INVESTIGATION ON UPLIFT CAPACITY OF SHALLOW FOUNDATIONS ON COHESIONLESS SOIL

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Abstract: Shallow foundations are commonly used in Sri Lanka for communication towers, power transmission towers and towers for wind turbines. The design of these foundations is based on several assumptions and therefore, a large factor of safety is imposed on estimated ultimate uplift capacity. In view of the above, the uplift capacity of shallow foundations on dry sand was determined in the present research by conducting laboratory model tests on circular and square foundation models. The results were compared with the uplift capacities obtained from analytical solutions for both circular and square flat foundations. Two foundation models (circular and square) at three different depths in dry sand were tested and the uplift force and upward displacement of each model were investigated. Uplift force versus upward displacement characteristics obtained from experimental analysis was compared with the uplift capacity obtained from analytical solutions. From both experimental and theoretical results, it can be concluded that the uplifting capacity of square foundation is higher than circular foundation at each depth. Also the uplifting capacity is increased with embedded depth of foundation for both types of foundations. Another important conclusion is that, the angle between the vertical plane and the failure plane is nearly half of the friction angle of the soil.
Keywords: Shallow foundations, cohesionless soil, Failure soil wedge, uplift capacity

1. Introduction

Uplifting force is the most dominant force in tower foundations. Therefore, there is a higher possibility of failure of such structures by uplifting rather than failed by bearing, sliding etc. It is generally considered that resistance to uplift is provided by both frictional resistance of soil along the failure surface and weight of soil in the failure zone of the foundation.

According to the literature, several analytical and semi-empirical methods have been developed to predict the ultimate uplift capacity of continuous, circular and rectangular foundations embedded in sand and hardly in clays. Some established theories include Balla's theory (1961) which is widely recognized as the pioneer work on tensioned foundations. Theory of Meyerhoff and Adams (1968), and theory of Vesic are also worth mentioning. Among those, the design equation proposed by Mayerhoff and Adams (1968) is widely employed in the estimation of uplift capacity of shallow foundations.

A number of those theories have been used to compare the predicted uplift capacity with full scale tensile testing in unsaturated soils by Danziger (1983), Pereira Pinto (1985) and Ruffier dos Santos (1999). These studies have indicated generally that the theories developed at the University of Grenoble match reasonably well the test results for different types of soils, failure modes, load inclinations, and embedded depths with proper adjustments to account for the effect of inhomogeneity provided by the compacted backfill.

The failure modes indicated are applicable for homogeneous soils. Stewart (1985), Sutherland (1988) investigated the tensile capacity of layered soils. To account for the inhomogeneity introduced by the compacted backfill, the tensile capacity is controlled by the weaker of the two materials, backfill or surrounding natural soil. If the backfill is weaker than the natural soil, the failure takes place at the vertical interface.

In general, all the theories discussed above over-estimate the safety of the footing due to the assumptions made in the approximation of the associated failure soil wedge. Because of these assumptions, there are large numbers of uncertainties in predicting the behavior of failure soil wedge for different soils and foundations. This requires the application of large factors of safety values, which leads to excessive cost.

In the current study, a detailed experimental investigation were carried out on square and circular foundation models to investigate the failure soil wedge and uplift capacity of shallow foundations on cohesionless soil. The results were compared with those of circular and square flat foundations.

2. Methodology

2.1 Experimental Investigation

Two types of foundation models were used in the present investigation, namely flat circular and flat square foundations. Circular and square flat models with the same plan dimensions were tested. The dimensions of all models in plan were kept the same for comparison purposes. 300 mm x 300 mm for plan area of square footing and 300 mm diameter in circular footing have been used. Figure 1 shows geometrical configuration of these models. The models were made from steel.

Figure 1: Foundations models

2.1.1 Experimental set up

Models were prepared inside a rigid box covered with Perspex sheets. Internal dimensions of the Perspex box were 1300 mm x1200 mm x1000 mm for length, width and height, respectively. Sand was filled inside the Perspex box using a funnel while maintaining a constant falling height. The failure patterns for three different embedded sand depths (100 mm, 200 mm and 300 mm) were tested for each foundation model. Sand layers were arranged in the testing box as shown in Figure 2. Density of sand in testing box was maintained constant (Relative density around 1.62) by pouring sand into the box through special bucket.

