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Comparative study on the behavior of lime-soil columns and other types of stone columns

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Abstract. An experimental study is carried out to evaluate the performance of Lime mortar- Well graded Soil (Lime-WS) columns for the improvement of soft soils. Tests are conducted on a column of 100 mm diameter and 600 mm length surrounded by soft soil in different area ratios. Experiments are performed either with the entire area loading to evaluate the load - settlement behavior of treated grounds and only a column area loading to find the limiting axial stress of the column. A series of tests are carried out in soaking condition to investigate the influence of moisture content on the load - settlement behavior of specimens. In order to compare the behavior of Lime-WS columns with Conventional Stone (CS) columns as well as Geogrid Encased Stone (GES) columns, the behavior of these columns have been also considered in the present study. Remarkable improvement in the behavior of soft soil is observed due to the installation of Lime-WS columns and the performance of these columns is significantly enhanced by increasing the area ratio. The results show that CS columns are not suitable as a soil improvement technique for extremely soft soils and should be enhanced by encasing the column or replaced by rigid stone columns.

Keywords: stone column; soft clay; lime; load intensity; limiting axial stress; settlement

1. Introduction

Amongst a various number of soft soil improvement techniques, reinforcing the ground with stone columns is regarded as an extensively used and cost-effective technique. This method consists of replacing of 15 to 35 percent of unsuitable native soft soil with crushed rock or gravel to form a group of granular column beneath the foundation. Stone columns increase the bearing capacity of the ground and reduce the settlement of superstructures built on them to an acceptable level. These columns also speed up the rate of consolidation process of soft soils and minimize the likelihood of liquefaction due to the earthquake in the loose sands (Mitchell and Huber 1985, Babu *et al*. 2012).

Many studies have been carried out to investigate the behavior of stone columns based on the physical and numerical modeling, theoretical analysis and full scale field tests (Engelhardt *et al*. 1974, DiMaggio 1978, Han and Ye 2001, McKelvey *et al*. 2004, Casrto and Karstunen 2010, Murugesan and Rajagopal 2010, Cimentada *et al*. 2011, Deb *et al*. 2011, Fattah *et al*. 2011). The

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basic theory of the mechanism of ultimate axial load capacity and load transfer of stone columns was first introduced by Greenwood (1970), Hughes and Withers (1974), and later by Priebe (1976), Datye and Nagaraju (1981) and Greenwood and Kirsch (1983). Bergado *et al*. (1984) conducted field tests and concluded that the installation of stone columns increases the bearing capacity of soft soils up to four times. Sivakumar *et al*. (2004) examined the load- deformation performance of specimens of soft clay reinforced with a floating single sand column of various lengths. They considered two different column installations: wet compaction and previously frozen columns. Black *et al*. (2007) conducted tests on isolated stone column and on a group of three columns with same area ratio with different lengths under drained triaxial conditions. They concluded that grouping of columns can lead to a possible reduction in the stiffness when compared with a single column at similar area ratio.

Stone columns develop their axial load carrying capacity from the lateral confinement offered by the surrounding soil (Barksdale and Bachus 1983). When stone columns are used in very soft and sensitive soils, they fail due to through excessive radial expansion in the absence of lateral confinement by the surrounding soil. The undrained shear strength of the surrounding soil is generally used as a criterion to decide the feasibility of the treatment. According to FGSV (1979) the lower bound of the aforementioned strength falls in the range of 15-25 kPa. Also, Wehr (2006) suggested the range of 5-15 kPa for this purpose. There are two other limitations with the use of the stone columns. One is related to the spacing of columns. It is suggested that for a significant improvement in bearing capacity for stone column treated ground, approximately 25 percent of the ground should be replaced by stones (Wood *et al*. 2000). The other is related to the ratio of length to diameter of these columns (about 4 to 5) (Hughes and Withers 1974, Mitra and Chattopadhyay 1999, Samadhiya *et al*. 2008). During the last two decades, these limitations have prompted investigations into the use of encased stone columns as well as rigid stone columns.

Van Impe and Silence (1986) were probably the first ones to recognize that stone columns can be encased by geotextile. Several experimental and numerical investigations have been carried out to show the efficiency of encased stone columns with respect to the column strength and stiffness (Raithel *et al*. 2002, Ayadat and Hanna 2005, Murugesan and Rajagopal 2006, 2007, 2009, 2010, Gniel and Bouazza 2009, 2010, Ghazavi and Nazari Afshar 2013).

First applications of rigid stone columns date from the late 1970s, mainly in road embankments in Scandinavian countries (Rathmayer 1975). Unlike conventional stone columns, rigid inclusions derive their stability without any lateral confinement of the surrounding soil. These columns show significantly greater stiffness than the surrounding soil. Nonetheless, this stiffness may vary widely depending on the type of inclusion developed, which can include: lime column, vibro concrete column, metal section, etc. (Simon 2012). Rigid stone columns appear to be best suited for strengthening the stone column in locally weak zones (Barksdale and Bachus 1983). From the results of the laboratory triaxial compression tests, Juran and Riccobono (1991) revealed that low-level cementation in compacted sand columns can significantly improve the settlement response and load carrying capacity. Rigid inclusion ground improvement is now a very cost-effective foundation solution for common construction projects. Several landmark applications punctuate its development and illustrate that this basic concept can be applied effectively to complex construction projects as well (Simon 2012). In spite of the extensive use of rigid stone columns as an efficient and economical method for soil improvement, a few number of publications on the behavior and design of these columns are reported in the literature (unlike other column-like ground improvement methods such as: piles, vertical sand drains, etc).

