An investigation of a hybrid of stone and concrete columns with geo-synthetics

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ABSTRACT: Stone columns are a cost-effective ground improvement technique that is typically employed for low-rise building and road embankments. However, they have a constraint related to loose interactions between column aggregates in the absence of sufficient lateral confinement. As a result, their performance is usually improved by inclusion of geosynthetics either in layers or as confinement. On the other hand, reinforced concrete piles are often regarded as the ultimate approach to ground improvement. In this study, the upper portion of the stone columns was replaced by different grades of unreinforced concrete in varying lengths. Having obtained the optimum configuration of the above, a geosynthetic reinforced bedding layer was introduced on top of the stone columns and its effect investigated. Test results for the optimum hybrid stone column yielded only a 5.4 folds maximum increase in bearing capacity compared to the control. While the use of a reinforced bedding layer, a fold factor of 9.9 was obtained.

Keywords: Stone columns, geosynthetics, soft soils, ground improvement, soil reinforcement

1 INTRODUCTION

1.1 *Background*

With increasing world population and urbanisation, land has become a valuable resource for which there is a never-ending demand. Ideally, constructions should be done on stable solid grounds and the strength of the soil normally dictates the type of foundations to be used. It must be highlighted that soil is a non-homogeneous material, its characteristics (permeability, shear strength, bearing capacity, the rate of consolidation etc.) varies from one point to another hence, it may not always provide the best conditions for building. However, with the advancement in ground improvements techniques in the last few decades, these types of soil can now be improved until it meets the desired properties.

Stone columns are usually made up of loosely compacted stones that act as reinforcement within the soil. They have been commonly used since the 1950s (Barksdale and Bachus 1983) and have proved to:-

- Improve the bearing capacity of the ground to support embankments and constructions on weak cohesive soil
- Support retaining structures
- Aid to mitigate landslide
- Reduce potential of liquefaction due to high porosity of the column.

The stone columns, which have a higher permeability, strength and stiffness compared to in-situ soil, facilitates drainage, consolidation and reinforces the ground. According to Barksdale and Bachus (1983), the construction of stone columns involves partial replacement (15 - 35 %) of weak soil material with compacted vertical column of stones that normally penetrates the full layer of the weak strata. Each column is normally designed to carry between 20 – 50 T of load. Besides, it is a cost-effective solution (Keykhosropur, Soroush, and Imam 2012, Asgari, Oliaei, and Bagheri 2013) and uses mainly natural occurring materials as its load transferring material.

The main concern about the stone column is that it bulges and its performance is governed by its lateral confinement (Murugesan and Rajagopal 2006, Gniel and Bouazza 2009, Keykhosropur, Soroush, and Imam 2012, Ghazavi and Nazari Afshar 2013). Numerous researchers have tried to confine the stone column material by either a geosynthetic membrane or a grid encasement of which both has proved their significance.

1.2 *Length of stone column*

The diameter of the stone column typically ranges from 0.8 – 1.2 m whereas its length typically varies between 4 -10 m. It was also recorded that typically a stone column length between 4 - 6D (D in the diameter of the stone column) is typically used for construction purposes (Barksdale and Bachus 1983). Dash and Bora (2013) investigated the performance of soft clay foundation using stone column and geo-sand cell mattress whilst observing the length to diameter ratio. They observed that the optimum length is 5D. It must be noted that increasing the length further does not result in a significant improvement in performance of the column and could favour bending failure as observed by Chen, Li and Xue (2015).

1.3 *Geocell/Geo-synthetic encasement*

It is not advisable to use normal stone columns in very soft soil (C_u < 15 kPa) due to lack of lateral confinement (Murugesan and Rajagopal 2006, Gniel and Bouazza 2009, Keykhosropur, Soroush, and Imam 2012, Ghazavi and Nazari Afshar 2013). In such case, they are normally confined in geosynthetic membranes to increase performance. The encasement increases stiffness, bearing capacity and reduces lateral bulging of the stone column (Ghazavi and Nazari Afshar 2013). The ultimate bearing capacity of the column increases with increasing length and stiffness of the geotextile membrane (Murugesan and Rajagopal 2006, Gniel and Bouazza 2009, Ghazavi and Nazari Afshar 2013) due to the increase in confining pressure. As a result, bulging occurs just below the encasement.

