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Review

Sustainable Soil Bearing Capacity Improvement Using Natural Limited Life Geotextile Reinforcement—A Review

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Abstract: Geotextiles are commercially made from synthetic fibres and have been used to enhance bearing capacity and to reduce the settlement of weak soil foundations. Several efforts have been made to investigate the possibility of using bio-based geotextiles for addressing environmental issues. This paper attempts to review previous studies on the bearing capacity improvement of soils reinforced with bio-based geotextiles under a vertical static load. The bearing capacity of the unreinforced foundation was used as a reference to illustrate the role of bio-based geotextiles in bearing capacity improvement. The effects of first geotextile depth to footing width ratio (d/B), geotextile spacing to footing width ratio (S/B), geotextile length to footing width ratio (L/B) and the number of reinforcement layers (N) on the bearing capacity were reviewed and presented in this paper. The optimum d/B ratio, which resulted in the maximum ultimate bearing capacity, was found to be in the range of 0.25–0.4. The optimum S/B ratio was in the range of 0.12–0.5. The most suitable L/B ratio, which resulted in better soil performance against vertical pressure, was about 3. Besides, the optimum number of layers providing the maximum bearing capacity was about three This article is useful as a guideline for a practical design and future research on the application of the natural geotextiles to improve the short-term bearing capacity of weak soil foundations in various sustainable geotechnical applications.

Keywords: ground improvement; natural geotextile; bearing capacity; settlement

1. Introduction

Over the years, the extensive gain of basic facilities and the standard of living in urban areas has caused a drastic increase in land prices globally. The building industry has therefore attempted to develop available cheap lands, which are often located on poor ground conditions. These cheap lands are often found in low lying areas, often comprising geologically recent marine and estuarine deposits. The soil deposits in these areas generally possess undesirable geotechnical properties, including low strength and high compressibility.

Ground improvement methods have been applied for many years to improve the engineering properties of weak soils, especially bearing capacity and compressibility. Bearing capacity failure occurs when the shear strength of the soil is less than the shear stress. The bearing capacity improvement of a shallow footing is essential in geotechnical engineering practice. Ground improvement techniques include densification through vibration, blasting and compaction, pre-compression, electro-osmosis, drainage, drying, the inclusion of admixtures, such as cement and lime, the setting up of stiffening columns, and chemical and natural reinforcement [1–26].

One of the methods to improve the bearing capacity of the soil mass is with geotextile reinforcement. Soil is naturally strong in compression but weak in tension [27]. High tensile strength reinforcement can, therefore, be used to improve the tensile ability of the soil [28] and hence its load-carrying capacity. According to EN ISO 10318-1 [29], a geotextile is defined as: planar, permeable, polymeric (synthetic or natural) textile material, which may be nonwoven, knitted or woven, used in contact with soil and other materials in geotechnical and civil engineering applications (p. 2).

Synthetic geotextiles are porous, chemically manufactured textile material. Polymers, including polypropylene and polyester, are typically used to manufacture geotextiles [30]. Geotextiles are furthermore produced in three different classes, which are knitted fabrics, woven fabrics and non-woven fabrics. Traditional and conventional composites are comprised of incorporation of glass fibres and carbon fibres, which are mixed with the epoxy resin or unsaturated polyester [31]. With excellent thermal and mechanical properties, these composites are broadly applied in many civil engineering works such as in roads, breakwaters, and harbour works, and land reclamation.

In geotechnical engineering, using environmentally friendly materials is of global interest. The use of synthetic geotextile in the geotechnical applications is facing great pressure on high pollutant emissions. To overcome this environmental concern, geotechnical researchers and practitioners have recently been developing a bio-based geotextile from abandoned natural materials, such as coir, kenaf, and bamboo [17,32–39]. The inclusion of bio-based geotextile layer(s) in soil foundations has been found to be a cost-effective solution to increase the ultimate bearing capacity and to reduce the settlement of shallow footings compared to the conventional means, such as replacing natural soils or increasing footings' dimensions.

Previous studies on the benefit of bio-based geotextile reinforcement on soil bearing capacity are reviewed and summarised in this paper. This article is useful as a guideline for a practical design and future research on the application of the natural geotextiles to improve the short-term bearing capacity of weak soil foundations in various sustainable geotechnical applications.

2. Natural Fibre

Natural fibres are directly obtained from basic sources, such as vegetables, animals and minerals, and are converted into non-woven fabrics. A natural fibre can be further described as an agglomeration cell, in which the diameter is negligible in comparison with the length [40]. Table 1 shows the advantages and disadvantages of natural fibres [41–44].

Table 1. Advantages and disadvantages of natural fibers [41–44].

Advantages	Disadvantages
Low density/light weight	Low strength properties, particularly its impact strength.
Low cost	Price can fluctuate, depending on the harvest amount or politics associated with agriculture
Fully biodegradable/Non-toxic	Low durability, this can be improved by flex treatments significantly.
Good insulation against electricity and noise	The low resistance to fire and moisture.
Source of income for rural/agricultural community	Different range of quality, influenced by weather

Natural plant fibres can generally be classified into three types [45–47]: (a) bast fibres, such as kenaf, jute, hemp and flax, that are considered to be relatively firm and can be used as a composite reinforcement, (b) leaf fibres, including henequen, banana, pineapple and sisal, that are known for increasing composite toughness with a little lower structural contribution, and (c) fruit fibres, such as kapok, cotton, and coir (from coconut husks), that show elastomeric type toughness. Amongst all plant fibres, bast fibres represent a great extent of natural fibres, which have the capacity for composites usage [48].

Recent studies have been conducted to investigate the tensile strength of bast fibres. The tensile strength of a fibre is typically ranging from 200 to 650 MPa [49]. The location of the fibre on the stalk and the height of the stalk influence the strength of the fibre. Fibres extracted from the bottom of the stalk exhibited higher strength than those from the top of the stalk. Correspondingly, fibres extracted from short stalks were relatively weaker than those obtained from tall stalks. Ochi [49] also reported that a single bast fibre had Young's modulus ranging from 15 to 38 GPa. Symington et al. [50] stated that the tensile strength of the bast fibres was approximately in the range of 275 to 495 MPa depending upon the degree of saturation. Amel et al. [51] discovered that fibre tensile strength could be influenced significantly by the extraction methods. Through these methods, the tensile strength ranged from 171 to 393 MPa. Table 2 shows some engineering properties of natural fibres [52–54]. The mechanical properties of natural fibres, especially tensile strength, were lower than chemical fibres, such as carbon or E-glass, commonly used in soil improvement. However, the moduli of some natural fibres were found to be quite comparable to glass fibres.

Table 2. Engineering properties of natural fibres [52–54].

Fibre	Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
Jute	1.3	393–773	26.5	1.5–1.8
Sisal	1.5	511–635	9.4–22	2.0–2.5
Flax	1.5	500–1500	27.6	2.7–3.2
Hemp	1.47	690	70	2.0–4.0
Pineapple	1.56	170–1672	60–82	2.4
Cotton	1.5–1.6	400	5.5–12.6	7.0–8.0
knaf	1.45	930	53	1.6
E-glass	2.55	3400	71	3.4
Carbon	1.4	4000	230–240	1.4–1.8

Amongst the natural fibres, kenaf fibre has fascinating mechanical and physical properties. Over the past few decades, several pieces of research have been conducted to identify the mechanical characteristics of kenaf and the manufacturing process. Zimmerman and Losure [55] reported that the density of the bast fibres was approximately 1.293 ± 0.006 g/cm^3. Aziz et al. [56] reported the bulk density of the fibres, which is a more accurate measurement of the density of the fibres as they exist on the stalk, to be 1.1926 g/cm^3. Amel et al. [51] reported almost similar values of approximately 1.19 g/cm^3 for the density of the fibres with small variations affected by the extraction method. Table 3 presents the kenaf's properties from different sources of research [53,57–68]. It was found that the density was varied because of the different initial retting method and the origin of kenaf fibres. Retting is a process where the useful fibres are separated from the core and the bark. In this process, the stalks are cut and immersed in water or put in moisture surroundings for a few weeks to deteriorate the natural binders. As a result, it is simpler to process the fibre bundles either by hand or machine. The natural fibres, such as kenaf fibre, had an uncertain cross-sectional area that varied along the length of the fibre [57]. As such, past investigations reported a wide range of variation in mechanical properties of natural fibres. Several studies were carried out in the past few years to measure and understand the influence of natural fibres as a reinforcing element, as shown in Table 4.

