CHAPTER 2

REVIEW OF LITERATURE AND SCOPE OF THE PRESENT STUDY

2.1 Introduction

An extensive study of the literature in the area of unreinforced and reinforced soil beds was carried out in this research and a review of the important literature is presented in this chapter. The literature review is divided into three sections, focusing on unreinforced foundations, planar reinforcement, and geocell reinforcement. The final section of the chapter outlines the scope of the current study.

2.2 Unreinforced foundations

The stability of a structure is dependent on the strength of the soil it is built on. In order for the structure to be safe, the foundation soil must have enough strength to resist shear failure and should not settle excessively. To allow the foundation to perform to its fullest potential, it is important to make sure that it does not exceed its safe bearing capacity.

Pauker [96] initiated the pioneering studies on foundation behaviour of homogeneous soil. In the study, the foundation behaviour of homogeneous sand was investigated and analyzed using Rankine’s [104] earth pressure theory. Later on, Prandtl [100] derived an analytical solution using experimental results to determine the ultimate bearing capacity of soil. Terzaghi [129] modified Prandtl's model by incorporating a semi-empirical equation that took into account the non-linear behaviour of the foundation, soil cohesion and friction, soil weight, and the depth at which the foundation was embedded, using the superposition principle. In the study, Terzaghi suggested that the ultimate bearing capacity of a strip foundation under a vertical load on homogenous soil can be represented as

$$q_U = cN_c + qN_q + \frac{1}{2}\gamma B N_\gamma \qquad (2.1)$$

where, q_U = ultimate bearing capacity; c = cohesion; q = surcharge pressure at footing level = γD_f ; D_f = depth of foundation; γ = unit weight of soil; B = width of foundation; N_c, N_q , $N\gamma$ = bearing capacity factors and function of the soil friction angle.

For sandy soil, the aforementioned equation can be simplified as below:

$$q_U = qN_q + \frac{1}{2}\gamma BN_\gamma \quad (2.2)$$

Later, Terzaghi's theory was improved to account for the effect of foundation shape and various modes of failure. Subsequently, various researchers, including Skempton [120], Meyerhof [85-88], De Beer [30], Hansen [39], and Vesic [132-133] studied the effect of some other conditions of foundation configurations, such as eccentrically applied load, inclined load, foundation shape, degree of saturation of the soil and soil compressibility. Nevertheless, most of these modifications have taken into account Terzaghi's bearing capacity theory and its proposed factors.

The equation for a foundation subject to a central vertical load, as proposed by Meyerhof [85], can be written as follows:

$$q_u = cN_c s_c d_c + qN_q s_q d_q + \frac{1}{2}\gamma BN_\gamma s_\gamma d_\gamma \quad (2.3)$$

For sandy soil, the above equation takes the following form:

$$q_u = qN_q s_q d_q + \frac{1}{2}\gamma BN_\gamma s_\gamma d_\gamma \quad (2.4)$$

where, s_c, s_q, s_γ = shape factors; d_c, d_q, d_γ = depth factors.

In the past, several researchers have suggested the bearing capacity factors along with shape and depth factors for estimating the bearing capacity of footing vertical loaded at the centre. These factors are summarized in Table 2.1 and Table 2.2.

Table 2.1 Summary of bearing capacity factors

Researchers	Bearing capacity factors	Proposed formula
Prandtl [100], Reissner [107], Terzaghi [129], Meyerhof [88]	N_c	$N_c = \left(N_q - 1\right)cot\varphi$
Krizek [67]	N_c	$N_c = \frac{228 + 4.3\varphi}{40 - \varphi}$
Prandtl [100], Reissner [107], Meyerhof [88]	N_q	$N_q = tan^2\left(45 + \frac{\varphi}{2}\right)e^{\pi tan\varphi}$
Terzaghi [129]	N_q	$N_q = \frac{e^{2(\frac{3\pi}{4} - \frac{\varphi}{2})tan\varphi}}{2\cos{(45 + \frac{\varphi}{2})^2}}$
Krizek [67]	N_q	$N_q = \frac{40 + 5\varphi}{40 - \varphi}$
Terzaghi [129]	N_γ	$N_\gamma \approx 1.8\ (N_q - 1)cot\varphi(tan\varphi)^2$
Biarez et al. [10]	N_γ	$N_\gamma = 1.8\ (N_q - 1)tan\varphi$
Meyerhof [88]	N_γ	$N_\gamma = (N_q - 1)\tan{(1.4\varphi)}$
Krizek [67]	N_γ	$N_\gamma = \frac{6\varphi}{40 - \varphi}$
Hansen [39]	N_γ	$N_\gamma = 1.5N_c tan^2\varphi$
Vesic [132]	N_γ	$N_\gamma = 2\left(N_q + 1\right)tan\varphi$
Ingra and Baecher [50]	N_γ	$N_\gamma = e^{(-1.646 + 0.173\varphi)}$
Hjiaj et al. [47]	N_γ	$N_\gamma = e^{\frac{1}{6}(\pi + 3\pi^2 tan\varphi)}tan\varphi^{\frac{2\pi}{5}}$
Salgado [109]	N_γ	$N_\gamma = \left(N_q - 1\right)\tan{(1.32\varphi)}$

Table 2.2 Commonly used expressions for shape and depth factors

Researchers	Factors	Equation
Meyerhof [88]	Shape	For φ = 0^0: $s_c = 1 + 0.2\,(\frac{B}{L})$ $s_q = s_\gamma = 1$ For φ ≥ 10^0: $s_c = 1 + 0.2\left(\frac{B}{L}\right)tan^2\left(45 + \frac{\varphi}{2}\right)$ $s_q = s_\gamma = 1 + 0.1\,tan^2\left(45 + \frac{\varphi}{2}\right)\,(\frac{B}{L})$
De Beer [30], Vesic [133]		$s_c = 1 + \left(\frac{N_q}{N_c}\right)(\frac{B}{L})$ (use N_c and N_q given by Meyerhof (1963)) $s_q = 1 + \left(\frac{B}{L}\right)tan\varphi$ $s_\gamma = 1 - 0.4\left(\frac{B}{L}\right)$
Meyerhof [88]	Depth	For φ = 0^0: $d_c = 1 + 0.2\left(\frac{D_f}{B}\right)$ $d_q = d_\gamma = 1$ For φ ≥ 10^0: $d_c = 1 + 0.2\left(\frac{D_f}{B}\right)tan\left(45 + \frac{\varphi}{2}\right)$ $d_q = d_\gamma = 1 + 0.1\,tan\left(45 + \frac{\varphi}{2}\right)\,(\frac{D_f}{B})$
Hansen [39], Vesic [133]		For D_f /B ≤ 1: $d_c = 1 + 0.4\left(\frac{D_f}{B}\right)$ (for φ = 0^0) $d_q = 1 + 2\,tan\varphi(1 - sin\varphi)^2(\frac{D_f}{B})$ For D_f /B>1: $d_c = 1 + 0.4\,tan^{-1}(\frac{D_f}{B})$ $d_q = 1 + 2\,tan\varphi(1 - sin\varphi)^2 tan^{-1}(\frac{D_f}{B})$ $d_\gamma = 1$ [Note: $tan^{-1}\left(\frac{D_f}{B}\right)$ is in radians]

The previous section discussed the bearing capacity of unreinforced soils when the loads are vertically applied at the centre. Similarly, the bearing capacity of reinforced foundations when subjected to vertical loads at the centre is addressed in the following section.

2.3 Studies with planar reinforcement

Binquet and Lee [11] performed a pioneering study on the response of the reinforced foundation system with planar reinforcement. In the study, sandy soil was reinforced with aluminum strips under a strip footing of width 75 mm in a test tank of length 1500 mm.