1.4 *Length of encasement*

Huang (2011) speculates that a length of reinforcement greater than 3.2D brings no additional benefit to the bearing capacity of a column and thus inefficient length of reinforcement should not be wasted. Murugesan and Rajagopal (2006) found similar relationship from their numerical analysis (using GEOFEM software). They found that increasing the depth of encasement above 3D bring limited improvement in bearing capacity of the column. Lateral confinement of the stone columns can also be increased by increasing the surcharge load around the footing. Placement of sand bed above stone column increases its bearing capacity and reduces settlement (Deb, Samadhiya and Namdeo 2011, Dash and Bora 2013, Deb and Mohapatra 2013). The bearing capacity can be further increased by encasing the layer of bed with a geocell and planer reinforced bed layer.

1.5 *Bedding layer*

Barksdale and Bachus (1983) stated that placing a granular blanket over a stone column improves its bearing capacity. The overlaid layer forces bulging to occur at a lower depth in the stone column, where the lateral pressures are higher, resulting in an increase in the ultimate load bearing capacity of the column. Indian Standard (2003) reported that the blanket should be compacted to a relative density of 75-80 % and that its minimum thickness should be 0.5 m. However, the underlying soil should be compacted first by means such as rolling/tamping to a minimum depth prior to placing the bedding.

Dash and Bora (2013) observed that the stone column alone can increase the bearing capacity by 3 fold however, combined bedding layer reinforced with geocell, a bearing capacity of 10 fold can be achieved. They also observed that the optimum thickness of the geocell layer is equal to that of the footing diameter, after which the increase in performance is minimal. Tafreshi and Dawson (2010) showed that a bed layer reinforced with geocell performed better compared to that of a geosynthetic reinforced layer for equal or less quantity of material. The geocell reinforced layer exhibited a better bearing capacity and lower settlement. They also observed that increasing the height of the geocell increases the bearing capacity and decreases settlement. It must be noted that in that case, the bed layer comprised of the same surrounding soil. Deb, Samadhiya et al. (2011) also reported an increase (of 233 %) in bearing strength of the bedding layer when geocell of an optimum thickness was used compared to a layer of an unreinforced sand.

2 PLANNING OF EXPERIMENT

2.1 *Spacing of stone column*

Stone columns grouped within a specific area undergo less bulging compared to a single loaded column. According to Indian Standard (2003), there is no specific guideline for the exact spacing of the stone columns as this is normally dependent on the site conditions, settlement tolerances, arrangements of the stone columns, installation techniques and the stiffness of the stone column. However, a typical spacing of 2 – 3D is normally adopted (Mani and Nigee 2013).

For the purpose of this experiment, a unit cell of 152 mm diameter was used in which a stone column of 50 mm diameter was installed centrally. This will be equivalent to a spacing of 2.69D for a square arrangement and 2.90D for an equilateral arrangement which, is within the advised range. Figure 1 illustrates the experimental setup and spacing of the stone column.

