THE EXPERIMENTAL INVESTIGATION OF FAILURE MECHANISM AND BEARING CAPACITY OF DIFFERENT TYPES OF SHALLOW FOUNDATIONS

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Abstract: The development in analysis and design of shell type foundations have led to the understanding that there are more advantages of shell type foundations compared to their conventional flat counterparts. The bearing capacities of conical and pyramidal shell foundations on dry sand were determined in the present paper by conducting laboratory model tests. The results were compared with those of circular and square flat foundations, respectively. Four foundation models on dry sand were tested in which influence of the shell configuration on the bearing capacity and settlement were investigated. The present experimental study indicated admirable performance of shell type foundations with respect to ultimate and settlement characteristics. Also characteristic of deformations or the failure mechanism of both shell and its flat counterparts were simultaneously investigated by using coloured and non-coloured sand layer by layer in dry sand model.

Keywords: Shell, conventional, conical, pyramidal, bearing capacity

1. Introduction

Due to many advantages, different types of shell foundations were attracted by researchers and people worldwide since mid of 20th century. Shell type foundations are not new to foundation engineering, because they had been adopted as structural element of building during World War II and the construction with inverted brick arch foundation by early Rome people.

According to the literature, the research conducted on geotechnical behaviour of shells as foundation elements has been considerably lagging behind that compared to their flat counterparts. Nicholls and Izadi (1968), performed an experimental investigation on conical and hyper shell footing to determine the contact pressure distribution as a function of the ultimate load. The conical and hyper shell models were compared with circular and square flat models, respectively. The results indicate that the contact pressure near the perimeter of the shell was about 1.5 times the contact pressure at the centre. Furthermore the ultimate bearing capacity and settlement of the shell were significantly improved as compared with their conventional flat counterparts.

Iyer and Rao (1970), reported a detailed experimental study conducted on the feasibility of using a funicular shell footing resting on sand as a replacement for a raft foundation. The results showed that the bearing capacity of the shell footing was considerably greater than that of the flat footing of the same plan dimensions. Furthermore, under the same applied load, the shell footing experienced lower settlement than that the flat one. These significant differences were attributed to the effects of geometry and the stiffness of shell elements.

Hanna and Abdel Rahman (1990), performed an experimental investigation to study the ultimate bearing capacity of triangular shell strip footing on sand. The results indicated that triangular shell footings provide a higher bearing capacity and produce less settlement under the same loading conditions as compared to strip flat footings.

With the availability of advance numerical modelling capabilities, now it is possible to investigate the behaviour of footing types with different geometric shapes. Recently, an analytical investigation was conducted by Kurian and Devaki (2005), in which finite element methods were used to examine the influence of the coefficient of interface friction, type of soil and different loading conditions. In their investigation three types of shell foundations were considered; conical, spherical and hyperbolic paraboloidal. However, it was revealed little about the characteristics of deformation or the failure mechanisms associated with shell foundations.

Although theoretical formulations of bearing capacity and failure mechanisms of conventional footing have been already established. Limited research has been conducted so far on the bearing capacity and failure mechanisms of non-conventional (shell) footings. Theoretical formulation of bearing capacity of non-conventional footings is also rigorous.

In view of the above, the present study aims to investigate the bearing capacity and failure mechanisms of conical and pyramidal shell models. The results were compared with circular and square flat models, respectively with same plan area.

2. Methodology

2.1 Model preparation

Two types of shell foundations were tested in the present investigation, namely conical and pyramidal shells. The results were compared with their flat counterparts. The plan areas of all models were kept the same for comparison purposes. Figure 1 shows geometrical configuration of these models.

To examine the effect of shell rises on their performance, the rise to half width ratio (a/b) was taken as (0.56) (refer to Figure 1). The models were made of jak wood. To avoid using of any nails in the structure of these models; each model was made from single plank of jak wood. The contact surfaces of all models were covered with a wax layer to simulate the smooth interface surface condition.

