Tikrit Journal of Engineering Sciences

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Review of the Behavior of Geogrid-Reinforced Sand Soil Supported a Shallow Footing under Different Loadings

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Abstract:
The soil can be subjected to different static loads, i.e., centric, eccentric, and inclined, and dynamic loads, i.e., repeated and seismic. Under such loads, the soil can suffer from deterioration of the soil bearing capacity, extensive deformation, and rotation. Soil reinforcement is a technique that enhances the soil response by acting as a tensile member, thereby increasing soil shear strength and improving soil performance, which in turn prevents foundation failure. Geosynthetic materials are the widely utilized reinforcing elements that include geotextile, geocell, and geogrid. Geogrid is a geosynthetic member consisting of ribs and apertures to allow interlocking with the soil. The present paper overviews the use of geogrid as a reinforcing element in sand soil supporting shallow foundations, particularly under various types of loads, including static, dynamic, and seismic. The research introduces soil-foundation reinforcement, geogrid reinforcement, and the parameters influencing the geogrid reinforcement. It also discusses the mechanism of reinforcement and the failure associated with reinforcing the soil supporting shallow footings. Furthermore, the study examines both static and dynamic loads, encompassing both experimental and numerical research. The expository data analysis is applied in the present study to analyze the available studies. The results showed that geogrid is effective in enhancing the soil performance when subjected to the different static and dynamic loads when installed with the optimum parameters. The parameters that influence the geogrid response are the depth of the first geogrid layer (u/B), the depth, width, and the number of geogrid layers (h/B), (b/B), and N, which are 0.2-0.5, 0.2-0.3, 3 to 4, and 3, respectively.

Keywords:
Geogrid parameters; Sand; Reinforcement; Static and dynamic loadings.

Highlights:
- Geogrid reinforcement improves the soil performance under static and dynamic loads.
- The effectiveness of geogrid reinforcement is influenced by u/B, h/B, b/B, and N.
- The geogrid enhanced the bearing capacity and reduced the settlement.

Article History:
Received: 18 Jul. 2024
Received in revised form: 29 Aug. 2024
Accepted: 22 Oct. 2024
Final Proofreading: 08 Sep. 2025
Available online: 10 May 2026

https://doi.org/10.25130/tjes.33.1.9

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Citation:
Al-Khafaji R, Shafiqu QSM. **Review of the Behavior of Geogrid-Reinforced Sand Soil Supported a Shallow Footing under Different Loadings**. *Tikrit Journal of Engineering Sciences* 2026; **33**(1): 2270.

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1.INTRODUCTION

Shallow footings are the most widely used types of foundation for buildings, retaining walls, and other lightweight structures throughout the world. By comparing spread footings to other foundation solutions like piles and caissons, spread footings are frequently the preferable choice [1]. The basic principle guiding the design of shallow foundations is to provide sufficient contact area between the soil and foundation, ensuring that any loads imposed on the foundation can be adequately supported by the underlying soil without experiencing failure or excessive settlement [2]. In some cases, the foundation and the underlying soil may experience an increase in settlement, rotation, and deterioration of shear strength due to being subjected to excessive loadings, eccentric loads, and dynamic loads such as impact loads, repeated loads, and seismic loads. In such cases, the soil performance should be enhanced to meet the requirements of bearing capacity and settlement. One of the newest and fastest-growing methods in geotechnical engineering is soil reinforcement. Through friction at the interlocking area between the reinforcing element and soil, the reinforcement is capable of controlling soil settlement and rotation and improving the soil bearing capacity [3]. A reinforced soil foundation (RSF) is a composite of layers of strips or sheets of reinforcing elements and soil strong enough to withstand a significant amount of tensile stress, limit the settlement, and rotation. Therefore, the primary purpose of reinforcement is to absorb the tensile stress that develops in the soil by interaction [4]. The most commonly utilized reinforcing materials with soils are polymeric materials commonly referred to as geosynthetics. Geogrid is the widely popular form of geosynthetic products that has been utilized to increase the bearing capacity and decrease settlement of shallow foundations [5]. Obtaining the optimum performance of geogrid requires installing it under optimal parameters, including the depth of the first geogrid layer, the vertical distance between successive layers, the width, and the number of geogrid layers. The present paper provides an overview of the utilization of geogrid as soil reinforcement for sand soil supporting shallow foundations subjected to various loadings, including static centric, eccentric loads and inclined loads, as well as dynamic loads such as impact and seismic loads.

2.RESEARCH SIGNIFICANCE

This article provides a summary of the performance of the geogrid-reinforced sand soil supporting shallow foundation when experiencing different static and dynamic loadings. For more than 30 years, since the development of the soil reinforcement concept, researchers have been interested in the issues associated with the bearing capacity, settlement, and rotation of shallow foundations, and have been trying to optimize the soil reinforcement using geogrid. Hence, they have extensively examined the ideal configurations of the geogrid reinforcement that gave the highest improvement, represented by strengthening the soil and the supporting foundation, and minimizing the deformation and the rotation during the different applied loads. This study provides a helpful guideline for the usage of geogrid in soil reinforcement, offering in-depth knowledge of the performance of geogrid-reinforced sand soil supporting shallow foundations. So far, a few short reviews have been reported for the use of geogrid-reinforced sand soil under static and dynamic loads. While covering the most up-to-date relevant research publications, this article pays extra attention to the influence of the geogrid-reinforced sand soil under different applied loads, including static and dynamic loadings. It represents a state-of-the-art comprehensive review, providing a thoughtful understanding of the topic for engineers in the industry and researchers in academia. To the best of the author's knowledge, there is a lack of comprehensive reviews on the use of geogrid as a reinforcing element in soil, employing a unique approach to address the contradictory findings present in the existing literature. In addition, this paper discusses recent publications that were covered in earlier review articles. A systematic literature review strategy was employed to compile a comprehensive body of published literature. Several research databases were used for this review, including Scopus, Web of Science, and Google Scholar. Following the collection process, statistical analysis was conducted to classify the examined parameters of geogrid reinforcement, their impacts, and the ability to improve the soil-foundation performance and the extent of effectiveness. Researchers investigated the soil reinforcement, including metallic and geosynthetic reinforcement, geogrid reinforcement, the parameters influencing geogrid reinforcement under different loadings, the mechanism of geogrid reinforcement, and the expected failure of reinforced sand soil and foundation, based on current literature. The review was divided into several subsections. The first subsection introduces the geogrid reinforcement and the reinforcement techniques. The second subsection describes the parameters influencing the soil reinforcement. The third subsection illustrates the reinforcement mechanism and the failure associated with reinforcement. The fourth subsection reviews the experimental and numerical studies conducted on the geogrid-reinforced sand soil under static and dynamic loads. The fifth subsection presents a critical analysis and discussion of the studies in subsection 6, utilizing statistical analysis to apply exploratory data analysis methods, including Histogram and quantity-quality plot (Q-Q plot) techniques.

3.REINFORCED SOIL FOUNDATION

3.1.The Principle of Soil Reinforcement

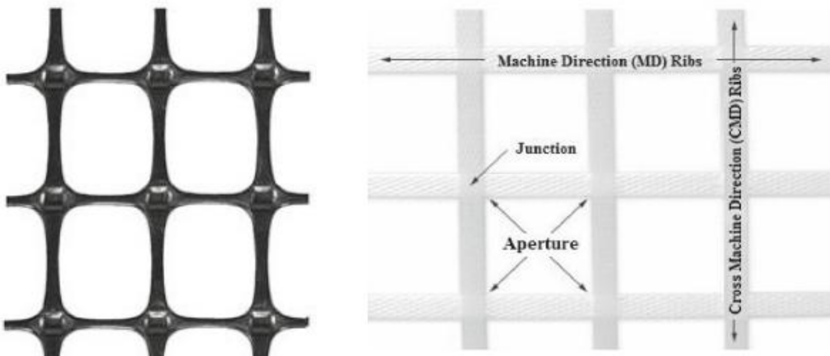
Reinforced soil, which is the soil being stabilized mechanically, is a composite material comprising soil and tensile elements, such as metallic strips, geonet, geocomposite geotextiles, or geogrids [6]. The primary benefits of soil reinforcement are providing shear resistance and tensile strength, resulting from the friction developed at the interlocking surface between the soil and the reinforcement. This method is applied explicitly in sandy soils to mitigate the impact of excessive loads on the soils and foundations, subsequently regulating the bond at the interfaces between soil and reinforcement [7]. Numerous studies have been performed to investigate the performance of shallow footings supported by geogrid-reinforced sand soil since the mid-1970s. These research efforts aim to understand how the bearing capacity and settlement characteristics can be enhanced when reinforcing materials are installed in the soil subjected to various loadings. [8].

3.2.Metallic and Geosynthetic Reinforcement

In the field of reinforcement, the soil was reinforced almost exclusively by using metallic materials due to their strength, stiffness, cheapness, and resistance to creep deformation. Nevertheless, the use of metallic reinforcement is associated with one outstanding problem, which is the difficulty in precisely predicting the corrosion rate during the cycle life of the structure. To alleviate such difficulty, non-metallic materials made of one or a combination of polymers have been adopted as reinforcing elements [6]. These materials are produced with strength and deformation characteristics that are mainly governed by the specific polymer and the fabrication process, resulting in the end product. Nevertheless, the non-metallic materials generally have less strength and more extensibility than the metallic reinforcement. The significant advantage of a polymer is that it has no corrosion problem. The most common polymeric materials used in soil reinforcement are geosynthetics [9]. As per ASTM 6637-01 [10], geosynthetics are products fabricated from polymeric substances utilized in conjunction with soil, rock, earth, or other elements as an integral component of a man-made project, construction, or system. The primary geosynthetic materials employed in building include geocomposite, geotextile, geogrid, geonet, and geocell. Among these, geocomposite, geotextile, and geogrid are commonly used as reinforcing materials. Improving the soil performance by reinforcement with geosynthetics stands out as a practical solution for enhancing the mechanical properties of weak and low-quality soil. Geogrids, in particular, are increasingly applied in various earthen structures, including retaining walls, embankments, pavements, and beneath foundations. This utilization aims to enhance the overall performance of these structures, especially in areas prone to seismic activity.

3.3.Geogrids

A geogrid is a polymeric, i.e., geosynthetic, substance with parallel sets of tensile ribs and apertures large enough to permit the striking through of surrounding soil, aggregates, stones, or other geotechnical substances, see Fig. 1. Geogrids are mostly used for reinforcing purposes [9]. Geogrids are produced through the tensile drawing of polymer substances with high modulus, like polypropylene and polyethylene. The first manufacturer of geogrids was Netlon Ltd. from the United Kingdom. Geogrids were first presented in the US in 1982 by the Tensar Corporation, which is now known as Tensar International Corporation.



Biaxial geogrid

Geogrid's rib formation in machine and cross machine directions during manufacturing process

Fig. 1 Biaxial Geogrid with Typical Dimensions [9].

