Iranian Journal of Science & Technology, Transaction B, Vol. 27, No. B1
Printed in Islamic Republic of Iran, 2003

A NEW SIMPLE SHEAR APPARATUS FOR TESTING UNSATURATED SOILS

A. RAHNENMA[1**] G. HABIBAGAHI, AND A. GHAHRAMANI
Dept. of Civil Engineering, Shiraz University, Shiraz, I. R. of Iran
[1]rahnema@shirazu.ac.ir

Abstract – A new simple shear apparatus which is capable of applying monotonic and cyclic load on soil specimens is fabricated. Cylindrical specimens are placed in a special triaxial type cell where confining pressure, pore air and pore water pressures can be controlled. The apparatus consists of an inner part and an outer portion. The inner portion that is inside the triaxial cell consists of a pedestal attached to a movable base. The movable base is mounted on a pair of horizontal rolling tables, which makes the inner portion capable of moving back and forth, horizontally. The outer portion consists of a cylindrical frame that holds the top cap and prevents its lateral movement. A high air entry ceramic disk is sealed into the pedestal using an epoxy resin. The specimen is sheared in a simple shear mode. The horizontal load required to shear the specimen, divided by the nominal area of the specimen gives the shear stress. Soil suction can be measured using the so-called axis-translation technique [1] by increasing the pore air pressure through the top low air entry disk and recording the pore water pressure through the high air entry ceramic disk. Using the fabricated apparatus it is possible to measure and control the vertical normal stress as well as the all-around confining pressure applied to the soil specimen. Hence, testing the soil under initial isotropic or anisotropic confining pressure could be easily achieved. In this paper, the main features of the apparatus are discussed via some test results carried out on unsaturated soil specimens.

Keywords – Simple shear test, unsaturated soil, triaxial, laboratory equipment, soil suction

1. INTRODUCTION

Many field-loading conditions for soil could be modeled by simple shear test. Simple shear apparatus permits for a smooth and continuous rotation of the principal stress directions, as opposed to a triaxial test configuration, which allows only for an instantaneous rotation through 90 degrees of the principal stress directions. A simple shear test configuration may also more closely represent the initial stress conditions and stress path experienced in the field, which cannot be accomplished in a triaxial test configuration for many types of field problems. Vertical and near vertical propagation of earthquake induced shear waves through soils are field loading conditions that are modeled best by a simple shear test configuration. In triaxial test apparatus, it is possible to apply a variety of confining pressures to the soil specimens and it allows experiencing several types of stress path tests. Also, different ratios of horizontal to vertical stresses allow different types of *K*-tests to be carried out. It is an important improvement if an apparatus has the advantages of having both simple shear and triaxial test configurations. In this paper, the main goal is to study the shear modulus of unsaturated soils determined explicitly from experimental results using a special apparatus.

*Received by the editors July 1, 2001 and in final revised form December 29, 2001
**Corresponding author

The general field of soil mechanics may be subdivided into two parts, one dealing with saturated soils, and another dealing with unsaturated soils. The differentiation between the two becomes necessary due to the basic differences in their nature and engineering behavior. An unsaturated soil has three phases, and the pore water pressure is negative relative to the pore air pressure. Therefore, testing unsaturated soils needs some instruments and techniques that are not available in conventional simple shear and triaxial apparatus. In the following section, the main features of the existing apparatus for testing unsaturated soils are briefly reviewed.

2. EXISTING APPARATUS FOR TESTING UNSATURATED SOILS

a) Triaxial test apparatus

Rahardjo *et al.* [2] fabricated a modified triaxial cell for both air and water pressure controls. The axis translation technique was used to apply the desired matric suction values. A 5 bar high air entry disk sealed onto the bottom pedestal of the modified apparatus was used to facilitate a separate control of the pore air and pore water pressures. The apparatus was capable of measuring the pore air and pore water pressures and volume change of the soil specimen during the constant water content, consolidated drained, consolidated undrained with/without pore pressure measurement and unconfined tests.

b) Consolidation test apparatus

Procedure for oedometer tests on unsaturated soil specimens is described in ASTM D4546. This ASTM standard describes three methods for saturating the soil specimen prior to performing the oedometer test. During saturation, the matric suction of the soil is brought to zero, and the result can be used to calculate the swelling pressure of the soil.