The main objectives of the present study are to investigate the performance of Lime-WS rigid stone columns used as the soil improvement technique and to compare the load-settlement behavior of Lime-WS column treated grounds with CS column as well as GES column improved grounds using laboratory model tests. Special attention was paid to select the scale of specimens as large as possible while still staying time efficient and cost- effective.

Lime is used in this study due to its relative cost-effectiveness compared with other materials used in rigid stone columns, in addition to its approved compatibility with soft soils. The use of lime for soft soil stabilization is not a new technique and is studied by many researches (Broms and Boman 1979, Bell 1988, Locat *et al*. 1996, Rao and Rajasekaran 1996, Matthew and Rao 1997, Rajasekaran and Rao 1998, Zhou *et al*. 2002). Based on the previous studies, lime stabilization techniques can be divided into two groups namely lime columns and lime mixtures for deep and shallow improvements, respectively. These studies are mainly focused on evaluating the percentage effect of lime content, curing time, etc. on the behavior of lime stabilized grounds. The method presented here is totally different from other lime stabilization techniques, especially lime columns. Lime columns are constructed by pneumatically pumping quicklime into the natural soft soil using a giant egg-beater auger (Rogers and Bruce 1991). This procedure is expensive and time consuming and therefore less suitable for the support of lightly and moderately loaded structures. The Lime-WS columns are made by mixing lime and well graded soil, including coarse aggregates and a specified amount of clay content through replacement method (Malekpoor and Toufigh 2010). Coarse aggregates affect the strength, durability and workability of the column and the clay increases its strength further. This increment in strength is due to: firstly, the chemical reaction between lime and silica in clay (such as: cation exchange, flocculation-agglomeration and pozzolanic reaction), and secondly, filling the spaces between coarse grains by clay particles and thus creating a stronger and more homogenous column (Zhou *et al*. 2002, Malekpoor and Toufigh 2010).

The model tests have been performed at single gravity and at corresponding low stress level. For the accurate conclusions and developing design charts, centrifuge and full scale tests should be conducted. It should be emphasized that the main purpose of this research was to make a comparison between the load intensity-settlement behavior of Lime-WS treated grounds and untreated ground as well as GES and CS column treated grounds using the laboratory scale tests and it is believed that the results are relevant. Similar justifications were given by Wood *et al*. (2000). However, a large number of studies have been carried out to demonstrate the behavior of CS as well as GES columns, in order to accurately compare the behavior of these columns with Lime-WS columns at the same condition, their behavior have been also considered in the laboratory programming.

2. Theoretical considerations

For the development of an accurate laboratory-scale model, all practical dimensions were reduced by an appropriate scale factor. It was considered that a well designed testing program would allow observation of key aspects of improved ground with Lime-WS columns. Special attention was paid to keep the key ratios identical in the laboratory modeling and actual field condition, namely the ratio of column length to column diameter, column diameter to diameter of entire specimen, and column diameter to aggregate size of used soil for constructing of the column. In practical applications, the diameter of the stone columns is chosen based on the design considerations and construction method. This value generally varies between 60 to 100 cm for CS columns and 25 to 60 cm for rigid stone columns. The other dimensional parameters such as length of the column and the area ratio have been presented according to the diameter of column. The stone columns are formed with typical aggregates size of 2-75 mm (IS 2003). Hence, the ratio of the column diameter to the maximum particle size will be in the range of 8-12. These remarks have been considered in the experimental program.

Unit cell idealization was used to simplify the design of the apparatus needed to assess the behavior of an interior column in a large group of columns. For an infinitely large group of columns subjected to a uniform loading applied over the area, the behavior of each interior column may be simplified to a single column installed at the center of a cylinder of soil representing the column's influence zone. Due to symmetry of load and geometry, lateral deformation cannot occur across the boundaries of the unit cell, and the shear stresses on the outside boundaries of the unit cell must be zero (Barksdale and Bachus 1983). The unit cell can be physically modeled as a cylindrical shape container having a smooth, rigid exterior wall symmetrically located the column. Priebe proposed unit cell concept for estimating the settlement of foundation resting on the infinite grid of stone columns (Priebe 1995). This concept has also been used by many researchers (Alamgir *et al*. 1996, Ambily and Gandhi 2007, Gniel and Bouazza 2009, Shivashankar *et al*. 2011).

Regarding the case of isolated CS columns, Hughes and Withers (1974) showed that model CS columns act individually when placed more than 2.5 diameters apart. Furthermore, Ambily and Gandhi (2007) conducted experimental and numerical analyses based on unit cell concept to investigate the behavior of CS columns. They concluded that as the spacing of the columns increases, axial capacity of the isolated column decreases, and settlement increases up to an s/d ratio of 3, beyond which the change is negligible. Accordingly, the columns and cell diameters used in the current study were selected to meet these conditions.

