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Performance of Geosynthetic Reinforced Shallow Foundations

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Abstract. Foundation is the key element of every structure which is a composite system, comprising of structural footing and the soil within the zone of significant depth of the load transfer. In general, a shallow foundation is preferred unless otherwise the structure and the ground demands for the selection of deep foundation. With the recent advancements in the reinforced soil technologies, geosynthetic reinforced shallow foundations have emerged as an alternative for getting a sustainable competent support instead of opting for deep foundations. different forms of geosynthetic elements can be adopted as soil reinforcements like strip, planar and the three-dimensional geocells. This paper summarizes the some of the recent developments in the studies on the performance of geosynthetic reinforced shallow foundations. It was noticed that reinforcement of any form can improve the performance of clay subgrades, depending on footing settlement, layer thickness, and subgrade strength. In general, the improvement was decreased with increase in subgrade strengths.

Keywords: Shallow Foundations, Geosynthetics, Geocell, Settlement, Bearing Capacity.

1 Introduction

There is an increasing demand for transforming comparatively week subsoil to competent land for various engineering purposes. Various ground improvement techniques are adopted for the purpose which increases strength and stiffness of soil, reduces compressibility that enhance the behavior of founding soil. The soil reinforcement trend has become an obvious choice in various geotechnical structures specially after the invention of geosynthetics due to its wide applicability, environmental feasibility, ease of access, durability and most importantly, the economy. Amongst the different ground improvement methods, the soil-reinforcement in different forms is being widely appreciated for its versatility and technical, economical, and environmental feasibility [1-4].

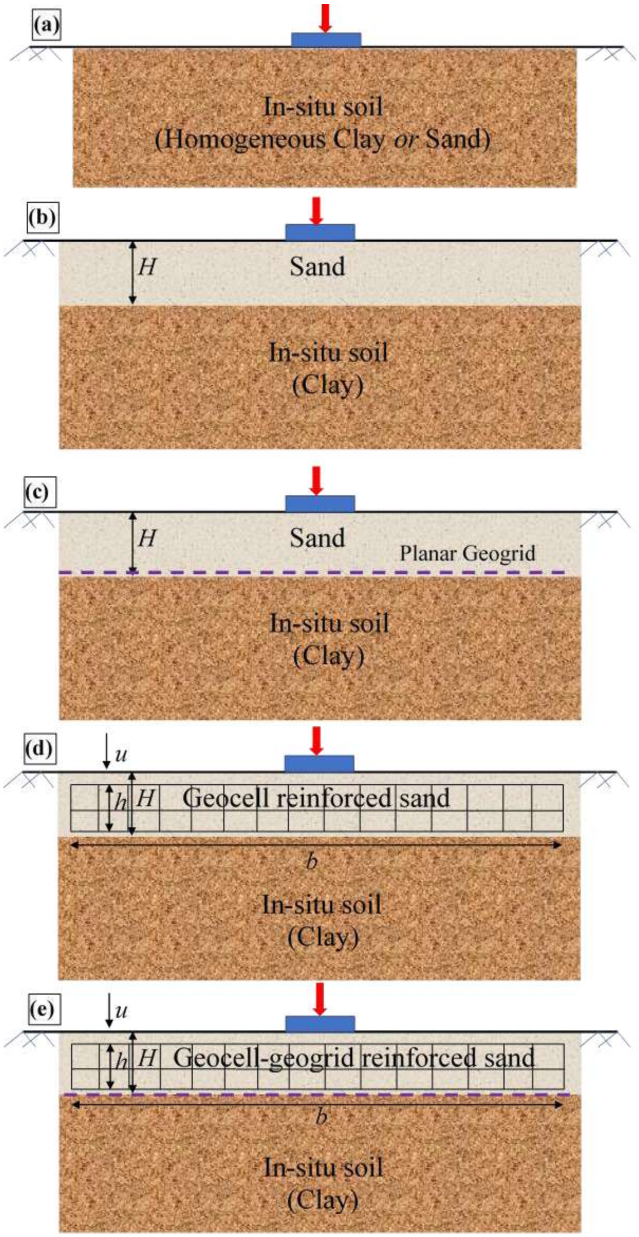


Fig. 1. Different shallow foundation systems: a) Homogeneous soil; b) Unreinforced layered; c) Geogrid reinforced, d) Geocell reinforced; and e) Geocell-geogrid reinforced systems

Different shallow foundation systems can be considered as shown in Figure 1. Fig. 1(a) shows the footing resting on the surface of a homogeneous semi-infinite in-situ soil which may be either fine grained soil (Clay type) or coarse-grained soil (sand type). Please note that here surface footing and homogeneous semi-infinite soil are the hypothetical cases. If the in-site soil bearing capacity is not sufficient for the intended structure, various options shown in Fig. 1(b) to 1(e) are possible. Fig. 1(b) indicate the top in-situ soil of thickness H was replaced with sandy soil representing unreinforced layered foundation system. One layer of planar geogrid reinforcement was considered at the sand clay interface as shown in Fig. 1(c) to represent geogrid reinforced foundation system. Multiple layers of reinforcement may be adopted practically placing close to the footing. Fig. 1(d) shows the use of three dimensional geosynthetic reinforcement, i.e., geocell (height h, length b) placed on the in-situ soil and filled with sand with a sand cushion bed of thickness u, which represent geocell-reinforced foundation system. If planar geogrid reinforcement is provided below the geocell as additional base reinforcement as shown in Fig. 1(e), it represents geocell geogrid reinforced foundation system. This paper summarises the performance of different shallow foundation systems, in particular with geogrid, geocell and geocell-geogrid reinforced foundation systems.

2 Experimental Studies on Model Shallow Foundations of Different Configurations

Biswas [5] conducted model tests on a circular footing of 150 mm diameter (D) resting on 1 m × 1 m × 1 m foundation bed having clay subgrades of different undrained shear strengths (c_u), ranging from 7 to 60 kPa representing different configurations as shown in Table 1. The layered systems were comprised of unreinforced and reinforced sand of varying layer thicknesses ($H = 0.63$ to $2.19D$) overlying the clay subgrades. The reinforcements used in these tests were planar geogrid, geocells, and geocell-geogrid combined. The foundation beds were prepared in the laboratory in a test tank and foundation performances were monitored under a rigid circular footing. More details regarding the experimental studies can be obtained from Biswas et al. [6-8] and Biswas and Krishna [9-10].