In general, there are three categories of geogrids: uniaxial, biaxial, and tri-axial, see Fig. 2. The three main manufacturing processes for commercially available geogrids are extruded, welded, or extruded [11]. The geogrids are fabricated through the draw and punch of a thick polyethylene sheet to create apertures, thereby enhancing the mechanical properties of the ribs and nodes, and are referred to as extruded geogrids. In order to create woven geogrids, polymeric materials, normally polyester and polypropylene, are combined, woven into a mesh configuration, and then covered with a polymeric fabric. Polymeric strip junctions are fused to manufacture welded geogrids. The extruded geogrid is the most commonly utilized type of geogrid [7]. The nominal rib thicknesses of the commercial geogrids currently available on the market for soil reinforcement are approximately 0.6-1.5 mm, and the joints are approximately 2.5-5 mm. Openings or apertures of the grids are typically rectangular or elliptical. The aperture sizes range from around 25 to 150 mm. The open area of geogrids is manufactured to occupy more than 50% of the total area. Geogrids with triangular apertures (Fig. 2(c)) have recently been introduced for use in building. A polypropylene sheet is punched and then oriented in three essentially equilateral orientations to produce geogrids with triangular apertures that have a high degree of molecular orientation [12].

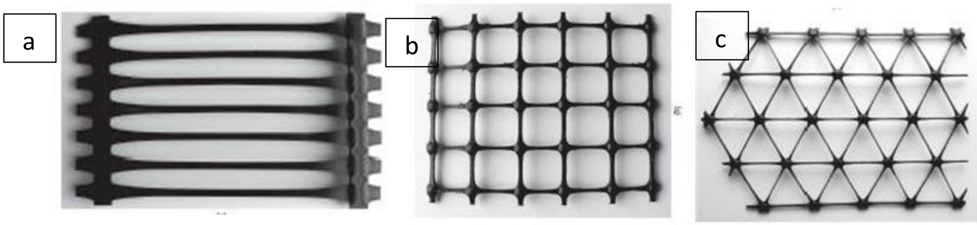


Fig. 2 Different Types of Geogrids (a) Uniaxial, (b) Biaxial, and (c) Triangular [11].

4.PARAMETERS OF GEOGRID REINFORCEMENT

The principal parameters affecting the behavior of reinforced foundation soil (RFS) include the depth of the first reinforcement layer, the vertical space between successive layers, and the length and the number of reinforcement layers. The effects of the aforementioned elements on enhancing soil performance are investigated in the literature as follows:

4.1.Depth of Initial Reinforcement Layer (u)

The ratio of the initial geogrid layer to the foundation width (u/B) is referred to as the depth ratio. It is indicated that the decrease in the value of u/B results in improvement in the final bearing capacity (BC) of a shallow foundation. As the top layer spacing increases, the bearing capacity ratio (BCR) values at the ultimate loads often drop. The u/B ratio is directly correlated with the bearing capacity (BC). The BC improves by utilizing an optimum value of u/B [13]. Selecting a suitable value for the vertical distance of the first layer is crucial to have sufficient overburden to generate adequate friction at the soil-reinforced interface. The influence of the geogrid becomes practically negligible when the ratio of the depth of the first layer exceeds the limited range, since the soil acts as unreinforced soil as the reinforcement is placed out of the shear failure zone [14].

4.2.The Vertical Spacing between the Geogrid Layers (h)

It is referred to as the vertical distance between the successive geogrid layers. When the value of (u/B) is optimum, it can be shown that the BCR improves. The selection of the optimum h value is also influenced by other parameters, including the number of reinforcing layers, the depth of the first geogrid layer, and the width of the geogrid reinforcement.

4.3.The Width of Reinforcement (b)

Numerous experiments have been conducted to examine how the BCR and ratio of the width to footing width (b/B) change for foundations supported by sand of various densities.

4.4.Number of Geogrid Layers in the Soil (N)

It represents the number of geogrid layers that need to be placed in the soil to achieve the optimum performance. The number of geogrid layers is associated with the other parameter mentioned previously. Different layers of geogrid are usually placed within the soil to achieve the best response.

5.MECHANISM OF GEOGRID REINFORCED SOIL

5.1.Reinforcement Mechanism

Soil reinforcement mechanism by geosynthetics involves describing how geosynthetic elements take the applied stresses and transform them, in addition to the types of stresses. Shukla and Yin [15] indicated that the reinforcement action occurred by four significant effects, as follows:

- Shear stress reduction effect: The shear stresses transmitted from the overlying soil are minimized by geosynthetics. This action is referred to as the shear stress reduction effect that leads to general shear failure in the soil instead of the local shear failure (Fig. 3(a)). Thus, it caused noticeable improvement in the bearing capacity of the soil-foundation system.

- Confinement effect: By restraining the movement of the granular soil, geosynthetic elements redistribute the applied load or restrain the granular fill and the soft soil if installed at the interface, resulting in a reduction in the normal stress on the underlying foundation soil (Fig. 3(b)). It plays a significant role in strengthening the soil due to the friction developed between the soil and the reinforcement element.
- Membrane effect is developed when a membrane tensile force is produced in the deformed geosynthetics that resist the normal and shear stresses (Fig. 3(c)).
- Interlocking effect: The use of geogrid adds another effect that assists in resisting the applied stresses, which is the interlocking effect. It developed due to the interlocking of the soil with the geogrid apertures, as shown in Fig. 3(d).

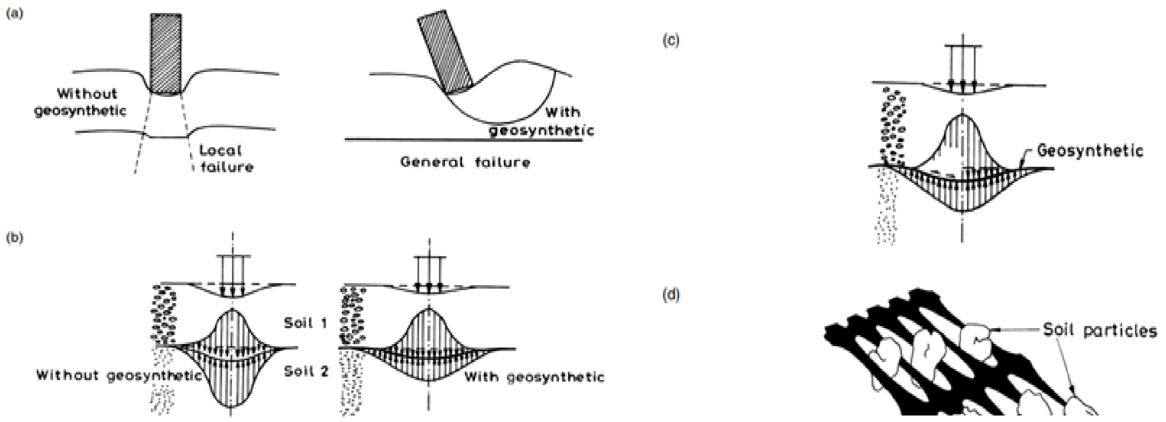


Fig. 3 Mechanisms of Soil Reinforcement: (a) Shear Stress Reduction Effect, (b) Confinement Effect, (c) Membrane Effect, and (d) Interlocking Effect [15].

5.2.Failure Mechanism of the Reinforced Soil-Foundation

Reinforced soils are characterized as mechanically stable substances, as opposed to those relying on chemical additives for soil enhancement. By adjusting the stiffness and bearing capacity of the footing, its mechanical strength is consequently increased. The mechanism of reinforcing soil primarily relies on the interaction between the sand soil and the geosynthetic reinforcement. This interaction manifests as shear resistance between the soil and the plane surface, passive resistance between the soil and the lateral surface, and interfacial shear within the aperture of the grid, i.e., on the surface of the rupture zone established during shearing [16]. These mechanisms contribute to the formulation of various theories explaining failure mechanisms, which include the following:

a) Deep foundation failure: A semi-rigid zone forms just beneath the foundation when the geogrid width equals the footing width (B), and this occurs at the area under the last layer of reinforced material. Failure zones become apparent beneath this zone, as shown in Fig. 4(a).

b) Wide slab failure, where the width of the triangular zone exceeds the foundation's width by 2B (Fig. 4(b)).

c) Bearing capacity failure occurs in the distance between the base of the footing and the top layer of reinforcement when the ratio of $u > 2/3$ B, see Fig. 4(c).

d) Pull-out failure occurs due to placing the reinforcement layer at a shallow depth with insufficient anchorage, which happens when $u < 2/3$ B and the number of layers is less than 3, see Fig. 4(d).

e) Breaking of reinforcement occurs when $u/B < 2/3$ and the reinforcement is long, heavy, and shallow, causing breaks under the edge or toward the center of the foundation, see Fig. 4(e).

f) Creep failure: occurs because of the long-term settlement due to the persisting surface load, see Fig. 4(f) [17].

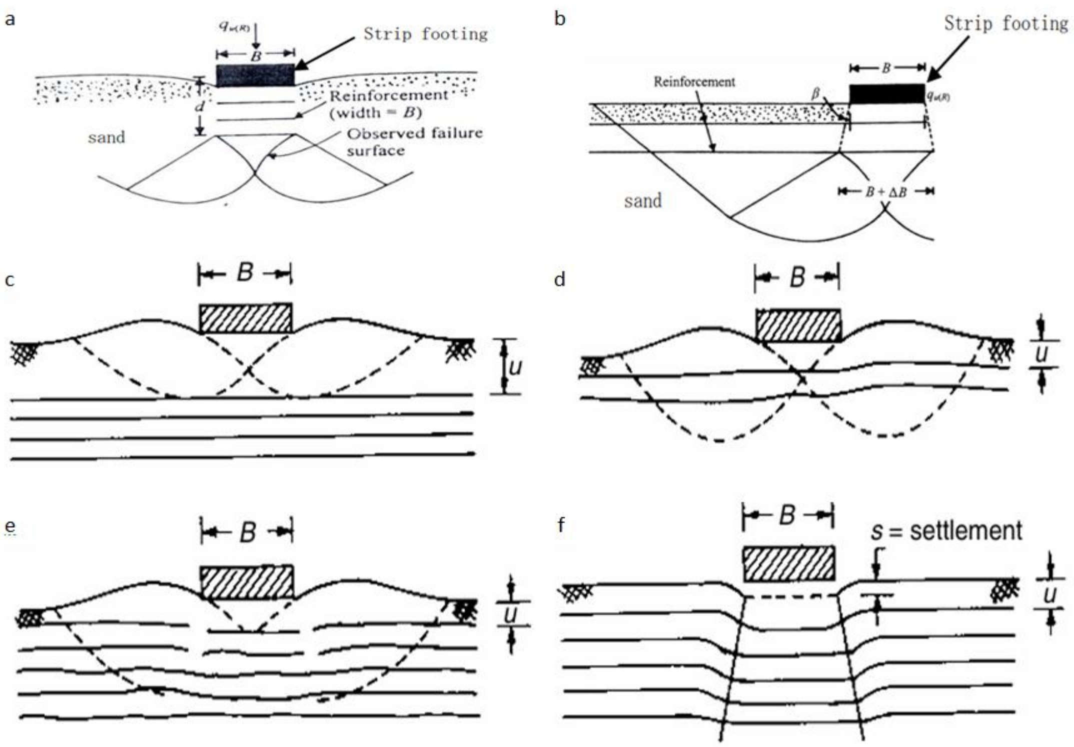


Fig. 4 Different Types of Failure of Reinforced Soil (a) Deep Foundation, (b) Wide Slab, (c) Bearing Capacity, (d) Pull-Out Failure, (e) Breaking of Reinforcement, and (f) Creep Failure [16].