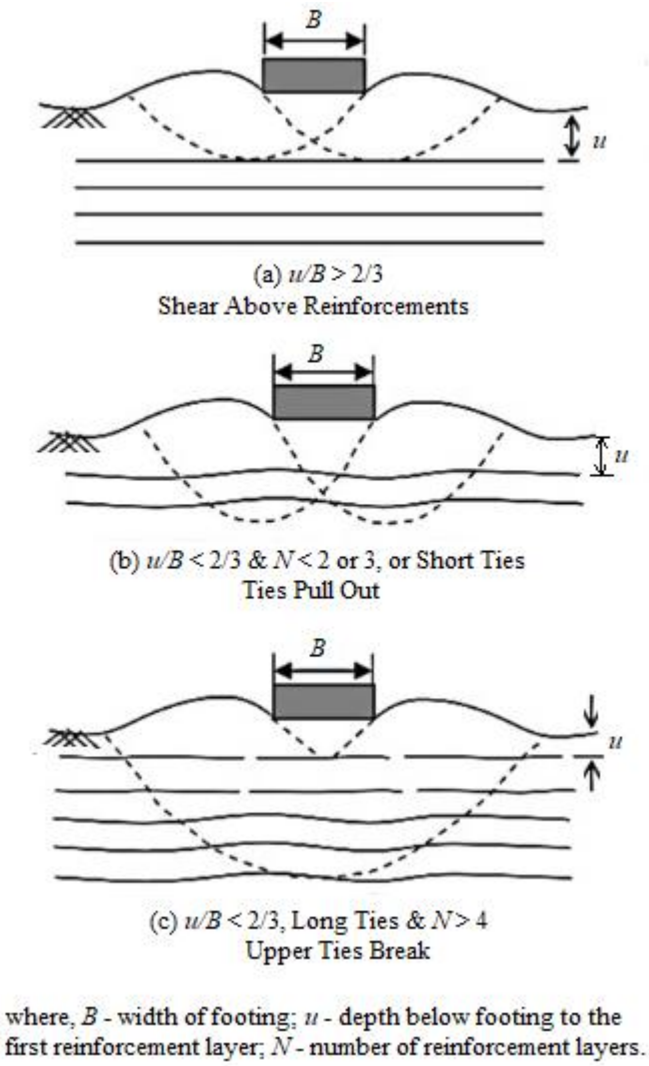

Fig. 2.1 Three modes of failure (after Binquet and Lee [11])

Three different foundation configurations were considered such as a deep homogeneous sand bed, a deep soft soil layer under the sand bed, and a deep finite pocket of very soft material under the sand bed. The study demonstrated three modes of foundation failure based on the placement depth of planar reinforcement such as “general shear”, “pull-out” (strips pull-out), and "tie-break" (tension), as shown in Fig. 2.1. The study also revealed that, with provision of planar reinforcement layer, the ultimate bearing capacity of sand could be increased by 2 to 4 times and settlement of sand could be reduced by 30%, as compared to unreinforced sand.

Akinmusuru and Akinbolade [2] studied the influence of vertical and horizontal spacing of reinforcement (reinforced with flat strips of rope fiber material) on the load carrying capacity of reinforced soil by undertaking laboratory tests in physical models. In performing these physical model tests the reinforcement was placed at different depths and in different numbers of layers. Besides, for all the tests, length of the reinforcements was kept constant (10 times the footing width). Based on the results of the tests, a maximum improvement of bearing capacity was observed when reinforcement layer was placed at a depth half the footing width. Any shallower depth of placement of reinforcement resulted in a decrease in performance of the footing, which was caused by insufficient overburden to provide adequate pullout capacity, resulting in early failure. Beyond a depth of 1.75 times the width of the footing, there was hardly any effect of the reinforcement on load carrying capacity of the soil. The ability of the foundation to support loads was almost the same for both horizontal and vertical spacing up to 0.5 times the footing width, after which, due to less confinement effect, there was a decline in the positive effect of the reinforcement. The researchers found that the maximum improvement in bearing capacity of reinforced sand foundation was 2.9 times that of an unreinforced sand foundation.

Fragaszy and Lawton [34] studied the influence of soil density (D_r = 51, 61, 70, 80, and 90%) and length of reinforcement strip on the load-settlement behavior of a rectangular footing. The material used for making the reinforcement in the study was metal aluminum strips. The study revealed that improvement was not dependent on soil density beyond a settlement level 10% of the footing width. The study also demonstrated that a marginal improvement in the bearing capacity of reinforced soil was obtained by increasing the length of reinforcement beyond 7 times the footing width.

Guido et al. [36] compared the performance of geogrid and geotextile reinforcement in a sand of 55% relative density. The parameters investigated were: depth below footing to the first reinforcement layer (u); vertical spacing of the reinforcement layers (z); number of reinforcement layers (*N*); width of the square sheet of reinforcement (*b*) and its tensile strength (*T*). In the study the performance improvement of bearing capacity was observed better for geogrid as compared to the geotextile reinforced earth slabs due to better interlocking of soil particles within the geogrid apertures. The improvement was also observed to be increased with reduction in the aperture size. The optimum values of the various parameters were found as $u = 0.25B$, $N = 3$, $b = 2\text{-}3B$ (*B*- footing width)

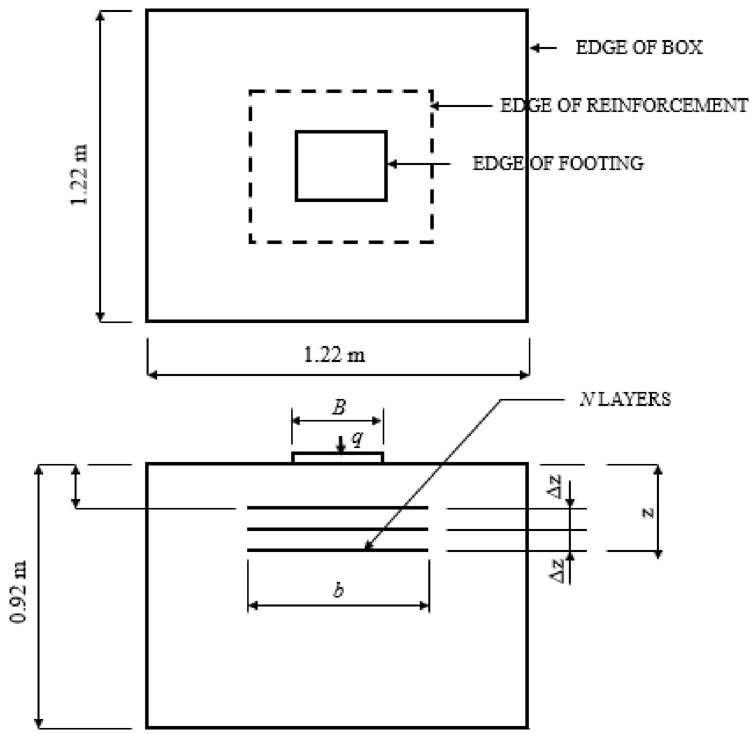

Fig. 2.2 Geometry of the model foundations (after Guido et al. [36])

Love et al. [76] performed a small-scale model test under plane strain conditions to determine the effectiveness of geogrid reinforcement placed at the sand-clay layer-interface. In the study, the undrained shear strengths (c_u) of the clay subgrades were considered as 6, 9, and 14 kPa. The experimental results indicated that with the inclusion of geogrid reinforcement there was a substantial decrease in stress on the clay sub-grade. It was observed that the reduction was depended on clay strength, and thickness and stiffness of granular layer. The study also demonstrated an additional benefit in bearing capacity due to 'membrane action' which was more significant only at large deformations.

Huang and Tatsuoka [48] conducted a series of plane strain model tests sandy soil with planar tensile-reinforcement material to understand the effects of length, configuration, rigidity, and rupture strength of the reinforcement. In the study a remarkable increase in bearing capacity were observed by placing the reinforcement just below the footing bottom, with length of reinforcement layers same as that of width of the footing. The investigations also revealed two types of mechanisms for increase in bearing capacity of a reinforced soil bed such as deep footing mechanism and wide slab mechanism. The reinforced zone behaved as part of a deep footing when densely reinforced. The reinforcement immediately under the footing bottom primarily contributed in the restraint of the potential planes of failure while the contribution of the reinforcement beyond the edge of footing was found to have only secondary effect. The wide slab mechanism was developed due to reinforcement provided beyond the edge of the footing. The study also demonstrated that the influence of stiffness of the reinforcement was negligible unless the reinforcement failed by rupture.

Mandal and Sah [82] carried out laboratory model tests on square footings supported by geogrid reinforced clay subgrade. In the study, the influence of placement depth of geogrid from the bottom of the footing was investigated. The study demonstrated a maximum BCR of about 1.36 when the geogrid was placed at a depth of 0.175 times the footing width from the base of the footing, beyond which it was found to decrease. The results also indicated a maximum reduction of settlement (*i.e.* 45%) with the introduction of the geogrid at a distance of 0.25 times the footing width from the base of the foundation.

Khing et al. [63] conducted a series of laboratory model tests to determine the ultimate bearing capacity of a strip footing supported by geogrid-reinforced sand. In the study maximum benefit was observed when the first geogrid layer was placed at 0.375 times the footing width from the base of the foundation. The investigations also revealed a very marginal increase in bearing capacity improvement factor when the width of geogrid reinforcement beyond 6 times the footing width.

Adams and Collin [1] conducted large scale model tests on geogrid and geocell reinforced foundations. The parametric study considered the number of reinforcement layers, vertical spacing, plan area of reinforcement, types of reinforcement and soil density. The improvement in BCR (2.6 times) was more significant when 3 layers of geogrid were used. In the study maximum benefit was observed when the top layer of reinforcement was placed within a depth of 0.25 times the footing width from the base of the footing. The study also revealed a higher improvement in bearing capacity for densely compacted sand when reinforced with a single layer of geogrid.

