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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF ULTIMATE LOAD CAPACITY OF SHELL FOUNDATIONS ON REINFORCED AND UNREINFORCED SAND*

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Abstract– The ultimate load capacities of conical and pyramidal shell foundations on unreinforced and reinforced sand were determined by laboratory model tests and numerical analysis. The results were compared with those for circular and square flat foundations. Eight foundation models on unreinforced and reinforced sand were tested in which the influence of shell configuration on ultimate load capacity was investigated. Both the experimental and numerical studies indicated that, if shell foundation thickness increases, the behavior of the shell foundation on either reinforced sand or unreinforced sand gets closer to that of flat foundations. A new factor was also defined to present a unique relation between the ultimate load capacity of shell and flat foundations.

Keywords– Shell foundation, ultimate load capacity, sand, reinforced, shell factor

1. INTRODUCTION

Due to their many advantages, shell foundations have attracted many researchers from the 70s worldwide. Iyer and Rao [1] conducted a series of experimental tests to investigate the bearing capacity of shell foundations and compared the results with their plain counterparts. The results indicated that the bearing capacity of shell foundations is more than that for flat foundations. This difference was related to the stiffness and geometry of shell elements. Kurian and Jeyachandran [2] conducted experimental tests on various shell foundations and their plain counterparts to investigate the effect of footing configuration on the bearing capacity. Agarwal and Gupta [3] performed tests on conical, hyper and their plain counterpart's foundation under axial loading on sand. The results indicated that an increase in the bearing capacity of shell foundations is related to the difference in footing configuration and interface within footing and soil. Hanna and Abdel-Rahman [4] investigated the behavior of shell foundations in terms of bearing capacity and settlement. They performed their tests on conical, triangular and pyramidal shell foundations and circular, strip and square flat foundations. They noted that shell foundations performance is better than flat foundations and failure surfaces in the former are deeper than the latter. Kurian and Varghese [5], Kurian and Mohan [6], and Kurian [7] reported on the bearing capacity and distribution of the contact pressure of shell foundations.

The behavior of flat foundations on unreinforced and reinforced soils, on the other hand, have been investigated by several researchers [8-13]. The effect of the shell thickness and its behavior on unreinforced and reinforced soil, however, did not receive any attention in the literature. In this research model, tests and numerical analysis were performed to investigate the ultimate load capacity variations of

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shell foundations due to the thickness variations on reinforced and unreinforced sand, and the results are presented as follows.

2. MATERIAL TESTED

The particle size distribution curve of the soil used in the experiments is shown in Fig. 1. The soil was classified as well-graded sand (SW) according to the Unified Soil Classification System (USCS). Other properties of the soil are shown in Table 1. The shear strength parameters and the maximum dry unit weight of the sand were obtained from direct shear and proctor tests. The densities of the soil in the direct shear tests were the same as in the loading tests.

