Experimental Study for Load-Settlement Behavior of Flat and Shell Footings on Sandy Silt Soil

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Abstract. Shell foundations are often used to raise the carrying capacity of a structure on weak soils. In cases where large superstructure loads must be transferred to poorer soils, shell foundations are more cost-effective than ordinary shallow foundations. Advances in the study and design of shell-type foundations have shown their superiority over traditional footings in poorer soils. The current study aims to investigate shell shape's influence on ultimate load capacity. Seven footing types' models were created along with an appropriate testing box. The soil needed for the study was from the region north of Mosul city, classified as silt with low plasticity (sandy silt) soil. A laboratory model experimentally determined the ultimate load capacities for inverted and upright conical, inverted and upright pyramid, and hemispherical shell foundations on silty soil. The achieved results were associated with those for conventional flat squares and circles. According to the findings, the "upright conical" shell footing has a load capacity of 12.7 kN, higher than the other foundations, and its efficiency was 51%. When comparing foundations, the "upright pyramidal" shell footing has better settling characteristics and a settlement factor of 0.017. As the shell factor decreases, the shell foundation begins to behave more like a flat foundation, which reduces the maximum load capacity of the shell foundation.

Keywords: Shell foundation, Shell efficiency, load capacity, load settlement

1. INTRODUCTION

One of the essential things a foundation must do is transfer the load from the structure to the ground without going over the allowed value or causing too much settlement. When transferring large loads to poor soils, shell foundations are preferred over traditional shallow foundations due to their high bearing capacity values. In contrast, an ordinary shallow foundation would be subject to excessive settling [1]. Therefore, research into alternate methods of changing flat foundations, such as shell structures traditionally utilized in roof constructions, has become a significant focus. Researchers have shown room for improvement in the performance of flat and shell foundations by adjusting their load capacity and impairment characteristics. Changes to flat and shell foundations have made them better regarding how much weight they can hold and how they break.

Kurian [2] examined how hypar and conical shell foundations fared on soft soil. Winkler springs were used to simulate varying soil conditions. Kurian [3] investigated the effects of subsidence in core soil on shell foundations. Kurian's third publication, from 1995, was a parametric investigation of the performance of conical shell bases. The research looked at how factors like shell height, thickness, and ring beams on each end of the shell affected the results. The results showed that when soil modulus increases, load-bearing capacity also increases [4]. Hanna and Abdel-Rahman compared the load capacity and settlement of standard flat-shell foundations with those of triangular, conical, and pyramidal shells lying on the sand under an axial load [5,6]. Kurian and Devaki [7] modeled three different shell foundation shapes: hyperbolic, paraboloidal, conical, and spherical. Hassan [8] used finite element analysis to study the behavior of hypar and conical shells resting on Winkler bases. Also, Lamya and Sheeja [9] used the computational finite element tool PLAXIS to analyze two kinds of shell foundations: conical and pyramidal [9].

Esmaili and Hataf [10] used model experiments and numerical analysis to determine how much weight three different conical and pyramidal shell foundations could hold on unreinforced and reinforced sand. Pyramidal and conical shell foundations load capacities on dry sand were determined by Fernando et al. [11]. Colmenares et al. [12] conducted an experimental and theoretical study of the engineering behavior of a conical shell foundation on mixed soils. El-kady and Badrawi [13] used experimental and computational models to minimize steel reinforcements and save money on shell foundation materials. Sidqi and Mahmood [14] used numerical modeling on upright and inverted reinforced concrete pyramidal shell foundations to study how edge angles affect load-bearing capacity, settlement, and contact pressure.

Idris [15] looked into how much weight folded plates could hold. The folded plate has a greater carrying capacity than the flat base. Ansari [16] examined edge angle effects on stress distributions below embedded triangular shell strip footings on loose, medium, and dense sands. Ebrahimi et al. [17] conducted experimental and computational analyses of conical and pyramidal shell foundations on loose, unreinforced, and geogrid-reinforced sand. Limit analysis was used to figure out how the ratio of the depth of the foundation to its width and the number of geogrid layers affected the bearing capacity ratio. Several studies have been published in the literature purview of Foundation Settlement and load capacity in experimental and theoretical ways [18-21].

