Planar geosynthetic-reinforced soil foundations: a review

Xiaopeng Guo¹ · Hao Zhang¹ · Liangliang Liu¹

Received: 13 August 2020 / Accepted: 19 November 2020 / Published online: 25 November 2020
© Springer Nature Switzerland AG 2020

Abstract

Geosynthetics-reinforced soil (GRS) foundation can improve the bearing capacity of the foundation and reduce the settlement of the footing, which has been widely applied to the treatment and improvement of soft soil foundation. In recent years, scholars have carried out a large number of studies to reveal the influence of different factors on the load and settlement behaviors of GRS foundations. In this study, the reinforcing mechanisms of reinforced materials are first summarized, and then the literature review of planar geosynthetic-reinforced foundations from the aspects of experimental studies, numerical simulations and theoretical analyses are presented. Finally, the current research trend of reinforced foundation and the prospects in the future study are discussed. Although the researches on the performance of GRS foundations are conducted extensively, there is no unified understanding on the failure mode and reinforcing mechanism of reinforced foundation. It is necessary to propose the accurate and simple calculation method to evaluate the ultimate bearing capacity of reinforced foundations based on the reinforcing mechanism and failure mode. In addition, the dynamic response of GRS foundations under cyclic loading and earthquake needs to be studied intensively. The paper summarizes the past and present developments of the GRS foundations and provide the views for the further researches.

Keywords Reinforced soil foundation · Planar geosynthetic · Plate load test · Numerical modeling · Ultimate bearing capacity

1 Introduction

In the engineering projects of soft soil area, shallow footings built on the soft soil foundation are usually subjected to the large settlement and low bearing capacity. To ensure the safety of the infrastructures, it is necessary to adopt ground improvement techniques to deal with above problems. With the development of polymer materials, geosynthetics reinforced soil (GRS) foundation treatment technology has emerged, which has been widely used in highway, railway, building and other engineering fields. The GRS foundation can effectively improve the bearing capacity and reduce the settlement of the footing [1]. Generally, geogrid and geotextile are used as the reinforcements in the reinforced soil foundations. The geogrid available in the market mainly includes uniaxial,

biaxial and triaxial geogrids, while the geotextile is divided into nonwoven and woven geotextiles.

Many researchers have investigated the performance of GRS foundations under footing load. A large amount of model tests was conducted to study the load-settlement behavior of GRS foundations under strip footing [2–4], circular footing [5, 6], square footing [7–10], rectangular footing [11, 12] and ring footing [13]. In addition to experimental studies, numerical modellings were used to validate the results of model tests and investigate the effect of various influencing factors on the performance of GRS foundations. Currently, the numerical analysis methods consist of finite element method [14–17], finite difference method [18–20], and discrete element method [21–24]. Based on the results of experimental and numerical studies, some researchers have proposed the analytical solutions to

✉ Xiaopeng Guo, 1510262@tongji.edu.cn; Hao Zhang, zhao0106@163.com; Liangliang Liu, liuliangliang@tongji.edu.cn | ¹School of Civil Engineering, Tongji University, 1239 Siping road, Shanghai 200092, China.

calculate the bearing capacity of reinforced foundation. The analytical methods usually include limit equilibrium method [25–27], limit analysis method [28, 29], and regression analysis method [30, 31]. Most of researches focus on the influence of the layout parameters of reinforcement, soil properties, footing types and forms of applied load on the bearing capacity and settlement of the reinforced foundations. The load-settlement curves are compared to analyze the effect of different influencing factors on the behaviors of reinforced foundations. However, there are few experimental studies on the failure mode and reinforcing mechanism of reinforced foundation [32–34]. Moreover, due to different understandings on the reinforcing mechanism and failure mode, as well as the diversity of foundation soil and reinforced materials, there is no unified and accurate calculation formula for the bearing capacity of reinforced foundation. Some of the analytical solutions are not easy to be applied to the engineering practice. Several scholars summarized the past findings, current trends and future prospects of studies concerning the geocell-reinforced foundations [35, 36]. However, to the authors' knowledge, there is no critical review concerning the planar geosynthetic (e.g., geogrid or geotextile) reinforced soil foundations.

This paper first summarizes the reinforcing mechanism of planar reinforcement in reinforced soil foundation based on the existing researches, and then presents the literature review of planar geosynthetic-reinforced soil foundations from experimental study, numerical modeling and theoretical analysis. Finally, the current research trend and the future prospect of the reinforced foundation are discussed. The paper presents the reader with the critical review of the past, present and future of planar geosynthetic reinforced foundations, which would be a very useful reference for further studies.

2 Reinforcing mechanism

Based on the published literatures, reinforcing mechanism of the horizontal reinforcement (e.g., geogrid and geotextile) can be summarized as: (1) lateral restraint effect; (2) tensioned membrane effect; (3) stress dispersion effect and (4) deep footing effect, as shown in Fig. 1. The lateral restraint effect refers to the relative movement of soil particles along the surface of reinforcement under the footing load, which mobilizes the friction force at the interface between reinforcement and soil. The interaction between reinforcement and soil can effectively restrict the horizontal displacement of soils, thus increasing the lateral confining pressure and the compressive strength of soils under the footing [25, 27]. Therefore, the ultimate bearing capacity of foundation increases. For geogrid, the grid plays a vital role in the soil-reinforcement interaction, which can better restrict the displacement of soils (such as gravel soil or sand with large particle size), and further enhance the constraint to the soils [37]. As for the tensioned membrane effect, the soils and reinforcements in the reinforced zone move downward due to the footing settlement under applied load. The reinforcements below the footing bend and thus the upward force in the curved reinforcements develops to counter the applied footing load, resulting in the improvement of the bearing capacity of soil foundation [27, 38]. For the multi-layer geosynthetic-reinforced foundation, owing to the combination of the lateral restraint effect and tensioned membrane effect, the overall stiffness of the reinforced zone is significantly improved. At the same time, the foundation is similar to the double-layered soil foundation with upper hard layer and lower soft layer, which spreads the footing

Fig. 1 Schematic view of the reinforcing mechanism: **a** lateral restraint effect; **b** tensioned membrane effect; **c** stress dispersion effect and **d** deep footing effect

load to a wider area. Binquet and Lee [39] first found the stress dispersion effect of reinforcement materials through laboratory model tests, and subsequently Schlosser et al. [40] applied this reinforcing mechanism to the derivation of the bearing capacity of reinforced foundation. When the length of the reinforcement is very short or equal to the width of the footing and the spacing between reinforcement layers is small, the deep footing effect can be formed. This effect indicates that the performance of reinforced foundation is similar to that of unreinforced foundation with a footing having an additional embedment depth equal to the depth of the reinforced zone [1], which can increase the embedment depth of the “equivalent footing” and thus improve the bearing capacity of the foundation. Schlosser et al. [40] first proposed the deep footing effect and then Huang and Tatsuoka [25] discovered the effect in the model tests. This effect has been used by Huang and Menq [30] and Huang and Hong [41] to derive the analytical method for calculating the ultimate bearing capacity of reinforced foundations.

At present, the reinforcing mechanisms of horizontal reinforcement mainly include the above four effects. They are summarized and proposed based on several assumptions and the results of the macro-scale plate load tests on the GRS foundations, while the interaction mechanism between reinforcement and soil based on the meso-scale tests needs to be studied further.

3 Experimental study

Up to date, the researches concerning the performance of planar geosynthetic-reinforced foundations and the various influencing factors are mostly based on the laboratory

reduced model test. Some scholars have also carried out the field test and large-scale model test to investigate the load-settlement behaviors of reinforced foundations under more actual stress conditions.

3.1 Reduced model tests

Due to the low cost and little time consuming, laboratory reduced model tests have become the main approach to study geosynthetic-reinforced soil foundations. The equipment for conducting plate load tests mainly include test box, loading device, rigid footing and sensors (load cell and displacement meter). Figure 2 shows a typical test equipment for performing the model tests on reinforced foundation.

Based on the small-scale model tests, the influence of different factors on the bearing capacity and settlement of reinforced foundation was studied thoroughly. These influencing factors mainly include the layout parameters and properties of reinforcement, the shape and size of footing, the form of load and the properties of foundation soil. Currently, scholars mainly analyzed the effect of different factors on the bearing characteristics of the foundation by comparing the load-settlement curves between the unreinforced and reinforced foundations. In general, the bearing capacity ratio (BCR) and the percentage reduction in settlement (PRS) were used as the dimensionless parameters to evaluate the reinforcement effectiveness of the geogrid or geotextile. The bearing capacity ratio (BCR) is defined as follows:

$$\text{BCR} = \frac{q_r}{q_u} \quad (1)$$

where q_r is the bearing capacity of reinforced foundation as the footing reaches a certain settlement; q_u is the

Fig. 2 Test apparatus for conducting plate loading tests on reinforced foundation: **a** schematic view and **b** photograph (adopted from [10])

bearing capacity of unreinforced foundation when the footing reaches the same settlement.