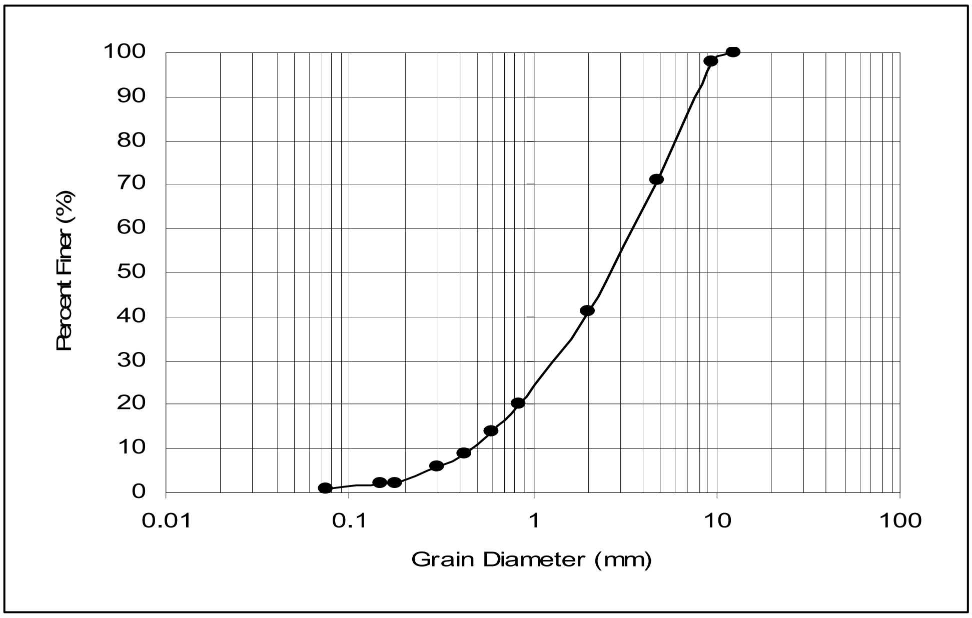

Fig. 1. Soil classification curve from sieve test

Table 1. Characteristics of the sand tested

Parameter	Value
Cohesion, c (kPa)	0
Peak angle of internal friction, $\phi(^0)$	37
Maximum dry unit weight, $\gamma_{d\,max}\left(\frac{KN}{m^3}\right)$	19
Optimum water content, $\varpi_{opt}(\%)$	9
Dry unit weight, $\gamma_d\left(\frac{KN}{m^3}\right)$	15
Minimum dry unit weight, $\gamma_{d\,\min}\left(\frac{KN}{m^3}\right)$	13.4
Relative density (%)	36
Uniformity coefficient	7.78
Curvature coefficient	1.24

3. FOOTING MODELS AND TEST APPARATUS

Two types of shell foundations were used in the present investigation, namely, conical and pyramidal shells to represent the axisymetric and three-dimensional conditions, respectively. To examine the effect of the shell thickness on the ultimate load capacity, three types of conical and pyramidal model shell foundations have been made and tested. Two types of flat foundations, i.e. circular and square foundations, were also made and tested for comparison. Figure 2 and Table 2 show the geometrical configuration and dimensions of these models, respectively. The overall view of the eight foundation models is shown in Fig 3.

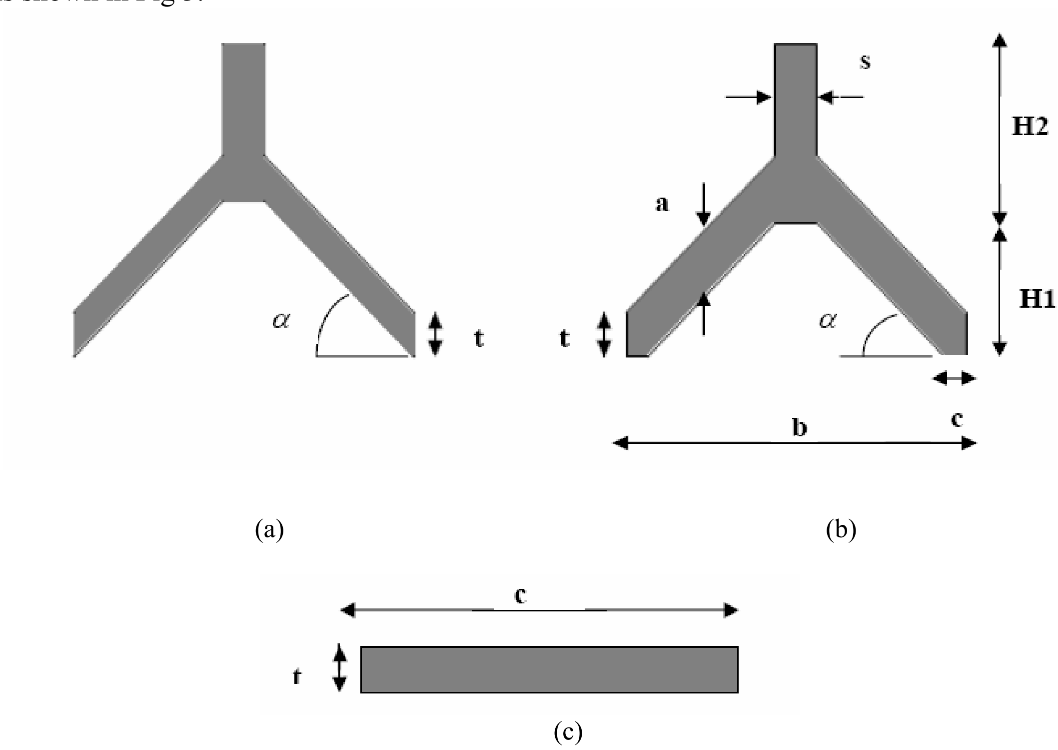

Fig. 2. Geometrical configuration of the foundation models, a) conical and pyramidal shell models, type I, b) Conical and pyramidal shell models, types II and III, c) Circular and square flat models

