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Effects of boundary friction on the strength and deformation of geosynthetic-reinforced sand in large-scale plane strain compression tests

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ABSTRACT: In this study, the boundary friction of a large-scale plane-strain apparatus is discussed. This plane strain apparatus is designed to study the tensile behavior of geosynthetic which is confined with soil. Though the scale of the test specimen is large (60 cm × 56 cm × 45 cm), boundary effects may significantly influence test results if not properly accounted for. Reducing or eliminating boundary effects on the test specimen is necessary especially in modeling the plane-strain condition. The study begins with understanding the information of several interfaces for lowering boundary friction. The frictional properties of these interfaces are obtained through performing large-scale (shear area is 45 cm × 45 cm) direct shear tests. To study the effects of different boundary friction on the tensile behavior of geosynthetic, the plane strain tests are conducted with different interfaces placed on the boundary of the plane strain device. The recorded tensile behaviors of geosynthetic corresponding to different boundary interfaces are compared. Based on the laboratory test results, the appropriate boundary that not only has acceptable low friction but also satisfies the economical consideration of sample preparation effort is suggested.

1 INTRODUCTION

The unit cell testing approach has been applied for studying the reinforced soil mechanical behavior. The unit cell approach is an accurate way to model the reinforced soil mechanism. To study the engineering behaviors or the interaction of soils/geosynthetics in laboratory, pull-out test device and direct shear device are used commonly. The pull-out test and direct shear test are for studying the interface behavior. The limit equilibrium design using the ultimate strength is considered to be conservative. For most of the retaining wall or embankment that is reinforced by geosynthetic, rather than the stability, the deformation of the soil structure is of more concerned. Geosynthetics in GRS walls designed according to current procedures have been shown to experience very low strains, typically less than 1%. A working stress or deformation based design approach should be more realistic than the limit state procedures. Therefore, this research focuses on using unit-cell testing approach to study the mechanical behaviors of geosynthetic and sand composite at small strains (between 0 and 5%). Triaxial compression device has been used prevalently to investigate the mechanical behavior of geosynthetic reinforced soil. However, triaxial compression device may not simulate the construction or the field condition reasonably. During the construction of a geosynthetic retaining wall or embankment, the overburden pressure increases with the filling and compaction of backfills. The overburden pressure compresses the soil-geosynthetic composite then induces a lateral tensile strain in the soil-geosynthetic composite. The geosynthetic reinforced soil is under a plane strain state. The plane strain compression test has been used for investigating the performance of soil-geosynthetic composite (Boyle 1995).

The elimination of friction between test device and test specimen is important to preserve the plane strain status. To use a large scale testing device is a common approach. Another approach is to place a lubricated or appropriate material as the specimen/device interface to reduce friction, for example (Boyle 1995, Tatsuoka 1984, 1985, Tawfiq and Caliendo, 1993, Tognon 1999, Fang et al. 2004). In this study, a large scale plane strain device is used to study the tensile behaviour of geosynthetic under soil confinement. A series of large scale direct shear tests are conducted to identify the appropriate interface with lower friction. The effects of different boundary friction on the plane strain test results are studied.

2 DIRECT SHEAR TESTS

2.1 *Test program*

In this study, the interfacial shear resistance of 6 interfaces were measured by conducting large scale direct shear tests. The picture of the direct shear device is shown in Figure 1. The shearing area is 45 cm × 45 cm. During the test, the lower shear box was replaced by a thick steel plate while the upper shear box was filled with Ottawa sand. The relative density of sand in the upper shear box was controlled to be about 77%. Different interfaces were placed between shear boxes. These candidate interfaces include placing plastic sheets with different thickness and with/without lubrication between them. The layout of the test specimens are shown in Figure 2. The shear resistance of direct contact interface without plastic sheet between sand and steel plate is also tested. The shearing rate was controlled to be 10 mm/min. The shear resistance corresponding to different normal stresses (0.1, 0.2, 0.5, 1, 2 ksc) were recorded.

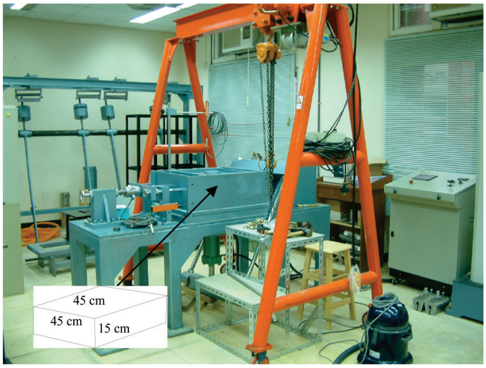

Figure 1. Large-scale direct shear apparatus.