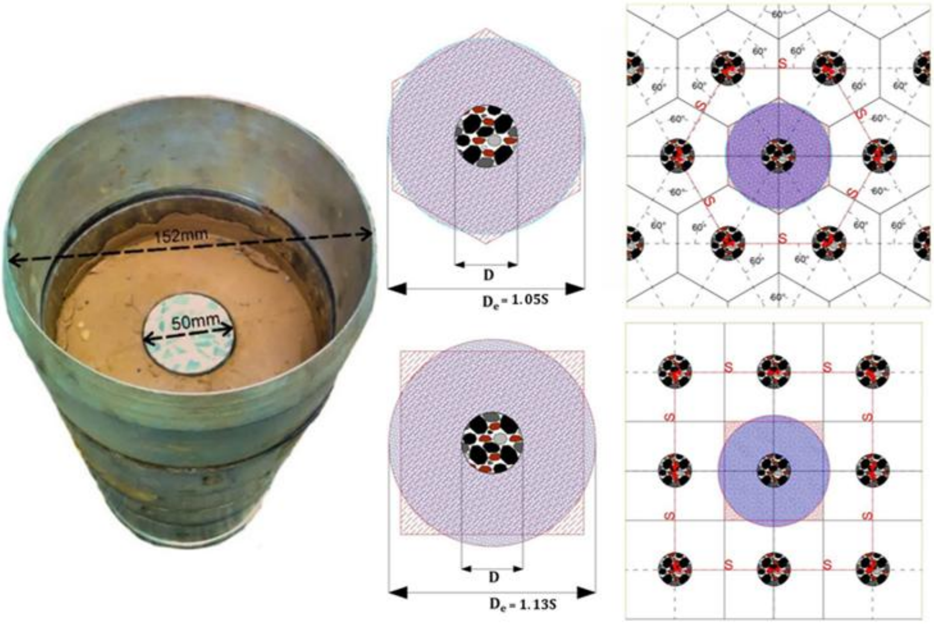

Figure 1: Position of hybrid stone column and typical diameter of unit cell (S is the spacing between the columns).

2.2 *Arrangement of experimental setup*

Experiments were first ran to get the optimum hybrid stone column. The length of the concrete as well as the thickness of the soil beneath the column were varied. The experimental setup of the configurations elaborated hereafter are as shown in Figure 2.

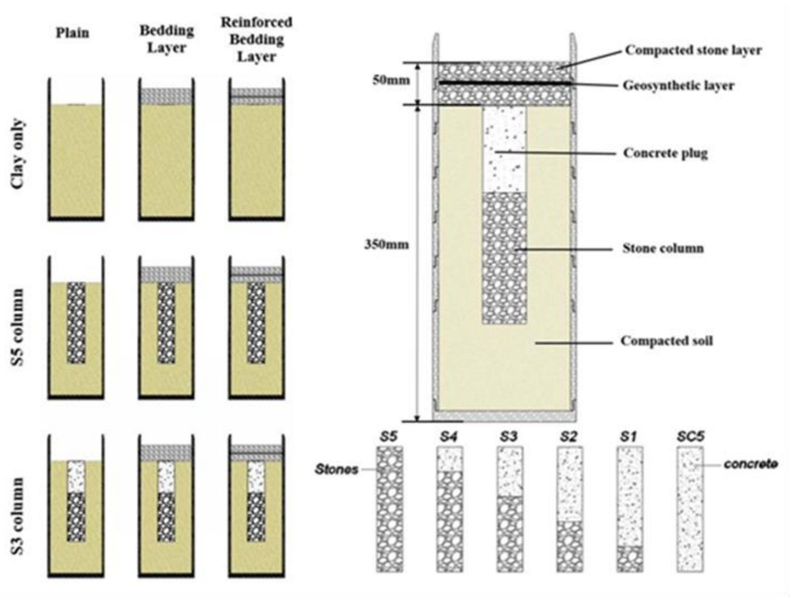

Figure 2: Configurations for testing.

2.3 *Determining adequate moisture content to run experiment.*

It was decided (from Figure 3) that the soil should be prepared at 20 % moisture content. CBR test was performed according to ASTM D1883 and the moisture content giving satisfactory performance was hence identified.

