Int. J. of Geosynth. and Ground Eng. (2017) 3:17
DOI 10.1007/s40891-017-0093-7

STATE OF THE ART/PRACTICE PAPER

Geocell-Reinforced Foundation Systems: A Critical Review

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Received: 8 April 2017 / Accepted: 3 May 2017 / Published online: 12 May 2017

Abstract The ever increasing infrastructure development requires adequate and competent ground, which is becoming scarce at present. Thus, developing techniques for improving the weak soil (having low bearing capacity and/or likely to undergo excessive settlement) into a competent acceptable condition is a major task for geotechnical engineering practice. In this perspective, the concept of 'reinforcing the soil' is being widely appreciated and extensively practiced. For last few decades, the soil-reinforcement in various forms, such as planar and/or three-dimensional, has been vividly applied in several fields of civil engineering. As compared to the planar form, the three-dimensional 'Geocell' is comparatively new invention in soil-reinforcement. It is a honeycombing interconnected cellular confinement system, made of geosynthetics, such as geotextiles and/or geogrids. It has been observed that 'Geocells' significantly enhances the load-bearing capacity of soils and reduces settlement of the concern geotechnical structure. Apart from load-bearing (especially in pavements and foundations), it has also been extensively used in various slope stabilization, embankment construction and railway track applications. With increasing trend and demand, the performance of geocell-reinforcement has rigorously been studied for its betterment and optimum parametric configurations. Studies have revealed a large numbers of parameters, such as reinforcement geometry, interaction with filled soil, etc., largely influencing the performance of geocell-reinforced systems. In view of that, this paper aims to present a critical review of the parametric behavior of geocell-reinforced systems which would be a very useful document for various applications and further research.

Keywords Soil reinforcement · Geosynthetics · Geocell · Foundation

Introduction

The ever increasing demand of competent land for urbanization has been a challenge for geotechnical engineers to develop an optimized methodology of transforming comparatively week soil into an acceptable condition. In most of the cases, the inadequacy arises in terms of unsatisfactory bearing capacity of the soil, and/or, excessive settlement of concern geotechnical-structure. In view of this, different techniques are invented which enhances the strength and stiffness of soil, reduces compressibility and vulnerability to liquefaction, prevent adverse physical or chemical changes upon environmental effects and minimize the natural unpredictability of soils. Amongst the various ground improvement methods, such as replacement with good-fill soil, preloading with vertical drains, different types of compactions, grouting, deep soil mixing, and various chemical treatments etc., the soil-reinforcement in different forms is being widely appreciated for its versatility in technical, economical, and environmental feasibility and simple applications.

The concept of 'reinforcing the earth' is being practiced since centuries in various forms: like straw, reed, bamboo, logs, timber planks etc. [1–6]. The credit of introducing

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systematic approach/concept of soil-reinforcement is with Vidal [7]. Over the time, soil-reinforcement has been modified as per requirements and inventions: in terms of material, shapes and sizes. The metallic strip-reinforcements of the beginning [8, 9] were replaced by sheet-type-reinforcements and afterwards, the versatile geosynthetics in different forms, such as geotextiles, geogrids, and geocells, have superseded them all [2–6].

In last few decades, soil-reinforcements in planar forms were used in several fields of civil engineering applications, such as foundations, pavements, retaining walls, embankments etc. A typical foundation application for planar reinforcement is presented in Fig. 1a, showing different influencing parameters associated with it. The benefits of planar reinforcements considering several aspects, such as material-strength, geometry, placement depths, number of layers etc., has been demonstrated by several investigators [10–18]. A brief of few important studies on planar reinforcements is presented in Table 1.

Geocell is a three-dimensional honeycombing structure of interconnected cells, devised by Webster and Watkins [19], which contains and confines the soil within. Unlike

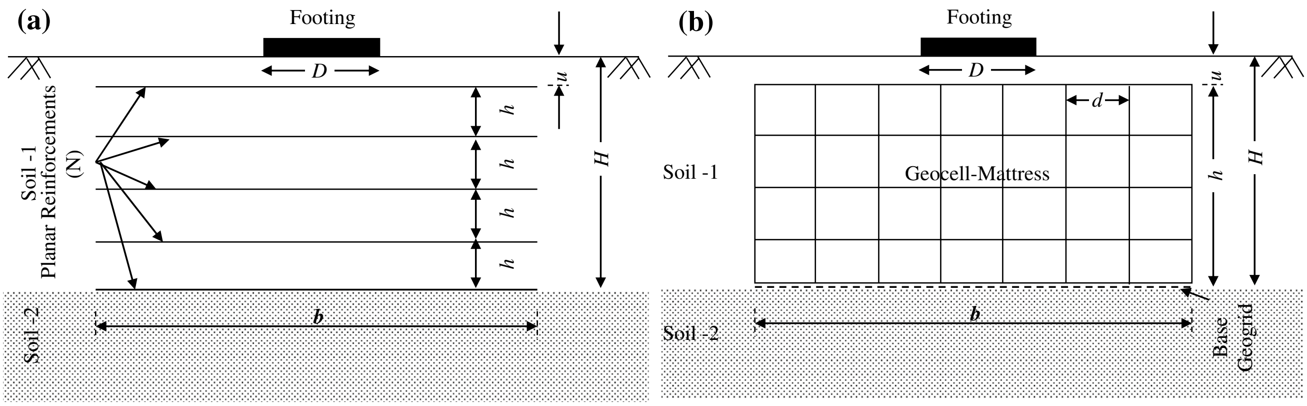

Fig. 1 Typical **a** planar and **b** geocell-reinforced foundation systems

Table 1 Brief of selected laboratory studies with planar-reinforced systems

Researches	Footing type	Reinforcement type	Optimum parameters found				
			u/B	b/B	h/B	N	BCR
Binquet and Lee [8, 9]	Strip	Aluminum strip	0.33	20	0.33	6	2–4
Akinmusuru and Akinbolade [89]	Square	Rope fiber	0.5	10	0.5	3	2.9
Fragaszy and Lawton [90]	Rectangular	Aluminum strip	0.33	6	0.33	3	1.7
Guido et al. [91]	Square	Geotextile/geogrid	0.25	3	0.25	3	2.8
Love et al. [92]	Strip	Geotextile/geogrid	–	–	–	–	–
Kim and Cho [93]	Strip	Geotextile	0.5–1.0	–	–	–	
Samatani and Sonpal [94]	Strip	Metal strip	–	–	–	–	–
Huang and Tatsuoka [95]	Strip	Metal strip	0.5	6	0.5	3	6.34
Mandal and Sah [96]	Square	Geogrid	0.175	–	0.2	1	1.56
Shin et al. [97]	Strip	Geogrid	0.4	10	0.4	5	1.4
Khing et al. [98]	Square	Geogrid	0.25–0.4	11	0.4	6	4
Omar et al. [11]	Rectangular/strip	Geogrid	0.33	8	0.33	6–7	3–4.5
Khing et al. [99]	Strip	Geogrid	0.67	6	0.67	1	1.3
Das and Omar [100]	Strip	Geogrid	0.33	8	0.33	–	3–5.5
Michael and Collin [101]	Square	Geogrid/geocell	0.25	–	0.5	3	2.6
Alawaji [102]	Circular	Geogrid	0.1	4	0.1	1	3.2
Sitharam and Sireesh [103]	Circular	Geogrid	0.3	6	0.4	6	3.24
Basudhar et al. [104]	Circular	Geotextile	0.25	3.5	1	3	5.5
Sawwaf [105]	Strip	Geogrid	0.6	5	0.5	4	2
Latha and Somwanshi [55]	Square	Geogrid	0.1	5–6	0.5	4	2–2.5

other techniques, the development of geocell was initiated from field-application, and upon successful implementation it has been rigorously studied in-house for its optimum use (through physical models tests and/or numerical analyses). Geocells are, generally, made of thermally welded or mechanically bonded geosynthetics of various types. It can be made in-field using planar geotextiles or geogrids; however, readymade geocells are also available commercially. The readymade geocells are easy to transport (in collapsed form) and can be stretched into mattress at site. The commercially available geocells are, generally, having invariable and shorter in heights (thickness) as compared to the in-field constructed geocells; in which case, height of the geocells can be selected as per design-requirements. In field, geocells are constructed with 'bodkin joints' [20–22] through 'dowel bars' (as per required length and strength) and filled with soil of required quality and quantity. At site, the 'dowels' are mostly made of metals, such as steel bars, as compared to mechanical or thermally welded joints for commercial ready-made geocell-mattresses. As the planar reinforcements, geocells are also used in foundations, pavements, railways, embankments, slopes etc., to improve the load-bearing capacity and stability of geo-structures. In last few decades, the benefits of geocell-reinforcements, considering several aspects, such as material, geometry, placement depths, filled-soil etc., have been demonstrated by several investigators. In Table 2, a few field applications and laboratory studies are summarized which have highlighted the benefits of three-dimensional geocell-reinforcements.