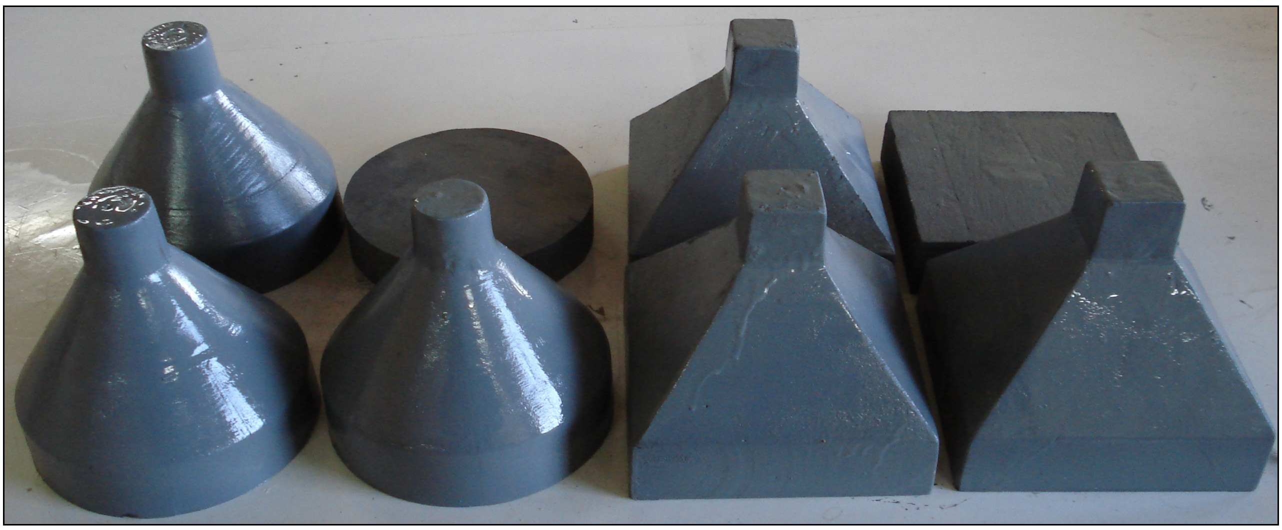

Fig. 3. The overall view of the eight foundation models

Table 2. Dimensions of the footing models

Dimensions	H1 (mm)	H2 (mm)	s (mm)	a (mm)	t (mm)	b (mm)	c (mm)	α (^{0})
Shell foundation type I	80	80	40	42	42	160	0	53
Shell foundation type II	64	96	40	58	42	160	12	53
Shell foundation type III	39	121	40	83	42	160	31	53
Flat foundation	_	_	_	_	42	_	160	0

A cylindrical tank of 1.00 meter in diameter and 1.00 meter in height was built, along with a static loading frame for testing the conical and circular foundation models. A box of 1.00×1.00×1.00 meter was built for testing the pyramidal model shell and square flat foundations. Displacements were measured using the dial gauges mounted on the foundation.

4. TEST PROCEDURE

A total of 32 loading tests were performed on the cited shallow footing models. For every loading test, the sand box was initially filled by pouring a 50 mm thick layer of sand in unreinforced and reinforced cases. Geogrid layers were placed in the sand in the following conditions: distance of first reinforcement layer to foundation base (u) = 5 cm, vertical distance of reinforcement layers (z) = 3 cm, number of reinforcement layers (N) = 4.

To obtain a uniform compaction, each layer was tamped using a wood plate, dropped from a 150 mm height (diameter of wood plate was 300 mm). Dry unit weight values were about 15 (kN/m3). This gave a relative compaction of about 79%.

After filling the box, the foundation was located on the sand surface at the center of the box while sandpaper was fixed to the internal area and base of the foundation to achieve a rough interface. To prepare the soil core under the shell foundation model, the space under the shell was filled with sand according to the required unit weight. The sand filling process of a shell model was done by placing a thin steel plate on the bottom of the shell model before placing it on its location. The steel plate was then slowly pulled out from underneath the shell.