The test results of different foundation systems along with brief review of earlier studies are presented in following sections, sequentially as unreinforced, geogrid reinforced, geocell reinforced, and geocell-geogrid reinforced foundation systems. The results are presented in terms of bearing pressure-settlement and surface deformation profiles. Besides, different bearing pressure ratios are introduced to compare the foundation performance and reinforcement contributions.

3 Foundations on Homogeneous Soil

Pauker [11] probably the first studied the Foundation behaviour on homogeneous sandy soil, based on the earth pressure theory proposed by Rankine [12]. The Pauker

[11]'s model was modified by Bell [13] considering both the cohesion and friction components of soil. Subsequently, Prandtl [14] has developed an analytical solution on experimental results, defining the ultimate bearing capacity. Terzaghi [15] has extended Prandtl[14]'s model semi-empirically, based on principle of superposition, considering cohesion and friction, weight of the soil, and the embedment depth. In this model, the non-linear behaviour of the foundation was proposed incorporating different 'bearing capacity factors', such as Nc, Nq and Nγ, as the function of friction angle of soil. Later, the study was further modified to take care of effects of footing shape and different modes of failures (Fig. 2). Afterwards, based on Terzaghi[15]'s theory, the classical soil mechanics has flourished by researchers considering different aspects of foundations, such as effect of soil-saturation [16], loading eccentricity and inclination [17-25], compressibility of soil [26-27].

Table 1. Details of laboratory model tests on different shallow foundations configurations [5]

Reference case	Types of Foundation System	Test Parameters		No. of Tests
		Variables	Constants	
Fig. 1(a)	Homogeneous clay and sand bed	c_u = 7, 15, 30, and 60 kPa D_r = 80% (Sand)	-	5
Fig. 1(b)	Unreinforced sand layers overlying clay subgrades	c_u = 7, 15, 30, and 60 kPa H/D = 0.63, 1.15, 1.67, 2.19	D_r = 80%	16
Fig. 1(c)	Sand beds overlying clay subgrades with planar geogrid at the interface	c_u = 7, 15, 30, and 60 kPa H/D = 0.63, 1.15, 1.67, 2.19	D_r = 80% $b/D = 6$	16
Fig. 1(d)	Geocell-reinforced sand layers overlying clay subgrades	c_u = 7, 15, 30, and 60 kPa h/D = 0.53, 1.05, 1.57, 2.09	D_r = 80% $u = 0.1D$, $d/D = 0.8$, $b/D = 6$	16
Fig. 1(e)	Geocell-geogrid reinforced sand layers overlying clay subgrades	c_u = 7, 15, 30 and 60 kPa h/D = 0.53, 1.05, 1.57, 2.09	D_r = 80% $u = 0.1D$, $d/D = 0.8$, $b/D = 6$	16

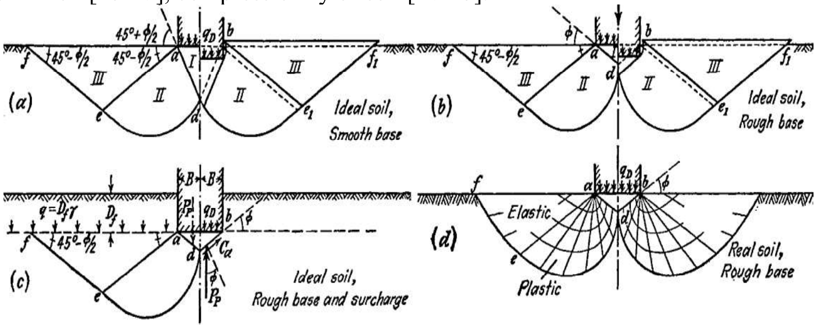


Fig. 2. Boundaries of zone of plastic flow after failure under different foundation conditions [15]

Typical bearing pressure-footing settlement responses of homogeneous clay foundations of different undrained shear strengths (c_u), ranging from 7 to 60 kPa, and homogeneous sand bed (D_r = 80%) are presented in Fig. 3(a). The figure also shows the results obtained from the repeated tests as reported in Biswas [5]. In general, higher pressure-settlement responses were obtained for clay beds with higher 'cu' values. In comparison with the homogeneous clay bed responses, it is found that clay up to c_u = 30 kPa depicted a softer response (less bearing pressure) than that of the sand bed. A comparison of theoretical ultimate bearing pressure, as per $q_u = 5.14\ c_u$ [17] with the maximum bearing pressures obtained from the experiments is presented in Fig. 3(b). The differences are in the range of 13-21% with respect to the theoretical values.

4 Foundations on Layered Soil

The foundations, in practice, encounters layered soils underneath due to Earth's natural stratigraphic nature which is considerably different than that analyzed as homogeneous. Button [28] has realized the issue and initiated the study on foundations on layered soil with saturated clay. Later, Brown and Meyerhof [29] had conducted several model tests on layered configuration under rigid strip and circular surface footing with saturated clay of varying strength. The most popular theory till date on layered soil has been developed by Meyerhof [30] through laboratory physical model studies. Two types of configurations were considered: dense sand over soft clay and loose sand over stiff clay (Fig. 4). Subsequently, it was modified by Meyerhof and Hanna [31] considering inclined loading. Afterwards, several studies have enriched the topic with different parametric variations with sand and/or clay [27, 32-39].