The percentage reduction in settlement (PRS) is defined as follows:

$$PRS = \frac{(s_u - s_r)}{s_u} \times 100 \quad (2)$$

where s_r is the footing settlement in reinforced foundation under a certain load, and s_u is the footing settlement in unreinforced foundation under the same load.

The layout parameters of reinforced materials (e.g., geogrid and geotextile) in reinforced foundation include

Fig. 3 Schematic view of the geogrid or geotextile reinforced foundations

the distance between the top reinforcement layer and the bottom of footing (u), the spacing between the reinforcement layers (h), the length of reinforcement (L), the number of reinforcement layers (N) and the depth of reinforced zone (d_r). In order to facilitate the comparison between different influence factors, except N the above parameters are expressed in dimensionless form by dividing the width of footing B , i.e., u/B , h/B , L/B , d_r/B [10, 42]. Figure 3 presents the schematic diagram of the geogrid or geotextile reinforced soil foundation. Table 1 summarizes the important small-scale model tests conducted on geosynthetic-reinforced foundations and corresponding optimum layout parameters. According to the published literature and results from Table 1, the optimum layout parameters for the reinforced foundation can be summarized as follows: (1) For the top layer of reinforcement, it is generally considered that the proper embedment depth u/B ranges from 0.3 to 0.4. When u/B is too small, the overlying soil can not effectively anchor the reinforcement. However, when u/B is too large, the shallow shear failure of foundation will occur above the top reinforcement layer, which is not conducive to the improvement of bearing capacity [50]. (2) There is an optimum vertical spacing of reinforcement h/B . Within the effective reinforced depth, the bearing capacity increases with the decrease of h/B , and decreases

Table 1 Summary of the reduced model tests on planar geosynthetic-reinforced soil foundation

Researchers	Footing	Soil	Reinforcement	Optimum reinforcement parameters					BCR_{max}
				u	h	L	N	d_r	
Guido et al. [37]	Square	Sand	Geogrid/Geotextile	0.25B	0.25B	3B	3	0.75B	2.8
Mandal and Sah [43]	Square	Marine clay	Geogrid	0.175B	–	–	1	0.175B	1.36
Shin et al. [44]	Strip	Clay	Biaxial geogrid	0.4B	0.4B	4.5–5B	5	2.0B	1.4
Omar et al. [2]	Square	Sand	Biaxial geogrid	0.4B	–	4.5B	–	1.4B	2–3
	Strip			0.4B	–	8B	–	2.0B	4–5
Khing et al. [45]	Strip	Sand	Biaxial geogrid	< 1B	–	6B	6	2.25B	4
Das and Omar [46]	Strip	Sand	Biaxial geogrid	0.33B	0.33B	8B	–	–	3–5.5
Das et al. [3]	Strip	Sand	Biaxial geogrid	0.3B	–	8B	–	2B	4–5
		Clay		0.4B	–	5B	–	1.75B	1.4–1.5
Yetimoglu et al. [47]	Rectangular	Sand	Uniaxial geogrid	0.3B	0.2B	4.5B	4	1.5B	3.63
Alawaji [48]	Circular	Sand	Biaxial geogrid	0.1D	0.1D	4D	1	0.1D	3.2
Sitharam and Sireesh [49]	Circular	Sand	Biaxial geogrid	0.3D	0.4D	6D	6	2.3D	3.24
Ghosh et al. [50]	Square	Pond ash	Jute-geotextile	0.3125B	0.3125B	5–7B	5–6	1.75B	3.54
Basudhar et al. [5]	Circular	Sand	Woven geotextile	0.25D	1D	3.5D	3	2.25D	5.5
Latha and Somwanshi [42]	Square	Sand	Geogrid	–	0.4B	4B	–	2B	2–2.5
Moghaddas Tafreshi and Dawson [51]	Strip	Sand	Nonwoven geotextile	0.35B	0.35B	5.5B	5–6	1.75–2.1B	2.5
Abu-Farsakh et al. [52]	Square	Sand	Geogrid/Geotextile	0.33B	–	6B	–	1.25B	1.6
Useche-Infante et al. [53]	Circular	Sand	Geogrid	0.25–0.4D	0.25D	3–5D	4–5	–	3.15–3.6

u , embedment depth of the top reinforcement layer; h , vertical spacing between the reinforcement layers; L , length of reinforcement; N , number of reinforcement layers; d_r , embedment depth of the reinforced zone; BCR_{max} , ratio of the ultimate bearing capacity of reinforced foundation to that of unreinforced foundation under optimum reinforcement parameters; B , width of the strip footing or square footing; D , diameter of the circular footing

slightly when h/B is less than a critical value [47]. The recommended value of h/B is about 0.2–0.4. (3) The bearing capacity of soil foundation increases with the increase of reinforcement length L/B . When L/B exceeds a certain critical value, further increase in the length of reinforcement will not significantly improve the performance of the reinforced foundation. The reason is that as reinforcement length is larger than anchorage zone, the frictional resistance and passive force provided by reinforcement beyond effective anchorage zone has very limited effect on improvement of bearing capacity [44, 46]. It is recommended that the optimal L/B ranges from 4 to 5. (4) The bearing capacity of the foundation increases with the increase in reinforced depth d_r . After the reinforced depth reaches a certain value, further increase of the reinforced depth can not increase the bearing capacity of the foundations [42]. Based on the previous studies, the effective d_r/B varies from 1.5 to 2. It should be mentioned that the optimum number of reinforcement layers N can be determined according to the above optimized u/B , h/B and d_r/B .

In addition to the layout of reinforcement layers, the properties of reinforcement layer have also an impact on the performance of reinforced foundations. Some researchers have carried out model tests to study the influence of properties of reinforcements, such as stiffness, strength and aperture size on the bearing capacity of foundation [52, 54]. The bearing capacity of reinforced soil foundation increases with the increase in strength and stiffness of reinforcements. However, when the stiffness is larger than a certain value, it would not result in significant increase of bearing capacity. Based on experimental and numerical studies, Yetimoglu et al. [47] found the critical stiffness of reinforcement is about 1100 kN/m while Latha and Swomwanshi [42] thought the critical value is proximately 333.3 kN/m. The difference between two value is mainly due to the type of reinforcement used in the sand. The aperture size of reinforcement has remarkable effect on the performance of reinforced foundations. The ratio of the apertures size to the medium soil grain size is an important factor in the interaction between soils and geogrid [55]. To achieve the best reinforcement effect, Tavakoli Mehrjardi and

Khazaei [54] recommended the optimum aperture size of geogrids should be about 4 times of medium grain size of backfill materials. Except the properties of reinforcements, the type and shape of reinforcement can significantly influence the load-settlement response of reinforced soil foundations. The geogrid performs better than geotextile in improving bearing capacity of foundations [37, 52]. The difference is attributed to the better interlocking between soil particles and geogrid. In addition, the biaxial geogrid is better than uniaxial geogrid to enhance the performance of soil foundation [42, 53].

In addition to the properties and layout parameters of reinforcement, the influences of footing and load on the load-settlement response of soil foundations are investigated in detail. The shape of the footing, such as strip footing, square footing, circular footing, rectangular footing and ring footing (see Fig. 4), and the size of the footing, such as the width, length, diameter, ratio of length to width, have an effect on the load-settlement characteristics [2, 5, 13]. In addition, the buried depth of the footing affects the load-settlement behaviors of the foundation. Shin and Das [4] studied the effect of relative density of sand on the ultimate bearing capacity of reinforced foundation under different buried depth (0–0.75 B) of footing by means of small-scale model tests. The results showed that BCR increased with the increase of the buried depth. In addition to the experimental studies with regard to the reinforced foundation under a single footing, some scholars have also carried out laboratory model tests to study the influence of reinforcement on the interaction between two closely spaced footings including square footing, circular footing, strip footing and ring footing [16, 56, 57]. Figure 5 shows the layout of two adjacent square and circular footings resting on the reinforced foundation.