2. MATERIALS AND METHODS

2.1 The Soil

The soil used in this work has been selected from Khawaja Khalil village (36° 28’ 43.13’’ N, 42° 57' 25.36’’ E) north of Mosul city. The samples are characterized as low-plasticity silt with a gypsum content of 5.7% and were obtained from a depth of 2–2.5 meters. The city of Mosul has a lot of challenges due to the environment being constructed on this soil, which is why it was selected. So, the bearing ability of this soil is low. The characteristics and behavior of shell foundations built on this soil will be investigated. The physical parameters of the soil are detailed in Table 1. Figure 1 depicts the standard and modified compaction efforts used to characterize the soil's compaction properties, and Figure 2 illustrates the grain size analysis.

Table 1: Physical properties of soil.

Parameter			**Value**
Natural water content (%)			9.8
Natural moisture unit weight (kN/m^3)			16.30
Natural dry unit weight (kN/m^3)			14.84
Specific gravity			2.67
Atterberg limits	Liquid limit (%)		NP
	Plastic limit (%)		NP
	Plasticity index (%)		NP
Percentage of soil grains	Gravel (%)		10
	Sand (%)		30
	Silt (%)		48
	Clay (%)		12
Soil classification (USCS)			**ML: Silt with low plasticity (sandy silt)**
Compaction test	**SPE***	Max. dry unit weight (kN/m^3)	17
		Optimum water content (%)	16
	MPE*	Max. dry unit weight (kN/m^3)	18.75
		Optimum water content (%)	12
Direct shear test	**SPE***		c = 8 kN/m^{2}and φ= 27°
	MPE*		c = 13 kN/m^2 an φ= 34°
Unconfined compressive strength (kN/m^2)			91.7
Gypsum content (%)			5.7
Total soluble salts (%)			3.5
Sulfate content (SO_3) (%)			Nil
Organic matter (%)			1.37
Electrical conductivity (mS/s)			720
pH			9.83
SPE*: Standard Proctor energy MPE*: Modified Proctor energy			

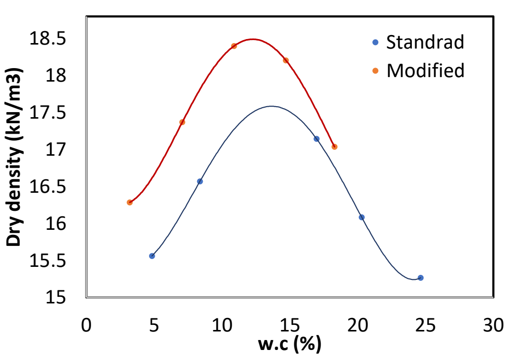


Figure 1: Compaction curves.

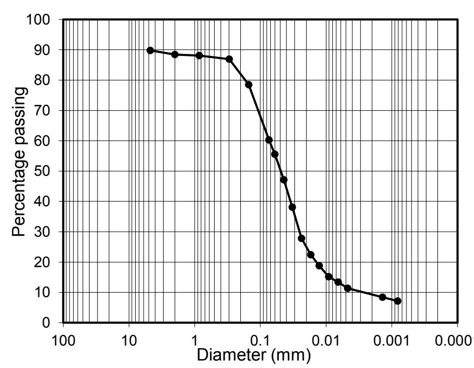


Figure 2: Grain size distribution curve.

2.2 Shell Model

Table 2 presents the specifications of the geometrical footing model used in the present study (area, angles, and thickness), and Figure 3 illustrates the footing model's geometries. An overall view of the shell foundations made into models exists in Figure 4. To create a rough surface condition, Epoxy glue was used to fix a thin layer of sand onto the surface of the model footing [22]. The volume of the shell foundation was calculated from the inside, and based on this volume, it was filled with soil in an amount that gave it the same density as the soil in the examination box. After that, the foundation and the soil inside are installed in the fifth layer of soil layers compacted in the soil box.