Sitharam and Sireesh [118] performed laboratory model tests to evaluate the bearing capacity of an embedded circular footing supported on geogrid-reinforced sand. The parametric study considered the effect of embedment depths of footing, surface deformations, strain in geogrid, and pressure distribution under the footing at 70% relative density of sand. In the study a highly localized strain in geogrid was observed just below the footing. Contrarily, almost negligible strain in geogrid was observed at about 2B from footing center. The study also revealed a higher load distribution and squeezing out of the sand from bottom of the footing in case of reinforcement placed at relatively lower depths. An improvement in bearing capacity of 3.0 folds as compared to unreinforced sand was found in the study.

Basudhar et al. [6] studied the performance of circular footing supported on geotextile-reinforced sand. Analytical and numerical analysis were performed to compare the experimental observations. The study highlighted the effect of footing size, reinforcement layer, reinforcement pattern, and relative density of soil on load-settlement response. Results showed a maximum of 5.5- fold improvement in bearing capacity with 3 layers of reinforcements.

Kazi et al. [61] performed laboratory model tests on the embedded strip footing supported on reinforced dense sand. Woven geotextile with and without wraparound ends was used as reinforcement materials. The parametric study considered the effect of number of reinforcement layers, embedment depth ratio, and wraparound ends. The study reported a substantial improvement in the load-carrying capacity and stiffness of the sand bed by increasing the number of reinforcement layers along with the provision of wraparound ends of the reinforcement.

Kou et al. [65] investigated the influence of planar reinforcement width on the pressure distribution around a flexible conduit under vertical load. The deflection of conduit and footing settlement against applied pressure were the two parameters studied in the model tests. In the investigation the reinforcement width was varied from B_c to $4B_c$; B_c was the diameter of the conduit. The test results showed an improvement in the load-carrying capacity of the footing due to the inclusion of a reinforcement layer. The study also highlighted that the reinforcement layer reduced the pressure on the crown and spring line of the conduit. Further, a better reduction of pressure on the crown and spring line of the conduit was reported by increasing the width of the reinforcement layer. The increase in the reinforcement layer also improved the reduction of both vertical and horizontal deflections of the conduit.

Singh et al. [114] carried out an experimental investigation to study the influence of placement depth of single-layer and double-layers of planar reinforcement in subgrade soil. In the study, the reinforcement layers were placed horizontally at different depths from the top surface of the subgrade soil. Three different types of geosynthetics reinforcements such as Glasgrid, Tenax 3D grid, and Tenax multimat were used in the experimental program. The investigators placed the single-layer reinforcement at three different depths such as at $H/2$, $H/3$, and $H/4$, where H is the height of the soil specimen from the top surface of the soil in the CBR mould. Contrarily, the double layers of reinforcement were placed at $H/4$ from the top surface and the bottom surface of the soil specimen. A substantial improvement in the CBR value of the soil and a reduction in the design thickness of the pavement layers above the subgrade soil were reported by the researchers. The study also revealed that for a single-layer reinforcement, the Tenax 3D grid performed better than the other two geosynthetics, while the Tenax multimat performed best for double layers reinforcement. An optimum placement depth of $0.3H$ to $0.36H$ and $0.41H$ to $0.62H$ were reported in the study for Tenax 3D and Glasgrid or Tenax multimat, respectively.

In several investigations, regression analysis was used to assess the correlation between the dependent and independent variables. Ranjan et al. [103], Bera et al. [8], and Latha et al. [72] used non-linear regression models to analyze the behaviour of foundations in terms of bearing pressures concerning various factors, such as layer thickness, footing settlements, reinforcement geometry, etc. The predicted behaviour was found to be in good agreement with the experimental results. An example of a regression model, as suggested by Bera et al. [8], is shown in Equation 2.5.

$$q_{rs} = a_{10} q_s^{a_{11}} \left(\frac{S}{B}\right)^{a_{12}} N^{a13} f^{a14} \left(\frac{L_S}{B}\right)^{a_{15}} a_{16}^{\frac{u}{B}} a_{17}^{\frac{S_v}{B}} \tag{2.5}$$

where, 'q_s' and 'q_{rs}' is the unreinforced and reinforced bearing pressures, respectively, at specific settlement level (*s/B*). The *B*, L_s, *N*, *f*, *u*, and S_v are the footing width, reinforcement lengths, number of reinforcement layers, friction ratio, depth of first layer reinforcement, and vertical spacing between the reinforcements, respectively. The a_{10}, a_{11}, a_{12}, a_{13} ... a_{ij}, etc. are the regression coefficients. Where '*i*' is the 'number of observations and '*j*' represents the 'number of independent variables or predictors'. The coefficient "a_{10}" (where *i* = 1 and *j* = 0) represents the regression coefficients for the first observation having the independent (or predictor) variable as '1' and creates the intercept term in the equation.

2.4 Studies with geocell reinforcement

Geocell reinforcement is a 3D, honeycomb-like structure made up of interlocking cells. The pioneering work of Rea and Mitchell [106], Webster [135], Webster and Alford [136], and Webster and Watkins [137] at the U.S Army Engineers Experiment Station has led to the development of commercially available geocells of the present day. The researchers carried out field tests using rectangular aluminum grids filled with beach sand on top of soft subgrade soil. The load applied was full-scale traffic. The results showed that the reinforced sand had significantly higher load-bearing capacity compared to the compacted soil alone. The behavior of the grid cell mattress was found to be similar to that of a slab. Based on these findings, it was concluded that using sand-filled grid cells on soft subgrade could provide performance equivalent to a layer of crushed stone that is 1.6 times thicker than the height of the geocell mattress.

Selected studies with reinforced foundations using geocell reinforcements (GR) are summarized in Table 2.3. The typical geometric configuration used in the majority of these studies is shown in Fig. 2.3. The parameters included are the diameter of geocell-pockets (*d*), the height of geocell reinforcement (*h*), the width of the geocell reinforcement (*b*), and placement depth of reinforcement below the footing bottom (*u*). In general, two types of soils, such as sand-sand, sand-clay, and clay-clay, are considered in most of the cases. However, as per general practice, the geocell- pockets are filled with granular materials such as sand or gravel.

Table: 2.3 Summary of research on various foundation types and geocell-reinforced foundations

Researchers	Research based on	Type of footing	GR material	Important scientific findings
Biswas et al. [12-13]; Dash [21-22]; Dash et al., [23- 29]; Hegde and Sitharam [41-43, 46]; Kargar & Hosseini [60]; Lal et al. [69]; Moghaddas Tafreshi & Dawson [90, 92];Nair and Latha [94]; Pokharel et al. [99]; Sireesh et al. [115]; Sitharam and Sireesh [118]; Sitharam et al. [119]; Tafreshi and Dawson [122-123]	Experimental Small scale (Plate load test)	Strip/Square/ Circle	Geogrid/ HDPE/ Geonet/ Jute Coir	1. The use of Geocell reinforcement (GR) in soil beds enhanced the bearing capacity (BC), and reduced the deformation and surface heaving of the footing; 2. The performance efficacy of GR was found higher as compared to planar reinforcement; 3. Optimum performance of GR occurred at about u/B = 0.1–0.2, b/B = 4–5 & $0.4 \le h/B \le 2$ where B = width of footing; b = width of geocell reinforcement; u = placement depth of geocell reinforcement from the bottom of the footing; h = height of geocell reinforcement.
Biabani et al. [9]; Dehkordi et al. [31]; Fazeli Dehkordi and Karim [33]; Guo et al. [37]; Leshchinsky and Ling [74]; Mehrjardi et al. [84]; Moghaddas Tafreshi et al.[91]; Shadmand et al. [111]; Shin et al. [113]; Tafreshi et al. [124-125]; Tanyu et al. [127]; Venkateswarlu et al. [131]; Wesseloo et al. [138]; Zhou and Wen [144]	Experimental Large scale (Plate load test)/Field test	Square/Circle	Non-woven/ HDPE	1. Significantly improved BC and settlement were observed due to the inclusion of GR 2. The outcome of large-scale tests showed that the principle of pressure-settlement behavior observed in the trials could be replicated in real-life projects. These findings would be useful in developing guidelines for the design and construction of geocell-reinforced foundations (GRF).
Avesani Neto [4-5]; Hegde & Sitharam [45]; Koerner [64]; Madhavi Latha et al.[79]; Maheshwari and Babu [81]; Moghaddas Tafreshi et al.[91]; Sitharam and Hegde [117]; Tang and Yang [126]; Zhang et al. [140-141, 143]	Analytical model	Strip/Square/ Rectangle	HDPE/ Non-woven	1. A few methods, including the equivalent composite method, composite beam design, and the Winkler model, could be used to determine the bearing capacity of GRF. 2. The BC of geocell-reinforced sand footings was calculated by considering three mechanisms such as confinement effect, load dispersion effect, and membrane effect.
Bathurst & Knight [7]; Latha et al.[70]; Madhavi Latha et al. [77]; Madhavi Latha & Rajagopal [78]; Mhaiskar & Mandal [89]; Sitharam and Hegde [117]	2D Numerical model	Strip/ Square/Circle	-	Numerical results showed that the stress and strain underneath the footing were reduced significantly by spreading the footing load over a wider surface area and confinement effect.
Biabani et al. [9]; Han et al. [38]; Hegde and Sitharam [44]; Latha and Somwanshi [71-72]; Leshchinsky and Ling [73-74]; Liu et al. [75]; Madhavi Latha and Somwanshi [80]; Saride et al. [110]	3D Numerical model	Square/Circle	-	1. The geometric configuration of GR had a significant influence on the load-bearing capacity and deformation of the soil bed; 2. Numerical simulation of multiple cells of GR with their actual shape could be performed to assess the load-bearing capacity of GRF