Table 3. Engineering properties of kenaf fiber [57].

Sources	Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
Cicala et al. [58]	N.A.	692	10.94	4.3
Akil et al. [59]	N.A.	930	53	1.6
Mohanty et al. [60] and Parikh et al. [61]	1.4	284–800	21–60	1.6
Cheung et al. [62]	N.A.	295–1191	2.86	3.5
Rassmann et al. [53]	1.5	350–600	40	2.5–3.5
Ribot et al. [63]	0.75	400–550	–	–
Yousif et al. [64]	0.6	–	–	–
Malkapuram et al. [65] Graupner et al. [66] and Shibata et al. [67]	0.749	223–624	11–14.5	2.7–5.7
Jawaid and Khalil [68]	1.2	295	–	3–10

3. Fibre Treatment

Natural fibre geotextiles have emerged in applications such as temporary reinforcement and biological soil stabilization [69]. Natural fibres are more affordable and lighter than synthetic fibres such as nylon (polyamide) or dacron (polyester). Chemical treatments can be applied to natural fibres to improve their tensile strength. Alkaline treatment is one of the most typical chemical treatments. Kawahara et al. [70] investigated the mechanical properties of alkali-treated kenaf fibres by changing the concentration of the aqueous solution of NaOH in a relatively low range, i.e., from 1% to 7%. The results showed that the tensile strength of the treated fibres was insignificantly improved. Nitta et al. [71] found that the tensile strength of the kenaf decreased when subjected to a high alkali concentration. Nosbi et al. [72] studied the behaviour of knaf fibres after long-term immersion in distilled water, seawater (pH = 8.4), and acidic solution (pH = 3). They found that the water absorption pattern of the kenaf fibre was non-Fickian's, where the moisture uptake behaviour was radically altered due to the moisture-induced degradation. They also observed that the kenaf fibres immersed in seawater yielded the highest absorption in comparison with distilled water and the acidic solution, respectively. Meon et al. [73] investigated the chemical treatment effect on mechanical properties of short kenaf fibres. The fibres were soaked in 3%, 6% and 9% of sodium hydroxide (NaOH) for a day and then dried at 80 °C for 24 h. The tensile properties of alkalization-treated fibres significantly improved. Furthermore, Meon et al. [73] determined that the optimum NaOH concentration was 6% for the chemical treatment. Rajappan et al. [74] reported that kenaf fibre is amongst the best natural fibre. Ramesh [75] revealed that knaf fibres treated with 8% NaOH solution would be damaged as the fibres were more twisted and fragile than the untreated ones. As a result, it was not recommended for the knaf fibres to receive alkali treatment with >8% NaOH solution. Ramesh [75] also observed that increasing NaOH concentration and immersion time could decrease the mechanical properties of knaf fibre. Akhtar et al. [76] conducted Scanning Electron Microscopy (SEM) analysis on chemical-treated knaf fibres. The surface of untreated fibres, which was covered by lignin, hemicellulose, and wax, would be removed by the chemical treatment and hence the adhesion properties and interfacial bonding between knaf fibres and soil were improved. Akhtar et al. [76] observed that untreated knaf fibres contained some impurities that were removed after alkaline treatment. After alkaline treatment, the knaf fibres appeared clean and rough as well as had a better physical appearance (Figure 1).

Table 4. Summary of the previous research on the ground improvement using a reinforcement layer.

Researchers	Soil Types	Reinforcement Material	Experimental Test	Purpose of The Study	Optimum Value of Important Parameter			
					L[1]	N[2]	d[3]	S[4]: S_1, S_2, S_3 …
Vinod et al. [39]	Loose Sand	Coir rope	Small scale vertical load tests	The most effective number of plies Bearing pressure-Settlement behaviour	3B	3	0.4B	0.12B–0.2B
Results	Most efficient coir rope reinforcement depth on bearing capacity of soil = 0.4B[5]. Three-layer reinforced specimen (N = 3) was recommended as an optimum value of coir rope reinforcement layer. Because, the percentage increased in the Bearing Capacity Ratio (BCR) for N = 4 over BCR for N = 3 was very low. 9-ply braided coir rope instead of 7-ply coir rope demonstrated better performance in the form of soil strength improvement and settlement reduction							
Rajagopal and Ramakrishna [36]	Clay Gravel	Coir Geotextile	Large scale plate load tests	Soil Stiffness Bearing Capacity Ratio, BCR	3B	1 2	0.6B–1.2B	-
Results	Clearly indicated the capability of coir geotextiles in improving the stiffness and load-bearing capacity of soft subgrades. The coir geotextiles are suitable for cost-effective field applications.							
Subaida et al. [38]	Clay	Coir Geotextile	Small scale vertical load tests	Bearing pressure-Settlement behaviour	-	-	one third of Plate diameter	-
Results	The coir reinforcement layer placed at the middle depth of the base layer caused the significant increases in bearing capacity of the specimen. The thin reinforced section shows more improvement in bearing capacity as compared to thicker sections with a reinforcement layer.							
Asaduzzaman and Islam [32]	medium dense soil	bamboo reinforcement	Small scale vertical load tests	BCR and Settlement	-	2–3	0.3B	-
Results	The improvement of soil bearing capacity only happened when the bamboo reinforcement layer placed within the deformation zone. Two-layer reinforced specimen (N = 2) was recommended as an optimum value of bamboo reinforcement layer. Because, the percentage increased in BCR for N = 3 over BCR for N = 2 was very low (4%). The settlement of footing decreased significantly with an increasing number of reinforcement layers up to N = 3.							
Kumar et al. [33]	Fine Sand	N/A-Geotextiles	Small scale vertical load tests	BCR	3B	1	0.2B–0.3B	-
Results	The optimum reinforcement depth for 2Bx2B, 3Bx3B and 4Bx4B size of geotextile are 0.2B, 0.3B, 0.3B respectively. Geotextile with size equal to 4Bx4B shows maximum improvement in bearing capacity.							
Lal et al. [34]	Sand	Coir geotextile Coir geocell	Small scale vertical load tests	Bearing pressure-Settlement behaviour	-	-	0.10B 0.25B	-
Results	For economic reasons, the suitable width of reinforcements was chosen to be medium size (bg/B = 3.2 and bp/B = 3.75). Most efficient coir geocell height on bearing capacity of soil= 0.5B d for planar reinforcement layer = 0.25B d for geocell reinforcement layer = 0.1B							
Sridhar and Prathapkumar [37]	Sand	Coir Geotextiles	Direct shear tests Small scale vertical load tests	BCR Settlement reduction factor, SRF	-	3–4	0.3B	Depth of each successive reinforcement layer = 0.5B
Results	From the direct shear test, the coir mat with opening size 20 × 20 mm provided maximum value of internal friction. BCR increases when the number of layers of reinforcement increases. When stress for coir geotextile increases, SRF increases as well.							
Mathew and Sasikumar [28]	Soft soil	Bamboo gridCoir geonet	Small scale vertical load tests	BCR and Settlement	-	3	1.5B	S_1 = 0.5B
Results	The performance of bamboo-grid-reinforced soil is better than coir-geonet-reinforced soil. The bearing capacity becomes increased and the settlement gets reduced for reinforced soil.							
Rashid et al. [15]	Sand	Woven knaf Geotextiles	Small scale vertical load tests	Influence of single reinforcement layer on Bearing capacity value (Nc)	-	1	0B–0.25B	-
Results	In comparison with the untreated soil, the bearing capacity of sand soil model was improved up to 414.9% by the knaf fibre. The high bearing capacity value of the sand is caused by the short distance between knaf geotextile and the level of sand surface.							

