Experimental Investigation of Equivalent Shear Strength of Loose Sand Reinforced with Stone Column

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Extended Abstract

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Introduction

Stone column installation method is one of the popular methods of ground improvement. One of the common uses of stone columns is to increase slope stability. Several studies have been performed to examine the behavior of stone columns under vertical loads. However, limited research, mostly focused on numerical investigations, has been performed to evaluate the shear strength of soil reinforced with stone column. The study presented herein is an experimental program, aimed to explore the shear strength of loose sand bed reinforced with stone column. Direct shear tests were carried out on specimens of sand bed material, stone column material and sand bed reinforced with stone column, using a direct shear device with in-plane dimensions of 305*305 mm^2 and height of 152.4 mm. Experiments were performed under normal stresses of 35, 55 and 75 kPa . In this study, 4 different area replacement ratios (8.4, 12, 16.4 and 25%), and 3 different stone column arrangements (single, square and triangular) were considered for investigation. The obtained results from this study showed that 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. This study also compares the equivalent shear strength values and equivalent shear strength parameters (internal friction angle and cohesion) measured during experiments with those predicted by analytical relationships. Results show that shear strength values and shear strength parameters measured from experiments are higher than those obtained from analytical relationships. Accordingly, a corrective coefficient was calculated for each column arrangement to represent the correlation between experimental and analytical results.

Material Properties of Loose Bed and Stone Column

Fine-grained sand with particle size ranging from 0.425 to 1.18 mm was used to prepare loose sand bed, and crushed gravel with particle size ranging from 2 to 8 mm was used as stone column 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 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 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 an accurate simulation of stone columns behavior.

Testing Procedure

In this study, large direct shear device with in-plane dimensions of 305*305 mm^2 and height of 152.4 mm was used to evaluate the shear strength and equivalent shear strength parameters of loose sand bed reinforced with stone column. Experiments were performed under normal stresses of 35, 55 and 75 kPa.

Two class C load cells with 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 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 an especial 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.

Testing Program

Experiments were performed on single stone columns and group stone columns arranged in square and triangular patterns. 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 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. In total, 12 direct shear tests were carried out, including 2 tests on loose sand bed material and stone column material, and 10 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 square arrangement and 3 tests on stone columns with triangular arrangement. Hollow pipes with wall thickness of 2 mm 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 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.

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%), different stone column installation arrangements (single, square and triangular), and different normal stresses (55, 75 and 100 kPa). The key findings of this study are as follows:

1. Shear strength increases with increase of area replacement ratio due to the higher strength of combined soil-stone column system, and due to the increase of stone column area effective in shear plane. The amount of shear strength increase with area replacement ratio is low for ratios lower than 15%. However, this amount is higher for area replacement ratios higher than 15%.
2. For stone columns with equal area replacement ratios, higher shear strength was mobilized in stone columns with square and triangular installation arrangements compared to single stone columns. Among the installation patterns investigated in this study, stone columns with square arrangement experienced the highest increase in shear strength value, while single stone columns experienced the lowest. One of the reasons of shear strength increase in square and triangular patterns is the increase of confining pressure applied by stone columns to the soil between them. Another reason is the increase the total lateral surface by changing the column arrangement from single column to square and triangular patterns. This increased lateral surface increases the lateral force imposed on the stone columns, resulting in higher shear strength mobilization of stone material.
3. The slope increase of shear strength-horizontal displacement curves shows that soil-stone column system has higher stiffness than loose sand bed, and this stiffness varies with area replacement ratio and installation pattern. The maximum stiffness values refer to stone columns installed in square pattern and the minimum values refer to single stone columns. In general, stone column installation pattern has an effective role in increasing stiffness.
4. Results show that shear strength parameters increase in soil reinforced with stone column. The maximum increase in internal friction angle refers to stone columns with square pattern and the minimum increase refers to single stone columns.

5. 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. It is worthy to mention that these relationships assume that the value of stress concentration ratio is equal to 1. Results from this study indicate that the value of stress concentration ratio should be accurately calculated and used in the relationships.
6. As discrepancy was observed between values measured from experiments and those obtained from analytical relationships, corrective coefficients were calculated to modify analytical relationships. These coefficients were computed and presented based on stone column installation pattern, area replacement ratio and the applied normal stress values.

Keywords: Stone Column, Equivalent Shear Strength, Loose Sand, Direct Shear Test

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