Table 2: Geometrical data of the footing models.

No.	Shape ID	Area (mm^2)	Shell angle (θ^0)	Thickness shell (mm)
1	Flat square	10000	180	5
2	Flat circle	11309	180	5
3	Upright conical	40715	63	5
4	Inverted conical	21771	63	5
5	Invertedpyramid	32500	63	5
6	Upright pyramid	17500	63	5
7	hemispherical	22619	-	-

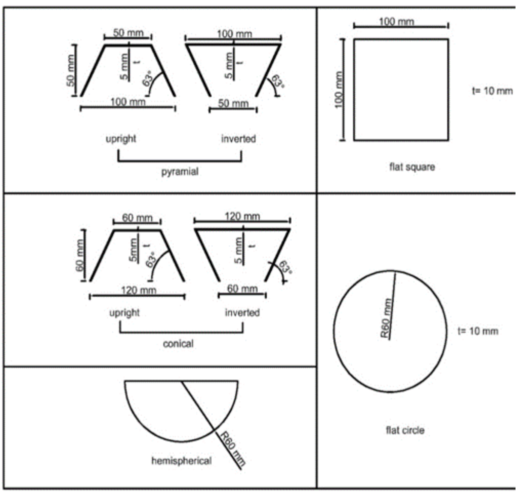
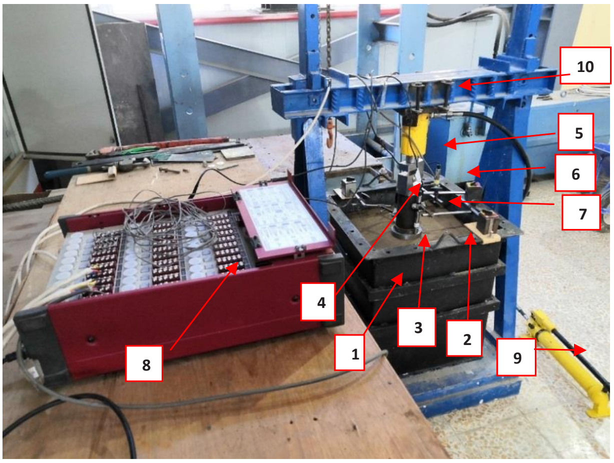


Figure 3: Geometrical configuration of the seven.

Figure 4: Overall view of shell footing model tested footing models made of steel

2.3 Model Description

A laboratory model with dimensions of (0.50×0.50×0.60 m) was constructed. The model was strengthened from the outside by two rows of steel bars (0.1×0.1 m), a loading system consisting of three strong columns (0.9×0.9 m) for each side, and a 20-ton loading cell connected from the top to a 20-ton hydraulic jack capacity. The footing was placed in the center with two transducers (LVDT) to record linear variable displacement, with an accuracy of (0.001mm) at the opposite for one run; the third (LVDT) was used to ensure that the walls of the examination box would be outside the boundaries of the shear zone expected to occur under the foundation upon failure. Three (LVDTs) were used for other runs, as shown in Figure 6, connected to a data logger unit where the readings were recorded every second [23]. The data were plotted using the Origin 2022 program. Ensure that the walls of the examination box containing the studied soil will be outside the boundaries of the shear zone expected to occur under the foundation upon failure. Based on Terzaghi's theory and drawing the failure surface under the foundation, it was found that the dimensions of the box are sufficient for the case that the box's walls do not affect the load-bearing values of the studied soil. Also, to obtain an adequate perception of the soil behavior during the examination, transducers (LVDT) (0.001mm) were installed at 2B from the base edge, as shown in Figure 5.



