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The Effect of Using Reinforced Granular Blanket and Single Stone Column on Improvement of Sandy Soil: Experimental Study

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ABSTRACT

A series of large-scale laboratory model tests in a unit cell was performed to explore the behaviour of loose sandy soil due to improvement. An unreinforced and geogrid reinforced granular blanket, a single end-bearing stone column, and their combination were used for this purpose. Since the rupture of the geosynthetic reinforcement in the reinforced granular blanket has never been experimentally investigated. A novel method of installing the geogrid was used. Thus, geogrid was allowed to completely mobilize and fail under loads. In this investigation, load-settlement characteristics have been generated by continuing loading even after geogrid rupture until the desired settlement. Parametric studies were carried out to observe the effect of important factors, such as the blanket thickness and the layout of geosynthetic sheets, including the number and place of geogrid layers within the granular blanket. Reinforcing the blanket with geogrid while changing the usual form of the load-settlement characteristics has had a significant effect on enhancing load-carrying capacity and reducing settlement. It can be said using a stone column, granular blanket, or combination of both techniques to boost load-carrying capacity was more effective than reducing settlement. However, the effect of single-layer and double-layer geogrid reinforcement on settlement reduction depends on their placement within the granular blanket. In addition, the efficiency of improvement methods has been superior under looser bed conditions. The best layout was to arrange one layer of geogrid near the top of the blanket or two layers in the middle and near the top.

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NOMENCLATURE

D_r	Relative density	D	Diameter of the footing
LR	Load ratio	S/D	Settlement ratio
LR_{max}	Maximum load ratio	BCR	Bearing capacity ratio
LR_{final}	Final load ratio	B_f	Footing width
S	Footing settlement	Z_u	Distance of the uppermost reinforcing row from the base of the footing

1. INTRODUCTION

Nowadays, soil improvement techniques [1-5] are widely used. Knowing about soil improvement techniques and their applications is essential to ensure the safety and cost-effectiveness of projects. These methods are used to modify the properties of soil to improve its stability, strength, and bearing capacity, which is vital when constructing structures such as buildings, bridges, and roads.

Stone columns have been used successfully to improve the engineering properties of different types of soils, such as soft clays, silts, and silty sands. However, despite the stone column's advantages in improving ground behaviour, its performance is challenging in soft or loose soils. In these soils, the circumferential

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confinement offered by the surrounding soil may not be sufficient to develop the appropriate load-carrying capacity. As a result, the stone column bulges and pushes the surrounding soil radially, reducing efficiency. Hence, studies have tried to employ various geosynthetics to reinforce the stone column and provide confining pressure around it [6-12], and reduce stress concentration at the column's top by placing a reinforced granular blanket [13, 14]. In response to this improvement, the stone column can take vertical loads and reduce bulging. The load-carrying capacity of the stone column and soil is increased due to the reinforced blanket's beam-like behaviour and ability to withstand some bending.

Deb et al. [15] developed a mechanical model to predict the behaviour of a geosynthetic-reinforced granular fill over soft soil that improved with stone columns. They found that adding the geosynthetic layer reduced the total and differential settlement, while the settlement reduction increased with further load intensity and modular ratio. Moreover, Deb et al. [16] extended a mechanical model to investigate the behaviour of multi-layer geosynthetic-reinforced granular fill over stone column-reinforced soft soil. It has been reported that compared to a single layer of reinforcement, using multi-layer geosynthetic reinforcement along with stone columns had less effect in reducing the settlement. However, when soft soil had not included stone columns, the multilayer-reinforced system remarkably efficiently reduced maximum settlement. Laboratory model investigations on the unreinforced and geogrid-reinforced sand bed over an end-bearing stone column-improved soft clay were performed by Deb et al. [17] in a cubic tank. They determined the optimum thickness of unreinforced and geogrid-reinforced sand beds and the optimal size of geogrid reinforcement placed at the bottom of the sand bed. Elsewhere, Debnath and Dey [18] conducted a series of laboratory model tests on an unreinforced sand bed and a geogrid-reinforced sand bed placed over a group of vertically encased stone columns floating in soft clay, as well as their numerical simulations. They reported increased load-carrying capacity, optimal thickness of the unreinforced and reinforced sand bed, and the optimum diameter of the geogrid placed at the bottom of the sand bed while utilizing a reinforced sand bed along with encased stone columns. Finally, Mehrannia et al. [19] studied the effect of floating stone columns, granular blankets, and the combination of both methods in unreinforced and reinforced modes on improving the bearing capacity of scaled physical models in a cubic tank. Their findings showed the enhanced bearing capacity of the clay bed by using improvement methods. It has also been noted that applying geogrid reinforcement in the middle of the granular blanket and geotextile as stone column encasement has considerably improved their efficiency.

Most stone column experimental studies have thus far been conducted on saturated clay beds. Meanwhile, laboratory studies on a stone column overlying with a granular layer of sand or gravel in a unit cell have been insufficiently examined. In none of the prior studies, the granular blanket has been reinforced with the horizontal geosynthetic reinforcement sheets in the unit cell. In addition, a few studies have been reported in the literature indicating the geosynthetic-reinforced granular blanket can noticeably enhance the bearing capacity of the foundation system [17, 18, 20]. However, earlier laboratory studies have modelled a single stone column with a reinforced granular blanket in cubic tanks, which has not considered the concept of the stone column within a group. Moreover, the reinforcement has been applied in optimum dimensions with sizes larger than the stone column diameter and the free end within the granular blanket.

The failure mechanism of planar geosynthetics reinforced foundations has yet to be well investigated and understood. Therefore, to better analyze the failure mechanisms, it is necessary to examine the rupture of the geosynthetic reinforcement layers during loading. Besides, the placement of geogrid reinforcement near the top of the blanket positioned over the stone column-improved bed has yet to be investigated. The present study investigates the effect of end-bearing stone columns, unreinforced and geogrid-reinforced granular blankets, and their combinations in a laboratory unit cell for improving the loose silty sand bed. A novel approach is also adopted to install granular blanket reinforcement in the unit cell, allowing the geogrid reinforcement to mobilize under the applied loads. A principal objective of this study is to conduct large-scale laboratory model testing to examine the effect of some parameters, such as the thickness of the blanket and reinforcing layout, including the number and place of geogrid reinforcement within the blanket. Other objectives of the present study are to reveal the rupture of geogrid reinforcement and to discover the relationship between the failure of the geogrid layers and the characteristics of load-carrying capacity and settlement of the model tests. It should note that compared to the load-carrying capacity, fewer experimental investigations have been conducted on reducing settlement, especially in physical modelling with the unit cell.

2. MATERIALS AND EQUIPMENT USED

2. 1. Sand and Aggregate Materials Since the reinforcement of fine-grained sandy soil using a stone column is intended, the test bed sample was prepared from an admixture of desert sand and clay, with a particle size distribution curve within the range of the Vibro Replacement method [21, 22]. Hence, the mixed sample can be classified as SM per the Unified classification system. A mix of fine sand and clay, with a relative density (D_r) of 25%, was used to provide the test sand bed in loose mode.