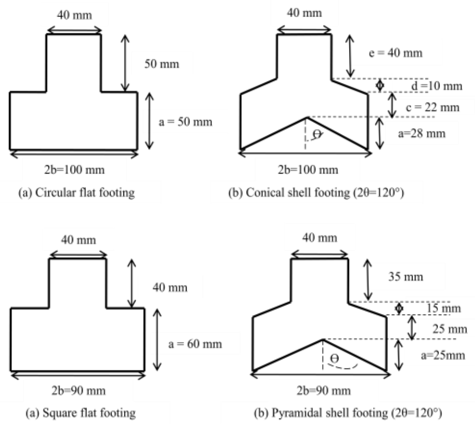

Figure 1: Sketch model of foundations

(i) Circular flat and its counterpart shell (conical) foundations

(ii) Square flat and its counterpart shell (pyramidal) foundation

Figure 2: Pictures of actual foundation models

2.2 Experimental set up

The perspex box was made of 5 mm thick perspex panels for four sides and rigid steel and concrete composite base to avoid the deformation due to loading. Steel angles were used to prevent buckling of surrounding perspex panels. Internal dimensions of the perspex box were 1300 mm×1200 mm×1000 mm for length, width and height, respectively. Sand (e_{min}= 0.474 and e_{max}= 0.787) was filled in the perspex box up to 400 mm.

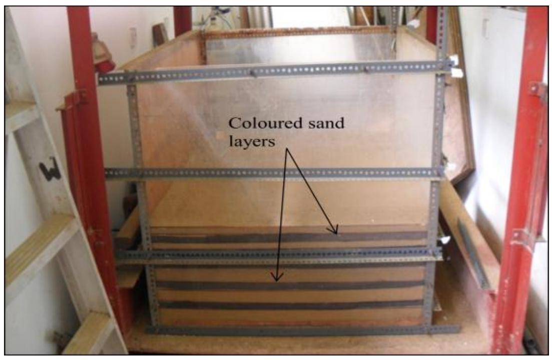

Figure 3: The perspex testing box with coloured and non – coloured sand layers

Air pluviation technique was used to pour sand into the perspex testing box with constant height of 1.2 m. The falling height was selected to prepare a dense sand bed to prevent punching shear failure. The special bucket was prepared with attached duct to pour sand. Density of sand in testing box was maintained constant in such a way that sand was poured into the box through a bucket assembly, which was moved by hand in a consistent manner over the testing bed to achieve uniform sand distribution and sufficient compaction

The loading system composed of a load cell of 10 tones capacity, which generates a downward displacement at a constant rate. This displacement was transformed into a force through a timber plank onto the foundation model which placed at the centre of prespex box. The load and settlement measurement setup used for the experimental is shown in Figure 4. A proving–ring of sufficient capacity was connected to the gear box to measure the applied load. Dial gauge was mounted onto the foundation model to measure the movement of footing during the testing.

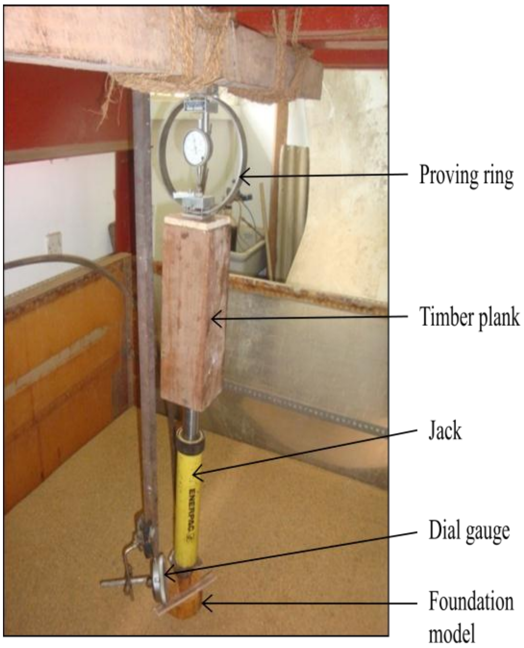

Figure 4: Load and settlement measurement set up

2.3 Material testing

In this experiment, dry sand was used as the main material for foundation. Also, the two layers of colour sand and non colour sand have been used to identify the failure pattern of sand. Mechanical properties and parameters were tested for both non coloured and coloured sand as shown in Table 1.

According to the Unified Soil Classification System (USCS) the soil was classified as poorly – graded sand (SP).