6.THE USE OF GEOGRID IN SOIL REINFORCEMENT UNDER DIFFERENT LOADINGS

6.1.The Experimental Studies

The use of geogrids in reinforcing sand soil was examined experimentally by Omar et al. [18], who examined the bearing capacity of the strip and square foundation. The study indicated that the maximum bearing capacity for the soil supporting square foundation can be achieved when the width of geogrid (b) is 4.5 B and for the strip foundation when 8B and the depth of the first geogrid layer (u/B) not exceeding 1 and the vertical distance between the successive layer (h) =0.33B (B: footing width). Meanwhile, Adams et al. [19], in their static examination for the bearing capacity and settlement of the shallow foundation founded on geogrid-reinforced sand soil, proved that the optimum u/B, h/B, and the optimum number of geogrid layers (N) are 0.48, 0.25-1.5, and 4.5, respectively. Boushehrian et al. [20] found that the optimum u/B and h/B values for the circular footing of a reinforced foundation are not unique; instead, they depend on the number of geogrid layers. Also, the selection of the rigid reinforcement would not result in a significant improvement in the soil-foundation performance. Patra et al. [21] demonstrated in their examination of bearing capacity that the soil response increases with the depth of embedment of the geogrid, and the optimum values of u/B, h/B, and b/B are 0.35, 0.25, and 5, respectively. These values have been confirmed by Shrigondekar and Ullagaddi [22], indicating that the optimum number of geogrid layers is 4, beyond which no further improvement can be gained. Yetimoglu and Saglamer [23] examined the bearing capacity of a foundation with a rectangular cross-section resting on geogrid-reinforced soil by conducting experimental and numerical investigations. The influence of different geogrid parameters, such as the depth of the initial layer, the vertical space between the layers, and the number and the width of the reinforcement layers, on the bearing capacity of the shallow foundation was examined. The results revealed that there is an optimum number of geogrid layers, i.e., 4 layers, beyond which no significant increase in the bearing capacity occurs, and a significant distance between the geogrid layers (0.2 B to 0.4 B, where B: footing width). In addition, the increase in the geogrid stiffness beyond these limits caused an unnoticeable enhancement in the bearing capacity. Alamshahi and Hataf [24] studied the performance of geogrid-reinforced sand soil supporting a rigid strip foundation built on a sand slope. Various parameters were examined, including geogrid types, vertical distance, the depth to topmost geogrid layers, and the number of geogrid layers (see Table 1). The results were analyzed to indicate the quantitative and qualitative relationships between the bearing capacity and the geogrid parameters. In addition, a prototype study was conducted using the finite element method. The results showed that installing geogrid reinforcement at the appropriate place enhances the bearing capacity of the foundation considerably. The optimal depth of the first geogrid layer and the vertical distance between the successive layers were 0.75 B (B: footing width), and two layers of geogrid are sufficient. Also, it was found that the grid-anchor is better than the ordinary geogrid. In addition, there is good agreement between the experimental and the numerical studies.

Table 1 The Geogrid Parameters Examined in the Study [24].

N	u/B	h/B	Test ID
1	0.5	–	15
	0.75	–	175
	1	–	11
2		0.5	255
	0.5	0.75	2575
		1	251
		0.5	2755
	0.75	0.75	27575
		1	2751
		0.5	215
	1	0.75	2175
		1	211
3		0.5	355
	0.5	0.75	3575
		1	351
		0.5	3755
	0.75	0.75	37575
		1	3751
		0.5	315
	1	0.75	3175
		1	311

Phanikumar et al. [25] conducted a series of experimental load tests on fine, medium, and coarse sand soil reinforced with geogrid supporting a shallow circular foundation subjected to various vertical loads. Table 2 summarizes the compressive load (N) applied in various conditions for a settlement of 0.5 mm. The results showed that the load-settlement response of the geogrid-reinforced soil was enhanced. The vertical load required for 0.5 mm settlement was 87 N for dense, 84 N for medium, and 83 N for loose conditions in reinforced sand. In contrast, in the case of unreinforced sand, it was 63 N, 38 N, and 47 N for loose, medium, and dense states, respectively. The results also showed that the increase in the number of geogrids (n) and the decrease in the spacing of geogrids caused an increase in the bearing capacity. Latha and Somwanshi [26] conducted an in-depth investigation into the bearing capacity of sand soil reinforced with geosynthetics, supporting a square footing measuring (150 × 150) mm. The investigation incorporated a range of influential factors, encompassing the geosynthetic material's type and tensile strength, the quantity of reinforcement, and the arrangement of geosynthetic layers beneath the footing. Four geosynthetic types—strong biaxial geogrid, weak biaxial geogrid, uniaxial geogrid, and a geonet—each characterized by distinct tensile strengths, were employed in the experimental setup. Test results varied regarding the width, number, and depth of the geosynthetic layers within the reinforced zone, as well as the depth of the reinforced zone below the footing. The results emphasized that the best reinforcement performance happened at a reinforcement layer width that was 2 to 5 times as wide as the footing, and that the ideal distance between geosynthetic layers was half the footing's breadth. The results also indicated that the bearing capacity enhancement was significantly influenced by the arrangement and configuration of reinforcement compared to the geosynthetic material's tensile strength. Similar observations were obtained by El Sawwaf and Nazir [27], indicating that the BC significantly increased with the increase in width of the geogrid layer up to a width equal to 5 B, above which no appreciable contribution to the ultimate load can occur.

Table 2 Details of the Reinforcement and the Sand Soil Used in the Study [25].

Sand			Compressive vertical load (N)	Enhancement (%)
		unreinforced	63	-
Fine sand	Reinforced	n=1, u=10 mm	63	32
		n=1, u=20 mm	67	6
		n=2, u=10 mm s=10 mm	94	49
		n=2, u=10 mm s=20 mm	90	43
		n=3, u=10 mm s=10 mm	95	57
Medium sand		unreinforced	38	-
	Reinforced	n=1, u=10 mm	44	16
		n=1, u=20 mm	41	8
		n=2, u=10 mm s=10 mm	46	21
		n=2, u=10 mm s=20 mm	44	16
		n=3, u=10 mm s=10 mm	49	29
Coarse sand		unreinforced	47	-
	Reinforced	n=1, u=10 mm	87	85
		n=1, u=20 mm	69	47
		n=2, u=10 mm s=10 mm	110	134
		n=2, u=10 mm s=20 mm	94	100
		n=3, u=10 mm s=10 mm	148	215

Maheshwari et al. [28] studied the seismic response of the saturated sand soil reinforced with a geogrid sheet using a shaking table system. The geogrid was placed in various arrangements, as shown in Fig. 5. The results showed that the inclusion of geogrid decreased the liquefaction of the saturated sand since the placement of geogrid decreased the developed pore water pressure because of the reduction in the interstitial pressure distribution and the increase of the angle of internal friction of the sand soil with geogrid reinforcement. The highest improvement in the soil resistance was achieved with five layers of geogrid, resulting in a 31% increase at 0.1 g acceleration.

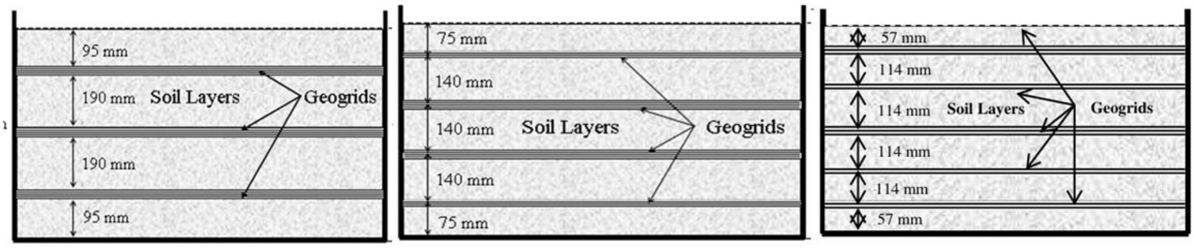


Fig. 5 The Geogrid Configurations [26].

Saran et al. [29] examined the liquefaction resistance of geogrid-reinforced sand soil with a relative density of 25% using a vibration table. The geogrid used in the study was biaxial and placed in 3, 4, and 5 layers. The liquefaction parameters examined in the study were the maximum pore water pressure (Umax), maximum pore water pressure built-up time (t1), and pore water pressure dissipation time (t3). Various levels of acceleration were applied, ranging from 0.1 g to 0.4 g. The frequency of the dynamic load was kept at 5 Hz at each test. The results showed that the placement of geogrid in the sand soil caused a decrease in Umax, t1, and t3. The results also showed that the increase of geogrid layers to 5 improved the liquefaction performance by approximately 31%. Senapati and Maheshwari [30] studied the deformation of Solani River soil in dry and saturated states reinforced with geogrid under cyclic load using a shaking table system. The soil samples were prepared to a dimension of (1.05 × 0.6 × 0.6) m. The shaking table produced horizontal shaking at different frequencies and accelerations, as shown in Fig. 6. The results indicated that the placement of geogrid reinforcement reduced the volumetric strain. It also showed that pore water pressure and settlement decreased with reinforcement, and the level of improvement increased with the use of 2 to 4 layers. It was also found that the variation of volumetric strain of unreinforced and reinforced soil increased as the loading cycles increased. In addition, the study proved that the geogrid was very effective in dry and saturated soils under cyclic loading.

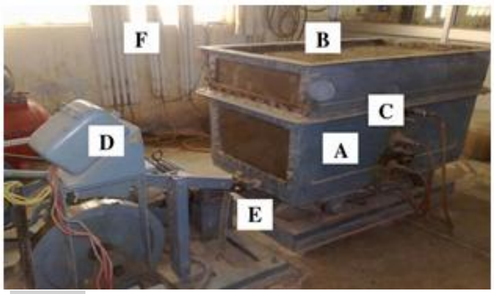


Fig. 6 The Shaking Table System and its Components [29].

Fattah et al. [31] investigated the role of geogrid-reinforced soil in transferring dynamic load to the underground structure represented by a PVC pipe of 110 mm in diameter placed in sandy soil. A physical model was created to investigate the response of soil, foundation, and underground tunnel to dynamic loading, as shown in Fig. 7. The soil had a relative density of 40%, the applied harmonic load was 0.5 tons, and a frequency of 2 Hz. The geogrid was placed at 0.5B, 1B, and 1.5B, with a width of 1B (B: footing width). The results showed that pressure above the crown of the tunnel decreased by approximately 14% to 33% with geogrid reinforcement. Also, it was approved that the settlement be reduced by 13% to 20% with geogrid reinforcement.

Fig. 7 The Model Setup [31].

Singh et al. [13] indicated that when (u/B) was relatively low, the BCR enhanced with the increase in the number of layers. When (u/B) exceeded 0.2, the BC increased somewhat as the number of geogrid layers increased. Better adjustment in bearing capacity of shallow footing is achieved by using a biaxial geogrid rather than a uniaxial geogrid. For instance, with the use of two uniaxial geogrids, the BC rose from 1.9 to 2.6, while using two layers of biaxial geogrids, the BC increased from 3 to 3.3. Maximum load intensity was reported to be 796 kN for one layer of geogrid, and it was enhanced to 1981 kN with four layers of geogrid. The highest BCRs were 5.38 for N=2, 6.21 for N=3, and 6.87 for N=4. Meanwhile, Shrigondekar and Ullagaddi [22] found that the ultimate bearing pressure was at its highest value when the vertical spacing between the geogrid layers was in the range of (0.25-0.4) B. Wang et al. [32] conducted a series of cyclic loading studies on shallow foundations with and without geogrid reinforcement, as shown in Fig. 8. The geogrid was examined with different parameters, such as the depth of the first geogrid layer (u), which ranged from 0.3 to 0.6 and 0.9, in addition to the different number of geogrid layers. The static loads applied were 160 kPa with a frequency of 2 Hz. The results proved that the geogrid was effective in decreasing the dynamic response and increasing the bearing capacity, particularly in the wraparound arrangement, as shown in Fig. 8(b) and (c). The result also showed that the optimum depth of the first geogrid layer in the dynamic study was similar to that in the static research, which was 0.3B. In addition, the incorporation of geogrid reinforcement did not alter the failure mechanism of the shallow foundation.