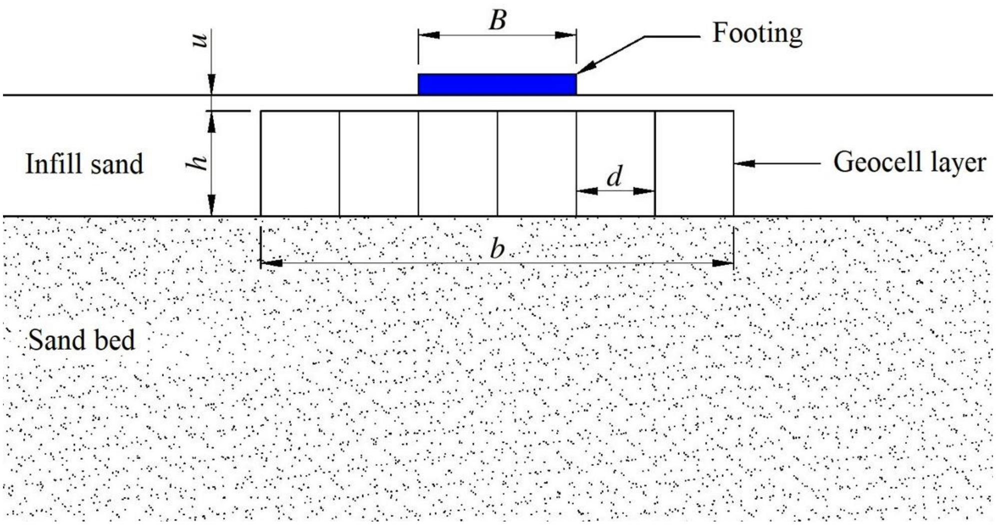

Fig. 2.3 Geometric parameters of a geocell-reinforced sand bed

Robertson & Gilchrist [108] reported the use of geocell mattresses as the most cost-effective solution for constructing a 4 m high embankment over a 4 m deep soft clay layer (c_u = 15 kPa). Considering the practical difficulty or a much longer construction period other ground improvement methods had been rejected, and economical appraisal was made only for the geocell mattress and excavation-replacement method. The cost comparison between these two methods showed a cost saving of 31% in the case of the geocell mattress method.

Cowland and Wong [20] conducted a comprehensive field study and construction of a road embankment reinforced with geocells on soft clay. The research found that after one year of completion, the average shear strength improved by 2-3 times compared to the original soil.

Koerner [64] proposed an empirical equation to calculate the ultimate bearing capacity of geocell-reinforced soil for centrally vertical-loaded footing. The confinement effect of the geocell reinforcement was incorporated into the empirical formula. The empirical equation was expressed below-

$$q_R = 2\tau + cN_c s_c + qN_q s_q + 0.5\,\gamma B N_\gamma s_\gamma \quad (2.6)$$

where, q_R = ultimate bearing capacity of geocell-reinforced sand, c = cohesion, q = surcharge load, B = width of applied pressure (footing), γ = unit weight of soil in failure zone, $N_c = N_q = N_\gamma$ = bearing capacity factors, $s_c = s_q = s_\gamma$ = shape factors, τ = shear strength between geocell wall and soil.

Mandal and Gupta [83] studied the efficacy of geocell-reinforced sand over soft clay. The schematic diagram of the test setup is shown in Fig. 2.4. In the study, different foundation configurations such as geocell opening size, and height were considered. The investigation revealed that the geocell exhibited a beam-like action up to a settlement of 5 - 10% of the footing width. However, they observed that a membrane action of the reinforcement was a more dominant parameter beyond 20% settlement. The authors reported a maximum bearing capacity improvement factor of 8.0 at h = 1.5B.

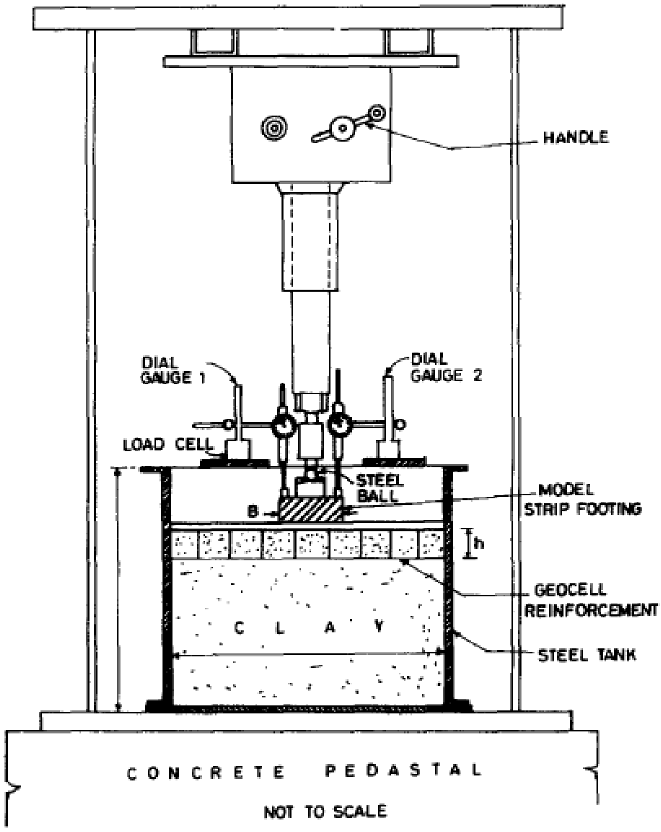

Fig. 2.4 Schematic diagram of the test set up by Mandal and Gupta [83]

Mhaiskar and Mandal [89] examined the effectiveness of using geocell reinforcement on soft clay subgrade through laboratory model tests and finite-element analysis. The parametric study considered the effect of various parameters such as the width, height of geocell, strength of geocell material, and relative density of the geocell infill sand. The experimental data was then modelled using a finite element software, ANSYS, which showed a close match with the results obtained from the tests. The study concluded that the use of geocell reinforcement leads to a significant increase in the load-bearing capacity and a decrease in the settlement of footing.

Krishnaswamy et al. [66] performed a series of small-scale model tests on geocell-supported embankments built on soft clay (c_u = 20 kPa). They used various types of uniaxial and biaxial geogrids to fabricate the geocells. The findings indicated that the load-bearing capacity was dependent on factors such as the pocket size, height, pattern of geocell formation, type of in-filled soil, and geogrid stiffness.

Dash et al. [23] carried out a comprehensive parametric study to understand the behaviour of geocell-reinforced foundations. The optimal values of various parameters as shown in Fig. 2.3, measured in terms of B, were found to be $u = 0.1B$, $h = 3.14B$, $b = 12B$, and $d = 1.2B$, resulting in a maximum eight times increase in bearing capacity. During the testing program, no visible failure was observed until the settlement reached 50% of the width of the footing. The study showed that the "Chevron pattern" of geocell arrangement was more effective than the "Diamond pattern." Further, about 30% more improvements in bearing capacity were reported with an additional planar reinforcement (geogrid) at the bottom of the geocell [24].

Dash et al. [29] investigated the effects of geocell-geometry and a base geogrid on the foundation behavior supported on soft clay beds (c_u = 3.13 kPa). The researchers reported a maximum improvement in bearing capacity about 7-fold by using optimum geocell geometry and a base geogrid. The optimum parameters were found to be $h = 1.68D$, $b = 5D$, and $d = 0.8D$.

Dash et al. [25] examined the comparative effectiveness of various reinforcements, such as geocell, planar geogrid, and randomly distributed mesh elements, when used in uniform sand with a constant D_r of 70% under strip loading. The study showed that the improvement in bearing capacity for foundations reinforced with randomly distributed mesh elements was about double that of the unreinforced bed, while it was four times greater with the planar geogrid and eight times greater with the geocell. The improvement was further increased by approximately 20% with the use of a base geogrid.

