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Case study

Sustainable utilisation of steel slag as granular column for ground improvement in geotechnical projects

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ABSTRACT

Granular column is an attractive mitigation method which is widely used in geotechnical engineering to enhance the bearing capacity, reduce settlement and accelerate consolidation. Utilisation of industrial wastes such as steel slag in soil stabilization can be an environment-friendly and cost-effective extraction technique to the disposal of solid waste materials. Previous studies investigated the bearing capacity and settlement of ground improved with granular columns with or without the geosynthetic encasement. However, very limited number of studies have investigated the response of ordinary stone columns without encasement and geosynthetic encased steel slag columns under lateral loading. In this paper, the lateral load capacity of steel slag granular column-soil composites has been investigated. For this purpose, a series of large direct shear tests were performed on the column-soil composites with the steel slag column and the ordinary stone column with or without the geosynthetic encasement. The effect of type of column materials (steel slag and sand), column diameter, number of columns, columns arrangement, and geosynthetic encasement on the shear strength parameters of column-soil composites have been studied. The experimental results show the effectiveness of using the steel slag columns to improve the lateral load-bearing performance of soil.

1. Introduction

To date, many studies have been done regarding the use of industrial wastes in civil applications as an alternative to construction materials which are cost-effective and environmental-friendly [1–3]. For example, many studies focused on utilization of the waste materials such as fiber waste materials, fly ash, blast furnace slag, stone waste, rubber shreds, zeolite, waste plastics and etc. as a replacement material for the ground improvement [4–13], concrete production [14–20], brick [21,22], mortar [1,23–25] and road pavement subgrade [26–28].

Steel slag is a solid waste in steel-making operations from either the conversion of iron to steel in a basic oxygen furnace (basic oxygen furnace slag (BOF)), or the melting of scrap in an electric arc furnace (electric arc furnace slag (EAF)) and has mainly been utilised as the aggregates in concreting and road construction [29–31]. In recent years, the rapid growth and the massive increase in steel demand and production resulted in the increase of steel slag generation. Steel slag is partially reused as natural fine and coarse

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aggregates replacement in asphaltic concrete [32], asphalt mixture [33], an aggregate for road construction [34–36], solid brick [37], ballast for railway and filling material in excavation [38]. Consumption of steel slag in developed countries as the replacement material in construction industry is approximately 60% of the total steel slag production whereas it is about 20% in developing countries [39,40].

Poh et al. [41] used mixture of steel slag fines and two different activators (quicklime and sodium metasilicate) as a soil improvement material. The results showed that the use of steel slag fines resulted in an increase in the strength and durability, and also reduced the expansion potential of the soil. Shen et al. [42] indicated that using the mixture of steel slag and other solid wastes as a road base material resulted in higher early strength than lime–fly ash or lime–soil mixtures and even higher long-term strength than those of cement stabilised specimens. Akinwumi et al. [43] studied the effect of adding pulverised steel slag on some geotechnical properties of a lateritic soil. The results showed that the increasing steel slag content in soil specimens from 5% to 10% resulted in a decrease of the soil plasticity and swelling potential and an increase of the permeability and cured strength of the soil. Ashango and Patra [12] used steel slag, rice husk ash, and quick lime to stabilize an expansive soil. The unconfined compressive test showed that the optimum mix proportion was soil- 65%, steel slag-20%, lime-5% and rice husk ash-10%. The unconfined compressive strength (UCS) of the optimum mix was enhanced about 45% and 90% for the uncured condition and cured condition at 30 days in a chamber maintained at 90–100% relative humidity and temperature of 28–32 °C, respectively. The results of cyclic triaxial tests showed that the stiffness of the optimum mix increased to 58–78% as compared to the natural soil specimens. Wu et al. [44] introduced an optimal slag-based composite with improved cementation efficiency to modify expansive soil properties. The tests results indicated that the cementation of the slag resulted in significant reduction of the swelling potential and improved the strength characteristics of the soil. Lang et al. [45] investigated the effectiveness of addition of steel slag to stabilize dredged sludge. The results proposed that steel slag content of 5–10% was the optimal content to improve the shear strength of cement-stabilised dredged sludge.

Various soil improvement methods such as ordinary granular (stone) columns have been reported in the previous studies to increase the strength characteristics and permeability, and decrease the compressibility characteristics of soils [46–55]. Nowadays, conventional piles and granular columns have been widely used to stabilize and improve the load bearing capacity and to reduce the settlement of soft and weak soils. The soil improvements via granular columns have many advantages, such as the lower compressibility and liquefaction potential, and the higher load carrying capacity and permeability [56]. The most important factors affecting the performance of granular columns are diameter, configuration and spacing of columns, granular material characteristics, relative compaction of column material, and lateral confinement provided by the surrounding soil [57–59]. However, the use of granular columns in soils with a shear resistance of less than 15 kPa may not be very effective due to the insufficient lateral support provided by the surrounding soft soil [60]. This limitation can be overcome by using a geosynthetic encasement to the granular column, which provides an additional confinement, leading to the mobilisation of higher shear resistance and preventing large bulging of the column [58,61–65]. On the other hand, the progressive accumulation of the soil particles results in clogging of the granular column which decreases the permeability of columns [66–68]. The geosynthetic encasement in the granular columns results in an additional lateral confinement and hence the additional shear resistance and it also helps to prevent the clogging of granular columns [50,62]. Murugesan and Rajagopal [46] carried out a series of shearing load test to study the bearing capacity and the shear stiffness of granular columns with and without the geosynthetic encasement. The results indicated a significant increase in the shear load capacity due to the encasing granular columns with the geosynthetic encasement. Previous studies have reported the advantage of using the geosynthetic encasement in increasing the bearing capacity and reducing the settlements of granular columns compared to that of without the geosynthetic encasement [61,62,69]. In the studies mentioned above, the granular columns were reinforced with geosynthetics by using vertical encasement. Ghazavi et al. [70] studied horizontally reinforced stone columns. The results showed that the bearing capacity of granular columns increased by using the horizontally geosynthetic layers as well as the vertically geosynthetic layers.

So far, many studies on the axial bearing capacity and settlements of the ordinary and encased granular columns have been conducted [49,71–76]. However, very little research attempts to study the lateral loading capacity of granular columns. Mohapatra et al. [52] studied the lateral load capacity of the ordinary and geosynthetic encased granular columns. The results indicated that the lateral load capacity of granular columns increased with the geosynthetic encasement. A marginal enhancement in the shear strength of ordinary granular columns was also observed with an increase in area replacement ratio (the ratio of the plan area of granular columns to the plan area of shear box). However, a substantial increase was observed in the shear strength of geosynthetic encased granular columns. Different types of shear failures were observed in the ordinary and geosynthetic encased granular columns under lateral loading. Cengiz et al. [47] studied the behavior of ordinary and geosynthetic encased granular columns under the static and cyclic lateral loads using physical modelling tests. The results showed a significant improvement of the overall friction angle of column-soil composites due to the installation of geosynthetic encased columns with a lower-bound area replacement value. Rezaei-Hosseinabadi et al. [39] carried out a series of large direct shear tests to study the lateral load capacity of the ordinary and geosynthetic encased granular columns. The results showed that the overall cohesion of the column-soil composites without encasement was almost constant. While, the cohesion of the column-soil composites with the geosynthetic encasement increased due to the increasing column diameter.

Despite all the studies, there is no work on comparing the lateral load capacity of soil deposits reinforced with the steel slag columns and the ordinary stone columns. This paper focuses on understanding the lateral load capacity of soil deposits reinforced with the steel slag column and the ordinary stone column with or without the geosynthetic encasement. The novelty of the current study is the utilisation of steel slag as the granular material in the columns to improve the weak soils. A series of large-scale direct shear tests were performed to determine the shear strength parameters of column-soil composites. The effects of different types of column materials (i.e., steel slag and sand), column diameter, number of columns, and geosynthetic encasement on the lateral load capacity of soil and stone column composite were investigated.

2. Experimental programme

2.1. Materials

In order to perform the experimental programme, two different soil categories were needed, the first soil category to be treated (host soil) and the second soil category to be used as the column materials. A uniform fine sand collected from Varzaneh area in Isfahan, Iran has been used as the host soil in this study. Varzaneh sand was classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). For the second soil category, two types of sands and two types of steel slags have been used in the experiments as the column materials. Table 1 shows the basic properties of the materials. Therefore, the host soil was treated with granular columns made of four different column materials (i.e. fine sand, coarse sand, fine steel slag and coarse steel slag). The grain-size distribution curves of all the materials are shown in Fig. 1. A photo of the materials is provided in Fig. 2. An electric arc furnace (EAF) produced in Mobarakeh steel company which is one of the largest steel producers in Iran was used in this study. EAF steel slag waste is among the more common waste materials used in civil engineering projects such as road construction [77]. It is worth noting that the steel slag particles have considerably higher surface roughness than sand particles which resulted in stronger interfacial transition zone, interlocking properties and surface friction.

Mineralogical composition of EAF steel slag was determined by the X-ray diffraction (XRD) technique. The XRD results are presented in Table 2. The granular columns were formed in the direct shear box using sand or steel slag aggregate passing through 19.1 mm sieve and retained at 0.075 mm sieve as shown in Fig. 1. The dimensions of shear box should be less than approximately 10 times the size of the largest particle in order to minimize the size effect on the shear strength parameters [52,78–80]. A woven geotextile was selected for the experimental programme. The physical and mechanical characteristics of woven geotextile are presented in Table 3. The geotextile was rolled over the tube and adjacent panels of geotextile were sewn together with flat seam using a portable hand sewing machine before preparing the samples.

2.2. Test set-up

In this work, a series of large-scale direct shear tests was conducted to study the behaviour of granular column-soil composites with or without the geosynthetic encasement. For this purpose, a large-scale direct shear apparatus with the box dimensions of 30 cm × 30 cm and a depth of 14 cm was used which facilitated testing the steel slag column-soil composites containing large granular particles of steel slag according to ASTM D3080. The large-scale direct shear consisted of upper and lower boxes, two linear variable displacement transducers (LVDT), a load cell and a data acquisition system. The samples were sheared under three different normal stresses (33, 65 and 130 kPa) and monotonic displacement control at a constant strain rate of 1 mm/min.