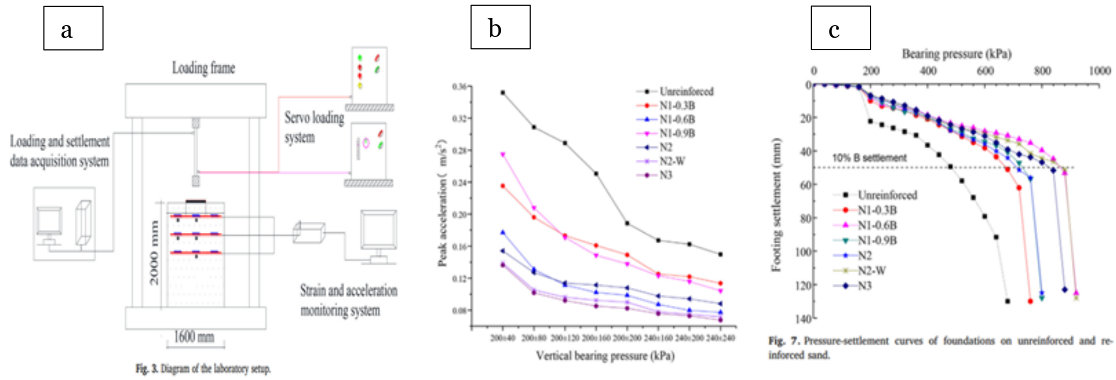


Fig. 8 (a) Test Setup, (b) Peak Acceleration, and (c) Footing Settlement of Soil with and without Reinforcement [13].

Badakhshan and Noorzad [33] examined the response of a circular foundation subjected to eccentric loads founded on geogrid-reinforced sand soil with a relative density of 60%. The geogrid parameters tested in the study included the vertical distance between geogrid layers and the number of layers (1 to 4), as well as different load eccentricities (0, 0.75, 1.5, 2.25, and 3) cm. The results showed that the optimum response of the foundation was obtained with u/B and h/B of 0.42B, and the optimum number of geogrid layers was 3. The results also showed that the local shear failure was the failure mechanism in both unreinforced and reinforced soil. The bearing capacity of the sand subjected to eccentric load was less than that under centric load in the unreinforced and reinforced cases. Rowshanzamir and Karimian [34] used different geogrid configurations as soil reinforcement for sand soil supporting a shallow foundation. The geogrid configuration used in the study was uniform (UR), trapezoidal with three layers (T1) and trapezoidal with four layers (T2), and inverted trapezoidal with three layers (IT1) and inverted trapezoidal with four layers (IT2), as shown in Fig. 9. The results showed that the reverse trapezoidal reinforcement layouts gave better and more appropriate coverage of the failure zone in limit equilibrium based methods. Hence, it results in higher improvement in the bearing capacity. Also, (IT1) gave the most significant bearing capacity because placing lengthy layers of geogrid at the upper levels close to the foundation caused higher efficiency of bearing capacity enhancement, followed by (UR), then (4IT). The lowest enhancement was obtained with (T2), followed by (T1), due to the placement of smaller-sized layers at the upper levels. The increase in the number of geogrid layers to 4, with relatively the same total area as that of the 3 layers, was ineffective.

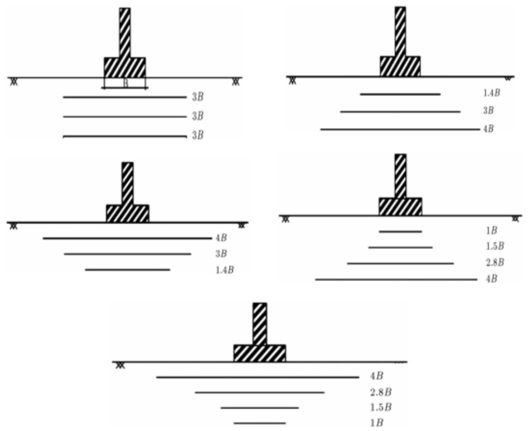


Fig. 9 Shallow Foundation with Different Reinforcement Configuration (a) Uniform (UR), (b) Trapezoidal with 3 Layers (T1), (c) Inverted Reinforcement with 3 Layers (IR1), (d) Trapezoidal Reinforcement with 4 Layers (T1), and (e) Inverted Trapezoidal with Four Layers (IT2) [34].

Cicek et al. [35] examined various parameters that may influence the soil response, including the width of the reinforcing element, the types of reinforcement, and the number of layers. Three types of geogrid and one geotextile were examined, as detailed in Table 3. The results were assessed based on load-settlement and bearing ratio (BR). The vertical spacing of the first geogrid layer (u/B) = 0.35 and the vertical distance between the layers (h/B) = 0.4. The results showed that increasing the reinforcement width noticeably improved the load-settlement and BR, as shown in Fig. 10. Furthermore, the results indicated that the load-settlement and BR of the reinforced soil were noticeably higher than those of the unreinforced soil. Geogrid 2 and geogrid 1 showed the highest improvement among the reinforcing elements, while geogrid 3 showed the lowest improvement. The results revealed that the optimum width of the geogrid layers was 5B. The optimum number of geogrid layers was 3 to 5 layers.

Table 3 The Properties of the Geotextile and the Geogrids [35].

Property	Geotextile	Geogrid 1	Geogrid 2	Geogrid 3
Material property	Polypropilen	Polyester	Polyester	Polypropilen
Type	woven	woven	woven	extruded
Ultimate tensile strength (kN/m)	60	35	55	45
Tensile strength for 2% strain (kN/m)	11	9	11	12
Tensile strength for 5% strain (kN/m)	25	15	24	30
Mass per unit area (g/m²)	310	220	300	390
Aperture size (mm)	–	20×20	40×40	14×70

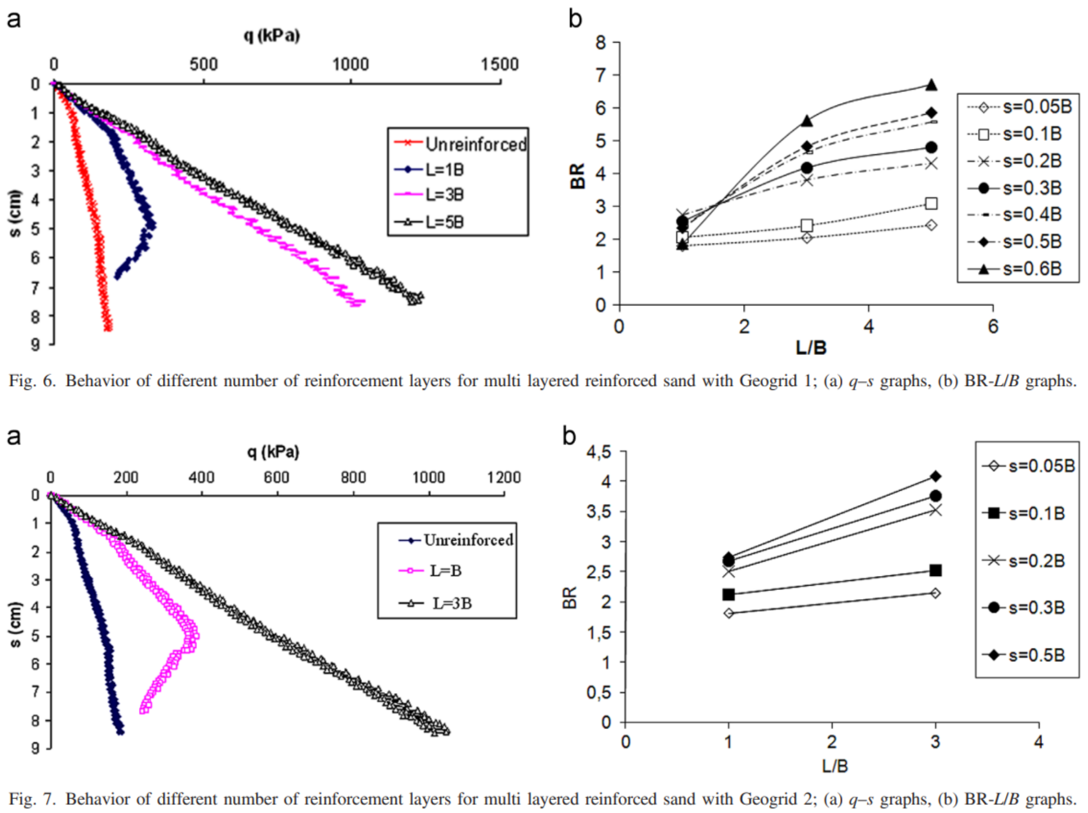


Fig. 10 The Load Settlement and the BR of Geogrid 1 and Geogrid 2 [35].

An experimental and numerical investigation on geosynthetic-reinforced soil beds supporting a model machine foundation was conducted by Venkateswarlu et al. [36]. Within a test pit of 2 m × 2 m × 0.5 m, testing for vertical mode block resonance was conducted on a rigid concrete base laid over different conditions of reinforced soil. The dimensions of the concrete footing were 0.6 m × 0.6 m × 0.5 m. The research investigated four distinct conditions: unreinforced, geocell reinforcement, two-geogrid layer reinforcement, and single-layer geogrid reinforcement. The outcomes revealed that the displacement amplitude of vibration was substantially decreased due to the incorporation of geosynthetics. The most significant reduction was noted with geocell reinforcement in comparison to other conditions. In particular, when compared to the unreinforced state, geocell reinforcement resulted in a 1.38-fold rise in the natural frequency of the soil system and a 61% drop in resonant amplitude. Furthermore, numerical analyses employing the FLAC3D finite difference software corroborated the experimental results. The numerical and experimental experiments demonstrated a considerable correlation in the dynamic performance of the soil reinforced with geosynthetics. The numerical outcomes demonstrated that the inclusion of geocell and geogrid reinforcement significantly controlled the lateral propagation of vibrations. Dhanya et al. [37] conducted an experimental and numerical study to examine the performance of geogrid-reinforced geo-base isolation (GSI) under static load, as shown in Fig. 11. The geogrid was utilized to enhance the bearing capacity, settlement, and rotation response of the shallow square foundation. The experimental results showed that the bearing capacity of the GSI increased by two times with the use of a single layer of geogrid and by three times with the use of a double layer, with a decrease in settlement by 30% and 45%, respectively. The numerical results showed that the governmental factors of improvement bearing capacity and lowering the settlement were the length, the number, and the position of the geogrid, along with the width of the GSI layer. The optimum depth of the first geogrid layer was (0.35-0.4) B for a single layer and (0.3-0.35) B for a double layer, with 0.2 B being the best geogrid space. The optimum length of the geogrid was 4 to 6 B, and the length of the geogrid should be higher than the width of the GSI.

