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Experimental study of geotechnical behaviour of different shell foundations on unreinforced and reinforced sandy soil

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Abstract

This paper presents the performance of three types of small-scale shell foundations (pyramidal frustum, semi-cylindrical and prismatic shell) of the same plan area on different states of sand provided with or without reinforcement. To understand the effect of reinforcement and its dependency on the vertical embedment depth, two cases were considered, i.e. reinforcement at a depth equal to 0.5 B (B=width of foundation) and another case at a depth equal to B. Bearing capacity for different shell foundations models and settlement behaviour were studied based on the load settlement curves and compared with that of conventional flat foundation model. The experimental results show that shell models perform better than the flat foundation model in terms of bearing capacity and settlement resistance on the different states of sand with or without reinforcement. The relationship of ultimate load with the angle of internal friction was found. Reinforcement embedded at 0.5B depth was found to be better than provided at B depth in all the states of sand. It is also noticed that the bearing capacity ratio is lower for the sand reinforced at a depth of B than that of 0.5B, showing the dependency on reinforcement embedment depth.

Keywords: Experimental study, Shell foundation, Reinforced, Unreinforced, Bearing capacity, Settlement

1. Introduction

Shell foundations depend on their geometrical form to derive their strength and high-performance efficiency while considering the material quality. They generally consist of geometrical curved, folded or bent thin surfaces compared to their overall planar dimensions. The bearing capacity and settlement resistance performance depend on soil type, grain size, foundation geometry, contact area, etc. Due to the difference in geometry, the contact area with soil is more in the case of shell foundations than in flat foundations. The concept of the shell foundations has been deliberated in many research papers, proving that the ultimate bearing capacities are higher and have better settlement resistance than the flat counterparts.

Hanna and Abdel-Rahman [1] examined the geotechnical characteristics of triangular strips, conical and pyramidal shells on different states of sand and showed that the shell foundations have better bearing capacity and settlement resistance than flat counterparts. The authors illustrated correlation of bearing capacity with the shell angle and introduced the shell gain and settlement factors. Yamamoto et al. [2] employed T bar, T-cone, shell, shell block and rigid-block to investigate the geotechnical behaviour by loading test and numerical limit analysis for surface and embedded conditions on sand. Conical and pyramidal shell foundations showed higher bearing capacity and better settlement resistance for the same plan dimensions [3, 4]. Increased bearing capacity is reported in upright triangular and inverted triangular shells over conventional flat strip foundations [5]. The load-carrying capacity of shell footings were observed to be higher than that of flat counterparts [6-8]. Idris et al. [9] illustrated that the bearing capacity of the folded plate foundation is higher than that of the flat plate foundation.

Increased bearing capacity and lower settlement is possible by including geosynthetics, namely geotextile, geogrid, geo-mat, geocell, etc., on different soil types [10-12]. The use of geotextile and geogrid as reinforcement for soil for investigating the ultimate bearing capacity of shell foundations is reported by several authors [13-17]. However, previous studies are limited to specific shapes of shell foundations despite the wide varieties of different forms that could be considered and studied along with reinforced soil. This paper focusses on the geotechnical behaviour of three shell models: prismatic shell, pyramidal frustum shell, and semi-cylindrical shell, which have the same plan area as the flat model on three states of sand. It also aims to determine the geotechnical performances, especially bearing capacity and settlement resistance of considered shell models with or without reinforcement corresponding to embedment depths of reinforcement.

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2. Materials and methods

2.1 Soil, model and reinforcement

The soil is described as poorly graded uniform sandy soil (SP) according to the Unified Soil Classification System (USCS) with a uniformity coefficient of $C_u = 4$, a coefficient of curvature $C_c = 1$, and a specific gravity of 2.65 as per IS 2720 (Part 4 and Part 3) [18, 19]. Figure 1 represents particle size distribution curve of the soil. Three states of sand have been used in the study: loose, medium, and dense.

