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Behavior of polymer columns in soft clayey soil: A preliminary study

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Abstract. Deep soil mixing with cement and cement–lime mixtures has been widely used for decades to improve the strength of soils. In this study, small-scale laboratory model tests of polymer columns in soft clayey soil were conducted to evaluate the feasibility of using various polymeric compounds as binders in deep soil mixing. Floating and end bearing polymer columns were used to examine the load–settlement relationship of improved soft clayey soils for various area replacement ratios. The results indicate that polymer columns show good promise for use in deep mixing applications.

Keywords: clayey soil; deep soil mixing; polyester; polymer column; floating column; end bearing column

1. Introduction

The soils at a given site sometimes do not meet the requirements of a planned construction project. Construction at such a site can encounter severe difficulties from a geotechnical engineering or economic point of view. Soft clays are one of the types of problematic soils that have low bearing capacity and are prone to excessive settlement. Ground improvement methods have been used for decades to overcome such problems. Stone columns, deep soil mixing, prefabricated vertical drains, surface and deep compaction, vacuum drainage and preloading have been used successfully to increase the bearing capacity and reduce the settlement of soft clayey soils (Bell 1993, Demir *et al*. 2013).

Several studies have examined the use of stone columns to improve the mechanical behavior of soft clayey soils (Malarvizhi and Ilamparuthi 2004, Ali *et al*. 2010, Vekli *et al*. 2012). Low lateral confinement pressure in a bed of soft clayey soils results in low bearing capacity and high settlement. Stone columns encased with geosynthetic materials, commonly referred to as reinforced stone columns, have been used to improve the bearing capacity and reduce the settlement of soft clayey soils (Ali *et al*. 2010, Murugesan and Rajagopal 2010, Khabbazian *et al*. 2010, Ghazavi and Afshar 2013, Tandel *et al*. 2014). However, installation of reinforced stone columns is quite time consuming and labor intensive.

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Deep soil mixing has been used extensively as an alternative to installation of stone or reinforced stone columns for improvement of soft clayey soils. The deep soil mixing method consists of mechanical mixing of cement, lime, or a cement–lime mixture with soft clayey soil. A great number of studies of deep soil mixing have been conducted (Porbaha *et al*. 1998, Bahner and Naguib 2000, Maher *et al*. 2007, Duraisamy 2008, Chai and Pongsivasathit 2010, Kitazume and Nishimura 2012, Sengor 2011, Malekpoor and Poorebrahim 2014, Sukontasukkul and Jamsawang 2012). Most of the researchers who have examined this topic have noted that deep soil mixing with cement, lime, or a cement–lime mixture with clayey soils increases the unconfined compressive strength and the bearing capacity of such soils. The use of cementitious components requires that sufficient time be allowed to pass for deep mixing columns to reach their final strength. This may not be possible in some cases when rapid improvement of soft soils is required. In such cases, other soil improvement methods should be considered.

Polymeric compounds have been used in soil stabilization applications in recent years. Some non-traditional soil stabilization binders, such as acids, asphalt emulsions, lignin derivatives, enzymes, tree resins, biopolymers, and silicates are available from the commercial sector. These additives may be in liquid or solid form and are touted as being applicable to most types of soils (Newman and Tingle 2004). However, deep mixing of soils with polymers is a new research subject. Akbulut *et al*. (2013), Arasan *et al*. (2015) and Bagherinia (2013) and Arasan and Nasirpur (2015) studied the use of polyester and SACP–PVAc (styrene acrylic copolymer–polyvinyl acetate) to improve clayey and sandy soils. Akbulut *et al*. (2013) investigated the unconfined compressive strength (UCS) of sandy soils with various percentages of polyester (between 1% and 5%) using deep-mixed samples cured for 7 and 28 days. Similarly, Arasan *et al*. (2015) investigated the unconfined compressive strength and freeze–thaw behavior of sandy soils with various percentages of polyester (between 10% and 30%) using deep-mixed samples cured for 3 hours and 1, 3, 7, and 28 days. They reported that the unconfined compressive strength increased with the polyester percentage, relative density, and curing period but that the number of freeze–thaw cycles did not have a significant effect on the unconfined compressive strength. The researchers noted that the unconfined compressive strengths of samples cured for 3 hours were higher than the suggested lower UCS limit (i.e., 0.5 MPa) for soils stabilized by deep mixing. Hence, it was concluded that polyester showed good promise as a candidate for rapid soil stabilization.