The load-settlement characteristics of reinforced foundation are not only related to the shape, size and layout of the footing, but also affected by the load form applied to the footing. In the laboratory model tests, the applied load is mainly uniform static load. Besides the uniform static load, some researchers have studied the performance of the reinforced foundation under different forms of load, including central load, eccentric load and cyclic load

Fig. 4 Type of footings used in the plate loading tests: **a** strip footing; **b** square footing; **c** rectangular footing; **d** circular footing and **e** ring footing. B is the width of strip footing; L is the length of rectangular footing; D is the diameter of circular and ring footing; d is the inner diameter of ring footing

Fig. 5 Schematic view of the layout of closely spaced square footing and circular footing. S is the center to center distance between two footings

[54, 58–61]. Figure 6 presents the different forms of load applied to the footing in the plate loading tests.

The soils in the reinforced foundation include the fill in the reinforced zone and the underlying soil below the reinforced zone. The type, particle size and relative density of the two parts of soils have an effect on the bearing capacity and settlement of reinforced foundation. At present, most of the foundation soils (including fill and underlying soil) in the small-scale model tests are dry sand or clay [3]. However, in some tests, the reinforced zone is filled with granular materials, such as sand and gravel [9], while the soil below the reinforced zone is clay or other soils with

low strength [11, 12, 57]. Under the same reinforcement layout, the ultimate bearing capacity of reinforced sand foundation is substantially greater than that of clay foundation [3]. This is because the increase in bearing capacity of foundation is due to the increased stiffness below the footing, the frictional resistance developed at the interface between soils and geogrid bibs and the passive force developed at the edge of geogrid ribs. The passive force is dependent on the friction angle of soil [3]. Thus, the passive force in sand is obviously larger than that in clay. The relative density of sand can also significantly affect the performance of soil foundation. The bearing capacity

Fig. 6 Type of loading applied to the footings: **a** uniform loading (adopted from [2]); **b** eccentric loading (adopted from [60]) and **c** repeated loading (adopted from [61])

increases with increasing of soil's density [5, 46, 53]. Das and Omar [46] performed model tests on strip footing resting on the geogrid-reinforced sand bed and found that the BCR decreases with the increase of relative density. However, Useche-Infante et al. [53] reported that the BCR increases with the increase of relative density based on the loading tests on circular footing. This is consistent with the finding by Durga-Prasad et al. [62] based on the plate load tests on geogrid-reinforced foundation under square footing. The difference in the relationship between BCR and relative density may be due to the shape of footing. This phenomenon is required to be investigated further. In recent years, Huang [63, 64] has conducted a series of tests to study the ultimate bearing capacity of saturated reinforced sand foundation. The test results show that the saturation of the foundation has a significant effect on the settlement of the foundation at the peak load, and the settlement of the foundation at the peak load is greater than that under the dry conditions. The settlement of saturated soil foundation is related to the negative excess pore pressure during loading.

Compared to the BCR, the PRS due to the inclusion of reinforcement is not widely considered in the experimental studies. A few of researches have demonstrated that the use of geosynthetic can effectively reduce the settlement of footing. Mandal and Sah [43] conducted the plate load tests on geogrid-reinforced clay bed and found that the maximum PRS by using geogrid is about 45%. Alawaji [48] carried out model tests on geogrid-reinforced sand foundation, and revealed that the maximum PRS can reach up to 95%. Moghaddas Tafreshi and Dawson [51] found that the PRS is approximately 64% by using the geotextile in sand foundation.

Although the deformation and bearing capacity of reinforced foundation under different influencing factors have been widely investigated, most of the model tests aim to study the performance of reinforced foundations under different factors by analyzing load-settlement responses. The researches with respect to reinforcing mechanism and failure mode are very limited. Several researchers have conducted the plate load tests to explore the evolution process of the displacement field and the failure mode of the soil in the reinforced foundation based on the digital image correlation (DIC) technology [32–34]. However, no further studies are performed to investigate the deformation and failure process of the reinforcement and the interaction between soil and reinforcement.

3.2 Field tests and large-scale model tests

The field test is the most direct and reliable way to study the load behavior of reinforced soil foundation. However, due to the complex geological conditions and the high

cost to conduct field tests, there are few studies concerning the field loading tests related to the reinforced foundation. Luo et al. [65] reported four different types of geosynthetic reinforced sand cushions in a 324 m long railway section to improve the performance of soft soil foundation, and monitored the embankment settlement, geogrid tension and earth pressure at embankment base under four reinforced sand cushions. They found that geosynthetics reinforced sand cushion can effectively reduce the settlement of soft soil foundation under the embankment load, and spread the embankment load to a wider area. Demir et al. [6] studied the load behavior of geogrid-reinforced sand foundations on the natural clay layer under different sizes of circular footing by means of 16 groups of field tests. The test results show that the soil modulus and bearing capacity of the foundation after reinforcement are significantly improved. Venkateswarlu et al. [20] carried out 38 groups of field resonance tests to study the dynamic response of machine foundation located on GRS foundation. Four test schemes were considered, i.e., unreinforced foundation, single layer geogrid reinforced foundation, double layer geogrid reinforced foundation and geocell reinforced foundation. The results show that the reinforcement especially for geocell can effectively reduce the vibration of the machine foundation.

Compared with the field tests, large-scale model tests can save the cost and time to construct models, and are more convenient to control the test conditions. Currently, scholars have performed a number of large-scale plate load tests to study the deformation and bearing characteristics of the foundation, and to further corroborate the results of the small-scale model tests. Adams and Collin [7] carried out 34 large-scale model tests to study the load-settlement characteristics of biaxial geogrid- or geocell-reinforced sand foundations. The inner size of the reinforced concrete test box used is 6.9 m × 5.4 m × 6 m (length × width × height), and the side lengths of the square concrete footings are 0.3 m, 0.46 m, 0.61 m and 0.91 m, respectively. The number of reinforcement layers, vertical spacing between reinforcement layers and the buried depth of first reinforcement layer were investigated. The results show that the bearing capacity ratio (BCR) of the reinforced foundation can reach up to 2.5. Abu-Farsakh et al. [8] conducted six large-scale plate load tests on geogrid reinforced silty clay foundation under the concrete footing with side length of 0.457 m, and studied the influence of the number of reinforcement layers, vertical spacing between reinforcement layers and tensile modulus of reinforcement. Moreover, the earth pressure in soil and strain distribution of reinforcement were monitored during the loading.

In addition to large-scale model tests under static load, some researchers have investigated the load-settlement

behaviors of reinforced foundations under cyclic loading [66]. Based on the large-scale test box with the size of $3 \text{ m} \times 1.6 \text{ m} \times 2.0 \text{ m}$ (length $\times$ width $\times$ height), Wang et al. [67] studied the deformation characteristics and bearing capacity of geogrid reinforced sand foundations under cyclic loading. The load-settlement curves, earth pressures within soils, dynamic acceleration responses and geogrid strain were monitored and analyzed. They reported that the dynamic load did not change the failure mode of reinforced foundation, but the reinforcement layout parameters had significant influence on the failure mode of soil foundation.

Table 2 summarizes the reteaches concerning the field tests and large-scale model tests of geosynthetic-reinforced foundations. From table, it can be seen that a majority of field or large-scale model tests are conducted on the geogrid-reinforced sand foundations or double-layered foundations. The types of footings used in the tests are circular and square footings. The performance of large strip or rectangular footings have not been investigated. This may be due to the limitation of load capacity of the loading device. The influencing parameters investigated mainly include the layout parameters of reinforcement, the unit weight of soil and the reinforcement stiffness. In future researches, other geosynthetics (e.g., geotextile), the size and shape of footings and the properties of backfill should be studied further. The results obtained from field and large-scale model tests are required to be compared with the results of

small-scale model tests, which can corroborate the findings of reduced model tests and provide references for the numerical studies.

4 Numerical study

Numerical simulations can corroborate the results obtained from model tests and further study the influence of the reinforcement parameters which are not involved in the model tests on the load-settlement characteristics of the reinforced foundation. It can also reveal the distribution of the soil displacement field, the deformation and tension distribution of the reinforcements, and the soil-reinforcement interactions during the loading. The numerical modelling methods include finite element method, finite difference method and discrete element method. By means of numerical programs, the load-settlement response, the distribution and evolution of the stress field, the displacement field of the foundation soil and the strain distribution of the reinforcement were investigated thoroughly. Table 3 summarizes the numerical modellings of the reinforced foundations. From table, it can be seen that a majority of numerical modellings on reinforced foundations are conducted using finite element program PLAXIS and finite difference software FLAC.