This paper presents a critical review on 'parametric influences' of the geocell-reinforced systems; in terms of, mostly, a foundation-application. A typical geocell-reinforced foundation is shown in Fig. 1b, for a circular footing of diameter *D*. The '*h*', '*b*', and '*d*' are representing the height, width, and pocket size of the geocell mattress, respectively. The placement depth of geocell-mattress below the footing (or the thickness of 'soil-cushion') is depicted as '*u*'. In Fig. 1b, two types of soils can be noticed: soil-1 is the native soil underneath; while, the geocell-reinforced fill-soil is indicated as soil-2. In general, geocells are placed directly over the native soil (or a base-geogrid may

Table 2 Brief of selected laboratory studies with geocell-reinforced system

Researches	Footing type	Reinforcement/geocell material	Optimum parameters				
			u/*B*	*b*/*B*	*d*/*B*	*h*/*B*	*BCR*
Mandal and Gupta [23]	Rectangular	Geogrid	–	2	0.55	1.5	8
Mhaiskar and Mandal [24]	Rectangular	Geogrid	0	3.4	0.625	2.8	3
Krishnaswamy et al. [30]	Strip	Geogrid	–	–	–	0.5	–
Dash et al. [25, 39–46]	Strip	Geogrid, non-oriented polymer	0.1	12	1.2	3.14	8
	Strip	Geogrid, non-oriented polymer	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. [51, 52]	Circular	Geogrid	0	5.5	0.8	2.4	6
Zhou and Wen [26]	Circular	Geogrid	–	1	0.13	0.1	3
Yoon et al. [77]	Square	Waste tire thread	0.2	4.17	0.54	0.39	3
Emersleben and Mayer [32]	Circular	Geogrid	0	–	0.77	0.67	1.5
Sireesh et al. [61]	Circular	FLAC^{3D}	0.4	5	0.8	1.8	4
Latha et al. [67]	Strip footing	GEOFEM	0.1	6	0.25	2.3	–
Rai [72]	Circular	Geogrid	0.1	6.67	0.4	0.8	14
Zhang et al. [31]	Circular	Geogrid	0.85	5.5	–	0.13	8
Pokharel et al. [47]	Circular	Geogrid	0.13	1.37	1.37	0.67	2.5
Tafreshi and Dawson [13]	Strip	Geogrid/geotextile	0.1	4.2	0.67	1.33	3
Tanyu et al. [33]	Circular	Textured HDPE	–	–	–	–	–
Rajagopal et al. [48]	Triaxial test, 100 mm dia., 200 mm ht.	Geotextile, soft mesh	–	–	–	–	–
Latha and Murthy [49]	Triaxial test, 38 mm dia., 76 mm ht.	Geogrid, geocell, fiber	–	–	–	–	–
Wu and Hong [50]	Triaxial test, 70 mm dia., 140 mm ht.	Geotextile	–	–	–	–	–

be provided in between) and pockets are filled with soil. As per general practice, geocell-pockets are filled with granular materials, like sand or gravel, for its better interfacial properties and higher control over the ‘in-filling’ process.

Studies on Geocell-Reinforced Foundation Systems

Figure 1b has depicted the general configuration of geocell-reinforced foundation system indicating various influencing parameters. In either of the applications, such as foundation, embankment, or pavement etc., performance of geocell-reinforced systems was investigated, mostly, in terms of improvement in load-settlement behavior under different combinations of configurations. It has been studied through physical model tests, analytical and/or numerical analyses, considering various combinations of influencing parameters. Following sections present brief discussions on selected studies on geocell-applications.

Physical Model Studies

In field, geocell-soil-mattress is formed by filling the geocell-pockets with granular material, such as gravel or sand, overlying soft subgrades of sand and/or clay. As per the conditions, rigorous experiments were performed in laboratory on geocell-reinforced foundations overlying soft/very soft clay subgrades [23–29]. Performances of geocell-reinforced embankment on soft clay was investigated by Krishnaswamy et al. [30] and Zhang et al. [31]; while, the suitability of geocell-reinforcements in pavement application over soft clay were reported by Emersleben and Meyer [32], Tanyu et al. [33]. Leshchinsky and Ling [34, 35], Indraratna et al. [36], Biabani et al. [37] have investigated benefits of geocell-reinforced ballast under cyclic loading, simulating the railway track conditions. Biswas et al. [27, 38] investigated the effect of subgrade strength on the performance of geocell-sand mattress resting on clay subgrades. In Fig. 2, typical laboratory model test set ups for geocell-reinforced foundation [27] and embankment [30] are presented.

A number of investigations have considered physical model tests on geocell-sand mattress overlain loose and/or dense sand subgrade. Dash et al. [39–44], Dash [45, 46], Tafreshi and Dawson [13] have reported detail parametric studies investigating the effect of geocell-geometry, formation pattern, placement depth, geocell-stiffness and relative density of in-filled sand etc. Pokharel et al. [47] investigated the effect of shape, type, embedment depth of footing, geocell-height and quality of in-filled material on sandy subgrades. Investigations in very small scale, in triaxial set-ups, were also performed [48–50]. These investigations mostly focused on the influence of confinement, packing of geocell-systems, pattern of failure, and compared the relative performance of geocell systems with the other variations (such as, planar and randomly distributed fibers). Figure 3 presents a typical triaxial set-up [48] for geocell-reinforced sample. The figure also indicates the confinement effect in terms of development of apparent cohesion. Few laboratory model tests were also performed on geocell-reinforced foundations, in-filled with clay overlying the clay subgrade [51, 52].

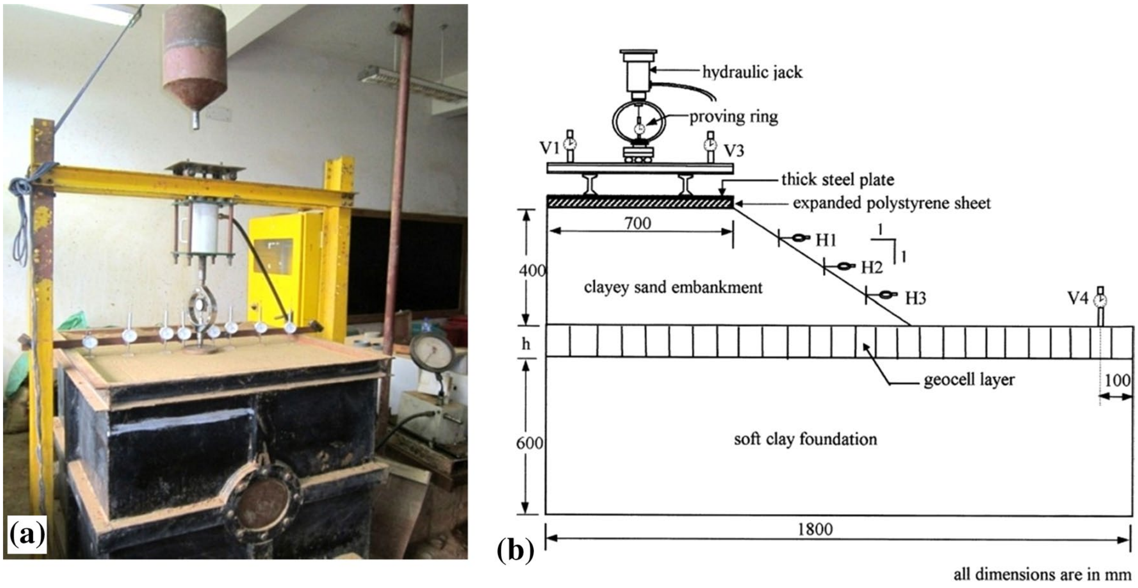

Fig. 2 Geocell-reinforced systems (**a**) as foundations (Biswas et al. [27]) and **b** Embankment systems (Krishnaswamy et al. [30])

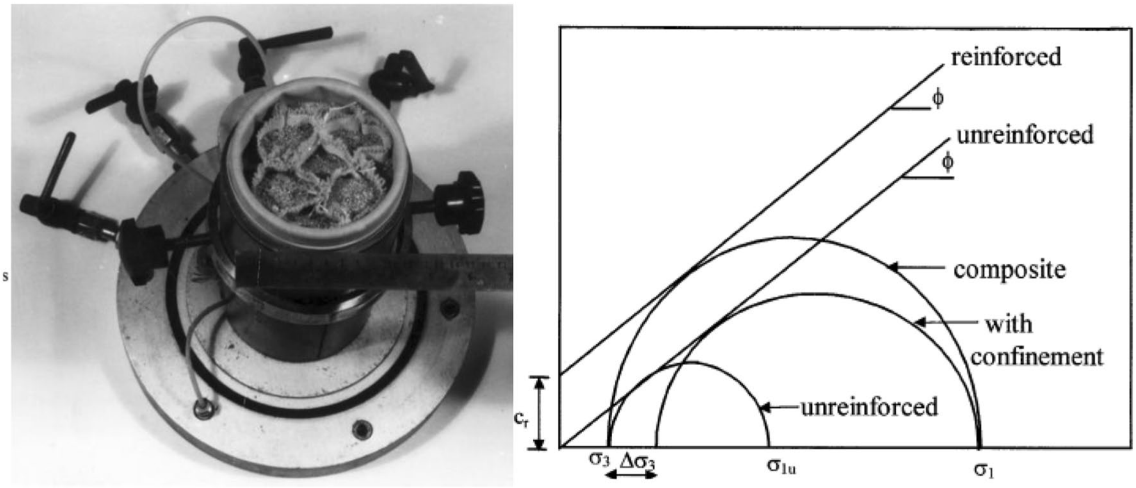

Fig. 3 Multiple geocell-system in triaxial test and development of apparent cohesion: Rajagopal et al. [48]