Sitharam et al. [119] conducted a series of laboratory model tests to evaluate the performance of geocell-reinforced clay (c_u = 5.6 kPa) foundation systems under the circular footing. The optimum performance of footing was observed by placing the footing directly over the geocell reinforcement layer (i.e. u = 0). Further, an additional 20% improvement in bearing capacity was achieved by placing a geogrid layer at the base of geocell reinforcement.

Sitharam et al. [116] carried out small-scale model tests to understand the behaviour of geocell-reinforced soft clay (c_u = 5.6 kPa) foundations under circular loading. In the investigation bearing capacity improvement factor (*IF*) and percentage reduction in footing settlement (*PRS*) were the two parameters used to quantify the performance improvement of the reinforced soil bed. The study reported an increase in the load-bearing capacity of the reinforced clay bed by about 4.5 times as compared to the unreinforced bed. The test results also revealed that a much stiffer foundation system could be achieved by using geocell reinforcement. It was reported that by placing geocell reinforcement just below the base of the footing 90% reduction of the settlement could be obtained. Further strength enhancement was observed by providing an additional planar geogrid layer at the base of the geocell reinforcement.

Dash et al. [27] examined the effect of height, width, pocket size, and embedment depth of the geocell layer on the subgrade modulus of geocell-reinforced sand foundations. The optimal values of u, b, h, and d were found to be 0.1, 12, 3.14, and 1.2 times B, respectively, leading to a maximum improvement of 8.2 times. Additionally, it was reported that the density of in-filled soil [21] and the aperture size and grid orientation of the geogrids used to fabricate the geocells [22] also played a key role in the performance of the foundation.

Palmeira & Tatsuoka [95] presented the advances in geosynthetic materials and their application in soil reinforcement and environmental protection projects. The researchers highlighted that the use of geosynthetic materials showed a better alternative to other conventional ground improvement methods due to the ease of construction and application, economy, and efficient environmental protection work.

Yoon et al. [139] studied the reinforcing effects of "Tirecell" in sandy soil. The tirecells were made from treads of waste tires. The schematic foundation configuration is reproduced in Fig. 2.5. The effects of the width of tirecells, the relative density of sand, the position of placement depth of the reinforcement layer from the bottom of the footing, and the numbers of reinforcement layers were the main parameters considered in the investigation. The study revealed that an improvement of bearing capacity of 2.5 times was observed in the case of loose sand while placing the reinforcement layer at 0.2*B* from the bottom of the footing.

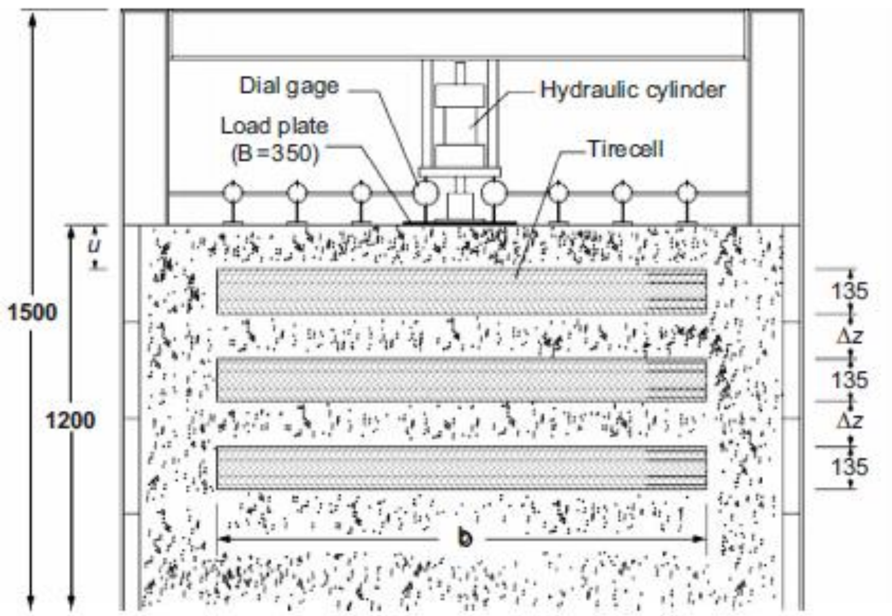

Fig. 2.5 Geometry of model tests used by Yoon et al. [139]

Zhou and Wen [144] investigated the strength enhancement of soft soil by providing a geocell-reinforced sand cushion. The researchers reported an increase in the subgrade reaction coefficient by 3000% due to the inclusion of the geocell layer. Further, an increase in improvement of the load-carrying capacity of soft soil was reported for geocell-reinforced sand cushion as compared to the non-reinforced sand cushion. Apart from the increase in the load-carrying capacity, a reduction in the settlement was also noted, with geocell reinforcement reducing the settlement by about 44%. The study also revealed that the geocell reinforcement produced more even settlement as compared to the geogrid reinforcement.

Sireesh et al. [115] performed the efficacy of a geocell-reinforced sand foundation system underlying a clay bed (c_u = 10 kPa) with a circular void. The different parameters varied were the thickness of the unreinforced sand layer, width, height of the geocell layer, and relative density of sand. A substantial improvement in load-bearing capacity with an increase in geocell height and density of the in-filled soil was reported in the investigation. The investigator also reported that the influence of the void became negligible when the height of geocells was greater than 1.8*B*.

Pokharel [97] carried out a series of large-scale plate load tests to evaluate the performance of geocell-reinforced soil under static and dynamic loads. A clear benefit of geocell reinforcement in terms of increased stiffness and bearing capacity was reported in the study. Further, the use of geocell reinforcement assisted the wider stress distribution and reduced the permanent deformation of soil under static and dynamic loads. About 2-fold improvement in bearing capacity was achieved by using Novel polymeric alloy geocells (NPA). The researchers also highlighted a higher stiffness and load-carrying capacity for the circular shape of the geocell as compared to an elliptical shape. Moreover, a substantial reduction in permanent deformation of the sand bed under cyclic load was reported by providing NPA geocells. The efficacy of the percentage of elastic deformation of geocell-reinforced soil bed increased with stronger infill materials as compared to the weaker fill material was also reported in the study.

Tafreshi and Dawson [122] carried out a comparative study to understand the behaviour of strip footings rested on planar and geocell-reinforced sand beds under a combination of static and repeated loads. Sinusoidal load cycles with 1 Hz frequency were used in the application of the load. The schematic diagram of the test setup is reproduced in Fig. 2.6. The study revealed better performance of footings supported on planar or 3D-reinforced sand as compared to unreinforced sand. Further, a better performance of geocell-reinforced sand was observed as compared to the planar reinforcement for the same mass of geotextile material used in the tests. A comparative study on behaviour of strip footings rested on planar and geocell reinforced sand beds with the same physical properties was investigated by Tafreshi and Dawson [123]. The different parameters varied were the reinforcement width, the number of planar layers of geotextile, and the height of the geocell layer below the footing base. A decrease in the efficacy of the geocell-reinforced foundation was reported by increasing the number of planar reinforcement layers, the height of the geocell layer, and the width of the reinforcement.

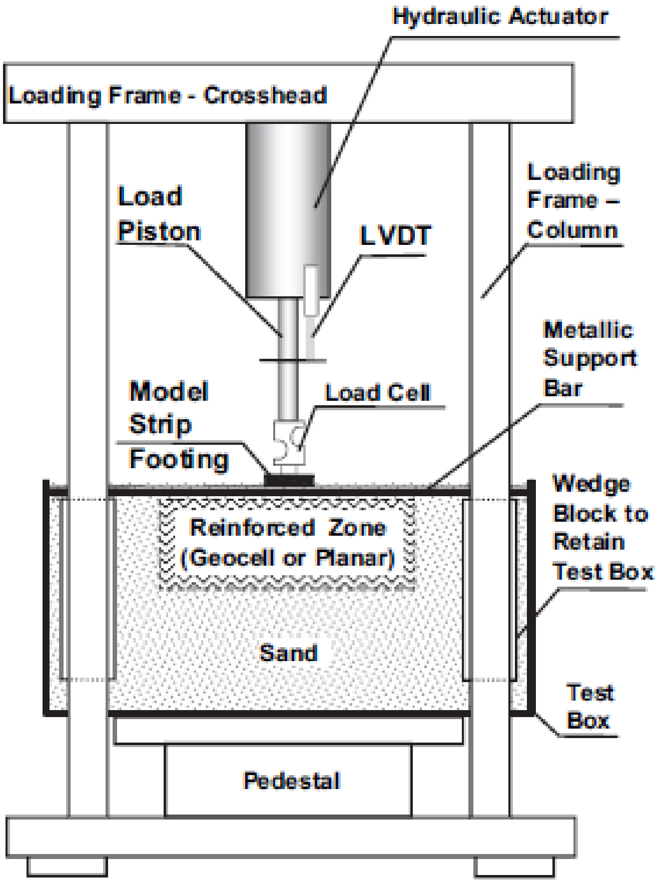

Fig. 2.6 Schematic diagram of the test set up by Tafreshi and Dawson [122]

Zhang et al. [141] suggested a calculation method for the bearing capacity of geocell-reinforced foundations, taking into account the lateral resistance, vertical stress dispersion, and membrane effect. The mechanisms defined are reproduced in Fig. 2.7. The results obtained from the developed empirical equation were verified by a laboratory experiment and Koerner's method [64]. The study reported that at the large settlement of foundations, the bearing capacity obtained from the developed empirical equation and laboratory experiment was almost similar compared to Koerner's method. The study also found that the use of geocell reinforcement on the crushed stone cushion significantly increased the bearing capacity of the soft subgrade.