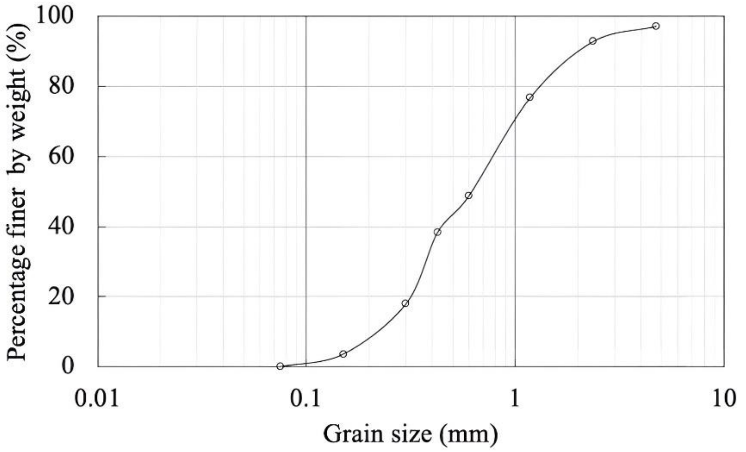

Figure 1 Particle size distribution curve

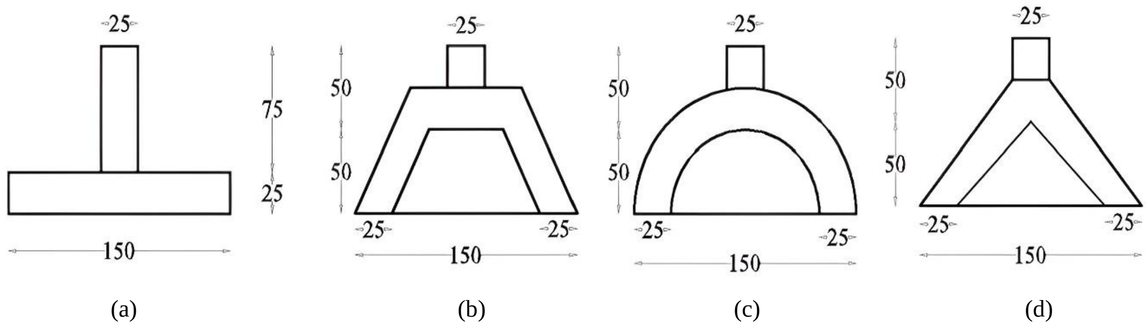

Figure 2 Cross-section view of foundations (a) flat, (b) pyramidal frustum shell, (c) semi-cylindrical shell, and (d) prismatic shell (all dimensions in mm)

Figure 3 Prepared sample of foundation models for the load test

Three shell models-prismatic, pyramidal frustum and semi-cylindrical shell were employed for the load test in addition to flat foundation models. Figure 2 shows the typical cross-sections of flat and other shell foundations of different shapes. Some of the cast cement concrete foundations of various shapes are shown in Figure 3. To enable proper comparison, the shell models have the same plan base area as the flat model. The shell foundations have an average shell inner rise of 50 mm and inner rise to base width ratio of 1:3.

A glass fibre-reinforced concrete grade of 25M with a water-cement ratio of 0.45 was used for preparing the small-scale foundation models. The glass fibre content is 0.4% of the total weight of the concrete. The glass fibre is an alkaline-resistant monofilament containing 16.5% zircon, 12mm long, 13.7µm diameter and 2.7g/m^3 density. The tensile strength is 1700MPa, and the modulus of elasticity is 72GPa, as provided by the manufacturer. The maximum size of coarse aggregate used in the mix was limited to 6 mm. Steel sheets 2mm thickness were fabricated to the required shape and dimensions as casting moulds. The concrete mixes were poured into casting moulds and demoulded after 24 hours. The casted specimens were removed and left for 28 days of water curing. The models were light grey in colour and had a slightly rough surface with sharp edges. The upper part of the semi-cylindrical shell foundation was slightly flattened to facilitate the proper placing of the column. The compressive strength of 100mm cubes is determined as per IS 516 [20] at 7 and 28 days is 21N/mm^2 and 40N/mm^2, respectively.

The reinforcement provided beneath the bottom soil was of fibreglass sheet as a geosynthetic, nonwoven chopped strand mat made from E glass with 225gsm, 0.2% moisture content, and tensile strength of 80N, approximately 1mm thickness as provided by the manufacturer. The fibreglass reinforcement was placed horizontally for a constant 600 (4B) mm length at depth of 0.5B and B. Beyond the 4B width of reinforcement, reinforcement has no significant effect [21].

2.2 Experimental setup and preparation of soil bed

A rigid galvanised iron tank of inner dimensions 1000mm X 1000mm X 1000mm of 4mm thickness, attached to a channel section frame provided with a hand-operated hydraulic jack, was designed and constructed for performing load tests, as shown in Figure 4. The load test tank was sufficiently rigid and large that there would not be horizontal displacement when the load was applied. The depth and width of the tank are greater than 4B and 5B, respectively [15]. The hydraulic jack provided vertical displacement at a constant rate of 2mm/min, and a proving ring of 25kN capacity was connected for reading the load applied to the models. To compute the displacement/ settlement of the models, dial gauges were attached at the centre of the model with the help of a reference beam. The load was recorded for every 0.3mm settlement. All the setups were removed or adjusted for pouring sand. The setup is per ASTM D 1194 [22].

The dry soil was poured into the tank using the pluviation method in 5 layers of 200 mm thickness and spread evenly. The conical pouring tip was continuously raised manually to maintain a drop height of 0.5m, 0.75m, and 1m for loose, medium and dense sand, respectively, [14, 23]. The pre-evaluated compaction with a calculated constant load was done with a plate board (10kg) for each layer at the start of the test to maintain uniform compaction and the desired sand density. The average relative densities achieved during the tests were found by inserting cans with known volume, as in [14]. The average values of the angle of internal friction and relative density are 30^o, 22.5% for loose, 34^o, 47.71% for medium, and 37^o, 71.16 % for dense sandy soil as per IS 2720 (Part 13) and IS 2720 (Part 14) [24, 25].