A significant number of blows for the compaction of the stone column and blanket materials in the laboratory process can affect the relative density of the loose sand bed and crush the aggregates of the stone column. Because of this, sand and aggregate materials with self-compacting properties and a particular grain size range were employed to lower the number of required hammer blows. The particle size distribution curves of materials used as loose sand beds, granular blankets and stone columns are presented in Figure 1.

According to guidelines suggested by Nayak [23] and Fattah et al. [24], the size of the aggregate used in the construction of the stone column should be 1/7 to 1/6 of the diameter of the stone column. Based on the works of Fox [25], Stoeber [26], and Mohapatra et al. [27], a value of 1/6 is satisfactory for this ratio. Therefore, crushed stone materials passing through sieve No 3/8 inch and remaining on sieve No 4 with grain sizes ranging from 4.75 mm to 9.5 mm were used to construct stone columns. The ratio of this material's largest to the smallest grain size is equal to 2. However, it is tough to ensure a uniform diameter of a stone column with a relative density greater than 50% [28]. Therefore, the relative density of the stone column was chosen as 50%, and for the granular blanket, it was 70%. Sand with grain sizes ranging from 0.6 mm to 1.7 mm was chosen as a granular blanket, with a grain size ratio of 2.8. Table 1 summarizes the properties of the sand and aggregate materials utilized in the laboratory model tests.

2. 2. Geogrid Reinforcement Finding geosynthetics with the required and reduced stiffness on a laboratory scale is extremely difficult. It is because manufacturers do not generate materials with the appropriate stiffness for the physical models. Therefore, fibreglass mesh with the specifications listed in Table 2 has been used to reinforce the blanket in the tests. Its resistance parameters have been determined based on the ASTM D6637 [29]. Gniel and Bouazza [30] also used fibreglass and aluminium mesh as reinforcement in their laboratory research to model a stone column encased by geogrid. The desirable aperture size of geogrid reinforcement is roughly 3.5 times the average soil particle size, D_{50} [31]. Accordingly, an available geogrid of the aperture size of 5 mm × 5 mm was used to reinforce the granular blankets. In addition, a comparison of the average size of sand blanket grains and the size of fibreglass mesh aperture indicates that Koerner [31] recommendation, as well as the scale effect, was taken into account.

2. 3. Unit Cell Stone columns are often installed in a triangle or square pattern in a group with a certain influence area for each column. In the present experimental study, unit cell idealization of a single stone column within a triangular pattern of a group of columns has been used. The unit cell is the equivalent cylindrical influence area of a single stone column within a group of columns [21].

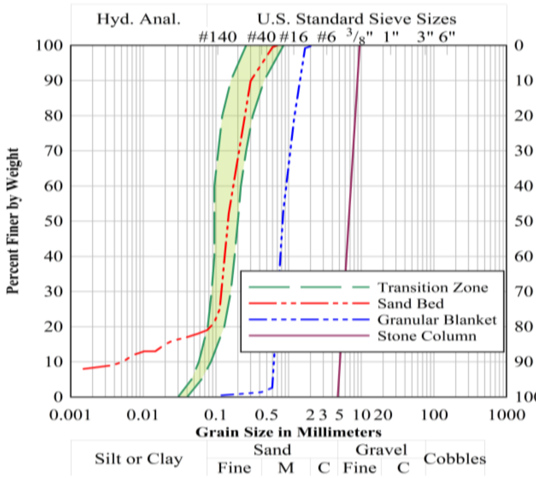

Figure 1. Particle size distribution curves for sands and aggregate materials

TABLE 1. Properties of sands and aggregate materials

Parameter	Sand Bed	Granular Blanket	Stone Column
Specific gravity	2.67	2.66	2.65
Minimum dry unit weight (kN/m^3)	14.67	13.96	14.03
Maximum dry unit weight (kN/m^3)	18.71	17.36	17.21
Bulk unit weight (kN/m^3)	15.51 (D_r=25%)	16.18 (D_r=70%)	15.46 (D_r=50%)
Internal friction angle (degree)	32 (D_r=25%)	35 (D_r=70%)	41 (D_r=50%)
Uniformity coefficient (C_u)	34.8	1.48	1.43
Curvature coefficient (C_c)	15	0.9	0.91
USCS classification	SM	SP	GP

TABLE 2. Properties of geogrid reinforcement

Parameter	Value
Ultimate tensile strength (kN/m)	8
Strain at ultimate strength (%)	3.17
Stiffness at ultimate strain (kN/m)	250
Mesh aperture (mm)	5×5
Mass (g/m^2)	75

In this research, all large-scale laboratory model tests have been performed in a cylindrical steel tank representing the unit cell with 208 mm inside diameter, 6 mm thickness, and 525 mm initial height. The height of the used unit cell can be increased up to 675 mm, by adding modular rings, each with a height of 15 mm made of the unit cell materials. Thus, while carrying out the blankets with variable thickness, in the cases where a fibreglass mesh is reinforcing the blanket, it can be appropriately restrained within the distance between the rings using the pressure resulting from the closure of the retaining nuts and the drop glue (Figure 2(a)).

As displayed in Figure 2(b), a support grid is placed on top of the unit cell, keeping the pipe's head in place. The inner surface of the unit cell was coated with electrostatic paint to reduce friction between the tank's wall and the materials within. In the unit cell theory, radial stiffness is infinite; thus, the outer body was braced by two steel rings to prevent any radial deformation.

2. 4. Test Setup In this study, the pressure was applied to the surface of the models in the unit cell using a hydraulic jack-frame arrangement with a nominal capacity of 10 tons and load cells connected to it with capacities of 5 tons and 10 tons. A circular steel plate of diameter 200 mm and thickness 20 mm was used as test footing to transfer the uniform stress on the model's surface. The footing has a diameter of 8 mm less than the inner diameter of the unit cell, and the foam has been rolled around it to provide three following functions:

- It prevents inaccuracy in the test caused by the footing's contact with the body of the unit cell.
- It positions the footing in the unit cell's centre, parallel to the unit cell wall.
- It maintains soil grains, especially the granular pad, from migrating around the footing.

The intended load was applied as displacement control with a 1 mm/min strain rate in all tests [32-37]. This strain rate has been set based on the type of materials, their moisture, and the performance of trial tests to control the gradual densification of sand throughout the unit cell's entire height.

To ensure that pressure is applied uniformly on the whole surface of the model tests, the load cell is joined to the footing with a pin connection, according to Figure 3. Another steel plate with a 100 mm diameter and a 15 mm thickness is also welded in the centre of the primary footing. A hole with a diameter and depth equal to 25 mm and 10 mm, respectively, was made in the second plate to adjust the steel ball placement connected to the bolt's end. Finally, a bolt and a steel ball attached to it transfer the load as a perpendicular force from the load cell to the footing. Two LVDTs with a displacement range of 100 mm and an accuracy of 0.01 mm were utilized to record changes in the footing's settlement. Two LVDTs were installed diagonally near the edges of the footing, as depicted in Figure 3(a).

3. PREPARATION OF MODEL TESTS

An identical procedure was utilized in all tests to prepare the sand bed and construct the stone column and the granular blanket. At each step, a given amount of each material was poured into the unit cell based on their determined unit weight and desired volume. Before filling the unit cell with sand, the inner surface was coated with oil and grease to minimize friction between the wall and the materials. A stone column with a displacement construction method was formed in the centre of the unit cell with an open-ended thin-walled pipe, having an approximate thickness of 1.8 mm, and an outside diameter of 75 mm. The surrounding of the stone column was covered by much thin nylon with a meagre tensile strength to prevent sand migration into the coarse-grained material of the column.