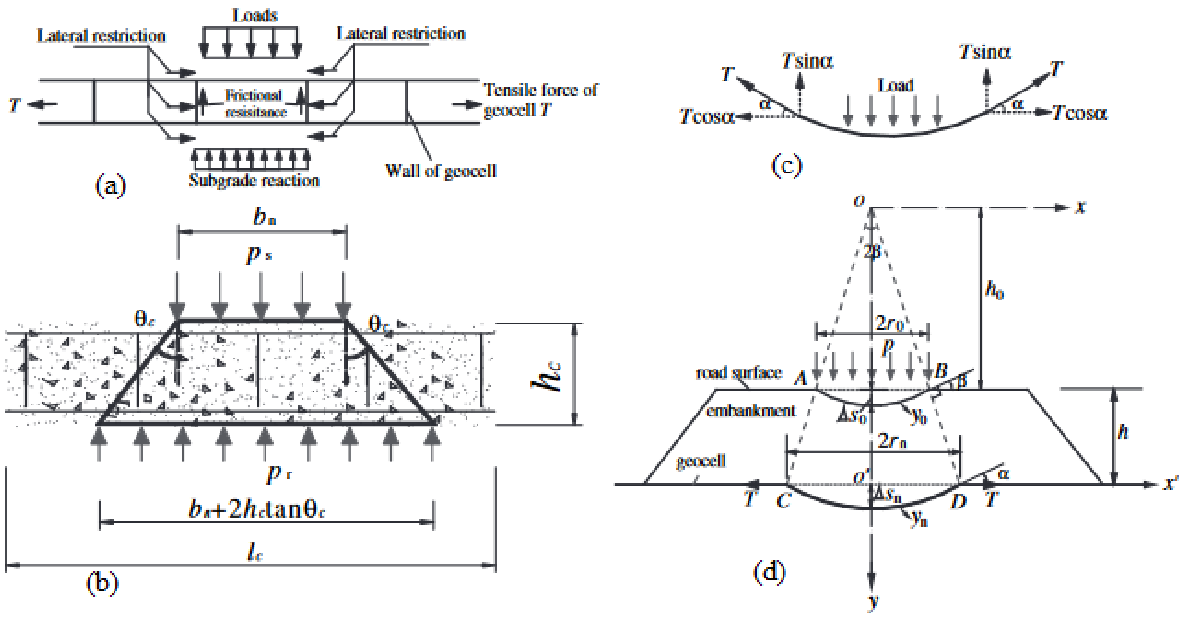

Fig. 2.7 Proposed bearing capacity calculation mechanisms by Zhang et al. [141]

Moghaddas Tafreshi and Dawson [90] conducted a comparative study on the response of strip footings supported by geocell-reinforced sand under a combination of static and cyclic loads. The cyclic load was applied with a 1 Hz frequency. In the study, a stable, resilient response was observed after the first 10 cycles of loading. Further, a decrease in the magnitude of final settlement and an increase in the cyclic load was reported by the researchers due to the use of geocell reinforcement. The investigators also reported a decrease in the reinforcement's efficiency in the reduction of total footing settlement as the height and width of the geocell increased.

Thakur et al. [130] studied the behaviour of geocell-reinforced recycled asphalt pavement (RAP) over a weak soil bed under cyclic plate loading. The cyclic load was applied with 0.77 Hz frequency. The study showed that geocell reinforcement reduced the vertical stresses transferred to the subgrade by distributing the load over a wider area. The investigators also reported the behaviour of thicker and thinner geocell-reinforced RAP bases as a "slab" and "tension membrane", respectively.

Avesani Neto et al. [5] suggested an empirical equation considering the effect of the bearing capacity of supporting soil and the geocell reinforcement mechanisms. The ultimate bearing capacity (q_R) of geocell-reinforced soil proposed by the researchers was as below:

$$q_R = p_u + 4\frac{h}{d} + K_0 pe\ tan\delta_s + (1-e)p \qquad (2.7)$$

where, $p_u =$ ultimate bearing capacity of unreinforced sand, p = load at the top of geocell mattress, γ_q = unit weight of soil within the geocell, $h =$ height of geocell, d = pocket size of geocell, $K_0 =$ coefficient of lateral earth pressure at rest, δ_s = angle of shearing resistance between infill soil and geocell wall, $e = \frac{BL}{(B+2d)(L+2d)}$, B = width of footing, L = length of footing.

Biswas et al. [12] performed small-scale model tests to study the influence of subgrade strength on the performance of geocell-reinforced foundation systems. A "chevron pattern" of geocell formation as shown in Fig. 2.8 was adopted to reinforce the foundation system.

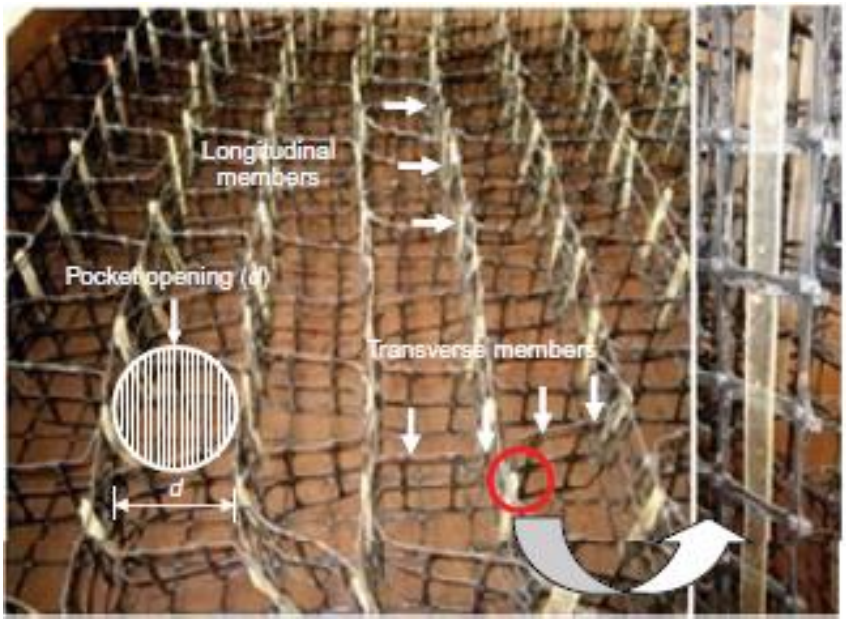

Fig. 2.8 Geocell mattress: chevron pattern, longitudinal and transverse members, pocket openings and bodkin joints by Biswas et al. [12]

The model tests were carried out with clay beds of different shear strengths (c_u = 7-60 kPa) and 80% relative density of sand. The thickness of reinforced and unreinforced sand layers was varied in the range of 0.63 to 2.19 *B* (*B* width of footing). A decreased bearing capacity improvement factor with the increase in subgrade strength was reported from the investigations. A maximum improvement of 11.57-fold for a very soft clay bed (c_u = 7 kPa) and 3-fold for a relatively stiff clay bed (c_u = 30 kPa) was observed after providing a geocell layer. Further, the authors reported an increased efficacy of the foundation system as the height of the sand or geocell-sand cushion layer over the clay bed was increased.

Tanyu et al. [127] conducted large-scale model tests to understand the behaviour of geocells in rutting and the resilient properties of a subbase in a pavement structure over a soft subgrade. The study found that geocells could reduce the plastic deflection of working platforms by 30-50%. Further, about 40-50% improvement in sub-base resilient modulus and about 2 times improvement in subgrade reaction was also reported in the study.

Hegde and Sitharam [43] conducted laboratory model tests and numerical studies to understand the behaviour of footing supported on geocell-reinforced sand and clay beds (Fig. 2.9). The experimental study utilized the commercially available geocells made from polyethylene with a pocket diameter equivalent to 0.25 m and an aspect ratio of 0.6.