In another study, Bagherinia (2013) investigated the unconfined compressive strength of samples of clayey soils cured for 14 days after mixing with various percentages of polyester, accelerator (cobalt naphthenate), catalyst (methyl ethyl ketone peroxide, MEKP), guar gum, locust bean gum, and lime. They reported that the highest unconfined compressive strength, 2.2 MPa, was obtained with 20% polyester, 2% accelerator (by weight of polyester), 0.4% catalyst (by weight of polyester), 0.25% guar gum, and 3% lime. Bagherinia (2013) also studied the effects of curing periods on the unconfined compressive strength and freeze–thaw resistance of samples cured for 14, 28, and 150 days. He observed that the unconfined compressive strength increased with increasing polyester percentage and that the number of freeze–thaw cycles did not have an effect on the UCS values of the stabilized samples. In addition, the highest unconfined compressive strength value obtained in that study corresponded to the sample with 0.25% guar gum and 20% polyester. The unconfined compressive strength values of the samples cured for 14, 28, and 150 days were 7.0, 7.2, and 13.4 MPa, respectively. These were judged by the researchers to be extraordinarily high unconfined compressive strength values for soils stabilized by deep mixing (Bruce *et al*. 1998, Bruce and Bruce 2003). Further laboratory-scale model tests and in situ studies of soil improvement by deep mixing with polyester are needed to draw further conclusions.

In comparison with traditional unconfined compression strength testing, there have been few laboratory model studies of soft clayey soils. Previous laboratory model studies have typically been focused on the column binder type, column type (i.e., end bearing or floating columns), column length, column diameter, and number of columns (i.e., the area replacement ratio). Kitazume *et al*. (2000) investigated the effect of the column type on deep-mixed clayey soil using centrifuge model tests. Duraisamy (2008) investigated the effects of the column diameter and curing period on cement columns formed by deep soil mixing method in soils and developed a design chart for cement columns based on his results. He also reported that a significant reduction in compressibility was achieved by increasing the diameter of the cement columns, increasing the number of cement columns, and increasing the amount of cement in the cement columns. Chai and Pongsivasathit (2010) performed a model study of floating columns installed in clayey soils in which they calculated the settlements of the columns. They concluded that floating columns could easily be used to improve soft clayey soils. Sengor (2011) studied the deformation characteristics of deep-mixed columns in soft clayey soils and found that the spacing of the columns, the replacement ratio, and the binder content influenced the compressibility characteristics of the soils. Sengor (2011) found that the cement content was the most important parameter in deep mixing applications. Yi *et al*. (2013) studied the performance of carbonated soil–MgO columns using laboratory-scale model tests. Similarly, Malekpoor and Poorebrahim (2014) investigated the behavior of compacted lime–soil columns in soft soils. They found that compacted lime–soil columns increased the load-bearing capacity of soft soils and decreased the settlement of such soils.

In this study, three different polymeric compounds were used to form deep soil mixing columns to improve the mechanical behavior of a soft clayey soil. A series of small-scale model tests was conducted for this purpose. Polymeric compounds were used as the binder in deep soil mixing columns. In the experiments, two different types of polymer columns were installed in the soft clayey soil bed: end bearing columns and floating columns. The effect of the area replacement ratio and the effect of the polymer columns in improving the load–settlement relationship of the soft clayey soil was also investigated.

2. Materials and methods

2.1 Preparation of clay beds

A manufactured clayey soil classified as a low-plasticity clay (CL) according to the Unified soil classification system (USCS) was used in the tests. The CL clay was dried in an oven at 105°C for one day. The dried clay was then powdered and sieved through a 1-mm sieve. The properties of the clay are shown in Table 1. The clay was used to prepare the cylindrical test beds into which columns made of polymeric compounds were installed. The clay beds were prepared at a unit weight of 17.5 kN/m^3 and a water content of 30%. To prepare the clay for formation of the clay beds, the clay and the required amount of water were mixed and then kept in a plastic bag for one day to ensure that the water content was uniform throughout the mixture. A cylindrical mold 155 mm in diameter and 115 mm in height was used to form each of the clay beds. Before the clay was placed in the mold, the inner surface of the mold was lubricated with grease to minimize friction between the clay and the mold. The mold was filled in three layers, and each layer was tamped gently using a wooden tamper to achieve a unit weight of 17.5 kN/m^3. It should be mentioned that water content of prepared clay bed was 30%, which was higher than optimum water content of