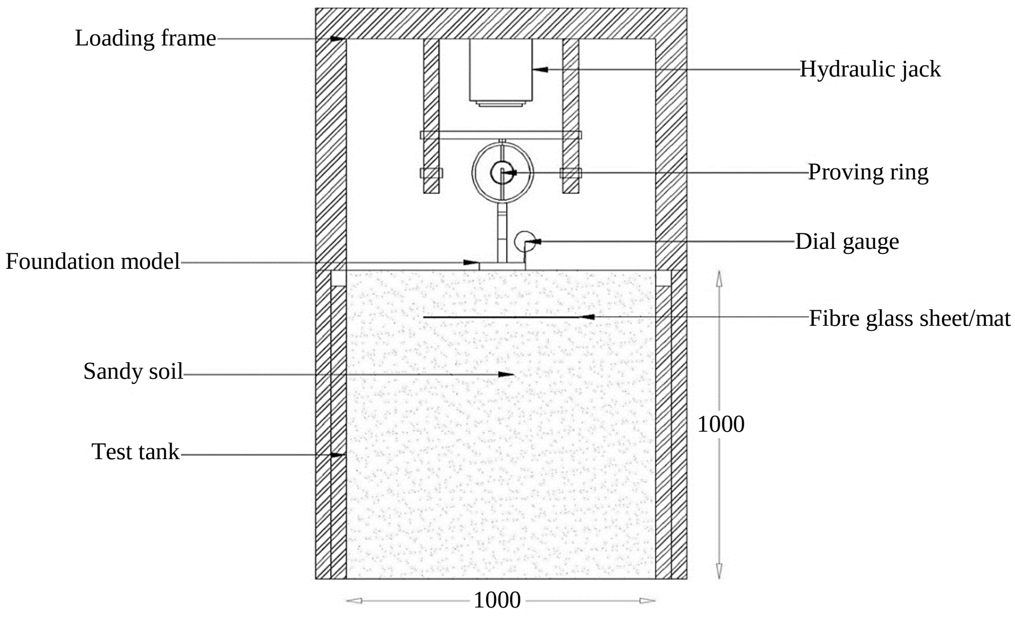

Figure 4 Experimental setup for the load test

The tank was filled with a considered state of sand without any reinforcement (UR) for the first setup. Prior to placement on the prepared sand surface, and the shell models were inverted and inner core was filled with the calculated weight of sand for the required relative density. A thin sheet covered the shell bottom to prevent escape of sand, and then the models were placed. Finally, the sheet was removed slowly, and the models were preloaded to ensure contact between inner core and sand [1].

To study the contribution of reinforcement corresponding to vertical embedment depth and for comparison with unreinforced soil, two reinforcement embedment depths were taken into account, i.e. the embedment depth is 0.5B (u/B=0.5), and embedment depth is B (u/B=1). As in the unreinforced case, the soil was filled up in layers for the reinforced conditions. When filling the last layer, the sand was levelled to a certain height, leaving 0.5B or B from the tip of the tank as required. The reinforcement was placed horizontally at the specified depths and filled with sand till the tip. The sand was compacted, and the load tests were conducted in a similar manner as in unreinforced soil. The sand state and parameters were repeatedly checked before the load test was conducted with preliminary tests. A series of load tests were conducted for all models, and the loads were continuously applied till the models failed. The load-settlement readings were recorded for every test till failure of the models.

3. Results and discussion

3.1 Effect of shell on ultimate load and settlement

A total of 108 load tests were conducted for the models on different sand states with or without reinforcement. The load settlement from the data exhibit increase of settlement increases with load until the model breaks without a clear peak. To determine the ultimate load, tangent method was employed where two tangents-one drawn from the initial portion and another from the latter portion of the load-settlement curve. The values of x and y corresponding to the intersection point indicate the ultimate load with the corresponding settlement, as given in Table 1. Figure 5 presents typical load-settlement curves of flat and shell foundations laid on a reinforced loose state of sand. Similar trends were also noticed for foundations on medium and dense states of sand, though the ultimate load was comparatively higher. Moreover, the curves were shorter in the case of medium and dense states of sand. Pyramidal frustum shell foundations had the highest ultimate load and lowest settlement, followed by semi-cylindrical, prismatic, and flat models. A higher ultimate load means a higher ultimate bearing capacity. The higher ultimate load and lesser settlement in shell foundations, as obtained from the experimental results, are consistent with the published literature [1-9].

The geometry interface difference between the shell and flat, and the shell part preventing the sand from moving outward is the reason for better performance of shell foundations. Moreover, a larger physical contact area exists between the shell and sand compared to the flat foundation. The pyramidal frustum shell foundation has largest projected horizontal contact area than other considered foundation models.

Table 1 Ultimate load (N) and settlement (mm) of flat and shell foundations

State of Sand	Types of foundation	Ultimate Load (N)			Settlement(mm)		
		UR	0.5B	B	UR	0.5B	B
Loose	Flat	160	360	240	6	4.2	4.5
	Pyramidal Frustum Shell	420	720	520	5	4.2	4.2
	Semi-Cylindrical Shell	380	650	450	6	4.2	4.2
	Prismatic Shell	320	600	420	6	4	5
Medium	Flat	220	460	300	6	4	4
	Pyramidal Frustum Shell	470	840	600	5	4	3.6
	Semi-Cylindrical Shell	420	760	520	6	4	3.4
	Prismatic Shell	390	700	500	6	4	4.1
Dense	Flat	280	580	390	6	3.5	3.9
	Pyramidal Frustum Shell	520	980	700	5	3.1	3.2
	Semi-Cylindrical Shell	500	860	600	6	3.1	3.2
	Prismatic Shell	440	820	570	6	3.2	3.4