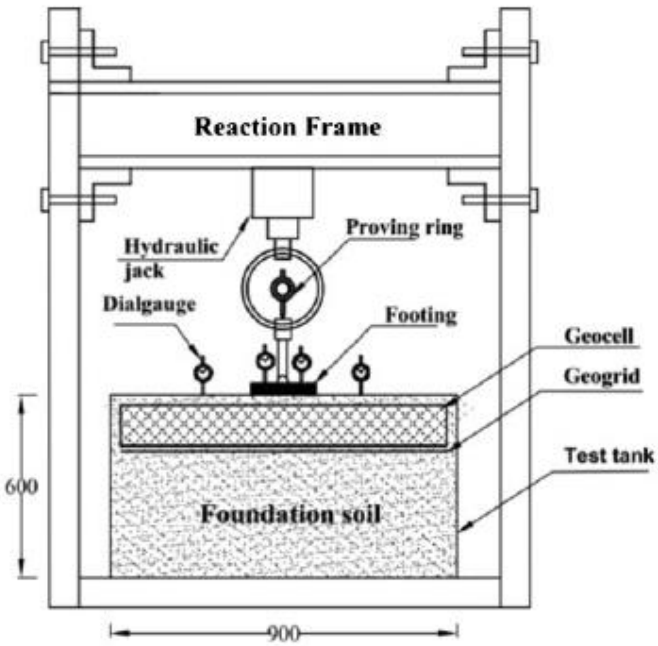

Fig. 2.9 Schematic view of the test set up by Hegde and Sitharam [43]

The test results revealed that the use of geocell increased the ultimate bearing capacity of the sand bed by 2.4 times and the clay bed by 3.2 times. The study also reported a complete arrest of surface heaving and prevention of rotational failure of footing by providing planar geogrid reinforcement at the bottom of the geocell mattresses.

Tafreshi et al. [125] investigated the performance of geocell-reinforced layers and rubber-soil mixture layers over soft soil beds under repeated load. The schematic cross-section of the test setup is shown in Fig. 2.10. The authors reported that the increase of geocell-reinforced layers and rubber-soil mixture layers decreases the loading surface deformation due to better load spreading of the composite system. In addition, the inclusion of a composite system prevented the punching shear and reduced the vertical stresses transferred to the foundation. The study also showed that a composite system was more effective than geocell layers alone in reducing the stress distribution down into the foundation under cyclic loading.

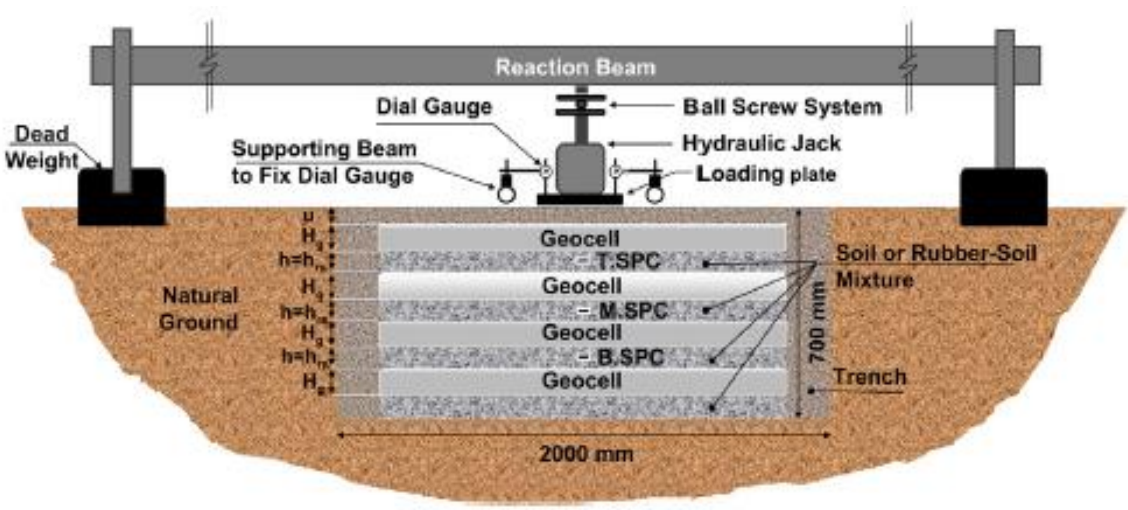

Fig. 2.10 Schematic cross-section of the test setup (not to scale) by Tafreshi et al. [125]

Indraratna et al. [49] performed large-scale cubical triaxial tests to investigate the behavior of geocell-reinforced and unreinforced sub-ballast under cyclic loads. The study found the significant influence of geocells on the sub-ballast performance under cyclic loading. The effect was pronounced at low confining pressure under high frequency (10-30 Hz) of loading.

Hegde and Sitharam [42] carried out a 3-D numerical analysis of geocell-reinforced soft clay beds by considering the actual geometry of geocell pockets**.** The study revealed that the tensile strength of geocell materials played a vital role in imparting the strength of the foundation beds as compared to other properties. The bearing capacity of foundation soil increased with an increase in the geocell height, angle of repose of infill materials, and decrease in the geocell pocket sizes as observed in the study. Moreover, further improvements in the performance of reinforced clay beds by virtue of the membrane effect were reported by the provision of additional geogrids below the geocell. The effect of infill materials on the performance of geocell-reinforced clay beds was investigated by Hegde and Sitharam [41]. The improvement in load carrying capacity of geocell-reinforced bed was observed to be increased by 13 times, 11 times, and 10 times for the aggregate, sand, and red soil infill materials, respectively.

Khalaj et al. [62] conducted a large-scale field test to understand the improvement of pavement foundation response with multi-layer geocell reinforcement under cyclic plate loads. The study showed a significant effect of stress reduction on pavement foundations due to the use of multilayer geocell reinforcement.

Nair and Latha [94] conducted laboratory model tests to study the performance of unreinforced and geocell-reinforced unpaved road sections under repeated loads. Less permanent settlements and more elastic settlements were reported for geocell-reinforced systems as compared to unreinforced systems. The study also showed that the performance improvement of reinforced soil increased with increase in the height of the geocell. However, this increase in performance improvement was observed up to a certain limit of geocell height, beyond which the performance improvement decreased with increase in geocell height.

Suku et al. [121] investigated the performance of geocell-reinforced base layers under repeated loads with a 1 Hz frequency. The amount of reduction of permanent deformation was reported to be more for the reinforced layer with higher aggregate layer thickness. The study also revealed that the reinforced layers achieved maximum rut depth reduction compared to the unreinforced layer.

Kargar and Hosseini [60] conducted a model-scale test to understand the effect of reinforcement geometry on the performance of strip footing supported on geocell-reinforced sand. The parametric study considered the height, pocket size, and width of geocell reinforcement. Substantial increases in the beneficial effect of geocell reinforcement were reported by increasing the height and decreasing the pocket size of the geocell. The study also reported the optimum width of geocell reinforcement as five times the width of footing. Besides, the authors reported that the ultimate bearing capacity of geocell reinforced sand decreased while substituting a single layer of geocell with multiple geocell layers (i.e. single geocell layer = 2 half of the geocell layer or 4 half of geocell layer).

Venkateswarlu et al. [131] conducted large-scale field tests and numerical analysis to study the performance of geosynthetic reinforced soil beds supporting machine foundations (Fig. 2.11).

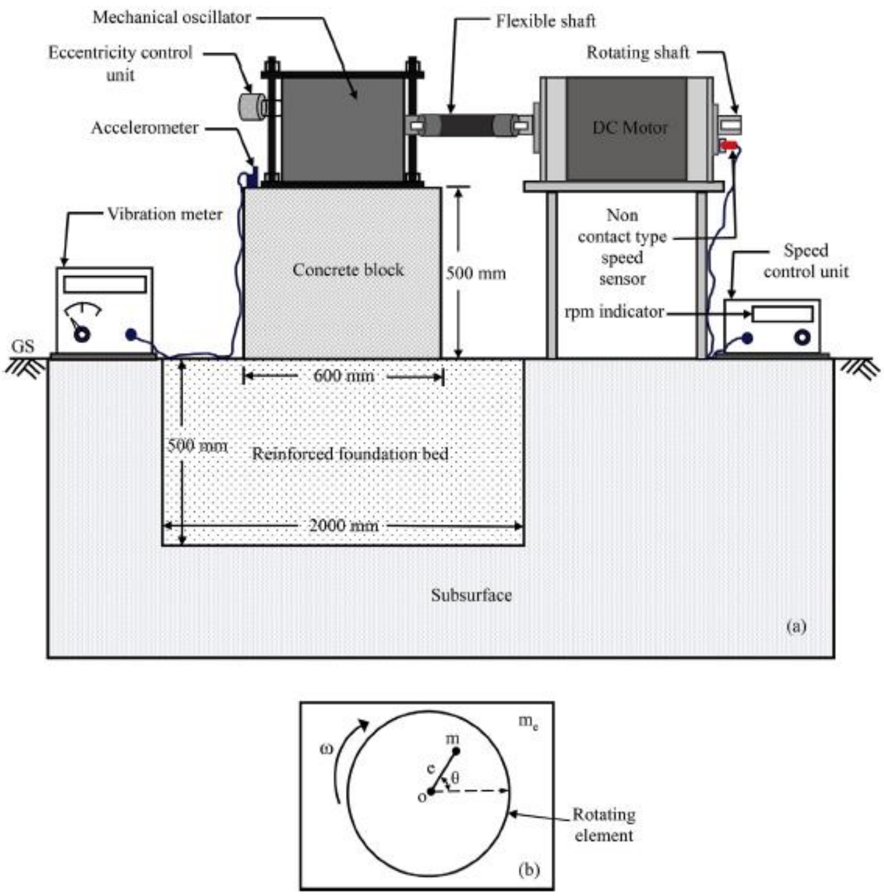

Fig. 2.11 Block vibration test setup (a) Schematic representation (b) rotating mechanism of a mechanical oscillator by Venkateswarlu et al. [131]

Significantly reduced displacement amplitude of vibration was reported with the inclusion of geosynthetics in the study. The study also showed that the use of geocell reinforcement results in decreased resonant amplitude by 61% and increased natural frequency of the soil system by 1.38 times as compared to unreinforced soil.