[1] L: length of the reinforcement element; [2] N: number of reinforcement layers; [3] d: top layer spacing, or depth to first reinforcement layer; [4] S: vertical space between subsequence reinforcement; [5] B: Width of the footing.

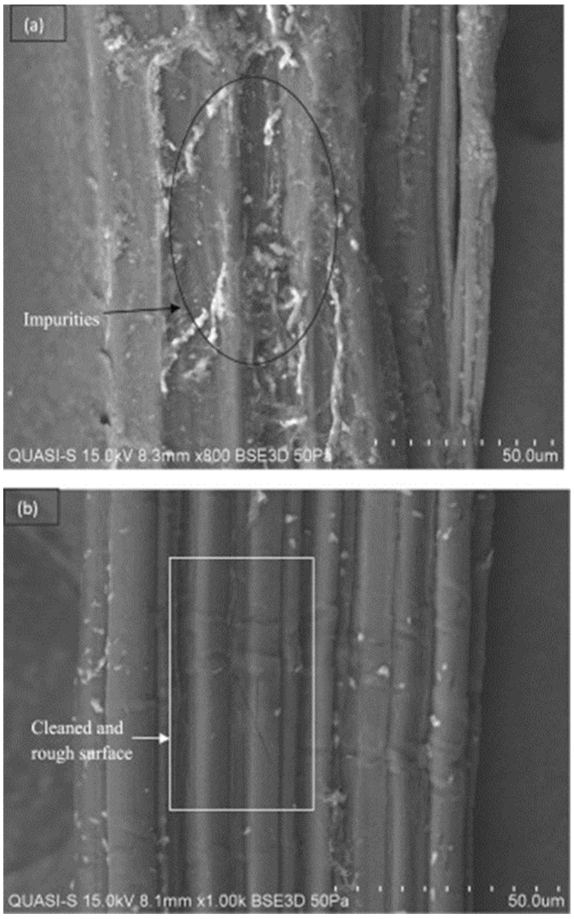

Figure 1. Scanning Electron Microscopy (SEM) micrographs of (**a**) treated and (**b**) untreated kenaf fibers [76].

Shirazi et al. [77] investigated the tensile behaviour of treated and untreated knaf geotextiles under dry and wet conditions via the wide-width strip test in accordance with the ASTM D4595-17 [78] standard. The influence of two different patterns of woven knaf, including plain and inclined patterns with two different opening sizes between their yarns (0×0 and 2×2 mm) were also investigated. The tensile strength of the knaf geotextiles, buried in natural ground was also examined after a duration of one year. The maximum tensile strengths of knaf geotextiles were observed for the treated plain pattern with an opening size of 0 mm and they were 47 kN/m and 42 kN/m, under dry and wet conditions, respectively. Shirazi et al. [77] reported that the 6% NaOH treatment of the knaf geotextiles with the plain pattern at a 0-mm opening size significantly improved the tensile strength up to 51.0% and 45.5%, as compared to the untreated knaf geotextiles under dry and wet conditions, respectively. The ultimate tensile strength of the treated knaf geotextile, buried in natural ground for one year, significantly decreased to 71.9%, as compared to the treated knaf geotextile (without buried in natural ground). However, the treated geotextiles still had a higher ultimate tensile strength and elongation at breakage than the untreated geotextiles, showing the advantage of NaOH treatment.

In addition, several authors, such as Rowell et al. [79], Wambua et al. [80], Jeyanthi and Rani [81], Razak et al. [82], Kumar et al. [83], Hafizah et al. [84], Sardar and Gowda [85], Naveenkumar et al. [86], have reported on knaf fibres reinforced with chemical fibres as a composite material. These past investigations have, however, focused only on improving the mechanical properties of knaf fibre by mixing with chemical fibres (e.g., polypropylene and poly-lactic acid) without environmental issues.

4. Geotextile-Reinforced Soil Systems

The soil reinforced with fibres has been used in building houses for more than two thousand years. This historical fact can be realized by the remainder of houses constructed with plant roots, thatch, and other natural fibres as the reinforcing materials to prevent cracking. Today, these buildings still exist in remote areas where the people reinforce low strength masonry walls using low strength fibre such as straw. Natural fibres can be utilised as a continuous form of sheet-like non-woven/woven geotextiles and strips. Natural fibres can be included inside the soil mass as a reinforcement layer. In the geotextile-reinforced soil systems, the tensile strength can be introduced into reinforced soil by planar inclusions. However, the shear strength of the reinforced soil at the interfaces will be decreased because the bonding strength between planar inclusions and soil is rather less than soil against soil. As such, the failure normally occurs at the interface between soil and reinforcement.

Furthermore, the number and spacing of reinforcement layers influence the effectiveness of the reinforced soil. Figure 2 shows a typical geotextile-reinforced soil system. The influence parameters are introduced as follows: (1) the width of the shallow footing (B); (2) the embedment depth of the footing (D_f); (3) the depth to the first reinforcement layer or top layer spacing (d); (4) the vertical spacing between the reinforcement layers (S_1, S_2, ... , S_N); (5) the number of reinforcement layers (N); (6) the total depth of reinforcement (H), and (7) the length of reinforcement (L). Figure 3 shows various types of the natural fibres from previous studies [15,32,34,35,38,39].

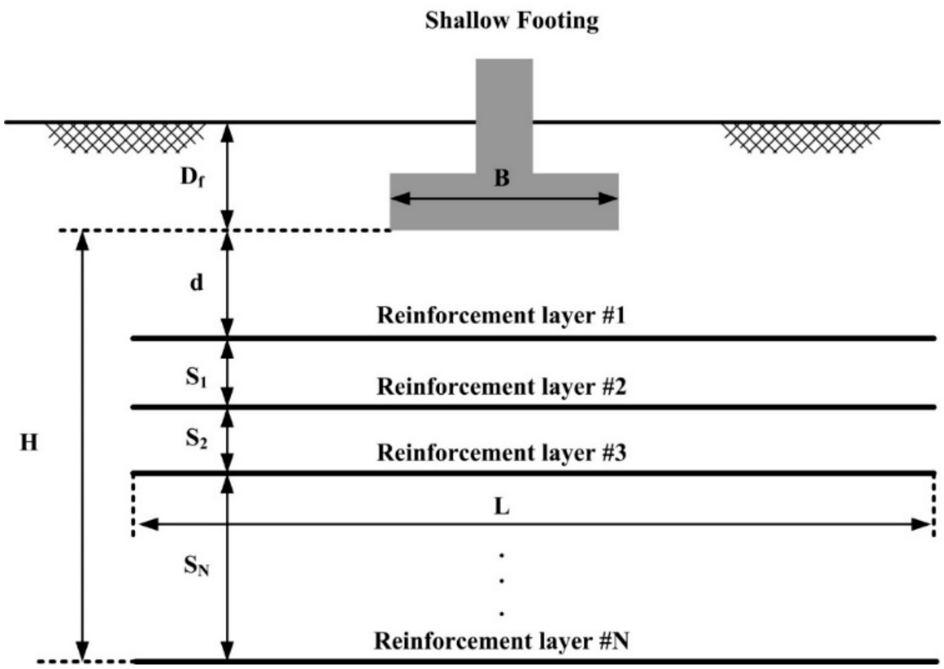

Figure 2. Typical geotextile-reinforced soil system.