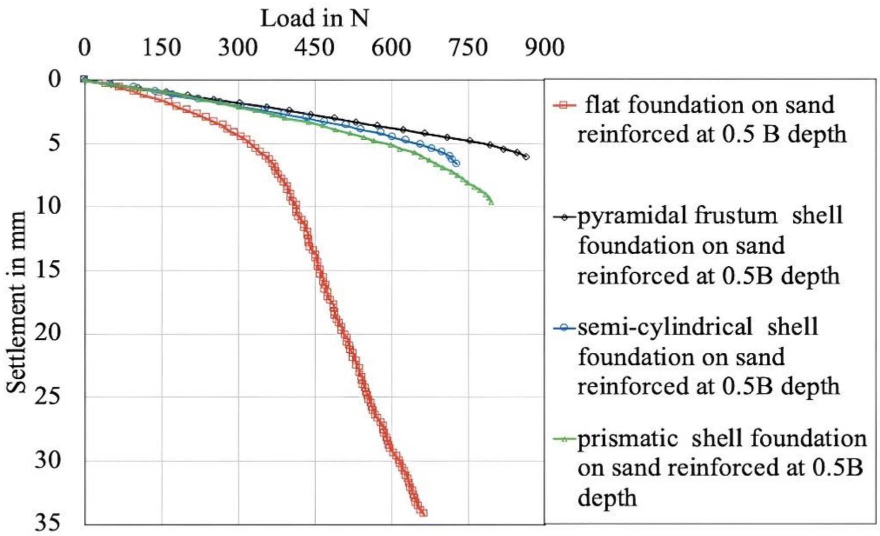

Figure 5 Load-settlement curves of the models on loose sand (reinforcement depth = 0.5B)

3.2 Effect of the angle of internal friction on ultimate load and settlement

The load settlement curves for flat and pyramidal frustum shell foundations with reinforcement embedded at 0.5B in different states of sand (loose, medium and dense) is shown in Figure 6. Significant changes in the curves occurred with the varying states of the sand. Sand with a higher angle of internal friction yields a higher ultimate load and corresponding lower settlement. Similar results were obtained for reinforcement embedded at depth B, irrespective of the shape of shell foundations. It shows an evident direct relationship between the ultimate load on foundations and angle of internal friction of soil. However, settlement is inversely related to the angle of internal friction.

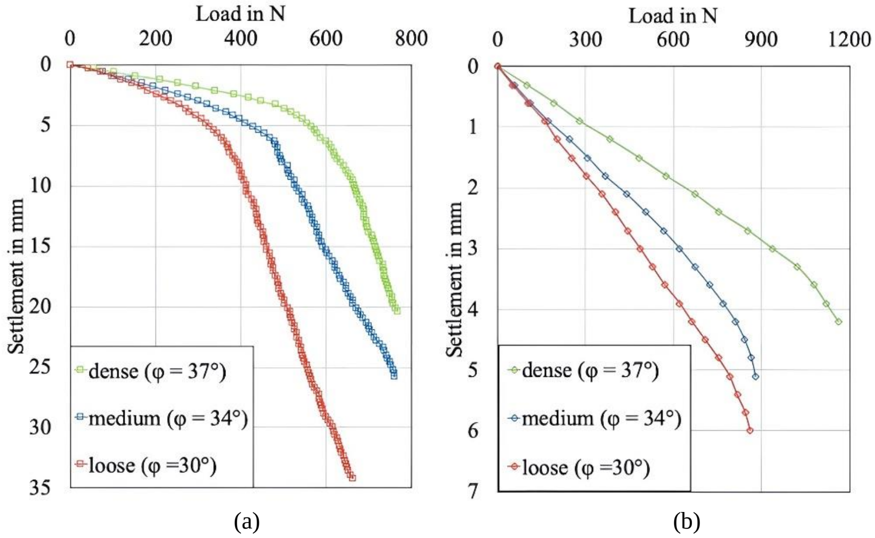

Figure 6 Load-settlement curves of a) flat and b) pyramidal frustum shell on sand reinforced at 0.5B depth

The variation of ultimate load with angle of internal friction for the foundation models is presented in Figure 7. Irrespective of the shape of foundation models, the ultimate load was found to increase with increasing angle of friction [1, 7, 14]. Angle of internal friction is proportional to the density of sand. Higher value of angle of internal friction of soil denotes higher density, thereby indicating better compaction. For all states of sand, ultimate load was highest for the pyramidal frustum shell foundation, while the flat foundation presented the least ultimate load. The results indicate the benefit of a pyramidal frustum shell for enhanced ultimate load over other shell foundations.