The footing was then loaded statically using dead weight and a hydraulic jack system in axisymmetric and three-dimensional conditions, respectively. Loading increments in each test were 500 N. After each loading step, as soon as settlement variations reached less than 0.01 mm/min, its value was read from a settlement gauge. After the readings, the load-settlement curve was plotted. The ultimate load was obtained by the tangent method. In this method, two tangents are plotted along the initial portion and the latter portion of the curve and the load corresponding to the intersection point of these two lines is taken as the ultimate load of the foundations.

5. TEST RESULTS

Figures 4 and 5 show load-settlement curves in three-dimensional condition on unreinforced sand and a comparison between the load-settlement curve of a conical shell foundation (type II) on unreinforced and reinforced sand, respectively. The ultimate load capacity obtained from the test results are illustrated in Tables 3 and 4.

To investigate the effect of foundation configuration on ultimate load, a new parameter called shell factor (SF) is introduced and defined as:

$$SF = 1 - \frac{a'}{A'} \tag{1}$$

Where:

$a^{/}$: Area of the flat portion of the base of shell and flat foundations

$A^{/}$: Base area of counterpart circular and square foundations

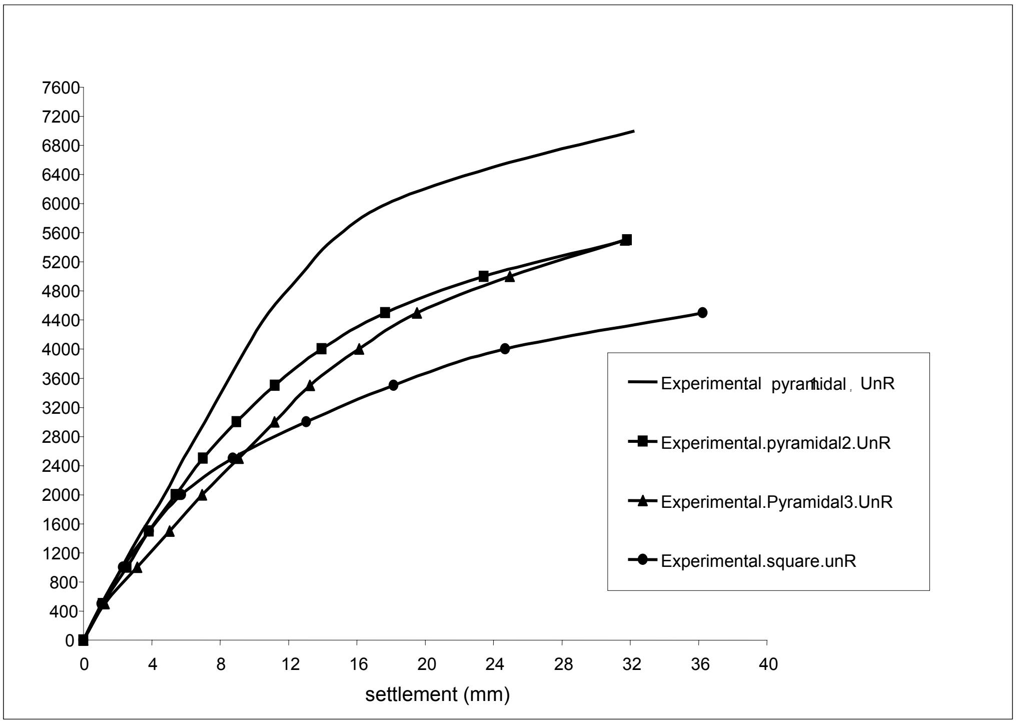

Fig. 4. Load-settlement curves for pyramidal foundations on unreinforced sand (UnR: Unreinforced)