Rahardjo and Fredlund [3] developed an apparatus for conducting one dimensional K_0 consolidation tests on unsaturated soil. The apparatus consists of a thick wall bronze cylinder. The soil specimen has a diameter of 102 mm and height of 200 mm. The apparatus is capable of controlling and measuring pore air and pore water pressures in the soil specimen. So during the consolidation process the pore air and pore water pressures could be measured independently at various depth and time intervals to obtain the pore pressure isochrones.

c) Direct shear test apparatus

Conventional direct shear equipment was modified by Gan *et al.* [4]. The shear test is conducted inside an air pressure chamber. A high air entry ceramic disk was located onto the base pedestal so that matric suction could be measured using axis translation technique. The apparatus tests a short cylindrical specimen of 100 mm in diameter. Test results consist mainly of the data on shear stress versus matric suction (*i.e.* τ versus (u_a-u_w)). Consolidated drained and constant water content tests can be performed with this direct shear apparatus.

d) Simple shear test apparatus

Up to now, all simple shear apparatus (SSA) are designed mainly for testing saturated soils. There is not any type of simple shear apparatus that is capable of testing unsaturated soils. Conventional simple shear test apparatus, usually conform to one of two general configurations: (1) the NGI-type apparatus [5], which tests a short cylindrical specimen; or (2) the Roscoe or Cambridge type apparatus [6], which tests a cuboidal specimen. Roscoe type apparatus have been invaluable for geotechnical profession for research on fundamental soil behavior, but are impractical for testing undisturbed field specimens due to mounting difficulties. NGI-type apparatus are particularly useful in engineering practice as they are well suited for mounting undisturbed field specimens. Casagrande and Rendon [7], Jaime [8], Ishihara and Yamazaki [9], described a simple shear apparatus in which a cylindrical specimen was enclosed laterally by a rubber membrane supported around its circumference, by a separate spiral spring or by a stack of Teflon coated annular plates. Budhu [10] compared the radial stresses developed in the NGI-type SSA with the horizontal normal stresses on the plane perpendicular to the plane of shear deformation and the intermediate principal effective stresses measured in the Cambridge University SSA MK4. Comparison of results from these tests in the two SSA showed that the radial stresses are equal to neither the horizontal normal stresses nor the intermediate principal effective stresses. However, these radial stresses did not appear to be valuable in calculating the stress state of a specimen in the NGI-type SSA. Bounlager *et al.* [11] proposed a device capable of applying bi-directional simple shear both in cyclic and monotonic loading. McCarron *et al.* [12] employed a MIT version of direct simple shear apparatus similar to the NGI simple shear device to study the strain rate effect on an overconsolidated marine clay. DeGroot *et al.* [13] described a multidirectional direct simple shear (MDSS) apparatus. It uses a cylindrical specimen that is consolidated under both a vertical effective stress and a horizontal shear. More recently, DeGroot *et al.* [14] discussed the effect of non-uniform stresses on MDSS. All of the above-mentioned simple shear apparatus were designed for testing "saturated" soils.