(a) (b)

Figure 2. Unit cell: (a) unit cell head modular rings and ring bracings, (b) PVC pipe supporting grid and method of reinforcement installation

(a) (b)

Figure 3. (a) Load cell hinge connection to footing and LVDT installation, (b) loading frame and jack

The weight of sand materials required to fill the tank in 50 mm thick layers of test bed was determined with the known unit weight of sand. This volume of sand was poured from a shallow 50 mm height at each step until a specific level of the unit cell to prepare a uniform sand bed of the desired relative density. Similarly, the stone column was constructed by dividing its height into equal parts of 50 mm. At each step, a particular weight of self-compacting aggregate material was poured into the PVC pipe. The filled depth of the pipe was measured at each step to monitor the proper relative density. If compaction has been required, mild tapping with a wooden tamper has been performed. No steel rod was used for the compaction of stone column materials due to the crushing of stone grains caused by the impact. The PVC pipe was slowly pulled out every 50 mm, according to the execution of each layer of the sand bed and stone column, so that the bottom of the pipe was always 50 mm in the sand bed and remained buried. In this approach, a 75 mm diameter end-bearing stone column with a length-to-diameter ratio equal to 7 was physically constructed in the centre of the unit cell.

Blankets with thicknesses of 35 mm and 65 mm were also prepared from self-compacting sand grains by pouring materials from a height in layers of 15 mm to 20 mm. Each layer was compacted with a wooden hammer to achieve the desired relative density. On reaching the predetermined depth of the reinforcement layer, the soil surface was levelled, and a reinforcement layer was laid on the sand surface. Finally, drop glue was utilized to attach the reinforcing mesh throughout the perimeter of the unit cell edge. Also, the contact pressure of the upper and lower rings caused by tightening the retaining nuts has helped to restrain the geogrid fully. This geogrid installation method might be regarded as one of the present study's innovations.

Figure 4 displays the models prepared for testing in the unit cell. To prepare all model tests, including the reinforced blanket, a 5 mm layer of granular fill was poured between the sand bed and the geogrid, as reported in the literature geogrid [38]. Vertical spacing between two geogrid layers was 30 mm, with 5 mm of granular material poured on top of the geogrid in models where the geogrid was placed near the top of the blanket.

4. SCALE EFFECTS FOR EXPERIMENTS AND TESTS PROGRAM

The similitude ratio is the ratio of each length size of the prototype model to its physical model equivalent size [18]. Dimensionless variables in the model and prototype must be equal; accordingly, it is feasible to calculate the ratio of the model's values to reality [39]. Based on the Buckingham [40] similitude theory, the ratio of the length scale of the model test to the prototype model is $1/\lambda$, which has been taken as 1/10 in this study. According to the laws of scale [36], the ratio of reinforcement stiffness in the prototype scale (J_p) to the model scale (J_m) could be calculated as $J_p = J_m{}^2\lambda$ [42]; the same relationship also held in terms of tensile strength.

In earthen constructions, geogrid reinforcements with tensile strengths of more than 400 kN/m and up to 1200 kN/m have often been utilized [43]. Using the average values and according to the laws of similarity, geogrid reinforcement with a tensile strength of 8 kN/m has been used for laboratory model tests. Typically, in the physical model of earthen constructions, there should be infinite soil grains in the contact surfaces of the soil and the structure or the contact surfaces of the soil layers, as well as in the model's boundaries. However, as there are no infinite grains on the contact surfaces of aggregates and the number of grains on these surfaces is finite, the size of the aggregates must be decreased [39]. Thus, the size of the stone column material depends on its diameter. In the current study, the maximum size of the aggregates has been taken as 9.5 mm, while the stone column diameter was 75 mm. In most projects, the diameter of the stone column ranges from 60 cm to 120 cm. Since the stone column diameter in the laboratory model tests has been considered equal to 75 mm, the similitude ratio becomes 8 to 16.

The prototype stone column has a length-to-diameter ratio ranging from 5 to 20 [44]; this parameter is equivalent to 7 in this investigation, with a stone column having a length of 525 mm and a diameter of 75 mm. Compared to other laboratory studies with a similar background [17-19, 45], some distinctions could note. In the present study, the bed soil is fine-grained sand. The test tank shape has been changed from a large cube tank to a laboratory-scale unit cell. The stone column's diameter has been extended to 75 mm, and the number of geogrid layers within the blanket has increased to two layers. Extensive studies have been carried out on geosynthetic-reinforced soil systems [46-48]. However, there is no unified understanding of the failure mode of reinforcement, and few experimental investigations have been conducted on this topic [49].

In the present study, the geogrid installation mode has been changed from applying with an optimal length and

(a) (b) (c)

Figure 4. (a) sand bed, (b) sand bed and granular blanket, (c) sand bed with stone column

a free end to an utterly restrained connection. As such, the geogrid's tensile strength is fully mobilized until it fails, significantly improving the load-carrying capacity and decreasing settlement. According to one of the study's principal purposes, the loading was continued once the geogrid failed. It continued until the desired settlement of 20 mm was attained, and the load-settlement characteristics of models involving the reinforced blanket were recorded. The performed tests are presented in Table 3, and abbreviations are according to the general plan developed for the investigation. According to the types of tests mentioned in Table 3, the flowchart of Figure 5 shows the research methodology. It is observed that considerable studies have been conducted to study the effectiveness of geosynthetic reinforcement on load-carrying capacity. As compared, limited experimental investigations have been conducted on reducing settlement [49]. The points noted are also seen in the reinforced blanket used to improve the performance of stone columns.

When the laboratory study of the improved soil with the geosynthetics-reinforced blanket with free ends is carried out in cubic tanks, further experiments should develop to determine the optimum reinforcement size. However, there has been no need for studies to identify the appropriate diameter of the geogrid in the current study because of the new method of connecting the geogrid sheets to the edges of the unit cell. One of the most significant challenges in confirming the accuracy of results in laboratory investigations is reproducibility. Hence, some tests were repeated to validate the findings. Inaccuracies can cause potential mistakes in material weighing and non-uniformity in the constructed test bed, stone column, or blanket.

5. EXPERIMENTAL OBSERVATIONS

5. 1. Effect of Unreinforced Blanket and Stone Column The results of loading on several model tests until they settled 20 mm, as reported in the literature [17, 18], have been reported in this section.

In addition, because of the laboratory limitations and increasing the internal pressure in the tank while applying load on the model tests, the settlement value of 20 mm was chosen.

The load-settlement characteristics of the unimproved loose sand bed, loose sand improved by only stone column, loose sand along with 35 mm and 65 mm thick unreinforced blanket, and a combination of these scaled physical models are depicted in Figure 6. The settlement given is the average of two LVDTs placed at diametrically opposite ends on the footing. Because of the application of load on the entire surface of the model and the impossibility of lateral soil deformation, the sandy soil was gradually densified upon increasing the overburden pressure. As a result, its stiffness slowly increased, and the models behaved similarly to hydrostatic loading conditions. The model loaded in the unit cell with a rigid plate can be compared to the one-dimensional consolidation test.