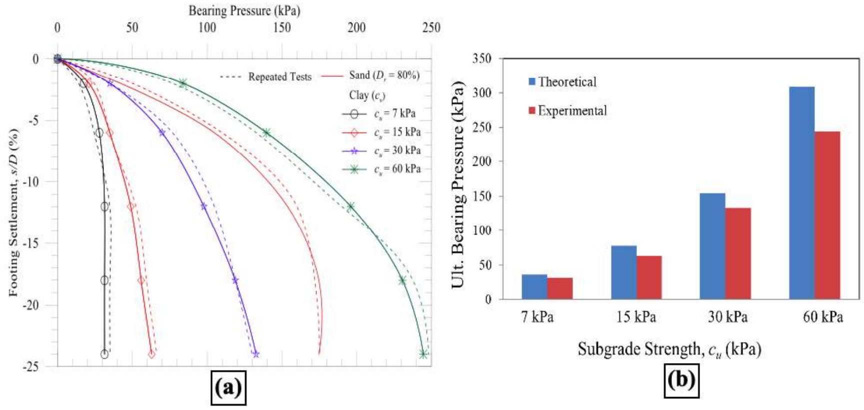


Fig. 3. (a) Pressure-settlement responses of homogeneous beds (after Biswas and Krishna [40]: Clay and Sand; (b) Comparison of ultimate bearing pressures for clay beds

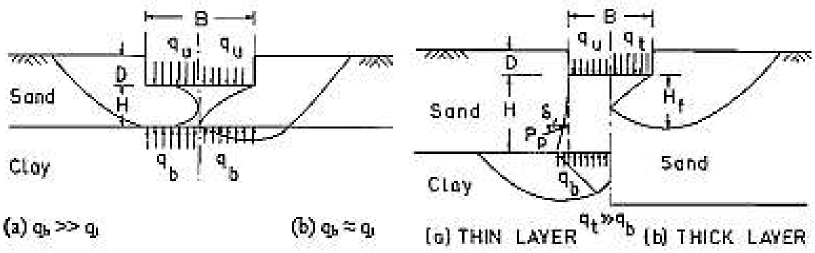


Fig. 4. Failure mechanisms in layered soils defined by Meyerhof [30]

Biswas and Krishna [40] presented the results of model tests on layered foundations having varying thicknesses of unreinforced sand (*H* = 0.63, 1.15, 1.67, and 2.19*D*) overlying clay subgrades of different strengths as shown in Fig. 5. In general, the figures are indicating significant improvement in bearing pressures as compared to corresponding homogeneous clay beds. Theoretical evaluation of bearing capacities for layered configurations having a sand layer overlying clay subgrade was done as per Meyerhof [30] and Meyerhof and Hanna [31] and presented in Fig. 6 for *H* = 1.15*D*.

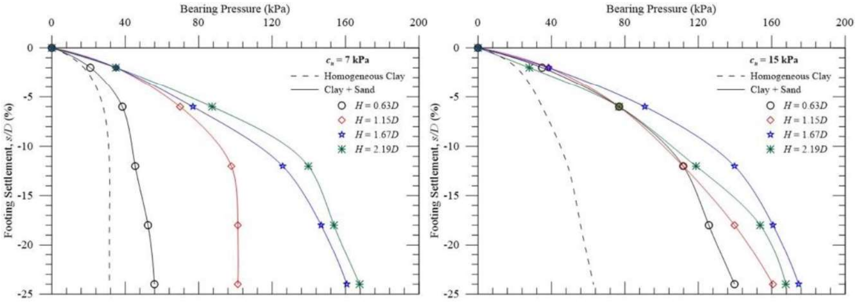


Fig. 5. Pressure–settlement responses of homogeneous and layered foundations having clay subgrades (c_u= 7 kPa and 15 kPa) for different layer thicknesses (*H*) [40]

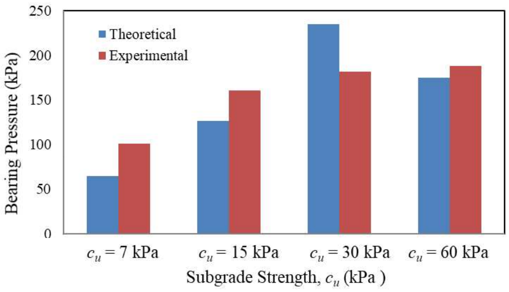


Fig. 6. Comparison of ultimate bearing pressures for layered soils with different clay subgrades for *H* = 1.15*D*

5 Reinforced Foundations: Strip/Sheet Type Reinforcements

Traditionally, deep foundations are adopted to transmit the structural loads to a comparatively stronger stratum avoiding the shallow soft soil and/or week layers. This is not always feasible with respect to economics and other technical issues, not even the other methods, such as soil-replacement, different compaction methods or physio-chemical treatments, to overcome the inadequacy [41-44]. In several such situations 'soil reinforcement' is found to be the most viable alternative and performed much better with greater control compared to conventional methods.

Binquet and Lee [45] pioneered the studies on the behaviour of planar-reinforced foundation systems identifying the mechanisms of failures as 'general shear', 'tie-pull out (or slippage)', and 'tie-break (or rupture)' (Fig. 7). However, the basic characteristics of strength development of soil reinforcement was introduced by Schlosser and Long [46], and afterward, the 'Sigma and Tau Model' by Hausmann [47]. The mechanism of improvement through soil-reinforcement interaction is also known as 'membrane action' [48].

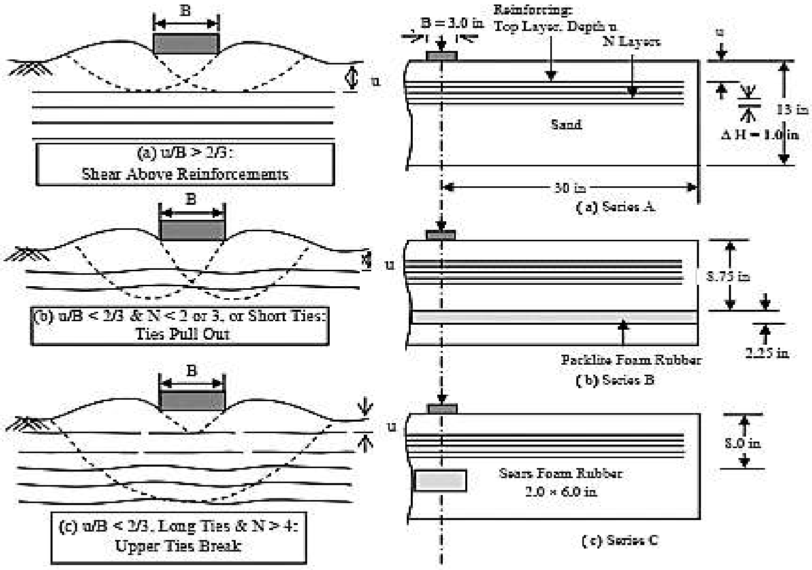


Fig. 7. Arrangement of model tests and modes of failure [45]