2.3. Sample preparation and tests programme

In this work, seven groups of large-scale direct shear tests were performed to investigate the effect of different types of column materials (i.e. fine sand, coarse sand, fine steel slag and coarse steel slag), column diameter, number of columns, and geosynthetic encasement on the lateral load capacity of soil and stone column composite. Details of each test group are presented in Table 4. The effect of column diameter or area replacement ratio (A_r) on the shear strength parameters of the column-soil composites was investigated in test group 1 for the fine steel slag column, in test group 4 for the fine sand column and in test group 5 for the coarse sand column. A_r is defined as the ratio of granular column area to the total area of shear box. It should be noting that the single granular column was placed at the center of the shear box. The effect of number of columns at constant A_r value on the shear strength parameters of the column-soil composites was investigated through test groups 2, 3, 6 and 7 for the fine steel slag columns, coarse steel slag columns, fine sand columns and coarse sand columns, respectively (see Fig. 4). As shown from Figs. 3 and 4, the direction of the linear columns was either vertical or parallel to the shear direction. The effect of direction of the linear column group was investigated through test group 2. However, the linear columns in the third test group were tested only with a column arrangement. The effect of geosynthetic encasement on the shear strength parameters of the column-soil composites was investigated in test group 1, 2, 6 and 7. Fig. 4 shows the configuration diagram of the test columns in the all test groups.

In order to prepare the samples with various column arrangements, the materials were oven dried at 105 °C for 24 h. Steel tubes

Table 1
Physical and geotechnical properties of materials.

Characteristics	Varzaneh sand	Fine sand (FS)	Fine steel slag (FSS)	Coarse sand (CS)	Fine steel slag (FSS)	Coarse steel slag (CSS)
Specific gravity	2.67	2.71	3.55	2.70	3.55	3.67
Plasticity index (%)	NP	NP	NP	NP	NP	NP
Minimum dry density(kN/m^3)	15.41	15.07	18.96	14.48	18.96	19.15
Maximum dry density (kN/m^3)	17.99	20.07	23.01	19.51	23.01	23.97
Friction angle (^{o})	36	42	49	43	49	55
Cohesion (kPa)	4.6	4.29	3.7	3.82	3.7	3.35

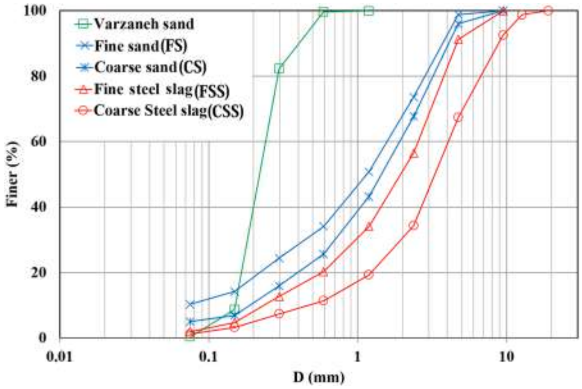

Fig. 1. Grain-size distribution curves of materials.

Fig. 2. Photo of materials used in the tests.

Table 2
Chemical composition of steel slag used in the study.

Composition	Value (%)
FeO	29.8
CaO	31.2
SiO_2	19.2
MgO	12.2
AL_2O_3	4.1
MnO	0.6
P_2O_5	0.5

Table 3
Physical and mechanical characteristics of geotextile.

Composition	Value (%)
Ultimate tensile strength (kN/m)	39
Mass per unit area (g/m^2)	750
Thickness (mm)	6.1
Strain at ultimate strength (%)	35
Initial modulus of parent material (kN/m)	180

with inner diameter corresponding the diameter of the columns were used and fixed in the shear box. The box and the steel tubes were then filled by the required amount of materials in 3 layers using a raining technique. Each layer of the Varzaneh sand (i.e., host soil) was compacted with a given relative density about 75–80%. At the same time, the required amount of materials for each layer of the columns was placed in the steel tubes and compacted using a tamping rod with a tamping foot equal to one-half the column diameter at the relative density about 65–70%. The steel tubes were gradually withdrawn after preparing each layer. In order to minimize the disturbance, steel tubes with smooth surfaces were used. At the end of withdrawing the steel tube, an extra pressure was applied on the granular columns and the host soil to create a flat surface. The tubes were lined with geotextile for the geotextile encased columns.

Table 4
Details of direct shear tests.

Test group	Type of column materials	Column diameter (cm)	Area replacement ratio, A_r (%)	Number of columns	Geotextile encasement	Number of tests
Group-1	Fine steel slag	5, 10, 15, 20, 25	2.2, 8.7, 19.6, 34.9, 54.5	1	Yes/No	30
Group-2	Fine steel slag	5, 5.8, 7, 10	8.7	1, 2, 3, 4	Yes/No	33
Group-3	Coarse steel slag	5, 5.8, 7, 10	8.7	1, 2, 3, 4	Yes	12
Group-4	Fine sand	5, 10, 15, 20, 25	2.2, 8.7, 19.6, 34.9, 54.5	1	Yes	15
Group-5	Coarse sand	5, 10, 15, 20, 25	2.2, 8.7, 19.6, 34.9, 54.5	1	Yes	15
Group-6	Fine sand	10, 5, 5.8, 7	8.7	1, 2, 3, 4	Yes/No	24
Group-7	Coarse sand	10, 5, 5.8, 7	8.7	1, 2, 3, 4	Yes/No	24

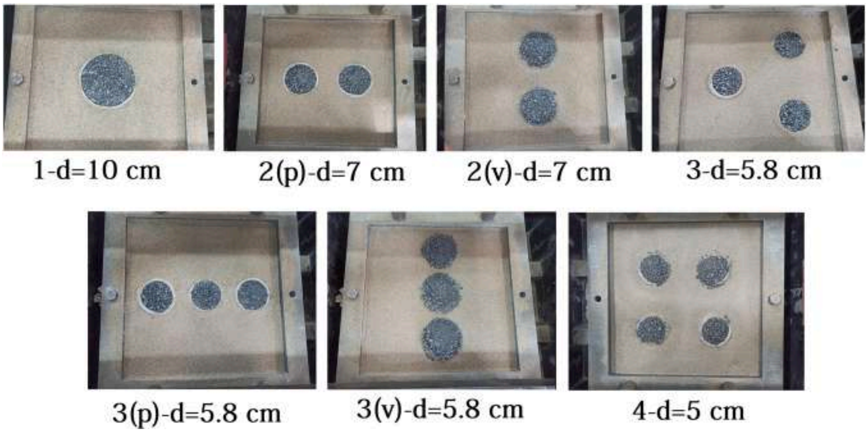

Fig. 3. Plan view of large direct shear box with different granular column arrangements.

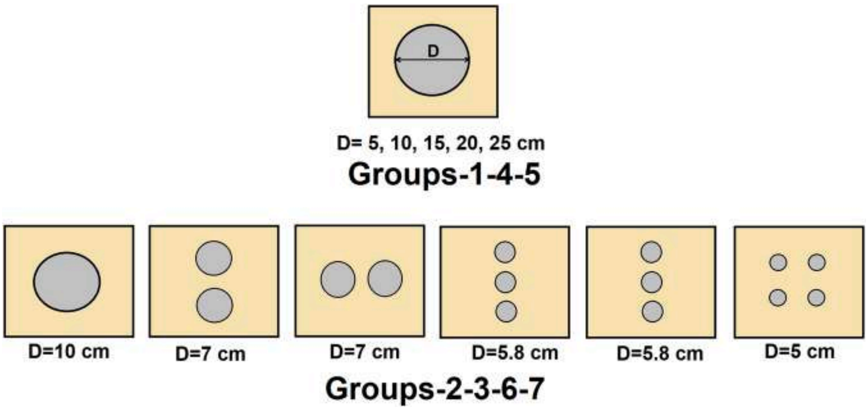

Fig. 4. Configuration diagram of the test columns in the all test groups.

3. Results and discussion

The results of the experimental programme are presented in this section. The effect of various parameters such as column material, column diameter, number of columns and geosynthetic encasement on the shear strength parameters of column-soil composites are discussed.

The shear stress-shear strain curves of the single column treated samples in test group 1, under normal stresses of 33, 65 and 130 kPa, with and without the geosynthetic encasement are presented in Fig. 5. Results show that both the peak and the critical-state shear strengths of the samples with and without the geosynthetic encasement increases with the increase in normal stress. Moreover, the partial replacement of the soil with the steel slag column without the geosynthetic encasement only resulted in an improvement of the peak shear stress, whereas it had negligible effect on the critical shear strength. The results of single column treated samples without the geosynthetic encasement suggested that the peak shear strength increased significantly when column diameter increased from 20 cm to 25 cm, while, it had negligible effect on the peak shear strength when the diameter was lower than 20 cm. The ratio of peak