Table 1 Index properties of clayey soil

Properties			Clayey soil
Clay content	< 0.002 mm	(%)	10
Finer content	< 0.075 mm	(%)	80
Specific gravity	G_S	-	2.77
Liquid limit	w_L	(%)	40
Plastic limit	w_P	(%)	25
Plasticity index	I_P	(%)	15
Optimum water content	OMC	(%)	15
Maximum dry unit weight	$\gamma_{d\max}$	(kN/m^3)	18.3
Hydraulic conductivity	k	(cm/s)	6.974 x 10^{-7}
Soil classification	USCS	-	CL

clay (i.e., 15%). Therefore, it could be said that the prepared clay bed was saturated. At the end of the filling process, the height of the clay bed was 115 mm. The utmost care was taken in the filling and compacting processes. The procedures described by Malarvizhi and Ilamparuthi (2004), Sengor (2011), Demir *et al*. (2013), and Malekpoor and Poorebrahim (2014) were followed in preparing the clay bed.

Table 2 Some properties of the polymeric compounds used

Polymeric compound type	Percentages of binder materials (%)			Photograph of sample	UCS (kPa)*
	Polyester	Guar gum	Lime		
PC1	100	-	-		117000
PC2	86.75	0.25	13		74000
PC3**	-	92	8		-

* Unconfined compressive strength of samples after 28 days of curing
** No unconfined compressive strength is given for this compound because it is a dry mixture

2.2 Column binders

Polyester, guar gum, and lime were used to form the polymeric compounds that served as the binder materials used to form the columns. Three different polymeric compounds were prepared and used. The percentages of the binder materials and of the UCS values of the polymeric compounds are shown in Table 2, along with photographs of samples of the compounds. It should be noted that the type, preparation, and percentages of the three binder materials used were chosen on the basis of the results of previous studies (Akbulut *et al*. 2013, Arasan *et al*. 2015, Bagherinia 2013, Arasan and Nasirpur 2015). The polyester was prepared according to the procedure described by Arasan *et al*. (2015). An unsaturated polyester, an accelerator (cobalt naphthenate), and a catalyst (MEKP) were used to prepare the polyester.

2.3 Experimental setup and test procedure

A special injection system was used to install the polymer columns in the clay beds. This special injection system was modified from a hand-operated oil pump of a similar nature made by Sengor (2011). The prepared polymeric compounds were placed in the shafts of the system and pumped into the clay bed. The floating columns were installed at lengths of 77 mm (i.e., 2/3 of the mold height), and the end bearing columns were installed at lengths of 115 mm (i.e., the full mold height). All of the polymer columns were 5 mm in diameter. The manner in which the polymer columns were installed from bottom to top was very similar to the Tremie pipe installation method, which is frequently used in field applications. It should be mentioned that the third polymeric compound, PC3 (the mixture of lime and guar gum), was installed in the dry state, in accordance with Duraismy (2008).

To investigate the effects of the column type and area replacement ratio (As) on the load–settlement relationship, two different types of columns (i.e., floating and end bearing columns) and four different area replacement ratios (i.e., 0.05, 0.10, 0.15, and 0.20) were used in the study. It should be mentioned that the area replacement ratio was calculated by dividing the total area of columns to area of improved soil. A summary of the experimental program is shown in Table 3. It should be noted that a total of 25 samples were prepared and tested in this study. Fig. 1 illustrates the floating and end bearing columns. Plan views of the polymer columns at the various area

Table 3 Summary of experimental program

Test No.	Test description	Type of column	Area replacement ratio	Number of columns
1	Clay bed	-	-	-
2	Clay bed with deep mixing columns	Floating	0.05	8
3	Clay bed with deep mixing columns	Floating	0.10	16
4	Clay bed with deep mixing columns	Floating	0.15	23
5	Clay bed with deep mixing columns	Floating	0.20	31
6	Clay bed with deep mixing columns	End Bearing	0.05	8
7	Clay bed with deep mixing columns	End Bearing	0.10	16
8	Clay bed with deep mixing columns	End Bearing	0.15	23
9	Clay bed with deep mixing columns	End Bearing	0.20	31