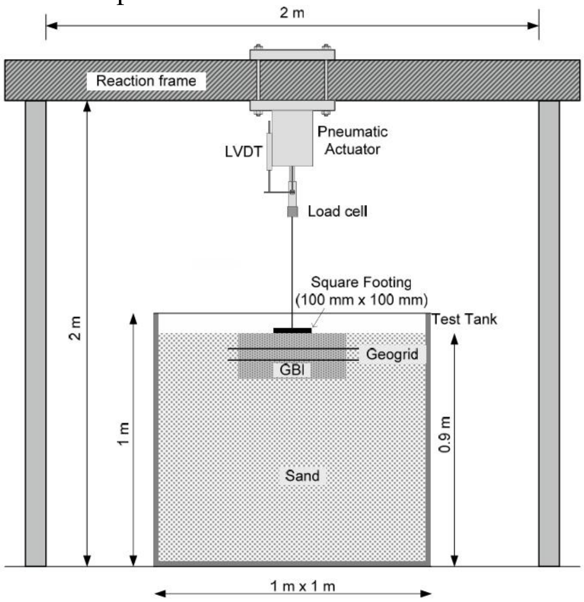


Fig. 11 The Test Setup [37].

According to Zhang et al. [38], the use of geogrid as a reinforcing layer increased the shallow foundation bearing capacity and dramatically lowered the settlement ratio. For the same footing size, this behavior was true up to three to four layers; however, when N = 5, there was no or slight variation in the value of BCR. Fakher and Fakhruldin [39] studied the effect of geogrid reinforcement (Tensar SS2) on the performance of sand soil supporting strip footing made of rigid stainless steel. The soil was reinforced with 1-4 layers of geogrids. The results showed that the performance of reinforced soil was significantly better than that of the unreinforced soil. Also, increasing the number of geogrid layers resulted in a 2.5-fold increase in bearing capacity and a 2.5-fold decrease in footing settlement when using 4 layers of geogrids. Bahadori et al. [40] studied the response of geogrid-reinforced saturated soil supporting a raft foundation using a shaking table, see Fig. 12. The foundation settlement and acceleration response were examined. The results showed that geogrid reinforcement was unbeneficial in reducing the foundation settlement, and the acceleration amplification was insignificantly minimized.

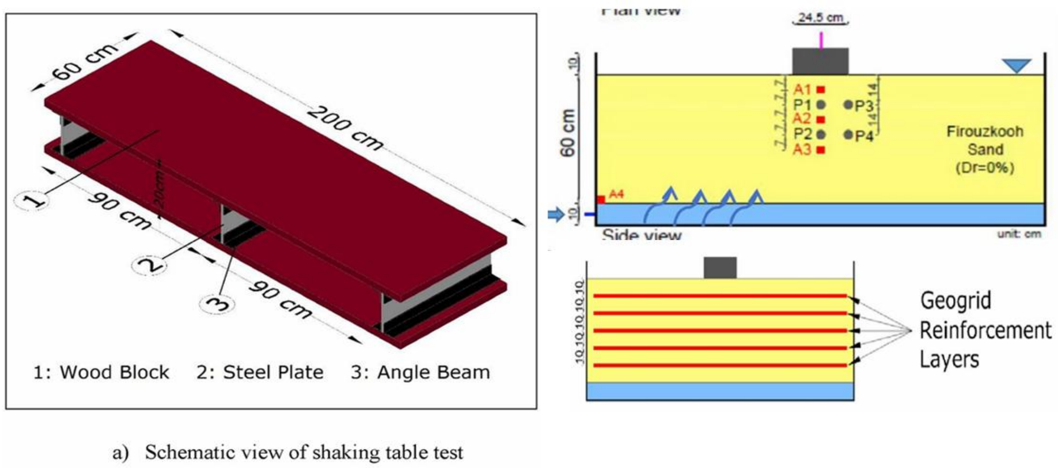


Fig. 12 The Shaking Table and the Model Setup [40].

Tolun et al. [41] studied the response of a circular foundation founded on geogrid-reinforced sand soil under static and dynamic repeated loads, see Fig. 13. The parameters examined in the study were the number of geogrid layers, the amplitude of repeated load, and the number of load cycles. The results showed that the vertical deformation of the footing reduced with geogrid reinforcement due to the lateral restraining and the interaction between the geogrid and the sand soil. The results also indicated that two layers of geogrid were sufficient in enhancing the soil response under the static and dynamic load, as the foundation settlement decreased by more than half, and no further improvement can be gained with more than 2 layers. The result disclosed that the increase in the repeated load amplitude increased the foundation settlement. The foundation displacement occurred after 100 load cycles; nevertheless, the use of geogrid reinforcement lowered the rate of increase from 100 to 2000 load cycles.

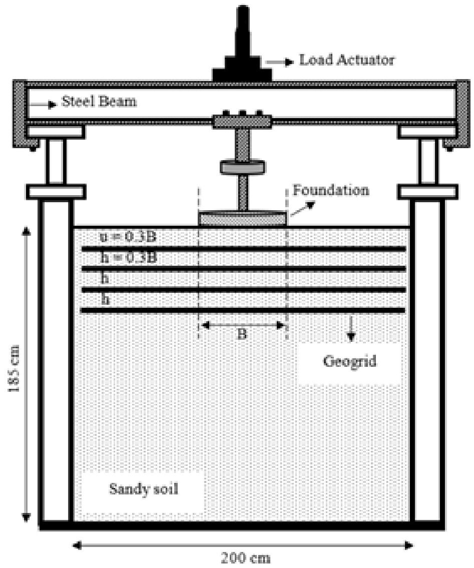


Fig. 13 The Model and the Apparatus [41].

Wang et al. [42] conducted dynamic experiments on a shallow footing in the form of a square foundation. The effects of various reinforcement configurations on the load-bearing properties of the footing subjected to repeated loads were tested (see Fig. 14). Measurements of soil acceleration rates, footing settlement, and geogrid strain were all part of the study. The depth of the first geogrid layer (u) and the vertical distance between the geogrid layers (h) examined were (0.3, 0.6, and 0.9) B, and the length of the geogrid was 3 B. The results demonstrated that the bearing capacity of the foundation resting on reinforced sand soil was consistently at least 12% higher than that on soil with no reinforcement. The bearing capacity of multi-layer reinforced foundations increased as the number of geogrid layers (N) increased from 1 to 3, with a maximum increase of 29% and the optimum u and h were 0.3 B. The following order was found to be the influence of reinforcing arrangements on footing bearing capacity: u value, manner of wraparound ends reinforcement, and N value, according to analysis of the ratio of bearing capacity (BCR) and the attenuation rate of acceleration (AAR). Diverse dynamic responses were produced by different reinforcement arrangements, with the order of sensitivity to acceleration responses being N value, wraparound ends reinforcement technique, and u value. The footing's failure mode and geogrid strain were both significantly impacted by the reinforcement configuration.

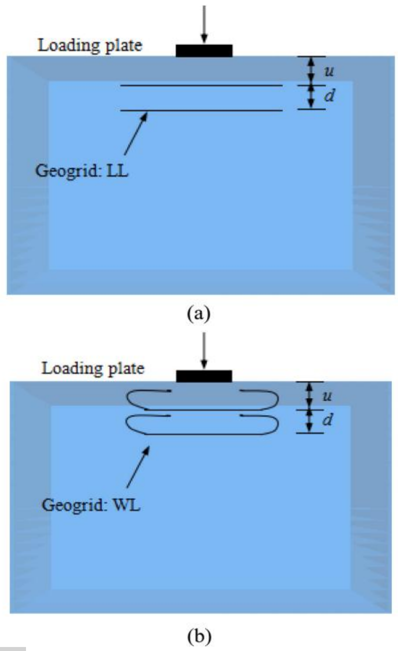


Fig. 14 (a) Model with Straight Geogrid, (b) Model with Wrapped Geogrid [42].

Gao et al. [43] examined the bearing capacity and deformation of soil reinforced with three types of geogrid—uniaxial, biaxial, and triaxial—and various geogrid numbers (1 to 3) layers. The image of the footing model was captured using a laser transmitter and digital camera, and then analyzed to investigate the deformation of the different cases. The results showed that the triaxial geogrid gave the best response in terms of the vertical and horizontal displacement and bearing capacity. The results also showed that the increase in the geogrid number caused an increase in the bearing capacity and a decrease in the foundation deformation, and the level of improvement decreased with the increase in the number of geogrid layers. Hussain et al. [44] investigated the geogrid parameters that influence its performance in sand soil. Three critical parameters were examined: depth, size, and the number of geogrid layers, see Table 4. The results showed that the optimum load-settlement response can be obtained when the distance between the geogrid layers is 0.5 B, and the geogrid size was 4.5 B (B: footing width), with three layers of geogrid.

Table 4 The Geogrid Parameters Studied in the Research [43].

Depth of reinforcing layer, u (m)	Width of reinforcing layer, b (m)	Number of reinforcing layers, N
0.5	1.5	1
0.1	3.0	2
1.5	4.5	3
2.0	6.0	4

Al-khafaji and Shafiqu [45] used a shaking table system to study the response of a square foundation resting on sand soil reinforced with InterAx geogrid when subjected to the 2017 Halabjah earthquake that occurred in Iraq. The soil was prepared with a relative density of 30%, and the number of geogrid layers was 1 to 3, with a distance of 0.3 B (B: footing width) between the layers. The horizontal and vertical displacement, the tilting of the foundation, and the acceleration response of the reinforced soil were tested. The results showed that the increase in the number of geogrid layers improved the foundation-soil response since it decreased the foundation deformation and tilting by 30% and 25%, respectively. The results also showed that acceleration amplification decreased noticeably in seismic waves propagated through the reinforced sand zone.

6.2.The Numerical Studies

In the numerical examination of Ghazavi and Mirzaeifar [46] using the FLAC-3D program to assess the possibility of increasing the soil bearing capacity at the lowest cost by using geogrid reinforcement, it was found that the critical u/B, h/B, and number of geogrid layers were 0.3, 0.3, and 3, respectively. Also, the soil relative density is a critical factor in improving the soil performance. Zidan [47] investigated the performance of circular footings set on reinforced sand under both static and dynamic force scenarios by using finite element analysis to create several axi-symmetry models, see Fig.15. Geogrid was modeled as an elastic element in these models. The hardening soil model with an elasto-plastic hyperbolic stress-strain relationship was used to characterize the soil. The number of geogrid layers, depth to the first geogrid layer, layer spacing, and load amplitude of dynamic loading were among the characteristics considered in the study. The results of the numerical analyses showed that the optimum number of geogrid layers was 3, the optimal first and distance between the geogrid layers are 0.2 B and 0.5 B, respectively (B: footing diameter). The results also showed that the increase in the number of cyclic loads reduced the bearing capacity and increased the settlement in unreinforced and reinforced soil. Nevertheless, the installation of geogrid layers contributes to improving the soil response.