1. Box model at (0.5×0.5×0.6 m).
2. Soil.
3. Footing model.
4. Loading cell.
5. Hydraulic jack.
6. LVDT gauges are used to show the deformation of soil.
7. LVDT gauges are used to measure settlement details.
8. Datalogger.
9. Hydraulic press.
10. Loading structure.

Figure 5: Experimental setup.

2.4 Setup and Procedure of the Test

The soil sample taken from the field was fragmented to prepare the model soil sample, then put it through a 4.75-mm sleeve and let it dry. Specific amounts of water were mixed in to get the proper moisture in the soil. After that, the soil was put in plastic bags and left for three days. According to the protocol stated by [24,25]. After that, the soil was filled into layers in a test box with a thickness of 0.1m for each layer using a specially made compactor with a capacity of 80 tons and the dimensions of the area of the compactor (0.5×0.5 m), as shown in Figure. 7. Oil was put on the model's borders to reduce friction between the model and the soil layers [23]. The model used soil with a moisture content of 16% and γ_{dry}=17 kN/m^3, similar to the max dry density determined in the laboratory by a standard proctor test. The loading speed was determined at 1-2 mm/min according to the recommendations of the researcher [11], whereby the loading is increased incrementally (500 N) in each test, waiting between each increment until the variation in the settlement reading amount reaches 0.01 mm/min, as the researcher recommended [10].

This research uses the term "shell efficiency factor" to describe the increase. Q_{us} of a shell footing compared to Q_{uf} one (η). According to Eq. (1), it is the ratio of the difference between the ultimate loads of shell footings and the ultimate load of a flat footing [6].

$$\eta = \frac{Q_{us} - Q_{uf}}{Q_{uf}} \quad (1)$$

Where (η) shell efficiency, (Q_{us}) shell footing ultimate load, and (Q_{uf}) flat footing ultimate load. A non-dimensional settlement factor (F_∂) was made so that shell footings could be compared to traditional flat ones in terms of how they settle. To account for the settling characteristics of the footings during the loading, the settlement factor was determined at the ultimate load (Q_u). Eq. (2) displays the settling factor (F_∂). Better settling qualities are indicated by a settlement factor with a lower value [6].

$$F_\partial = \frac{\delta_u \gamma A_b}{Q_u} \quad (2)$$

Where (Q_u) ultimate load, (γ) soil unit weight, (A_b) area of the footing in the horizontal projection, and (δ_u) settlement at ultimate load.

Figure 6: Transducers (LVDT).

Figure 7: Hydraulic compactor.

3. RESULTS OF TESTS

The load-settlement data for specific tests were plotted and summarized in Figures 8 and 9, showing the load settlement curves for flat and shell footings on silty soil. Figure 8 presents load-settlement curves for conical inverted, upright, hemispherical, and conventional flat circles. In contrast, Figure 9 shows load-settlement curves for the inverted pyramid, upright pyramid, and Flat Square; also, load capacity was determined for all tests by the tangent method, sketching two tangents. The first tangent represents the curve's starting point, while the second represents the finishing point. The maximum load that a foundation can support is found when two tangent lines meet [26]. All results of the ultimate load have been approved in terms of load (kN) [6,10,27]. Generally, as seen from these figures, all selected shell footing models give higher resistance than applied loads from conventional flat footing behaviors, especially for an upright pyramid. Compared to flat footing, shell footing can improve the ultimate load and be more extensive. Figure 10 illustrates the values for each ultimate load ($Q_{us,f}$,) and settlement (δ_u).

In the present investigation, the increase in the ultimate load of a shell footing compared to its flat counterpart has been identified as the shell gain factor (η). It is defined in Eq.(1) [6]. Table 3 illustrates the calculated shell gain factors (η) obtained from the experimental investigation. In general, the results from Table 3 suggest that the shell efficiency factor (η) of upright conical shell footing is higher than the other type of shell foundation, i.e., the effect of shell configuration is effective for this because the soil inside the shell wedge got stiffer, one unit, and effectively interlocked where shell footing prevents soil from moving outward. Moreover, the shell gain factor (η) reduces remarkably for the inverted pyramid shell footing.

