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Bearing Capacity of End-Bearing Deep Mixing Columns

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ABSTRACT: Soft clay soils are widely spread worldwide. Such soils are known to experience low values of shear strength and large settlements that take place for long periods due to its low shear strength and high compressibility. To overcome the expected problems that can be resulted from construction on such type of soil, we can either improve these soils or go for deep foundation. Usually ground improvement techniques are more cost effective compared with using deep foundations. Among these improvement techniques, the deep soil mixing method (DM) is considered as one of the most popular technique in which weak soil is mixed mechanically with binding agents, such as cement or lime to form treated soil columns. The existence of such soil-cement columns under shallow foundation leads to an improvement in the bearing capacity and a decrease in the settlement of soft clay soil below the foundation. In this study, an experimental setup was designed to evaluate the bearing capacity of strip footing over a soft clay improved by end-bearing deep mixing columns. The obtained results showed a significant improvement in the bearing capacity of the model footing resting on improved soil with columns compared with the case without columns. A comparison between the obtained experimental results and two analytical approaches as proposed by Broms; and Bouassida&Porbaha was performed to assess the bearing capacity and to evaluate the performance of the composite ground.

KEYWORDS: Soft clay improvement, deep mixing columns, bearing capacity, settlement.

I. INTRODUCTION

The deep mixing (DM) is a popular technique for soft soil stabilization where stabilizing agents (e.g. cement or lime) in a powder form (dry mixing) or slurry form (wet mixing) is injected and mixed with original weak soils with special equipment to form soil-cement columns [1]. After columns installation, a composite soil ground is formed with stronger and firmer characteristics due to the chemical reactions that take place between soil and the stabilizing agent [2]. These reactions increase the strength of the soil and thus enhance the bearing capacity and settlement performance of foundations on such weak soils. Usually, soil-cement columns are introduced to lightweight, temporary structures or embankment resting on weak soil where low to moderate loading condition applies in order to improve the soft soil performance. This method has been utilized broadly to increase bearing capacity and decrease settlement [3]. The configurations of deep mixing columns could be applied in different patterns such as single, panel, block and grid depending on each project specifications [4]. The column-group type is the most economical and easy to construct compared to other application types [5]. In common treatment applications, the replacement area ratio, known also as improvement area ratio varies between 10% and 50% [6].

Numerous studies on the bearing capacity of improved soil by deep mixing technique including experimental and analytical work have been reported [7-15]. The majority of previous experimental studies have investigated different operative parameters such as: undrained shear strength of soil and columns, rigidity of the foundations, replacement area ratios, embedment ratios and column preparation and installation procedures. Most of these experimental studies have taken on an installation procedure in two ways: either by a replacement technique in which casing pipes were used followed by removing soil using an auger in conjunction with soil-cement mixture filling or preparing the soil-cement columns outside the ground model inside casing then inserting them into the soil. Only few experimental studies have taken the approach of carrying out a small-scale equipment simulating the in-situ conditions for column installation [16-19]. However, their objective was to assess the effect of deep mixing on soil strength characteristics with varying different parameters such as: curing time, injection pressure, water-cement ratio, rotation rate.

This research aims to assess the bearing capacity of strip footing resting on improved soft soil by end-bearing deep mixing columns through a laboratory testing program. Finally, two different analytical approaches were considered as a sort of comparison with the current obtained experimental test results.

II. LABORATORY TESTING PROGRAM

2.1 Tested soil

A series of small-scale model tests were performed using a rigid steel tank of dimensions (Length x width x height) equal (700 mm x 300 mm x 500mm) and 4mm thickness side walls. The tank sides were tightly stiffened to prevent any lateral deformation during the consolidation process of clay and the loading stage. A thin grease layer was smeared on the inner tank sides to minimize any friction between clay soil and the tank walls. The size of the tank was large enough to fit the columns arrangement, so that there would be no overlap between the tank walls and the zone of failure of columns.