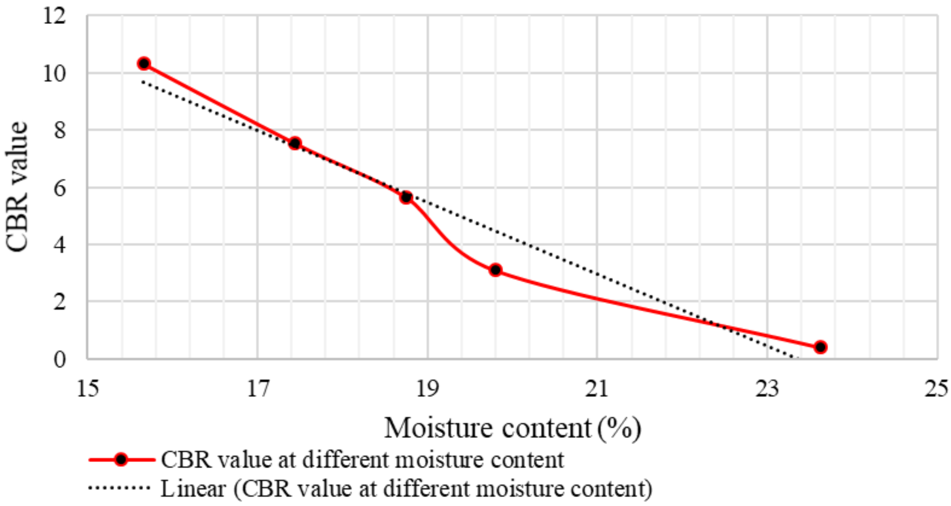

Figure 3: Variation of CBR with different moisture content of the soil sample.

2.4 *Materials used*

2.4.1 *Clay and stone column material*

The soil used passed 600 µm sieve. The Atterberg limit test was performed in accordance to ASTM D4318. The liquid limit was 37 % and the plasticity index was 19. The soil was classified as lean clay as per ASTM D2487. A direct shear test under consolidated drained conditions were performed as per performed as per ASTM D3080. The angle of friction $\phi' = 27.1\,°$ and drained cohesion $c' = 13.1$ kPa.

2.4.2 *Stone material for concrete column.*

Starting from the oldest reference dealing with stone column aggregate size that could be procured , namely Barksdale and Bachus (1983), the grading of the material was carefully analysed. They stated that the average column size is normally 1 m in diameter. Hence, the sieve size was scaled down by 20 (1000 mm divided by 50 mm diameter column) to have a tentative idea of the grading that should be used for a 50 mm diameter stone column.

2.4.3 *Geosynthetic- Rockgrid*

A composite geogrid made from high strength polyester, namely Rockgrid 50 x 50 was used as a reinforcement for the bedding layer of the stone column. Table 1 shows the properties of the reinforcement used.

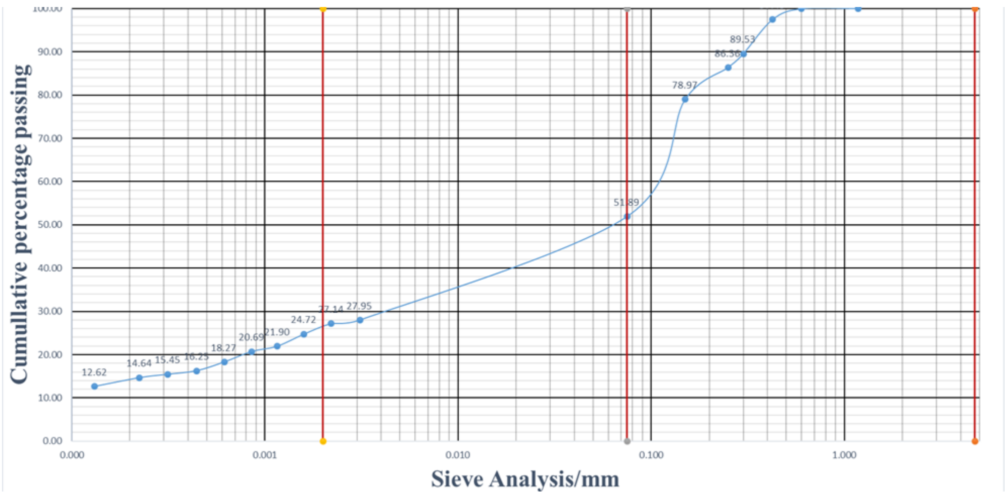

Figure 4: Grading of soil and stone column materials.