3. Experimental investigation

3.1 Material used

The normally-consolidated clay used was of CL classification, excavated from a construction site in Kerman - Iran. This soil was collected from a depth of 4.5 to 6 m. The basic physical and engineering characteristics of clay soil are listed in Table 1. The consolidation properties of used clay were obtained from 1D consolidation test that was conducted on unremoulded clay sample with a diameter of 55 mm and a height of 19.50 mm. The soil used for construction of column was of SW-SC with clay content percentage of approximately 11 by weight. The grain size distributions of used soils are shown in Fig. 1. Normal hydrated lime with the chemical properties given in the Table 2 was used to construct Lime-WS columns. Crushed stone aggregates of size 5-10 mm were used to construct CS and GES columns. Properties of stone aggregates are presented in Table 3. Commercially available biaxial geogrid was used to encase the stone column. The geogrid reinforcement properties are tabulated in Table 4. Since the geogrid was stitched to form cylindrical sleeve to encase the column, the influence of stitching on the tensile strength and stiffness of the geogrid was also determined and presented in Table 4.

3.2 Test setup

Experiments were conducted on composite specimens consisted of clay as the surrounding soil

Table 1 Properties of used clay soil

Parameter	Value
Specific gravity (G_S)	2.72
Water content	12.60%
Liquid limit	40.00%
Plastic limit	21.00%
Undrained shear strength (in-situ condition)	17.00 kPa
Compression index (C_C)	0.17
Swelling index (C_S)	0.035

Table 2 Chemical analysis of the hydrated lime

Component oxides	Composition (%)
Calcium oxide (CaO)	73.70
Magnesium oxide (MgO)	1.619
Silica (SiO_2)	1.15
Iron oxide (Fe_2O_3)	0.24
Alumina (Al_2O_3)	0.11
Sulphur trioxide (SO_3)	0.015
Manganese (Mn)	0.005
Chloride as NaCl	0.011
Loss on ignition	23.15

and column at the center. Three types of columns were considered in this study, namely: Lime-WS, CS and GES columns. Tests were carried out on the both floating and end bearing columns. In the specimens containing floating columns, a layer of soft soil with thickness of 2D, was used beneath the column. All the experiments were conducted with four different area ratios of 5, 10, 15 and 20% which correspond to spacing of 4.3D, 3D, 2.5D and 2D, respectively (where D is the diameter of the column) and on a 100 mm diameter, and 600 mm height column; so that L/D ratio is 6, which is required to develop the full limiting axial stress on the column (McKelvey *et al.* 2004). Two series of tests were setup with respect to specimens' moisture condition. The first series of tests were conducted on specimens which were kept in plastic covers after preparation and prior to testing. A curing time of 60 days was considered for composite specimens containing Lime-WS columns. In order to investigate the behavior of columns in the soaked condition, the second series of specimens were placed in water for 96 hour prior to testing. In the field, the entire of the treated ground will be subjected to loading from the superstructure. This situation was simulated in the laboratory by loading the entire area of the specimen to study the load-settlement behavior of the improved ground. Tests with column area loaded were used to determine the limiting axial stress of columns. A 50 mm thick sand layer was placed at the top to serve as a blanket for the case where the entire area was loaded. The load was applied with the help of loading frame through a proving ring at a constant displacement rate of about 0.3 mm/min. Two dial gauges were fixed at 180° angles to each other for measuring the settlement of specimens during the application of the load. A typical test arrangement is shown in Fig. 2 and the overall experimental testing program is given in Table 5.

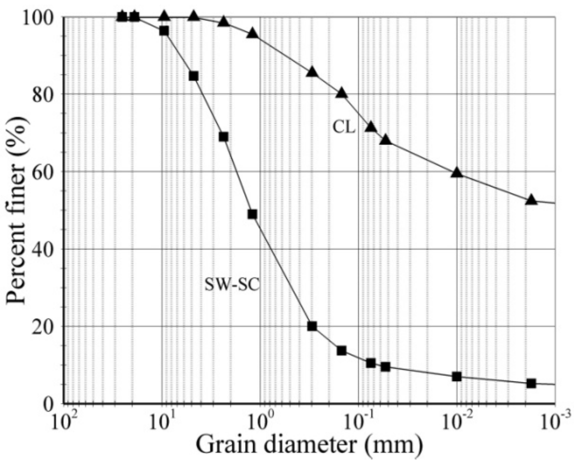


Fig. 1 Grain size distribution for soft clay and well graded sand with clay

Table 3 Properties of used stone aggregates

Parameter	Value
Size range	5-10 mm
Specific gravity (G_S)	2.66
Maximum dry unit weight ($\gamma_{d\,\max}$)	17.40 kN/m^3
Minimum dry unit weight ($\gamma_{d\,\min}$)	14.80 kN/m^3
Relative density	95.00%
Angle of internal friction (φ)	41°
Modulus of elasticity (E_s)	52000 kPa
Angle of dilatancy (ψ)	11°