Various forms of soil reinforcement are devised, available and used in different occasions. The metallic strip soil-reinforcement is the most primitive type [45, 49-51], which suffers from corrosion, cost effectiveness, and limited beneficial effects. Depending on performances, environmental feasibility, economics etc., reinforcements are modified in terms of material and configurations: gradually, the strip reinforcements were replaced by sheet-type reinforcement which was superseded by three dimensional geocells. The invention of geosynthetics has been a revolution in this modifying technology which has taken care of the issues mentioned above successfully with much higher degree of satisfaction and become an obvious choice in this present era. It has been successfully used as planar form [6, 52-57].

Several researchers have studied the beneficial effects of planar reinforcement, of different forms with different model parameters, on the performance of different types of shallow footings. Fig. 8 [58] presents a typical configuration considered in most of the studies [1, 49, 53, 55-57, 59-61] indicating 'q' as applied load on the footing of width 'B'. The other parameters shown in the figure are: 'u' – the placement depth of the first layer reinforcement from footing bottom, 'h' – the vertical spacing between the reinforcements, 'b' – the reinforcement width, 'N'- the number of reinforcement layers, and 'd' – is the total depth of reinforced soil. Selected studies on reinforced foundations using planar reinforcements are summarised in Table 2 indicating the influencing parameters. It can be seen from the Table 2 that upto 6 layers of reinforcement were considered while the maximum reported bearing capacity ratio (BCR) is about 6. As per the reported studies, it may be mentioned that with a reinforcement side about 5-6 times footing width (B), having placed at a vertical interval of 0.3-0.5B with 5-6 layers up to a depth of about 3-4B from footing bottom can optimize the bearing capacity improvement of the foundation by an amount of 1.5-2.0 times that of the unreinforced condition.

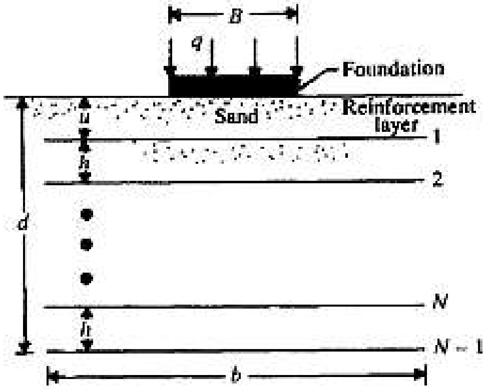


Fig. 8. Typical geogrid-reinforced foundation [58]

Bearing pressure – settlement responses of reinforced foundation beds (as shown in Fig. 1c) with sand layer thicknesses (*H*) were varied as 0.63, 1.15, 1.67, and 2.19*D* overlying the clay subgrades of different undrained shear strengths (c_u = 7, 15, 30, and 60 kPa) are shown in Fig. 9. As seen from the figures, providing one reinforcement layers at the interface the performance of layered foundation system significantly improved. For very soft clay subgrade (c_u = 7 kPa), the maximum bearing pressure for reinforced system at s/D = 24% is 175 kPa (at $H = 2.19D$); while the corresponding value for the homogeneous clay bed was only 31 kPa. In the case of stiff clay subgrade (c_u = 60 kPa), the reinforced beds showed higher performance up to $H \leq 1.15D$

(compared to the homogenous bed), for s/D in the range 2-18%. The theoretical approaches proposed by Love et al. [48] and Burd and Frydman [38] were considered for the theoretical evaluation of bearing capacity and compared with the experimental results as shown in Fig. 10.

Table 2. Summary of selected studies on shallow foundations with planar reinforcement

Reference	Footing Type	Reinforcement Type	Optimum Parameters Found				
			u/B	b/B	Δh/B	N	BCR
Binquet and Lee [45]	Strip	Aluminum strip	0.33	20	0.33	6	2- 4.
Akinmusuru and Akinbolade [65]	Square	Rope fiber	0.5	10	0.5	3	2.9
Fragaszy and Lawton [49]	Rectangular	Aluminum strip	0.33	6	0.33	3	1.7
Guido et al. [52]	Square	Geogrid/geotextile	0.25	3	0.25	3	2.8
Kim and Cho [66]	Strip	Geotextile	0.5-1.0	-	-	-	
Huang and Tatsuoka [51]	Strip	Metal Strip	0.5	6	0.5	3	6.34
Mandal and Sah [53]	Square	Geogrid	0.175	-	0.2	1	1.56
Shin et al. [60]	Strip	Geogrid	0.4	10	0.4	5	1.4
Omar et al. [67]	Rectangular/strip	Geogrid	0.33	8	0.33	6-7.	3-4.5
Khing et al. [68]	Strip	Geogrid	0.67	6	0.67	1	1.3
Das and Khing [69]	Strip	Geogrid	0.67	6	0.67	1	1.3-1.4
Alawaji [63]	Circular	Geogrid	0.1	4	0.1	1	3.2
Das and Omar [64]	Strip	Geogrid	0.33	8	0.33	-	3-5.5
Michael and Collin [54]	Square	Geogrid/geocell	0.25	-	0.5	3	2.6
Sitharam and Sireesh [55]	Circular	Geogrid	0.3	6	0.4	6	3.24
Basudhar et al. [1]	Circular	Geotextile	0.25	3.5	1	3	5.5
Sawwaf [62]	Strip	Geogrid	0.6	5	0.5	4	2
Latha and Somwanshi [56]	Square	Geogrid	0.1	5 – 6	0.5	4	2- 2.5