Analytical Studies

Different analytical models are developed for estimating the behavior of geocell-reinforced systems. Rajagopal et al. [48], Latha et al. [53–55] assumed that the enhanced load-bearing capacity is due to generation of apparent cohesion through geocell-confinement (Fig. 3). This approach considered 'hoop stresses' and lateral strain to estimate the induced cohesion (c_r) [56, 57]. Hence, in determining the geocell-behavior, the generated membrane stiffness was replaced by 'equivalent soil-stiffness' and analyzed as 'layered-soil of different strengths' [55, 56, 58]. A different approach proposed by Dash et al. [43] considering load dispersion through the geocell-reinforced soil layer. Zhang et al. [31] proposed similar, but, a detailed and more realistic mechanism by discretizing different mechanisms, such as lateral restrain (confinement), stress dispersion, and membrane action (Fig. 4). This approach approximated the geocell-reinforced-soil as a 'layer with higher flexural rigidity'. Similar concept was also reported by Fabymole

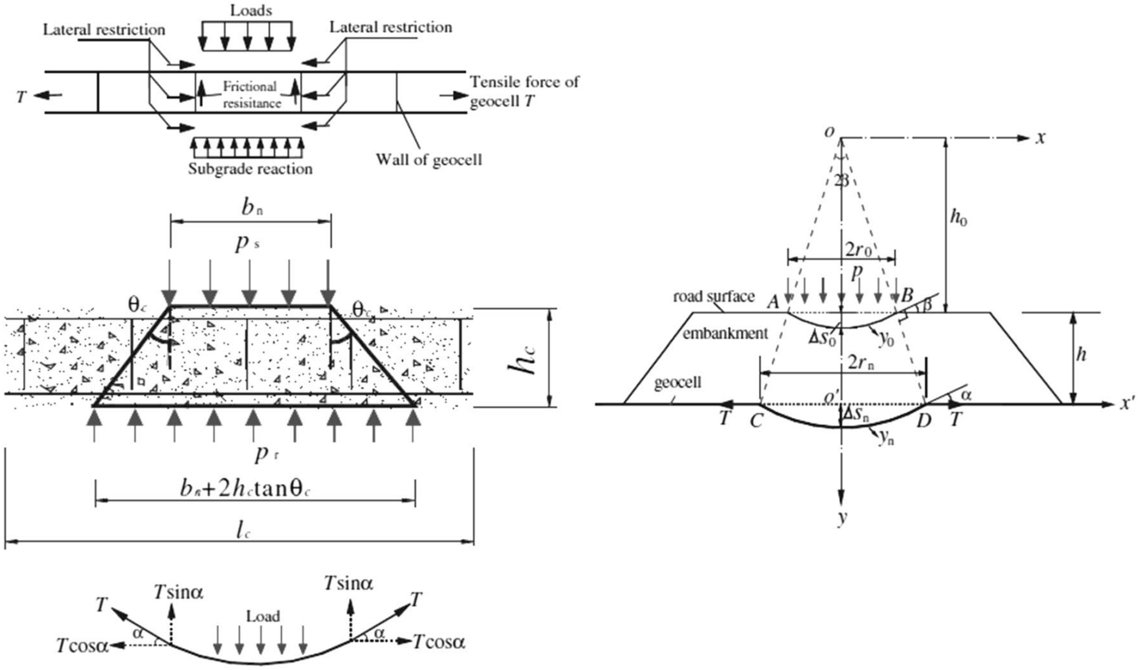

Fig. 4 Discretized geocell-mechanism: confinement, membrane action and stress distribution: Zang et al. [31]

et al. [59] based of the result of instrumented physical model tests.

Numerical Studies

Considerable numbers of numerical simulations are also performed on geocell-reinforced systems, which were capable of rigorous parametric variations. Han et al. [60], Sireesh et al. [61–63], Yang et al. [64], Fabymole et al. [59], Hegde and Sitharam [65, 66] used FLAC^{3D} for analyzing the behavior of geocell-reinforced foundation systems in varying conditions. Finite element analysis (in GEOFEM) considering the equivalent stiffness of geocell-reinforced layer, was reported by Latha et al. [54, 67]. The results indicated considerably good predictability of the foundation behavior, as observed in laboratory physical model tests. Similar approach was also reported by Buthurst and Kight [68], Latha and Somwanshi [55], Sitharam and Hegde [69], Mehdipour et al. [70]. In these studies, the confinement and interfacial resistances of geocells were replaced by a 'stiffer-soil layer' having 'equivalent strength and stiffness' that of the reinforced-soil. However, it is not a very realistic approach as it avoids the uncertainties involved in parametric variations. Therefore, though it produced good predictability of foundation performance, but, results were mostly limited to specific study and are not efficient enough to generalize the behavior. A more realistic approach, by modeling the geocell-mattress as multiple-cell system, was reported by Sireesh et al. [63] and Hegde and Sitharam [28]. Figure 5 presents the numerical model developed by Hegde and Sitharam [28] for geocell and geocell with base-geogrid. The performance of single-cell-geocell was also investigated few occasions [35, 64]; but, the behavior differs considerably to that of a multiple cell geocell-system actually used.

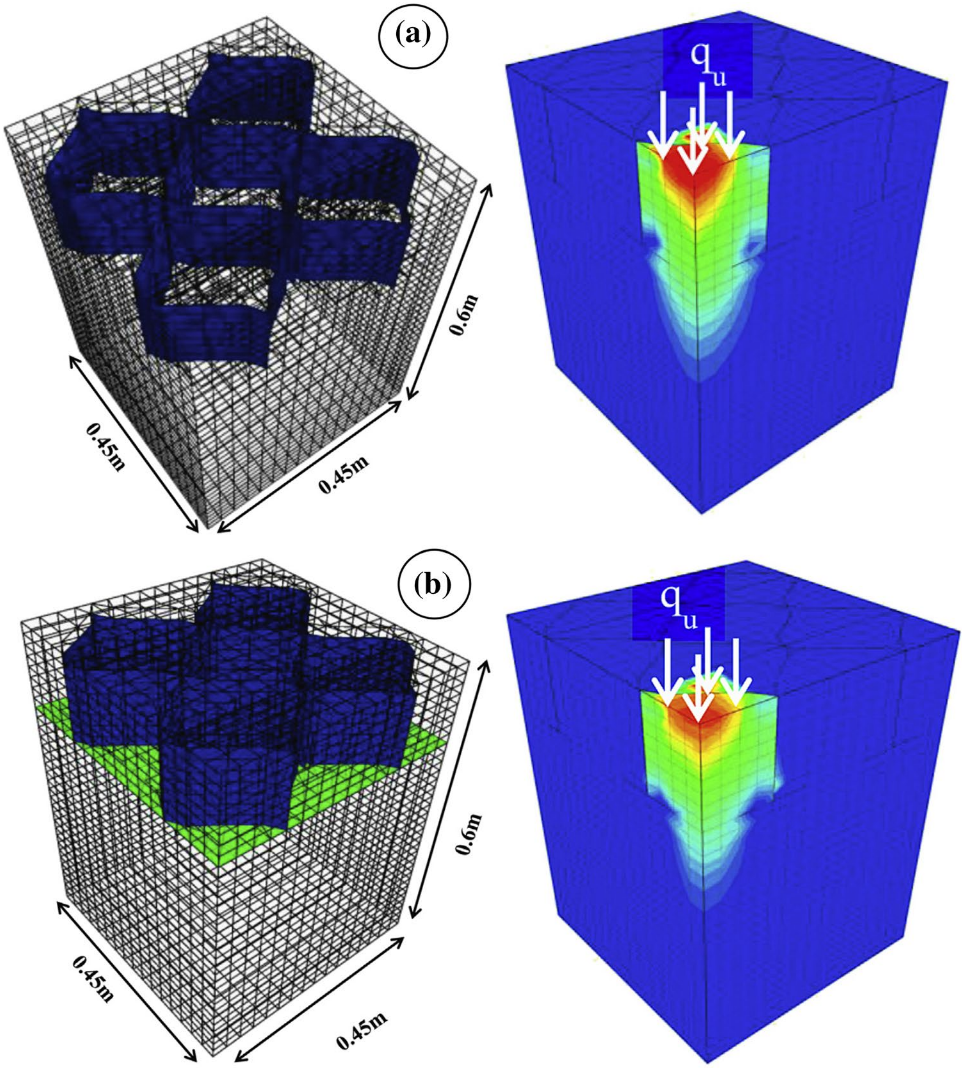

Fig. 5 Behaviour of geocell-reinforced foundations in FLAC^{3D} (Hegde and Sitharam [28]): **a** geocell only and **b** with base geogrid

Reinforcing Mechanism

The primary reinforcing action for geocell is to confine the in-fill soil from shearing away upon applied load. In addition, the perforated (and/or textured) geocell-walls derive anchorage (and/or interfacial friction; Fig. 6) through surrounding soil in resisting the incoming load [23, 39, 45, 48]. Besides, geocell-walls cut the potential failure planes (as would develop in unreinforced condition) and force it to go deeper in to the soil [23, 30, 38] to increase the stability and bearing capacity of soil (Fig. 7). The interconnected pockets provide all-round confinement to in-filled soil and behaves as a semi-rigid composite slab. It redistributes the applied load to a wider area with lesser intensity to improve the load-bearing capacity of underlying soil. The semi-rigid-slab configuration improves the performance by resisting differential settlement of concerned structure and generates membrane resistance. The soil-confinement is developed by the 'hoop strength' of geocells, in combination with the passive resistance of surrounding soil (and/or cells) [23, 48]. Together, it induces a significant apparent cohesion to the in-filled soil, even for dry sand [48]. The interconnected geocell-soil composite mattress, having high shear and bending rigidity, can support significant load even after squeezing of 'in-filled soil'. Overall, the mechanism of geocell-reinforcements can be discretized as 'confinement', 'membrane action', and 'stress distribution' (Fig. 4; [31]).