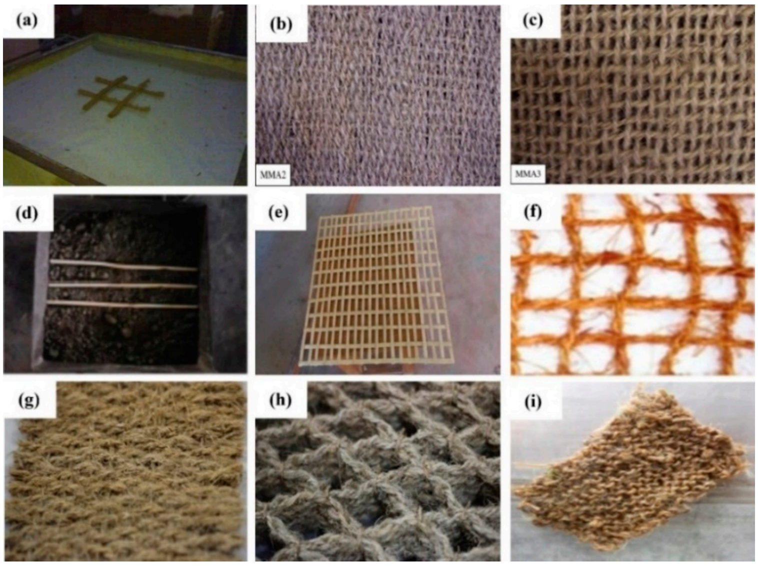

Figure 3. Various kinds of natural geotextile. (**a**) Coir rope reinforcement [39], (**b**) Woven coir geotextiles 38], (**c**) Woven coir geotextiles [38], (**d**) Bambo reinforcement [25], (**e**) Bamboo grid [35], (**f**) Coir geonet [28], (**g**) Coir geotextile [34], (**h**) Coir geocell [34], (**i**) knaf fibre geotextile [15].

5. Previous Studies on Natural Reinforcement Layer

Natural geotextiles are widely accepted because of their economical cost and sustainable reasons and have high load-bearing potentials [87]. Vinod et al. [39] carried out plate load tests to study the effectiveness of horizontal coir rope reinforcement on the bearing capacity improvement and settlement reduction of loose sand under vertical pressure on a square model footing. They examined the effect of influence parameters, including the vertical spacing between geotextile layers, embedment depth, length, and braided rope layers on bearing pressure-settlement behaviour. Figure 4 shows the bearing pressure versus the footing settlement curve for different conditions. With the braided coir rope reinforcement layer(s) inside the sand, the bearing capacity significantly improved at all levels of normalized settlement. Vinod et al. [39] reported that the best performance of the model footing happened when the braided coir rope reinforcement placed at 0.4B below the base of model footing. The bearing capacity of the reinforced sand improved rapidly and linearly with increasing the number of coir rope reinforcement layers up to N = 3. The increase in the bearing capacity of the four-layer reinforcement system (N = 4) when compared to the three-layer reinforcement system (N = 3) was very low. Thus, the optimal N = 3 was recommended. It was evident that using 9-ply braided coir rope instead of 7-ply coir rope demonstrated better performance in the form of bearing capacity improvement and settlement reduction. Bearing capacity increased proportionately with a decrease in the vertical spacing of reinforcement within a depth of about 0.6B while the settlement reduction factor is independent of the vertical spacing. A uniform increase in bearing capacity could be observed when the vertical spacing of the reinforcement decreased from 0.2 to 0.12B. The bearing capacity immensely increased with increases in coir rope length ratio up to 3.

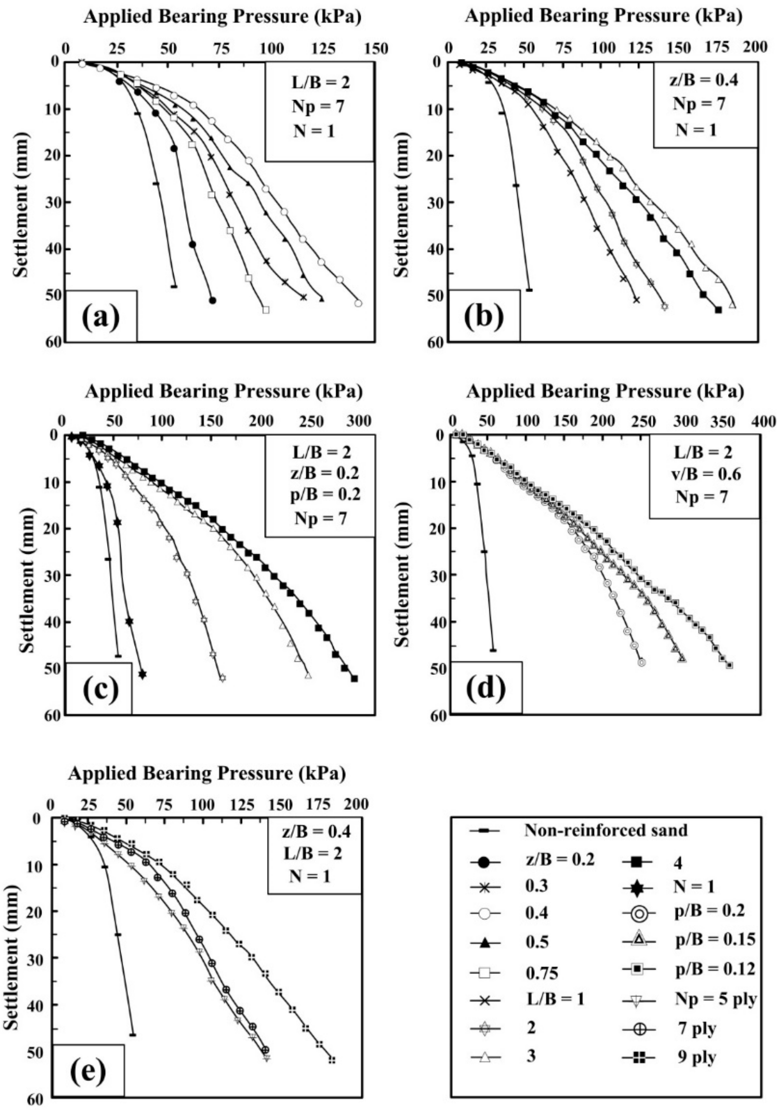

Figure 4. Bearing pressure against footing settlement curve for different: (**a**) reinforcement embedment depth, (**b**) the lengths of the reinforcement, (**c**) the number of layers of reinforcement, (**d**) the vertical spacing of the reinforcement, and (**e**) the number of plies of reinforcement (modified from Vinod et al. [39]).

Rajagopal and Ramakrishna [36] studied the application of geotextiles for the road bases. The influence of the reinforcement location on the bearing capacity based on the standard plate load test was studied. Rajagopal and Ramakrishna [36] conducted four large-scale plate load tests to investigate the strength and stiffness of the coir reinforced road bases as follows (Figure 5): Type I on soft clay subgrade alone, Type II on gravel sub-base course over soft clay subgrade, Type III on gravel sub-base course over soft clay subgrade and one layer of coir geotextile at clay-gravel interface, and Type IV on gravel sub-base course over soft clay subgrade and two layers of coir geotextile, one at the clay–gravel interface and the other at a mid-depth of the gravel layer. The coir geotextiles were commercially available floor mats that were woven from coir fibres. The geotextile (coir mat) had a thickness of 7.2 mm. The ultimate tensile capacity of this mat was reported to be 37 kN/m at a strain of 43% from wide-width tensile tests according to ASTM D4595-17 [78] standards. In the case of the Type-I series of tests, the clay was covered with a 5-mm-thick fine sand layer. In the case of reinforced tests, the coir geotextile was placed at the required levels after wetting.