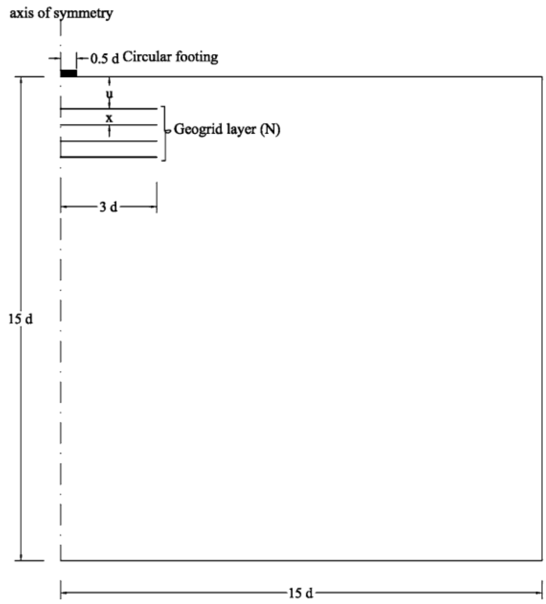


Fig. 15 The Circular Footing Rested on Geogrid-Reinforced Soil [47].

Sakr et al. [48] examined the performance of large-scale foundations and structures founded on unreinforced and geotextile-reinforced sand soil subjected to seismic loads. The ability of geotextile to reduce the deformation and pore water pressure underneath the foundation under an earthquake was examined using PLXIS2D. The building was modeled as a three-story concrete structure with a basement placed on a raft foundation supported on soil with and without geotextile (Fig. 16). The number of geotextiles ranged from 1 to 3 layers, and the effect of geotextile width was also investigated. The results showed that the increase in geotextile layers results in a decrease in the horizontal displacement and bending moment. The results also proved that geotextile increases the foundation stability by 63% causing a significant increase in the building stability. In addition, it was found that the reinforced soil performed as a coherent mass, improving the building stability and absorbing the ground excitation, inhibiting the acceleration amplification and the shear strain associated with seismic loads. Furthermore, the pore water pressure decreased by 70% with the installation of 3 layers of geotextile.

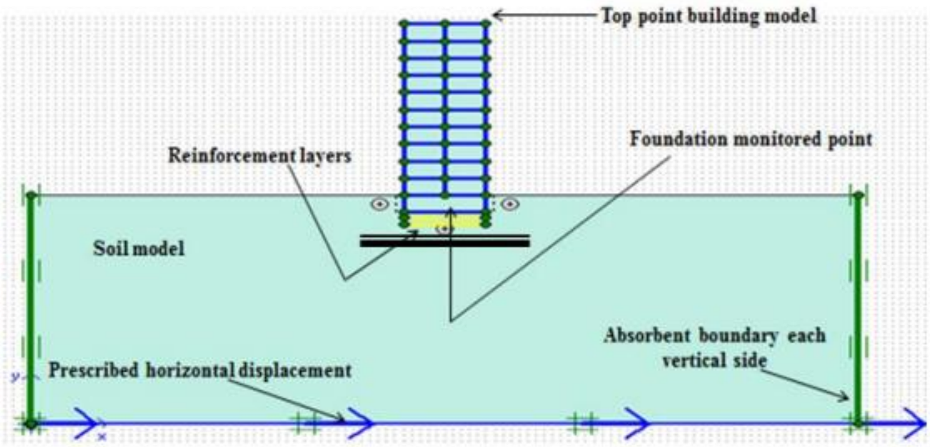


Fig. 16 The Details of the Model with the Earthquake Boundary Condition [48].

El-Shesheny et al. [49] conducted a comprehensive investigation employing numerical simulations to analyze the response of square footings situated on sand reinforced with geogrid, see Fig. 17. The primary objective was to indicate the enhancement in bearing capacity caused by the integration of reinforcing layers within the sand. Utilizing the finite element analysis, the study examined the effects of both static and dynamic force conditions on the reinforced soil foundation. The key parameters affecting the reinforced soil encompassed the number of geogrid layers and the depth of the influence zone, with examination of variations in the spacing between these reinforcing layers. The outcomes highlighted the crucial role of the number of reinforcing layers in determining the bearing capacity of the reinforced soil. The results showed that the optimum number of geogrid layers is four. The results also revealed that the bearing capacity increased with a decrease in the vertical spacing between the geogrid layer, and 0.5 B was the optimum value.

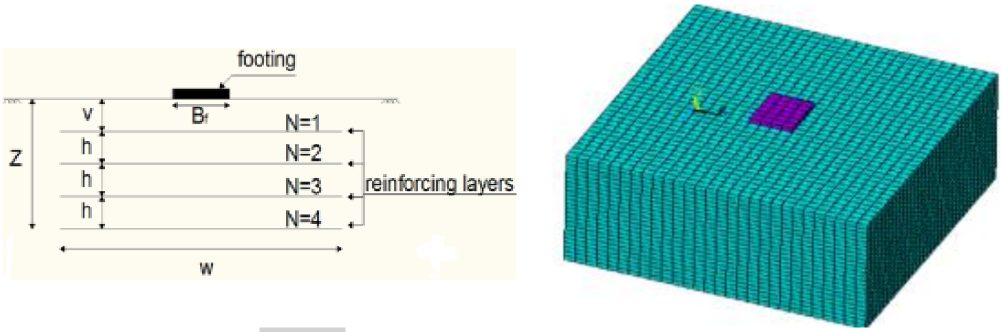


Fig. 17 The Model Simulated in the Study [49].

Dhanya et al. [50] examined the response of a raft foundation with dimensions of 10 m supporting a two-story building founded on geogrid-reinforced sand rubber mixture (SRM) using PLAXIS 2D, see Fig. 18. Five earthquake histories were selected, which were the 2001 Bhuj earthquake, 2009 Andaman earthquake, 2011 Sikkim earthquake, 2015 Nepal earthquake, and 2016 Myanmar earthquake. The acceleration, seismic settlement, tensile force mobilized, and inter-story drift were examined. The results showed that two layers of geogrid were adequate to improve the response of the sand rubber mixture since it considerably reduced the seismic settlement by 55%. The acceleration amplitude decreased as it passed through the reinforced SEM. The inter-story drift of the reinforced SRM was 20% less than that of the ordinary SRM since the geogrid provides additional confinement that restrains the lateral displacement of the building. Useche-Infante et al. [51] conducted a series of circular foundations with a diameter of 10 cm supported by geogrid-reinforced sand. Two types of geogrids were used: uniaxial and biaxial. Different geogrid parameters and soil relative density were examined (see Table 5). Also, a regression model was developed to calculate the bearing capacity of the reinforced sand. The results showed that qualitative and quantitative relationships were established between the bearing capacity and the geogrid parameters. The outcomes also revealed that the load-settlement characteristics of the reinforced soil were enhanced significantly. The improvement is also related to the relative density of the sand; the increase in the relative density gave better bearing capacity. Add to that the optimum number of geogrid layers, the distance of the first layer, the distance between the geogrid layers, and the width of reinforcement were 5 and 0.25 B, 0.25 B, and 4 B (B: footing width), respectively.

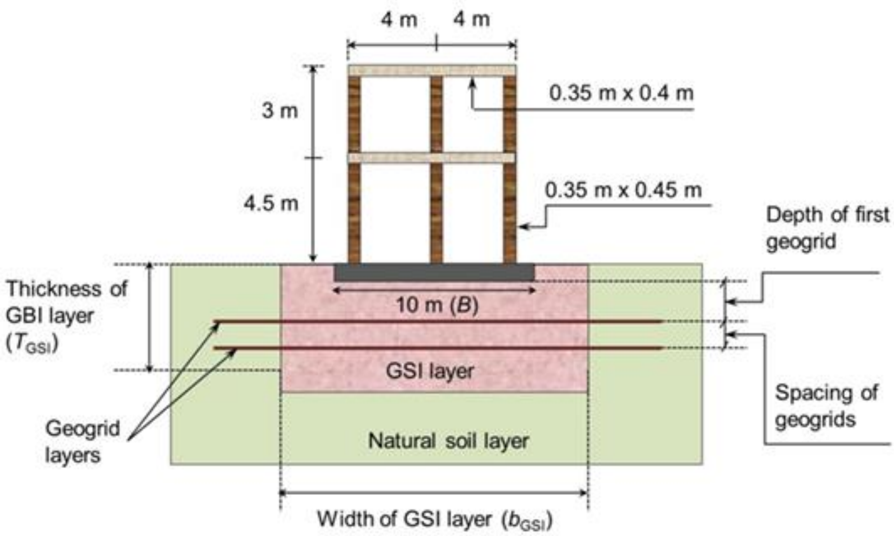


Fig. 18 The Test Model [50].

Table 5 Verification of Regression Models [51].

D_r/100	s/B	u/B	D/B	N	J/100	BCR measured
0.3	0.085	0.25	3	1	3.15	1.13
0.6	0.080	0.25	3	1	3.15	1.46
0.9	0.089	0.25	3	1	3.15	1.71
0.3	0.082	0.25	3	1	3.60	1.49
0.6	0.078	0.25	3	1	3.60	1.81
0.9	0.081	0.50	3	1	3.60	1.99
0.6	0.088	0.75	3	1	3.15	1.28
0.6	0.081	0.75	3	1	3.15	1.00

Chen and Abu-Farsakh [3] used the ABAQUS program to examine the effect of scale effect on the reinforced soil. The model was first verified using the laboratory results. Then, the load-settlement performance of various foundation sizes on soil reinforced with geosynthetics was numerically investigated (Fig. 19). The examination involved three reinforcement configurations and two soil-reinforcement interfaces. The results showed that the increase in the footing size decreased the bearing capacity of the reinforced soil when other geogrid parameters, i.e., reinforcement depth ratio and the successive distance between the layers, remained constant. Also, the reinforcement ratio (Rr) is the key factor in the scale effect of reinforced soil foundation systems.

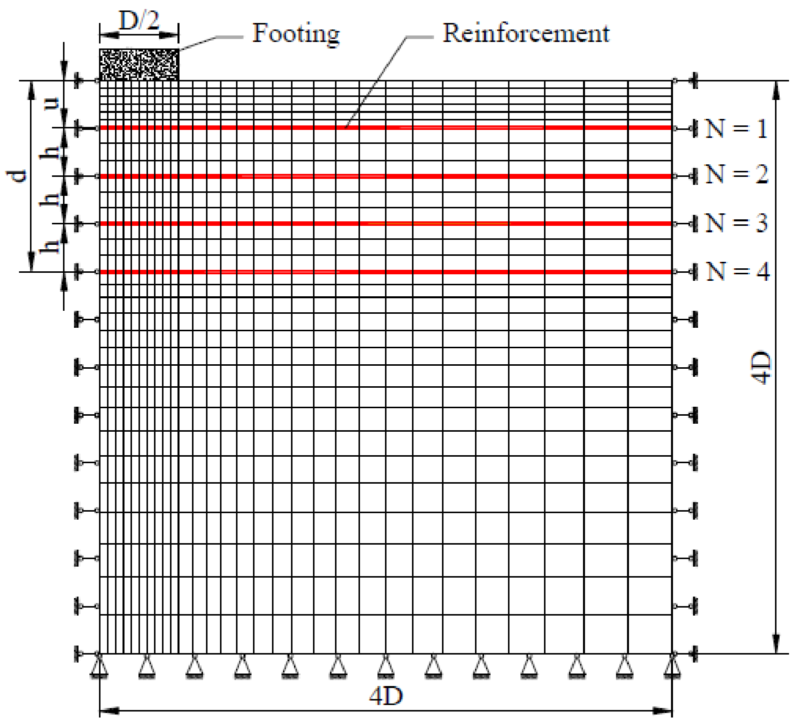


Fig. 19 Finite Element Model of the Circular Footing on Reinforced Soil [3].

