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Laboratory study of shear strength of loose sand in the case of Individual stone columns, Equivalent trench, and Equivalent area method

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ABSTRACT: Due to the complexity of a three-dimensional (3-D) arrangement of multiple columns, a 3-D problem has been commonly converted into a two-dimensional (2-D) model, which has equivalent properties and dimensions by the equivalent trench method and the equivalent area method. These methods are used extensively in analytical and numerical studies. However, no comparison of the results of the above methods and laboratory studies has been done. Therefore, in this research, the experiments performed on reinforced soil in a large direct shear device with dimensions of 305×305×152 mm3. Experiments performed with individual stone columns (single, square and triangular arrangement), equivalent trench and equivalent area method. The effective parameters include the area replacement ratio, 8.4,12, 16.4 and 25 percent, and vertical loads (55, 75 and 100 kPa) Has been studied. Results showed that improves the stiffness of composite soils and increase in shear strength of individual stone columns (single, square and triangular arrangement) and equivalent trench and stone column arrangement had an impact on improving the shear strength of stone columns. The most increase in shear strength and stiffness values was observed for square arrangement of stone columns and the least increase was for single stone columns. Comparing the results of individual stone columns and equivalent trench in any arrangement, showed that equivalent trench arrangement could be used in two-dimensional models instead of three-dimensional individual stone columns. In the equivalent area method, there is no increase in shear strength and shear strength parameters compared to sandy bed.

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1. INTRODUCTION

The behavior of stone columns under vertical loads is reasonably well understood [1-3]. In the column studies, due to the complexity of a three-dimensional (3-D) multi-column problem, various methods have been proposed to convert the 3-D problem into a two-dimensional (2-D) model, which has equivalent properties and dimensions. All the plane strain equivalency methods can be classified into the two basic types, the equivalent trench method and the equivalent area method [4, 5]. This paper presents laboratory studies to investigate and compare shear strength and shear strength parameters of loose sand in the case of Individual stone columns, equivalent trench, and equivalent area method.

2. MATERIALS

Fine-grained sand with particle size ranging from 0.425 to 1.18 mm was used to prepare the loose sand bed, and crushed gravel with particle size ranging from 2 to 8 mm was used as individual stone column and equivalent trench material. The sand material used as bed material had a unit weight of 16 kN/m^3 and a relative density of 32.5%, and the stone material used in stone columns and equivalent trench had a unit weight of 16.5 kN/m^3 and a relative density of 80%. The required standard tests were performed to obtain the mechanical parameters of bed material and stone column material. As the diameters of model scale stone columns and equivalent trench were smaller than the diameters of stone columns installed in the field, the particle dimensions of stone column material were reduced by an appropriate scale factor to allow accurate simulation of stone columns behavior. The size of the crushed stone was chosen under the guidelines suggested by Nayak [6], Mohapatra et al. [7] in which the particle size is approximately 1/6 to 1/7 of the diameter of the stone columns. A value of 1/7 for this ratio was considered adequate, based on the works of Nayak [6].

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3. TESTING PROCEDURE

In this study, a large direct shear device with in-plane dimensions of 305×305 mm^2 and a height of 152.4 mm was used to evaluate the shear strength and equivalent shear strength parameters of loose sand in the case of Individual stone columns, Equivalent trench and Equivalent area method (Fig. 1). Experiments were performed under normal stresses of 55/75 and 100 kPa. Two class S load cells with the capacity of 2 ton were used to measure and record vertical forces and the developed shear forces during the experiments, and a Linear Variable Differential Transformer (LVDT) was used to

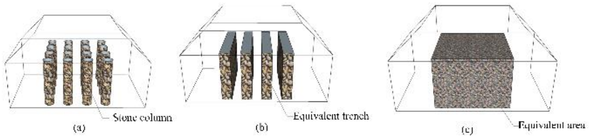

Fig. 1. a) individual stone column b) equivalent trench c) equivalent area

measure horizontal displacement. All achieved data from the experiments including data on vertical forces, shear forces, and horizontal displacements, were collected and recorded using a data logger, and special software was used to transfer data between the computer and the direct shear device. All specimens were sheared under a horizontal displacement rate of 1 mm/min.

4. TESTING PROGRAM

Experiments were performed on individual stone columns (single, square and triangular patterns), equivalent trench and equivalent area method (Fig. 1). The selected area replacement ratios were 8.4, 12, 16.4, and 25% for single stone columns, and 8.4, 12 and 16.4% for square and 16.4% for triangular stone column arrangements.

To eliminate boundary effects, the distance between stone columns and the inner walls of the shear box was kept as high as 42.5 mm [6]. In total, 21 direct shear tests were carried out, including 2 tests on loose sand bed material and stone column material, and 8 tests on stone columns with different arrangements. From the tests performed on group stone columns, 4 tests were performed on single stone columns, 3 tests on stone columns with the square arrangement and 1 tests on stone columns with triangular arrangement, 7 tests on equivalent trench and 4 tests on equivalent area method.