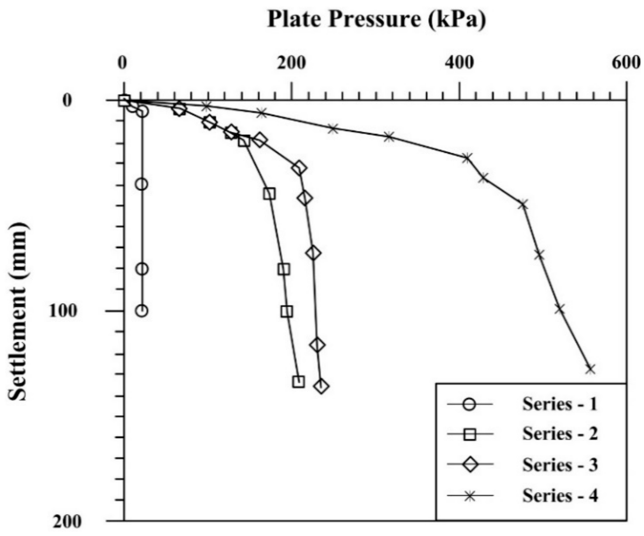

Figure 5. Performance with a 150-mm-thick gravel layer (modified from Rajagopal and Ramakrishna [36]).

Rajagopal and Ramakrishna [36] reported that the single-layer reinforcement at the clay–gravel interface insignificantly improved the load-bearing capacity. The effect of the single layer of geotextile was significant when the gravel layer was thicker than 200 mm. When a thin layer of gravel was provided, there was not an adequate bond with the coir geotextile for the load transfer. In the case of two layers of coir geotextile, the reinforcement layer at the mid-depth of gravel prevented lateral movement, and hence higher loads were mobilised in the coir reinforcement, which contributed to the increase in ultimate bearing capacity. This indicates the excellent bond between the coir and the gravel. In the cases of unreinforced and single-layer reinforcement, the ultimate bearing capacity has developed within a settlement of 15 to 40 mm, whereas the two-layer system had developed ultimate bearing capacity at a relatively higher settlement of approximately 100 mm. This result confirms the advantage of placing the additional reinforcement layers within the gravel layer.

Subaida et al. [38] applied a vertical monotonic load on a rigid circular plate on unreinforced and coir geotextile-reinforced pavements via a small-scale laboratory model test. Two types of woven coir geotextiles with two different aperture sizes, with the ultimate tensile capacity of 36 kN/m at a strain of 36.1% and 13 kN/m at a strain of 20.7%, respectively, were used in the study. The coir geotextiles were installed at the bottom of base course (between the base and the subgrade). Figures 6 and 7, respectively, indicate the variation in bearing pressure against the settlement for 167-mm-thick and 267-mm-thick base courses under a vertical monotonic load. The pavement section with 167 mm thick base as compared to the unreinforced section demonstrated an increase in bearing capacity of 45% and 75% when the geotextiles were placed at the bottom of base and within the base course, respectively. The pavement section with a 267-mm-thick base, as compared to the unreinforced section, showed a small increase in bearing capacity of 11.8% and 17.9% when the geotextiles were placed at the bottom of the base and in the middle of base course, respectively. The coir reinforcement placed at the middle of the base course caused a significant increase in bearing capacity. The thin reinforced section, furthermore, showed a higher bearing capacity improvement when compared to the thick reinforced section.

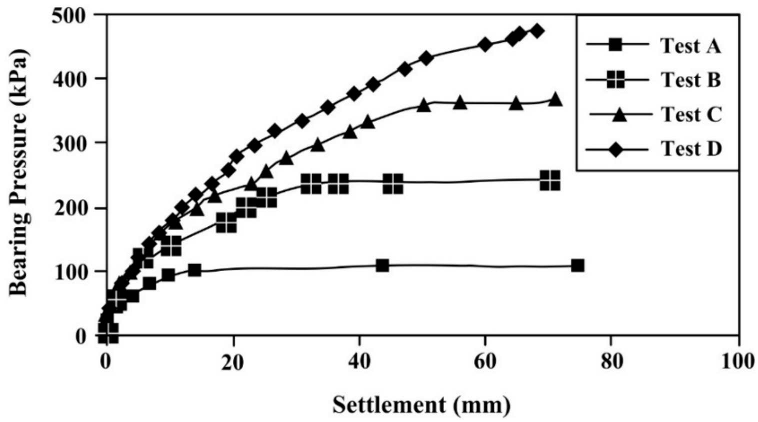

Figure 6. Variation in bearing pressure and settlement for a 167-mm-thick base under monotonic load tests (modified from Subaida et al. [37]).

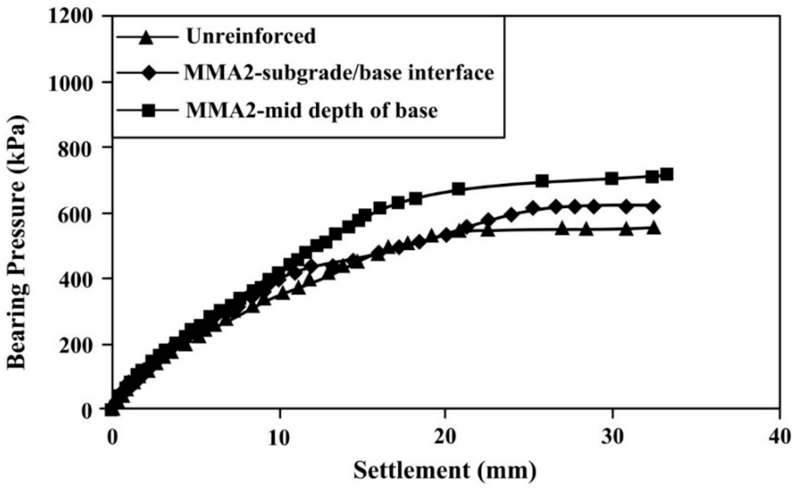

Figure 7. Variation in bearing pressure and settlement for a 267-mm-thick base under monotonic load tests (modified from Subaida et al. [38]).

Asaduzzaman and Islam [32] carried out a number of small-scale laboratory tests on square footings with three different dimensions of 3 × 3 inch, 3.5 × 3.5 inch and 4 × 4 inch to investigate the effect of bamboo reinforcement on the bearing capacity of uniform medium dense soil. The length and diameter of the bamboo stem were 12 and 12.7 mm, respectively. To investigate the effect of reinforcement layers, the multiple reinforced-layer systems were introduced, including single-layer, two-layer, and three-layer bamboo reinforcement at three different depths: 19.1, 38.1, and 57.2 mm. Figures 8 and 9 show the variation in bearing capacity ratio (BCR) and settlement, respectively for the single and multi-layer systems, where BCR was defined as the ratio of ultimate bearing capacity over undrained shear strength. The improvement of soil bearing capacity only occurred when the bamboo reinforcement was placed within the deformation zone. The BCR of the single-layer, two-layer, and three-layer bamboo-reinforced soil when compared to the unreinforced soil increased to 1.77, 1.89, and 2.02 times, respectively. The effective embedment depth in the single-layer reinforcement system, which resulted in the maximum bearing capacity and minimum settlement, was about 0.3 times the footing width. The BCR of medium dense soil could be improved by increasing the number of reinforcing layers (N). The BCR was at its maximum for the three-layer reinforced soil (N = 3), while the increase in BCR for N = 3 over BCR for N = 2 was very low (4%). Thus, N = 2 was recommended as an optimum value of the bamboo reinforcement. The settlement of footing decreased significantly with an increasing number of reinforcement layers up to N = 3.