Jaiswal and Chauhan [52] investigated the behavior of geosynthetic-reinforced sand soil supporting strip foundations under static and seismic loadings using the finite element method. The sand soil had two densities: loose and dense, and the geotextile was in a wraparound configuration, as shown in Fig. 20. The reinforcement parameters were h/B, b/B, u/B, and d/B = 0.2, 4, and 0.3, respectively (B: footing width = 2m). The geosynthetic element was modeled as a structural geogrid element. The results showed that the ultimate bearing capacity improved with the geogrid reinforcement, with a delay in the settlement failure. The results also showed that the improvement level in the loose reinforced sand was higher than that in the dense reinforced sand. The improvement in bearing capacity of loose reinforced sand was 1.89, while in the case of dense reinforced sand, it was 1.36. In addition, the failure zone was increased when the soil was subjected to seismic load in both reinforced and unreinforced soil; nevertheless, the presence of reinforcement limited the failure zone in both horizontal and vertical directions.

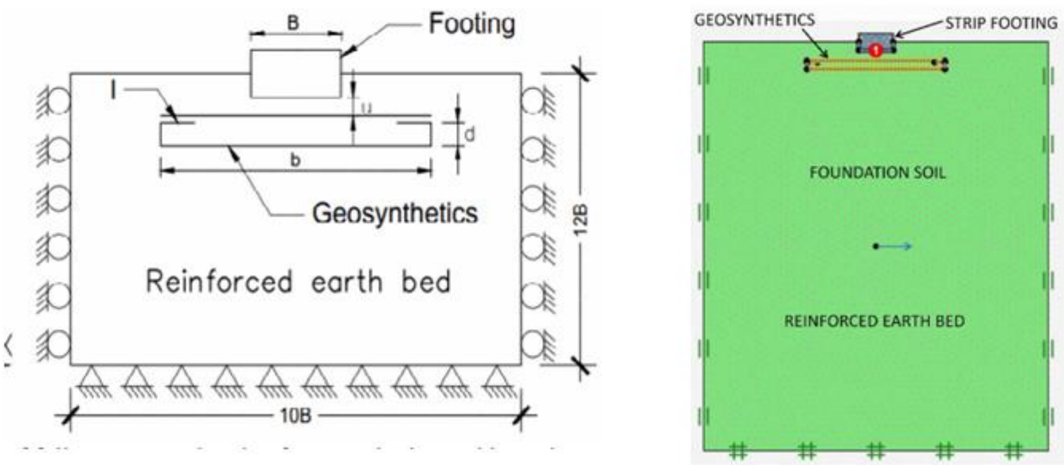


Fig. 20 The Strip Footing Rested on Wraparound Geotextile-Reinforced Soil [52].

Sanjay et al. [53] studied the performance of a square footing supported by soil reinforced with geogrid by using a laboratory model and numerical examination via PLAXIS 3D. A biaxial geogrid was used in the laboratory study. While in the numerical study, the model was imported from 3D AutoCAD. The experimental results showed that the increase in the number of the geogrids up to 3 reduced surface heaving and settlement. Nevertheless, the further increase in the number of geogrids to 4 causes an insignificant enhancement in the bearing capacity. The numerical results showed good correlation with the laboratory results. Gupta and Mital [54] studied the response of a square foundation rested on soil reinforced with geogrid under the effects of different eccentric and inclined forces with dimensions of (e/B, e/L = 0, 0.05, 0.10, and 0.15) and α = 0, 7°, 14° (α: inclination angle of load). The results of biaxial geogrid reinforcement were compared with the PLAXIS 3D results. In the numerical investigation, the geogrid was used as a rigid substance with 7 kN/m^2 ultimate tensile strength. The results revealed that the ultimate bearing capacity (UBC) decreased by 33% and 31% as the load eccentricity increased from 0 to 15. The placement of the footing on the soil reinforced with geogrid resulted in a decrease in the UBC of 21% and 24%. The correlation between the laboratory and the PLAXIS results was reasonable. Abdolhosseinzadeh et al. [5] utilized finite element method (FEM) to model a circular foundation resting on sand soil reinforced with geogrids examining the effect of geogrid geometric aspects on the bearing capacity (Fig. 21). The parameters studied in this research include the depth of the initial reinforcing layer, the vertical spacing between the successive layers, the optimal number of geogrid, and reinforcement width. The details of the geogrid parameters are tabulated in Table 6. The results revealed that the geogrid layers enhanced the bearing capacity of the foundation up to 50%. This improvement remained constant at a length of 3 R. In addition, there was an alteration in the soil behavior from elastoplastic to hardening elastoplastic when the length of the geogrid increased. Moreover, the use of five layers of geogrid increased the bearing capacity ratio by 49%. In terms of the distance between the layers, increasing the distance resulted in a decrease in the bearing capacity, with s = 0.3 R being the optimal.

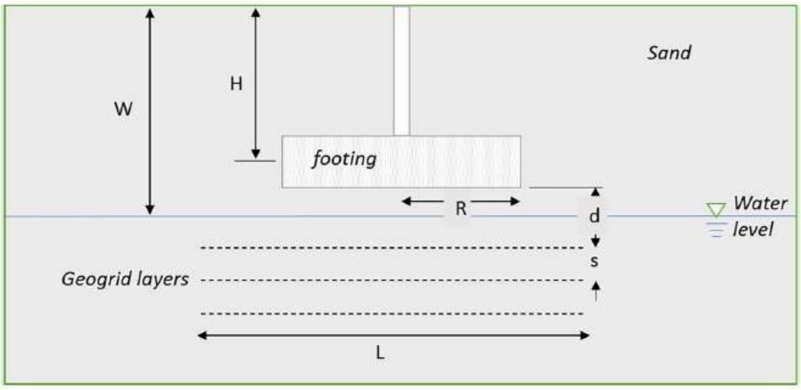


Fig. 20 Geometry of the Model [5].

Table 6 Geometry Parameter in the Study [5].

Introduction	Parameter	Value
Length of geogrid	L	1R, 2R, 3R, 4R, 5R, 6R
Number of layers	N	2, 3, 4, 5, 6, 8
Distance of layers from each other	s	0.1R, 0.2R, 0.3R, 0.5R, R
Distance of geogrid reinforcements from the footing	d	0.1R, 0.2R, 0.4R, 0.6R, 0.8R, R
Buried depth of the footing	H	0.1R, 0.2R, 0.4R, 0.6R, 0.8R, R
Radius of footing	R	1 m

7.CRITICAL ANALYSIS AND DISCUSSION

An extensive literature review was conducted to examine studies on static and dynamic loadings, utilizing various experimental and numerical methods. Several points can be drawn, as follows:

- Most studies examining the optimum geogrid parameters, including u/B, h/B, b/B, and N, are static research, as they focus on these parameters to improve load-settlement and bearing capacity in the soil. Although the dynamic studies assessed some of the parameters, they relied on the static studies in selecting the others. For example, in some of the dynamic studies, the values of u/B and h/b have been chosen from the static literature; however, the geogrid width and the number of geogrid layers are examined, contributing to the dynamic studies that pay more attention to assessing whether the geogrid is effective in curtailing the dynamic loads or not.
- From the collected studies, it was noticed that most of the available data were on the static loads. Nevertheless, the number of studies assessing the influence of geogrid reinforcement has been increasing recently, accompanied by a decrease in static load studies. This shift reflects researchers' growing interest in investigating the geogrid's effectiveness in dynamic fields, following its proven efficiency under static loads.
- To indicate the optimum geogrid parameters, which are u/B, h/B, b/B, and N, statistical analysis was conducted on the collected data given in Section 6 using the exploratory data analysis (EDA) that includes Histogram and quantity-quality plot (QQ), as follows:

  The Histogram and QQ plots, presented in Fig. 22, showed that the optimum parameters for maximizing improvement in soil and foundation under different loads are u/B in the range of 0.2 to 0.5, with 0.3 being the most commonly reported value among researchers. In terms of the h/B, the optimum value was in the range of 0.2 to 0.3, with 0.3 being the best value. The width of the geogrid layer was agreed upon to be 3 to 4, with 3 geogrid layers. The QQ plot indicated that the available data is close to a straight line, which means that the data has a normal distribution.

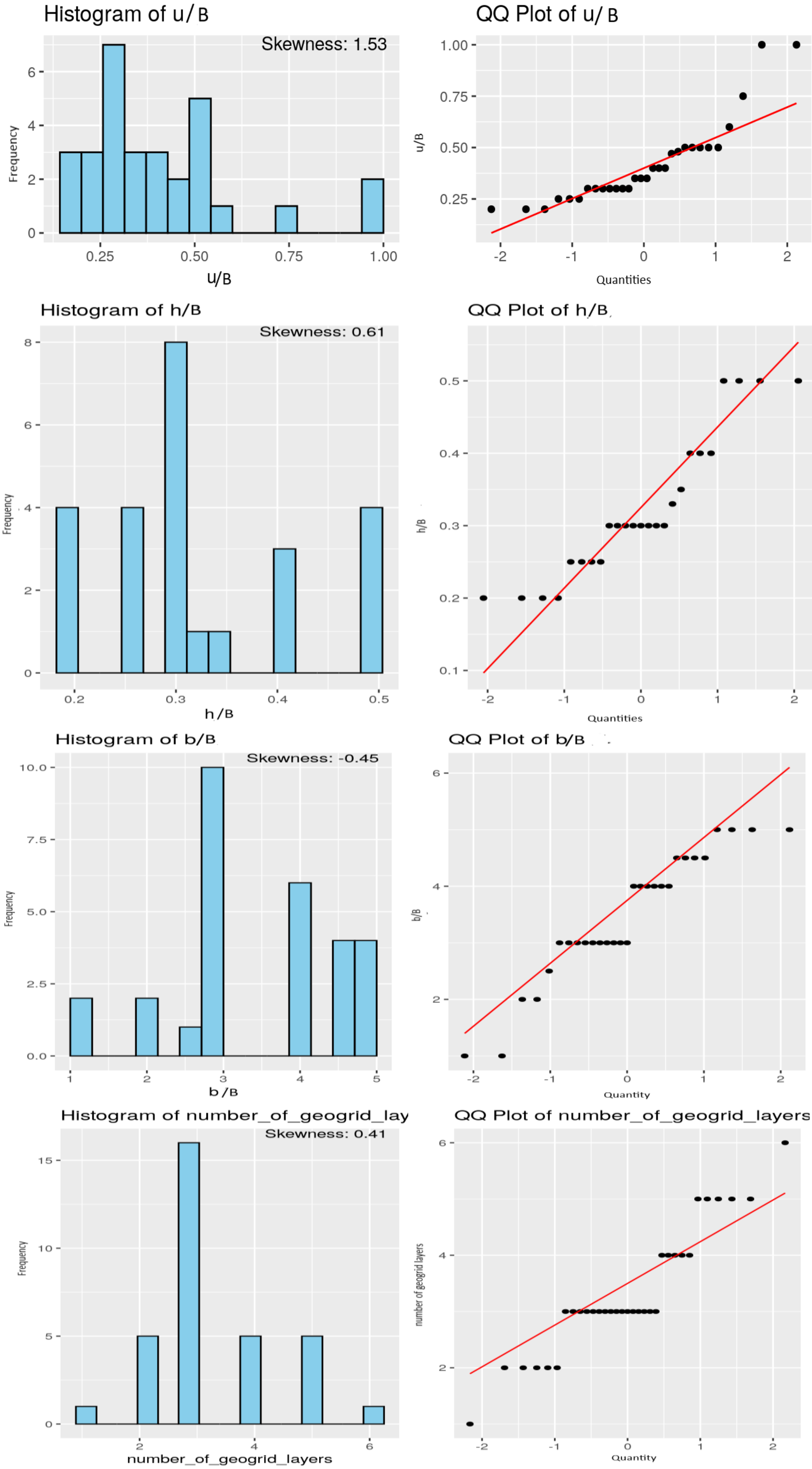


Fig. 22 The Histogram and the QQ Plot of the Geogrid Parameters.