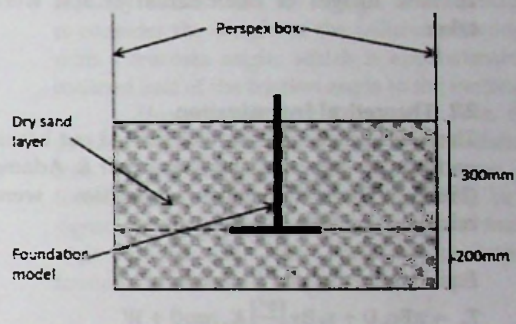

Figure 2: Foundation arrangement for 300 mm embedded depth in the Perspex box

The loading system was composed of an drawpu load, which generates an puward displacement. This displacement was transformed into onto the foundation model which placed at the center of Perspex box. A proving-ring of sufficient capacity was connected to the wercs kcaj to measure the applied load. The dial gauge was mounted on the foundation model to measure the movement of footing during the testing. Refer to Figure 3 for a photo of the loading arrangement employed in the current study.

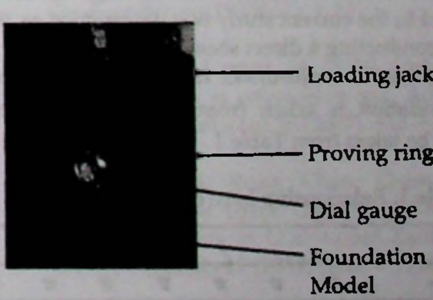

Figure 3: Loading arrangement

Foundation model was placed at the center of the testing box. Each foundation has been embedded on sand up to required level. Load application set up was simultaneously prepared and rested on foundation model. After the testing tank was prepared, all the measuring devices and connections were checked again to ensure for the accuracy of data and safety purposes.

The loading was applied under displacement control rate of 1 - 2 mm/ min. The proving ring value was measured at every 0.5 mm settlement of foundation model, which was measured by dial gauge set on fixed vertical steel rod. At the same time, observations of deformation of surrounding soil were taken into account until the total settlement reached 25 mm. Images of deformation of soil were taken.

2.2 Theoretical Investigation

Theoretical investigation was carried out based on formulas proposed by Mayerhoff & Adams (1968). The theoretical capacities were calculated by following equations.

Equation for circular foundation,

$$T_u = \pi B c_u D + s_f B\gamma \left[\frac{D^2}{2}\right] K_u \tan\emptyset + W$$

Equation for square foundation,

$$T_u = 2c_u D(B + L) + \gamma D^2(2s_f B + L - B)K_u \tan\emptyset + W$$

Where,

T_u -Uplift capacity
B - Width of foundation
D - Embedded depth
S_f-Side friction adjustment factor
K_u -Lateral earth pressure coefficient
C_u -Cohesion
W -Weight of foundation + Weight of uplift soil(directly on the foundation)
γ- Density of sand
$\emptyset$ - Friction angle

K_u is taken as the coefficient at rest ($=1 - \sin\emptyset$) in the above formulae. Friction angle of sand used in the current study was determined as 38^0 by conducting a direct shear test.

Side friction adjustment factor (S_f)for shallow foundation is taken from $1 + {mD}/{B}$where m can be taken from Table 1

Table 1: Relationship between Ø and m

		ϕ						
ϕ =		20°	25°	30°	35°	40°	45°	48°
Limiting	H/B	2.5	3	4	5	7	9	11
	m	0.05	0.10	0.15	0.25	0.35	0.50	0.60
Maximum	s_f	1.12	1.30	1.60	2.25	4.45	5.50	7.60

3. Results

3.1Experimental Results

The uplift load and settlement were recorded and plotted for each foundation. Figure 4 shows the settlement versus uplift load curves for square foundations in three different depths which were embedded in dry sand. Figure 5 shows the settlement versus uplift load curves for circular foundations at three different depths on dry sand.