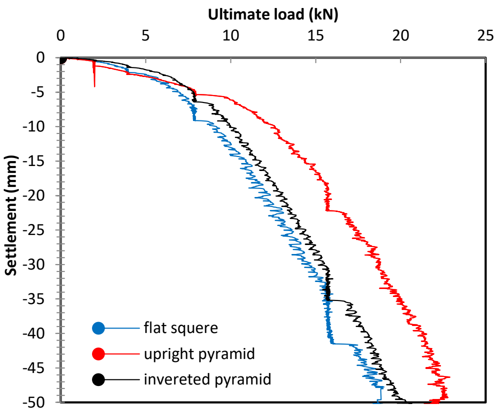


Figure 9: Summary of load settlement curves.

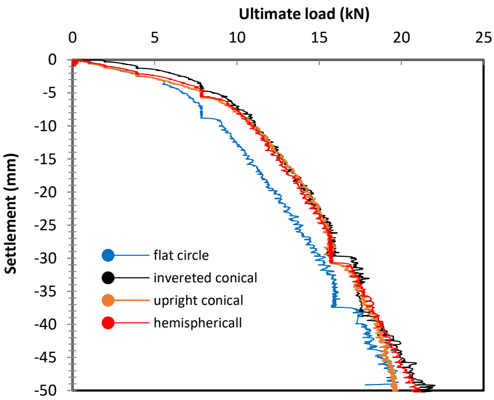


Figure 8: Summary of load settlement curves.

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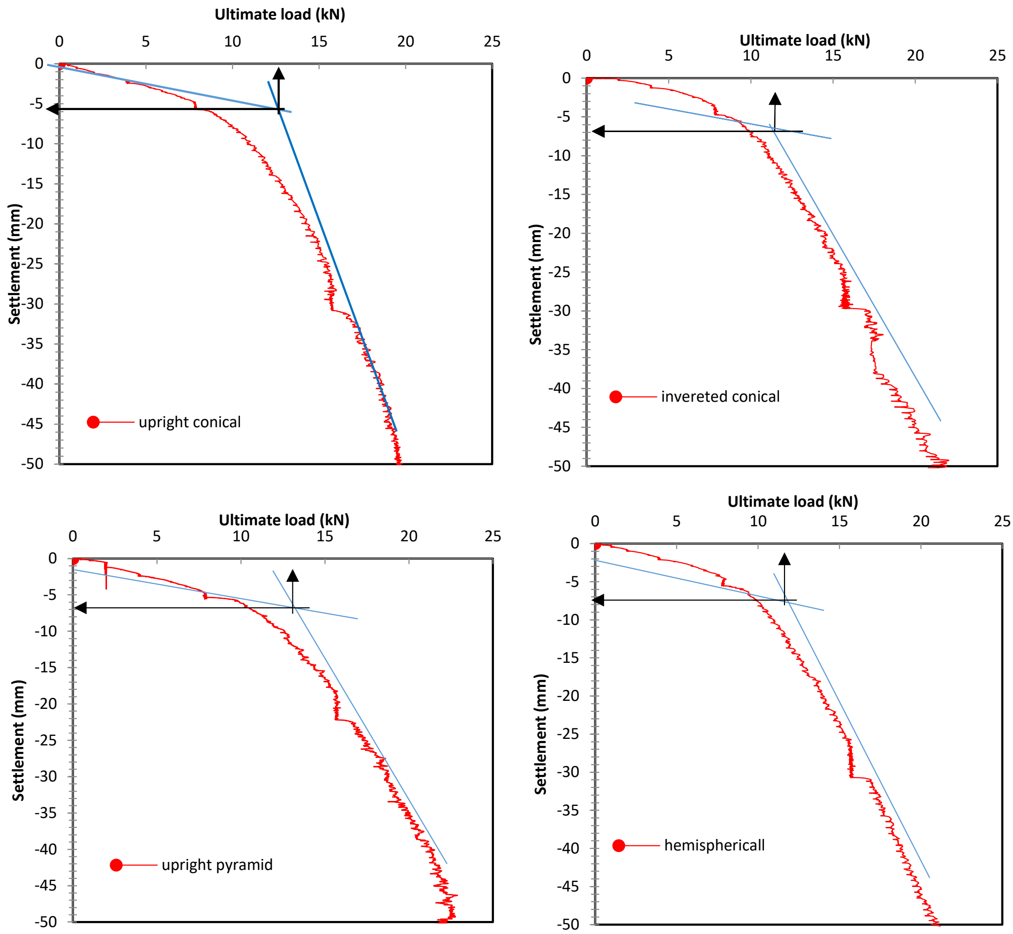