Influencing Parameters

A variety of studies have revealed various influences of several parameters on the performance of geocell-reinforced systems. Significant number of laboratory model tests, physical and/or analytical studies, indicated that the

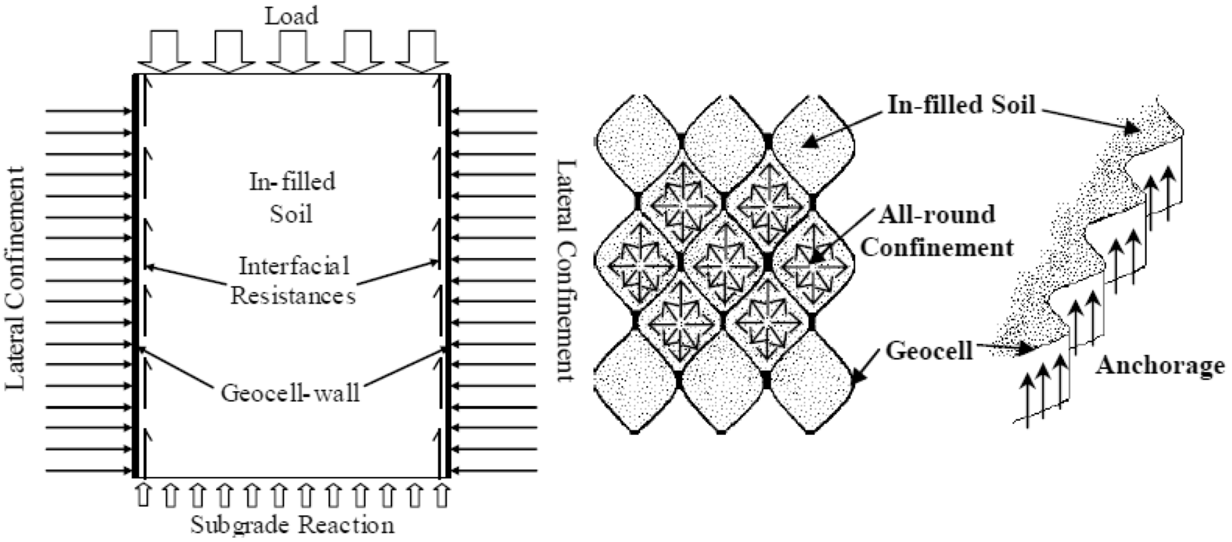

Fig. 6 Reinforcing mechanisms of geocell reinforcement: Biswas et al. [38, 88]

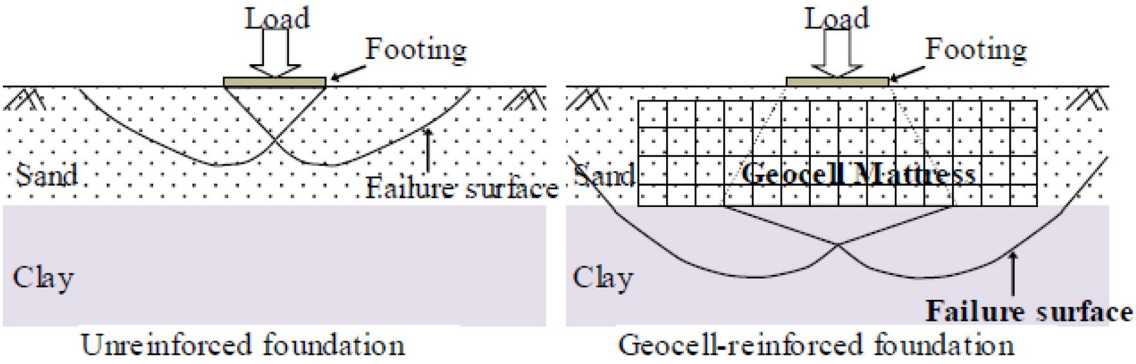

Fig. 7 Development of slip surfaces in unreinforced and geocell-reinforced foundations: Biswas et al. [38]

variance of effects are largely depended on the configurations of geocell-reinforced structures. A brief discussion on the influencing parameters and their effects are presented in following sections, mostly in perspective of a foundation (or load bearing) application.

Formation Pattern

Generally, geocell-mattress is formed either in 'Chevron' or 'Diamond' patterns (Fig. 8). Studies have indicated that the formation pattern is having marginal influence on the performance of geocell-reinforced systems. It is found that 'chevron pattern' is comparatively more beneficial over diamond pattern. The higher efficiency is the result of greater structural rigidity of geocell-mattress, comes with more number of joints per unit area. For example, in Fig. 8, it may be noticed that, in the same mattress area, the 'chevron pattern' is having 20 joints as compared to only 12 joints for the 'diamond pattern'. Thus, the 'chevron pattern', having higher shear and bending rigidity, can sustain greater load and redistribute it more efficiently to the underlying subgrade [30, 39, 71, 72]. Besides, for greater structural rigidity, it can sustain for longer duration, even after shearing away of in-filled soil. Pokharel et al. [47] reported that the circular pocket provides higher improvement than the elliptical-shaped geocells, through a single-cell system. However, the interaction is different for multiple-cell-system as compared to the single-geocell [48, 73, 74]. Thus, it may be conclude that the 'chevron pattern' would be better configuration to follow for geocell-reinforced structures.

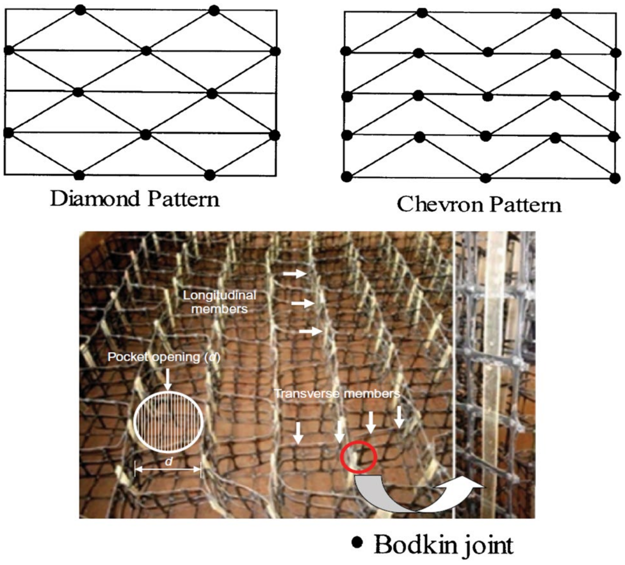

Fig. 8 Patterns of Geocell-formation (Dash et al. [39]; Biswas et al. [38])

Pocket Size

Geocell-pocket-size is generally expressed as the diameter (*d*) of an equivalent circular area of geocell-pocket opening (Figs. 8, 9). It is found that the smaller the pocket-size, the higher is the load-bearing capacity of geocell-reinforcement. This is attributed to increased stiffness of geocell-soil composite structure. Smaller geocell-pockets provide higher confinement to in-filled soil and increases shear and bending rigidity through more number of joints per unit area. Moreover, the smaller the pockets are, the higher is the effective surface area for geocell-soil interfacial resistances. This can derive a very high anchorage/frictional resistances through geocell-walls against possible incoming loads. Combining the above, the geocell-soil-composite mattress behaves as a semi-rigid slab which redistribute the load to underlying subgrade more efficiently with lesser intensity to enhance overall performance. However, in field, construction of very small pockets is difficult; so as the compaction of in-filled soil. It has been found that the pockets of geocell-mattress should be smaller than the footing (or loading) area in such a way that the footing can cover, at least, one full pocket opening [23, 24, 39, 41]. Based on laboratory model studies, the optimum pocket size is recommended as 0.8*D* [41, 72], where '*D*' is the footing (or loading) diameter.

Width and Height of Geocell Mattress

Laboratory model studies, physical and/or analytical, have indicated that performance of geocell-reinforced system is highly depended on the geometry of geocell-mattress, which includes width (or length) and height (or thickness). A schematic diagram of geocell-mattress is presented in Fig. 9, indicating geometric features of geocell-mattress. It is found that, with increase in width of geocell-mattress, the load distribution becomes more uniform and it can transfers the incoming load with much lesser intensity to

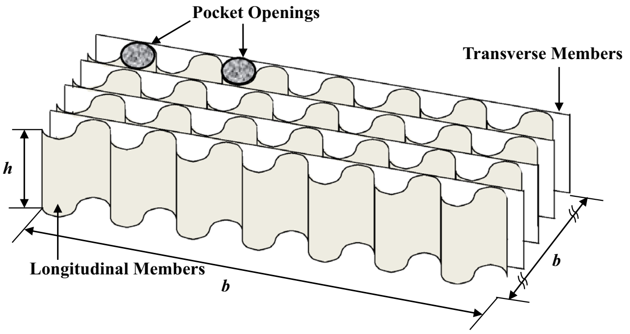

Fig. 9 Schematic of geocell-mattress showing different geometric parameters

underlying subgrade. Larger geocell-mattress produces significant interfacial resistance through surrounding soil and derives high membrane resistance to support greater load for better stability. The optimum width of geocell mattress is found to be 4–6*D*, where '*D*' is the footing diameter [24, 51, 62]. Beyond this, improvement was insignificant with respect to increased dimension (Fig. 10a). It is attributed to development of farthest rupture planes for a shallow foundation, which, as per Chummar [75], is expected to be well within 3*D* at either sides of the footing.