Table 2 Summary of the field tests and large-scale model tests on planar geosynthetic-reinforced foundation

Researchers	Type of test	Footing	Backfill soil	Foundation soil	Reinforcement	Size of test pit/box	Parameter investigated
Adams and Collin [7]	Large-scale test	Square	Sand	Sand	Geogrid/Geocell	6.9 m $\times$ 5.4 m $\times$ 6.0 m	N, u, h, L, γ
DeMerchant et al. [68]	Large-scale test	Circular	Aggregate	Aggregate	Geogrid	3.2 m $\times$ 2.2 m $\times$ 1.6 m	N, u, L, γ, J
Luo et al. [65] ^a	Field test	–	Sand	Clay	Geogrid	–	N
Abu-Farsakh et al. [8]	Field test	Square	Silty clay	Silty clay	Geogrid	3.66 m $\times$ 3.66 m $\times$ 1.83 m	N, h, J
Zhou and Wen [69] ^b	Large-scale test	–	Sand	Clay	Geogrid/Geocell	3.06 m $\times$ 1.18 m $\times$ 2.0 m	N
Chen et al. [66]	Large-scale test	Circular	Crushed limestone	Silty clay	Geogrid	2.0 m $\times$ 2.0 m $\times$ 1.7 m	Aperture shape
Demir et al. [6]	Field test	Circular	Granular fill	Clay	Geogrid	2.8 m $\times$ 2.8 m $\times$ 2.0 m	N, D
Demir et al. [15]	Field test	Circular	Granular fill	Clay	Geogrid	2.8 m $\times$ 2.8 m $\times$ 2.0 m	N, u, h
Venkateswarlu et al. [20]	Field test	Square	Silty sand	Silty clay/sand	Geogrid/Geocell	2.0 m $\times$ 2.0 m $\times$ 0.5 m	N, u
Wang et al. [67]	Large-scale test	Square	Sand	Sand	Geogrid	3.0 m $\times$ 1.6 m $\times$ 2.0 m	N, u

N , number of reinforcement; u , depth of the top layer of reinforcement; h , spacing between reinforcement layer; L , length or width of reinforcement; γ , unit weight of soil; J , tensile stiffness of reinforcement; D , diameter of footing

^aThe test was conducted in a segment of railway with the length of 324 m and the type of loading is embankment load

^bThe loading test was performed using air bag

Table 3 Summary of the numerical simulations on geosynthetic-reinforced soil foundations

Researchers	Method	Software	Footing type	Reinforcement
Yetimoglu et al. [47]	Finite element	DACSAR	Rectangular	Geogrid
Kurian et al. [14]	Finite element	–	Square	–
Lee et al. [70]	Finite element	PLAXIS ^{2D}	Strip	Geotextile
Basudhar et al. [5]	Finite difference	FLAC ^{2D}	Circular	Geotextile
Laman and Yildiz [13]	Finite element	PLAXIS ^{2D}	Ring	Geogrid
Deb et al. [18]	Finite difference	FLAC ^{2D}	Strip	–
Basudhar et al. [71]	Finite element	–	Strip	Geotextile
Ghazavi and Lavasan [72]	Finite difference	FLAC ^{3D}	Square	Planar geosynthetic
Latha and Somwanshi [10]	Finite difference	FLAC ^{3D}	Square	Geogrid, Geonet
Latha and Somwanshi [42]	Finite difference	FLAC ^{3D}	Square	Geogrid, Geonet
Zidan [73]	Finite element	PLAXIS ^{2D}	Circular	Geogrid
Chakraborty and Kumar [74]	Finite element	–	Circular	Geogrid
Demir et al. [15]	Finite element	PLAXIS ^{3D}	Circular	Geogrid
Naderi and Hataf [16]	Finite element	PLAXIS ^{3D}	Circular, Ring	Geogrid
Noorzad and Manavirad [75]	Finite element	PLAXIS ^{2D}	Strip	Geotextile
Bhandari et al. [22]	Discrete element	PFC ^{2D}	–	Geogrid
Kazi et al. [76]	Finite element	PLAXIS ^{2D}	Strip	Geotextile
Şadoğlu [77]	Finite element	PLAXIS ^{2D}	Strip	Geotextile
Tran et al. [78]	Finite element Discrete element	PFC ^{2D}	Strip	Geogrid
Hussein and Meguid [79]	Finite element	ABAQUS ^{3D}	Square	Geogrid
Badakhshan and Noorzad [59]	Finite element	ABAQUS ^{3D}	Circular, Square	Geotextile
Lai and Yang [80]	Finite difference	FLAC ^{2D}	Strip	Geotextile
Nasr and Azzam [60]	Finite element	PLAXIS ^{2D}	Strip	Geogrid, Geotextile
Oliaei and Kouzegaran [19]	Finite difference	FLAC ^{3D}	Square	Planar geosynthetic, Geocell
Venkateswarlu et al. [20]	Finite difference	FLAC ^{3D}	Square	Geogrid, Geocell
Gao and Meguid [23]	Discrete element	PFC ^{3D}	Square	Geogrid
Ouria and Mahmoudi [81]	Finite element	–	Strip	Geotextile
Aria et al. [82]	Finite element	PLAXIS ^{3D}	Strip	Wraparound geotextile
Zidan and Mohamed [17]	Finite element	PLAXIS ^{2D}	Strip	Geogrid
Wang et al. [24]	Discrete element	PFC ^{2D}	Strip	Geogrid

4.1 Finite element and finite difference modellings

There are two kinds of numerical modelling methods for reinforced foundation. One method is to regard the reinforced zone (including backfill and reinforcement) as a homogeneous soil, and to use the equivalent calculation methods to obtain the equivalent parameters of the homogeneous soil. Based on the equivalent parameters, a numerical model composed of the equivalent homogeneous soil and the surrounding soil is built [5, 32]. The other is to consider the inhomogeneity of the reinforced soil foundation. The backfill, reinforcement and soil-reinforcement interface are considered and simulated separately in the numerical models [10, 14, 18, 42].

In the literature, the finite element software for modeling reinforced foundation is PLAXIS 2D or 3D [13, 15–17]. In the models, the geogrid or plate structural element is

generally used to simulate the reinforcement and the behavior of structural elements is modeled as linear-elastic material. The Mohr Coulomb constitutive model is mostly used to simulate the soil behavior. In addition, the interaction between soil and reinforcement is modeled using interface element. The finite difference software used is FLAC 2D or 3D [10, 18–20, 42]. The reinforcement is usually simulated by cable or geogrid structural elements, and the soil is generally modeled by Mohr Coulomb constitutive model. The interaction between the soil and reinforcement was simulated using the grout properties of the cable or geogrid elements. Figure 7 shows the numerical model of reinforced foundation using PLAXIS and FLAC. The modeling results show that the numerical results are in good agreement with the test results. The distribution of displacement field, stress field and tensile force of reinforcement in the foundation are obtained and analyzed.

Fig. 7 Numerical model of the reinforced foundation using different softwares: **a** PLAXIS 2D (adopted from [75]); **b** PLAXIS 3D (adopted from [15]); **c** FLAC 2D (adopted from [18]) and **d** FLAC 3D (adopted from [20])

Moreover, based on the verified numerical model, the influence of other factors on the deformation and bearing behaviors of the reinforced foundation can be further investigated.

In the above numerical models, the reinforcement is regarded as continuous linear-elastic or elastic–plastic material, and the structural element in the numerical models is used to simulate the horizontal reinforcing material. However, it is difficult to simulate the real geometry of geogrid in practice, such as the grid aperture and the interaction between grid ribs and surrounding soil particles. Hussein and Meguid [79] used three-dimensional finite element software ABAQUS to simulate the geogrid-reinforced foundation (see Fig. 8). In the model, the real geometry of geogrid was considered and the solid element was used to simulate the geogrid. The interaction between soil and geogrid was modeled by interface element. The results show that the numerical results are in good agreement with the test results and the three-dimensional numerical model can well capture the interaction mechanism between soil and geogrid.

4.2 Discrete element modellings

Compared to the finite element and finite difference numerical simulations, the discrete element method to simulate the reinforced foundation can better reveal the interaction between granular soils and reinforcement, and analyze

the micromechanical characteristics of soil particles. Up to date, the researches about the numerical simulations using discrete element method is limited. The particle flow code software PFC 2D or 3D is used to simulate reinforced foundations [21, 23, 24]. In the two-dimensional numerical model, the spherical particles are bonded together to simulate the horizontal reinforcement [22], while in the three-dimensional numerical model, a large number of spherical particles are bonded to model the geometry of the geogrid [23]. The spherical particles with different sizes are used to simulate different types of soil or several particles are combined to simulate different shapes of foundation soil (e.g., angular gravel). The physical and mechanical properties of soils are simulated by defining micro parameters of particles (i.e., friction coefficient and stiffness coefficient). In addition, some scholars have simulated the reinforced foundation using finite-discrete element method. In this model, the finite solid element is used to simulate the reinforcement material, and the discrete element particles are used to model the surrounding soils [78]. Figure 9 presents the geogrid model and reinforced foundation model using discrete element method and finite-discrete element method.