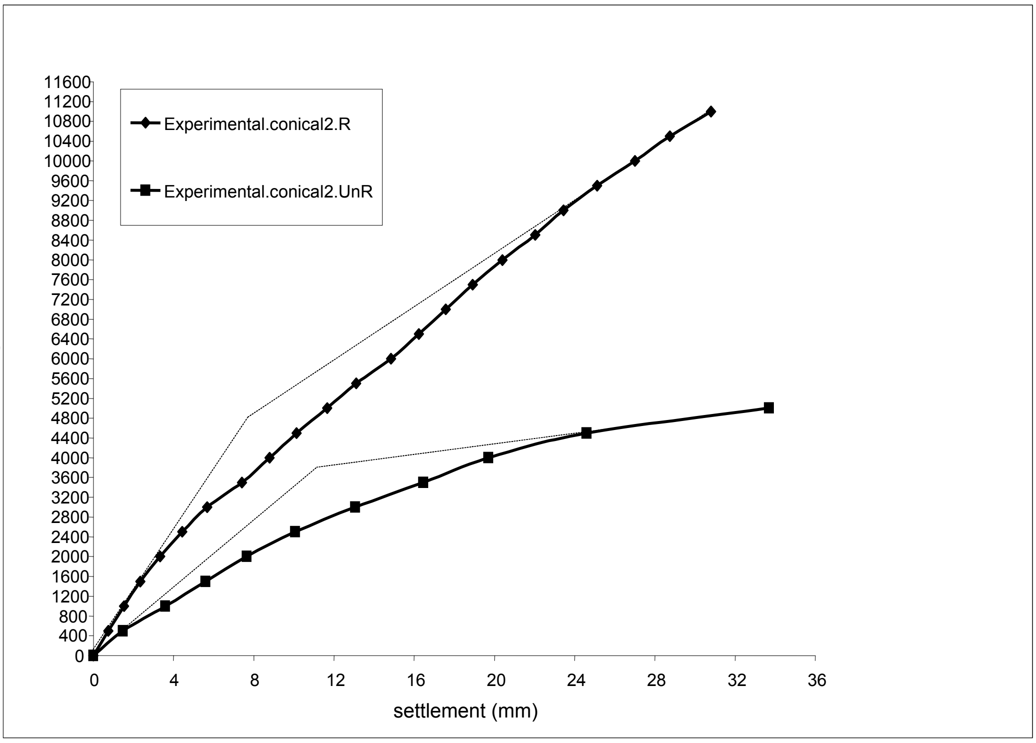

Fig. 5. Load-settlement curve of conical shell foundations (type II), on unreinforced and reinforced sand (UnR: Unreinforced, R: Reinforced)

Table 3.Ultimate load for axisymmetrical tests

Foundation types / Ultimate load (N) on	Conical type I	Conical type II	Conical type III	Circular
Unreinforced sand	4750	3800	3400	3100
Reinforced sand	6300	4800	4400	3750

Table 4. Ultimate load for three-dimensional tests

Foundation types / Ultimate load (N) on	Pyramidal type I	Pyramidal type II	Pyramidal type III	Square
Unreinforced sand	5850	4200	3850	3300
Reinforced sand	6700	5400	4500	3950

It should be noted that for flat foundations $a^{/} = A^{/}$. The values of $a^{/}$ and SF have been calculated for the model foundations and presented in Table 5. Furthermore, Fig. 6 shows the variation of the ultimate load against SF .

Table 5. Values of $a^{/}$ and SF for model foundation

Foundation model	Conical I	Conical II	Conical III	Circular	Pyramidal I	Pyramidal II	Pyramidal III	Square
$a^{/}(cm^2)$	0	55.79	125.63	201.06	0	71.04	159.96	256
SF	1	0.723	0.375	0	1	0.723	0.375	0