TABLE 3. Summary of the experimental tests

Tests series	Type of tests	Test name
1	Sand bed (without stone column and blanket)	SB
2	Sand bed with a 35 mm and 65 mm thick unreinforced blanket	SB+UB35 SB+UB65
3	Sand bed with a layer reinforcement at the bottom or near the top of the 35 mm thick blanket	SB+1bRB35 SB+1tRB35
4	Sand bed with two-layer reinforcement at the bottom and middle of the 65 mm thick blanket	SB+2b&mRB65
5	Sand bed with two-layer reinforcement at the middle and near the top of the 65 mm thick blanket	SB+2m&tRB65
6	Sand bed with stone column	SB+SC
7	Sand bed with stone column and a 35 mm and 65 mm thick unreinforced blanket	SB+SC+UB35 SB+SC+UB65
8	Sand bed with stone column and a layer reinforcement at the bottom or near the top of the 35 mm thick blanket	SB+SC+1bRB35 SB+SC+1tRB35
9	Sand bed with stone column and two-layer reinforcement at the bottom and middle of the 65 mm thick blanket	SB+SC+2b&mRB65
10	Sand bed with stone column and two-layer reinforcement at the middle and near the top of the 65 mm thick blanket	SB+SC+2m&tRB65

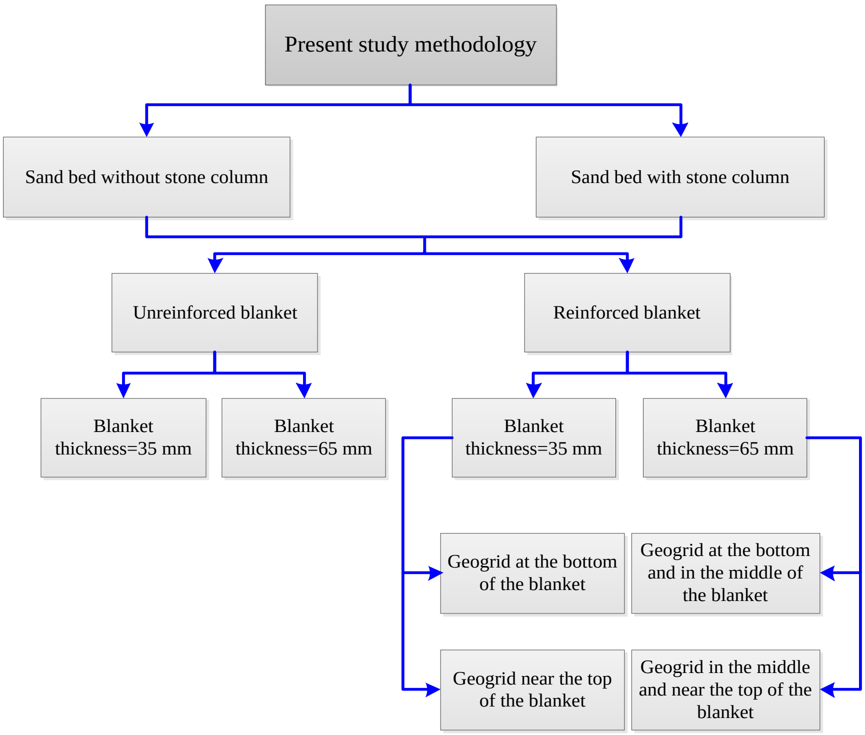

Figure 5. Research methodology of laboratory model tests

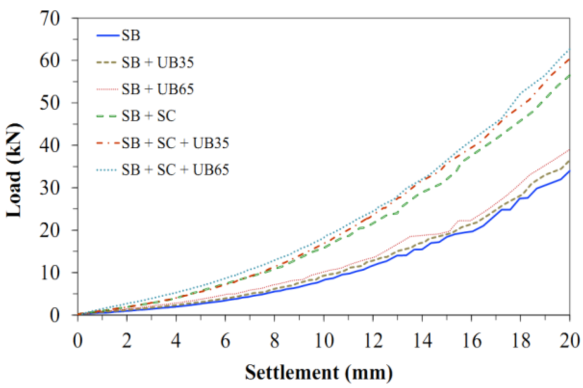

Figure 6. Load-settlement characteristics of loose sand, unreinforced granular blanket, and stone column model tests

In this kind of experiment, since the loading is in the stress path line K_0, failure does not occur in terms of bearing capacity [16]. Soils subjected to hydrostatic loading exhibit nonlinear behaviour [50]. Hardening behaviour in load-settlement characteristics has rarely been reported in laboratory studies conducted by researchers in the unit cell under rigid loading on the entire model surface.

Similar behaviour has been observed only in the laboratory modelling undertaken by Gniel and Bouazza [30], which considers unit cell idealization on a saturated clay bed improved with a geogrid-encased stone column. However, an approximate similar behaviour in laboratory models loaded in the unit cell on saturated clay improved with the stone column by Ambily and Gandhi [51] can be seen. Figure 6 shows the load rises with the settlement and the chart deviation of models without stone columns from those with columns increases. The slope of the load-settlement charts becomes steeper while the presence of a stone column. Based on a comparison of the load-carrying capacity of the models at a constant settlement value, it can be said the effectiveness of the improvement methods is more considerable under looser bed soil conditions. For example, in the case of a 10 mm settlement, the stone column enhances the load-carrying capacity by 92%. While placing 35 mm and 65 mm thick unreinforced blankets on top of the stone column and circumferential soil boosts the load-carrying capacity up to 105% and 122%, respectively. In the 20 mm settlement, the load-carrying capacity of the sand bed with a stone column rises by 66%. In contrast, combining the stone column and unreinforced blanket with the given thicknesses improves the load-carrying capacity by 78% and 84%, respectively.

According to Deb et al. [17], the load-carrying capacity of a soft clay bed with an end-bearing stone column was improved by 69%. Again, it is noted that the load-carrying capacity of a sand bed with an optimum thickness of 50 mm (0.5 times the diameter of the footing) over a stone column-improved soft soil was grown by 141%. The findings of their study are related to a 20 mm settlement and the presence of a single stone column in a large cubic tank. Debnath and Dey [18] observed that the floating stone column group augmented the load-carrying capacity of the improved clay bed by 172%. They also reported a 363% rise in load-carrying capacity in settlement of 20 mm, where a sand bed with the optimal thickness of 40 mm (0.2 times the diameter of the footing) was positioned over the geotextile-encased floating stone columns group.