In order to prepare soft clay soil for testing, the soil was prepared by mixing the kaolin entirely with an initial water content close to the value of its liquid limit (30%) using an electric mixer for 20 minutes to reach full saturation and homogeneity. The prepared kaolin is layered as 400mm height over a 50 mm thickness drainage layer of clean fine sand at the bottom of the tank. A rigid steel plate with numerous regular drilled holes was utilized to perform consolidation process. A geotextile layer at the top of the clay soil and two drainage outlets at the bottom of the tank were provided to permit the two-way drainage during consolidation process. The consolidation pressure is carried out ceaselessly and uniformly by increasing the vertical stress in increments to a final stress of 30 kPa using a 20 kN capacity hydraulic jack. This load is maintained for a period of three days to reach a homogeneous soft clay with an average targeted shear strength value of about 16 kPa. The basic properties of kaolinite clay are listed in Table (1).

Table 1. Physical properties of used kaolinite

Properties	Value
Specific Gravity, G_s	2.64
Liquid Limit, L.L (%)	29.4
Plastic Limit, P.L (%)	15.0
Plasticity Index, P.I (%)	14.4
Compression Index, C_c	0.62
Swelling Index, C_s	0.12
Saturated Unit Weight, γ_{sat} (kN/m ³)	18.9
Dry Unit Weight, γ_d (kN/m ³)	15.6
Undrained Shear Strength, c_u (kN/m ²)	16.4

2.2 Column's installation

An experimental test setup was designed to install columns of 50mm diameter simulating the in-situ conditions for drilling and injection during the deep mixing. Fig. (1) shows the experimental test setup. This setup consists of three main parts: (1) mixing auger; (2) an electrical inverter to control the motor speed and the up-down movement of the mixing auger; and, (3) slurry injection unit. The mixing auger rotates axially by means of rotational forces generated by an auger motor while it moves up and down using a fixed screw nut. The mixing auger is equipped with a mixing head consists of five inclined mixing blades rotating during mixing and two free blades not rotating during mixing to prevent the soil rotating together with the mixing blades. The size and shape of the mixing head are adopted after the model presented by Shen et al.[16]. The electrical converter controls the rotation rate of the motor. The chosen values for rotation rate and transitional speed was adopted to 60rpm and 200 mm/min respectively as recommended by

AFNOR[20] and stated by many other investigators [12,17,18]. The slurry injection unit comprises a grout tank fitted with a stirrer and an air compressor. The cement slurry is prepared in a 1:1 ratio as a common ratio to prevent cement deposition. The slurry is injected through two nozzles provided at the end of the mixing head and dissipated to the surrounding soil under controlled pump pressure of 50 kPa (about 3–4 times the shear strength) and a rate of 0.7 liter/min which was suitable for the soil not to be disturbed for all test series as stated by Shen et al.[16]. According to several laboratory unconfined compression strength tests on soil–cement columns samples at different curing times, it was revealed that at 14 days, the undrained shear strength of the soil–cement columns was reached about 90% of the strength at 28 days. Thus, it was decided to cure the improved soil for 14 days before testing.