Table 4 Properties of geogrid

Parameter	Value
Maximum tensile strength	18.00 kN/m
Tensile strength at 1% strain	4.10 kN/m
Strain at maximum tensile strength	11.00%
Maximum tensile strength from tests with seam	14.50 kN/m
Strain at maximum tensile strength from tests with seam	8.00%
Elastic axial stiffness at 1% strain	750 kN/m
Elastic axial stiffness at 1% strain from tests with seam	603 kN/m
Mesh aperture size	4 mm * 4 mm
Thickness	3 mm

3.3 *Preparation of specimens*

All the specimens were prepared with an identical method. To maintain similar properties throughout the tests, the clay bed was prepared at 12.60% moisture content and 13.40 kN/m^3 unit weight (equal to in situ conditions) in all cases. Before filling the tank with clay, polythene sheet was laid on the internal walls of it to avoid any friction between clay and walls of the tank. For preparation of each test bed, required clay soil was air dried and checked for initial moisture content. The additional water quantity required to achieve desired moisture content was added and thoroughly mixed to form a uniform paste. Clay was filled in the tank in layers with measured quantity by weight. Each layer was subjected to uniform compaction with a tamper to achieve 50 mm height and corresponding unit weight. The construction of columns was performed by replacement method to obtain repeatable rest specimens. Thin open- ended steel pipe of 100 mm inner diameter and wall thickness of 2 mm was used to construct the columns. After preparation of the bottom layer to a depth of twice the diameter of the column, the steel pipe was placed at the center of the soil bed, and construction of clay soil and column were carried out simultaneously. The outer surface of the pipe was lubricated by applying a thin layer of grease for easy withdrawal of pipe without any significant disturbance of the surrounding soil.

Construction of the Lime-WS column was carried out in two stages; first, the dry soil was thoroughly mixed with the lime at the desired moisture content (a ratio of water-soil of 0.35) for approximately 15 minutes until the mixture became uniform and homogenous, then the mixture was poured into the steel pipe in a slurry form. According to the results of previous researches, 20% lime (the ratio is the dry weight of lime over the dry weight of soil) was used for constructing

Table 5 Overview of experimental testing program

Test description	A_r (%)	Loading condition		Column condition		Moisture condition	
		Entire area	Column area	Floating	End bearing	Natural	Soaked
Untreated specimens	5	√	-	-	-	√	√
	10	√	-	-	-	√	√
	15	√	-	-	-	√	√
	20	√	-	-	-	√	√
Composite specimens containing Lime-WS columns	5	√	√	√	√	√	√
	10	√	√	√	√	√	√
	15	√	√	√	√	√	√
	20	√	√	√	√	√	√
Composite specimens containing CS columns	5	√	√	√	√	√	√
	10	√	√	√	√	√	√
	15	√	√	√	√	√	√
	20	√	√	√	√	√	√
Composite specimens containing GES columns	5	√	√	√	√	√	√
	10	√	√	√	√	√	√
	15	√	√	√	√	√	√
	20	√	√	√	√	√	√

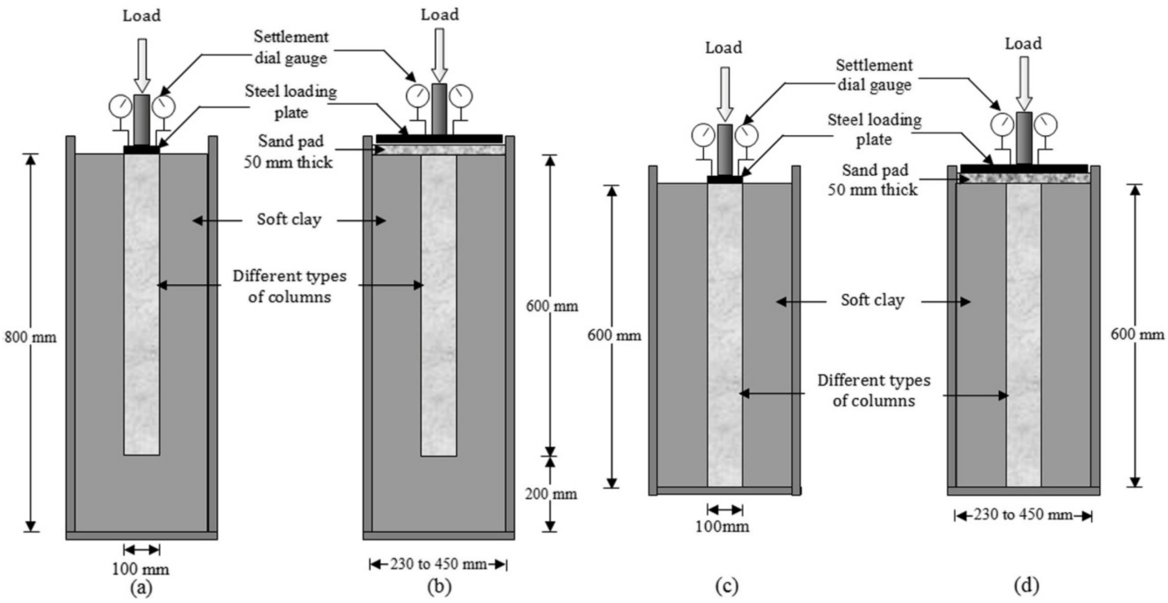


Fig. 2 Test setups: (a) floating column with column area loading; (b) floating column with entire area loading; (c) end bearing column with column area loading; and (d) end bearing column with entire area loading

of the Lime-WS columns.