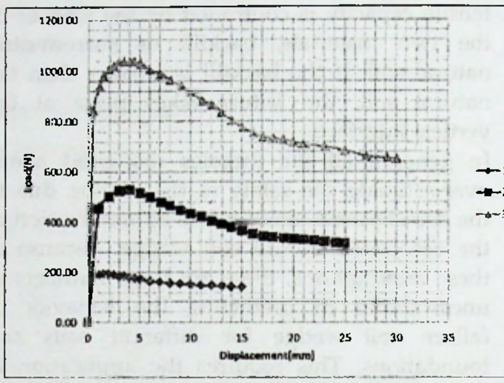

Figure 4: Uplift load-settlement curves for square foundations

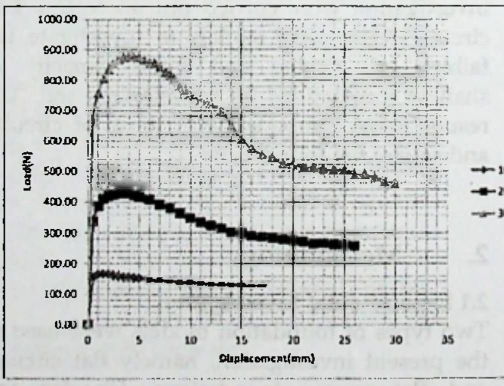

Figure 5: Uplift load-settlement curves for circular foundations

Uplift capacity of each foundation has been tabulated in Table 2

Table 2: Experimental uplift capacity

Embedded depth (mm)	Uplift capacity of square foundation(N)	Uplift capacity of circular foundation(N)
100	193	166
200	529	428
300	1037	880

Cross section through center of foundation of failure soil wedge has been illustrated in Figure 6 and Figure 7.

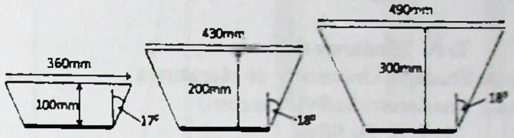

Figure 6: Cross section of failure soil wedge for square foundation model

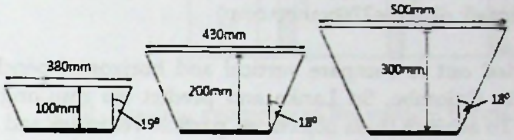

Figure 7: Cross section of failure soil wedge for circular foundation model

3.2 Theoretical Results

The uplift capacity has been calculated using equations that are given in section 2.2. Theoretical uplift capacities has been tabulated in Table 3

Table 3: Theoretical uplift capacities

Embedded depth (mm)	Uplift capacity of square foundation(N)	Uplift capacity of circular foundation(N)
100	176.58	139.44
200	421.55	332.02
300	751.88	591.67

4. Discussion

For all the cases, the uplifting capacity obtained from experimental investigation is significantly higher than those obtained by employing commonly used analytical solutions with simplified assumptions. From the failure patterns of soil wedges observed during the experiment as shown in the Figure 6 and Figure 7, it is further identified that the angle between vertical plane and failure plane (frustum angle) is nearly half of the friction angle of the soil.

In addition, it was observed that the uplift capacity of square foundation was higher than the uplift capacity of circular foundation due possibly to the difference in areas. The significant difference between experimentally and analytically obtained uplift capacity values could be due to higher weight of soil in pullout zone and frictional resistance developed along the failure surfaces of the soil wedges.

5. Conclusions

After a meticulous evaluation of result obtained from the experiments and comparing results with the conventional theoretical formulas, the following conclusions are drawn.

The currently used theoretical formulas for estimating of uplift capacity of shallow foundation show significantly lower value compared to the experimental value. In order to obtain a reasonable value for the uplift capacity that is used for design, it is advisable to consider the weight of the failure soil wedge with a frustum angle, which is approximately inclined half of the friction angle to the vertical.

However, it should be noted that, the particle size of soil relative to the foundation size would decrease with the increase of foundation size. As a result, there can be a significant difference in the test results of small scale model tests with that of phototype foundations.

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