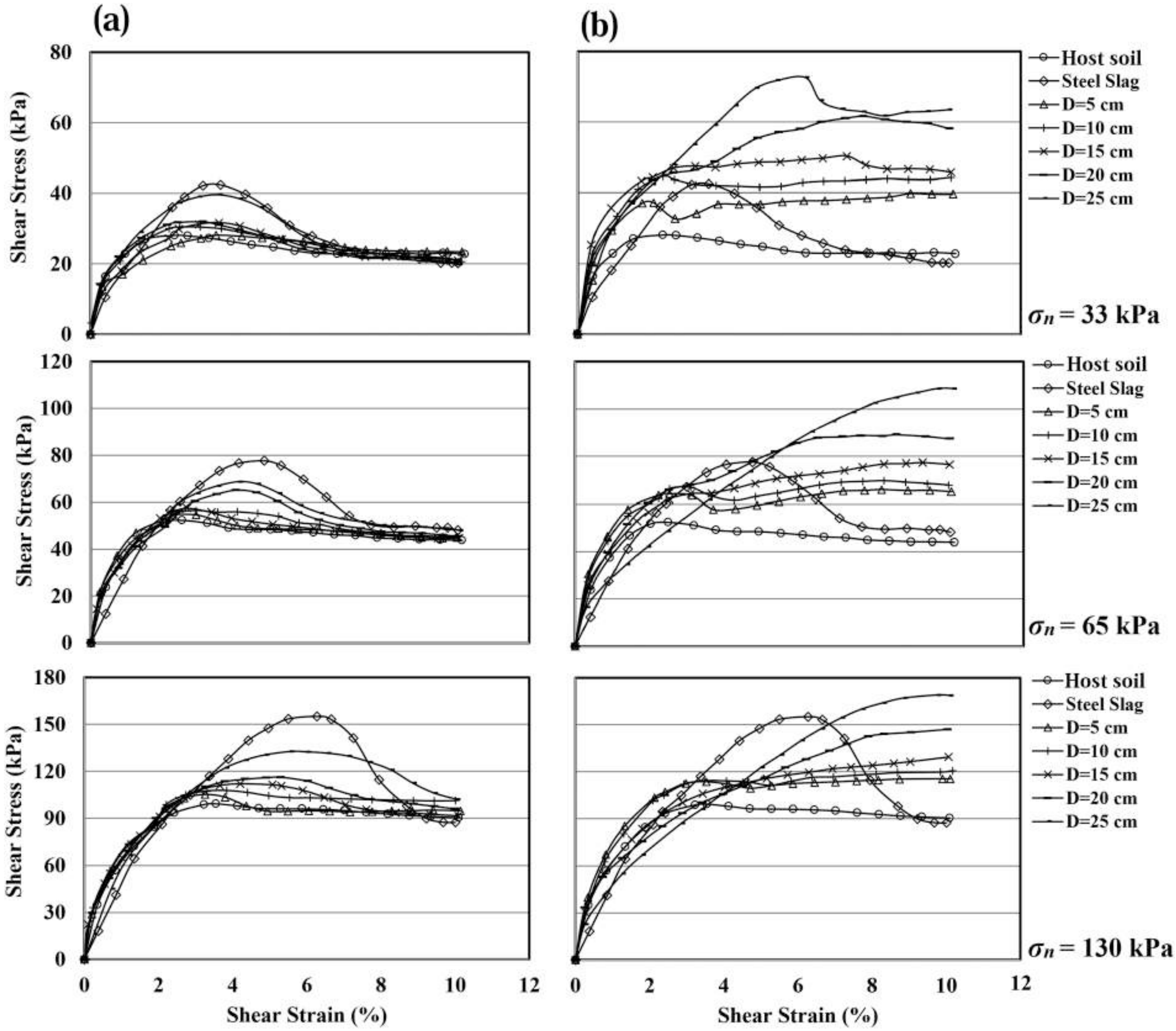

Fig. 5. Direct shear test results for samples reinforced with single steel slag column under various normal stress (a) without the geosynthetic encasement (b) with the geosynthetic encasement.

shear strength of the sample containing 25 cm diameter granular column to that of untreated sample is about 1.33–1.48 depending on the normal stress value. The results of single column treated samples with the geosynthetic encasement suggested that both the peak and critical shear strength increased significantly when the column diameter increased from 5 cm to 25 cm. The peak and critical shear strength of the treated sample containing 25 cm diameter encased granular column increased by 116% and 137% on average respectively, as compared to the untreated one. In addition, the shear strain corresponding to the peak shear strength increased when the column diameter increased (see Fig. 5(b)). It can be noted that the geosynthetic encasement caused an increase in the peak shear strength and the corresponding shear strain which led to strain hardening in the samples as shown in Fig. 5(b). Therefore, effectiveness of the increase in column diameter to improve the large displacement shear strength of the column-soil composites was more pronounce when the geosynthetic encasement was used which were in good agreement with those reported in the literature [46,64]. Plastic shear hardening almost without softening is observed in the treated sample with 20 cm or 25 cm column (with the exception of treated sample with 25 cm granular column under normal stress of 33 kPa). The geosynthetic encasement confines the granular materials and makes the granular column act like a semirigid pile which results in an increase of shear strength of the granular column-soil composite. It could be conducted that the increase in critical shear strength might be attributed to the tensile forces developed in geosynthetic.

Fig. 6 shows the shear strength envelopes corresponding to the peak state of the samples with and without the geosynthetic encasement. It can be seen from the figure that the peak friction angle increased as the column diameter increased in both cases with and without the geosynthetic encasement. However, the peak friction angle did not change for the same column diameter with or without the geosynthetic encasement. The peak friction angle increased from 36 to 44 when the host soil was treated with 25 cm granular column. The cohesion of column-soil composites without the geosynthetic encasement were more or less the same which was about 4 kPa. However, the cohesion of column-soil composites with the geosynthetic encasement increased when the column diameter increased from 5 cm to 25 cm. This observation could be due to the mobilisation of tensile forces in circumferential and vertical directions in the geosynthetic encasement. The cohesion increased from 4.6 kPa to 42.5 kPa when the host soil was treated with 25 cm encased granular column. In other words, the cohesion of the treated sample with 25 cm encased granular column increased by 824% as compared to the untreated one which is a significant enhancement.

Fig. 7 shows the peak shear stress versus the area replacement ratio (A_r) for the column-soil composites with the geosynthetic encasement (solid line) and without the geosynthetic encasement (dashed line) under various normal stress levels. As shown in the figure, the peak shear strength of column-soil composites without any geosynthetic encasement increased significantly when A_r increased from 35 to 54.5 which are corresponding to the column diameter of 20 cm and 25 cm, respectively. However, a continuous increase in the peak shear strength of treated sample with encased granular column has been observed when A_r increased from 2.2 to 54.5 which are corresponding to the column diameter of 5 cm and 25 cm. In general, the impact of A_r on the increase of the shear strength is more important for the samples with the geosynthetic encasement compared to those without the geosynthetic encasement. In addition, the peak shear strength of samples with the geosynthetic encasement was more than that of the samples without the geosynthetic encasement at a given normal stress. The difference in the shear strength of samples with and without the geosynthetic encasement was more significant under high normal stress level. The soil-geosynthetic interface friction increased with the increasing normal stress.

Fig. 8(a) displays the shear strength envelopes corresponding to the peak state of the samples with the geosynthetic encasement for test group 2. The effect of number of encased granular columns is presented in Fig. 8(a). The direction of the linear column group is indicated by P for and V which represent parallel and vertical directions relative to the shear force direction, respectively. Herein, A_r was constant at a value of 8.7%. As shown from Table 4, the diameters of columns were considered as 5, 5.8, 7 and 10 cm for the samples containing 4, 3, 2 and 1 columns, respectively. It should be noting that the total area of the columns was identical in all the experiments, therefore, the increase in number of columns resulted in an increase in the column circumference. It can be seen from Fig. 8(a) that the friction angle and the cohesion of column-soil composites increased as the number of columns increased. The friction angle of encased column-soil composites increased slightly from 38° to 41° while the cohesion of encased column-soil composites increased about 1.58 times with increase the number of columns from 1 to 4 under a given A_r value. The change in cohesion was more obvious than the change in friction angle which could be due to the increase of geotextile length at the location near the shear surface when the number of columns increased. It seems that the group column performance was more effective when the column diameters decreased under constant A_r. This might be due to the increase in interlocking of host soil and granular column particles w with the surface asperities of geotextile which led to the improvement of the interface shear properties. Similar results have been reported for the effectiveness of number of encased granular columns on the capacity and settlement response of composite ground [81–83]. Fig. 8 (b) shows the effect of encased granular column-group arrangement or direction on the shear strength envelopes corresponding to the peak state of the samples containing 2 and 3 columns with the geosynthetic encasement. The results show that the friction angle and cohesion of the column-soil composites increased slightly with increase the number of columns from 2 to 3 regardless of the arrangement or direction of the encased granular columns. The friction angle of the column-soil composites is almost independent of granular columns arrangement with the geosynthetic encasement for a given number of columns. However, the granular column-group parallel to the shearing direction resulted in a higher cohesion for a given number of column. The cohesion of encased granular column-soil composites increased from18 kPa to 21 kPa when the direction of linear granular columns changed from vertical to parallel for the sample containing 2 columns. This change was from 21 kPa to 25 kPa for the sample containing 3 columns. This could be attributed to the shadowing effect and the edge effect used in group of piles design under lateral load [84,85]. The effect of linear columns direction on the cohesion of encased granular column-soil composites is more significant with the increase of the number of columns from 2 to 3. The shear strength of samples increased when the normal stress increased. For a given number of columns, the encased granular column-group configuration had little effect on the shear strength of granular column-soil composites.

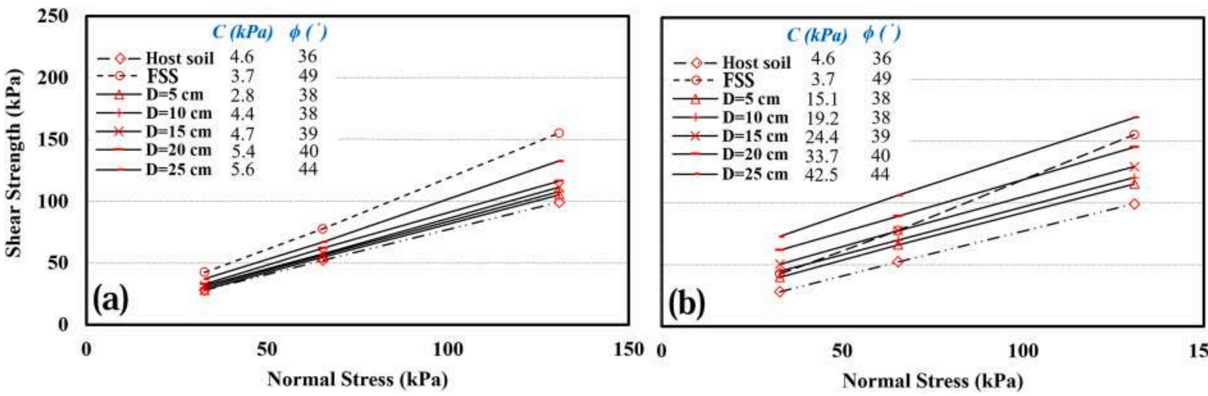

Fig. 6. Shear strength envelopes corresponding to peak state of the samples reinforced with single steel slag column (a) without the geosynthetic encasement (b) with the geosynthetic encasement.

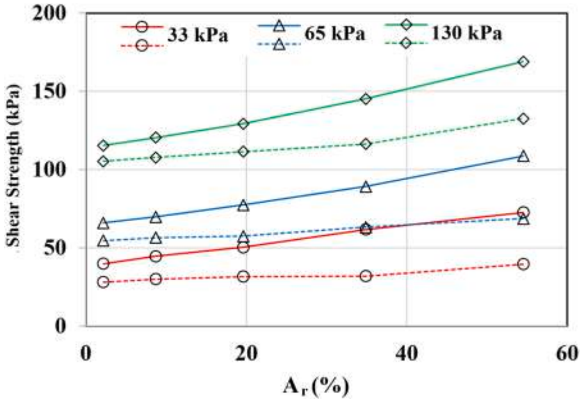

Fig. 7. Shear strength of samples reinforced with single steel slag column with (solid line) and without (dashed line) geosynthetic encasement versus area replacement ratio.