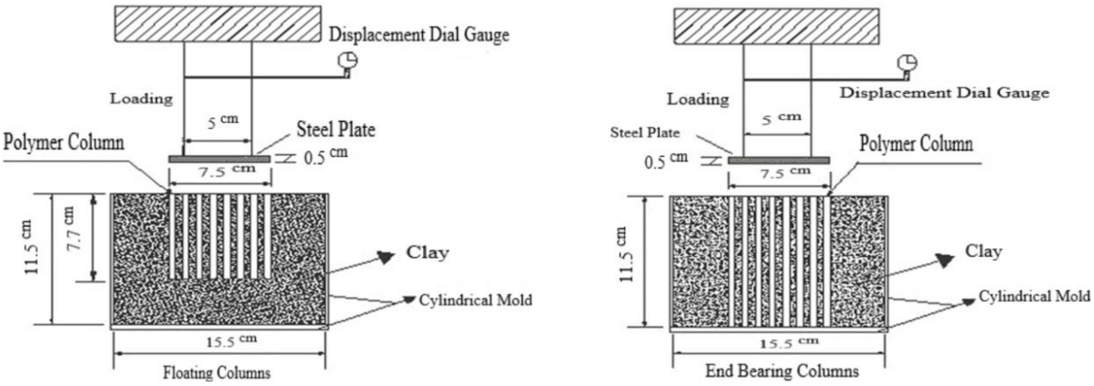
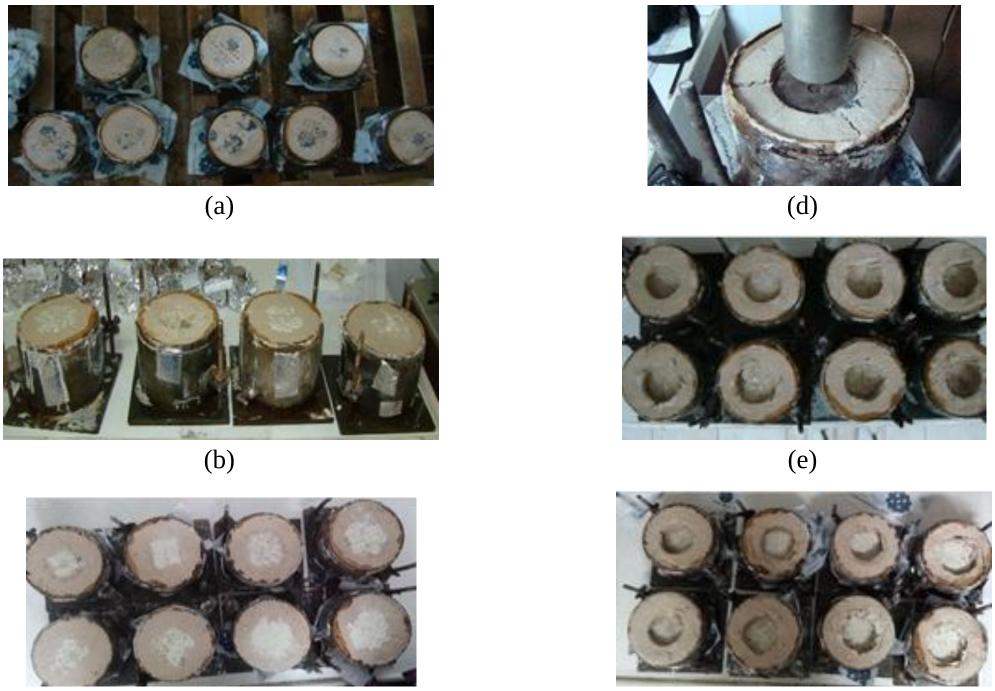


Fig. 1 Schematic illustration of test setup

(a) (b) (c) (d)

Fig. 2 Plan view of (a) 8-column system (*As* = 0.05); (b) 16-column system (*As* = 0.10); (c) 23-column system (*As* = 0.15); (d) 31-column system (*As* = 0.20)



(a) (d)

(b) (e)

(c) (f)

Fig. 3 Test bed samples (a) PC1; (b) PC2; and (c) PC3 after installation and (d) PC1, (e) PC2 and (f) PC3 after testing of polymer columns replacement ratios are shown in Fig. 2. After installation of the polymer columns in the clay beds, the prepared samples were cured for 28 days in a moisture room at a temperature of 20 ± 3°C and a relative humidity of 80% (Fig. 3). The procedures described by Malarvizhi and Ilamparuthi (2004), Sengor (2011), Demir *et al*. (2013), and Malekpoor and Poorebrahim (2014) were used to cure and test the samples. It is also mentioned that by Arasan *et al*. (2015) the polymeric compounds gain their ultimate strength in a short period of time such as a few hours. Hence, in this study early behavior of samples has not examined.