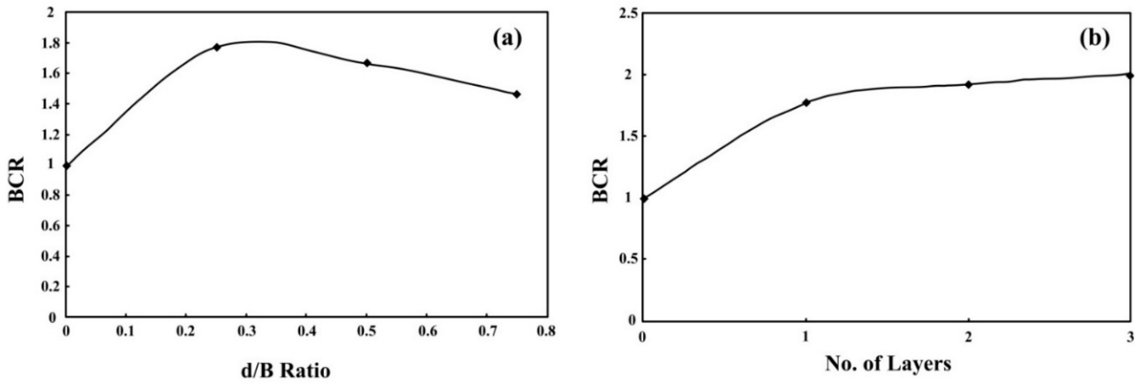

Figure 8. Bearing capacity ratio (BCR) variation against (**a**) the d/B ratio of the single-layer system and (**b**) the number of reinforcing layers (modified from Asaduzzaman and Islam [32]).

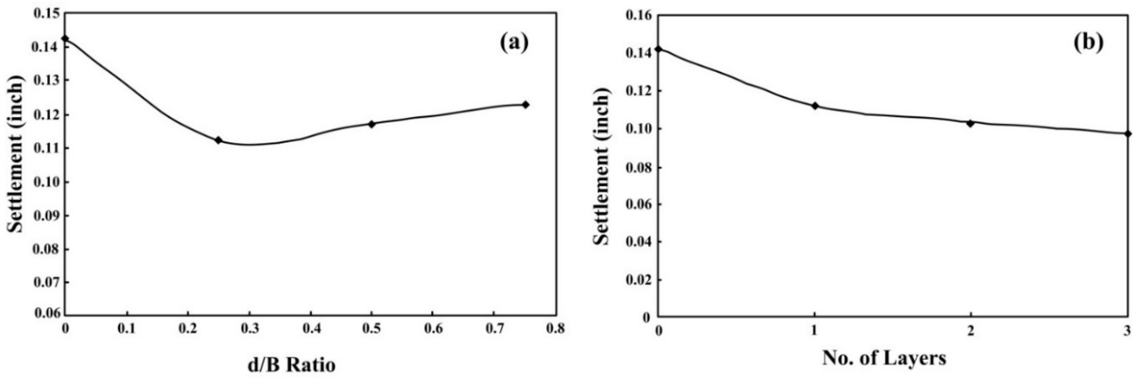

Figure 9. Settlement (inch) variation against (**a**) the d/B ratio of the single-layer system and (**b**) the number of reinforcing layers (modified from Asaduzzaman and Islam [32]).

Kumar et al. [35] reported the BCR of square footings on geotextiles reinforced sand based on the laboratory model test results. The sand was filled in a tank model using the raining sand technique to achieve the required density of sand. Geotextiles with various sizes of 2b × 2b, 3b × 3b and 4b × 4b (b = width of footing) were placed below footing at various depths of 0.1b, 0.2b, 0.3b, 0.4b and 0.5b. The 10 cm × 10 cm square footing was installed at a depth of 0.5b from the surface. A footing was loaded with a constant strain rate of 1 mm/min through a gear arrangement system supported against the reaction frame. From Figure 10, the maximum improvement in bearing capacity and settlement reduction was found when the geotextile with an optimum size of 3B × 3B was placed at 0.3 times footing width.

Lal et al. [34] studied the performance of coir fibre geotextile reinforcement in both planar and geocell forms via vertical load tests on a square model footing. Laboratory test results (Figure 11) demonstrated the variation of bearing pressure and footing settlement ratio (the ratio of settlement over footing width) for both planar and geocell forms at a medium width ($b_g/B = 3.2$ and $b_p/B = 3.75$), where b_g is the width of coir geocell reinforcement, b_p is the width of planar reinforcement. The coir geocell reinforcement offered a better performance than the planar reinforcement even at small settlement levels. The most efficient depths of the first planar and geocell reinforcement layer were 0.25 and 0.1 times the footing width, respectively. Because of the buckling of the geocells, increasing the geocell height more than 0.5 times the footing width did not show any significant effect on the load-deformation performance.

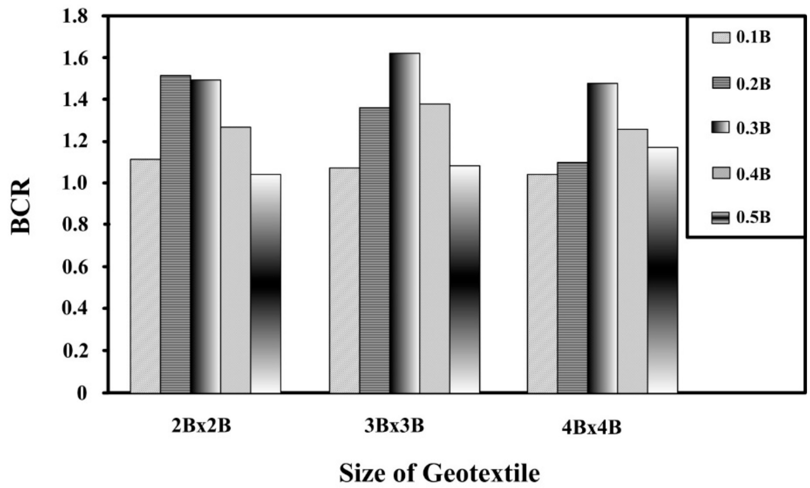

Figure 10. Bearing capacity ratio with geotextile placed at a depth 0.1B to 0.5B below footing (modified from Kumar et al. [33]).

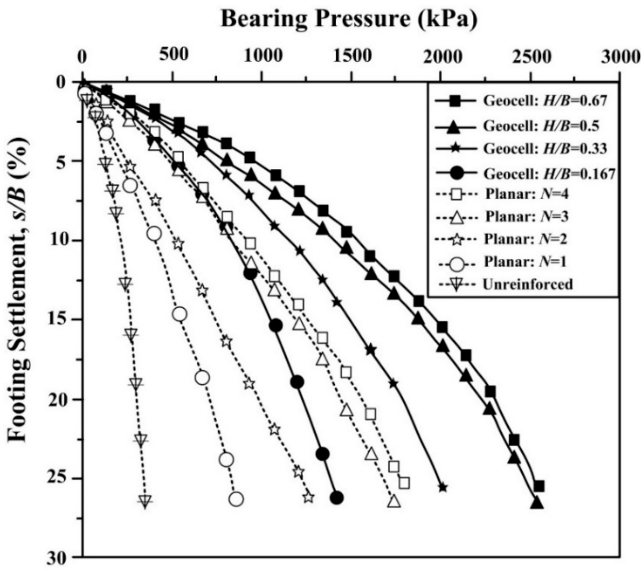

Figure 11. Variation in applied pressure and settlement for medium width coir geotextile in both planar and geocell forms (b_g/B = 3.2 and b_p/ B = 3.75) (Lal et al. [34]).

Sridhar and Prathapkumar [37] analysed the impact of a number of coir geotextile reinforcements on the bearing capacity of sand. The breaking load and elongation of the studied coir geotextile were equal to 252 N and 31%, respectively. A series of small-scale direct shear tests were undertaken to determine the most effective mesh opening size of the coir mat. The coir mat with an opening size of 20 × 20 mm provided the highest internal friction angle with a marginal variation of 1° when compared to the coir mat with a 10 × 10 mm opening. Figure 12 indicates that the ultimate bearing capacity for the single-layer reinforced sand was five times higher than that for the unreinforced sand. With the coir mat, the movement of sand particles in the openings was prevented by the confining stress of the mesh structure, and hence improved the bearing capacity.