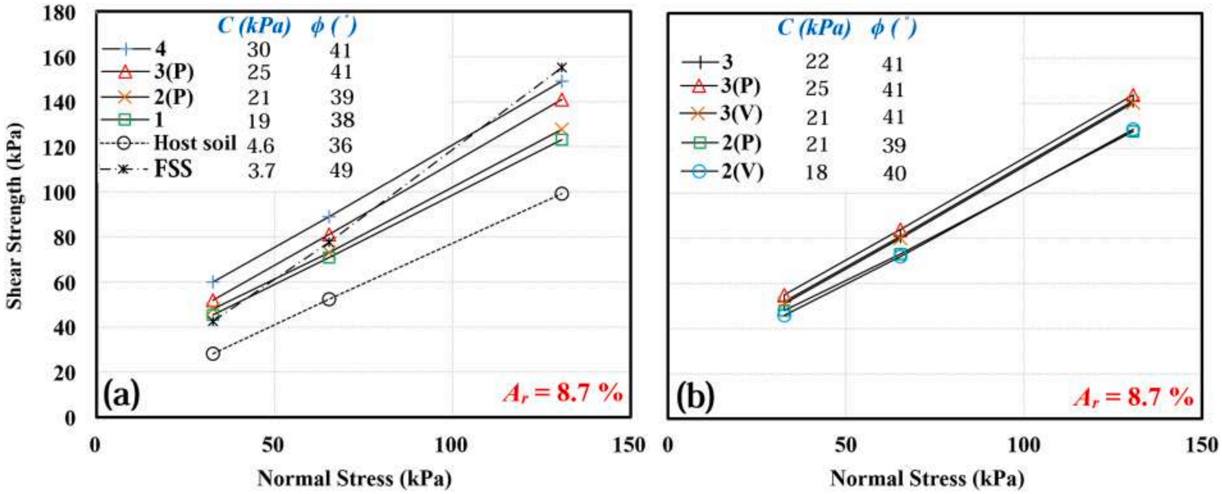

Fig. 8. Shear strength envelopes corresponding to peak state of the samples treated with encased steel slag columns (a) effect of number of granular columns (b) effect of columns arrangement.

Fig. 9(a) shows the shear strength envelopes corresponding to the peak state of the samples without the geosynthetic encasement for test group 2 under a constant area replacement ratio ($A_r = 8.7\%$). It can be seen from the figure that the number of columns had no significant effect on the overall cohesion. However, the friction angle increased from 38° to 41° with the increase of the number of columns from 1 to 4. Fig. 9(b) shows the variation of shear strength of the treated samples without the geosynthetic encasement with respect to the number of columns under various normal stress levels. As shown from Fig. 9(b), the shear strength increased slightly when the number of columns increased for a given normal stress level. The increase of the shear strength is less than 16% due to increasing the number of columns under a given A_r value. A comparison of Fig. 9(a) and 8(a) shows that the geosynthetic encasement only results an increase of the cohesion of column-soil composites for a given A_r. The effect of the geosynthetic encasement on the enhancement of the cohesion was more significant when the number of columns increased. The geosynthetic encasement increased the cohesion of column-soil composites by 322% in the sample containing one granular column and by 650% in the sample containing four columns.

The results of the test group 3 are presented in Fig. 9. Fig. 9(a) shows the shear strength envelopes corresponding to the peak state of the samples with the coarse steel slag columns with the geosynthetic encasement under a constant area replacement ratio ($A_r = 8.7\%$). The cohesion of coarse steel slag column-soil composites as well as the fine steel slag column-soil composites increased when the number of columns increased. The cohesion of encased coarse steel slag column-soil composites increased about 1.6 times with increase the number of columns from 1 to 4 under a given A_r value. The overall friction angle increased slightly from 49° to 51° with the increase of the number of columns from 1 to 4 which was similar to the results presented for fine steel slag column-soil composites (Fig. 8(a)). Fig. 10(b) shows the variation of shear strength of the coarse steel slag column-soil composites with the geosynthetic encasement with respect to the number of columns under various normal stress levels. As shown from Fig. 9(b), the shear strength increased slightly when the number of columns increased for a given normal stress level. The increase of the shear strength is less than

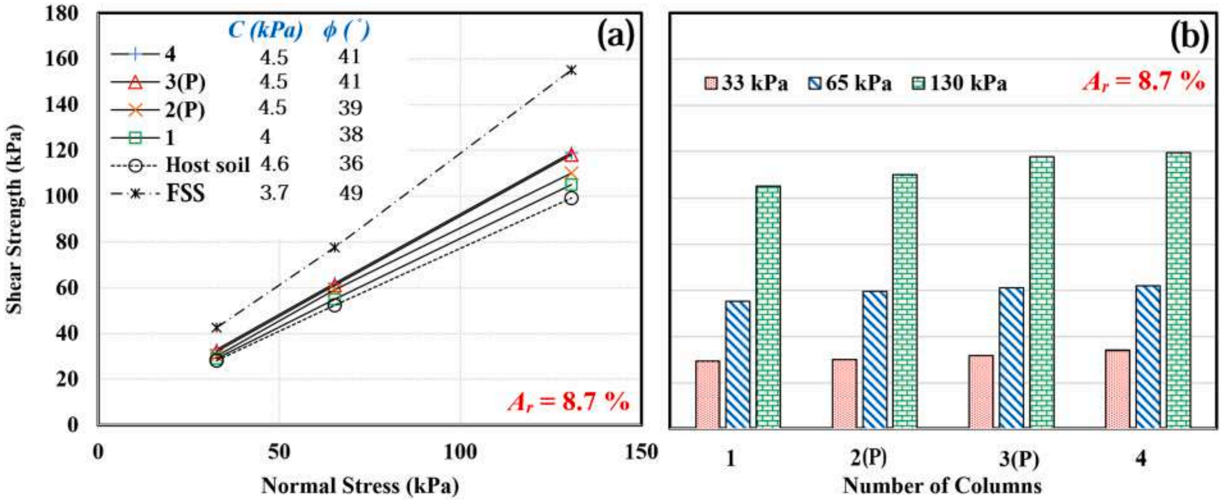

Fig. 9. Direct shear test results for the samples treated with fine steel slag columns without the geosynthetic encasement under a constant area replacement ratio (A_r = 8.7%) (a) shear strength envelopes (b) shear strength versus number of columns.

24% due to increasing the number of columns under a given A_r value. A comparison of Fig. 8(a) and 9(a) shows that the cohesion of coarse steel slag column-soil composites than those of fine steel slag column-soil composites for a given number of columns.

Fig. 11 indicates a typical interaction between steel slag and geotextile when stress is applied. Under the stress imposed, the geotextile deforms and thereby interlocks the steel slag particles which resulted in mobilisation of frictional resistance at the steel slag-geotextile interface. As shown from Fig. 11, the coarse steel slag improved skid and rolling resistance by providing more interlocking between the sand particles and the geotextile surface. This interlocking resulted in an increase of the mobilised tensile forces in the geotextile. Therefore, the cohesion of the column-soil composites with the geosynthetic encasement increased with the increase of the tensile forces developed in the geosynthetic.

Fig. 12 displays the shear strength envelopes corresponding to the peak state of the fine and coarse sand column-soil composites with the geosynthetic encasement in test groups 4 and 5. Fig. 13 shows a plot of the peak shear strength versus A_r for the fine (dashed line) and coarse (solid line) sand column-soil composites with the geosynthetic encasement under various normal stress levels. The overall friction angle increased as the column diameter increased in the both fine and coarse sand columns. The friction angle increased from 36° to 37° for the fine sand column-soil composites and increased from 36° to 39° for the coarse sand column-soil composites when the diameter of column increased from 5 cm to 25 cm. The cohesion of sand column-soil composites increased when the column diameter increased from 5 cm to 25 cm, which results are same as the steel slag column-soil composites. The cohesion increased from 13.5 kPa to 36 kPa for the fine sand column-soil composites and increased from 14.5 kPa to 39.5 kPa for the coarse sand column-soil composites when the diameter of column increased from 5 cm to 25 cm. As shown from Fig. 13, the shear strength improvement in the

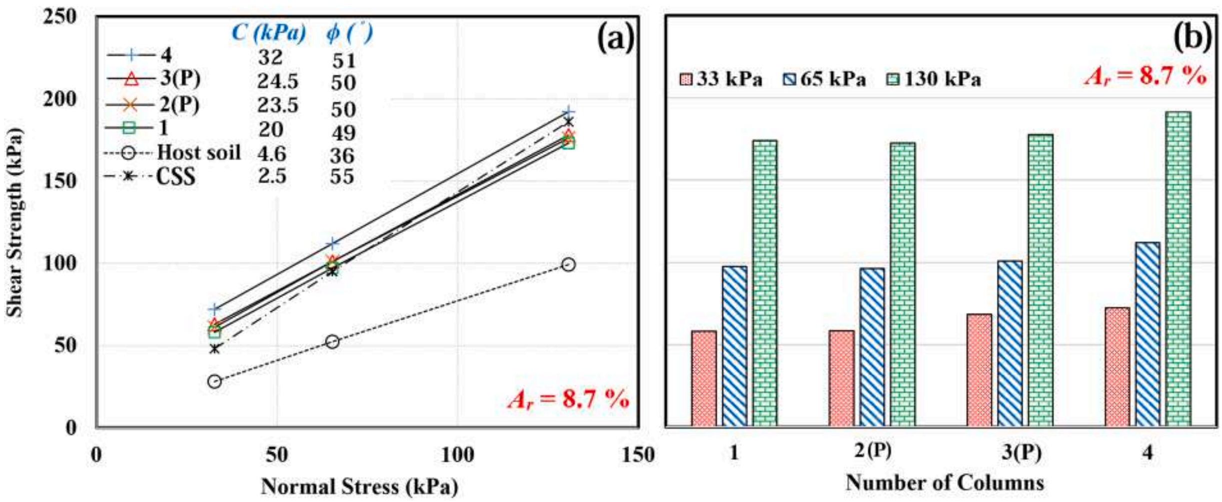

Fig. 10. Direct shear test results for the samples treated with coarse steel slag columns with the geosynthetic encasement under a constant area replacement ratio (A_r = 8.7%) (a) shear strength envelopes (b) shear strength versus number of columns.