For construction of CS column, after preparing of the clay bed and placing the pipe at its center, the crushed stone aggregates required to form the column was charged into the pipe in the layers of 50 mm thickness (after compaction) and compacted to achieve a density of 16.50 kN/m^3. The operation of preparing surrounding soil, charging the aggregates, compaction and raising the pipe was repeated until the construction of the specimen completed to the full height.

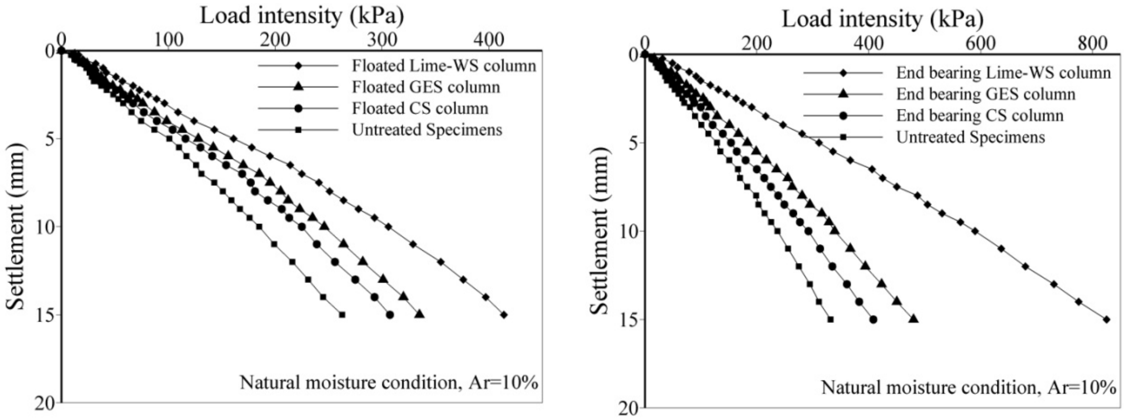
In order to prepare the specimens containing GES columns, the cylindrical encasement sleeve was formed by overlapping 15 mm wide section of geogrid and then stitching the overlapped part and placing it around the steel pipe. Based on previous studies, only the 50% of the top portion of the column was encased (Murugesan and Rajagopal 2006).

4. Results and discussion

4.1 Entire area loaded

These tests were conducted using a circular loading plate having a diameter slightly less than the diameter of the tank. Loading of the both column and the surrounding soil with confinement of the tank walls represents an actual field condition for an interior column from a group of columns.

A relationship between typical load intensity and settlement in natural moisture condition and for an area ratio of 10% is presented in Fig. 3. This figure depicts that floating Lime-WS columns increase the stiffness of soft soils and application of end bearing columns is effective in further increment of the same. As compared to untreated soft soil, an improvement of 17% in load



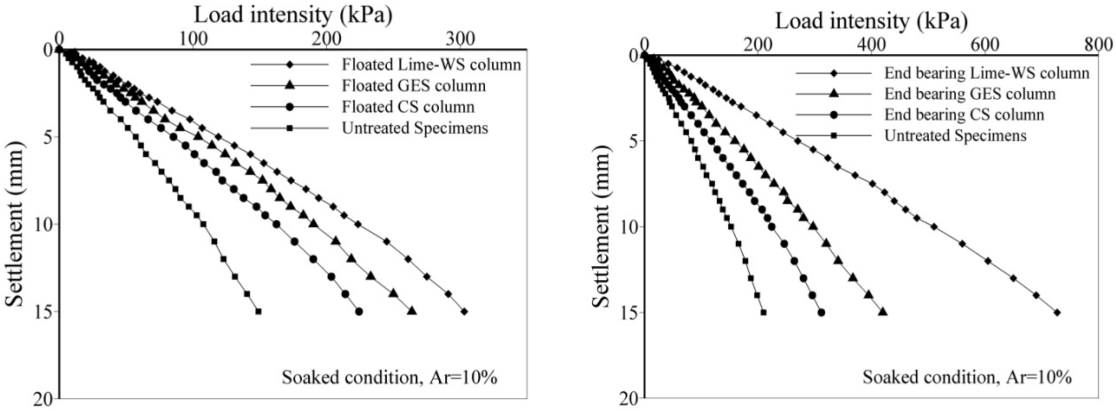
(a) Floating columns (b) End bearing columns

Fig. 3 Load intensity-settlement behaviors of different types of columns under entire area loading in natural moisture condition

intensity has just been achieved when the soft soil is improved by floating CS column. This value is 23% for end bearing CS column treated. Encasing the column with geogrid provided proper lateral support to the column and enhanced its behavior to some extent. As compared to soft clay bed, the load intensity has been increased up to 28% and 44%, when the soil is improved by floating and end bearing GES columns, respectively. These ratios are 58% and 148% for composite specimens containing floating and end bearing Lime-WS columns.