Similar to the width of geocell-mattress, the height (or thickness) of geocell-mattress is equally important in influencing the behavior of geocell-reinforced structures. Through rigorous research, the optimum value of geocell-height was found to be in the range of 1.5–2.0*D*. The 'range' is depended on subgrade strength [27, 38], stiffness of geocell-materials [27, 39] and density of in-filled soil [39, 48, 72]. Figure 10b shows the effect of geocell height on the performance of model foundations [62]. It is found that with increase in geocell-height, the rigidity of geocell-mattress enhances. The enhancement is attributed to increased number of joint-layers (bodkin joint) which increases flexural rigidity of geocell-mattress to behave like a semi-rigid slab [39, 43]. Dash et al. [39] similitude this behavior with 'deep beam action'. In addition, the increased height generates supplementary interfacial resistances through enhanced surface area. It is observed that a part of thick geocells, just under the footing bottom, are prone to buckle under high load. It is due to stiffness of the top of geocell-mattress, which was 'not affected' by increase in geocell-heights. Therefore, bending takes place at the top of geocell-mattress at high stress and resulted in greater footing-settlement to reduce overall performance [27, 38, 72]. The effect was very prominent for thicker geocells ($h > 2D$) and stiffer subgrades [38, 76] (Fig. 11); however, it was slightly reduced by dense in-filled soil through passive resistance.

Placement Depth

Usually, the geocell-pockets are slightly overfilled by same in-filled soil. The overfilling serves in two ways: it distributes the load uniformly to a wider area which helps in reducing the stress intensity on geocell-mattress. In addition, the soil-cushion compensates constructional settlement [13, 20, 27, 38, 39, 77] and increases the density

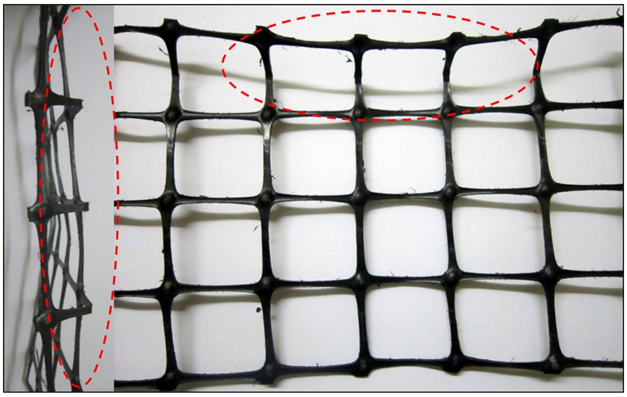

Fig. 11 Bending of geocell-wall just under the footing: Biswas et al. [38]

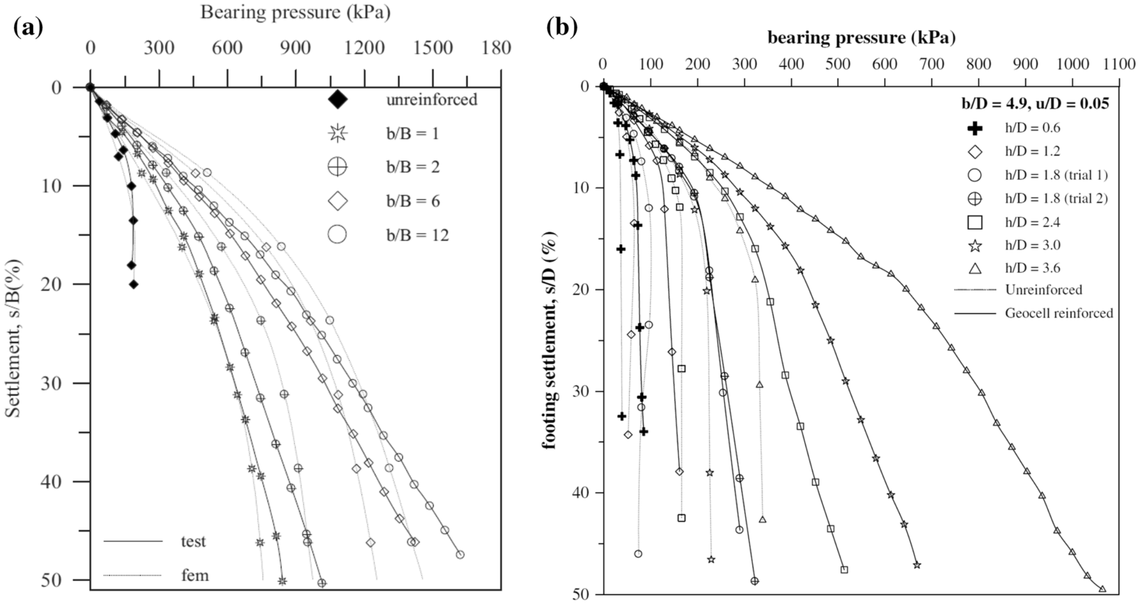

Fig. 10 Effect of geocell **a** width: Latha et al. [67], and **b** height: Sireesh et al. [61]

of in-filled soil. This, eventually, enhances load-bearing capacity and improves overall performance of geocell-reinforced systems. In most of the studies, the optimum thickness of soil cushion (*u*) (or the placement depth of geocell-mattress below the footing) was in the range 0.1–0.33*D*. Beyond the thickness, the unreinforced soil squeezed out under shear leading to early settlement of footing. In case of clay-filled geocell, the optimum performance noticed at $u=0$; i.e., when the footing directly placed on geocell-mattress [51, 52]. Figure 12a shows a typical performances for geocell-reinforced foundations at different placement depths [39].

Density of In-Fill Soil

Dash et al. [39], Dash [45], Pokharel et al. [47], Latha et al. [67] and Rai [72] observed that the performance of geocell-foundations improves with increase in density (or relative density, D_r) of the in-filled soil (Fig. 12b). This was attributed to stiffness of encased soil which itself can carry sufficiently higher load, and being more compacted it could attract greater load by enhancing shear parameters. In other hand, it causes reduction in load transfer to the geocell-walls. This, eventually, affect the stain mobilization on geocell-wall which results in developing less interfacial (or anchorage) resistance [39]. The increase in in-filled soil density also help in reducing the early bending in geocell-wall, by providing high confinement. Considering the facts, it is recommended that the in-filled soil-density should be kept as high as possible for better performance of geocell-systems.

Geosynthetics Properties

The properties of geocell-making materials (geogrids and/or geotextiles), such as stiffness, textures, orientation of ribs, and aperture opening size (d_a) etc., imparts significant influence on the reinforcing mechanism of geocell-systems [30, 39, 46, 48]. It is seen that in case of larger aperture openings (such as geogrid) better interlocking and anchorage is developed as compared to solid walled or perforated walled geocells. On other side, geosynthetics having smaller apertures contributes in higher confinement and greater surface area towards deriving higher degree of wall-friction. It is reported that the optimum performance is derived when aperture size (d_a) is about 80 times of mean grain size (D_{50}) of the in-filled soil (Fig. 13a). Dash [46] found that the geogrid having horizontal and vertical orientation of ribs (square and/or rectangular aperture; Fig. 14) gives better resistance against incoming load and possible settlement than the inclined orientation (diamond openings; Fig. 14). It is also reported that not the tensile strength of geogrid, but the stiffness of overall geocell-mattress delivers higher impact on geocell-reinforced foundation system [39]. The performance was attributed to high confinement that a stiffer geogrid yields, as compared to geogrid having higher tensile strength but less stiffness.