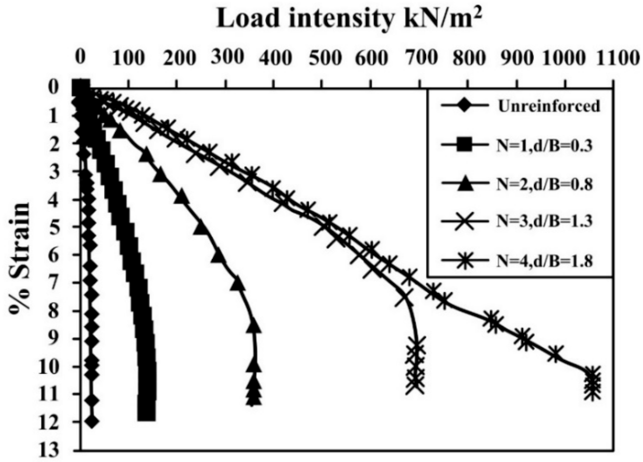

Figure 12. Load intensity against strain for coir geotextile-reinforced sand (modified from Sridhar and Prathapkumar [37]).

Figure 13 presents the variation in BCR against d/B ratios at different s/B = 2%, 4%, 6%, 8%, and 11%. Sridhar and Prathapkumar [37] stated that increasing the number of reinforcement layers caused the BCR for coir-mat-reinforced soil to increase. The Settlement Reduction Factor (SRF) was recommended to study the effect of reinforcement layers on settlement. Figure 14 illustrates SRF variation against stress for a one-, two-, three-, and four-reinforcement-layer system. With the increase in stress (which denotes higher shear strength mobilization), the SRF of coir mat-reinforced sand increased. Nonetheless, for N = 2, N = 3 and N = 4, the SRF increased insignificantly, even with the increase in stress. The optimum number of reinforcement layers in terms of bearing capacity and SRF were thus N = 3 to 4.

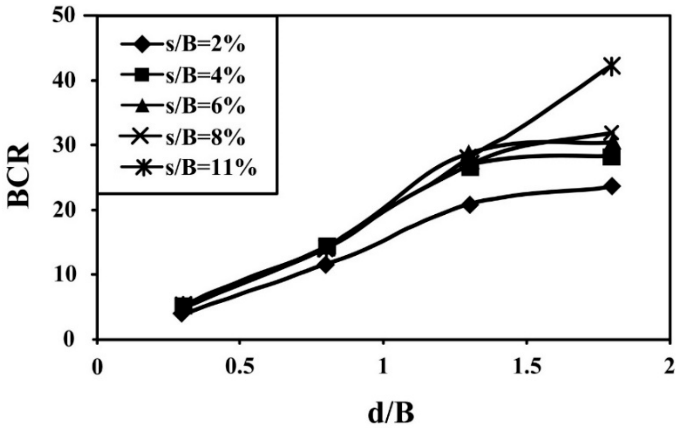

Figure 13. BCR variation against d/B ratios (modified from Sridhar and Prathapkumar [37]).

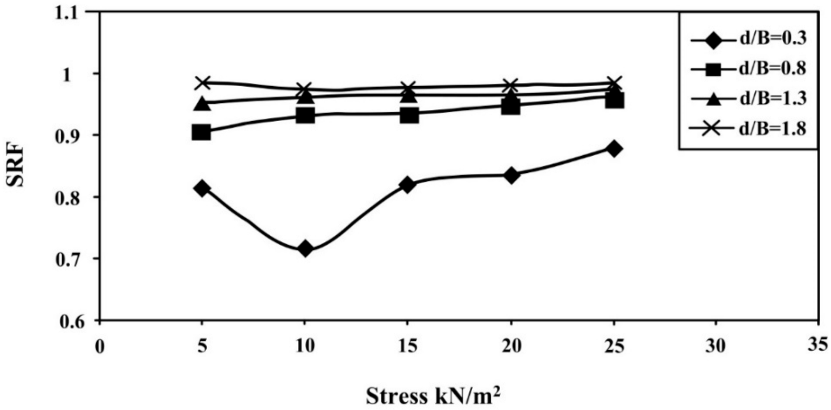

Figure 14. Settlement reduction factor variation against stress (modified from Sridhar and Prathapkumar [37]).

Mathew and Sasikumar [35] studied the effects of both bamboo grid and coir geonet reinforcement on the performance of soft soil under a vertical load. They conducted a series of laboratory plate load tests on a square shaped steel plate of 100 mm in size and 12 mm in thickness. The reinforced model tests were performed separately for one to five bamboo grid layers and one to four coir geonet layers of a mesh size of 20 × 16.75 mm with a ratio of spacing between the base of footing and first reinforcement layer to the width of the model square footing, u/B = 0.5 and ratios of depth of the last reinforcement layer from the base of model footing to the width of the model square footing d/B = 0.5, 1.0, 1.5, 2.0 and 2.5. Figure 15 shows the comparison of load-settlement behaviour between the unreinforced soil and the soil reinforced with bamboo grid and coir geonet at different layers. The performance of the bamboo-grid-reinforced soil was better than that of the coir-geonet-reinforced soil. Figures 16 and 17 show the variation in BCR versus the d/B ratio of an unreinforced and reinforced model for both bamboo grid and coir geonet, respectively. In both cases, the bearing capacity increased with d/B ratio up to 1.5 and then decreased. In other words, the optimum number of layers for the development of maximum bearing capacity was three. Table 5 summarizes the recommended values of influence parameters for natural geotextle reinforced soil to achieve the maximum load capacity.

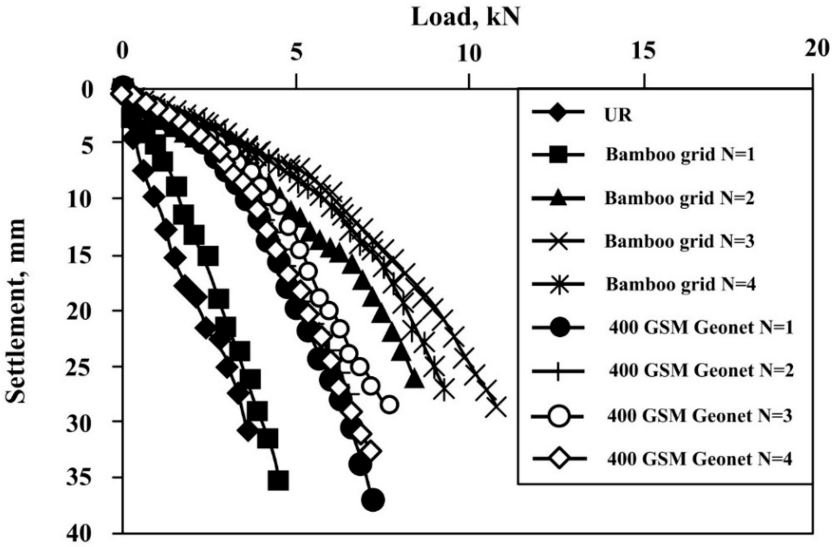

Figure 15. Comparison of the load settlement behaviour of bamboo-grid-reinforced soil and coir geonet (modified from Mathew and Sasikumar [35]).