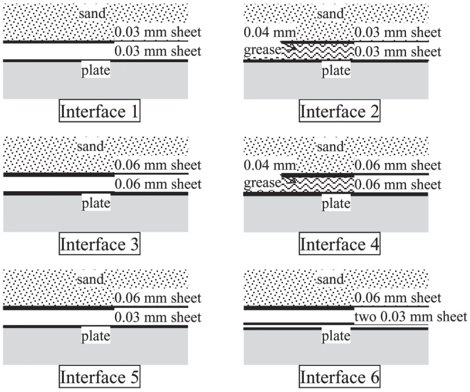

Figure 2. Six interfaces used during direct shear test.

2.2 *Test results*

The measured friction resistances of each interface are normalized to be friction angle and are shown in Figure 3. The test results reveal that the friction angles of each interface are high under low stress level and they decrease with higher normal stress. Generally, friction angle remain constant when the normal stress is greater than 1 ksc. The direct contact interface has the largest friction angle, it is about 23° to 30°. The placement of plastic sheets between sand and steel plate can reduce friction but effect is not very significant. It can decrease the friction angle by about 8°. The application of grease between plastic sheets provides much effect on reducing the friction angle. For the interfaces with lubrication (interfaces 2 and 4), the measured friction angles are as low as about 5°.

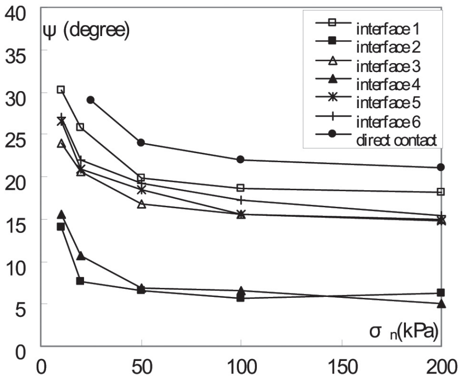

Figure 3. Friction angles of different interfaces under different normal stress.

3 PLANE STRAIN TESTS

3.1 *Test device*

The unit cell device that is built by Boyle (1995) pertains plane strain state and permits direct measurement of the reinforcing loads and lateral strain is capable to model the composite reinforced soil behavior. It allows for testing of wide width strip reinforcing specimen confined by 100 mm of soil on both sides. The testing device used in this research modified from the testing device developed by Boyle (1995). The picture of this device is shown in Figure 4. The size of the specimen box containing geosynthetic-reinforced soil is 60 cm × 56 cm × 45 cm. It allows for testing on very wide-width geosynthetic specimens to lessen the necking effect. The geosynthetic material situating at the middle height of the box is confined on both sides by 30 cm thick soils. This device can model the field condition well because the thickness is similar to field application. The specimen box with its reaction frame was constructed of steel to minimize device deformation.

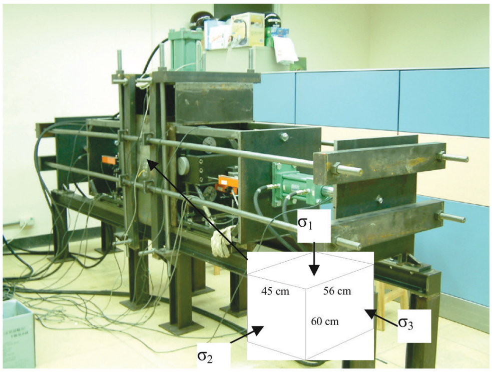

Figure 4. Large-scale plane-strain apparatus.

The rigid vertical steel face maintains the geosynthetic-soil composite in a plane strain state during the application of lateral stress or the vertical loading. The hydraulic jacks between the rigid reaction frame and specimen provide the application of lateral stress (direction-3) and vertical loading (direction-1) on the specimen. The forces and deformation of the soil-geosynthetic composite are well measured and stored by a set of load cells and LVDT and data acquisition system. The limitations accompanying with performing tests on this large-scale device are:(1) the maximum loading supplied by the jack is 10 tons; (2) the allowed deformation in the vertical direction is 5 cm; (3) the allowed displacement on each side of soils in the lateral direction is 10 cm.