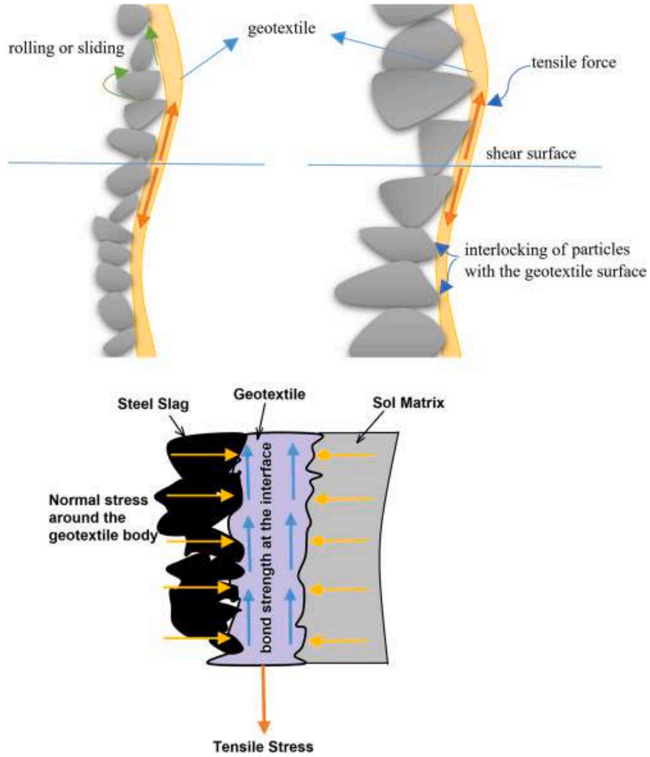

Fig. 11. Improvement of developed tensile forces of the geosynthetics due to utilisation of coarse steel slag.

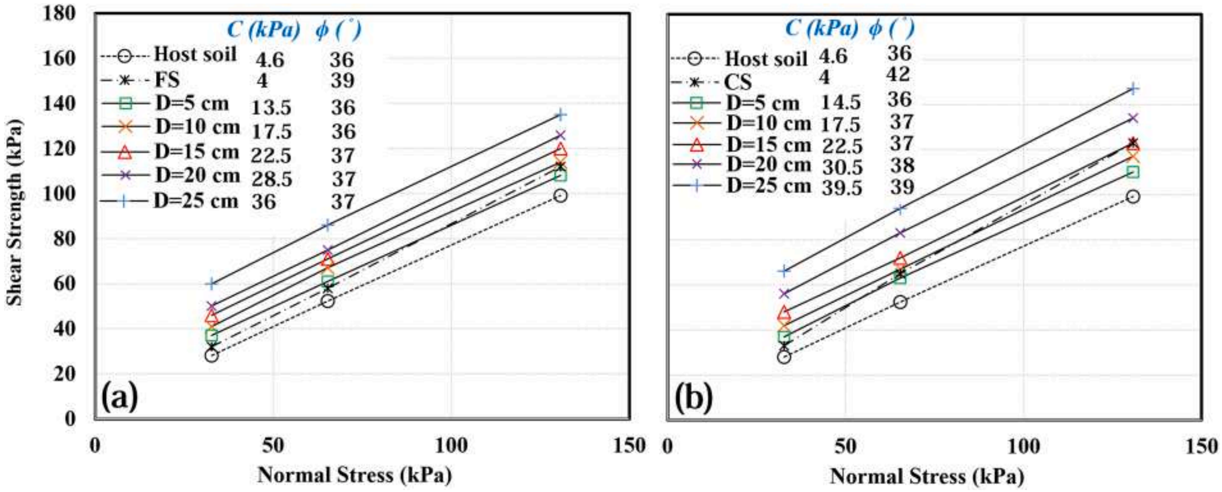

Fig. 12. Shear strength envelopes corresponding to peak state of the samples reinforced with encased single column (a) fine sand column (b) coarse sand column.

column-soil composites was more when coarse materials were used as stone columns. Fig. 13 indicates that the shear strength of samples with the fine or coarse sand columns increased with the increasing A_r, while, the effect of A_r on the shear strength of samples with the coarse material was more than that of the fine material. The difference in shear strength of samples with fine or coarse sand column was more significant under high normal stress. Comparing Figs. 13 and 5(b)shows that the shear strength parameters of the fine steel slag column-soil composites were greater than those of the fine or coarse sand column-soil composites. This indicated the proper performance of steel slag column method for stabilisation of soil.

The results of the test groups 6 and 7 are presented in Figs. 14 and 15. Figs. 14 and 15 show the shear strength envelopes corresponding to the peak state of the fine and coarse sand column-soil composites with and without the geosynthetic encasement, respectively. As it can be seen from Fig. 14, the friction angle and cohesion increased as the number of columns increased. However,

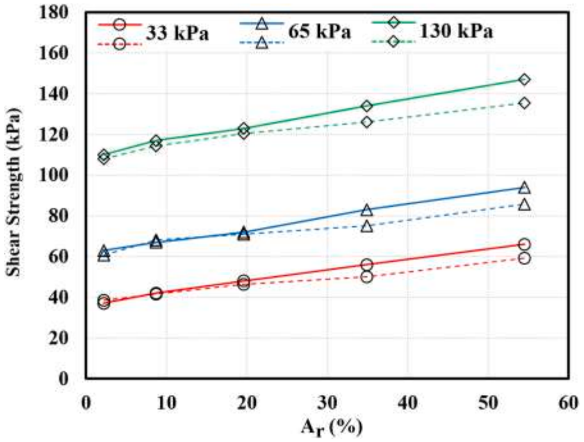

Fig. 13. Variation of shear strength of samples reinforced with encased single coarse steel slag column (solid line) or encased single fine steel slag column (dashed line) versus area replacement ratio.

the number of columns had a more important effect on the cohesion than the friction angle. The cohesion increased from 15 kPa to 23 kPa for the fine sand column-soil composites and increased from 17 kPa to 26 kPa for the coarse sand column-soil composites when the number of columns increased from 1 to 4. The friction angle increased slightly from 36° to 38° for the fine sand column-soil composites and increased slightly from 37° to 39° for the coarse sand column-soil composites when the number of columns increased from 1 to 4. Fig. 15 indicates that the cohesion was almost independent of the number of columns for the column-soil composites without the geosynthetic encasement. The overall friction angle of the column-soil composites without the geosynthetic encasement increased slightly with the increase number of columns. The friction angle increased slightly from 36° to 38° for the fine sand column-soil composites and increased slightly from 36° to 39° for the coarse sand column-soil composites when the number of columns increased from 1 to 4. The shear strength parameters of coarse sand column-soil composites were almost more than those of the fine sand column-soil composites which are the same of the steel slag cases.

4. An empirical approach to predicting the shear strength

According to the test results, as shown in Fig. 16, the cohesive strength of granular column-soil composites is a function of the cohesion of host soil (C_s) and granular material of columns (C_g), and the geosynthetic properties (G_p), if any. The effect of geosynthetic on the cohesive strength is dependent on the mechanical properties of geosynthetic, the ratio of geosynthetic length to total circumference of granular column-soil composite at the failure plane (L_c / L_t) and the interlocking of host soil and granular material of column with the geosynthetic surface which can be defined as a function of the friction angles of host soil (ϕ_s) and granular material of columns (ϕ_g). As shown from Fig. 11, the interlocking of host soil and granular material of column with the geosynthetic surface is

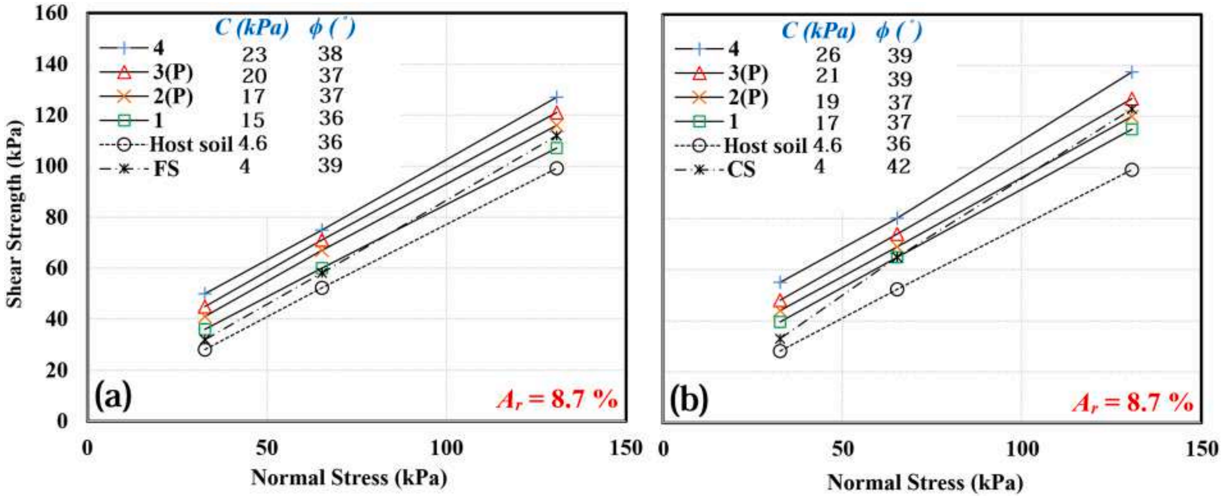

Fig. 14. Shear strength envelopes corresponding to peak state of the samples reinforced with encased granular column under a constant area replacement ratio (A_r = 8.7%) (a) fine steel slag column (b) coarse steel slag column.