Table 1: Properties of Composite Geogrid used for reinforcement.

Material	**Rockgrid PC 50/50**	**Polyester, staple fibre 150g/m² needle punched, Nonwoven/high strength polyester yarns**		
Short Term Tensile Strength	Machine	kN/m	50	ISO 10319
	Across	kN/m	50	
	Elongation	%	10	
Long Term Design Strength (LTDS*) 120 years		kN/m	26	
Creep Limited Strength 120 Years		kN/m	30	ISO 1341
Water Flow rate	Normal to Plane	L/s/m²	150	ISO 11058
	In Plane 20kPa	L/s/hr	20	ISO 12958

3 TEST SETUP AND PREPARATION

3.1 *Installing stone column*

The soil material was compacted in layers of 50 mm thickness. To ensure uniformity throughout all the test, the soil material was all prepared at once to ensure that they all had the same moisture content (around 20%). It must be noted that enough compaction energy as stipulated by ASTM D698 was used to compact the materials.

3.2 *Rate of displacement*

Referring to ASTM D1883 , a penetration rate of 1.3 mm/min is used for testing the California Bearing Ratio (CBR). The model was tested using the Zwick 1494 machine as shown in Figure 5.

Figure 5: Zwick 1494 machine

4 RESULTS AND DISCUSSION

4.1 *Improvement factor*

From Figure 5, it can be seen that the grade of concrete does not necessarily influence the performance of concrete. Hence, a grade 10 concrete will be ideal for the construction of the hybrid stone column considering the economics behind it. It is also noted that the optimum hybrid stone column is around S2 and S3 configuration. However, hybrid stone column S3 was chosen as the one having optimum performance since it will be economically better.

Table 2: improvement factor of various hybrid stone columns for various grade of concrete.

Test series	Variable parameter	Bearing capacity reinforcement factor									
		s/D= 10%	s/D= 20%	s/D= 30%	s/D= 40%	s/D= 50%	s/D= 60%	s/D= 70%	s/D= 80%	s/D= 90%	s/D= 100%
S1D2	G10	5.5	4.4	4.3	4.5	4.7	4.7	4.6	4.4	4.4	4.3
	G20	3.7	3.7	3.8	3.9	4.1	4.3	4.4	4.4	4.4	4.3
	G30	4.1	3.9	4.0	4.2	4.2	4.1	4.0	4.0	3.9	3.9
	G40	4.3	4.4	5.0	5.3	5.2	5.1	5.0	4.9	4.9	4.8
S2D2	G10	6.2	5.1	5.0	5.1	5.3	5.3	5.3	5.3	5.3	5.2
	G20	3.6	3.9	4.2	4.4	4.8	5.1	5.3	5.4	5.5	5.4
	G30	3.6	3.8	4.0	4.2	4.4	4.4	4.4	4.4	4.4	4.4
	G40	4.2	4.3	4.6	4.9	4.9	4.8	4.8	4.9	4.8	4.8
S3D2	G10	3.9	3.9	4.2	4.5	4.6	4.6	4.7	4.8	4.9	4.9
	G20	3.4	3.9	4.2	4.5	4.7	4.9	5.1	5.3	5.4	5.6
	G30	3.9	4.1	4.2	4.4	4.6	4.6	4.7	4.7	4.8	4.9
	G40	4.5	4.7	4.8	4.9	4.9	4.8	4.8	4.9	4.8	4.8
S4D2	G10	4.0	3.9	4.3	4.5	4.6	4.6	4.6	4.7	4.7	4.7
	G20	2.6	3.5	3.9	4.1	4.1	4.1	4.2	4.3	4.4	4.5
	G30	3.4	3.7	3.8	3.9	4.1	4.2	4.2	4.3	4.3	4.4
	G40	4.0	4.4	4.5	4.5	4.5	4.4	4.4	4.3	4.4	4.3
S5D2	G10	3.4	3.7	3.9	3.9	3.8	3.7	3.7	3.7	3.7	3.7
	G20	3.7	3.9	3.9	3.8	3.7	3.7	3.7	3.7	3.7	3.8
	G30	3.7	3.9	3.9	3.8	3.7	3.7	3.7	3.7	3.7	3.8
	G40	3.7	3.9	3.9	3.8	3.7	3.7	3.7	3.7	3.7	3.8
SC5D2	G10	4.5	3.4	3.4	3.7	3.7	3.6	3.6	3.6	3.6	3.6
	G20	2.6	2.6	2.6	2.6	2.6	2.5	2.5	2.8	2.6	2.6
	G30	2.9	3.3	3.8	4.2	4.3	4.3	4.2	4.1	4.0	3.8
	G40	5.4	5.1	4.7	4.3	4.1	4.0	3.9	3.9	3.8	3.8