It can be said, compared to the stone column, the usage of the unreinforced blanket has a far lower effect on the improvement rate, especially when the thickness of the blanket is lower and roughly half the diameter of the stone column. While compared to an unreinforced granular blanket placed on the surface of loose soil, an end-bearing stone column will be more able to carry the load and reduce settlement. The effect of the stone column and the unreinforced blanket in enhancing the load-carrying capacity diminishes as the sand bed becomes gradually dense in the unit cell. The stone column causes a considerable role in decreasing settlement, whereas the unreinforced blanket has a minor effect. Exampling, at a loading intensity of 20 kN, the extent of settlement reduction of the model improved with a stone column reaching 30%. In contrast, with 35 mm or 65 mm thick unreinforced blankets positioned over the stone column, the settlement drops 32% or 35%, respectively. The percentage of settlement reduction under 34 kN loading intensity for models improved with a stone column alone, a stone column along with a 35 mm thick unreinforced blanket, and a stone column along with a 65 mm thick unreinforced blanket is estimated to be around 23%, 26%, and 28%, respectively. Deb et al. [17] reported that for a loading intensity of 0.5 kN, compared to unimproved soil, the settlement has been reduced by 67% and 91%; when the soil is improved by only stone column and by stone column along with unreinforced, respectively.

It suggests that the effect of stone columns and unreinforced blankets in reducing settlement is declined due to the sand bed's gradual densification while loading and its hardening behaviour. Based on the points noted, the role of the unreinforced granular blanket and the stone column in enhancing the load-carrying capacity is more significant than reducing settlement.

5. 2. Effect of Geogrid-reinforced Blanket

Several studies about the effect of geosynthetic reinforcement on soil foundation improvement have applied the reinforcement with the free end and the optimum length. Based on a literature review undertaken by Guo et al. [49], it is 4 to 5 times the width of the foundation. The optimum reinforcement length is affected by the number of reinforcing layers, density and type of soil [52]. As the geogrid has been installed and restrained in the current study, experiments have not been required to identify the appropriate size. Thus, blankets with thicknesses of 35 mm and 65 mm were reinforced with one and two layers of geogrid. The 35 mm thick blankets were reinforced with a single layer of geogrid at the bottom or near the top of the blanket, while blankets with a thickness of 65 mm were reinforced with two layers of geogrid at the bottom and middle or middle and near the top. A geogrid layer was applied at the bottom of the granular fill over stone column-improved soft soil in the studies by Deb et al. [15-17] and Debnath and Dey [18]. Mehrannia et al. [19] used single and double-layers geogrid reinforcement within the middle of the blanket but did not explain how the two layers were arranged relative to each other. Hamidi and Lajevardi [45] reinforced the granular mattress with a geogrid layer at the bottom or middle of it. Figure 7 displays the ruptured geogrid after emptying the unit cell from the granular material of the blanket at the end of the experiment.

It can be seen the geogrid has been ruptured throughout the inner perimeter of the tank. A similar rupturing mechanism has been observed in all blankets, including one or two rows of geogrid reinforcement.

The following section examines the influence of some factors on load-carrying capacity and settlement variation by comparing the load-settlement characteristics under various improving conditions. Figures 8 and 9 illustrate the load-settlement features of the unimproved sand bed and the sand bed, along with the 35 mm and 65 mm thick blankets reinforced with geogrid. Figure 9 indicates the cases where the loose sand bed has also included a stone

Figure 7. A ruptured sample of the blanket's geogrid reinforcement at the end of the test

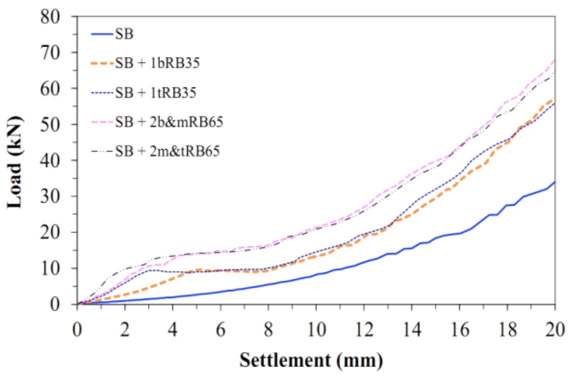

Figure 8. Load-settlement characteristics of sand bed without stone column having a geogrid-reinforced granular blanket

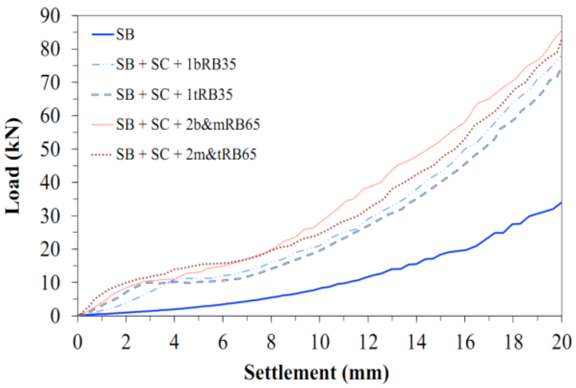

Figure 9. Load-settlement characteristics of sand bed including stone column and geogrid-reinforced granular blanket

column. The charts reveal that reinforcing the blanket with geogrid significantly boosted the load-carrying capacity and reduced the settlement of the model tests. First, the slope of the load-settlement graphs increases until reaching a certain value; then, it becomes nearly constant within a range of the chart, after which the gradient rises again. As compared to unreinforced models, the inclusion of geogrid in the blanket alters the charts' shape and slope.

In addition, a noticeable prominence in load-settlement features and a change of direction of chart concavity at the threshold of geogrid rupture in the settlement ranging from 1-5 mm is observed. The shift in concavity direction and varying the slope from ascending to constant trend are related to the yielding of geogrid.

With the continuance of loading, geogrid rupture ultimately, and with the gradual process of sand densification, the chart returns to its ascending mode.

Increasing the number of reinforcing layers helps to increase load-carrying capacity further and reduce settlement more. The charts in Figures 8 and 9 show that the load-settlement characteristics would be somewhat different with the inclusion of two layers of geogrid reinforcement. During the load enhancement process, two stages of slope variation and concavity direction change are observed when two geogrid layers are placed in the blanket. The first prominence is related to the failure of the first layer of geogrid reinforcement, followed by the failure of the second layer, which forms another prominence. There have been no reports of changes in the slope and direction of the concavity of the load-settlement characteristics in investigations of reinforced blankets with sheet geosynthetic reinforcement. These changes are caused by the way reinforcement operations and their failures. In the studies of Chen et al. [37], the rupture of sheet reinforcement layers under the foundation was reported, and the change in the form of a load-settlement curve was observed.

The comparison of Figure 6 with Figures 8 and 9 reveal that despite the geogrid rupture, the final load value at the settlement of 20 mm has grown compared to the case where the geogrid was not used. In addition, it can be said because of the sandy soil's hardening characteristic; its densification has been possible under the conditions causing tension in the geogrid. Under conditions with a stone column, the geogrid rupture at a higher intensity of load and less settlement due to the stiffer bed caused by the presence of a stone column. Models with reinforced blankets have similar load-settlement characteristics in the geogrid rupture range, regardless of whether stone columns are included. All models with a layer of geogrid near the top of the blanket have load-settlement characteristics with steeper slopes and less settlement at the same load extent compared to the model with geogrid at the bottom. Similar findings have been observed while using two geogrid layers in the middle and near the top of the blanket, compared to placing the geogrid in the bottom and middle of the blanket. While the overburden pressure over the model developed, loose sand hardened, and its density and strength grew as the settlement increased. Therefore, the effect of all improving methods for reducing the settlement diminishes as the load-settlement curves grow gradually. The reduction in settlement following the failure of the geogrid reinforcement has a considerable drawdown in the models, including reinforced blankets. For example, the settlement of the model with a 35 mm thick reinforced blanket, including a layer of geogrid at its bottom resting on the stone column-improved sand bed for a loadings intensity of 5 kN, 15 kN, and 25 kN is reduced by 69%, 44%, and 38%, respectively. However, when the geogrid reinforcement is placed near the top of the blanket, with the given loads, the settlement decreases by 80%, 38%, and 35%, respectively. The comparison suggests that the drawdown in settlement reduction following the geogrid rupture is more severe in the model tests with a single layer of geogrid near the top of the blanket. It is also observed for reinforced blankets, including two geogrid layers in the middle and near the top.