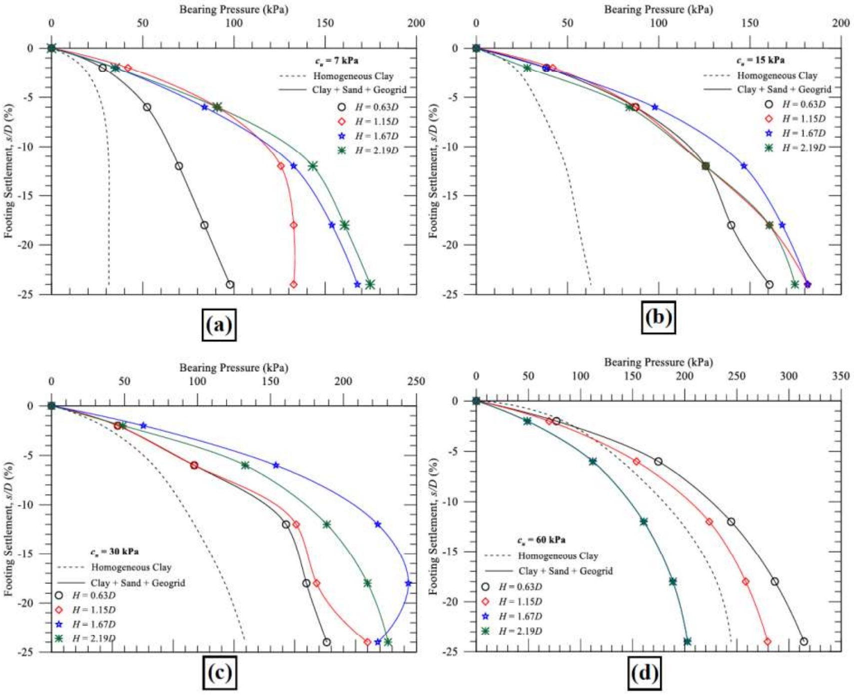


Fig. 9. Bearing pressure-settlement responses of geogrid-reinforced foundation having different clay subgrades: a) c_u = 7 kPa; b) c_u = 15 kPa; c) c_u = 30 kPa; and d) c_u = 60 kPa

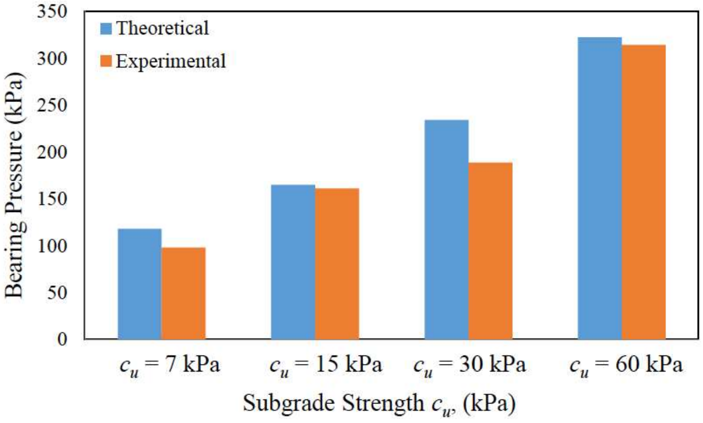


Fig. 10. Comparison of ultimate bearing pressures for geogrid reinforced foundation system with different clay subgrades for $H = 0.63D$

6 Reinforced Foundations: Cellular/Geocell Reinforcements

The cellular system, popularly known as Geocells, usually made of geotextiles or geogrids. Geocell is a three-dimensional, honeycombing, interconnected and alround cellular confinement system devised by Webster and Watkins [70]. The geocell pockets generally filled with granular materials as sand or gravel. It contains and confines the soil within by restricting the shearing upon application of applied load and the composite-matrix behaves like a semi-rigid slab to redistribute it onto the underlying subgrade with a reduced intensity to improve overall bearing capacity of the foundation system [71]. Considerable numbers of studies are reported till date[3, 7, 9, 71-82] mentioning its superiority. Biswas and Krishna [9] have documented a critical review of the parametric effect on the geocell-reinforced geo-systems. Table 3 presents summary of various research works conducted but with geocell reinforcement. In this case the maximum BCR value reported is about 9. This signifies the extent of the improvement that could be achieved with inclusion of geosynthetic reinforcement in the shallow foundations.

Bearing pressure – settlement responses of geocell reinforced foundation beds (as shown in Fig. 1d) with sand layer thicknesses (H) were varied as 0.63, 1.15, 1.67, and 2.19D (with u of 0.1 D) overlying the clay subgrades of different undrained shear strengths (c_u = 7, 15, 30, and 60 kPa) are shown in Fig. 11. In general, bearing pressures are increased with layer thickness up to $H = 1.15D$ for all the subgrades. However, the increase in bearing pressures is not consistent with the variation in geocell-heights for $h \geq 1.57D$ on comparatively stiffer subgrades ($c_u > 7$ kPa).

The behaviour of geocell-soil composite is quiet complicated and difficult to analyse due to its heterogenic configuration. Few attempts are made involving mechanics and empirical relations to estimate its performance; however, each of the study is having their inherent drawbacks in compromising/idealizing the soil-reinforcement interaction. Amongst such, the mechanism proposed by Zhang et al. [83] (Fig. 12) and Latha et al. [84] are able to minimise the difference between the estimated and experimental findings. Zhang et al. [83] has discretized individual components and mechanisms to superimpose them to get the geocell behaviour; whereas, Latha et al. [84] has converted the geocell-soil layer into an equivalent composite layer of soil with enhanced shear parameters. In this method, the geocell-soil layer is simulated as a composite soil having higher cohesion with unaltered internal friction angle. The geocell induced cohesion is termed as apparent cohesion (c_r) and calculated as $c_r = \frac{\Delta\sigma_3}{2}\sqrt{K_p}$.

With the modified shear parameters, the equivalent stiffness of geocell (E_g) layer is calculated

$$E_g = 4(\Delta\sigma_3)^{0.7}(K_u + 200M^{0.16})$$

where, '$\Delta\sigma_3$' is the additional confining pressure due to membrane stress calculated as

$$\Delta\sigma_3 = \frac{2M}{D_0}\left(\frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a}\right),$$

where, 'ε_a' is the axial strain at failure, 'D_o' is the initial diameter of geocell pocket, 'M' is secant modulus corresponding the axial strain in geocell wall, 'K_p' is coefficient of passive earth pressure and 'K_u' is the dimensionless modulus for the unreinforced sand as defined in their study.