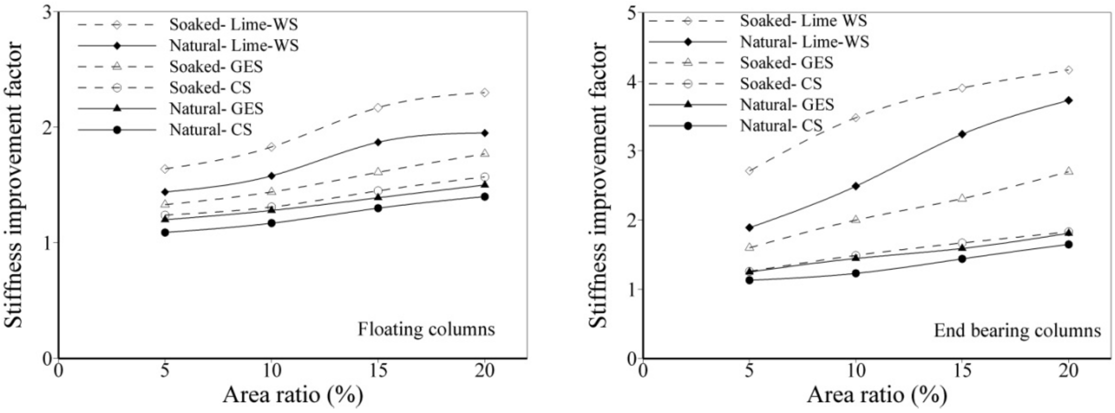
The results show that CS columns are not as suitable as an extremely soft soil improvement technique and should be enhanced by geogrid encasement or replaced by rigid stone columns. Fig. 3(b) reveals that a Lime-WS column is the most suitable choice, among the 3 options, when the columns are used in the end bearing condition on rigid base. Almost a similar behavior has been observed for other area ratios.

Fig. 4 shows a relationship between load intensity and settlement for an area ratio of 10% in soaked condition. When the specimens were soaked prior to testing, their stiffness decreased and thus the settlement increased. The most important reason for load intensity differences in composite specimens under natural and soaked conditions is the negligible stiffness of the surrounding soft clay in soaked condition. As the behavior of the CS columns depends heavily on the behavior of the surrounding soil, the soaking greatly reduced the strength of CS column treated specimens. By encasing the column, the influence of the stiffness of the surrounding soil on the load-carrying capacity of the treated specimen decreases. When the cohesive strength of the columns significantly increases (Lime-WS columns), the stiffness of the composite ground is almost independent of the stiffness of the surrounding soil. As compared to untreated ground, an improvement of 103% and 248% in load intensity have been achieved when the soft clay soil was improved using floated and end bearing Lime-WS columns, respectively. These ratios are 76% and 100% for GES columns treated grounds. Although a relative low load-carrying capacity was achieved for the GES treated specimens in comparison with Lime-WS treated ones in soaked condition, these columns can act also as a vertical drains in saturated unconsolidated soft soils and accelerate the rate of consolidation as well as the time of consolidation settlement and therefore reduce the post consolidation settlement.



(a) Floating columns (b) End bearing columns

Fig. 4 Load intensity- settlement behaviors of different types of columns under entire area loading in soaked condition



(a) Floating columns (b) End bearing columns

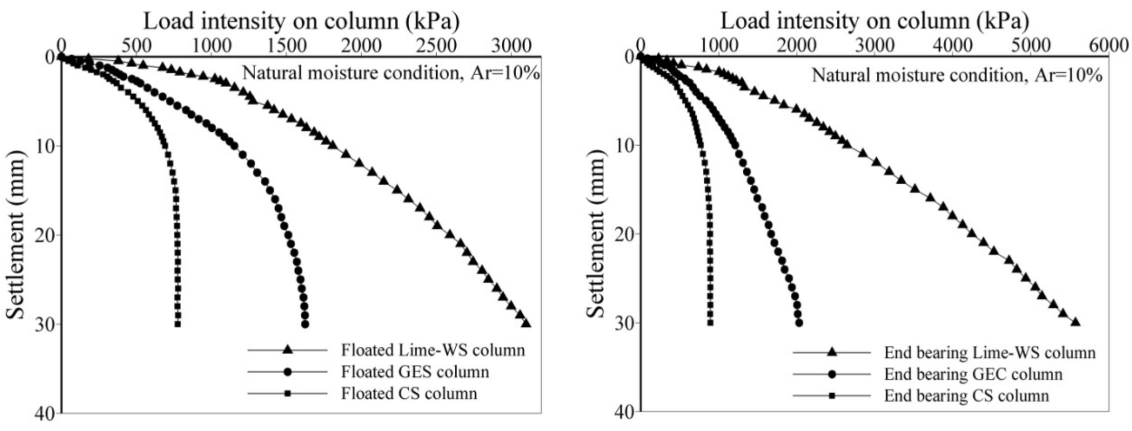
Fig. 5 Variation of stiffness improvement factor (*β*) with area ratio (A_r) for different types of columns