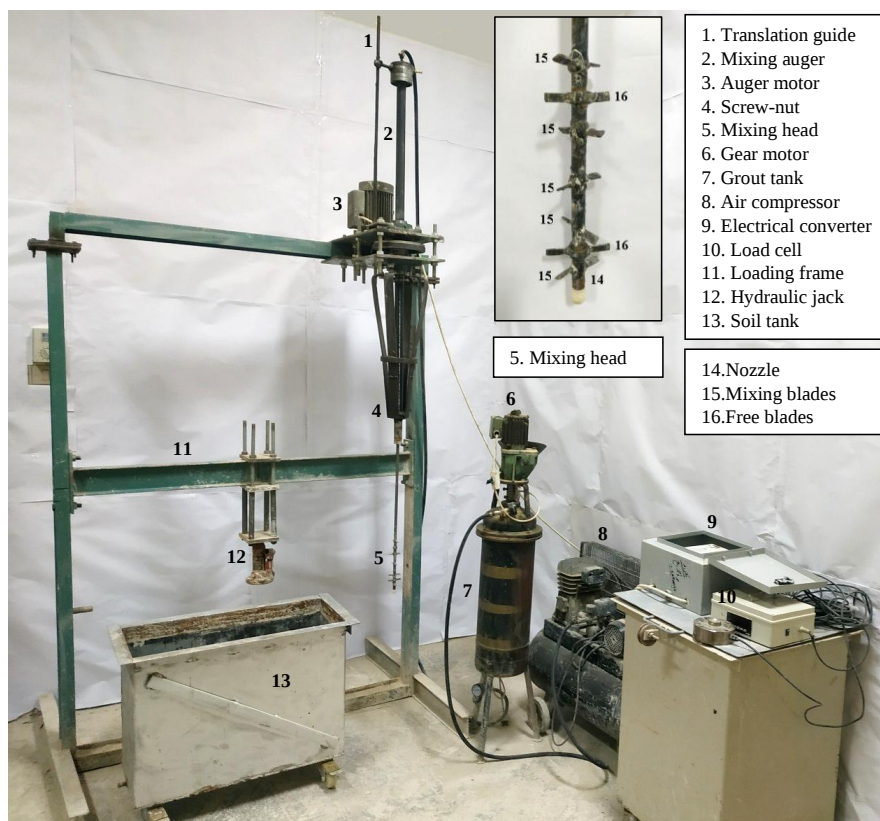


Fig. 1. Experimental test setup

2.3 Testing program

Four model tests consist of one unimproved soil, three improved soil with end bearing columns with different replacement area ratios of (13.1%; 19.6% and 26.2%) respectively were carried out as shown in Fig. (2). A rigid steel rectangular plate with dimensions of (length x width x thickness) equal (300mm x 200mm x 20mm) were used to represent a rigid model footing resting over improved soft soil with the end bearing columns. All tests were performed under undrained condition since the test loading was fast. The loading procedures were conducted under the stress control conditions with an increment of 1 kPa per minute to allow direct control of stress. Settlement of the tested model footings were recorded by four digital dial gauges with accuracy of 0.01mm placed on opposite corners of the rectangular footing.