Subsoil Strength

The subsoil strength, probably, is the most important influencing factor for the overall performance of geocell-reinforced foundation system. As seen in Fig. 1b, it may be

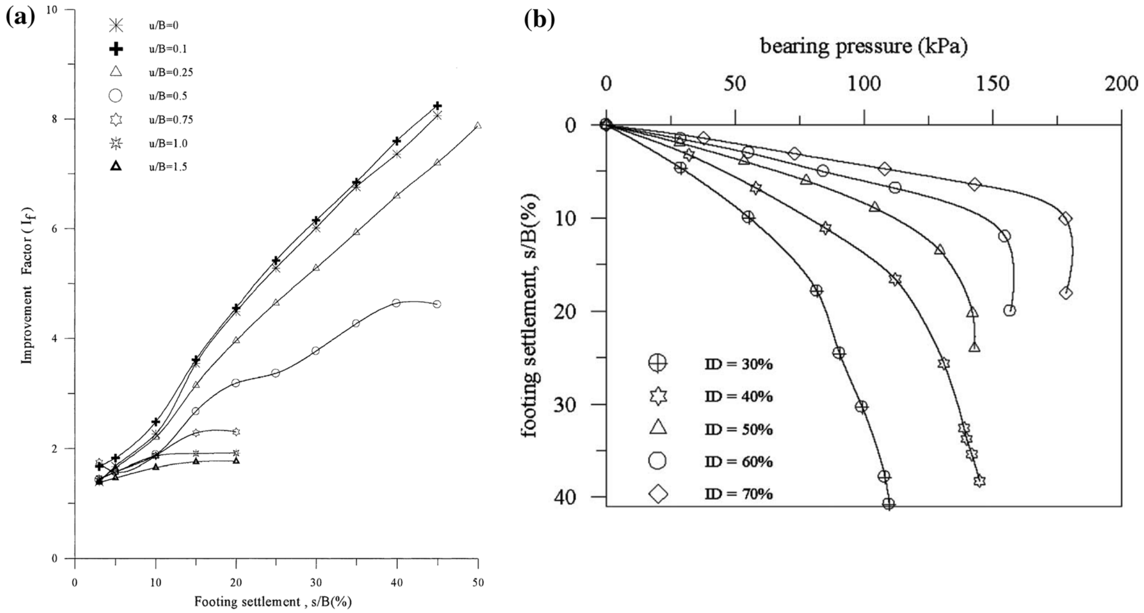

Fig. 12 Effect of **a** depth of placement: Dash et al. [39], and **b** relative density of in-filled sand: Dash [45]

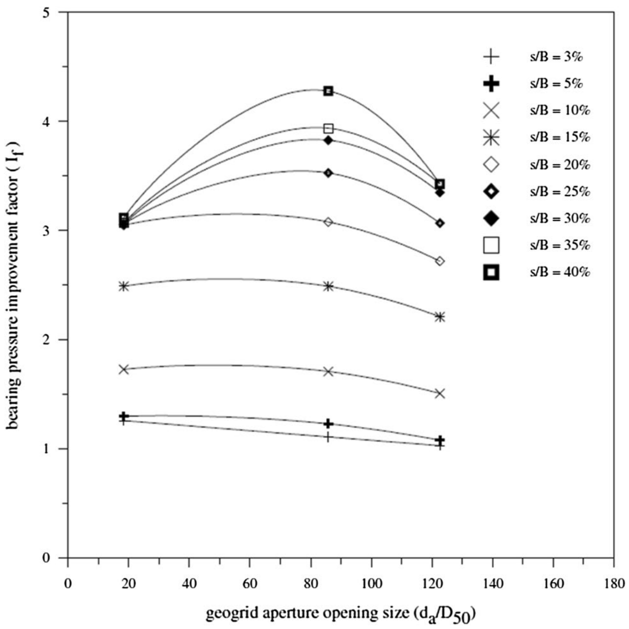

Fig. 13 Effect of aperture openings of geogrid: Dash [46]

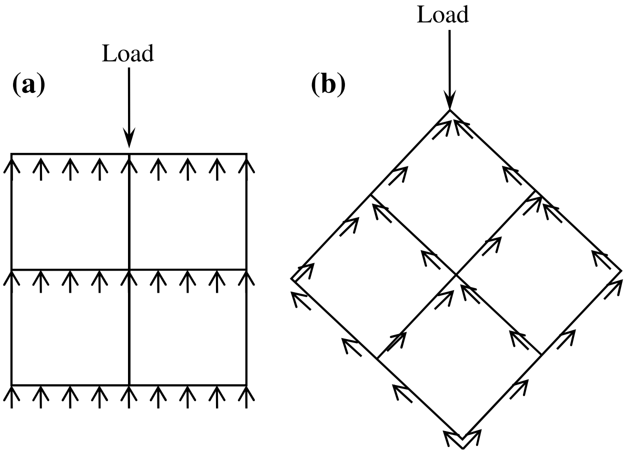

Fig. 14 Resistance against the incoming load for geogrids having **a** square/rectangular and **b** diamond openings

understood that the entire geocell-reinforced foundation is supported and depends on the behavior of underlying subgrade (i.e. soil-2) [27, 38]. Figure 15 presents the effect of subgrade strength in terms of 'pressure-settlement' and 'improvement in pressure-settlement responses' reported by Biswas et al. [27, 38] and Biswas [72]. Though, the influence of subgrade strength has not been exploded fully, but, it is noticed that stiffer geocell-mattress can derive much higher support from stiff subgrades [27, 38, 72]; whereas, significantly high improvement can be derived in case of softer subgrades [27, 38]. It was found that the effect of bending in geocell-walls, just under the footing, were very prominent for stiffer subgrades which results in high localized settlement causing reduction in overall performances. In addition, the stiff subgrade offers higher support against possible settlement of geocell-mattress which results in reduced interfacial and membrane resistances.

Additional Base-Geogrid

In general practice, a layer of planar geosynthetics is laid over the native soil before constructing (or placing) the geocell-mattress (Figs. 16, 17). The base-geogrid serves in two ways: it creates a temporary platform to the geocell-mattress and supports constructional movement. Besides, it enhances the overall performance by providing membrane-resistance. Eventually, the base-geogrid causes the subgrade being stiffer as compared to the native ground. However, in case of stiffer subgrade, the same results in adverse effect as localized bending in geocell-walls (for high stress concentration) and reduces the performance [25, 27, 38, 51]. It has also been reported that the base-geogrid reduces the 'tilting (or rotation)' of geocell-mattress [39].

A summary of reported optimum values of influencing parameters of geocell-reinforcement is presented in Table 3. In the table, the dimensional parameters are expressed in non-dimensional form with respect to diameter of the footing (*D*).

Field Applications (Case Studies)

Geocell-reinforcement was introduced in field much earlier than the parametric studies started in laboratories. Webster and Watkins [19] and Webster and Alford [78] pioneered this technology and led to the development of commercial geocells of present days. They used sand-filled interconnected thin-walled aluminum cells, overlying soft subgrade, against full-scale traffic load. It was observed that the reinforced-sand provided significantly greater load-carrying capacity and reduced about 60% of the unreinforced materials. Johnson [79] used geocells in construction of Greatham Creek Bridge, England (Fig. 18). Robertson and Gilchrist [80] mentioned geocells as the best alternative, in terms of cost effectiveness and overall performance, for construction of a 4 m high embankment over a deep soft clay.

Paul [81] reported use of geocells to support an embankment over deep soft deposits in Scotland. Application of geocell was found to be the most economical, convenient, and rapid method of construction. Settlement pins were installed in embankment, on top of geocell-mattress, for monitoring the performance which indicated insignificant differential settlement even after a long period of time. Bush et al. [20] described a detail construction

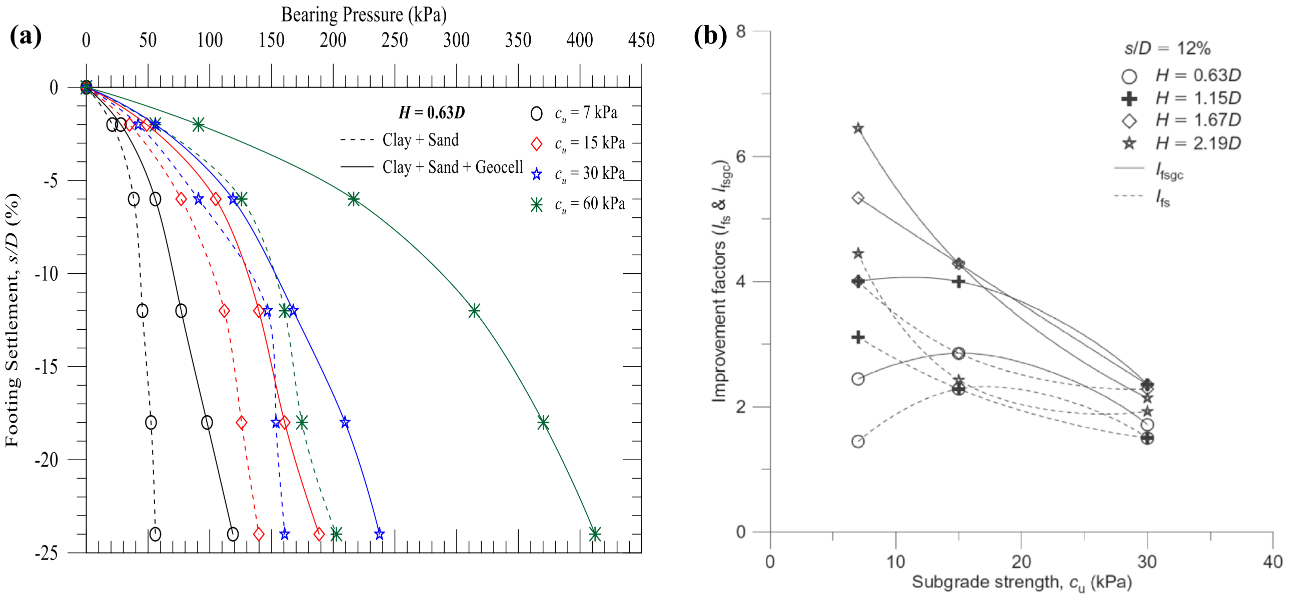

Fig. 15 Effect of subgrade strength on **a** pressure-settlement (Biswas [76]) and **b** improvement in pressure-settlement responses (Biswas et al. [27])