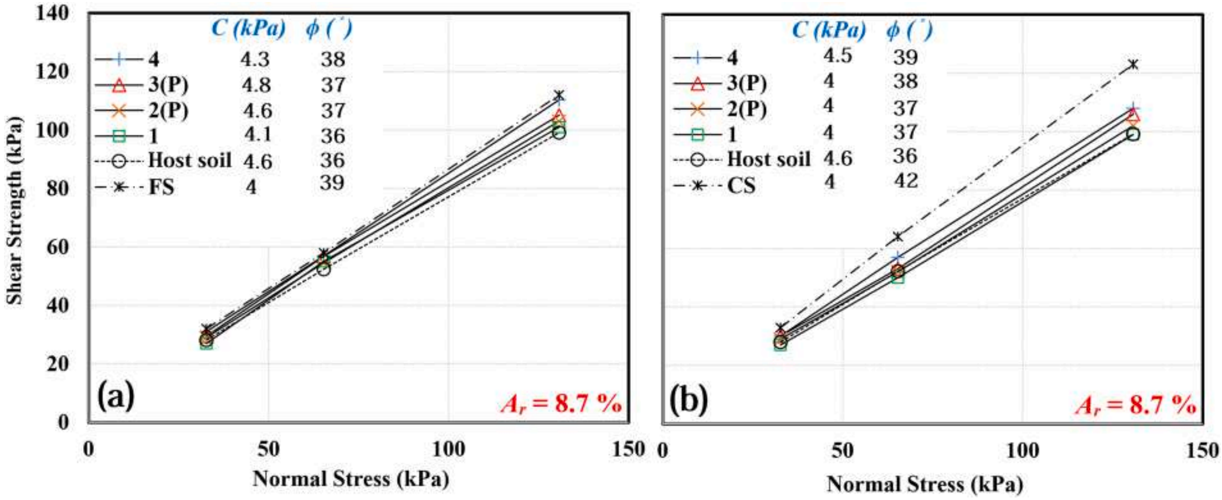

Fig. 15. Shear strength envelopes corresponding to peak state of the samples reinforced with granular column under a constant area replacement ratio (A_r = 8.7%) (a) fine steel slag columns (b) coarse steel slag columns without the geosynthetic encasement.

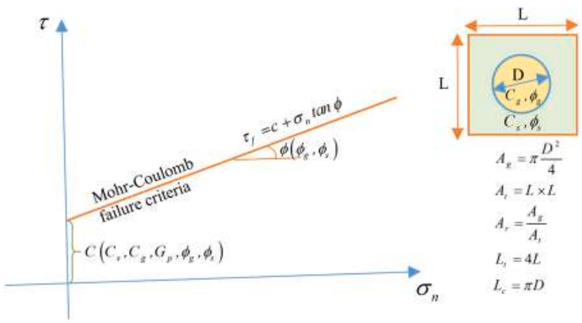

Fig. 16. Details of Mohr-Coulomb failure criteria.

mainly dependent on the surface roughness and angularity of the host soil and granular material grains. Therefore, the shear strength of the granular column-soil composites with or without the geosynthetic encasement can be defined as a function of cohesion and friction angle values (see Fig. 16):

$$C = \left(G_p \times \frac{L_c}{L_t} \times \frac{\phi_g}{\phi_s}\right) + \left(C_s \times (1 - A_r)\right) + C_g \times A_r \tag{1}$$

where A_r is the area replacement ratio and σ_n is the normal stress on the failure plane. L_c denotes the geosynthetic length or the circumference of columns (cm) on the failure plane. L_t is the total circumference of granular column-soil composite under shear (L_t = 120 cm in this study) (Fig. 16).

The equivalent friction angle of granular column-soil composites is a function of the mobilised friction angles of host soil and granular material of column. Therefore, the equivalent friction angle of the granular column-soil composites with or without the geosynthetic encasement can be defined as (see Fig. 16):

$$\phi = \left(\phi_g \times A_r\right) + \phi_s(1 - A_r) \tag{2}$$

To sum up, the shear strength of granular column-soil composites can be calculated using a general equation as follows:

$$\tau = \left[\left(G_p \times \frac{L_c}{L_t} \times \frac{\phi_g}{\phi_s}\right) + \left(C_s \times (1 - A_r)\right) + C_g \times A_r\right] + \left[\sigma_n \times \tan\left[\left(\phi_g \times A_r\right) + \phi_s(1 - A_r)\right]\right] \tag{3}$$

where τ denotes the shear strength of granular column-soil composites (kPa) on the failure plane.

In this study, 70% of experimental data were used to produce model and the remained fraction of data was used for validation. The model parameter (G_p) was obtained using the nonlinear least squares analysis, which was equal to 53. More details about nonlinear least squares analysis could be found in a recent studies [86,87]. In order to validate the applicability of the proposed equation (Eq. 3), the measured shear strength of granular column-soil composites was compared with the predicted value (see Fig. 17). As shown from

Fig. 17, the value of R^2 between the measured and the predicted values is about 0.97. This appears to be the result of using the proposed equation to predict the shear strength of granular column-soil composites easily and precisely.

5. Conclusions

Utilisation of industrial wastes in civil engineering applications as a construction material is cost effective and environment friendly. This study focused on the utilisation of steel slag materials as granular columns to improve problematic soils. On the other hand, the effects of properties of column materials, diameter of column, number of columns, columns arrangement and geosynthetic encasement on the lateral load capacity of granular column-soil composite were investigated. In this study, a series of large direct shear tests were done to study the response of granular column-soil composites with or without the geosynthetic encasement under a lateral loading condition. Based on the results, the following conclusions can be drawn:

1. The inclusion of steel slag or sand column in soil leads to an increase of the shear strength. The granular column has stronger effects when the column diameter is more than 20 cm (or A_r larger than 54%). Geosynthetic encasement results in further enhancement of shear strength. The overall friction angle of granular column-soil composites increases when the column diameter increases which is almost independent of geosynthetic encasement. The overall cohesion of granular column-soil composites without any geosynthetic encasement is almost constant. However, it increases due to increasing column diameter when granular column encased with geosynthetic. The increase of number of columns has a greater effect on the cohesion of coarse granular column-soil composites than those of fine granular column-soil composites. In general, the shear strength of geosynthetic encased granular column is more than that of non-encased granular columns. The difference in shear strength of samples with and without the geosynthetic encasement is more significant under high normal stress.
2. When A_r is constant, both friction angle and cohesion of granular column-soil composites with the geosynthetic encasement increases as the number of columns increases. The overall cohesion increases due to the increase of geotextile surface in the shearing surface with the increase of columns under a constant A_r value. The overall friction angle increases slightly with the increase of number of columns under a constant A_r value, which may be due to increasing interlocking of sand particles with the geotextile surface, and embedment of the sand particles into the geosynthetic surface. However, the number of columns has little effect on the overall cohesion and friction angle of column-soil composites without any geosynthetic encasement for a given A_r value.
3. The pattern of arrangement of granular columns under a constant A_r value and number of columns has little effect on the shear strength of granular column-soil composites. The results show that the overall friction angle is almost independent of the arrangement of the encased granular columns. However, the granular column-group parallel to the shearing direction results in a higher overall cohesion which may be attributed to shadowing effect and the edge effect.
4. The shear strength of steel slag column-soil composites are greater than those of the sand column-soil composites, which indicates the proper performance of steel slag column method for stabilisation of soil.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

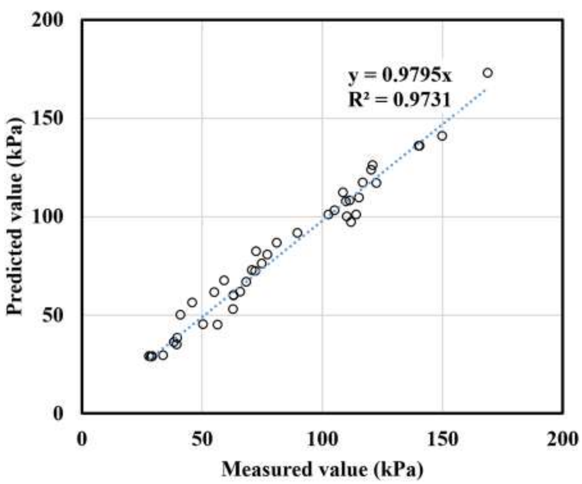

Fig. 17. Comparison of measured and predicted shear strength values of column-soil composites.

Data availability

All data, and models generated or used during the study appear in the published article.

References

[1] H.K. Hamzah, G.F. Huseien, M.A. Asaad, D.P. Georgescu, S.K. Ghoshal, F. Alrshoudi, Effect of waste glass bottles-derived nanopowder as slag replacement on mortars with alkali activation: durability characteristics, Case Stud. Constr. Mater. 15 (2021), e00775, https://doi.org/10.1016/j.cscm.2021.e00775.

[2] J. Patricio, Y. Kalmykova, L. Rosado, A method and databases for estimating detailed industrial waste generation at different scales – With application to biogas industry development, J. Clean. Prod. 246 (2020), 118959, https://doi.org/10.1016/j.jclepro.2019.118959.

[3] M. Salehi, M. Bayat, M. Saadat, M. Nasri, Experimental study on mechanical properties of cement-stabilized soil blended with crushed stone waste, KSCE J. Civ. Eng. 25 (2021) 1974–1984, https://doi.org/10.1007/s12205-021-0953-5.

[4] S.Z. Ashiq, A. Akbar, K. Farooq, H. Mujtaba, Sustainable improvement in engineering behavior of Siwalik Clay using industrial waste glass powder as additive, Case Stud. Constr. Mater. 16 (2022), e00883, https://doi.org/10.1016/j.cscm.2022.e00883.

[5] M.I. Panfilova, N.I. Zubrev, S.Y. Efremova, M.I. Yakhkind, V.P. Gorbachevskii, Strengthening of water-saturated soils of the bases of underground structures with composite solutions modified by industrial waste, boehmite, Case Stud. Constr. Mater. 12 (2020), e00323, https://doi.org/10.1016/j.cscm.2019.e00323.

[6] H.M. Jafer, W. Atherton, M. Sadique, F. Ruddock, E. Loffill, Development of a new ternary blended cementitious binder produced from waste materials for use in soft soil stabilisation, J. Clean. Prod. 172 (2018) 516–528, https://doi.org/10.1016/j.jclepro.2017.10.233.

[7] T. Zhang, S. Liu, H. Zhan, C. Ma, G. Cai, Durability of silty soil stabilized with recycled lignin for sustainable engineering materials, J. Clean. Prod. 248 (2020), 119293, https://doi.org/10.1016/j.jclepro.2019.119293.

[8] D. Yang, A. Sasaki, M. Endo, Reclamation of a waste arsenic-bearing gypsum as a soil conditioner via acid treatment and subsequent Fe(II)–As stabilization, J. Clean. Prod. 217 (2019) 22–31, https://doi.org/10.1016/j.jclepro.2019.01.217.

[9] A. Sharma, R.K. Sharma, Strength and drainage characteristics of poor soils stabilized with construction demolition waste, Geotech. Geol. Eng. 38 (2020) 4753–4760, https://doi.org/10.1007/s10706-020-01324-3.