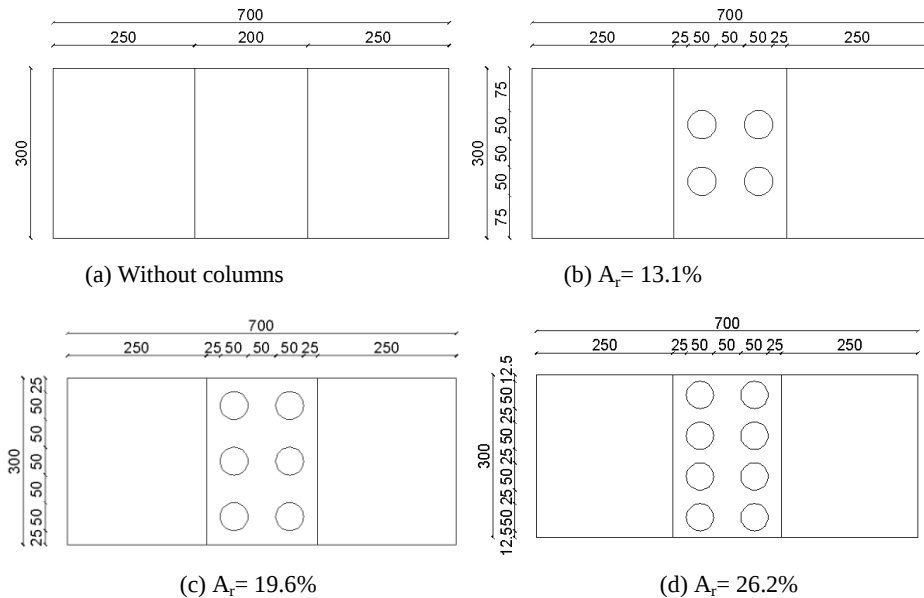


Fig. 2. Columns configuration

III. RESULTS AND DISCUSSION

The stress-settlement relationships for all tests are plotted in terms of vertical stress versus normalized settlement, settlement/width of footing (Δ/B) as shown in Fig.(3) to eliminate the scale effect as stated by Rashid et al.[15]. For the case of unimproved soil, the classical double tangent method was used to evaluate the ultimate bearing capacity (UBC). The (UBC) of the unimproved soil reached a value of about 100 kPa at a normalized settlement of about 3.4%. It can be seen that; the soil exhibits progressive failure which may indicates that the unimproved soil shows a ductile behavior. On contrary, the relationships of the end-bearing tests were almost linear and the (UBC) of the model footings was determined as the peak points (failure points) of the stress-settlement relationship. Beyond these peak points, the entire composite ground failed and no extra stress could be afforded. This behavior of soil failure was noticed and reported by Yin and Fang [14].

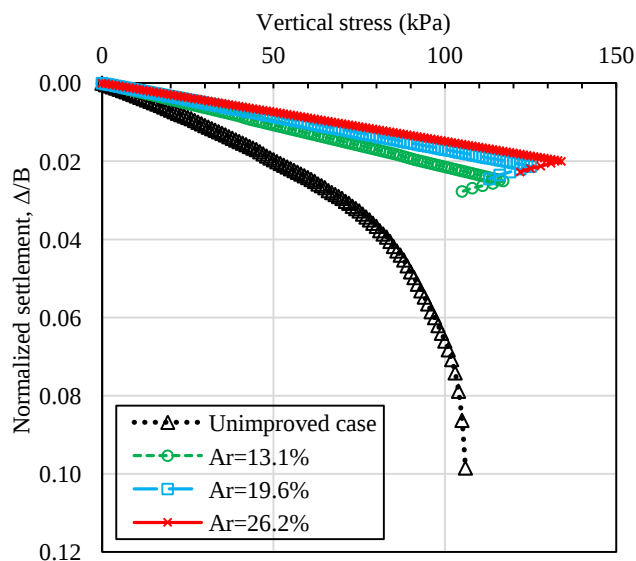


Fig. 3. The relationship between vertical stress and normalized settlement

Fig. (4), shows a remarkable effect of replacement area ratio on the ultimate bearing capacity (UBC). Higher values of (UBC) are achieved at higher replacement area ratio. The ultimate bearing capacity of the footing resting on improved soft clay with end-bearing columns reached an increase equals about (1.17, 1.25 and 1.34) times of the initial case without columns for (A_r) of (13.1%, 19.6%, and 26.2%) respectively.

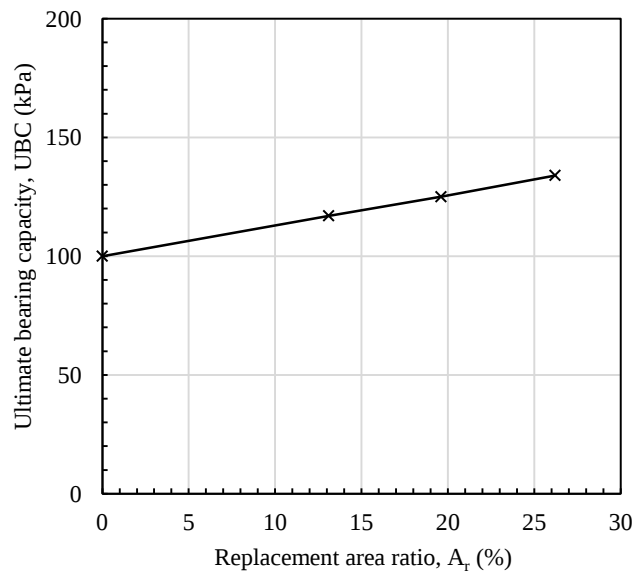


Fig. 4. Variation of ultimate bearing capacity with replacement area ratio

In order to predict the bearing capacity with accuracy, Broms, 2000[8] and Bouassida and Porbaha[10-11] were used as analytical approaches to calculate the bearing capacity of the improved soil. The (UBC) of the improved soil by end-bearing columns was determined as suggested by Broms as follows:

$$q_u = 0.7q_{uc}\alpha + \lambda c_{us}(1 - \alpha) \dots \dots \text{(Broms-a)} \dots \dots \dots (1)$$

$$q_u = 0.7q_{uc}\alpha + \lambda c_{us}\left(1 + \frac{B}{L}\right) \dots \dots \text{(Broms-b)} \dots \dots \dots (2)$$