The column S3D2G10 was isolated and various modifications were made to the model in order to further improve its performance. Figure 5 shows improvement factor when the optimum hybrid stone column was further reinforced

Table 3: Improvement factor for geosynthetic reinforcement

Test	Bearing Capacity Reinforcement Factor									
	s/D= 10%	s/D= 20%	s/D= 30%	s/D= 40%	s/D= 50%	s/D= 60%	s/D= 70%	s/D= 80%	s/D= 90%	s/D= 100%
Clay + bedding layer	2.21	1.66	1.67	1.62	1.64	1.67	1.80	1.92	2.01	2.02
S5 + unreinforced bedding layer	2.44	2.83	2.47	2.18	2.15	2.38	2.70	3.02	3.42	3.56
S3 + unreinforced bedding layer	3.25	2.02	1.32	1.56	2.06	3.10	3.82	4.31	4.76	5.26
S5	1.88	1.98	1.98	1.93	1.89	1.87	1.88	1.87	1.89	1.93
S3	3.93	4.24	4.50	4.60	4.56	4.68	4.80	4.94	4.89	4.94
Clay + reinforced bedding layer	2.34	2.60	2.80	3.30	3.76	4.23	4.57	4.89	5.25	5.41
S5 + reinforced bedding layer	2.16	2.96	3.45	4.13	4.84	5.53	6.26	6.91	7.57	8.08
S3 + reinforced bedding layer	2.73	3.63	4.23	5.02	5.80	6.68	7.49	8.31	9.16	9.94