Based on the investigation of Deb et al. [17], for a loading intensity of 1.0 kN, as compared to an unreinforced sand bed, a 44% reduction in the settlement has been observed when the geogrid-reinforced sand bed is used, whereas, for a loading intensity of 1.3 kN, the settlement reduction is 55%. They resulted that the geogrid reinforcement is more effective for higher loading intensity than for lower loading intensity.

As remarked in the introduction, Deb et al. [16] investigated mechanical models with multi-layer reinforced granular fill. They concluded that, compared to single-layer reinforcement, a granular fill reinforced with multi-layer geosynthetic had less effect on reducing settlement since a significant reduction in the settlement was related to the stone column. In addition, they discovered that when stone columns have not been used, the multi-layer reinforcement curtails the settlement. The results of the present study show that at the geogrid rupture threshold, the settlement reduction is relative and depends on the place of reinforcing layers. For example, as compared the model having a layer of geogrid near the top of the blanket (35 mm thick) over a stone column-improved sand bed, with employing two layers of geogrid at the bottom and middle of the blanket (65 mm thick) over the stone column-improved sand bed, the settlement drops by 40% more. When two geogrid layers are placed in the middle, and near the top of the blanket, settlement reduction grows by 60%. Compared to a 35 mm thick blanket reinforced with a geogrid layer at the bottom, the extent of settlement reduction with the placement of two layers at the bottom and middle of the 65 mm thick blanket grows by up to 63%. By placing two layers in the middle and near the top of the blanket, settlement is lower by up to 75%. Thus, the number of reinforcing layers and places will affect the settlement reduction.

Furthermore, the final load-carrying capacity of the model tests at 20 mm settlement has been compared. In the case of using one row of geogrid at the bottom of the blanket or two rows in the middle and bottom of the blanket, up to 5% higher load-carrying capacity has been observed compared to placing a single layer of geogrid near the top of the blanket or two layers in the middle and near the top of the blanket. Due to the distance of the geogrid from the bottom of the footing, the reinforcement is ruptured in a more amount of settlement. As a result, the bed soil has reached a higher density, and the load-carrying capacity has increased. Also, while the presence of a stone column, the final load-carrying capacity grows up to 38% in models having reinforced blankets with one row of geogrid. It is up to 28% in models with reinforced blankets, including two geogrid layers, compared to similar models without stone columns.

5. 3. Improved Load Ratio The load ratio parameter [42] is derived by dividing the improved sand bed load-carrying capacity (with a blanket, stone column, or a combination of both methods) by the sand bed load-carrying capacity without improvement. This parameter, known as "LR", is related to the improved and unimproved models' load-carrying capacity in an equal settlement. In addition, the settlement ratio parameter (S/D), which is by dividing the footing settlement by the diameter of the footing, can be defined. Therefore, the preceding charts can be generated in different spaces when the axes are dimensionless, as illustrated in Figures 10 and 11. The LR curve related to models without reinforced blankets peaks and then drops with a mild downward trend that the inclusion of blankets or the presence of stone columns causes the maximum load ratio (LR_{max}). Fine-grained sand bed compressibility is

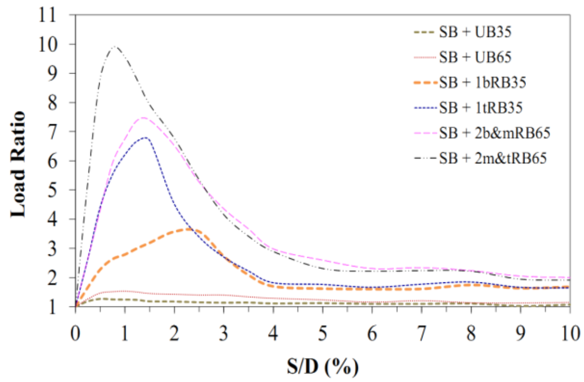

Figure 10. Load ratio-settlement ratio characteristics of improved model tests with an unreinforced and geogrid-reinforced granular blanket

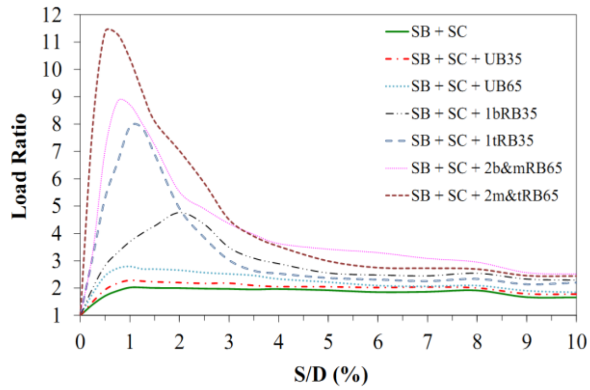

Figure 11. Load ratio-settlement ratio characteristics of improved model tests with stone column and granular blanket

higher than coarser-grained materials used in stone columns and blankets.

The range of variations in the dry unit weight of these materials confirms this. However, adding a blanket or the presence of a stone column changed the stress distribution and affected the sand's hardening behaviour to some extent. Therefore, reducing the amount of stress in the depth of the improved sand bed models can be attributed to the fact that the stone column carries a significant share of the vertical stress. However, there is also the potential for relative displacement of stone column aggregates under pressure. In addition, the granular blanket's performance on the carriage of some overburden pressure has also affected the sand bed's hardening behaviour.

The load ratio-settlement ratio characteristics for the models with reinforced blankets reveal a prominent peak. These noticeable peaks are caused by the geogrid's tensile strength mobilization, followed by a sudden drop yielded by the geogrid's rupture. After the failure of the reinforcement layers, the resistance was only generated by sand and aggregate materials, which explains the sudden drop in LR variations. The mobilization of the tensile strength of the geogrid reinforcement lay within 0.5-2.5% of the settlement ratio. In the model tests with a reinforced blanket including two layers of geogrid, the LR increases with the settlement ratio, then drops suddenly after the prominent peak point. It indicates that all reinforcement layers ruptured within a relatively short period. As Figure 11 points, the LR_{max} is enhanced to 4.77 in model tests with a layer of geogrid at the bottom of the reinforced blanket with a thickness of 35 mm resting on the stone column-improved sand bed. In this model, when the geogrid reinforcement is placed near the top of the blanket, the LR_{max} grow to 7.9. It is while the settlement has been reduced from 4 mm to 2.5 mm. In other words, altering the geogrid's position from the bottom to near the top of the blanket results in 66% further growth of LR_{max} and 38% less settlement. Therefore, placing the geogrid near the top of the blanket is significantly boosted load-carrying capacity and is reduced settlement; thus, it could be regarded as the optimum place for a layer of geogrid reinforcement.