Fig. 8 Three-dimensional numerical model of the reinforced foundation using program ABAQUS (sourced from [79])

Fig. 9 Numerical models: **a** geogrid using PFC (adopted from [23]); **b** reinforced foundation using PFC (adopted from [24]) and **c** reinforced foundation based on finite-discrete element method (adopted from [78])

5 Analytical study

The analytical solutions of ultimate bearing capacity and settlement of reinforced foundation are proposed based on the previous test results and several assumptions. The analytical study concerning the settlement of reinforced foundation is very limited. Therefore, this paper only summarizes the theoretical researches on the bearing capacity of reinforced foundation. The methods

to calculate the ultimate bearing capacity of reinforced foundation include limit equilibrium method, limit analysis method, finite element method, regression analysis method and sliding line analysis method, etc. Among them, most of scholars use the limit equilibrium method to deduce the formula of the ultimate bearing capacity of reinforced foundation based on the assumed failure modes and test results. The failure modes of reinforced foundation can be summarized as six modes shown in Fig. 10. Mode 1 and mode 2 are the failure of the soils

Fig. 10 Failure modes of the reinforced foundations (adapted from [1, 25–27, 30, 39])

above the top reinforcement layer or between layers. The reason is that the distance between the footing and first layer of reinforcement (u/B) and the vertical spacing between reinforcement layers (h/B) are too large, resulting in the local shear failure. In the engineering project, the occurrence of failure mode 1 and 2 can be avoided by decreasing u and h . Meyerhof and Hanna [83] first proposed the failure mode 3, which was used to calculate the bearing capacity of double-layer foundation under inclined load. Afterward, Huang and Tatsuoka [25] verified this mode through laboratory model tests. In this mode, the punching shear failure in the reinforced zone occurs first and then the general shear failure surface develops beneath the reinforced zone. Mode 4 was first proposed by Schlosser et al. [40] and then used by Huang and Menq [30] for the derivation of bearing capacity formula. In this failure mode, it is considered that the punching shear failure along the diffusion angle α in the reinforced zone occurs first, and then a general slip surface is formed below the reinforced zone. Based on the model test results, Chen and Abu-Farsakh [27] summarized the failure mode (Mode 5) of reinforced foundation. They considered that the punching shear failure with depth of D_p occurs first within the reinforced zone,

and then the general shear surface develops. The value of D_p depends on the relative strength between the reinforced zone and the underlying unreinforced soil. Mode 6 is similar to Prandtl failure mode, in which the general shear failure surface initiates from the edge of footing and develops through the whole reinforced zone. At present, the analytical solutions for the ultimate bearing capacity of reinforced soil foundation is proposed based on Modes 3, 4, 5 and 6. Table 4 summarizes the analytical solutions on the ultimate bearing capacity of reinforced foundation.

5.1 Limit equilibrium method

Based on a failure mode and limit equilibrium method, most of researchers develops the calculation methods of the ultimate bearing capacity of reinforced foundation considering the contribution of reinforcing materials to the bearing capacity of the soil foundation. The basic formula is as follows:

$$q_r = q_u + \Delta q \quad (3)$$

Table 4 Summary of the analytical solutions on the ultimate bearing capacity of reinforced foundation

Researchers	Method	Footing type	Reinforcing mechanism	Failure mode
Binquet and Lee [39]	Limit equilibrium	Strip	Tensioned membrane effect	–
Yamanouch and Gotoh [84]	Limit equilibrium	Strip	Tensioned membrane effect Surcharge effect	–
Huang and Tatsuoka [25]	Limit equilibrium	Strip	Deep footing effect Tensioned membrane effect Stress dispersion effect	Mode 3 and 6
Huang and Menq [30]	Regression analysis	Strip Square	Deep footing effect Stress dispersion effect	Mode 4
Wayne et al. [26]	Limit equilibrium	Rectangular Square	Tensioned membrane effect Lateral restraint effect	Mode 3
Huang and Hong [41]	Regression analysis	Strip Rectangular	Deep footing effect Stress dispersion effect	Mode 4
Wang and Wang [85]	Limit equilibrium	Strip	Tensioned membrane effect Lateral restraint effect	Mode 6
Yamamoto and Kusuda [28]	Limit analysis	Strip	–	Mode 6
Kumar and Saran [86]	Limit equilibrium	Rectangular	Tensioned membrane effect	–
Michalowski [33]	Limit analysis	Strip	–	Mode 6
Bera et al. [31]	Regression analysis	Square	–	–
Liang and Yang [87]	Limit equilibrium	Strip	Lateral restraint effect	Mode 6
Sharma et al. [1]	Limit equilibrium	Strip Square	Tensioned membrane effect Lateral restraint effect	Mode 3 and 6
Chen et al. [9]	Limit equilibrium	Strip Square	Tensioned membrane effect Lateral restraint effect	Mode 5
Kumar and Sahoo [36]	Limit analysis	Strip	–	–
Latha et al. [88]	Regression analysis	Square	–	–
Chen and Abu-Farsakh [27]	Limit equilibrium	Strip	Tensioned membrane effect Lateral restraint effect	Mode 5
Cicek and Guler [89]	Limit equilibrium	Strip	Tensioned membrane effect	Mode 6

where q_r is the ultimate bearing capacity of reinforced foundation, q_u is the ultimate bearing capacity of unreinforced foundation, and Δq is the contribution of reinforcement to the bearing capacity of foundation. The theoretical method for calculating the ultimate bearing capacity of reinforced foundation was first proposed by Binquet and Lee [39] based on the limit equilibrium method and considering the tensioned membrane effect of reinforcement. After that, some scholars modified the solution to calculate the ultimate bearing capacity of unreinforced foundation proposed by Terzaghi, and then deduced the calculation method for the reinforced foundation [84]. The effect of the settlement of cushion, the side pressure effect of reinforcement and the vertical tension of reinforcement on the bearing capacity of reinforced foundation were considered in these solutions. Huang and Tatsuoka [25] based on failure Modes 3 and 6, derived the calculation formula of the bearing capacity of the reinforced foundation with consideration of the balance between the reinforced blocks. Based on Mode 3 and considering the tensioned membrane effect of reinforcement, Wayne et al. [26] proposed the analytical method to evaluate the ultimate bearing capacity of reinforced foundation. Sharma et al. [1] considered the contribution of tensioned membrane effect and lateral restraint effect to the bearing capacity of foundation, and based on Modes 3 and 6, developed the theoretical solution of the ultimate bearing capacity of reinforced foundation under strip and square footings, respectively. Then Chen and Abu-Farsakh [27] put forward

the calculation formula of the ultimate bearing capacity of reinforced foundation based on Mode 5.

Some of the researchers propose the calculation method for the ultimate bearing capacity of reinforced foundation based on the reinforcing mechanisms, without considering the failure modes. Wang and Wang [85] considered the contribution of tensioned membrane effect and lateral restraint effect of reinforcement to the improvement of bearing capacity, and deduced the calculation formula of bearing capacity increment of reinforced foundation. Kumar and Saran [86] assumed that the reinforced material bends at the intersection of the stress dispersion line and the stress field distribution in the reinforced foundation is the same as that in the unreinforced foundation. Based on the elastic half-space theory, they developed the formula to calculate the bearing capacity of the reinforced foundation. Shi [90] considered the stress dispersion effect in the reinforced zone, the deep footing effect, the upward tension of the reinforcement material and the lateral restraint effect caused by the horizontal tension of the reinforcement, and then proposed the analytical solution of the bearing capacity increment of reinforced foundation.

5.2 Limit analysis method and other analytical methods

In addition to the limit equilibrium method, the limit analysis method is also widely used in the derivation of

the calculation method for the ultimate bearing capacity of reinforced foundation. The limit analysis upper-bound solution is mostly used to calculate the ultimate bearing capacity of horizontal reinforced foundation based on the principle of energy dissipation [28, 33, 91]. By calculating the energy dissipation under the action of external forces, the energy dissipation on the cross-section, and the energy dissipation of reinforcements on the sliding surface, the ultimate bearing capacity of the reinforced foundation is finally determined. Some scholars also use the finite-element limit analysis method to evaluate the ultimate bearing capacity of reinforced foundation [92, 93].

Except limit equilibrium method and limit analysis method, other analytical methods are also used to calculate the bearing capacity of reinforced foundation, including regression analysis method [30, 31, 41, 88], finite element method [32], and slip line method, etc.