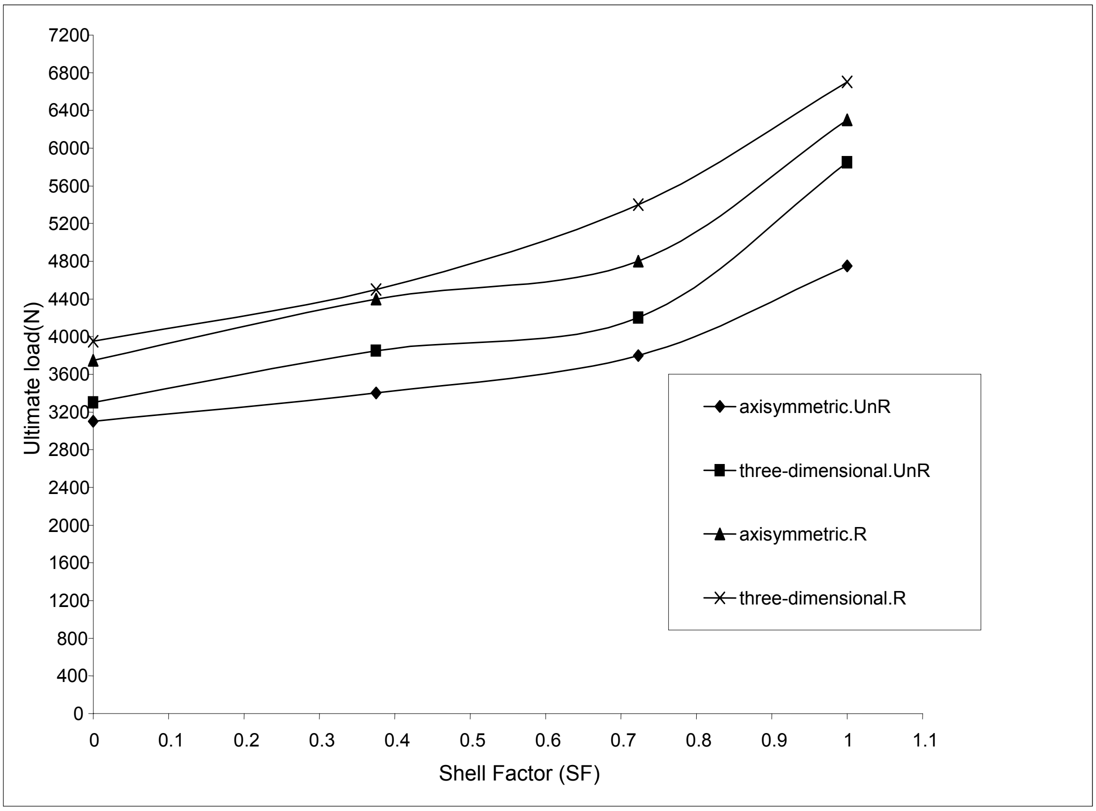

Fig. 6. Variation of ultimate load capacity with respect to SF.(UnR:Unreinforced, R:Reinforced)

As is shown in Fig. 6, by increasing SF (i.e. the foundation behavior approaching from flat to shell condition), the ultimate load increases for all cases. The reason is that the increase of the shell factor will lead to an increase of the soil core's volume. Then, the increase in soil core volume allows the soil underneath the foundation to find its way towards the core region, postponing the dilatational lateral movement of the soil that causes its failure. This phenomenon also increases the stiffness of the soil-foundation system. To clarify the point further, it should be noted that if flat foundation, shell type III, II and I are loaded with the same load, immediately after loading the failure wedge under the flat foundation starts to form, but for shell foundations the failure wedge is not created until the core soil is compacted and integrated with the shell. This happens firstly for flat foundation, secondly for shell foundation type III, thirdly for shell foundation type II and fourthly for shell foundation type I. Therefore, the ultimate load capacity of flat foundation is the lowest and that of shell foundation type I is the highest.

The values of ultimate load normalized with respect to those values for flat counterpart foundations (i.e. circular and square footing) are illustrated in Fig. 7. This figure depicts that a unique relation can be found for the ultimate load capacity of the shell foundation to that for their flat counterparts ratio (Qu shell/Qu flat) with respect to SF as follows:

$$\frac{Q_{ushell}}{Q_{uflat}} = 0.812SF^2 - 0.0777SF + 1 \tag{2}$$

The same relation could be used for foundation on reinforced and unreinforced sand.