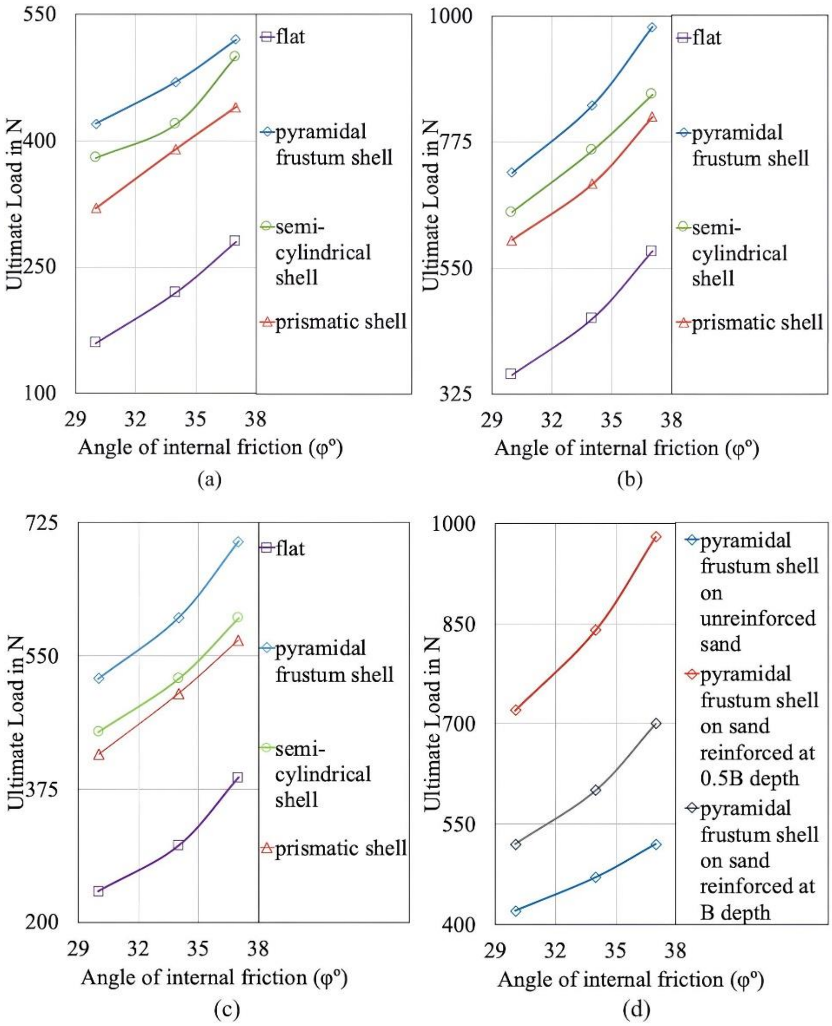

Figure 7 Ultimate loads versus the angle of internal friction: a) unreinforced, b) reinforced at 0.5B depth, c) reinforced at B depth, and d) pyramidal frustum shell foundation on reinforced and unreinforced sand.

3.3 Shell gain factor (η) and settlement factor (F_{δ})

The shell gain factor, η gives percentage increase in the ultimate load of shell foundation to that of flat foundation (Eq-1). While the settlement factor, F_{δ} (Eq-2), indicates settlement characteristics [1].

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

Where Q_{us} is the ultimate load of shell foundation, and Q_{uf} is the ultimate load of flat foundation.

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

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

A high shell gain factor indicates better performance of the shell foundation in terms of load capacity. A low settlement factor denotes higher settlement resistance. Shell gain factor and settlement factor for flat and shell foundations is presented in Table 2. Among different types of foundations, the shell gain factors of the pyramidal frustum shell foundation are highest, followed by semi-cylindrical and prismatic shell foundations. Pyramidal frustum shell foundation recorded the highest and lowest shell gain factor (η) of 163% and 86% on loose and dense unreinforced soil respectively. On other hand, settlement factors of the pyramidal frustum shell foundation are the lowest, confirming the best performance in settlement characteristics. Flat foundations showed lowest performance concerning the settlement factor.

Figure 8 shows the relationship between angle of internal friction with shell gain factor and settlement factor. For all the shell foundations, shell gain factor and settlement factor decreases noticeably with increase in the angle of internal friction of sand. The percentage increase in shell gain factor decreases with increase in the density of sand. The effect of shell thereby diminishes as the state of sand get denser. The sand contained within the shell and the foundation model act as a unit block in dense soil. The shell gain factor and settlement factor is dependent on the angle of internal friction [1, 14].

Table 2 Shell gain factor (η) and settlement factor (F_{δ} x10^{-3})

State of Sand	Types of foundation	Shell gain factor (η)			Settlement factor (F_{δ} x10^{-3})		
		UR	0.5B	B	UR	0.5B	B
Loose	Flat	-	-	-	13.5	4.2	6.75
	Pyramidal Frustum Shell	163	100	117	5.71	2.8	3.88
	Semi-Cylindrical Shell	138	78	88	7.12	2.92	4.21
	Prismatic Shell	100	67	75	7.99	2.91	5.07
Medium	Flat	-	-	-	10.19	3.35	4.98
	Pyramidal Frustum Shell	114	83	100	5.30	2.37	2.99
	Semi-Cylindrical Shell	91	65	73	6.69	2.46	3.06
	Prismatic Shell	77	52	67	6.80	2.53	3.63
Dense	Flat	-	-	-	8.29	2.34	3.87
	Pyramidal Frustum Shell	86	69	79	4.96	1.63	2.36
	Semi-Cylindrical Shell	79	48	54	5.82	1.75	2.59
	Prismatic Shell	57	41	46	6.25	1.79	2.73