6 Current research trend and future prospect

In recent years, more and more researchers pay attention to the deformation and bearing capacity of reinforced foundation under repeated or cyclic loads [22, 54, 61, 67]. Tavakoli Mehrjardi and Khazaei [54] conducted model tests to study the influence of soil particle size, aperture size of geogrid and size of footing on the load-settlement behavior of geogrid reinforced foundation under repeated load. Suku et al. [61] investigated the effect of geogrid reinforced gravel soil foundation on reducing pavement settlement and improving the overall performance of the road through cyclic plate load tests. Wang et al. [67] carried out large-scale model tests to study the mechanical deformation characteristics of geogrid reinforced sand foundation under cyclic load. However, compared with the uniform load, the cyclic load (or repeated load) and other forms of dynamic load need to be further investigated. In addition, the applications of the GRS foundation become more and more widely. Many scholars have investigated the role of geogrid or geotextile in railway track, mechanical foundation, highway pavement and the protection of shallow buried pipeline [20, 94–100]. Venkateswarlu et al. [20] performed field resonance tests to study the dynamic response of GRS foundation under machine foundation. The results showed that the reinforcement can effectively reduce the vibration of machine foundation, and the geocell reinforcement performed better than geogrid. Esmaeili et al. [94] explored the role of geogrid reinforced ballast in enhancing lateral restraint and overall stability of railway track through laboratory model tests and field tests. Kerman et al. [99] studied the effectiveness of geotextiles

placed between subgrade and subbase under cyclic traffic load to reduce the migration of fine aggregate in the subgrade to coarse aggregate in the subbase, and found that geotextiles have a good isolation effect on improving the durability and reliability of pavement. Elsesheny et al. [98] carried out large-scale model tests to investigate the deformation characteristics of the pipeline within the soil foundation reinforced by geogrid under the cyclic load, and studied the influence of the number of reinforcement layers. The results show that the reinforcement can effectively reduce the deformation of the pipeline and enhance the lateral restraint to the pipeline. In addition, some scholars have studied the effect of GRS foundation on reducing differential settlement of the ground surface and improving the stability of embankment as the faults passed through [101]. Although the application of reinforced foundation is wide, the performance of the reinforced foundation combining the geogrid or geotextile with other types of reinforcing materials (such as geocell, EPS geofoam, geobag, etc.) are required to be investigated further.

The small-scale model test is mostly used in the experimental study to investigate the performance of reinforced foundation, but the large-scale model test or field test is still limited. Due to the size effect, the results of small-scale model tests can not fully capture the actual behavior of the reinforced soil foundations in field. Therefore, more and more large-scale tests or field tests should be conducted. However, considering that large-scale test and field test will cost a lot of time and money, centrifuge model test could be an alternative approach to study the load-settlement behavior of reinforced foundations in the future.

It is difficult to obtain the stress field, soil displacement field, and strain distribution of reinforcement in the tests. Numerical simulations can overcome these shortcomings. Many researchers analyzed the deformation and load behavior of reinforced foundation under different layout parameters of reinforcement, reinforcement properties and soil properties by comparing the load-settlement curves in the numerical modellings. Furthermore, the deformation of reinforcement, stress field and soil displacement field were obtained. However, the influence of the rupture of reinforcement on the bearing capacity and deformation characteristics of reinforced foundation is not considered in the numerical modellings. Hence, it is necessary to investigate the rupture of the reinforcement layer on the performance of reinforced foundations. In recent years, the discrete element numerical simulations have been applied to study the micro characteristics of reinforced foundation under footing loading [23, 24, 78]. On this basis, the load settlement response and failure pattern of reinforced foundation after the fracture of reinforced material can be further studied in the future.

Up to now, the researches on the analytical solutions of the bearing capacity of reinforced foundation is relatively scarce. Due to the different understandings on the reinforcing mechanism and failure mode of reinforced foundation, there is no relatively unified and accurate calculation method of the ultimate bearing capacity. In the future, it is essential to focus on the reinforcing mechanism, verify the proposed failure mode (see Fig. 10), and establish the relationship between failure mode and layout parameters of reinforcement. However, because of the opaque of natural soils, the soil-reinforcement interaction is difficult to be investigated. Recently, the application and development of transparent soils provide the possibility for the study of failure mode and interaction between soil and reinforcement. Chen et al. [102] carried out laboratory model tests based on transparent soil technology to investigate the deformation and failure processes of reinforcements, but did not explore the strain distribution of reinforcement during the loading.

7 Conclusions

This paper first summarizes the reinforcing mechanism of reinforced materials, then presents the literature review of planar geosynthetic-reinforced foundations from experimental study, numerical modeling and theoretical analysis, and finally discusses the current research trends and future prospects of reinforced foundation. Based on the analyses and discussions of the existing literature, the following main conclusions can be drawn:

- Based on a large number of model tests, the optimum layout parameters for the geosynthetic-reinforced foundations can be obtained. The proper embedment depth (u) of the top reinforcement layer ranges from 0.3 B to 0.4 B , where B is the width or diameter of the footing. The optimum spacing between reinforcement layers (h) is between 0.2 B and 0.4 B . The optimal length of reinforcement (L) varies from 4 to 5 B . The effective reinforced depth (d_r) ranges from 1.5 B to 2 B . The optimum number of reinforcement layers N can be determined according to the above optimized u , h and d_r .
- In addition to the layout of reinforcements, the properties of reinforcement including stiffness, strength and aperture size have significant effect on the performance of reinforced foundations. The bearing capacity of reinforced foundation increases with the increase in strength and stiffness of reinforcements. However, when the stiffness is larger than a certain value, it could not result in significant increase of bearing capacity. The optimum aperture size of geogrids should be about 4 times of medium grain size of soils.
- Except the properties of reinforcements, the type and shape of reinforcement can significantly influence the load-settlement response of reinforced soil foundations. The geogrid performs better than geotextile in improving bearing capacity of foundations. In addition, the biaxial geogrid is better than uniaxial geogrid to enhance the performance of soil foundation.
- At the same reinforcement layout, the ultimate bearing capacity of reinforced sand foundation is substantially greater than that of clay foundation. The relative density of sand can also significantly affect the performance of soil foundation. The bearing capacity of foundation increases with increasing of relative density.
- The reinforcing mechanisms of the planar reinforcement (e.g., geogrid and geotextile) are summarized as: lateral restraint effect; tensioned membrane effect; stress dispersion effect and deep footing effect. Based on test results and assumptions, a total of six failure modes of reinforced foundations are proposed to develop the analytical solutions for calculating bearing capacity of reinforced foundations.

In the future, it is necessary to focus on the investigation of the performance of reinforced foundations combining the geogrid or geotextile with other types of geosynthetics (such as geocell, geobag and EPS geofoam), and to conduct field loading test, large-scale model test or centrifugal model test to study the performance of reinforced foundation under more real stress conditions. In addition, it is essential to pay attention to the deformation and strain distribution of reinforced materials, which is the key parameter for calculating the ultimate bearing capacity of reinforced foundations. However, due to the different understandings on the reinforcing mechanism and failure mode of the reinforced foundation, the current researches on the calculation method for the ultimate bearing capacity of the reinforced foundation is relatively limited. There is no unified and recognized calculation formula of the bearing capacity. The interaction between reinforcement and soil and the type of failure mode based on mesoscale analysis will be the focus of future researches.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Sharma R, Chen QM, Abu-Farsakh M, Yoon S (2009) Analytical modeling of geogrid reinforced soil foundation. *Geotext Geomembr* 27:63–72