3. PROPOSED SIMPLE SHEAR APPARATUS FOR TESTING UNSATURATED SOILS

An apparatus for conducting simple shear tests on unsaturated soil specimens was fabricated and is shown in Fig. 1. The apparatus is capable of controlling, as well as measuring pore air and pore water pressure in the soil specimens, separately. Simple shear tests are conducted inside a special triaxial type cell and normal stress and confining pressure can be applied to the soil specimen. The apparatus consists of two separate portions, an inner part (parts No. 4, 5 and 6 in Fig. 1) and an outer part (parts No. 3 and 7 in Fig. 1). The inner portion, which is inside the triaxial cell, contains a pedestal (part No. 5 in Fig. 1) with a grooved water compartment supporting a 5 bar high air entry disk sealed into the central part of the pedestal as shown in Fig. 2. The high air entry ceramic disk is in direct contact with the soil specimen and used to measure the soil water pressure. Since the high air entry ceramic disk has a very low permeability (4.0×10^{-10} m/s), it is time consuming if a change in degree of saturation is desired during the test. Hence, a coarse annular porous stone, as shown in Fig. 2 (a), was installed in the pedestal to facilitate saturation if required during testing. Evidently, this annular stone is dry at the outset of the test and will be only used to saturate the specimen if required during the test. The pedestal is attached to a movable base with a pedestal shaft (Fig. 3). The movable base is mounted on a pair of horizontal rolling tables, which makes the inner portion capable of moving horizontally back and forth (Fig. 3). The pore air pressure, u_a, can be measured and controlled to impose a given matric suction, (u_a-u_w), in the soil specimen. The loading cap was provided with a coarse porous stone and a perforated circular plate, 1 mm in thickness. Function of the perforated plate is described in section 6 of this paper. A tube connected to the top cap permits the air pressure to be controlled in the soil specimen (Fig. 4.). The movable base is attached to a load cell and then to a motorized gearbox. The horizontal load needed for shearing the soil specimen can thus be measured via the load cell transducer. In order to determine the net shear load applied to the soil specimens, a series of calibration tests were performed at different cell pressures to measure the total lateral resistance of the movable base due to rubber sleeve. flexible connection and the rolling tables. The horizontal displacement of the specimen can be measured using linear variable differential transducers (LVDTs). The outer portion consists of the base, the holding frame and the attaching parts to the shear equipment frame. The holding frame (part 3 in Fig. 1) keeps the top cap from lateral movement while the soil specimen is being sheared. The triaxial cell type (part 2 in Fig. 1.) was a 1700 kPa cell, with the loading ram passing through its cap. Dead weights were used to apply the normal load to the soil specimens through a loading frame hanging over the loading ram as shown in Fig. 1. The friction between the loading ram and the cell top was negligible. Therefore, no correction was considered for the normal loads. The base (Fig. 5) consists of six valves connecting to the pedestal and top cap. Four valves are used to apply, control, and measure the cell, pore air, and pore water pressures. The other two valves are connected to the coarse annular ring mounted on the pedestal and used to saturate the specimen if needed. The important portion of the apparatus is the connection between the outer part and inner section. This connection must allow horizontal movement of the inner part relative to the outer section and must be watertight to avoid water leaking. To achieve these goals, a connection was designed with details shown in Figs. 6 and 7. It consists of several 1 mm thick washers. The pedestal shaft passes through these washers that are seated on the base of the outer part (Fig. 6). Four short steel links pass through four holes made in the washers and serve as links between the pedestal and the fixed base. These steel links are attached to a pair of steel balls in the pedestal and the fixed base, and play the role of a ball-and-socket pin connection. A rubber tube fixed with a pair of O-rings covers the washers in order to avoid water leaking from the cell (part 2 in Fig. 6). Horizontal movement of the pedestal causes a smooth movement of washers on each other and provides a smooth inclined cylinder that is covered with the rubber tube. The volume of both vertical and inclined cylinders is the same. Therefore, no change occurs in the cell volume or water pressure inside the triaxial cell while the soil specimen is being sheared. With the current configuration of the apparatus, it is capable of carrying out simple shear tests up to a shear strain of 25%. However, if higher shear strains are desired it may easily be achieved by minor modifications in the ball-and-socket connections of the pedestal.