- The plots of the correlation between the different geogrid parameters given in Fig. 23 revealed that the u/B, h/B, and the number of the geogrid layers have a good correlation with each other, confirming the selected studies, as most of the research indicates that the u/B and h/B are correlated with the number of geogrid layers. When u/B and h/B are relatively low, the bearing capacity increases with the number of layers.

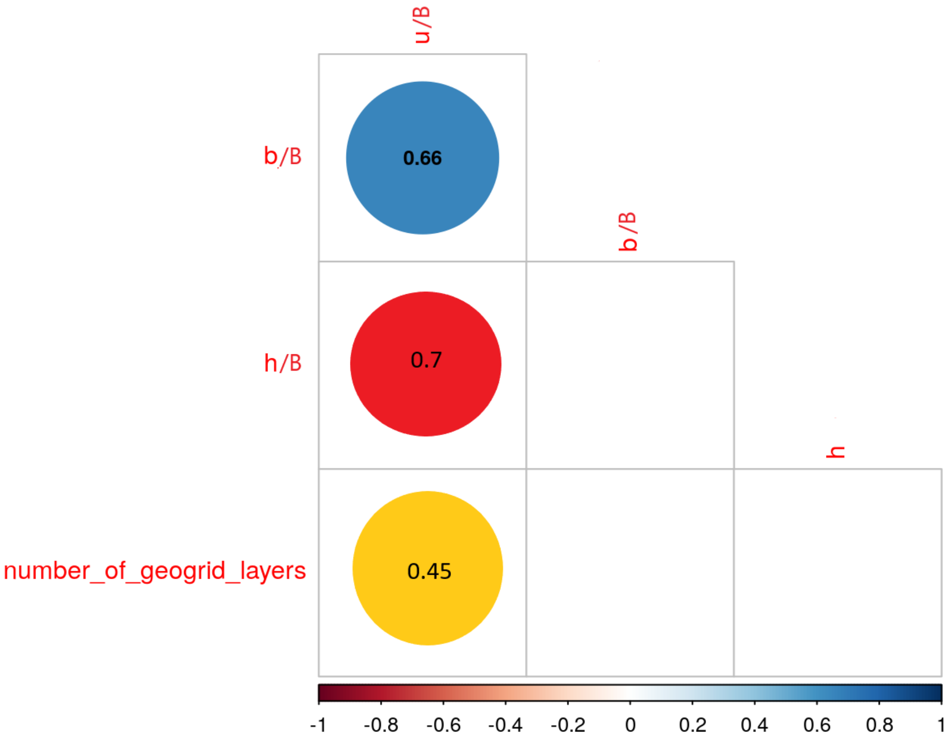


Fig. 23 The Correlation between the Different Geogrid Parameters.

- Figure 24 presents the expository data analysis, including the types of loads, i.e., static, dynamic or earthquake dynamic, the study types (experimental or numerical), and the improvement (improved or not). The results showed that the studies examining the performance of the geogrid as a reinforcing element in the soil outnumber those on dynamic loads or earthquakes because research on the role of geogrid in dynamic loads has been examined recently. Also, it was noticed that the number of experimental studies is more than the numerical studies. It may be due to the recent advancement of the numerical tools, which were not available earlier. Also, from the available literature, Fig. 24 showed that the geogrid is highly effective in improving the bearing capacity and settlement of the soil-foundation system. In the dynamic studies, the geogrid also played a significant role in controlling the cyclic and repeated loads, minimizing the vibration associated with the dynamic loads, and increasing the number of cycles required to cause foundation failure. Under the seismic loads associated with an earthquake, the foundation's horizontal and vertical displacement, the tilting was reduced, and the acceleration amplification and the developed pore water pressure were limited in the case of geogrid-reinforced sand soil, contributing to the geogrid-reinforced sand soil acting as a stiff raft and developing lateral straining that controls and minimizes the soil movement under the various applied loads. Nevertheless, one of the available studies indicated the opposite. Thus, further research is needed to assess the performance of the geogrid under earthquake conditions and confirm its effectiveness. The studies on the use of geogrid under seismic loads are still in their early stages of investigation.

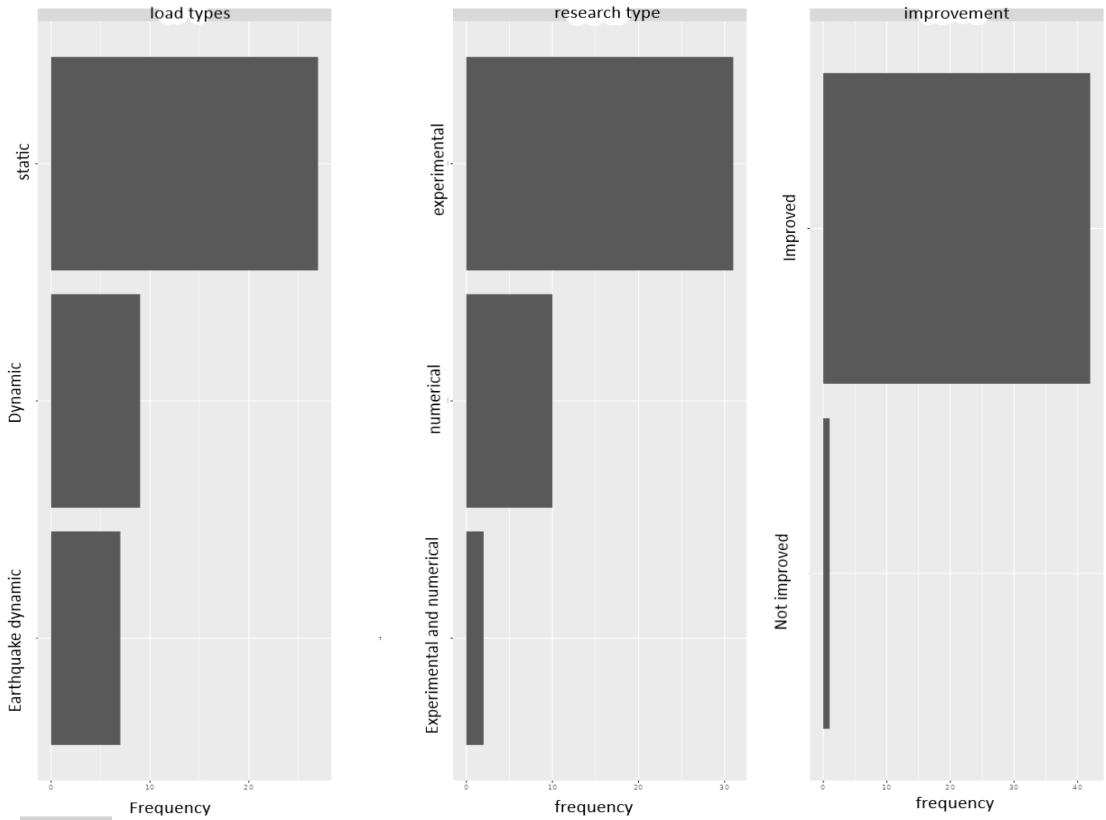


Fig. 24 The Exploratory Data Analysis for Load Types, Research Types, and Improvement.

4.CONCLUSION

This paper reviews the response of the geogrid-reinforced sand soil supporting shallow foundations when subjected to various types of loadings, including static centric and eccentric loads, dynamic loadings, including repeated loads, and seismic loads. From the extensive review, the following can be concluded:

- Soil reinforcement is the most commonly used method for soil improvement, particularly in sand soil. Geosynthetic reinforcement is preferred over other metallic reinforcement since it does not suffer from corrosion and lasts for a long time. The most common geosynthetic reinforcement element is a geogrid.
- Geogrid is a geosynthetic element consisting of ribs and apertures. It is available in several types, which are woven, welded, and extruded according to the manufacturing process. Geogrids can also be classified in accordance with the ribs' direction into uniaxial, biaxial, and triaxial.
- Several aspects affect the performance of reinforced foundation soil (RSF) under different loadings, including the depth of the first reinforcement layer (u), the width of the reinforcement (b), the distance between the two reinforced layers (h), and the number of reinforcement layers (N), by conducting an exploratory data analysis of the experimental and numerical studies on the geogrid under static and dynamic loads. The optimum (u/B) ranged from 0.2 to 0.5, with 0.3 being the best value. (h/B) was in the range of (0.2-0.3), and 0.3 is the best. (b/B) is 3 to 4, and N was (3) (B: footing width).
- By conducting an exploratory data analysis for research types, load types, and improvement. It was indicated that the number of static and experimental research studies exceeds that of numerical and dynamic studies.
- The analysis of both experimental and numerical research also showed that the geogrid reinforcement is very effective in reinforcing the sand soil and improving the performance of the shallow foundation under different loadings. When a shallow foundation is subjected to excessive centric and eccentric static loads, the bearing capacity and settlement in the reinforced sand are less than those in the unreinforced sand. Under repeated dynamic loads, the number of cycles required to produce failure increased when the foundation rested on geogrid-reinforced sand soil. Under the seismic loads associated with an earthquake, the foundation's horizontal and vertical displacement, the tilting was reduced, and the acceleration amplification and the developed pore water pressure were limited in the case of geogrid-reinforced sand soil. Nevertheless, the use of geogrid to resist seismic loads needs further investigation to confirm the applicability.
- The numerical studies were conducted mainly using the finite element method, PLAXIS 2D, PLAXIS 3D, and the ABAQUS program. The numerical studies were

mainly employed to investigate the prototype models (full-scale models) that are difficult to model in a laboratory setting. The numerical examinations were applied for the different load conditions: static centric, eccentric and inclined, and dynamic loads.

- The numerical results also showed good agreement with the experimental studies. Numerical studies have confirmed that geogrid is effective in enhancing the soil performance of shallow foundations and supported soils under various loadings. The optimum geogrid parameters obtained in the numerical studies are correlated with those of the experimental examinations.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the Civil Engineering Department, College of Engineering, Al-Nahrain University, as a Ph.D. student, in accordance with administrative order (2674/1/1/H.N) and university order (7227/2/3R.J) dated 20/10/2021.

NOMENCLATURE

AAR	Attenuation rate of acceleration
b	Width of reinforcement
B	footing width
BC	Bearing capacity
BCR	Bearing capacity ratio
DD	Diameter change
FEM	Finite element analysis
h	Vertical distance between the geogrid layers
Rr	Reinforcement ratio
RSF	Reinforced soil footing
SSS	Settlement of the soil surface
N	Number of geogrid layers
u	Depth of initial Reinforcement Layer

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