The shear strength parameters of non-coloured, coloured sand and its interface of sand - wax surface were obtained from direct shear tests. The densities of the sand in the direct shear tests were the same as that in the model tests.

Table 1: Characteristics of materials

Parameter	Value
An angle of shearing resistant (φ °) of non coloured sand	43
The cohesion of non coloured sand ,(kPa)	0
An angle of shearing resistant (φ °) of coloured sand	44
The cohesion of coloured sand ,(kPa)	0
An angle of internal friction (δ °) between non coloured sand and jak wood	39
The adhesion between non coloured sand and jak wood (kPa)	0
Unit weight of the sand (dry unit weight ,γ_d) , (kNm^{-3})	16.3
Uniformity Coefficient - C_U	3.00
Curvature Coefficient - C_C	1.34
Relative density (%)	61.35

2.4 Test procedure

Foundation model was placed at the centre of the perspex box. Each foundation was embedded first on sand such that their D/B ratios are 0.28, where D is the depth of embedment and B is the footing width. Load application set up was simultaneously prepared and rested on foundation model.

After the perspex box was prepared, all the measuring devices and connections were checked again to ensure the accuracy of data and safety. After checking was completed, the loading was applied under displacement control condition at a rate of 1 -2 mm/ min.

The proving-ring values were taken at every 1.0 mm settlement of the foundation model. At the same time, observations of deformation of surrounding soil were taken until the total settlement reached 50 mm. In addition, pictures of deformation of soil were also taken.

At the end of each test, the load application set up and foundation model were removed from perspex box carefully. At the centre of perspex box where foundation model was set up, a perspex panel was inserted into the sand and one half of sand in perspex box was removed layer by layer until the deformation of coloured sand was not significant. Lateral supports were applied on inserted perspex panel.

Then, failures pattern of coloured sand was observed and the height of influence zone was measured. Also pictures of failure pattern of sand were taken.

3. Results and Discussion

The load – settlement data were recorded and plotted for each loading test. Figure 5, shows typical load settlement curve for an embedded flat circular and conical shell foundation on dry sand. Figure 6, shows typical load settlement curves for an embedded flat square and pyramidal shell foundation on dry sand. The ultimate load (Q_U) is defined as the point of maximum load obtained from the load – settlement (Q-δ) curves at 25 mm settlement.

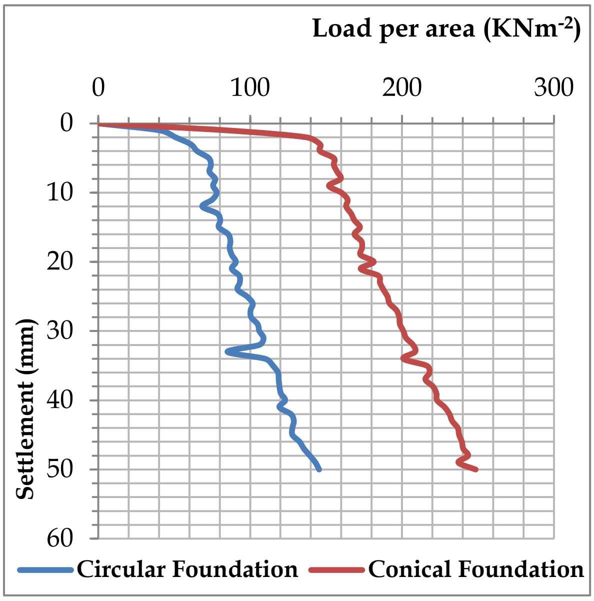

Figure 5: Load – Settlement curves for flat circular and conical foundations

Figure 5, has shown that conical shell foundation shows better carrying capacity compared to their conventional flat counter part.