Upon adding the stone column to the model with layer(s) of geogrid reinforcement, the growth of the load ratio increased further. Similar to using a single layer of geogrid, when two layers of the geogrid move away from the base of the footing while getting closer to the top of the stone column, the effect of the column in enhancing the load-bearing and reducing the settlement is intensified. Although, placing two geogrid reinforcement layers in the middle and near the top of the blanket is the optimal arrangement. With the presence of a stone column and the blanket reinforced with two layers of geogrid in the middle and near the top of the blanket, the maximum value of LR_{max} has been obtained equal to 11.38.

Mehrannia et al. [19] reported that at a settlement of 50 mm, the bearing capacity rose by 85% and 92%, respectively, for the model including a layer of geogrid in the middle of the blanket with a thickness of 75 mm over the clay bed as well as for a clay bed model having floating stone column along with a similar blanket. Moreover, in the research of Deb et al. [17], the maximum enhancement in the load-carrying capacity of geogrid-reinforced sand bed over stone column-improved soft clay was reported as 233%; such a condition that the sand bed had an optimum thickness of 30 mm (0.3 times the diameter of the footing), which included a geogrid layer at the bottom. Debnath and Dey [18] obtained 8.45 times the load-carrying capacity with the geogrid-reinforced sand bed over the geotextile-encased stone column group floating in a soft clay bed; the geogrid reinforcement has been placed at the sand bed's bottom with a 30 mm optimum thickness (0.15 times the diameter of the footing).

According to Figures 11 and 12, the LR_{max} could be derived within the geogrid rupture range and the LR_{final} at the end of loading of model tests. The main differences between LR_{max} and LR_{final} can be summarized as follows:

- LR_{final} values are lower than LR_{max} values in all model tests.
- The model tests that improved with the stone column show further LR_{final} compared to experiments without the stone column but with the reinforced blanket.
- The difference between LR_{max} and LR_{final} in models without the reinforced blanket ranges from 19%-52%, whereas the variation in models with the reinforced blanket is between 108%-417%.
- The difference between LR_{max} and LR_{final} for models with the reinforced blanket and the stone column is less than that of similar ones without the stone column.
- The models with one row of geogrid near the top of the blanket have a higher LR_{max} than the one with a stone column and one row of geogrid at the bottom.
- The LR_{max} of models with a single layer of geogrid near the top of the blanket is 1.5 to 2 times that of models with one geogrid layer at the bottom, but it is not valid for LR_{final}.
- The LR_{final} for models improved by the stone column alone and the models improved with one geogrid layer reinforced blanket without stone column are almost the same, which differs from the LR_{max}.
- The models with stone column and unreinforced blanket have a higher LR_{final} than those without stone column but with one geogrid layer reinforced blanket, which is the inverse of LR_{max}.
- The models with a stone column and reinforced blanket with a single layer of geogrid have a higher LR_{final} than models with the reinforced blanket including two geogrid layers, which is the inverse of LR_{max}.
- In the final load, improving the sand bed with the stone column and the unreinforced blanket is a better alternative than improving the bed only with a reinforced blanket. In addition, it can be said utilizing the stone column along with the reinforced blanket is a more suitable alternative than employing each of these techniques alone.

6. DISCUSSIONS

The blanket material and geogrid reinforcement in the reinforced zone move downward when the footing settles under the applied load. However, since the geogrid reinforcement under the footing is curved, an upward force is mobilized to resist the applied load, increasing the load-carrying capacity [53, 54]. This force is one of the main reinforcing mechanisms with horizontal geosynthetic layers, known as the membrane effect. As illustrated in Figure 12, Das [55], Wayne et al. [56], and Chen [57] presented complete reinforcement rotation to model the membrane tensioned effect. Chen [57]

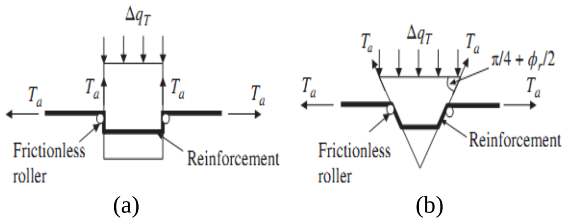

Figure 12. Complete rotation of geosynthetic: (a) vertical punching, (b) active triangular wedges (modified from Das [55], Wayne et al. [56], Chen [57])

attributed the contribution of geosynthetic reinforcement to providing lateral confinement to the punching wedge.

The effect of lateral confinement could be noted among other geosynthetic reinforcing mechanisms. It is related to the relative movement of soil grains along the surface of the geogrid reinforcement under the foundation load, which mobilizes the frictional force at the reinforcement-soil interface. The interaction between the geogrid reinforcement and the soil effectively limits the soil grains' horizontal movement, increasing the soil's lateral confining stress and compressive strength beneath the foundation [54, 58]. Based on the method of installing the geogrid reinforcement and conditions of restraining its edges in the present study, there seems to be only the possibility of relative movement of soil grains and geogrid support under the conditions of developing strain in the geogrid during loading. Therefore, it can be said the membrane tension effect has dominated the development of lateral confinement in these types of tests. According to Giroud and Han [59], the influence of the membrane effect becomes increasingly significant with large deformations. When geogrid gets closer to the base of the footing, further reinforcement deformation occurs; hence the development of the membrane effect increases.

Numerical studies of Debnath and Dey [18] conducted in the 3D software ABAQUS 6.12 confirm this. They reported that most geogrid deformations and stresses occurred mainly in the area immediately below the footing, with small deformations away from the loaded area.

Given the restraint of the geogrid at the unit cell's edges and the conditions for its rupture, it is feasible to infer the full participation of the membrane tension effect and reinforcing tensile strength in enhancing the load-carrying capacity and reducing the settlement. When the geogrid is placed near the top of the blanket, more curvature occurs on the surface of the geogrid reinforcement under the footing, mobilizing the membrane effect and increasing the contribution of its tensile strength. Under these conditions, the vertical component of the geogrid's tensile strength somewhat balances the upper loads on the reinforcement. In response to the combined effect of tensile mobilization strength and the geogrid reinforcement membrane effect due to its curvature, vertical stress diminishes in the region under the geogrid [17, 18, 60-62].

Placing the geogrid at the bottom of the blanket causes a reduction of curvature of geogrid reinforcement under the applied load as well as the reduction of both membrane effect contribution and tensile strength mobilization [63]. Therefore, it has reduced the effectiveness of reinforcement, resulting in a further transferred part of the load being to the stone column. In this condition, the stone column is more involved in carrying the load and reducing the settlement. Also, when geogrid reinforcement is further away from the load, it ruptures at a higher footing settlement. But the model's further settlement will correspond to more densification of the sand bed.

Also, since the load ratio parameter is calculated by dividing the improved model's load-carrying capacity by the model without improvement in the same settlement, if the geogrid fails at more amount of settlements blanket, the LR_{max} would be lower. This issue reveals the benefit of placement of a single layer or two layers of geogrid reinforcement closer to the top of the blanket in models without and with stone columns.