Figure 10: Setting values of ultimate load ($Q_{us,f}$) and settlement (δ_u).

Table 3 presents the settlement factors (F_∂) calculated from the present experimental investigation based on Eq. (2) [6]. Generally, the settlement factor decreases with any shell footing. This means that shell footings have better settlement characteristics. Figure 11 shows that the ratio of the ultimate load capacity of a shell foundation to that of its flat equivalent (Qu shell/Qu flat) has a special connection about (η). When (η) approaches 1, the behavior of the foundation transitions from a shell to a flat, and the ultimate load decreases.

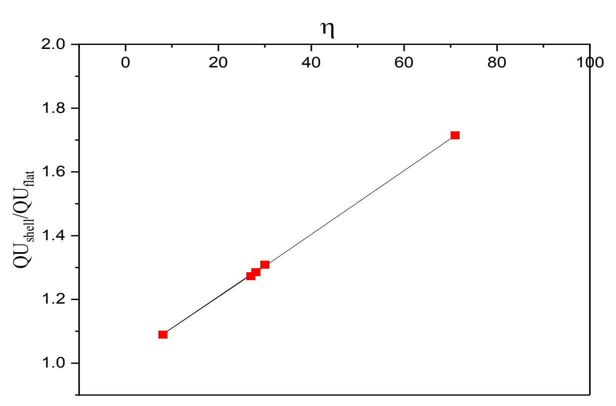

Figure 11: Variation of normalized ultimate load capacity concerning (η).

Table 3: Shell efficiency (η) and settlement factor (F_∂) values.

No.	Shape ID	Ultimate load ($Q_{us,f,}$) kN	Settlement (δ_u) mm	shell efficiency η%	settlement factor (F_∂)
1	Flat square	9.4	6	-	0.108
2	Flat circle	8.4	5.2	-	0.11
3	Upright conical	12.7	8	51	0.029
4	Inverted conical	10.7	4.7	27	0.08
5	Upright pyramid	12.3	5.2	30	0.017
6	Invertedpyramid	10.2	3.2	8	0.05
7	hemispherical	10.8	6	28	0.103

4. CONCLUSIONS

This paper examines load settlement behavior for seven foundation models (two conical and two pyramidal shells, one hemispherical, one circular, and one square flat foundation). The following findings may be made from the experimental observations:

- Shell foundations exhibit higher ultimate capacities than flat foundations of equivalent dimensions.
- The increase in the ultimate capacity of shell foundations as compared to their counterparts was represented by a shell gain factor (η). The upright conical footing was observed to have a higher shell gain factor than the other footing.
- The present experimental investigation used a non-dimensional settlement factor (F_∂) to analyze the settlement characteristics of shell foundations compared to their conventional flat counterparts. The results showed that the calculated settlement factor (F_∂) indicated that shell foundations exhibit better settlement characteristics than their conventional counterparts. Furthermore, it was observed that the upright pyramid shell footing has better settlement characteristics when compared to the other shell footings.

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