A loading frame was used to load the samples at a constant strain rate of 0.8 mm/min. A vertical load was applied to each of the samples using a circular steel plate 75 mm in diameter. A dial gauge was attached to measure the settlement of the plate during the application of load. A diagram of the test setup is shown in Fig. 1. A loading test was first conducted on a clay test bed sample containing no columns (Test No. 1) for comparison with the results of loading tests on the clay test bed samples containing polymer columns (Test Nos. 2-9). The PC1, PC2, and PC3 test samples (i) after installation; and (ii) after testing are shown in Fig. 3.

3. Results and discussion

3.1 Installation of polymer columns

Successful installation of columns is important for both deep mixing and stone column applications. Figs. 3, 4, and 5 show that the polymeric columns tested in this study were installed successfully. Fig. 4 show separated columns in test samples. While the columns of PC1 and PC2 could be separated easily, the columns of PC3 could not be separated, because of the hydration reaction that occurred between the lime and the clay. As Fig. 4 shows, the group column effect increases with an increase in the number of polymer columns.

3.2 Load–settlement behavior of polymer columns

The load–settlement behavior of PC1, PC2, and PC3 for both floating and end bearing polymer columns is illustrated in Figs. 6, 7, and 8, respectively. The ultimate load capacities of the samples with 8, 16, 23, and 31 floating PC1 columns were approximately 323%, 713%, 923%, and 1370% higher, respectively, than the ultimate load capacity of the clay bed with no columns, as shown in Fig. 6(a). The ultimate load capacities of the samples with 8, 16, 23, and 31 end bearing PC1

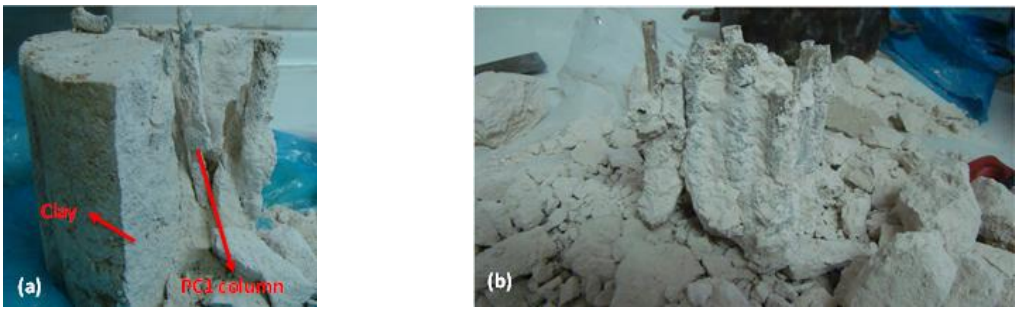
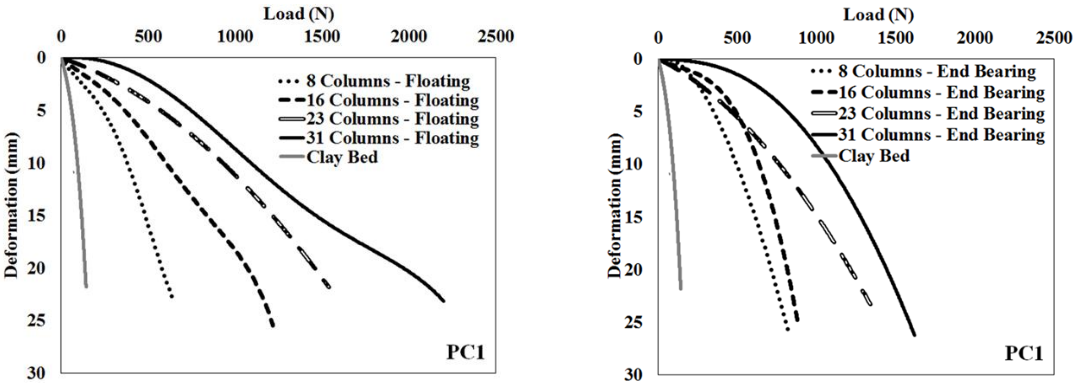


Fig. 4 View of (a) PC1-End bearing-8 columns; and (b) PC1-End bearing-31 columns after testing