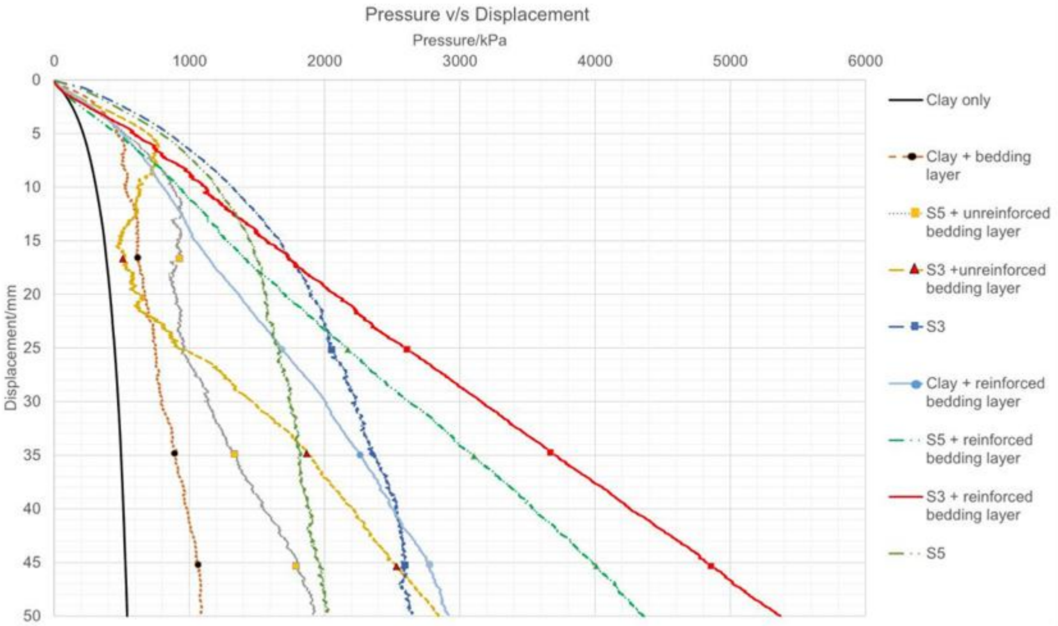

Figure 6: Pressure-displacement graph for various tests involving Geo-composite.

It can be seen from Figure 5 and Figure 6 that when a bedding layer was introduced on top of the clay, the improvement factor doubled. When it was then reinforced with the composite geo-grid the factor increased by 440. When compared to the performance of the hybrid stone column, S3, the final improvement brought by the clay and the reinforced bedding layer was greater after 41 mm penetration. This result indicated that applications where displacements are initially permitted, it would be much better to put a reinforced bedding layer over a weak soil considering the ease of installation and economic advantages it can bring along.

When a bedding layer was placed over the hybrid stone column S3, the performance drastically decreased compared to that of column S3 alone. It was suspected that this could have been due to heaving that was observed within the bedding layer. However, the rate of performance escalated after about 25 mm penetration and finally its performance was slightly higher than S3.

It was also noted that when a reinforced bedding layer was placed over the hybrid stone column S3, an improvement factor of nearly 10-fold was experienced. Even when a reinforced bedding layer was placed over the normal stone column, the final improvement (after 23 mm displacement) was more than that obtained from using the hybrid stone column (S3) only.

4.2 *Bulging*

Bulging is the main load transfer mechanism of a stone column (Mani and Nigee 2013). Hence the passive resistance of the soil usually governs the performance of the stone column. Barksdale and Bachus (1983) observed that the bulging of stone columns varies from 2-3D while Indian Standard (2003) adopted a length of bulging of 4D. Ghazavi and Nazari Afshar (2013) used plaster of Paris to observe the deformation of stone columns after testing. They found that bulging occurred between a length of D to 2D from the head of the columns. Murugesan and Rajagopal (2006) used numerical analysis and observed a lateral bulging up to 2.5 D from the top of the stone columns. Gniel and Bouazza (2009) investigated the effect of geogrid reinforced columns and observed that bulging length was restricted to 2D. From the modelling of the plaster column in AutoCAD, it was seen from Figure 7 that full bulging occurred for column S2 to S5 only. From the results, it is observed that bulging length ranged from 2 to 2.34D. It can also be observed that as the bulging is forced into a deeper level into the soil, there is a slight decrease in the bulging length.

Type of hybrid stone column	Bulging length
SC5	0D
S1	1D
S2	2D
S3	2.18D
S4	2.34D
S5	2.16D

Figure 7: Bulging diagram and length of different types of hybrid stone columns.

5 CONCLUSIONS

This study utilised a bespoke bench scale laboratory apparatus to conduct the investigation. From the results obtained, the following conclusions were drawn;

- The optimum hybrid stone column, S3, combined with a reinforced bedding layer yielded highest increase of 9.9 folds in bearing capacity compared to unreinforced soil.
- If properly employed, the inclusion of geosynthetics in stone columns yields superior soft ground improvement performance.

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