Where:

q_u : is the ultimate bearing capacity of improved soil; q_{uc} : is the unconfined compressive strength of the column; c_{us} : is the undrained shear strength of the soft soil; α : area improvement ratio (area of the columns to the total area); λ : non-dimensional coefficient of a value of 5.5 as suggested by Bergado et al.[21]; B: width of footing; L: length of footing.

The obtained results were also compared with the lower and upper bound solutions of the (UBC) proposed by Bouassida and Porbaha[10-11] which based on the yield design theory assumed that the unimproved soil and the DCM columns were considered to have the same unit weight and purely cohesive materials. According to their theory, the lower and upper bound of UBC can be estimated as follows:

$$q_{\min} = c_{us}[4 + 2\alpha(k_c - 1)] \dots \dots \dots (3)$$

$$q_{\max} = c_{us}(2\sqrt{2} + 2\sqrt{[1 + \alpha(k_c - 1)][2 + \alpha(k_c - 1)]}) \dots \dots \dots (4)$$

Where, k_c : cohesion ratio, (c_{uc}/c_{us}); (undrained shear strength of column/ undrained shear strength of soil soft)

The obtained values of the bearing capacity from the experimental test results, and the calculated values of the bearing capacity using the two approaches are presented in Table 2. A comparison between the bearing capacity factor ($BCF = q_u/c_{us}$) obtained from the experimental test results with the calculated values from the two approaches of Broms; Bouassida and Porbaha is shown in Fig. (5). According to Bouassida and Porbaha [10-11], Broms approach tends to underestimate the bearing capacity if the cohesion ratio is bigger than 30. In this study, the cohesion ratio equals 11.3 which matches Bouassida and Porbaha hypothesis. As shown in Fig. (5), the BCF obtained from the experimental test results was not precisely in the range of lower and upper bounds of the UBC proposed by Bouassida and Porbaha.

Furthermore, (Broms-b) approach appears to significantly overestimate the bearing capacity compared to the experimental results. While, the BCF calculated based on experimental tests was found to be compatible with (Broms-a) approach, as the relative differences between the BCF and (Broms-a) approach were found to be equals 4.1%, 1.3%, and 0.3 % for tests G4-40, G6-40, and G8-40, respectively. Therefore, it can be concluded that (Broms-a) approach gives a better estimation of the bearing capacity of the soft soil improved by cement columns. Also, for all aforementioned methods, it was found that the BCF of improved soil increases with the area improvement ratio increase but with different rate of increase according to each calculation method, which may be attributed to higher stiffness of the composite ground.

Table 2. Measured and calculated bearing capacity values

Test	Calculated bearing capacity as per Broms approach (2000), (kPa)		Calculated bearing capacity as per Kinematic approach (Bouassida and Porbaha, 2004a and b), (kPa)		Measured bearing capacity from the experimental test results (current study)
	Broms (a)	Broms (b)	Lower bound	Upper bound	
G4-40	112.3	184.3	109.8	138.4	117
G6-40	123.3	201.1	131.7	160.6	125
G8-40	134.4	218.2	153.9	183.1	134