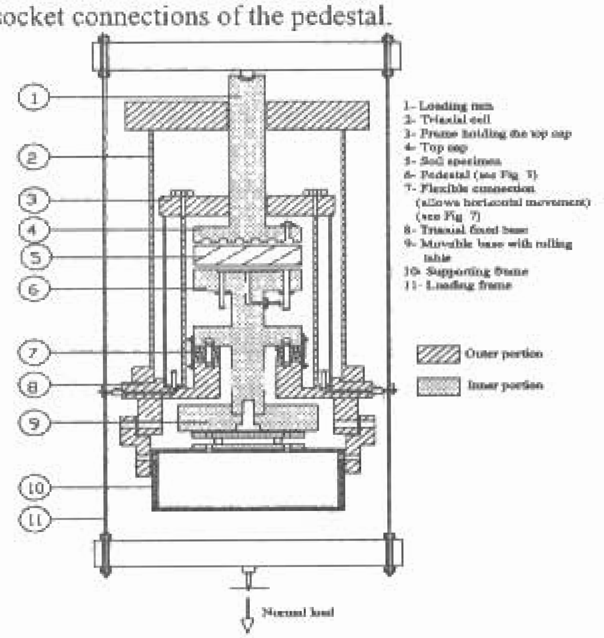

Fig. 1. Proposed simple shear apparatus for testing unsaturated soils

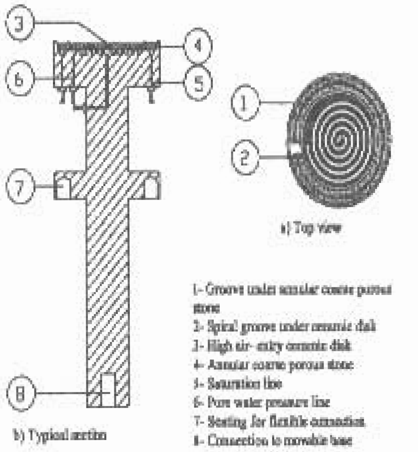

Fig. 2. Supporting pedestal (part 6 in Fig. 1)

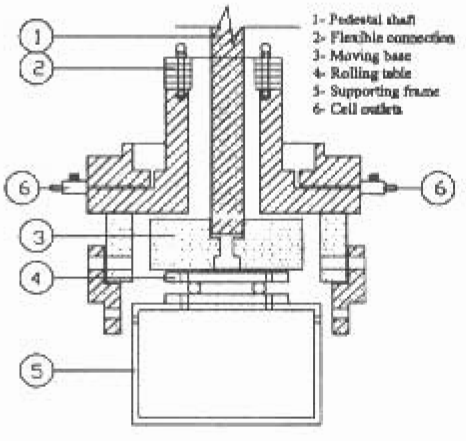

Fig. 3. Details of apparatus sitting

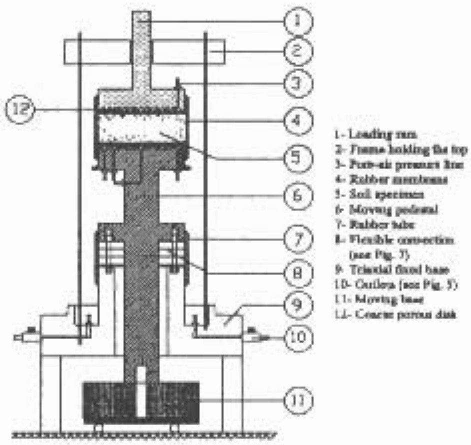

Fig. 4. Schematic view of inner part (the hatched parts) and outer fixed base

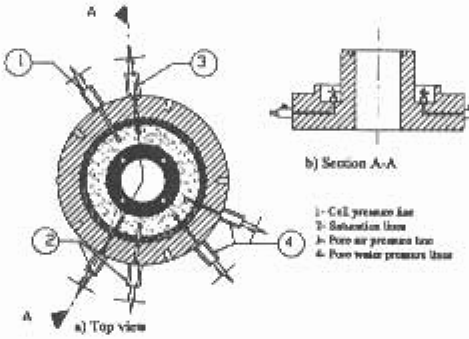

Fig. 5. The triaxial fixed base (part 8 in Fig. 1)