[10] K.M.N.S. Wani, B.A. Mir, Stabilization of weak dredged soils by employing waste boulder crusher dust: a laboratory study, Geotech. Geol. Eng. 38 (2020) 6827–6842, https://doi.org/10.1007/s10706-020-01472-6.

[11] R.K. Sharma, Utilization of fly ash and waste ceramic in improving characteristics of clayey soil: a laboratory study, Geotech. Geol. Eng. 38 (2020) 5327–5340, https://doi.org/10.1007/s10706-020-01366-7.

[12] A.A. Ashango, N.R. Patra, Behavior of expansive soil treated with steel slag, rice husk ash, and lime, J. Mater. Civ. Eng. 28 (2016), 06016008, https://doi.org/10.1061/(asce)mt.1943-5533.0001547.

[13] M.R. ShahriarKian, S. Kabiri, M. Bayat, Utilization of zeolite to improve the behavior of cement-stabilized soil, Int. J. Geosynth. Gr. Eng. 7 (2021) 35, https://doi.org/10.1007/s40891-021-00284-9.

[14] T. Wang, R.S. Nicolas, A. Kashani, T. Ngo, Sustainable utilisation of low-grade and contaminated waste glass fines as a partial sand replacement in structural concrete, Case Stud. Constr. Mater. 16 (2022), e00794, https://doi.org/10.1016/j.cscm.2021.e00794.

[15] W. Ahmad, A. Ahmad, K.A. Ostrowski, F. Aslam, P. Joyklad, A scientometric review of waste material utilization in concrete for sustainable construction, Case Stud. Constr. Mater. 15 (2021), e00683, https://doi.org/10.1016/j.cscm.2021.e00683.

[16] F. Mahdi, H. Abbas, A.A. Khan, Flexural, shear and bond strength of polymer concrete utilizing recycled resin obtained from post consumer PET bottles, Constr. Build. Mater. 44 (2013) 798–811, https://doi.org/10.1016/j.conbuildmat.2013.03.081.

[17] D. Foti, Use of recycled waste pet bottles fibers for the reinforcement of concrete, Compos. Struct. 96 (2013) 396–404, https://doi.org/10.1016/j.compstruct.2012.09.019.

[18] S.C. Bostanci, Use of waste marble dust and recycled glass for sustainable concrete production, J. Clean. Prod. 251 (2020), 119785, https://doi.org/10.1016/j.jclepro.2019.119785.

[19] M. Jalal, N. Nassir, H. Jalal, Waste tire rubber and pozzolans in concrete: a trade-off between cleaner production and mechanical properties in a greener concrete, J. Clean. Prod. 238 (2019), 117882, https://doi.org/10.1016/j.jclepro.2019.117882.

[20] K.G. Tonet, J.P. Gorninski, Polymer concrete with recycled PET: the influence of the addition of industrial waste on flammability, Constr. Build. Mater. 40 (2013) 378–389, https://doi.org/10.1016/j.conbuildmat.2012.09.049.

[21] Ö. Andiç-Çakır, A.E. Son, S. Sürmelioğlu, E. Tosun, M. Sarıkanat, Improvement of traditional clay bricks' thermal insulation characteristics by using waste materials, Case Stud. Constr. Mater. 15 (2021), e00560, https://doi.org/10.1016/j.cscm.2021.e00560.

[22] J. Taaffe, S. O'Sullivan, M.E. Rahman, V. Pakrashi, Experimental characterisation of Polyethylene Terephthalate (PET) bottle eco-bricks, Mater. Des. 60 (2014) 50–56, https://doi.org/10.1016/j.matdes.2014.03.045.

[23] I. Martínez, M. Etxeberria, E. Pavón, N. Díaz, Influence of demolition waste fine particles on the properties of recycled aggregate masonry mortar, Int. J. Civ. Eng. 16 (2018) 1213–1226, https://doi.org/10.1007/s40999-017-0280-x.

[24] F.N. Değirmenci, Utilization of natural and waste pozzolans as an alternative resource of geopolymer mortar, Int. J. Civ. Eng. 16 (2018) 179–188, https://doi.org/10.1007/s40999-016-0115-1.

[25] H. Singh Chouhan, P. Kalla, R. Nagar, P. Kumar Gautam, Influence of dimensional stone waste on mechanical and durability properties of mortar: A review, Constr. Build. Mater. 227 (2019), 116662, https://doi.org/10.1016/j.conbuildmat.2019.08.043.

[26] A. Mohajerani, S. Lound, G. Liassos, H. Kurmus, A. Ukwatta, M. Nazari, Physical, mechanical and chemical properties of biosolids and raw brown coal fly ash, and their combination for road structural fill applications, J. Clean. Prod. 166 (2017) 1–11, https://doi.org/10.1016/j.jclepro.2017.07.250.

[27] A.F. Cabalar, D.I. Hassan, M.D. Abdulnafaa, Use of waste ceramic tiles for road pavement subgrade, Road. Mater. Pavement Des. 18 (2017) 882–896, https://doi.org/10.1080/14680629.2016.1194884.

[28] E. Miękoś, M. Zieliński, K. Kołodziejczyk, M. Jaksender, Application of industrial and biopolymers waste to stabilise the subsoil of road surfaces, Road. Mater. Pavement Des. 20 (2019) 440–453, https://doi.org/10.1080/14680629.2017.1389766.

[29] J. O'Connor, T.B.T. Nguyen, T. Honeyands, B. Monaghan, D. O'Dea, J. Rinklebe, A. Vinu, S.A. Hoang, G. Singh, M.B. Kirkham, N. Bolan, Production, characterisation, utilisation, and beneficial soil application of steel slag: a review, J. Hazard. Mater. (2021), 126478, https://doi.org/10.1016/j.jhazmat.2021.126478.

[30] F. Kehagia, Skid resistance performance of asphalt wearing courses with electric arc furnace slag aggregates, Waste Manag. Res. 27 (2009) 288–294, https://doi.org/10.1177/0734242X08092025.

[31] C. Shi, Steel slag—its production, processing, characteristics, and cementitious properties, J. Mater. Civ. Eng. 16 (2004) 230–236, https://doi.org/10.1061/(asce)0899-1561(2004)16:3(230).

[32] Y.C. Teoh, Performance evaluattion of steel slag as natural aggregates replacement in asphaltic concrete, 2008.

[33] T. Sofilić, V. Merle, A. Rastovčan-mioč, M. Ćosić, U. Sofilić, Steel slag instead natural aggregate in asphalt mixture, Arch. Metall. Mater. 55 (2010) 657–668. 〈https://urn.nsk.hr/urn:nbn:hr:115:071239〉. accessed June 30, 2021.

[34] P. Chaurand, J. Rose, J. Domas, J.Y. Bottero, Speciation of Cr and V within BOF steel slag reused in road constructions, J. Geochem. Explor 88 (2006) 10–14, https://doi.org/10.1016/j.gexplo.2005.08.006.

[35] P. Chaurand, J. Rose, V. Briois, L. Olivi, J.L. Hazemann, O. Proux, J. Domas, J.Y. Bottero, Environmental impacts of steel slag reused in road construction: a crystallographic and molecular (XANES) approach, J. Hazard. Mater. 139 (2007) 537–542, https://doi.org/10.1016/j.jhazmat.2006.02.060.

[36] I. Barišić, I. Netinger Grubeša, B. Hackenberger Kutuzović, Multidisciplinary approach to the environmental impact of steel slag reused in road construction, Road. Mater. Pavement Des. 18 (2017) 897–912, https://doi.org/10.1080/14680629.2016.1197143.