Fig. 5 depicts the variation of the stiffness improvement factor (ß), defined as the ratio of load intensity of the treated ground to that of untreated ground for the same settlement, with the area ratio in different moisture conditions. It is interesting to note that much higher improvement is achieved in the soaked condition as compared to natural moisture condition. Based on the results, it can be concluded that Lime-WS columns increase the stiffness of soft soils even for an area ratio of 5% and when the area ratio increases, the *β* factor increases noticeably. However, when the area ratio exceeds 15%, the increment rate of the load intensity is decreased. In other words, under similar conditions, the difference between *β* values of 5% and 10% and also 10% and 15% area ratios is more than that of 15% and 20% area ratios. It can also be perceived form this figure that when the area ratio is less than 15%, the *β* factor for CS columns treated grounds is very low, specially for floating columns and in natural moisture condition. While the area ratio is larger than 15%, the strength of the specimen increases, mainly in the soaked condition. The similar behavior has been reported in the literature by Ambily and Gandhi (2007). Encasing the CS column has enhanced its behavior and this improvement was remarkable in the soaked specimens. This behavior can be related to the presence of the geogrid which allowed the column to withstand further loads by providing additional lateral confinement to the column.

4.2 Column area alone loaded

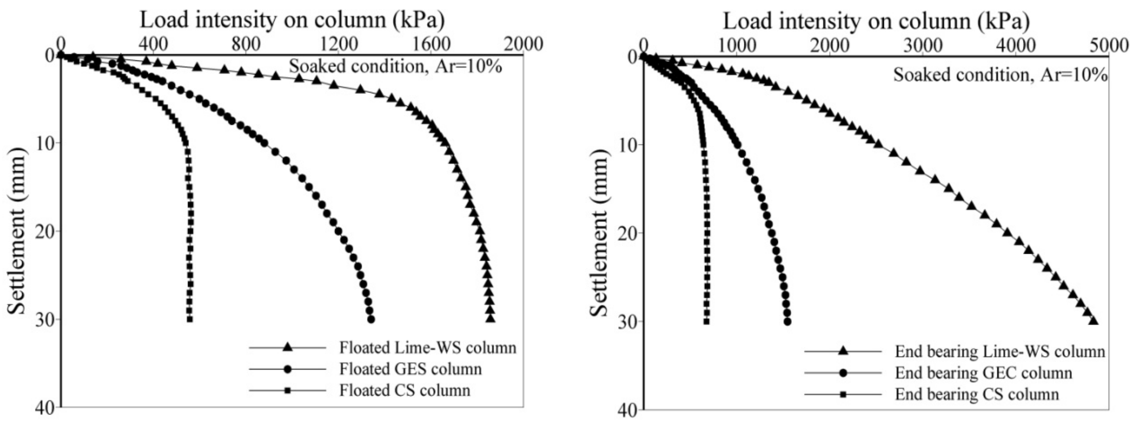
Laboratory model tests were carried out with load applied just on the column area to find the limiting axial stress of the considered columns. Fig. 6 shows a typical relationship between limiting axial stress and settlement for different types of columns in natural moisture content. Curves are depicted up to 30 mm settlement. Loading the Lime-WS columns up to more than 30 mm settlement did not result in failure and they tended to withstand the load further, while both of the CS and GES columns failed at lower settlements. It is illustrated in this figure that Lime-WS columns tolerate more load than other types of column. There are two reasons for this fact. The first is because of the high cohesive strength of this column as compared to CS as well as GES columns. The second is related to the interaction of the Lime-WS and the surrounding soil. Due to undrained behavior of Lime-WS column, it is not possible to extract undisturbed deformed shape of column using slurry of cement or other methods. However, investigation of different parts of the specimens after testing revealed that the lime migrated to the surrounding soil and the column engaged very well with soil which results in fractional resistance to be increased. Owing to high cohesive strength of the column in comparison with the surrounding soil, the floating Lime-WS columns fail by punching. When the base of the column is rigid (end bearing column), the limiting axial stress increases considerably.

Fig. 7 illustrates the relationship between limiting axial load and settlement under soaked condition for an area ratio of 10%. Comparison of the results of Figs. 6 and 7 reveals that the soaking has the most effect on the behavior of CS columns and has the least effect on the



(a) Floating columns (b) End bearing columns

Fig. 6 Load intensity-settlement behaviors of different types of columns under column area alone loading in natural moisture condition

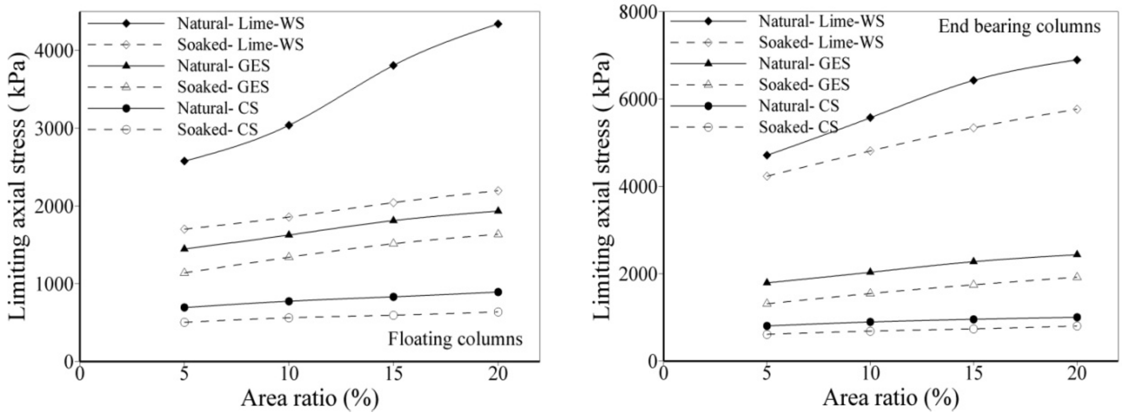


(a) Floating columns (b) End bearing columns

Fig. 7 Load intensity-settlement behaviors of different types of columns under column area alone loading in soaked condition

behavior of Lime-WS columns. The limiting axial stress of the CS columns decreased considerably under soaked condition, thus these columns are not an appropriate choice for this case. The encased columns have tolerated higher limiting axial stress as compared to the CS columns.