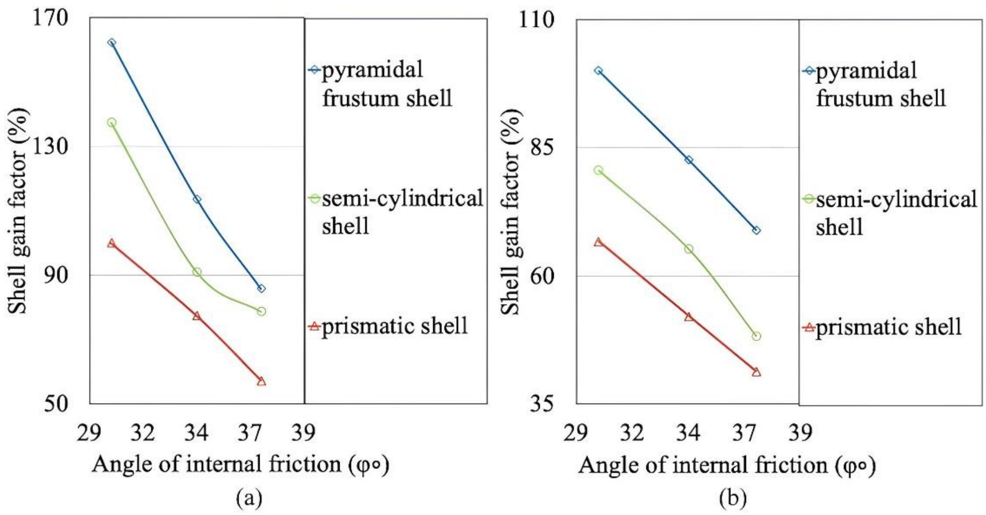

Figure 8 Shell gain factor versus the angle of internal friction: a) unreinforced, b) reinforced at 0.5B depth, and c) reinforced at B depth and settlement factor versus the angle of internal friction: d) unreinforced, e) reinforced at 0.5B depth, and f) reinforced at B depth.

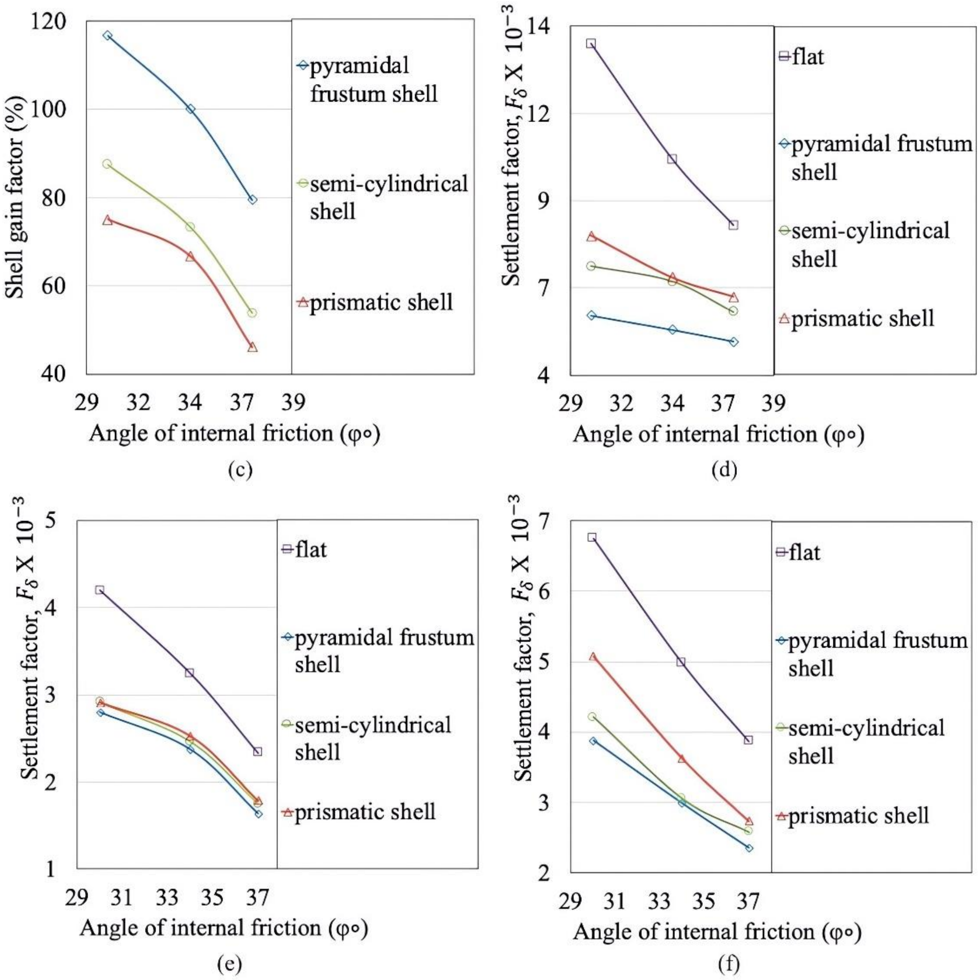

Figure 8 (continued) Shell gain factor versus the angle of internal friction: a) unreinforced, b) reinforced at 0.5B depth, and c) reinforced at B depth and settlement factor versus the angle of internal friction: d) unreinforced, e) reinforced at 0.5B depth, and f) reinforced at B depth.

3.4 Influence of the reinforcement on bearing capacity and settlement

The load-settlement curves for the flat and pyramidal frustum shell foundation in reinforced dense sand are shown in Figure 9. It is evident that the load-carrying capacity of the foundations differs with reinforcement present at varying depths. Providing reinforcement at 0.5B depth significantly enhances the ultimate bearing capacity and reduces the settlement resistance in reinforced dense sand.