Table 3. Summary of selected studies on shallow foundation with geocell reinforcement

Reference	Footing Type	Reinforcement/ Geocell material	Optimum Parameters Found				
			u/B	*b/B*	*d/B*	*h/B*	*BCR*
Mandal and Gupta [88]	Rectangular	Geogrid	-	2	0.55	1.5	8
Mhaiskar and Mandal [89]	Rectangular	Geogrid	0	3.4	0.625	2.8	3
Bathurst and Jarrett [3]	Strip	Geoweb/Geogrid	-	-	-	-	-
Krishnaswamy et al. [77]	Strip	Geogrid	-	-	-	0.5	-
Dash [90-91]	Strip	Geogrid, non-oriented polymer	0.1	12	1.2	3.14	8
Dash et al. [76, 85, 92-94]			0.1	8	1.2	2	9
	Circular	Geogrid	0.1	4	0.7	0.8	4
	Circular	Geogrid	0.33	6	0.8	1.68	7
	Strip	Geogrid	0.1	8	1.2	2.75	8
	Strip	Geogrid	0.1	10	1.2	1.6	-
	Strip	Geogrid	0.1	12	1.2	3.14	8
	Circular	Geogrid	0.1	8	1.2	1.6	6
	Strip	Geogrid	0.1	8	1.6	1.2	4.5
Sitharam et al. [95]	Circular	Geogrid	0	5.5	0.8	2.4	6
Yoon et al. [96]	Square	Waste tire thread	0.2	4.17	0.54	0.39	3
Zhou and Wen [78]	Circular	Geogrid	-	1	0.13	0.1	3
Emersleben and Mayer [97]	Circular	Geogrid	0	-	0.77	0.67	1.5
Sireesh et al. [98]	Circular	FLAC^{3D}	0.4	5	0.8	1.8	4
Minaxi Rai [99]	Circular	Geogrid	0.1	6.67	0.4	0.8	14
Zhang et al. [83]	Circular	Geogrid	0.85	5.5	-	0.13	8
Pokharel et al. [79]	Circular	Geogrid	0.13	1.37	1.37	0.67	2.5
Tafreshi and Dawson [80]	Strip	Geogrid/geotextile	0.1	4.2	0.67	1.33	3
Tanyu et al. [100]	Circular	Textured HDPE	-	-	-	-	-

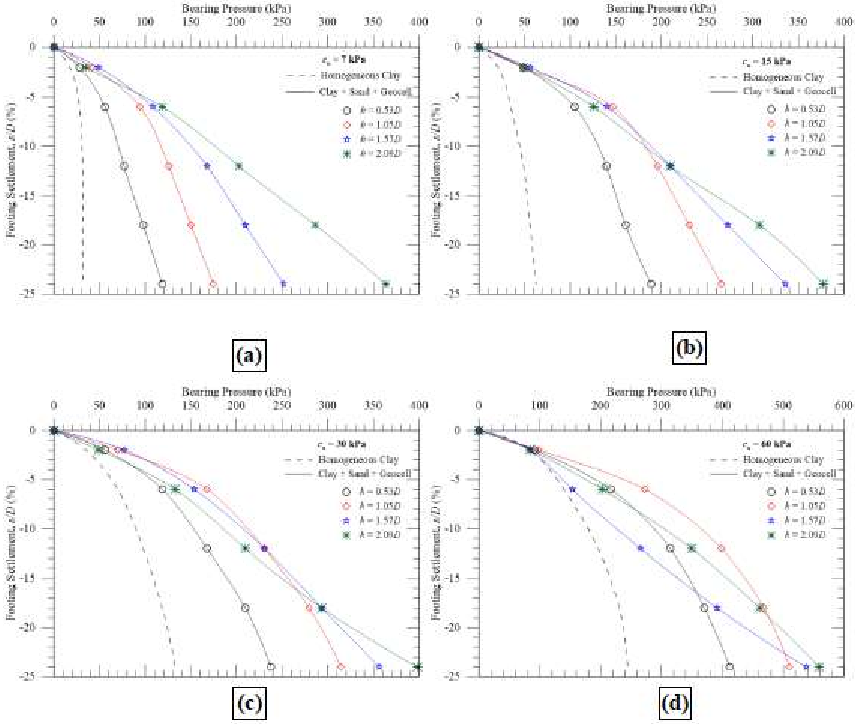


Fig. 11. Bearing pressure-settlement responses of Geocell-reinforced foundation having different clay subgrades: a) c_u = 7 kPa; b) c_u = 15 kPa; c) c_u = 30 kPa; and d) c_u = 60 kPa

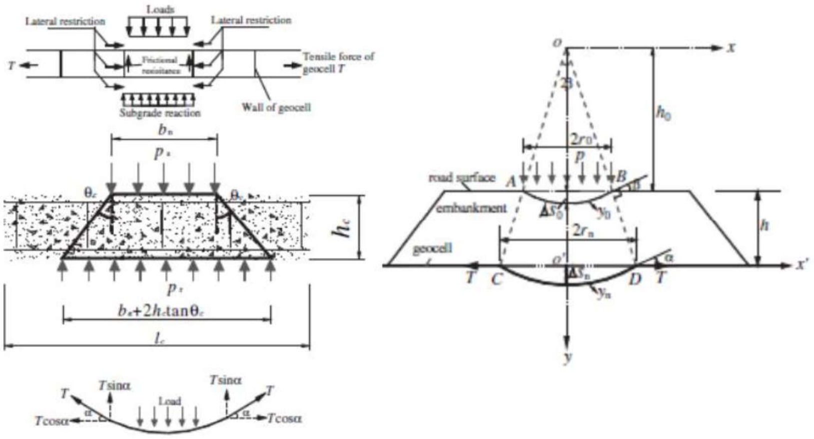


Fig. 12. Discretized geocell-mechanism consisted of confinement, membrane action and stress distribution as proposed by Zhang et al. [83]

For the theoretical estimation of bearing capacity of geocell reinforced foundation systems, M is considered as average secant modulus of the geogrid as 200 kN/m; $D_o = 0.8D$. Comparison of theoretical and experimental bearing pressures for geocell reinforced foundation systems is presented in Fig. 13. The comparison presents a reasonably good agreement. The differences in bearing pressures can be noticed which may be attributed to the buckling of geocell-walls and squeezing out of sand which could not be considered in analysis.