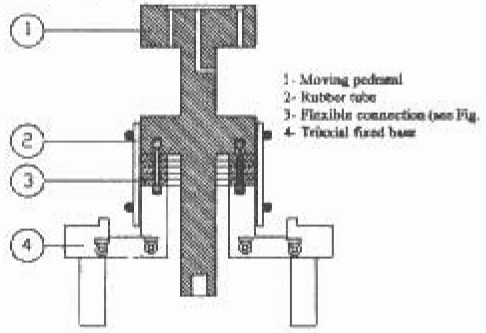

Fig. 6. Connection between outer and inner parts

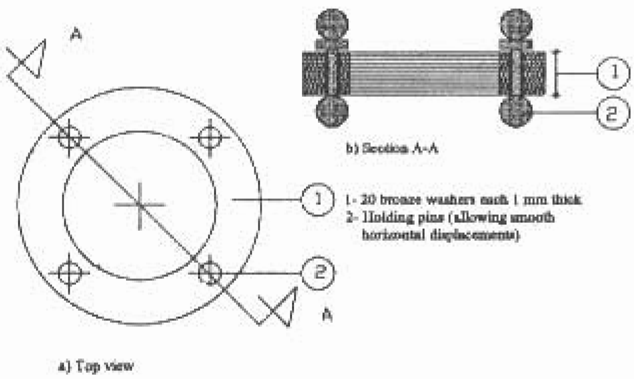

Fig. 7. Details of flexible connection

4. EXPERIMENTATION

In order to investigate capabilities of the proposed apparatus for testing unsaturated soils, a testing program was planned. The soil specimen was a short cylindrical specimen with 100 mm diameter and a height of 20 mm. The specimen was placed on top of the ceramic disk and covered with a rubber membrane (see Fig. 4.). In the following sections, soil properties, specimen preparation and testing method are discussed in details.

5. SOIL PROPERTIES

The soil used was obtained in bulk volume from a site in Seevand area located 100 km north of Shiraz in Fars Province of Iran. Previous geotechnical works at the site has revealed the collapsing nature of the soil. Table 1 summarizes index properties of the soil tested. The soil is classified as CL-ML according to the Unified Soil Classification System.

Table 1. Properties of soil tested

Parameter	Value
Liquid limit (LL)	24
Plastic limit (PL)	19
Plasticity index (PI)	5
Shrinkage limit (SL)	14
Specific gravity (G_s)	2.58
Clay (percent)	30
Silt (percent)	66
Sand (percent)	4
Maximum dry density (γ_{dmax} , kN/m^3)	18
Optimum water content (w_{opt} , %)	13.5

6. SOIL SPECIMENS

Soil specimens were prepared by compacting statically moist soil having predetermined water content into a cylindrical split mold 100 mm diameter. The soil was compacted together with two circular perforated plates 1 mm thick one located beneath and another over the soil specimen in the mold. A 1 mm edge was provided in the top cap and the pedestal to secure the specimen in place via the perforated plates. These measures were considered in order to ensure uniform and full transfer of shear load to the soil specimens. The soil volume was constant (100 mm in diameter and 20 mm high) and its weight was varied so that identical dry densities could be obtained from soil having different moisture contents.

7. TESTING PROGRAM

A series of tests were conducted to study the pore pressures (or suction), volume change, and shear behavior of the soil specimens under anisotropic consolidation pressure. In these tests, the soil specimens with some pre-defined conditions in terms of initial water content and dry density were prepared. Each specimen was mounted on the pedestal and left in the cell until the pore water pressure measured through the ceramic disk was stabilized. This period varied between 15 to 30 hours for different specimens. No attempt was made to change the moisture content of the specimens during this period. Hence, the water contents of the specimens at suction equilibrium and prior to loading were identical to the initial water contents given in Table 2. Cell pressure was applied and the vertical force was then increased to reach a desired stress ratio $((\sigma_3-u_a)/(\sigma_1-u_a))$. For the testing program considered in this investigation, the stress ratio was set to 0.5. Volume change of the soil specimen was measured by monitoring the amount of water entering the cell and taking into account volume change of the system. The specimen was sheared at a rate of 0.0015 mm/min. The specimens were saturated at shear strains of 8%, 12% and 22%. Allowing water to enter the soil specimens via the high permeability annular porous stone and applying a small water pressure of 10 kPa fulfilled the saturation process under constant applied stress. Saturating the soil specimens using this procedure reduced the suction pressure to a negligible amount and shearing force dropped rapidly. The amount of collapse deformation and the change in shearing force during saturation was measured. The shearing rate was selected based on the previous experience on unsaturated soil tests, as well as the pore water pressure response of the ceramic disk. From the applied air pressure and the pore water pressure measured through the ceramic disk, the suction values were obtained.