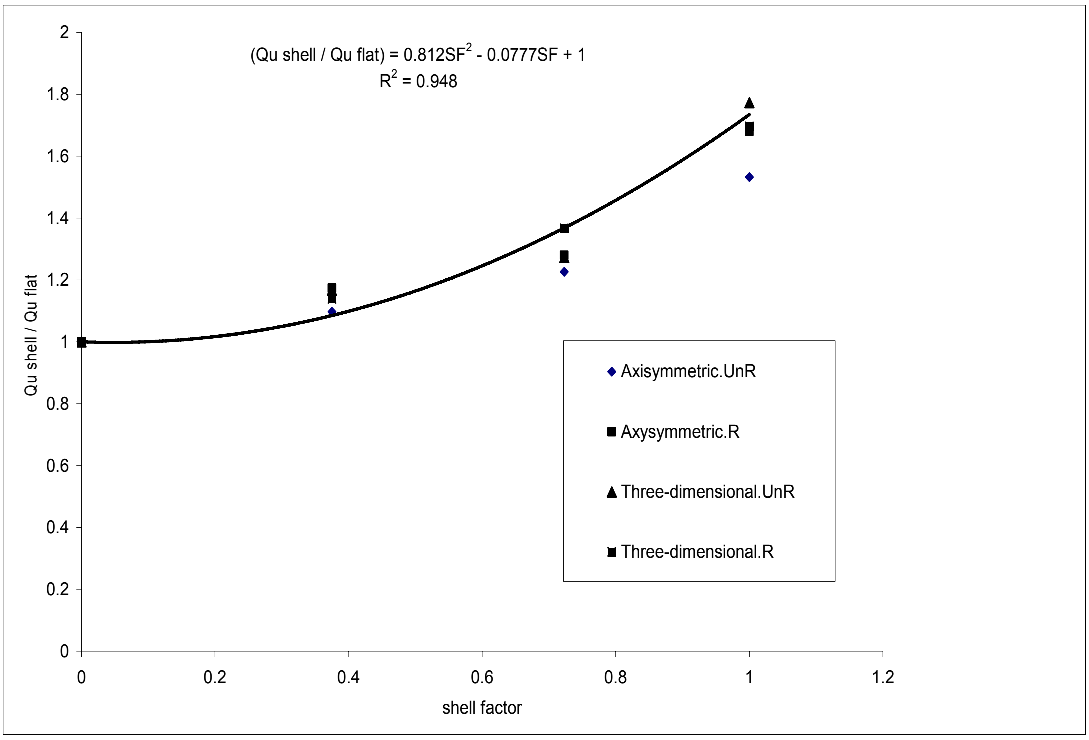

Fig. 7. Variation of normalized ultimate load capacity with respect to SF.
(UnR: Unreinforced, R: Reinforced)

6. NUMERICAL ANALYSIS

The finite element program PLAXIS-2D [14] was used to model circular and conical foundations on reinforced and unreinforced sand. The Soil model in this analysis was the Mohr-Coulomb. The axisymmetric condition and 15-node triangular elements were used for the analysis. In all models the mesh size was considered to be medium. Modulus of elasticity (E) was obtained from a triaxial test. Since in the Plaxis program the quantity of zero for cohesion is not defined, a small value for cohesion was considered. The parameters used for this analysis are shown in Table 6. To model the friction between the foundation and reinforcement with the soil, the interface elements were used.

Table 6. Soil properties used in numerical analysis

Parameter	Value
Dry unit weight, $\gamma_d(\frac{KN}{m^3})$	15
Unit weight, $\gamma(\frac{KN}{m^3})$	15.54
Modulus of elasticity, $E(Kpa)$	8000
Poisson ratio, ν	0.3
Cohesion, $C(KPa)$	0.5
Angle of friction, $\phi(^0)$	37
Dilation angle, $\varphi(^0)$	2
Tensile strength of geogrid (kN/m)	8

7. COMPARISON BETWEEN TEST AND NUMERICAL RESULTS

Typical obtained and calculated load-settlement curves from test and numerical analysis are shown in Fig. 8 and the values of ultimate load capacity obtained from numerical analysis and experimental tests are compared and summarized in Table 7. As can be seen in this table, the values of numerical analysis are close to those of laboratory test models, validating the results obtained in both studies. Of course, the small differences between the experimental and the numerical values are related to errors and environmental conditions in the laboratory.