Figures 7(b) and (c) illustrate the relationship between ultimate load and angle of internal friction for reinforcements embedded at depths of 0.5B and B respectively. The ultimate load increases with the angle of internal friction, as in unreinforced sand. Figure 7(d) relates the ultimate load and angle of internal friction of pyramidal frustum shell foundation both in unreinforced and reinforced sand.

Shell gain factor is highest on unreinforced loose sand while lowest being in reinforced dense sand with reinforcement present at depth of 0.5B. The influence of reinforcement is more pronounced in the loose state of sand. Moreover, shell model foundations has lower settlement factor than that of flat model foundations, indicating better geotechnical performance. Figure 8(b), (c), (e) and (f) exhibit decrease in shell gain and settlement factors of reinforced sand with increase in the angle of internal friction similar to that in unreinforced sand. Progressive densification of sand between the foundation and the reinforced layer during loading causes decrease of shell gain and settlement factors. Reinforced sand layer and the foundation acted as a single unit. The reinforcement reduces distortion rate and the ultimate shear stress in the sheared zone. Moreover, the reinforcement prevented the vertical soil from spreading. Increment in the bearing capacity of reinforced sand is due to the development of internal soil tensile strains, which increases the lateral confining stresses [26].

3.5 Impact of the Reinforcement on BCR and SRF

Bearing capacity ratio (BCR) is the ratio of bearing pressure of reinforced soil to the bearing pressure of unreinforced at specific settlements. Figure 10 presents variation of BCR with s/B for flat foundations. BCR for flat foundation model is observed to be higher for sand reinforced at a depth of 0.5B than that of reinforcement at depth of B for all states of sand. A similar pattern was also seen for the shell foundations as well. The results indicate decrease in effectiveness of reinforcement with depth leading to reduction in ultimate load. This shows that the effectiveness of reinforcement depends on vertical embedment depth. Higher bearing capacity and lesser settlement occur at lower u/B though there is no clear optimum embedment depth for surface foundations on sand [11]. According to Chakraborty and Kumar [27, 28], the bearing capacity tends to increase with u/B till optimum depth which depends on the type of foundation. Optimum depth of reinforcement is also affected by the type of reinforcement provided in the foundation soil [26].

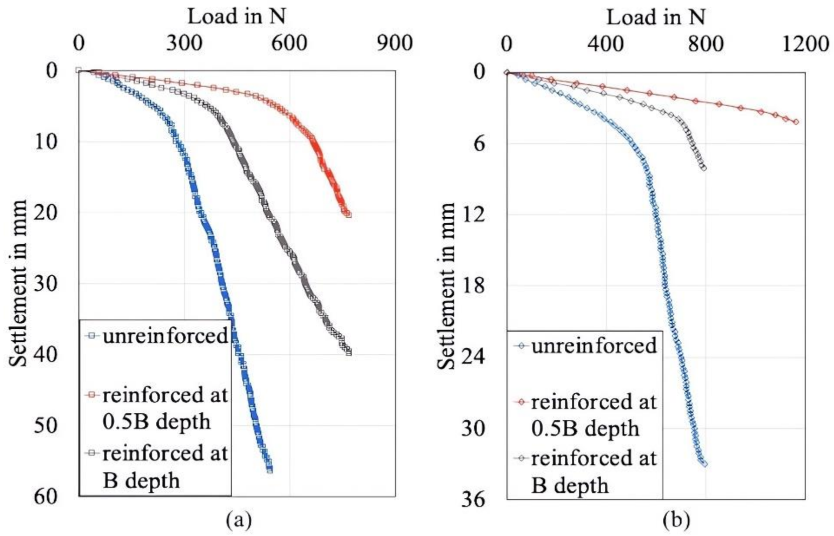

Figure 9 Load-settlement curves of a) flat and b) pyramidal frustum shell foundation on dense sand

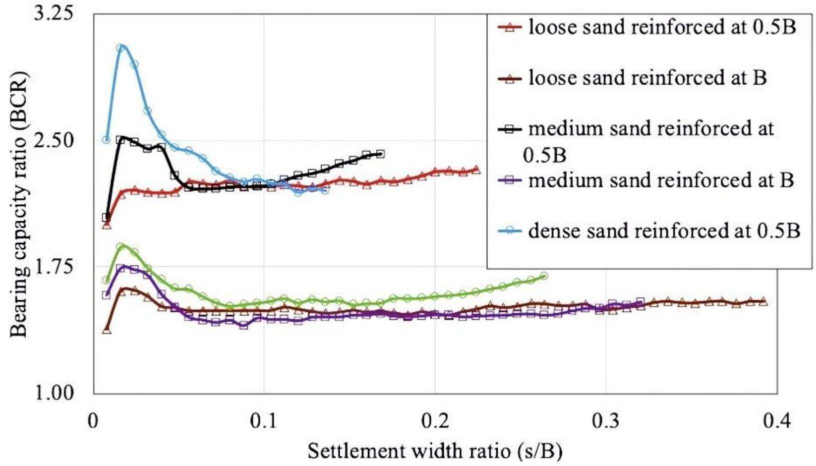

Figure 10 Relationship between BCR and s/B ratio for flat foundations

Bearing capacity ratio is also higher for denser sand for the same embedment depth of reinforcement. For both the reinforcement depth of 0.5B and B, the bearing capacity ratio increased up to a certain point beyond which it decreased and remained almost constant till failure of the foundation models. Few authors have reported increase of BCR with s/B ratios [29, 30].