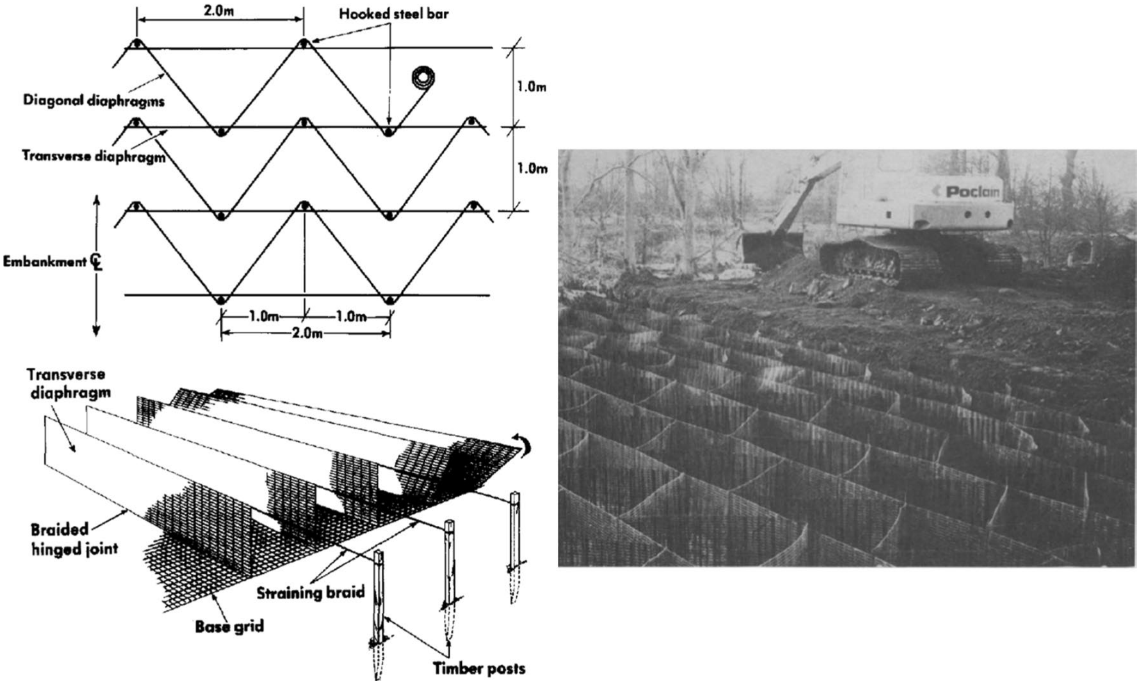

Fig. 16 Construction of geocell-mattress: Bush et al. [20]

of geocell-mattresses supporting embankments over soft ground. In this case, geocells were constructed with a polymer grid sheet, joined through 'bodkin joint' (Fig. 19). The bodkin-joints were formed by pulling the ribs of transverse geogrids through the longitudinal geogrid and inserting a dowel through the loop created. The construction was performed in sequence: initially, a series of interlocking cells (connected to a biaxial geogrid at base) was constructed using uniaxial polymer geogrids and filled with granular material. The filling was done by filling first two rows of cells to half height, before filling the first row to full height (Fig. 20). This method was followed to avoid

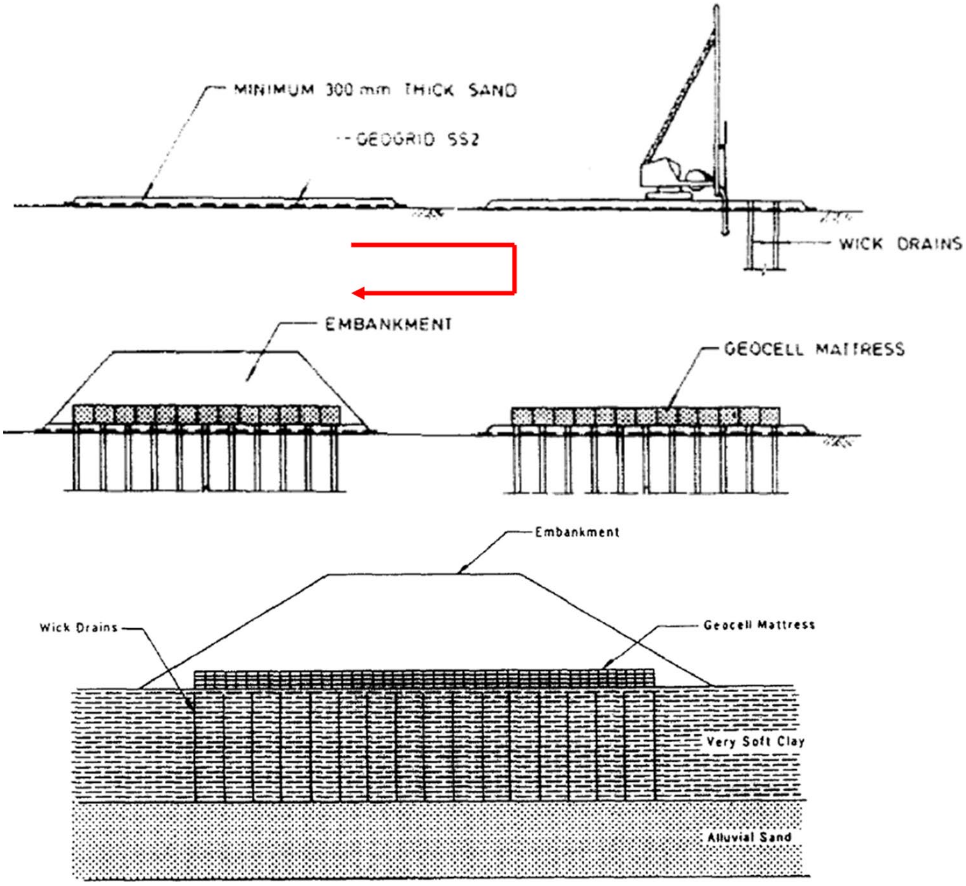

Fig. 17 Construction sequence of geocell-mattress: Cowland and Wong [84]

Table 3 Optimum value of the parameters

Parameters	Values (range)
Formation pattern	Chevron
Rib orientation	Horizontal and vertical
Geogrid opening (d_a/D_{50})	80
Stiffness of geogrid	As high as possible
Pocket size (*d*)	0.8*D* (or *B*) (at least smaller than loading size)
Width (*b*)	4–6*D* (*B*)
Height of geocell (*h*)	1.5–2*D* (*B*)
Depth of placement (*u*)	0.1–0.33*D* (*B*)
D_r of in-filled sand (%)	As high as possible

distortion of cells. The cells were over-filled by 150 mm to encounter compaction settlement due to constructional traffic. It was reported that it saved 1/3rd of the cost compared to the conventional solutions. Dean and Lothian [82] reported construction of an embankment with uniaxial geogrid-made-geocell and filled with crushed rock over a deep soft deposit. Amongst the other alternatives, like construction of a viaduct, replacement of soft deposit with rock or pre-consolidation of soft soil etc., the geocell-reinforcement was found to be the most convenient, rapid, and economical method. Boyle and Robertson [83] used geocells in constructing flexible gravity walls and steepened slopes.

Cowland and Wong [84] presented a field investigation and construction process with performance monitoring of a geocell-reinforced road embankment over soft clay (Fig. 17). The embankment was fully instrumented with piezometers, inclinometers, profile gauges, settlement plates, surface settlement markers and lateral movement blocks. The monitoring was performed at regular intervals just after the instrumentations was over. Vane shear tests were carried out after 1-year of completion of construction and found an average increased in shear strength as about 2–3 times (depending on soil-types). Gupta and Somnath [85] used geocells in construction of box-culverts over marine clay deposits (more than 6 m depth) in New Bombay. The tubular gabions were constructed over soft soil, with their ends resting on hard moorum, before constructing the geocell-mattress. In this arrangement, the gabions were served as granular piles and the geocell-mattress was as flexible pile-cap. Koerner [86] reported a field study on geocell-reinforced pavement filled with compacted sand over soft subgrade. The pavement was tested under

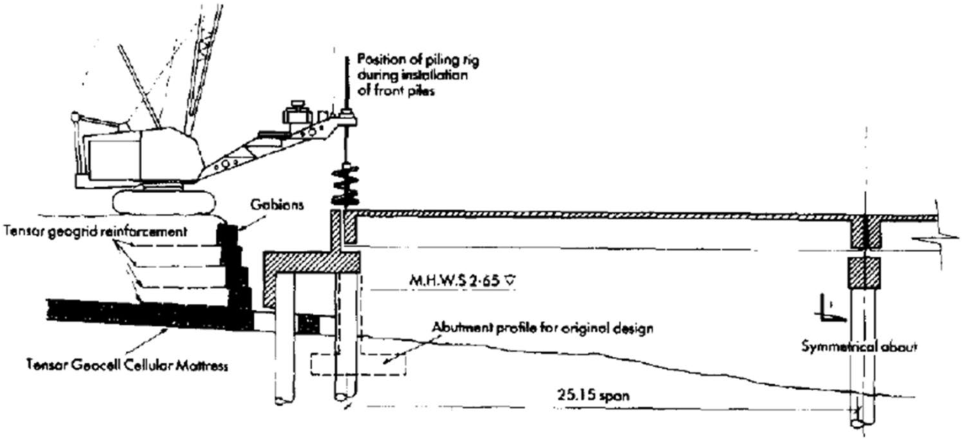

Fig. 18 Schematic of geocell foundation for approach embankment of Greatham Creek, Cleveland: Johnson [79]

