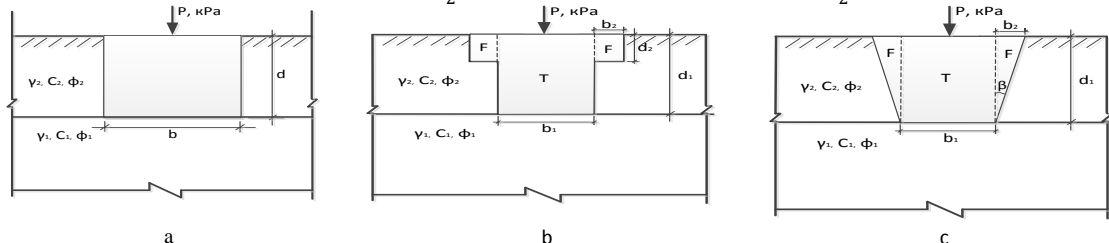

Fig. 8: Scheme for evaluation of load bearing capacity of rectangular (a), T (b) and wedge (c) shape foundation

For homogeneous soils, where $c_1 = c_2 = c$, $\gamma_1 = \gamma_2 = \gamma$, $\varphi_1 = \varphi_2 = \varphi$, equation (5) becomes:

$$q_{ult\,(T)} = 3cN_c + \gamma N_q(d_1 + 2d_2) + \gamma N_\gamma \left(\frac{b_1}{2} + b_2\right), \qquad (6)$$

In likewise manner, for wedge shape foundation, and in accordance with fig. 8c, equation (1) becomes:

$$q_{ult\,(W)} = c_1 N_{c1} + \gamma_2 d_1 N_{q1} + \frac{1}{2} b_1 \gamma_1 N_{\gamma1} + 2sin\beta(c_2 N_{c2} + \gamma_2 \frac{d_1}{2} N_{q1} + \frac{1}{2} b_f \gamma_2 N_{\gamma2}). \qquad (7)$$

where$\beta = tan^{-1}\frac{b_2}{d_1}$;$b_f = \sqrt{d_1^2 + b_2^2}$,(see fig. 8c).

For homogeneous soils, equation (7) becomes:

$$q_{ult\,(W)} = cN_c(1 + 2sin\beta) + \gamma d_1 N_q(1 + sin\beta) + \gamma N_\gamma(\frac{b_1}{2} + b_f sin\beta). \qquad (8)$$

Equations (5) and (7) aggress with the experimental results (figs. 5-7),which show the load bearing capacity increasing in the order:T shape > wedge shape > rectangular shape.This generally translates to reduce stresses on the soil base, at a given loadunder T shape and wedge shape, when compared to rectangular shape. Also using dimensions of $b_1 = \frac{2}{3}b$, $b_2 = \frac{1}{4}b_1$, $d_2 = \frac{2}{5}d$ (notations defined on fig. 8) for wedge and shapes foundations, reduces volume of excavation and reduce materials cost to up to 17 and 20 % respectively for wedge and shapes, when compared with the rectangular shape.

V.   CONCLUSION

The study shows that bulk of the load resistance of subsoil bases of shallow foundations with rectangular vertical cross-sectional shapes is mostly offered by the soil beneath the foundation base, while for those with wedge and T-shape vertical cross-sectional shape, additional resistance is also offered by soil along their vertical stems, which generally translate to increase in load bearing capacity of the foundations. The experimental and theoretical evaluations show the load bearing capacity increasing in the order: T shape > wedge shape > rectangular shape. The economics of using wedge and T shapes shallow foundations is also demonstrated.

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