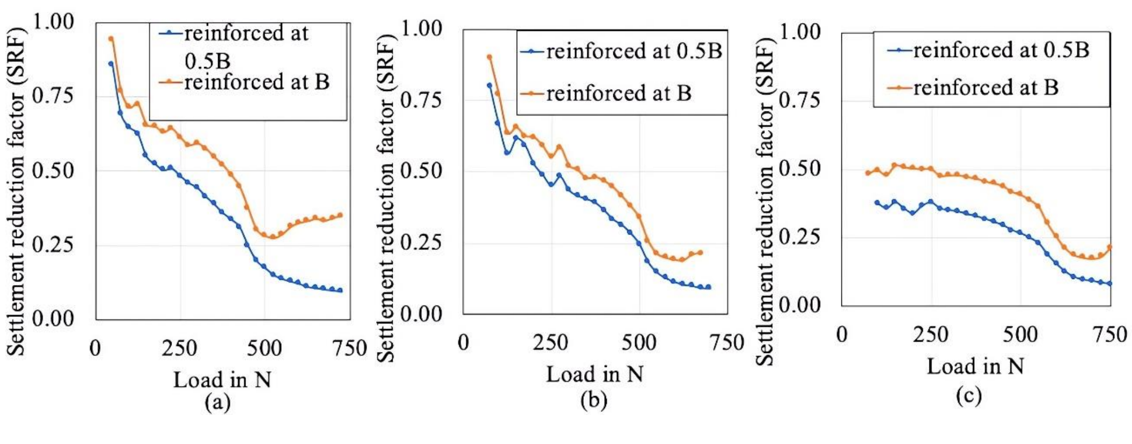

Figure 11 SRF and load relationship of pyramidal frustum shell foundation at a) loose, b) medium, and c) dense sand

Settlement reduction factor (SRF) is used to illustrate the enhancement achieved by providing reinforcement on settlement behaviour. The settlement reduction factor (SRF) is the ratio of the settlement of reinforced soil to the settlement without reinforcement at specific loads. Figure 11 presents the relationship of SRF with the load for pyramidal frustum shell foundation for all states of sand. Resemblance in trend were seen in the flat and other shell foundations. SRF decreases as the load increases till the ultimate load [10]; however, it slightly follows an upward or flatter trend towards the end of the curves. For the same load, the SRF of sand reinforced at depth of B is higher than that reinforced at 0.5B depth. It indicates lower settlement for reinforcement provided at 0.5B depth thus showing influence of reinforcement depth on the settlement behaviour.

3.6 Effect of scale on sand and model

For sandy soil, the ultimate bearing capacity of the model would be N times smaller than that of the prototype according to ASTM D 1194 [22] when the plate model is N times smaller than the prototype. Cerato and Lutenegger [31] predicted that the relative density of the granular soil in the laboratory represented higher relative densities due to stress dependency and critical state strength. Deformation of small-scale model and prototype could be different due to the dilatancy of the sandy soil and its dependency on stress-strain behaviour [32]. For the small-scale model experimental study, particle size impacts the foundation's bearing capacity, especially on the sand. Concerning similitude or scaling laws, models are generally made N times smaller than the prototype.

In the present study, base plan size of the models adopted was 150 mm x 150 mm assuming a prototype of size 1500 mm x 1500 mm (N=10). The bearing capacity of similar prototype in the field can therefore expected to be approximately 10 times greater in the same type and state of soil. The soil used in the experimental program has D_{50}/B =0.004 which is less than 0.01 [33]. Moreover, the wall of iron tank was polished to avoid boundary effect.

4. Conclusions

The geotechnical behaviour of various shell foundations and flat counterparts on sandy soil was analysed using models with or without the inclusion of reinforcement. An overall conclusion drawn from the study are:

a) Shell foundations achieve a higher ultimate load and lower settlement characteristics than the flat foundation for the same plan area on reinforced and unreinforced sand in different states of sand. Pyramidal frustum shell foundation performs the best, followed by the semi-cylindrical shell foundation and the prismatic foundation.
b) Ultimate load increases with the increase in the angle of internal friction. However, the percentage increase in the case of shell foundation is lesser than that of flat foundations as the sand get denser. Shell foundations therefore performed better on loose sand.
c) Shell foundations reached higher ultimate load on reinforced soil with highest ultimate load and lowest settlement for embedment of reinforcement at depth of 0.5B.
d) Shell gain factor of all models reduced after inclusion of reinforcement and as the sand got denser. The lowest shell gain factor was obtained on the sand reinforced at u/B = 0.5.
e) With the increase in relative density of sand, the settlement factors of all models decreased. Reduction in settlement factor was also noticed in reinforced sand with lowest value at reinforcement provided at 0.5B.
f) Reinforcement enhances the ultimate bearing capacity and reduces the settlement for all foundations, irrespective of the state of the sand. All the foundation models perform best at the reinforced depth of 0.5B in dense sand.
g) The BCR for sand reinforced at 0.5B depth is higher while the SRF is lower at the same depth.
h) A study with a full-scale shell foundation in the field may be performed for better understanding of the geotechnical behaviour.

Investigations on shell foundations in reinforced soil is of utmost importance for clear understanding of the geotechnical behaviour related to its strength and settlement so that such foundations can be used in the field in the near future.

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