Fig. 5 Views of (a) PC3-Floating -31 columns; and (b) PC3 column after testing

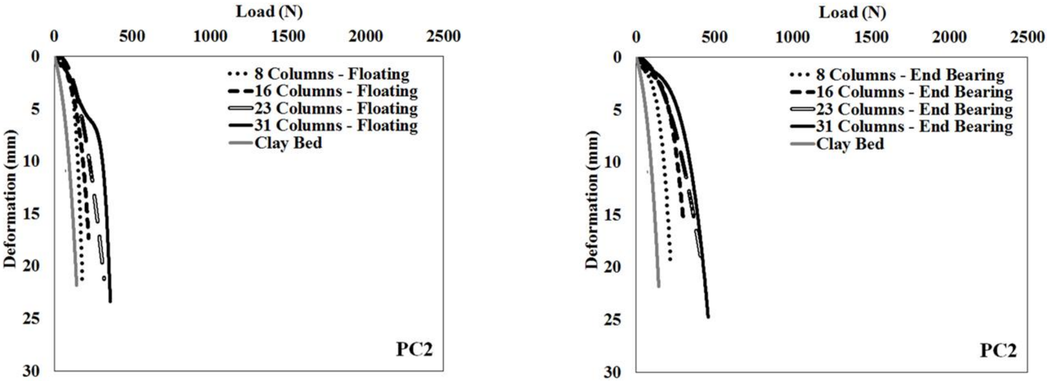


(a) (b)

Fig. 6 (a) Load–settlement curves for floating PC1 columns;
(b) Load–settlement curves for end bearing PC1 columns

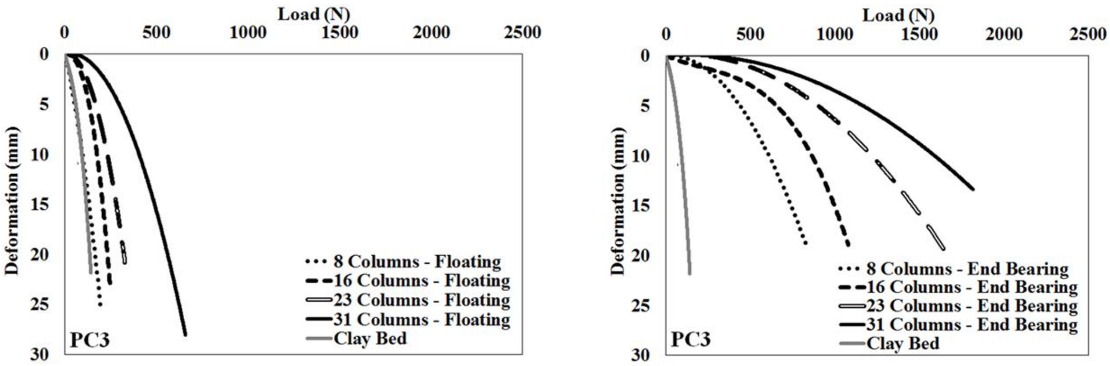
columns were approximately 446%, 440%, 793%, and 980% higher, respectively, than the ultimate load capacity of the clay bed with no columns, as shown in Fig. 6(b). A comparison of Figs. 6(a) and (b) shows that the ultimate load capacities of the 16, 23, and 31 floating PC1 columns were higher than those of the same number of end bearing PC1 columns. The ultimate load capacities of both the floating and end bearing PC2 columns were somewhat higher than the ultimate load capacity of the clay bed with no columns, as shown in Fig. 7. A comparison of Figs. 7(a) and (b) shows that the ultimate load capacities of the floating PC2 columns were not considerably different from those of the end bearing PC2 columns. The ultimate load capacities of the 8, 16, 23, and 31 floating PC3 columns were approximately 33%, 66%, 120%, and 340% higher, respectively, than the ultimate load capacity of the clay bed with no columns, as shown in Fig. 8(a). The ultimate load capacities of the 8, 16, 23, and 31 end bearing PC3 columns were approximately 460%, 620%, 996%, and 1113% higher, respectively, than the ultimate load capacity of the clay bed with no columns, as shown in Fig. 8(b). Fig. 8 shows that the ultimate capacities of the end bearing PC3 columns were higher than those of the floating PC3 columns.