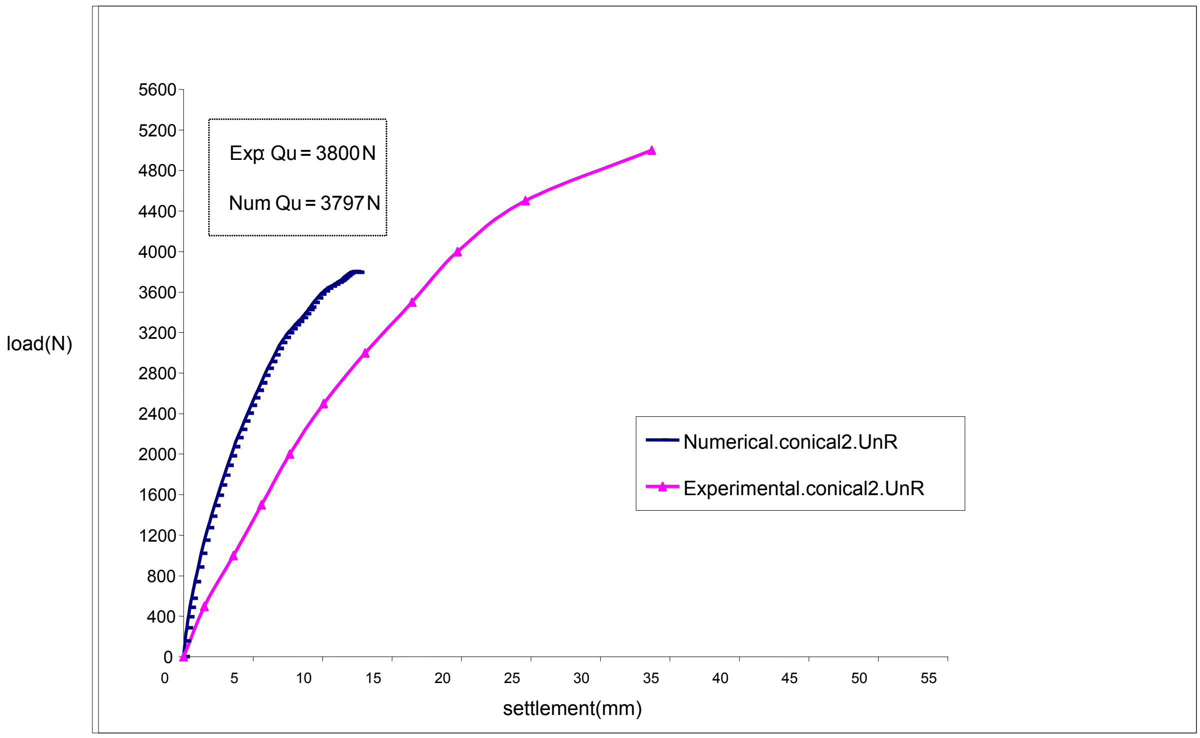

Fig. 8. Load-settlement curve from test and numerical analysis (UnR: Unreinforced)

Table 7. Values of ultimate load for experimental and numerical analysis

Foundation types / Ultimate load (N)	Conical I-UnR	Conical II-UnR	Conical III- UnR	Circular -UnR	Conical I-R	Conical II-R	Conical III-R	Circular-R
Numerical	4139	3797	3522	3361	5727	4376	4108	3542
Experimental	4750	3800	3400	3100	6300	4800	4400	3750
Discrepancy (%)	14	0	3	8	10	9	7	6

8. CONCLUSION

According to the experimental and numerical investigations on eight foundation models, including three types of conical and pyramidal shell and one type of circular and square flat foundation, the following conclusions can be drawn:

1) A shell factor (SF) was introduced to represent the effect of shell configuration on ultimate load capacity of models on reinforced and unreinforced sand. By decreasing the shell factor, the behavior of the shell foundation gets closer to that for flat foundation and the ultimate load capacity decreases. As has been shown in Fig. 7, concerning the type of shell and soil, for SF = 1, the ultimate load of shell foundation is 50% to 80% higher than that of their flat counterparts. This indicates the advantage of using shell foundations.
2) According to this research, a unique relation can be found to represent the variations of ultimate load capacity of shell foundations to that of their flat counterparts ratio ($Q_{u\ shell}/Q_{u\ flat}$) with respect to SF. Eq. (2) shows the foregoing relation for conical and pyramidal shell foundations and their flat counterparts on reinforced and unreinforced sand.
3) The ultimate load capacity of shell foundations is higher than that for counterpart flat foundations.
4) The ultimate load capacity for conical and pyramidal shell foundations on reinforced sand is greater than that for unreinforced sand. This indicates the effect of reinforced structure.
5) The finite element analysis results show a reasonably good agreement with laboratory experimental results; with a discrepancy of within 0 to 14%, Table 7.

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