Muthukumar et al. [93] investigated the performance of square footing rested on jute geocell-reinforced sand. The parametric study considered the depth of the sand cushion above geocell (u), the width of geocell (b), and the height of geocell (h) concerning the width of footing (B). In the study, they reported the optimum value of u, b, and h as $0.1B$, $4B$, and $0.6B$, respectively. They also reported 3.5 times higher bearing pressure with the inclusion of jute geocell reinforcement as compared to the unreinforced soil.

Hegde and Palsule [40] conducted an experimental and numerical analysis to study the performance behaviour of planar and 3D geosynthetics reinforced-sand subgrade under cyclic loads. The laboratory model tests were carried out by applying a cyclic load of magnitude 275 kPa with 1 Hz frequency. The test results revealed that a significant improvement in subgrade sand could be attained by introducing geosynthetic material. It was reported that a three-fold reduction in footing settlement could be obtained with the provision of reinforcement in subgrade sand. The authors also reported that the use of geosynthetic reinforcement completely arrested the surface heaving of subgrade sand. Further, better performance for 3D reinforcement as compared to planar geogrids was reported in the study.

George et al. [35] conducted large-scale repeated load tests to study the effectiveness of HDPE geocell-reinforced reclaimed asphalt pavement bases (GRRB). The schematic diagram of the large-scale laboratory setup is reproduced in Fig. 2.12. It was reported that the HDPE geocell layer increased the resilient modulus of the recycled asphalt pavement (RAP) base layer by 2.5–3.3 times as compared to the unreinforced RAP bases. It was also observed that the HDPE geocell layer reduced the permanent deformation of the RAP base by 70–80% as compared to unreinforced RAP bases.

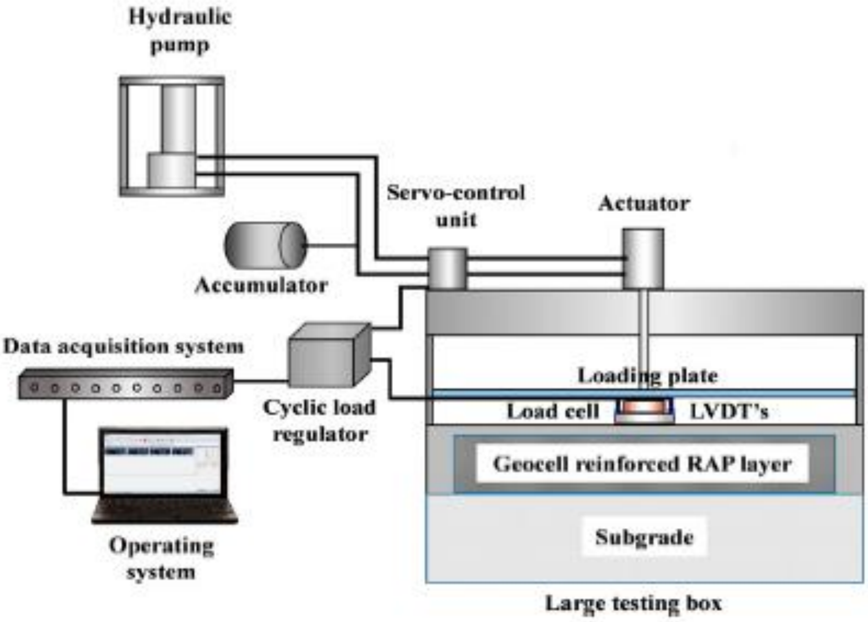

Fig. 2.12 Schematic diagram of the large-scale laboratory test setup by George et al. [35]

2.5 Summary of literature review and scope of the present study

Generally, the use of reinforcement in any form showed a significant performance improvement of soil in terms of an increase in load-carrying capacity and a reduction in settlements. The studies with geocell-reinforcement proved to be a better alternative to other conventional soil-strengthening techniques, in terms of improved load-carrying capacity and deformation characteristics, ease of construction and application, economy, and environmental perspective. The geocell reinforcement indicated greater improvements as compared to the planar or randomly oriented reinforcement. In general, about 2-8 folds improvements in load-carrying capacity and about 20-50% reduction in the settlement were reported by introducing geocell reinforcement. It was observed that the performance of the foundation systems increases with geocell height and width. However, the improvement was marginal for $h > 1.5B$ and $b > 6B$. The performance was decreased with an increase in geocell-pocket size (d). The optimum placement depth (u) of the geocell-mattress was found to be 0.1-0.3B below the footing. Similarly, as the planar reinforced foundations, mostly softer clay subgrade having c_u in the range of 3-50 kPa and loose to medium dense sand having a relative density of less than 70% were considered for geocell-systems.

A wide range of research has been reviewed on geocell-reinforced soil with various types of foundation configurations under monotonic loading. It is observed that most of the previous studies (Biswas et al. [12], Dash et al. [23-24, 28-29], Hegde and Sitharam [41-43], Krishnaswamy et al. [66], Sitharam et al. [119]) were focused on the performance of geocell reinforcement under a single shape of footing i.e., either circular, square or strip footing. The studies are mostly related to the performance benefits of a single type of footing on geocell-reinforced soils. Nevertheless, no studies have been performed to understand the effect of the shape of footing on geocell-reinforced soils. Since, in practice, different shapes of footing may be required to support a structure, therefore, it is important to understand the effect of shapes of footing in geocell-reinforced soils.

In a geocell-reinforced foundations system, various geocell geometry such as geocell pocket size (*d*), the height of geocell layer (*h*), the width of geocell layer (*b*), depth of placement of geocell layer (*u*), stiffness of reinforcement layer (*k*), and relative density of infill sand ($D_{r,\ infill}$) was the primary concern of studies. Although several studies (Dash et al.[23, 27-29], Kargar and Hosseini [60], Krishnaswamy et al. [66], Mandal and Gupta [83], Mhaiskar and Mandal [89], Muthukumar et al. [93], Sireesh et al. [115], Tafreshi and Dawson [123]) were carried out to understand the effect of such parameters on the performance of geocell-reinforced sand beds under static loads. However, most of those studies were related to geocell made from geogrids or factory-made geocells of polymeric materials. Moreover, in earlier studies, the influence of relative density of subgrade sand (D_r) was not considered on the performance behaviour of geocell-reinforced sand beds.

Concerning the behaviour of geocell-reinforced sand under repeated loading, in most of the previous studies (Hegde and Palsule [40], Indraratna et al. [49], Khalaj et al. [62], Suku et al. [121], Tafreshi and Dawson [122], Tafreshi et al. [125], Thakur et al. [130]), the focus was on low to high frequency (i.e. 0.5 Hz to 30 Hz) repeated loads. However, there are some structures like petroleum tanks, water tanks, parking yards, etc. where the frequency of loading and unloading is very low (< 0.1 Hz). Further research is, therefore, required to understand the behaviour of geocell-reinforced sand beds under repeated loads at very low frequencies. Moreover, there is a need of research to understand the effects of various parameters such as *d*, *h*, *b*, *u*, and D_r on the performance of geocell-reinforced sand under repeated loads.

Further, an extensive review of the literature indicated that only a few researchers [5, 64, 141] had attempted to propose an empirical method for predicting the bearing capacity of geocell-reinforced sandy soil. Hence, there is a need for research to develop a simplified formula (considering the influencing parameters) for the prediction of the bearing capacity of geocell-reinforced sand, so that practicing engineers can easily estimate the values for preliminary design work.

To address the aforementioned research gap, this study deals with a series of laboratory load tests conducted to investigate the effect of various parameters such as footing shape, the relative density of sand subgrade, geocell geometric dimensions, and relative density of infill sand (in the geocells) on the performance of geocell-reinforced sand under static and repeated loads. The study aims at a better understanding of the benefits of the use of geocells beneath the footing and determines the most influencing parameters for best usage under static and repeated loading.