The shallow failure is more likely to happen when the spacing above the uppermost reinforcement is greater than 2/3 times the width of the footing, according to Binquet and Lee [53]. Mandel and Salencon [64] developed a solution for a footing on sand bounded by a rigid base. Figure 13 presents footings with finite width and illustrates that the bearing capacity ratio (BCR) grows as the sand friction angle increases. However, when the distance of the uppermost reinforcing row (z_u) from the base of the footing with width B_f increases, the bearing capacity ratio approaches one. The results of three laboratory investigations are consistent with these curves [65]. According to these curves, the bearing

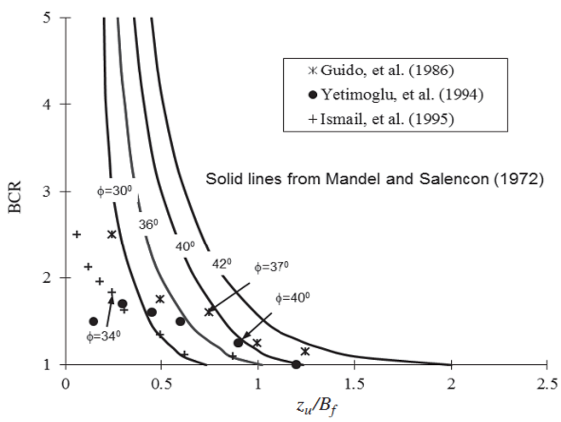

Figure 13. Bearing capacity ratio due to shallow failure above the uppermost reinforcement (after Wayne et al. [56], with permission from ASCE)

capacity ratio grows as the spacing between the reinforcement and the base of the footing diminishes, mainly when the friction angle and density of the soil are low. When z_u is minimal, the overburden pressure related to the shallow footing on the uppermost reinforcing layer is low, and the reinforcement's pullout capacity is limited. Under such a condition, the slip surface extends below the uppermost reinforcement [65]. The current laboratory study is related to the unit cell and the simulation of the centre part of the soil from a wide loading area, which is different from the condition of applying a load via a finite-width foundation. As such, there is no reason for concern about the low overburden pressure on the uppermost reinforcing layer.

Thus, in response to the overall outcome of these curves, if the load is applied over a large area or through multiple adjacent footings, the load-bearing capacity growth will be more remarkable where the geogrid reinforcement is closer to the base of the footing. In addition, an increase in normal stress would increase the shear strength at the contact surface between soil and geogrid [66, 67]. The conditions of the side stone columns differ from those of the others in an infinite group, and the unit cell assumption is unrealistic for them. As a result, the findings of this study cannot be generalized to side stone columns or stone columns of a small group.

7. SUMMARY AND CONCLUSIONS

In this study, the load-settlement characteristic of sand bed models improved with unreinforced and geogrid-reinforced granular blankets, the end-bearing stone column, and with the combination of these methods investigated through large-scale laboratory model tests. The unit cell was used in this study to simulate the behaviour of a single stone column in an infinite group of stone columns. The thickness of the blankets has been taken as 35 mm and 65 mm, and the stone column was 75 mm in diameter with a length-to-diameter ratio equal to 7. A new approach was utilized to install the geogrid, which allows complete mobilizing of the tensile strength and rupture of the geogrid reinforcement.

The role of this mechanism on the load-carrying capacity and settlement characteristic of the physical models was identified. It should be noted that the geogrid reinforcement rupture mechanism has not been investigated earlier in reinforced blanket studies; thus, the findings of this research can be applied in practice. The following are the most prominent conclusions from the current laboratory study:

- As compared to the stone column, the unreinforced granular blanket had a far lower effect on enhancing the load-carrying capacity and reducing settlement. It can be said using a stone column, granular blanket, or combination of both techniques to boost load-carrying capacity was more effective than reducing settlement. However, when the sand bed gradually densified under loading, the effect of the stone column and granular blanket on increasing the load-carrying capacity and reducing settlement was diminished. In addition, the efficiency of improvement methods has been superior under looser bed conditions.
- The results indicate that including geogrid reinforcement in the blanket significantly improves the load-carrying capacity and reduces the settlement of all model tests. However, the effect of single-layer and double-layer geogrid reinforcement on settlement reduction depends on their placement within the granular blanket.
- The comparison of reinforcement layouts of the reinforced blanket with the geogrid indicates that when the geogrid is closer to the base of the footing, it will play a more effective role in enhancing the load-carrying capacity and decreasing the settlement. In models with reinforced blankets, the extent of reduction in the settlement after the rupture of the geogrid reinforcement has a significant drop.
- In models with stone columns causing stiffer beds, the geogrid reinforcement ruptured under more loading intensity and at less extent of settlement. Regardless of the number of reinforcing layers, the stone column significantly improves the LR_{max} and reduces settlement in models with a geogrid layer at the bottom of the blanket.
- In the final load, improving the sand bed with stone columns and unreinforced blankets is preferred over improving the sand bed with only reinforced blankets. Overall, the combination approach of the stone column and reinforced blanket is a preferable alternative rather than using either of these techniques individually.

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Persian Abstract

چکیده

در این پژوهش مطالعه نمونه‌های بزرگ مقیاس آزمایشگاهی در سلول واحد به منظور بررسی رفتار خاک ماسه‌ای سست بهسازی شده با بالشتک دانه‌ای غیر مسلح و مسلح، ستون سنگی اتکایی و ترکیبی از آن‌ها انجام شده است. با توجه به اینکه تا کنون در مطالعات تجربی به گسیختگی مسلح کننده در بالشتک دانه‌ای مسلح پرداخته نشده، روشی نوین جهت نصب ژئوگرید در سلول واحد به کار رفته تا در نتیجه آن امکان بسیج کامل مقاومت کششی ژئوگرید و گسیختگی آن تحت تنش‌های وارده محقق گردد. در این تحقیق رفتار بار- نشست نمونه‌ها حتی پس از گسیختگی ژئوگرید و تا رسیدن به نشست موردنظر ادامه یافته است. تمرکز مطالعات در راستای بررسی تاثیر متغیرهایی چون ضخامت بالشتک و آرایش تسلیح شامل تعداد و محل قرارگیری صفحات ژئوگرید در بالشتک دانه‌ای، طی ساخت مدل‌های فیزیکی بستر ماسه‌ای بدون ستون سنگی و دارای ستون است. مسلح سازی بالشتک با ژئوگرید ضمن متمایز نمودن شکل نمودارهای بار- نشست نسبت به سایر مطالعات با زمینه مشابه، اثر قابل توجهی بر افزایش باربری و کاهش نشست نمونه‌ها داشته است. میزان تاثیر استفاده از ستون سنگی، بالشتک ماسه‌ای یا هر دو روش بر افزایش توان باربری بستر بیشتر از کاهش نشست بوده است. چگونگی تاثیر مسلح‌کننده بالشتک بر کاهش نشست بستر، به محل قرارگیری آن در بالشتک وابسته است. این روش‌های بهسازی در حالتی که خاک بستر در شرایط سست‌تری قرار داشته موثرتر بوده‌اند. می‌توان قرارگیری یک لایه ژئوگرید در بالا یا دو لایه در میانه و بالای ضخامت بالشتک را موقعیت‌های بهینه قرارگیری مسلح‌کننده در ضخامت بالشتک تلقی نمود.