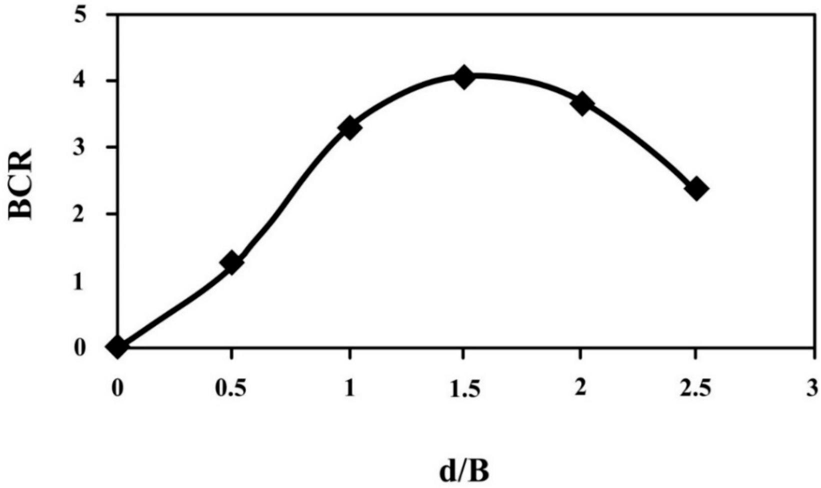

Figure 16. BCR versus the d/B ratio for bamboo-grid-reinforced soil (modified from Mathew and Sasikumar [35]).

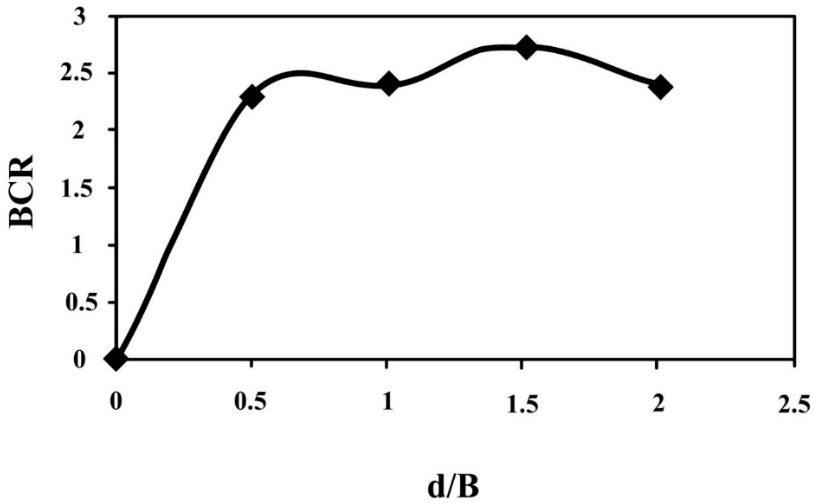

Figure 17. BCR versus the d/B ratio for coir-geonet-reinforced soil (modified from Mathew and Sasikumar [35]).

Table 5. Typical and recommended parameters of the soft soil reinforcement system.

Parameters	Symbol	Typical Value	Recommended
Influence depth of Top layer spacing	d/B	0–1	0.25
Space between consecutive reinforcement layer	S/B	0.2–0.7	0.25
Number of geotextiles	N	3–4	3

Rashid et al. [15] conducted laboratory model tests to examine the effects of single-layer woven knaf geotextile reinforcement on the bearing capacity of the reinforced sand. The simulated strip footing had dimensions of 150, 100, and 15 mm in length, width, and thickness, respectively. The length and width of studied knaf geotextile with a 5-mm aperture were 190 and 150 mm, respectively. The knaf geotextiles were placed at different locations, including the soil surface and three other depths of 50, 75, and 100 mm. Figure 18 shows the variation in applied vertical stress against displacement/footing width. The vertical stress gradually increased with the increase in settlement until it reached a plateau at a displacement/footing width ratio of approximately 0.3. The distance between the location of knaf geotextile and the sand surface level affected the bearing capacity. A higher bearing capacity occurred when the knaf geotextile was located close to the sand surface. The bearing capacity of the knaf-reinforced sand was enhanced up to 414.9% when compared to that of the untreated sand.

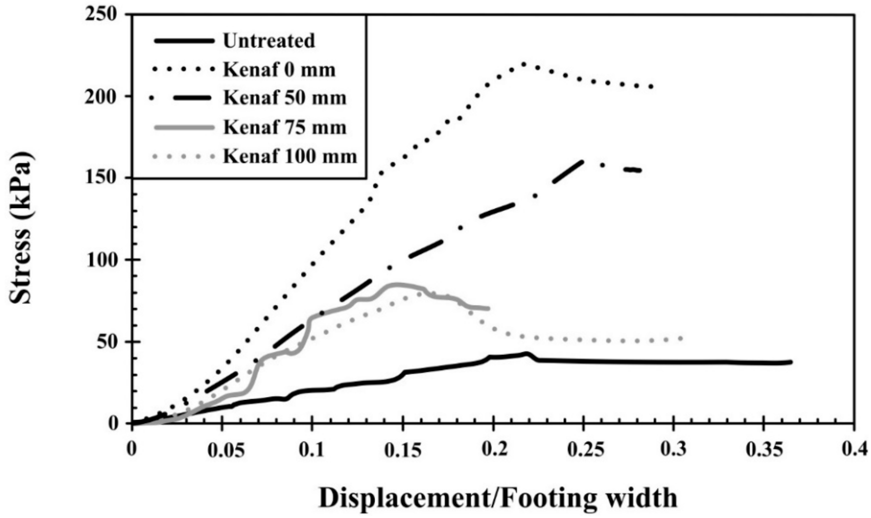

Figure 18. Variation in vertical stress and displacement/footing width (modified from Rashid et al. [15]).

6. Summary and Conclusions

This study attempts to review previous experimental studies to illustrate the potential advantages of utilising natural geotextiles as an earth reinforcement for the improvement of the bearing capacity. This reviewed article is a valuable reference for developing future sustainable research on the usage of natural geotextiles in geotechnical and pavement engineering applications. The use of limited life geotextiles for improving short-term bearing capacity is effective and sustainable as compared to that of synthetic geotextiles. Bio-based geotextiles are extensively used for geotechnical applications due to their economical cost. In order to improve the durability properties, the surface modification techniques with an alkali is the most effective means.

This article concentrated on the number and position of the natural geotextiles inside the soil mass. The advantages of utilising the biodegradable materials as natural geotextile reinforcement for bearing capacity improvement was presented. The utilisation of natural geotextiles is challenging in terms of the environmentally friendly perspectives. The inclusion of natural geotextiles as a reinforcement leads to a significant increase in the bearing capacity of the soil foundation. The effectiveness of geotextiles (e.g., knaf, coir, bamboo) was found to be dependent upon: (1) the location of the first geotextile layer (top layer spacing) within the soil mass; (2) the vertical spacing between the reinforcement layers; (3) the number of reinforcements, and (4) the length of the reinforcements. A number of factors such as height (h), width (b), and pocket size of the geocell (d) can also impact the efficiency and effectiveness of geocell on the improvement of soil bearing capacity.

The soil bearing capacity improvement only exists when the natural reinforcement layer is placed within the deformation zone. Generally, the bearing capacity of the soil increases with a decrease in the vertical spacing of the geotextile reinforcement. With the increase in the embedment depth of the reinforcement layer, the BCR decreases. The geotextile-reinforced soil exhibited a ductile behaviour where strain hardening effects were observed, even at large settlements. The optimum number of reinforcement layers was recommended in the range of 3 to 4. The bearing capacity increased appreciably with an increase in the length of natural geotextiles up to the length ratio of 3. The most effective ratio of geocell width to foundation width was found to be 3.2.

Most of the previous studies are limited to laboratory scale model tests, without the numerical analyses of the influence of the natural geotextile reinforcement under vertical loading. Moreover, they mainly focused on the short-term behaviour of the reinforced soil foundations. For a future study, it is recommended to investigate the short-term and long-term performance of the natural geotextile reinforced soil foundation under both full-scale tests and numerical simulation, which will be very useful to geotechnical engineers and practitioners for field applications.

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