Hollow pipes with wall thickness of 2mm and inner diameters equal to stone column diameters were used to construct stone columns. To prepare the specimens, first, the hollow pipes were installed in the shear box according to the desired arrangement. Then, bed material with a unit weight of 16.5 kN/m^3 was placed and compacted in the box in 5 layers, each 3 cm thick. Stone material was uniformly compacted to construct stone columns with uniform unit weight. The compaction energy was 67 kJ/m^3 in all tests.

5. RESULTS AND DISCUSSION

In this paper, the behavior of stone columns under shear loading was experimentally investigated in large direct shear device by performing tests with different area replacement ratios (8.4, 12, 16.4, and 25%), individual stone column installation arrangements (single, square and triangular), Equivalent trench and Equivalent area method and different normal stresses (55, 75 and 100 KPa). The key findings of this study are as follows:

1. In all stone column arrangements, shear strength increased with the increase of area replacement ratio due to the increase of the stone column area effective in the shear plane. For the same area replacement ratios, shear strength values obtained from experiments on stone columns with square and triangular installation arrangements were higher than those obtained from experiments on single stone columns. Shear

Table 1.

Area replacement ratio		25%	16.4%	12%	8.4%
Individual stone columns	single	S-G-C-%۲۵	S-G-C-۱۶/%۴	S-G-C-%۱۲	S-G-C-۸/%۴
	square		S-G-SQ-۱۶/%۴	S-G-SQ-%۱۲	S-G-SQ-۸/%۴
	triangle				S-G-TR-۱۶/%۴
Equivalent trench	single	S-G-C-W-%۲۵	S-G-C-W-۱۶/%۴	S-G-C-W-%۱۲	S-G-C-W-۸/%۴
	square		S-G-SQ-W-۱۶/%۴	S-G-SQ-W-%۱۲	
	triangle				S-G-TR-W-۱۶/%۴
Equivalent area	mix	S-G-MIX-%۲۵	S-G-MIX-۱۶/%۴	S-G-MIX-%۱۲	S-G-MIX-۸/%۴

S= sand material G=gravel material C=single arrangement, SQ=square arrangement, TR=triangle arrangement, w=equivalent trench, mix=equivalent area

strength was highest for stone columns with square pattern and lowest for single stone columns. The steeper slope in shear strength –horizontal displacement diagram shoes that the combined soil-stone column system has higher stiffness than loose sand bed and the stiffness varies according to area replacement ratio, arrangement pattern and the highest and lowest stiffness values refer to square arrangement and single stone column respectively.

2. Results show that shear strength parameters increase in soil reinforced with the stone column. The maximum increase in internal friction angle refers to stone columns with a square pattern and the minimum increase refers to single stone columns. The equivalent shear strength values measured from experiments are higher than those obtained from analytical relationships. Accordingly, it is conservative to use analytical relationships to calculate shear strength parameters.

3. Results showed that the increase of shear strength in all arrangements of the equivalent trench compared to the shear strength of sand bed. Results show that stiffness and shear strength increase with the increase of area replacement ratio. The shear strength value obtained for the equivalent trench arrangement corresponding to square arrangement had the highest increase, while the shear strength value obtained for the equivalent trench corresponding to a single arrangement had the lowest increase. Accordingly, it can be concluded that the type of equivalent trench arrangement influences on increasing stiffness and the equivalent trench resulting

from individual stone column in the square arrangement (two trenches) made the highest increase in stiffness value. The Comparison Between the results from experiments on equivalent trench arrangements and individual stone columns in the corresponding arrangements shows that the difference between shear strength and shear strength parameters was not significant and accordingly, equivalent trench arrangement can be used as a replacement for individual stone columns.

4. Results show that in equivalent area arrangement, there is not a significant increase in shear strength compared to the loose sand bed. In area replacement ratios from 8.4% to 25% the volume of stone material used in equivalent area arrangement was low and stone material was floating in sand material and the connection between stone particles was not possible. This prevented shear strength and internal friction angle increasing. Results from this study show that for the area replacement ratios used in this study shear strength in equivalent area method was lower than shear strength in other arrangements.

5. Results from the performed experiments show that shear strength is equivalent area method is lower than that in equivalent trench and individual stone column. Accordingly, shear strength modifying coefficient, which is the ratio of shear strength in different stone column arrangements (individual stone column and equivalent trench) to shear strength in equivalent area arrangement, is given by Equation 1.

$$\tau_{(ISC,ETM)} = \alpha\tau_{(EAM)} \tag{1}$$

$\tau_{(ISC)}$ shear strength in the individual stone column, $\tau_{(ETM)}$ shear strength in the equivalent trench method and $\tau_{(EAM)}$ is shear strength in the equivalent area method.

6. Results showed that the value of shear strength modifying coefficient in the range of 1.05 to 1.26 for the maximum shear strength, and in the range of 1.1 to 1.13 for the shear strength value corresponding to 10% horizontal displacement. According to the results, the average value of the coefficient is 1.17 for the maximum shear strength and 1.12 for the shear strength value corresponding to 10% horizontal displacement, regardless of the pattern of stone column and equivalent trench arrangement.

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