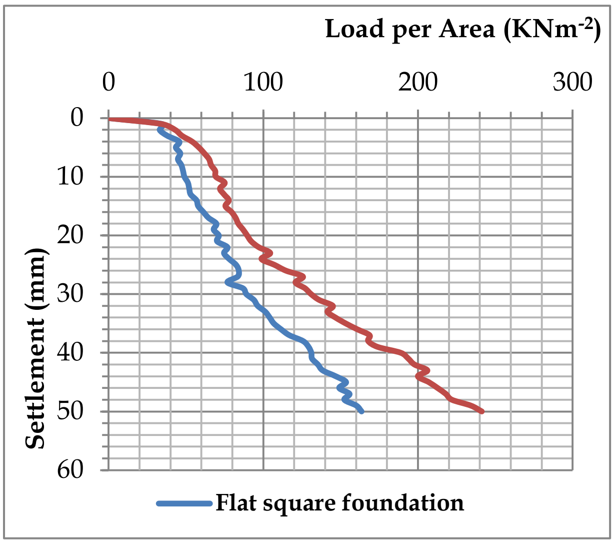

Figure 6: Load – Settlement curves for flat square and pyramidal foundations

Figure 6, has also shown that pyramidal shell foundation shows better carrying capacity compared to their conventional flat counter part.

The values of the ultimate load (Q_U) and corresponding settlement (δ_U) obtained from the present experimental investigation are presented in Table 2. Settlement of 25 mm has been taken as ultimate settlement, even though experimental test had been conducted upto 50 mm settlement. This is the allowable settlement for general building with individual foundation is limited to 25 mm without having any distress to the structural elements. It can be seen from the results that the conical shell foundation shows the maximum ultimate bearing capacity followed by the pyramidal shell.

To examine the settlement characteristic of shell footings as compared to their flat counterparts, a non-dimensional settlement factor (F_δ) was introduced in Eq. [I] (Hanna and Abdel Rahman – (1998));

$$F_\delta = \frac{\delta_U \times \gamma \times A_h}{Q_U} \quad ---- \quad [I]$$

Where δ_U is the settlement at the ultimate load, $\boldsymbol{\gamma}$ is the soil unit weight, A_h is the area of the footing in horizontal projection and Q_U is the ultimate load.

The ultimate load capacity and non-dimensional settlement factor (F_δ) obtained from the test results are given in Table 2.

Table 2: Ultimate load capacity and non-dimensional settlement factor of foundations

Foundation model	Ultimate load capacity , (kN)	Non-dimensional settlement Factor, (F_δ)
Flat Circular Foundation	0.769	4.2×10^{-3}
Shell Conical Foundation	1.496	2.2×10^{-3}
Flat Square Foundation	0.667	4.9×10^{-3}
Shell Pyramidal Foundation	0.868	3.8×10^{-3}

It can be seen that shell footings have higher ultimate load than conventional flat ones. Also it is clear that the shell conical footing gives maximum ultimate load compared to the others.

It should be noted that a lower value of the settlement factor (F_δ) indicates better settlement characteristics. According to the result given in Table 2, it is clear that shell conical foundation is better than pyramidal footing from settlement point of view.

The increase in the ultimate load of a shell footing as compared to its flat counterpart is recognized in the present investigation as the shell gain factor (η%).

It was defined in Eq. [2] as the ratio between the difference in the ultimate loads of shell and flat footing over the ultimate load of the flat footing. (Hanna and Abdel Rahman (1998));

$$\eta = \frac{Q_{us} - Q_{uf}}{Q_{uf}} \quad ----[2]$$

Where η is the shell gain factor, Q_{US} is the ultimate loads of shell footing, and Q_{UF} is the ultimate load of flat footing.

It can be noted that the shell gain factors (η) for the conical footing is higher than that of the pyramidal footing.

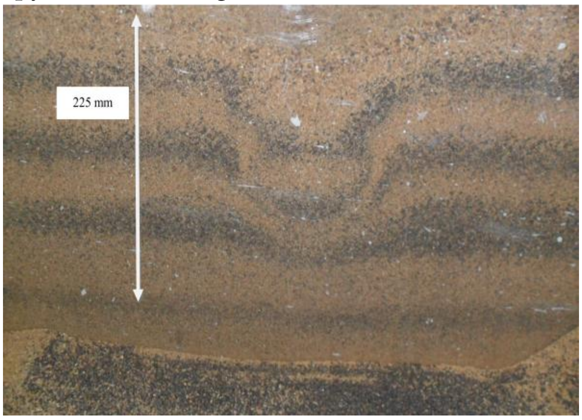

Figure 7: Failure pattern of soil body underneath to the circular flat foundation

To investigate the shape of rupture the surface for flat and shell foundations, coloured sand layers were used in the current study. The results were captured by photograph throughout the loading process. Figure 7, 8, 9 and 10 shows the test at the ultimate state for the flat circular, shell conical, flat square and shell pyramidal footing respectively. Coloured layers of soil body have shown better variation of failure pattern underneath each foundation.