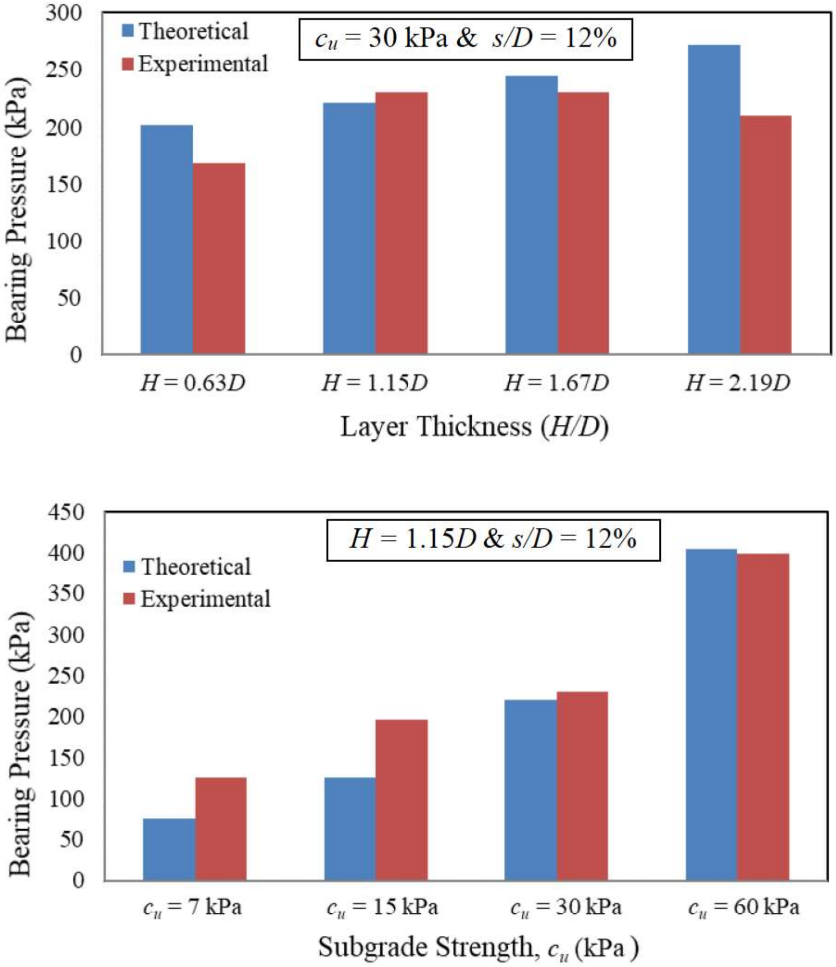


Fig. 13. Comparison of ultimate bearing pressures for geocell reinforced foundation systems with different clay subgrades

7 Geocell-Geogrid Reinforced Foundations

Providing a layer of planar geogrid over the soft ground before placing the geocell-mattress serves in two ways: i) It facilitates the easy movement during construction and ii) Enhances the overall performance of the geocell-reinforcement by providing additional support [70,75]. Dash et al., [76, 85]; Sitharam et al., [86] and Hegde and Sitharam [87] have highlighted the benefits of using base geogrid in addition to the geocell-reinforcement through their experimental studies.

Biswas and Krishna [10] presented the studies on geocell-geogrid reinforced shallow foundations of various configurations (Fig. 1e) with varied sand layer thicknesses (H = 0.63, 1.15, 1.67, and 2.19D) and the clay subgrades of different undrained shear strengths (c_u = 7, 15, 30, and 60 kPa). Figure 14 presents the bearing pressure – settlement responses obtained from the experimental studies. It is seen from the figure that the bearing pressures of the geocell-geogrid foundations were increased significantly with footing settlement (*s/D*).