In general, the polymer columns increased the load capacity of the soft clayey soil, in comparison to the load capacity of the clay bed with no columns. The load capacities are also



(a) (b)

Fig. 7 (a) Load–settlement curves for floating PC2 columns;
(b) Load–settlement curves for end bearing PC2 columns



(a) (b)

Fig. 8 (a) Load–settlement curves for floating PC3 columns;
(b) Load–settlement curves for end bearing PC3 columns

higher than the values reported in the literature on model studies of deep mixing and stone columns (Malarvizhi and Ilamparuthi 2004, Ali *et al*. 2010, Malekpoor and Poorebrahim 2014). Additionally, the unconfined compressive strength values of polymeric compounds (Table 2) are higher than the accepted limit value (i.e., 2 MPa) for deep mixed clayey soils with cement (Bruce *et al*. 1998, Bruce and Bruce 2003). These results suggest that the use of columns made of polyester (i.e., PC1) and columns made of lime and guar gum (i.e., PC3) may be more advantageous than the use of stone and encased stone columns. The results obtained in this study are consistent with the results of unconfined compression tests of the same polymers in previous laboratory studies (Bagherinia 2013).

3.3 Bearing capacity ratios of polymer columns

To determine the efficiency of the polymer columns and the type of polymeric compound that is most effective in improving the ultimate bearing capacity of soft clayey soil, values were calculated for the bearing capacity ratio (BCR) parameter, defined as follows

$$BCR = \frac{\text{Load bearing capacity obtained from polymer column reinforced soil}}{\text{Load bearing capacity obtained from soft soil with no polymer column}} \quad (1)$$

It should be noted that the load-bearing capacity was calculated at a settlement value of 7.5 mm (i.e., 10% of the group column diameter) (Malarvizhi and Ilamparuthi 2004, Binquet and Lee 1975, Sarıcı *et al*. 2013).

Figs. 9-11 show the variation in BCR with the number of columns of PC1, PC2, and PC3, respectively. As Fig. 8 shows, the BCR values of the floating PC1 columns are 4.9, 6.4, 10.0, and 11.5 for 8, 16, 23, and 31 columns, respectively. The BCR values of the end bearing PC1 columns are 5.4, 8.2, 8.4, and 11.3 for 8, 16, 23, and 31 columns, respectively. The floating and end bearing columns yield similar BCR values and exhibit similar load–settlement behavior when a polymeric compound of polyester is used as the column binder. In other words, there is no apparent difference in behavior observed for floating and end bearing PC1 columns, as Fig. 9 shows. This may be due to generation of frictional forces between the columns and the soft clayey soil. In the literature on this subject, most researchers have reported that end bearing columns have more bearing capacity then floating columns (Malarvizhi and Ilamparuthi 2004). There are a few studies in the literature, however, which report that the load-bearing capacity of floating columns is higher than that of end bearing columns (Malekpoor and Poorebrahim 2014). Malekpoor and Poorebrahim (2014) explained that for end bearing columns made of lime, loads are transmitted to the rigid bottom, and bulging failure is more likely to occur when the ratio of the length to the diameter of a single column is higher. In this study, the BCR values of the 23 and 31 floating PC1 columns were higher than those of the corresponding end bearing columns because of the high length/diameter ratios of the end bearing PC1 columns (i.e., length/diameter = 115 mm / 5 mm = 23). Ali *et al*. (2010) found that columns do not contribute to the bearing capacity of a soil when the length/diameter ratio exceeds a value of 6. For this reason, floating columns should be used when bedrock is present at a considerable depth below the soil surface. Chai and Pongsivasathit (2010) suggested that floating columns should also be favored over end bearing columns because of their lower construction cost and lesser environmental impact.

As Fig. 10 shows, the BCR values of the 8, 16, 23, and 31 floating PC2 columns were 1.8, 2.0, 2.6, and 3.6, respectively, and the BCR values of the 8, 16, 23, and 31 end bearing PC2

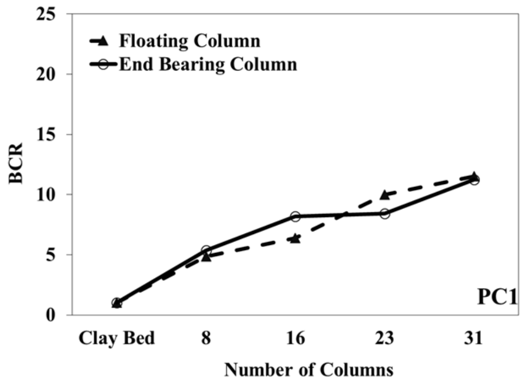


Fig. 9 Effect of number of PC1 columns on BCR values

columns were 2.0, 3.1, 3.3, and 4.1, respectively. Although the BCR values of the floating and end bearing PC2 columns were similar, the BCR values of the end bearing columns were slightly higher than those of the floating columns.