2. Omar MT, Das BM, Puri VK, Yen SC (1993) Ultimate bearing capacity of shallow foundations on sand with geogrid reinforcement. *Can Geotech J* 30:545–549
3. Das BM, Shin EC, Omar MT (1994) The bearing capacity of surface strip foundations on geogrid-reinforced sand and clay—a comparative study. *Geotech Geol Eng* 12:1–14
4. Shin EC, Das BM (2000) Experimental study of bearing capacity of a strip foundation on geogrid-reinforced sand. *Geosynth Int* 7(1):59–71
5. Basudhar PK, Saha Roy S, Deb K (2007) Circular footings resting on geotextile-reinforced sand bed. *Geotext Geomembr* 25:377–384
6. Demir A, Laman M, Yildiz A, Ornek M (2013) Large scale field tests on geogrid-reinforced granular fill underlain by clay soil. *Geotext Geomembr* 38:1–15
7. Adams MT, Collin JG (1997) Large model spread footing load tests on geosynthetic reinforced soil foundations. *J Geotech Geoenviron Eng* 123(1):66–72
8. Abu-Farsakh M, Chen QM, Sharma R, Zhang X (2008) Large-scale model footing tests on geogrid reinforced foundation and marginal embankment soil. *Geotech Test J* 31(5):413–423
9. Chen QM, Abu-Farsakh M, Sharma R (2009) Experimental and analytical studies of reinforced crushed limestone. *Geotext Geomembr* 27:357–367
10. Latha GM, Somwanshi A (2009a) Effect of reinforcement form on the bearing capacity of square footings on sand. *Geotext Geomembr* 27:409–422
11. Saha Roy S, Deb K (2017a) Bearing capacity of rectangular footings on multilayer geosynthetic-reinforced granular fill over soft soil. *Int J Geomech* 17(9):04017069
12. Saha Roy S, Deb K (2017b) Effects of aspect ratio of footings on bearing capacity for geogrid-reinforced sand over soft soil. *Geosynth Int* 24(4):362–382
13. Laman M, Yildiz A (2007) Numerical studies of ring foundations on geogrid reinforced Sand. *Geosynth Int* 14(2):52–64
14. Kurian NP, Beena KS, Kumar RK (1997) Settlement of reinforced sand in foundations. *J Geotech Geoenviron Eng* 123:818–827
15. Demir A, Yildiz A, Laman M, Ornek M (2014) Experimental and numerical analyses of circular footing on geogrid-reinforced granular fill underlain by soft clay. *Acta Geotech* 9:711–723
16. Naderi E, Hataf N (2014) Model testing and numerical investigation of interference effect of closely spaced ring and circular footings on reinforced sand. *Geotext Geomembr* 42:191–200
17. Zidan AF, Mohamed M (2019) Numerical analysis of bearing capacity of multiple strip footing on unreinforced and reinforced sand beds. *SN Appl Sci* 1:1499
18. Deb K, Sivakugan N, Chandra S, Basudhar PK (2007) Numerical analysis of multi layer geosynthetic-reinforced granular bed over soft fills. *Geotech Geol Eng* 25(6):639–646
19. Oliaei M, Kouzegaran S (2017) Efficiency of cellular geosynthetics for foundation reinforcement. *Geotext Geomembr* 45:11–22
20. Venkateswarlu H, Ujjawal KN, Hegde A (2018) Laboratory and numerical investigation of machine foundations reinforced with geogrids and geocells. *Geotext Geomembr* 46(6):882–896
21. Vinod JS, Nagaraja S, Sitharam TG, Dinesh SV (2011) Numerical Simulation of reinforced granular soils using DEM. *Geo Front* pp 4242–4251
22. Bhandari A, Han J, Parsons RL (2015) Two-dimensional DEM analysis of behavior of geogrid-reinforced uniform granular bases under a vertical cyclic load. *Acta Geotech* 10:469–480
23. Gao G, Meguid MA (2018) Effect of particle shape on the response of geogrid-reinforced systems: insights from 3D discrete element analysis. *Geotext Geomembr* 46(1):685–698
24. Wang ZJ, Jacobs F, Ziegler M, Yang GQ (2020) Visualisation and quantification of geogrid reinforcing effects under strip footing loads using discrete element method. *Geotext Geomembr* 48(1):62–70
25. Huang CC, Tatsuoka F (1990) Bearing capacity reinforced horizontal sandy ground. *Geotext Geomembr* 9:51–82
26. Wayne MH, Han J, Akins K (1998) The design of geosynthetic reinforced foundations. In: *Proceedings of ASCE's 1998 annual convention & exposition*. Vol 76. ASCE Geotechnical Special Publication pp 1–18
27. Chen QM, Abu-Farsakh M (2015) Ultimate bearing capacity analysis of strip footings on reinforced soil foundation. *Soils Found* 55(1):74–85
28. Yamamoto K, Kusuda K (2001) Failure mechanisms and bearing capacities of reinforced foundations. *Geotext Geomembr* 19:127–162
29. Michalowski RL (2004) Limit loads on reinforced foundation soils. *J Geotech Geoenviron Eng* 130(4):381–390
30. Huang CC, Menq FY (1997) Deep-footing and wide-slab effects in reinforced sandy ground. *J Geotech Geoenviron Eng* 123(1):30–36
31. Bera AK, Ghosh A, Ghosh A (2005) Regression model for bearing capacity of a square footing on reinforced pond ash. *Geotext Geomembr* 23(3):261–285
32. Yamamoto K, Otani J (2002) Bearing capacity and failure mechanism of reinforced foundations based on rigid-plastic finite element formulation. *Geotext Geomembr* 20:367–393
33. Michalowski RL, Shi L (2003) Deformation patterns of reinforced foundation sand at failure. *J Geotech Geoenviron Eng* 129:439–449
34. Zhou J, Kong XL, Wang XC (2008) Bearing capacity behaviours and failure modes of reinforced grounds. *Chin J Geotech Eng* 30(9):1265–1269 ((in Chinese))
35. Hegde A (2017) Geocell reinforced foundation beds—past findings, present trends and future prospects: a state-of-the-art review. *Constr Build Mater* 154:658–674
36. Biswas A, Krishna AM (2017) Geocell-reinforced foundation systems: a critical review. *Int J Geosynth Ground Eng* 3:17
37. Guido VA, Chang DK, Sweeney MA (1986) Comparison of geogrid and geotextile reinforced earth slabs. *Can Geotech J* 23:435–440
38. Binquet J, Lee KL (1975a) Bearing capacity tests on reinforced earth slabs. *J Geotech Eng Div ASCE* 101(GT12):1241–1255
39. Binquet J, Lee KL (1975b) Bearing capacity analysis on reinforced earth slabs. *J Geotech Eng Div ASCE* 101(GT12):1257–1276
40. Schlosser E, Jacobsen HM, Juran I (1983) Soil reinforcement: general report. Paper presented at 8th European conference on soil mechanics and foundation engineering, Balkema, Helsinki, pp 83–103
41. Huang CC, Hong LL (2000) Ultimate bearing capacity and settlement of footings on reinforced sandy ground. *Soils Found* 40(5):65–73
42. Latha GM, Somwanshi A (2009b) Bearing capacity of square footings on geosynthetic reinforced sand. *Geotext Geomembr* 27:281–294
43. Mandal JN, Sah HS (1992) Bearing capacity tests on geogrid reinforced clay. *Geotext Geomembr* 11(3):327–333
44. Shin EC, Das BM, Puri VK, Yen SC, Cook EE (1993) Bearing capacity of strip foundation on geogrid reinforced clay. *Geotech Test J ASTM* 16(4):534–541
45. Khing KH, Das BM, Puri VK, Cook EE, Yen SC (1993) The bearing capacity of a strip foundation on geogrid-reinforced sand. *Geotext Geomembr* 12(4):351–361
46. Das BM, Omar MT (1994) The effects of foundation width on model tests for the bearing capacity of sand with geogrid reinforcement. *Geotech Geol Eng* 12(3):133–141