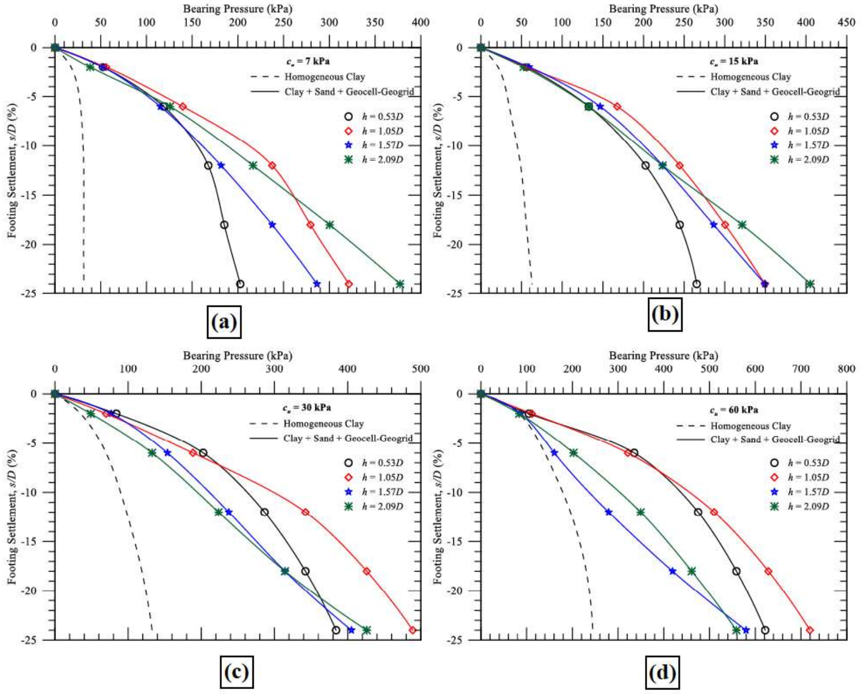
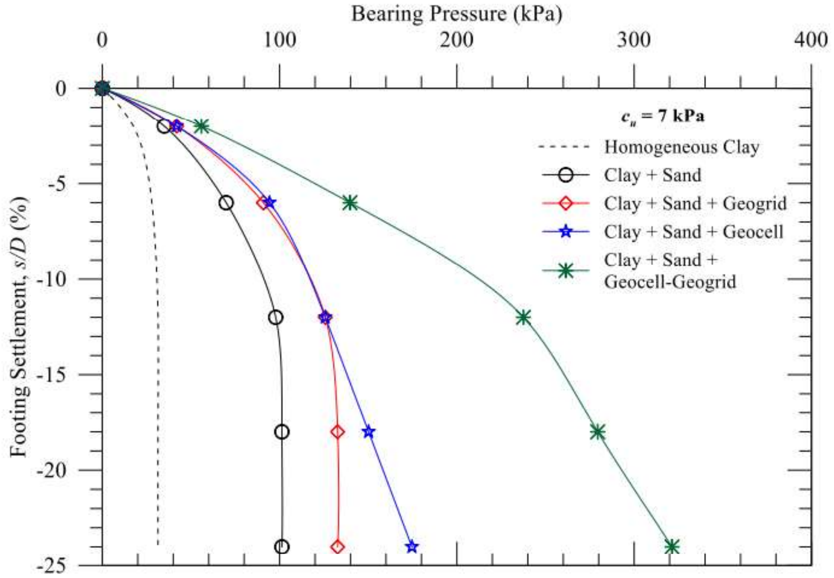


Fig. 14. Bearing pressure-settlement responses of Geocell- geogrid reinforced foundations with different clay subgrades: a) c_u = 7 kPa; b) c_u = 15 kPa; c) c_u = 30 kPa; and d) c_u = 60 kPa

8 Comparative Discussion of Different Foundations

From the above sections it obvious that the foundation performance in terms of bearing pressure is depending on various parameters i.e., settlement (*s*), subgrade strength (c_u), thickness of the top layer (*H*) and type of reinforcement. Figure 15 provides the comparison of bearing pressure - settlement responses of different foundation systems with top layer thickness (*H*) as 1.15*D* for two clay subgrades of c_u = 7 kPa and 30 kPa. It can be noticed that the load bearing capacity of the foundation beds were increased with increasing superiority of reinforcement types: i.e., unreinforced < geogrid < geocell < geocell-geogrid. Significant improvements in bearing pressures for reinforced foundations, compared to the unreinforced systems, can be noticed. However, for reinforced foundations, a comparatively higher level of footing settlements (*s/D* > 6%) is required for considerable improvement in bearing pressures, depending on subgrade clay strength and reinforcement superiority. For instance, for c_u = 7 kPa, improvement for geocell-reinforced configuration, compared to the geogrid reinforcement, was significant beyond 18% of *s/D*. It is attributed to the complex interaction in between foundation soil and the reinforcements. For very soft clay such as c_u = 7 kPa, the subgrade could easily be penetrated upon footing load. In this case, the interfacial resistance through reinforcement was considerable; however, due to less/no resistance against penetration, subgrade support was minimal. In case of comparatively stiffer subgrades ($c_u \geq$ 15 kPa), foundations were responded in other way; i.e. minimal interfacial resistance and maximum subgrade support.



(a)

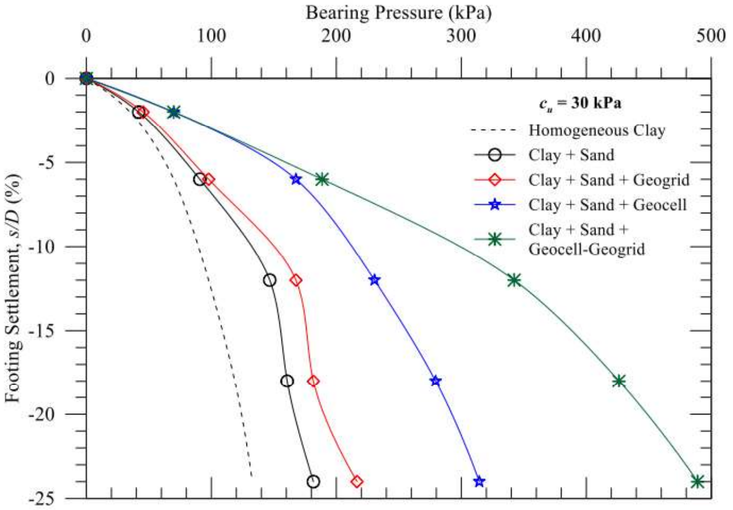


Fig. 15. Comparison of Pressure-settlement responses of different foundations systems (H = 1.15D): a) c_u = 7 kPa; b) c_u = 30 kPa;

9 Conclusions

Reinforced shallow foundations may provide alternative solution to deep foundation under certain circumstances. Test results in terms of bearing pressure-settlement responses obtained from different model studies are discussed, sequentially for unreinforced (homogeneous and layered), geogrid reinforced, geocell reinforced, and geocell-geogrid reinforced foundation systems. It was noticed that reinforcement of any form can improve the performance of clay subgrades, depending on footing settlement, layer thickness, and subgrade strength. In general, the improvement was decreased with increase in subgrade strengths (c_u). A maximum of about 12-fold improvement in bearing pressure was obtained for very soft clay subgrade of 7 kPa with geocell-geogrid configuration; while, the maximum bearing pressure of about 720 kPa was noted for the similar reinforcement configuration with c_u = 60 kPa. Optimum height of geocell-mattress for softer subgrades ($c_u \leq 15$ kPa) was 1.57D. In the case of stiffer subgrades ($c_u > 15$ kPa) the optimum height was 1.05D. The geocells contribution, in improved bearing pressures, was higher for stiffer subgrades, while geogrid contribution was higher for softer subgrades.

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