Table 3: Shell gain factors of respective shell configuration

Foundation Model	Shell Gain Factor (η%)
Shell Conical Foundation	94.54
Shell Pyramidal Foundation	30.13

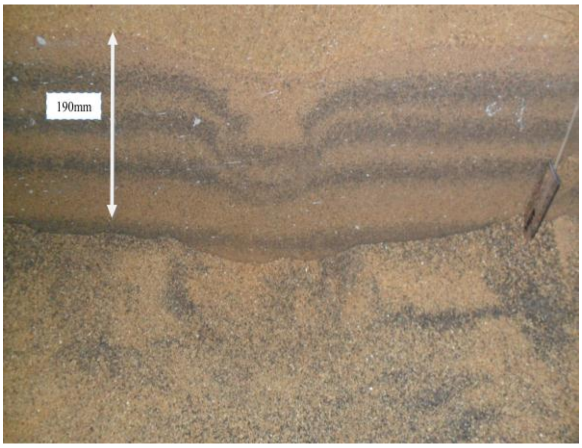

Figure 8: Failure pattern of soil body underneath to the conical shell foundation

Figure 9: Failure pattern of soil body underneath to the square flat footing

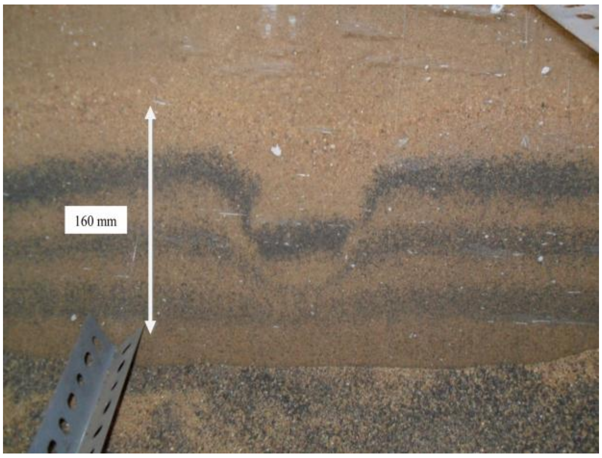

Figure 10: Failure pattern of soil body underneath to the pyramidal shell foundation

Figure 7 and 8 show that there is no differences in failure mechanism in both conventional circular footing and its shell counterpart.

Similarly, Figure 9 and 10 show that there is no difference in failure mechanism of both conventional square and its shell counterpart.

The depths of the influence zone of soil body under each foundation are tabulated in Table 4.

Table 4: Height of influence zone of sand due to loading on footing

Type of Foundation Model	Height to Influence zone (mm)
Flat Circular Foundation	225
Conical Shell Foundation	190
Flat Square Foundation	200
Pyramidal shell Foundation	160

It can be seen that shell type footing have less height of influence zone compared to flat ones. Also, pyramidal footing has shown less height of influence zone compared to conical one.

4. Conclusion

The load–settlement behaviour of shell footings were investigated and compared to their flat counterparts. Based on the experimental investigations on four foundation models, the following conclusion can be drawn:

1) The ultimate capacities of shell foundations are higher than that of their flat counterparts with the same plan dimensions.
2) A shell gain factor (η) was used to represent the increase in the ultimate capacity of shell foundations as compared to their counterparts. Shell gain factor of conical footing is higher than the pyramidal footing.
3) A non-dimensional settlement factor (F_δ) was used to examine the settlement characteristics of shell foundations against their conventional flat counterparts. The results of the calculated settlement factor (F_δ) deduced from present experimental investigation reveal that shell foundations have better settlement characteristics than the conventional ones. Also it shows that conical shell footing has better settlement characteristics compared to pyramidal shell footing.
4) The coloured layers of sand in perspex box indicated that influence zone of flat footing are deeper than those for the corresponding shell one. Also, lowest influence zone was observed for pyramidal shell footing.
5) Failure mechanism under the shell foundation is similar to its conventional flat counterpart.

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