3.2 *Test program*

Four tests performed using the large-scale plane strain-testing device are listed in Table 1. Loosely compacted Ottawa sand (relative density = 30%) were tested at various boundary frictions to determine their plane strain response. For test #1, interfaces 1 was placed on both inner side wall of vertical steel faces in direction 2 to provide larger boundary friction, while interface 2 was applied in test #3 to provide smaller boundary friction. The prepared specimen was allowed to consolidate by applying confining pressure, σ_3, and vertical loading, σ_1. The specimens were then loaded by increasing the vertical pressure, σ_1, by 10 kPa every 30 seconds. This pressure increase was manually controlled using pressure regulators. The confining pressures were controlled at 32 kPa during tests. The vertical loading increased continuously until the limit of the device capacity or the peak strength was reached. The similar tests were also conducted on the soil-geogrid composite (tests #2 and #4). The geogrid used in this study is made of woven polyester fibers with rectangular apertures (the openings between the longitudinal and transverse ribs) of 5 cm by 3 cm (percent open area is 0.45). The ultimate tensile strengths using wide-width specimens are 100 kN/m and 30 kN/m in longitudinal and in transverse directions, respectively. During the test, the load cells connecting the rigid reaction frame and clamps holding geogrid measured the tension induced in geogrid.

Table 1. Test program of plane strain tests.

Test Number	Interface	Reinforcement
1	interface 1	no
2	interface 1	yes
3	interface 2	no
4	interface 2	yes

3.3 *Test results*

The applied vertical loading (σ_1), recorded lateral strains (ε_3), for each test are shown in Figure 5. The vertical loadings increase with the increase of induced lateral strain. The stress-strain behaviour is reasonable for loosely compacted soil specimens.

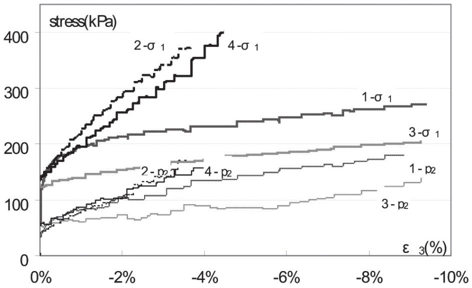

Figure 5. Relationships between induced lateral strains (ε_3), applied vertical loading (σ_1), and measured earth pressure in 2-direction (p_2).

It is observed that under the same boundary friction condition, the applied vertical loading is greater for the tests without reinforcement than the tests with geogrid reinforcement to induce the same lateral strain (e.g., 2-σ_1 is greater than 1-σ_1). The test results demonstrate that the geogrid can constrain the development of lateral deformation and thus provide effective reinforcement for Ottawa sand.

It is also observed that under the same reinforced condition, the applied vertical loading is greater for the tests with larger boundary friction than the tests with lower boundary friction to induce the same lateral strain (e.g., 2-σ_1 is greater than 4-σ_1). The similar observations are also found through comparing the measured earth pressure on the fixed steel walls (p_2). It indicates that the existence of greater boundary friction between device and test specimen constrains the development of lateral deformation.

For tests #2 and #4, the tensions in geogrid on both ends, denoted as T_R and T_L, respectively, corresponding to different strain (ε_3) are plotted in Figure 6. It is observed that the tension is greater for

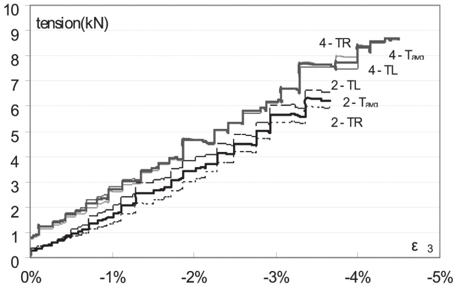

Figure 6. Measured geogrid tension corresponding to different strains (ε_3).

the tests with smaller boundary friction than the tests with greater boundary friction to induce the same tensile strain (e.g., 4-T is greater than 2-T). Moreover, the difference between measured tensions at both ends is smaller. The results indicate the development of tensile strain of reinforcement under plane strain condition is easier and more uniform when the boundary friction between device and test specimen is smaller.

The tensile modulus (tension/strain) of geogrid under different test conditions is listed in Table 2. The modulus of geogrid is greater when it is confined in soil under working strain range. The modulus is greater when the specimen is tested in a device with smaller boundary friction.

Table 2. Modulus of geogrid under different test conditions.

test condition	modulus at different strain (kN/m)		
	1%	2%	3%
in-isolation	610	405	360
test #2	550	525	566
test #4	880	700	616

4 CONCLUSIONS

This paper presents the preliminary results of the ongoing research. Firstly, a series of large scale direct shear tests is performed on different interfaces to find the appropriate one for later use in the large scale plane strain testing device. It is found that the application of grease between plastic sheets provides the best effect on reducing the friction angle. A series of plane strain tests are performed to study the behaviour of soil/geosynthetic composite under two boundary frictions. The test results reveal the following conclusions:

(1) the geogrid can provide effective reinforcement for Ottawa sand.
(2) greater boundary friction between device and test specimen constrains the development of lateral deformation.
(3) the development of tensile strain of reinforcement is easier and more uniform when the boundary friction is smaller.
(4) the tensile modulus of geosynthetics will be underestimated when the boundary friction is large.

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