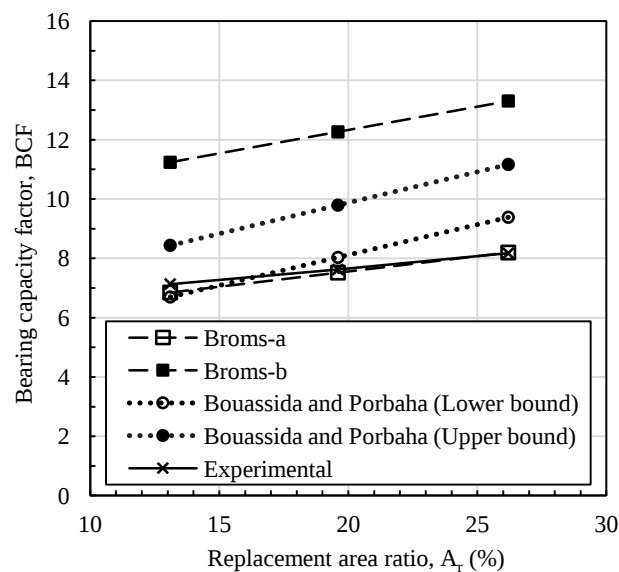


Fig. 5. Variation of bearing capacity factor with replacement area ratio

Considering the normalized vertical settlement at failure, it was clear that, as the replacement area ratio increases, the vertical settlement associated to failure decreases. This behavior could be attributed to the fact that, with the increase of replacement area ratio the entire composite ground tends to be stiffer and possess a somewhat brittle behavior then can withstand more stress level with less vertical settlement. Moreover, more shear stress may be mobilized around the side area occupied by the group of columns. The average value of normalized vertical settlement of the footing was found to be around 2.1% at failure point. This finding is in conformity with the results obtained by other researchers [10, 11,15]. The improvement in settlement behavior of the footing was expressed as a reduction percentage in settlement (RPS) as follows:

$$\text{RPS (\%)} = (\Delta_o - \Delta_c) / \Delta_o \dots \dots \dots (5)$$

Where: Δ_o is the footing settlement resting on unimproved soft clay corresponding to its ultimate bearing capacity.

Δ_c is the footing settlement resting on improved soft clay with columns corresponding to its ultimate bearing capacity.

Fig. (6) shows a remarkable reduction in the achieved settlement especially at higher replacement area ratios, reaching about (26.5%, 35.3% and 48.5%) for (A_r) of (13.1%, 19.6% and 26.2%) respectively.

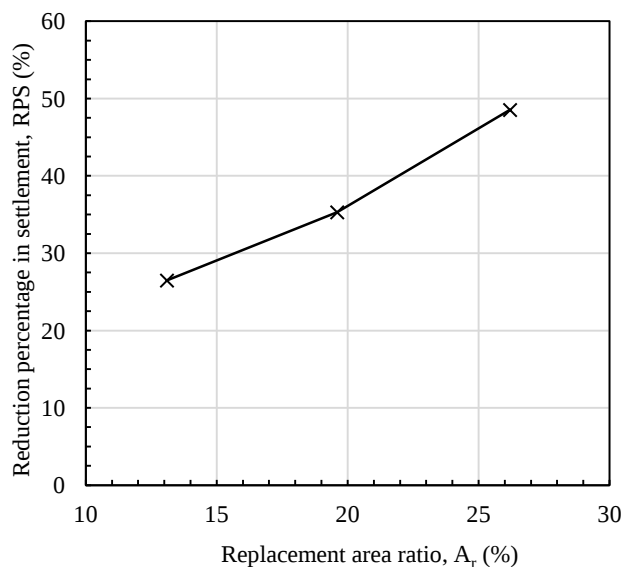


Fig. 6. Variation of reduction percentage in settlement with replacement area ratios

IV. CONCLUSION

An experimental test setup was designed for testing a model strip footing resting on improved soft clay soil by end-bearing deep mixing columns subjected to vertical loading. The obtained results were used to investigate the bearing capacity of the composite ground and comparing the measured results with the calculated results of two analytical approaches proposed by Broms; Bouassida and Porbaha. Based on the test observations and obtained results, the following findings can be concluded:

- (1) The end-bearing deep mixing columns enhanced the bearing capacity of soft clay soil significantly in a range of (17-34) % depending on the replacement area ratio.
- (2) The end-bearing deep mixing columns improved the settlement behavior of the footing reaching a reduction in the settlement in a range of (26.5-48.5) % depending on the replacement area ratio.
- (3) Based on the two analytical approaches used for calculating bearing capacity, it was found that (Broms-b) approach gives a better estimation for the bearing capacity of the improved soft clay with deep mixing columns.

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