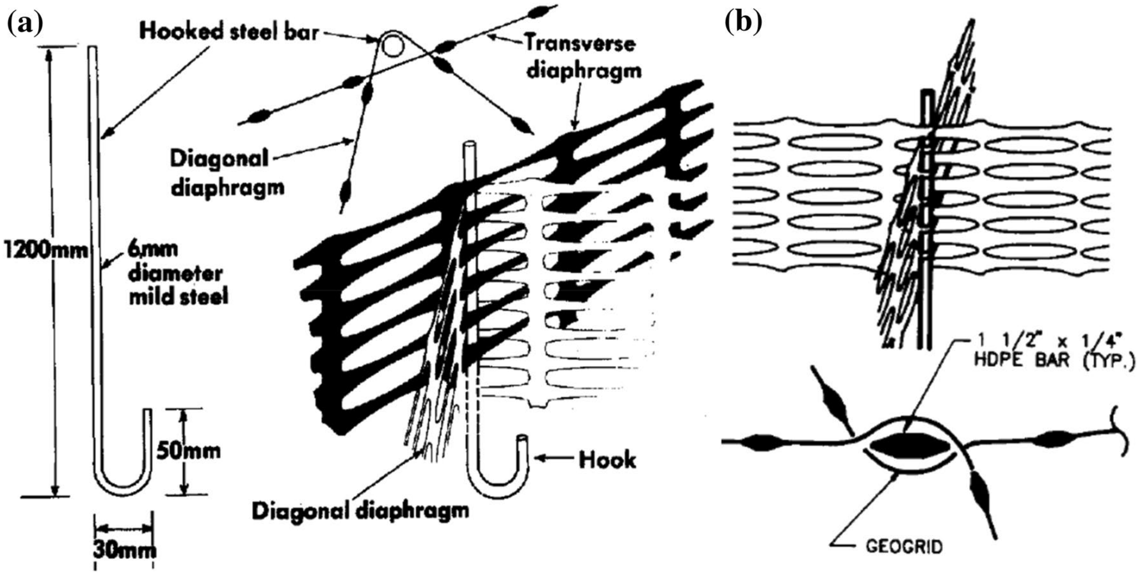

Fig. 19 Bodkin join for geocell-mattress **a** Bush et al. [20], and **b** Carroll and Curtis [22]

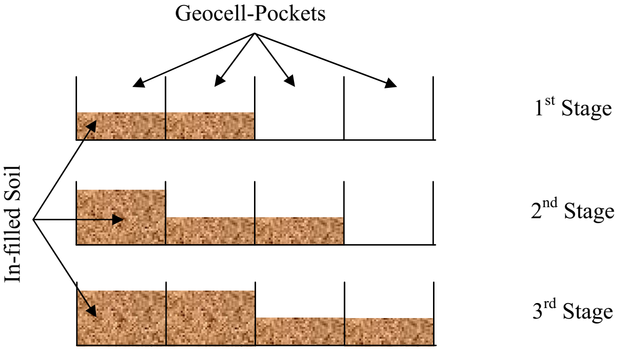

Fig. 20 Sequence of soil in-filling

tandem-axle truck for 10,000 passes. The reinforced system resulted in slight rutting, as compared to deep ruts occurred only after ten passes over the unreinforced subgrade. Forsman et al. [87] reported a study on the performance of a geocell-reinforced road over deep peat deposit. The geocells were fabricated using geogrids and filled with light expanded clay aggregate. Such 'fill' was used because of expected large settlements in the peat deposit. The tests were instrumented using vertical extensometers, profile gauges, settlement plates, and strain gauges. Plate load test and falling weight deflectometer tests were conducted to measure the modulus of subgrade. The geocell layer was found to be effective in increasing the bearing capacity and reducing settlements. Even after a year and half, no significant settlement was observed on road surface. Emersleben and Mayer [32] performed model tests on circular footing and compared the results with in-situ test on geocell-reinforced subgrade (Fig. 21). A special type of soil, *Glyben*, was used to simulate the soft subgrade ($c_u = 15$ kPa). In model tests, about 1.5-fold improvement in bearing

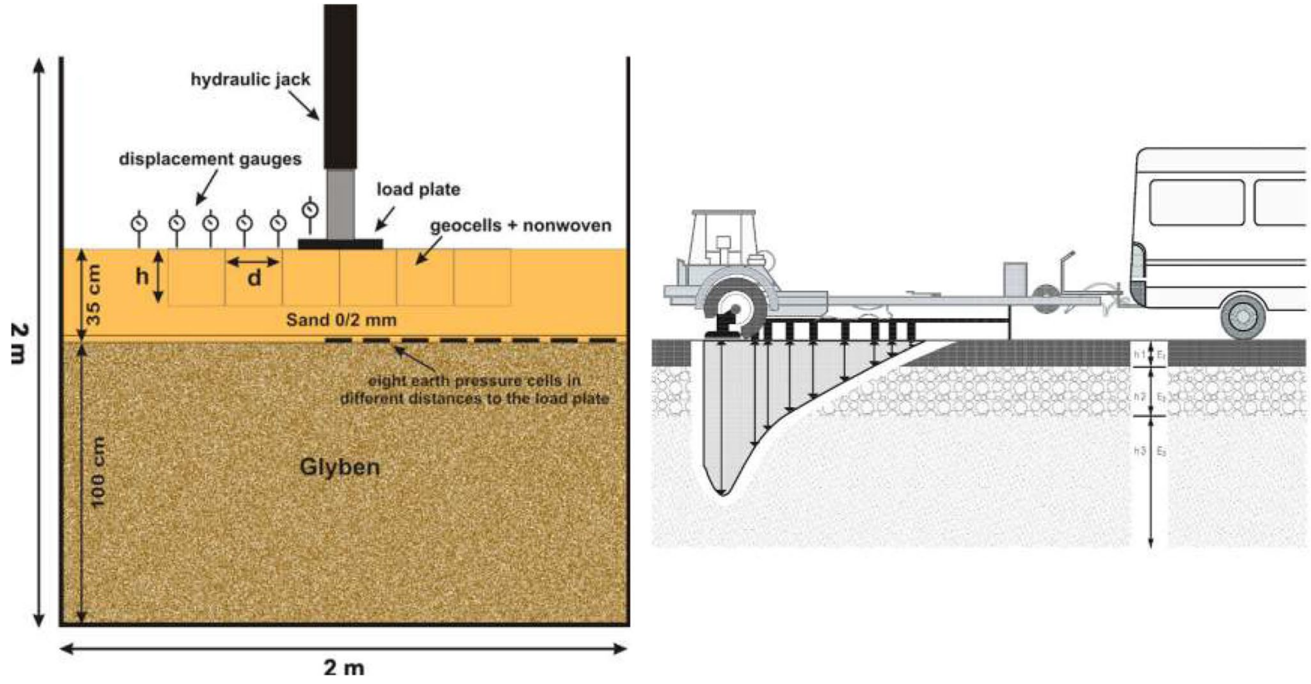

Fig. 21 Schematic of laboratory model set up and field test with falling weight deflectometer measurements [32]

capacity and about 30% reduction in vertical stresses was noticed. The in-situ tests, such as 'vehicle crossing and vertical stress measurements' and 'falling weight deflectometer', showed reasonably good agreements with the model test results.

Conclusions

This paper discussed the parametric behavior of various geocell-applications. The developments and detail mechanism of geocell-reinforced systems are briefly explained. Besides, attempts were also made to establish the inter-relationships between parameters for optimum results in varying configurations for maximum benefits. As per the findings, followings should be the critical considerations for designing a geocell-reinforced systems:

- Primarily, the design and behavior of geocell-reinforced systems is depended on subgrade strength. The initial selection of geocell-geometry (height, width, pocket size etc.) has to be as per type and/or quantity of improvement required and available subgrade strength.
- According to the desired intensity of load transfer (or bearing capacity of subgrade soil) and loading (or footing) diameter (or width), the width and height of geocell-mattress has to be designed. However, the density (or relative density) of the in-filled soil is preferable to be at maximum possible.
- The type (interfacial properties), stiffness and tensile strength of geocell-making material (i.e. geogrid and/or geotextiles) has to be according to degree of confinement and rigidity of the geocell-soil mattress desired. This will effect in overall stiffness and slab-like-behavior of geocell-soil composite mattress (i.e. load transfer to underlying subgrades).
- A base geogrid may be placed below the geocell-soil matrix, but, need to verify the applicability with respect to geocell-height and subgrade strength.

In general, it is found that the 'Chevron' pattern of geocell-formation with $0.8D$ pocket opening, having $6D$ width and $1.5–2D$ height may be adopted, when placed at $0.1D$ depth below the footing (of diameter 'D') and in-filled with granular soil of densest possible state. However, it is always suggested that for every individual application, one must consider all other influencing parameters as per the subgrade strengths, for the optimum combinations of configurations. At present, the application of geocell-reinforcement is mostly guided by experience and design of geocell-reinforced soil structures is yet to be fully explored. In view of this, this paper may be used as a preliminary guide for researchers and practitioners.

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