As Fig. 11 shows, the BCR values of the 8, 16, 23, and 31 floating PC3 columns were 1.3, 2.6, 3.1, and 5.9, respectively, and the BCR values of the 8, 16, 23, and 31 end bearing PC3 columns were 6.9, 11.3, 17.1, and 20.2, respectively. The BCR values of the end bearing PC3 columns are the highest (e.g., 20.2) observed in this study (Fig. 11). As mentioned previously, most previous studies have concluded that end bearing columns have better load-bearing capacity than floating columns (Malarvizhi and Ilamparuthi 2004). Similarly, a few researchers have reported that soil settlement decreases as the column length increases (Bergado *et al*. 1991, Sunnetcioglu 2012). An examination of all of the results combined shows that the maximum BCR value was that of the 31 end bearing PC3 columns. The reason for this is believed to be that hydration of the lime in PC3 with the clay effectively increases the column diameter, as shown in Fig. 5, and this increase in column diameter results in an increase in load-bearing capacity. This increase in the effective column diameter due to hydration results in a column group that behaves as a single column 75 mm in diameter (Fig. 5).

On the other hand, it has been observed that for both floating and end bearing columns, an increase in the number of columns or an increase in the area replacement ratio increases the BCR

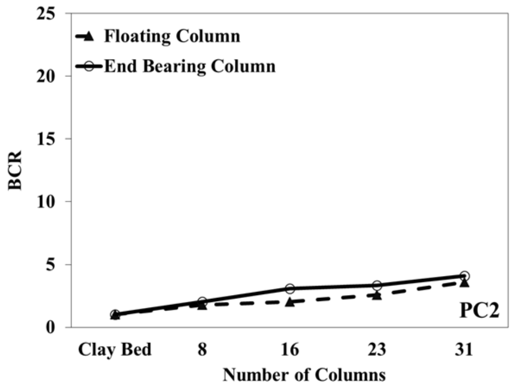


Fig. 10 Effect of numbers of PC2 columns on BCR values

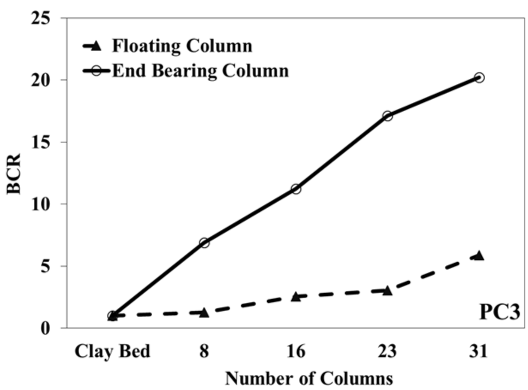


Fig. 12 Effect of number of PC3 columns on BCR values

of columns in soft clayey soils. Malekpoor and Poorebrahim (2014), for example, noted that an increase in the area replacement ratio increases the load-bearing capacity of columns in soil samples.

4. Conclusions

In this study, laboratory-scale model tests were conducted to investigate the load–settlement behavior of groups of polymer columns in soft clayey soils. The following conclusions can be drawn from the test results and the discussion presented in this paper:

- Polymer columns can be successfully installed in soft clayey soils.
- Both end bearing and floating polymer columns increase the load-bearing capacity of soft clayey soils. However, floating columns constructed using polyester should be used when bedrock is far below the soil surface. Floating columns are also more economical than end bearing columns.
- Increasing the number of columns increases the load-bearing capacity. In this study, the column group effect was observed to be most pronounced for the end bearing PC3 columns.
- Based on the load-bearing capacities obtained in this study and the values reported in the literature, using columns made of polyester (PC1) or columns made of lime and guar gum (PC3) could be used for deep improvement applications in soft clayey soils.
- The load-bearing capacity of a soft clayey soil with a group of 31 end bearing PC3 columns installed is up to 20 times greater than that of the soft clayey soil without any columns.

The results of this study suggest that polymer columns may be used successfully to improve the load-bearing capacity of soft clayey soils. It should be noted that large-scale model tests and field studies of polymer column applications are needed to confirm the results of this study. It is also recommended that a detailed cost analysis of the use of polymer columns be made, taking into consideration the relative costs of cement, lime, and the polymers considered for use.

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