From the results, it was concluded that the Lime-WS columns have more axial load-carrying capacity than GES columns. However, the behavior of GES columns was dependent on the ultimate strength and stiffness of the geogrid to a great extent (Murugesan and Rajagopal 2010). The previous parametric studies revealed that for a load intensity of 20 kN/m^2, as the stiffness value of the geogrid increases from 60 to 1000 kN/m^2/m, settlement reduction ratio (which is



(a) Floating columns (b) End bearing columns

Fig. 8 Variation of limiting axial stress with area ratio (A_r) for different types of columns defined as the ratio of the settlement of treated ground to that of the untreated ground under identical surcharges) decreases from 0.45 to 0.2, but when the stiffness is doubled, the ratio is just 0.17. Therefore, it can be inferred that when an appropriate geogrid configuration is used, the settlement reduction ratio is decreased effectively and it will be cost-effective (Malarvizhi and Ilamparuthi 2007). As mentioned earlier, the GES columns can also accelerate the consolidation rate of saturated unconsolidated soft soils. The select of appropriate method depends also on other factors, especially availability of equipments and material, and also economical considerations. Comparing the load intensity-settlement behavior of floating Lime-WS column in the natural and soaked condition (see Figs. 6(a) and 7(a)) clearly reveals the effect of soaking on the behavior of this column. It is observed that the failure mode of this column under soaked condition was a punching failure mode, which led to a lower limiting axial stress.

Typical variation of limiting axial stress (corresponding to 30 mm settlement) with area ratio for various types of columns in natural and soaked moisture conditions is shown in Fig. 8. It is clear that the limiting axial stresses are higher in the Lime-WS columns as compared to those of other types of stone columns. It can be also observed that higher area ratio results in higher axial stress. However, for the Lime-WS columns, when the area ratio is more than 15%, the increment rate of the limiting axial stress is negligible. It is clearly found out from Fig. 8(a) that in the floating columns, the limiting axial stresses of CS as well as GES columns is slightly different under soaked and natural moisture conditions. But in the case of Lime-WS column, the limiting axial stress in the natural moisture condition is much higher than that in the soaked condition. As mentioned before, this difference appeared to be mainly influenced by the negligible stiffness of the soft clay used beneath the columns under soaked condition.

The major disadvantage of Lime-WS columns is their brittle behavior. This limitation may be overcome by the addition of tensile inclusions, such as fibers, to Lime-WS materials resulted in ductile behavior associated with high strain. This idea should be verified through future experimental investigations.

5. Conclusions

Large scale model tests were conducted to evaluate the load- settlement behavior of Lime-WS, GES and CS columns in soft soils using unit cell concept. The model tests have been performed in the laboratory at single gravity and at corresponding low stress level. Based on the results and discussion presented in the previous sections, the following conclusions may be drawn.

- Inclusion of Lime-WS columns considerably improved the stiffness and reduced the settlement of soft soils. The application of end bearing column further enhanced the load intensity- settlement behavior of Lime-WS treated soils. As compared to untreated ground, in the natural moisture condition and for an area ratio of 10%, an improvement of 58% and 148% in load intensity have been achieved when the soft clay soil was improved using floated and end bearing Lime-WS columns, respectively. For soaked condition and area ratio of 10%, these values are 103% and 248% for composite specimens containing floating and end bearing columns, respectively.
- The results revealed that Lime-WS column tolerates more load than GES and CS columns under different testing conditions. This is due to the high cohesive strength of this column along with its well interaction with the surrounding soil. The GES column has higher stiffness compared to a CS column irrespective of whether the column is end bearing or

floating.

- The stiffness improvement factor (*ß*) as well as limiting axial stress was increased by increasing the area ratio. The rate of increment of these factors was remarkable for Lime-WS columns in lower area ratios, whereas that was significant for GES and CS columns, in higher area ratios.
- In all model types, soaking the specimens resulted in an increase in settlement for a given load. As the behavior of the CS columns depends strongly on the stiffness of the surrounding soil, the soaking greatly reduced the stiffness of CS column treated grounds and had the least effect on the behavior of Lime-WS columns improved specimens.
- Although a low strength was achieved for the GES treated specimens in comparison with Lime-WS treated ones in soaked condition, these columns can act as a vertical drain in saturated unconsolidated soft soils and accelerate the rate of consolidation as well as the time of consolidation settlement. Accordingly, the rational decisions can be made with respect to the actual field conditions.

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