[37] S.M.A.C. de Freitas, L.N. Sousa, P. Diniz, M.E. Martins, P.S. Assis, Steel slag and iron ore tailings to produce solid brick, Clean. Technol. Environ. Policy 20 (2018) 1087–1095, https://doi.org/10.1007/s10098-018-1513-7.
[38] O. Gencel, O. Karadag, O.H. Oren, T. Bilir, Steel slag and its applications in cement and concrete technology: a review, Constr. Build. Mater. 283 (2021), https://doi.org/10.1016/j.conbuildmat.2021.122783.
[39] M.J. Rezaei-Hosseinabadi, M. Bayat, B. Nadi, A. Rahimi, Utilisation of steel slag as a granular column to enhance the lateral load capacity of soil, Geomech. Geoengin. 00 (2021) 1–11, https://doi.org/10.1080/17486025.2021.1940315.
[40] H. Kumar, S. Varma, A review on utilization of steel slag in hot mix asphalt, Int. J. Pavement Res. Technol. 14 (2021) 232–242, https://doi.org/10.1007/s42947-020-0025-0.
[41] H.Y. Poh, G.S. Ghataora, N. Ghazireh, Soil stabilization using basic oxygen steel slag fines, J. Mater. Civ. Eng. 18 (2006) 229–240, https://doi.org/10.1061/(asce)0899-1561(2006)18:2(229).
[42] W. Shen, M. Zhou, W. Ma, J. Hu, Z. Cai, Investigation on the application of steel slag-fly ash-phosphogypsum solidified material as road base material, J. Hazard. Mater. 164 (2009) 99–104, https://doi.org/10.1016/j.jhazmat.2008.07.125.
[43] I.I. Akinwumi, J.B. Adeyeri, O.A. Ejohwomu, Effects of steel slag addition on the plasticity, strength, and permeability of lateritic soil, in: ICSDEC 2012 Dev. Front. Sustain. Des. Eng. Constr. - Proc. 2012 Int, Conf. Sustain. Des. Constr., American Society of Civil Engineers, 2013, pp. 457–464, https://doi.org/10.1061/9780784412688.055.
[44] J. Wu, Q. Liu, Y. Deng, X. Yu, Q. Feng, C. Yan, Expansive soil modified by waste steel slag and its application in subbase layer of highways, Soils Found. 59 (2019) 955–965, https://doi.org/10.1016/j.sandf.2019.03.009.
[45] L. Lang, C. Song, L. Xue, B. Chen, Effectiveness of waste steel slag powder on the strength development and associated micro-mechanisms of cement-stabilized dredged sludge, Constr. Build. Mater. 240 (2020), 117975, https://doi.org/10.1016/j.conbuildmat.2019.117975.
[46] S. Murugesan, K. Rajagopal, Shear load tests on stone columns with and without geosynthetic encasement, Geotech. Test. J. 32 (2009) 76–85, https://doi.org/10.1520/gtj101219.
[47] C. Cengiz, I.E. Kilic, E. Guler, On the shear failure mode of granular column embedded unit cells subjected to static and cyclic shear loads, Geotext. Geomembr. 47 (2019) 193–202, https://doi.org/10.1016/j.geotexmem.2018.12.011.
[48] C. Cengiz, E. Guler, Sample preparation method for large scale shear testing of soft-clay and granular-column composites, MethodsX 7 (2020), 100939, https://doi.org/10.1016/j.mex.2020.100939.
[49] G.L.S. Araujo, E.M. Palmeira, R.P. Cunha, Behaviour of geosynthetic-encased granular columns in porous collapsible soil, Geosynth. Int. 16 (2009) 433–451, https://doi.org/10.1680/gein.2009.16.6.433.
[50] M.S.S. Almeida, I. Hosseinpour, M. Riccio, D. Alexiew, Behavior of geotextile-encased granular columns supporting test embankment on soft deposit, J. Geotech. Geoenviron. Eng. 141 (2015), 04014116, https://doi.org/10.1061/(asce)gt.1943-5606.0001256.
[51] J. Black, V. Sivakumar, M.R. Madhav, B. McCabe, An improved experimental test set-up to study the performance of granular columns, 2006. doi:10.1520/gtj14195.
[52] K. Rajagopal, S.R. Mohapatra, Behaviour of geosynthetic encased granular columns under vertical and lateral loading, GA 2016 - 6th Asian Reg. Geosynth. Infrastruct. Dev. Proc, Conf. Geosynth, 2016, pp. KN83–KN99.
[53] I. Hosseinpour, M.S.S. Almeida, M. Riccio, Full-scale load test and finite-element analysis of soft ground improved by geotextile-encased granular columns, Geosynth. Int. 22 (2015) 428–438, https://doi.org/10.1680/jgein.15.00023.
[54] S.H. Chong, J.Y. Kim, Nonlinear vibration analysis of the resonant column test of granular materials, J. Sound Vib. 393 (2017) 216–228, https://doi.org/10.1016/j.jsv.2016.12.018.
[55] A. Zukri, R. Nazir, Sustainable materials used as stone column filler: a short review, IOP Conf. Ser. Mater. Sci. Eng. 342 (2018), https://doi.org/10.1088/1757-899X/342/1/012001.
[56] K.H. Xie, M.M. Lu, A.F. Hu, G.H. Chen, A general theoretical solution for the consolidation of a composite foundation, Comput. Geotech. 36 (2009) 24–30, https://doi.org/10.1016/j.compgeo.2008.02.012.
[57] P. Verma, A.K. Sahu, Effect of grouted granular column on the load carrying capacity of the expansive soil, Int. J. Recent Technol. Eng. 8 (2019) 2606–2612, https://doi.org/10.35940/ijrte.C4924.098319.
[58] I. Hosseinpour, C. Soriano, M.S.S. Almeida, A comparative study for the performance of encased granular columns, J. Rock. Mech. Geotech. Eng. 11 (2019) 379–388, https://doi.org/10.1016/j.jrmge.2018.12.002.
[59] E.R. Orekanti, G.V. Dommaraju, Load-settlement response of geotextile encased laterally reinforced granular piles in expansive soil under compression, Int. J. Geosynth. Gr. Eng. 5 (2019) 17, https://doi.org/10.1007/s40891-019-0168-8.
[60] M.S.S. Almeida, I. Hosseinpour, M. Riccio, Performance of a geosynthetic-encased column (GEC) in soft ground: Numerical and analytical studies, Geosynth. Int. 20 (2013) 252–262, https://doi.org/10.1680/gein.13.00015.
[61] J. Jayarajan, R. Karpurapu, Settlement analysis of geosynthetic encased granular column treated soft clay deposits, Int. J. Geotech. Eng. 14 (2020) 473–489, https://doi.org/10.1080/19386362.2019.1698218.
[62] S.K. Dash, M.C. Bora, Influence of geosynthetic encasement on the performance of stone columns floating in soft clay, Can. Geotech. J. 50 (2013) 754–765, https://doi.org/10.1139/cgj-2012-0437.
[63] S. Aryal, P.K. Kolay, Long-term durability of ordinary portland cement and polypropylene fibre stabilized kaolin soil using wetting–drying and freezing–thawing test, Int. J. Geosynth. Gr. Eng. 6 (2020) 1–15, https://doi.org/10.1007/s40891-020-0191-9.
[64] S.R. Mohapatra, K. Rajagopal, J. Sharma, Direct shear tests on geosynthetic-encased granular columns, Geotext. Geomembr. 44 (2016) 396–405, https://doi.org/10.1016/j.geotexmem.2016.01.002.
[65] S. Murugesan, K. Rajagopal, Model tests on geosynthetic-encased stone columns, Geosynth. Int. 14 (2007) 346–354, https://doi.org/10.1680/gein.2007.14.6.346.
[66] S. Pal, K. Deb, Filtration performance of geotextile encasement to minimize the clogging of stone column during soil liquefaction, Geotext. Geomembr. 49 (2021) 771–788, https://doi.org/10.1016/j.geotexmem.2020.12.008.
[67] K. Deb, S. Shiyamalaa, Effect of clogging on rate of consolidation of stone column–improved ground by considering particle migration, Int. J. Geomech. 16 (2016), 04015017, https://doi.org/10.1061/(asce)gm.1943-5622.0000492.
[68] S. Pal, K. Deb, Postearthquake reconsolidation settlement of stone column-treated liquefiable sand, Int. J. Geomech. 20 (2020), 04020183, https://doi.org/10.1061/(asce)gm.1943-5622.0001818.
[69] J. Jayarajan, R. Karpurapu, Bearing capacity and settlement response of ordinary and geosynthetic encased granular columns in soft clay soils: analysis and design charts, Indian Geotech. J. 51 (2021) 237–253, https://doi.org/10.1007/s40098-020-00457-9.
[70] M. Ghazavi, A. Ehsani Yamchi, J. Nazari Afshar, Bearing capacity of horizontally layered geosynthetic reinforced stone columns, Geotext. Geomembr. 46 (2018) 312–318, https://doi.org/10.1016/j.geotexmem.2018.01.002.
[71] C. Yoo, S.B. Kim, Numerical modeling of geosynthetic-encased stone column-reinforced ground, Geosynth. Int. 16 (2009) 116–126, https://doi.org/10.1680/gein.2009.16.3.116.
[72] S. Murugesan, K. Rajagopal, Studies on the behavior of single and group of geosynthetic encased stone columns, J. Geotech. Geoenviron. Eng. 136 (2010) 129–139, https://doi.org/10.1061/(asce)gt.1943-5606.0000187.
[73] I. Hosseinpour, M. Riccio, M.S.S. Almeida, Numerical evaluation of a granular column reinforced by geosynthetics using encasement and laminated disks, Geotext. Geomembr. 42 (2014) 363–373, https://doi.org/10.1016/j.geotexmem.2014.06.002.
[74] I. Hosseinpour, M.S.S. Almeida, M. Riccio, Ground improvement of soft soil by geotextile-encased columns, Proc. Inst. Civ. Eng. Gr. Improv 169 (2016) 297–305, https://doi.org/10.1680/jgrim.16.00009.
[75] Y.S. Hong, C. Sen Wu, Y.S. Yu, Model tests on geotextile-encased granular columns under 1-g and undrained conditions, Geotext. Geomembr. 44 (2016) 13–27, https://doi.org/10.1016/j.geotexmem.2015.06.006.

[76] M. Khabbazian, V.N. Kaliakin, C.L. Meehan, Numerical study of the effect of geosynthetic encasement on the behaviour of granular columns, Geosynth. Int. 17 (2010) 132–143, https://doi.org/10.1680/gein.2010.17.3.132.
[77] E.A. Oluwasola, M.R. Hainin, M.M.A. Aziz, Evaluation of asphalt mixtures incorporating electric arc furnace steel slag and copper mine tailings for road construction, Transp. Geotech. 2 (2015) 47–55, https://doi.org/10.1016/j.trgeo.2014.09.004.
[78] A.B. Cerato, A.J. Lutenegger, Specimen size and scale effects of direct shear box tests of sands, Geotech. Test. J. 29 (2006) 507–516, https://doi.org/10.1520/gtj100312.
[79] A. Fakhimi, H. Hosseinpour, Experimental and numerical study of the effect of an oversize particle on the shear strength of mined-rock pile material, 2011. doi: 10.1520/GTJ103111.
[80] A.D. Orlando, D.M. Hanes, H.H. Shen, Scaling effects in direct shear tests, AIP Conf. Proc. 1145 (2009) 413–416, https://doi.org/10.1063/1.3179949.
[81] S. Bryson, H. El Naggar, Evaluation of the efficiency of different ground improvement techniques, in: Geotech. Eng. Challenges Innov. Geotech. ICSMGE 2013, 18th Int. Conf. Soil Mech, 2013, pp. 683–686.
[82] R. Manohar, S. Patel, Ground improvement with stone columns–a review, Lect. Notes Civ. Eng., Springe Sci. Bus. Media Dtschl. GmbH (2021) 197–217, https://doi.org/10.1007/978-981-15-5644-9_14.
[83] J.T. Shahu, Y.R. Reddy, Estimating long-term settlement of floating stone column groups, Can. Geotech. J. 51 (2014) 770–781, https://doi.org/10.1139/cgj-2012-0477.
[84] B.S. Khati, V.A. Sawant, Comparison of lateral response of pile group in series and parallel arrangement near sloping ground, Int. J. Geotech. Eng. 14 (2020) 686–695, https://doi.org/10.1080/19386362.2019.1617478.
[85] S.K. Khatibi, Experimental comparison of shadowing effect and edge effect in pile group of integral bridge, Arab. J. Geosci. 14 (2021), https://doi.org/10.1007/s12517-021-07615-0.
[86] M. Bayat, A. Ghalandarzadeh, Modified models for predicting dynamic properties of granular soil under anisotropic consolidation, Int. J. Geomech. 20 (2020), 04019197, https://doi.org/10.1061/(asce)gm.1943-5622.0001607.
[87] S.H. Sahlabadi, M. Bayat, M. Mousivand, Freeze – thaw durability of cement-stabilized soil reinforced with polypropylene / basalt fibers, J. Mater. Civ. Eng. 33 (2021) 1–14, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003905.