47. Yetimoglu T, Wu JTH, Aaglamer A (1994) Bearing capacity of rectangular footings on geogrid-reinforced sand. *J Geotech Eng* 120(12):2083–2099
48. Alawaji HA (2001) Settlement and bearing capacity of geogrid reinforced sand over collapsible soil. *Geotext Geomembr* 19(2):75–88
49. Sitharam TG, Sireesh S (2004) Model studies of embedded circular footing on geogrid reinforced sand beds. *Ground Improv* 8(2):69–75
50. Ghosh A, Ghosh A, Bera AK (2005) Bearing capacity of square footing on pond ash reinforced with jute-geotextile. *Geotext Geomembr* 23:144–173
51. Moghaddas Tafreshi SN, Dawson AR (2010) Comparison of bearing capacity of a strip footing on sand with geocell and with planar forms of geotextile reinforcement. *Geotext Geomembr* 28(1):72–84
52. Abu-Farsakh M, Chen QM, Sharma R (2013) An experimental evaluation of the behavior of footings on geosynthetic-reinforced sand. *Soils Found* 53(2):335–348
53. Useche-Infante D, Aiassa Martinez G, Arrúa P, Eberhardt M (2019) Experimental study of behaviour of circular footing on geogrid-reinforced sand. *Geomech Geoeng* 1–19
54. Tavakoli Mehrjardi GT, Khazaei M (2017) Scale effect on the behaviour of geogrid-reinforced soil under repeated loads. *Geotext Geomembr* 45:603–615
55. Tavakoli Mehrjardi Gh, Ghanbari A, Mehdizadeh H (2016) Experimental study on the behavior of geogrid-reinforced slopes with respect to aggregate size. *Geotext Geomembranes* 44(6):862–871
56. Lavasann AA, Ghazavi M (2012) Behavior of closely spaced square and circular footings on reinforced sand. *Soils Found* 52(1):160–167
57. Saha Roy S, Deb K (2019) Interference Effect of Closely Spaced Footings Resting on Granular Fill over Soft Clay. *Int J Geomech* 19(1):04018181
58. Badakhshan E, Noorzad A (2015) Load eccentricity effects on behavior of circular footings reinforced with geogrid sheets. *J Rock Mech Geotech Eng* 7:691–699
59. Badakhshan E, Noorzad A (2017) Effect of footing shape and load eccentricity on behavior of geosynthetic reinforced sand bed. *Geotext Geomembr* 45(2):58–67
60. Nasr AM, Azzam WR (2017) Behaviour of eccentrically loaded strip footings resting on sand. *Int J Phys Model Geo* 17(3):177–194
61. Suku L, Prabhu SS, Babu GS (2017) Effect of geogrid-reinforcement in granular bases under repeated loading. *Geotext Geomembr* 45(4):377–389
62. Durga-Prasad B, Hariprasad C, Umashankar B (2016) Load-settlement response of square footing on geogrid reinforced layered granular beds. *Int J of Geosynth and Ground Eng* 2(36):1–10
63. Huang CC (2016) Ultimate bearing capacity of saturated reinforced horizontal ground. *Geosynth Int* 23(1):1–8
64. Huang CC (2017) Model tests on the bearing capacity of reinforced saturated sand ground. *Geosynth Int* 24(2):114–124
65. Luo Q, Liu JY, Zhang L (2003) Application of geosynthetics-reinforced sand blanket to settlement reduction of soft ground. *Chin J Geotech Eng* 25(6):710–714 ((in Chinese))
66. Chen QM, Abu-Farsakh M, Tao MJ (2009) Laboratory evaluation of geogrid base reinforcement and corresponding instrumentation program. *Geotech Test J* 32(6):516–525
67. Wang JQ, Zhang LL, Xue JF, Tang Y (2018) Load-settlement response of shallow square footings on geogrid-reinforced sand under cyclic loading. *Geotext Geomembr* 46(5):586–596
68. DeMerchant MR, Valsangkar AJ, Schriver AB (2002) Plate load tests on geogrid-reinforced expanded shale lightweight aggregate. *Geotext Geomembr* 20:173–190
69. Zhou HB, Wen XJ (2008) Model studies on geogrid- or geocell-reinforced sand cushion on soft soil. *Geotext Geomembr* 26:231–238
70. Lee KM, Manjunath VR, Dewaikar DM (1999) Numerical and model studies of strip footing supported by a reinforced granular fill-soft soil system. *Can Geotech J* 36(5):793–806
71. Basudhar PK, Dixit PM, Gharpure A, Deb K (2008) Finite element analysis of geotextile-reinforced sand-bed subjected to strip loading. *Geotext Geomembr* 26(1):91–99
72. Ghazavi M, Lavasan AA (2008) Interference effect of shallow foundations constructed on sand reinforced with geosynthetics. *Geotext Geomembr* 26:404–415
73. Zidan AF (2012) Numerical study of behavior of circular footing on geogrid-reinforced sand under static and dynamic loading. *Geotech Geol Eng* 30(2):499–510
74. Chakraborty D, Kumar J (2015) Bearing Capacity of Circular Footings on Reinforced Soils. *Int J Geomech* 15(1):04014034
75. Noorzad R, Manavirad E (2014) Bearing capacity of two close strip footings on soft clay reinforced with geotextile. *Arab J Geosci* 7:623–639
76. Kazi M, Shukla SK, Habibi D (2015) An improved method to increase the load-bearing capacity of strip footing resting on geotextile-reinforced sand bed. *Indian Geotech J* 45(1):98–109
77. Şadoğlu E (2015) Numerical analysis of centrally and eccentrically loaded strip footing on geotextile-reinforced sand. *Geosynth Int* 22(3):225–234
78. Tran VDH, Meguid MA, Chouinard LE (2015) Three-dimensional analysis of geogrid-reinforced soil using a finite-discrete element framework. *Int J Geomech* 15(4):04014066
79. Hussein MG, Meguid MA (2016) A three-dimensional finite element approach for modeling biaxial geogrid with application to geogrid-reinforced soils. *Geotext Geomembr* 44:295–307
80. Lai J, Yang BH (2017) Laboratory Testing and numerical simulation of a strip footing on geosynthetically reinforced loose sand. *J Test Eval* 45(1):51–60
81. Ouria A, Mahmoudi A (2018) Laboratory and numerical modeling of strip footing on geotextile-reinforced sand with cement-treated interface. *Geotext Geomembr* 46(1):29–39
82. Aria S, Kumar SS, Mohyeddin A (2019) Numerical investigation of wraparound geotextile reinforcement technique for strengthening foundation soil. *Int J Geomech* 19(4):04019003
83. Meyerhof GG, Hanna AM (1978) Ultimate bearing capacity of foundations on layered soils under inclined load. *Can Geotech J* 15(4):565–572
84. Yamanouch T, Gotoh K (1979) A proposed practical formula of bearing capacity for earth work method on soft clay ground using a resinous mesh. *Technol Rep Kyushu Univ* 52(3):201–207
85. Wang Z, Wang XQ (2000) Limit analysis for reinforced foundations. *J Tsinghua Univ Sci Technol* 41(6):112–1114 ((in Chinese))
86. Kumar A, Saran S (2003) Bearing capacity of rectangular footing on reinforced soil. *Geotech Geol Eng* 21(3):201–224
87. Liang B, Yang YH (2008) Theory and experiment on bearing capacity of reinforced sandy soil. *Chin J Geotech Eng* 30(1):123–127 ((in Chinese))
88. Latha GM, Somwanshi A, Reddy KH (2013) A multiple regression equation for prediction of bearing capacity of geosynthetic reinforced sand beds. *Indian Geotech J* 43(4):331–343
89. Cicek E, Guler E (2015) Bearing capacity of strip footing on reinforced layered granular soils. *J Civ Eng Manag* 21(5):605–614
90. Shi YZ (2007) The methods of calculating bearing capacity of foundation reinforced with geotextile grid. *Soil Eng Found* 21(1):59–62 ((in Chinese))

91. Cao WG, Tan JH, Hu WD (2018) Upper bound of ultimate bearing capacity for the reinforced grounds. *Rock Soil Mech* 39(6):1955–1962 **((in Chinese))**
92. Kumar J, Sahoo JP (2013) Bearing capacity of strip foundations reinforced with geogrid sheets by using upper bound finite– element limit analysis. *Int J Numer and Anal Met* 37(18):3258–3277
93. Chakraborty M, Kumar J (2014) Bearing capacity of circular foundations reinforced with geogrid sheets. *Soils Found* 54(4):820–832
94. Esmaeili M, Zakeri JB, Babaei M (2017) Laboratory and field investigation of the effect of geogrid-reinforced ballast on railway track lateral resistance. *Geotext Geomembr* 45:23–33
95. Yan K, Kumar S, Alireza M (2018) Experimental investigation for pressure distribution on flexible conduit covered with sandy soil reinforced with geotextile reinforcement of varying widths. *Tunn Undergr Sp Tech* 80:151–163
96. Plácido R, Portelinhab FHM (2019) Evaluation of geocomposite compressible layers as induced trench method applied to shallow buried pipelines. *Geotext Geomembr* 47:662–670
97. Abdollahi M, Moghaddas Tafreshi SN, Leshchinsky B (2019) Experimental numerical assessment of geogrid-EPS systems for protecting buried utilities. *Geosynth Int* 26(4):333–353
98. Elshesheny A, Mohamed M, Sheehan T (2019) Buried flexible pipes behaviour in unreinforced and reinforced soils under cyclic loading. *Geosynth Int* 26(2):184–205
99. Kerman B, Stoffels SM, Xiao M (2020) Evaluation of effectiveness of geotextile in reducing subgrade migration in rigid pavement. *Geosynth Int* 27(1):97–109
100. Singha RP, Nimbalkar S, Singh S, Choudhury D (2020) Field assessment of railway ballast degradation and mitigation using geotextile. *Geotext Geomembr* 48:275–283
101. Yang KH, Chiang J, Lai CW, Han J, Lin ML (2020) Performance of geosynthetic-reinforced soil foundations across a normal fault. *Geotext Geomembr* 48(3):357–373
102. Chen JF, Guo XP, Xue JF, Guo PH (2019) Load behaviour of model strip footings on reinforced transparent soils. *Geosynth Int* 26(3):251–260

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.