Table 2. Conditions of testing specimens

		Specimens		
Parameter	Symbol and unit	S1	S2	S3
Initial water content	w_i (%)	10	12	15
Final water content	w_f (%)	23.6	23.5	23.7
Dry density	γ_d (kN/m^3)	14	14	14
Cell pressure	σ_3 (kPa)	450	450	450
Air pressure	u_a (kPa)	425	430	425
Normal stress	σ_n (kPa)	25	25	25
Mean stress	σ_m (kPa)	458.3	458.3	458.3
Initial matric suction	$(u_a - u_w)_i$ (kPa)	378	295	85
Shear strain when saturated	γ (%)	7.6	11.6	22

8. TEST RESULTS

Results of simple shear tests performed on the soil specimens with different initial water contents are shown in Figs. 8-10. Figure 8 shows variation of shear stress versus shear strain, while Figs. 9 and 10 show variation of volumetric strain and matric suction versus shear strain, respectively. The specimens were saturated during the shear test at different strain levels. Based on the test results shown in Fig. 8, the specimens with lower initial water content showed a stiffer response and higher shear strength. All specimens did not show significant change in volume or suction prior to saturation as indicated in Figs. 9 and 10. However, specimens with lower initial water content experienced a larger reduction in volume upon saturation, as indicated in Fig. 9. Furthermore, the shear load capacities of the specimens were also greatly reduced upon saturation with specimens of lower initial water contents (higher suctions) experiencing larger reduction in shear load.

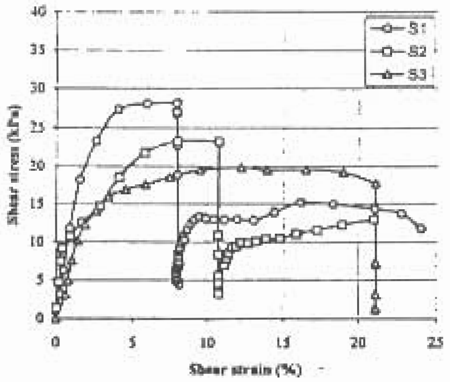

Fig. 8. Stress strain behavior of unsaturated specimen during simple shear tests

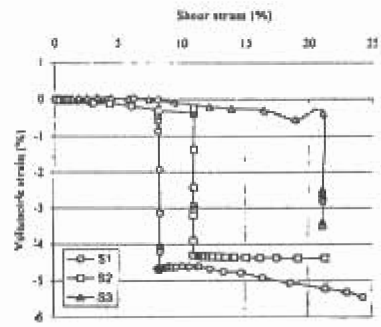

Fig. 9. Volume change of specimens during simple shear loading

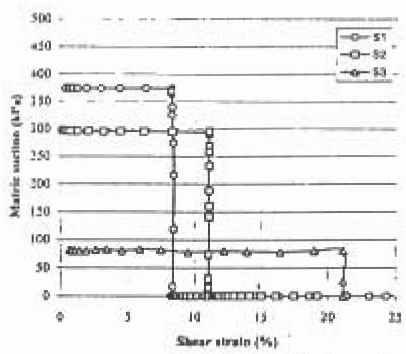

Fig. 10. Variations of matric suction during simple shear test

9. CONCLUSION

A simple shear apparatus for testing unsaturated soils was proposed. The apparatus is capable of applying both cyclic and monotonic simple shear load. The apparatus has a fixed top cap and a sliding bottom pedestal. The system also has a stiff internal support to minimize lateral compliance of the top cap. The apparatus is capable of testing specimens with 100 mm diameter and 20 mm height. Using this apparatus, it is possible to control or measure: soil suction, horizontal and vertical force/displacements as well as volume change of the specimen. Some simple shear tests were conducted on unsaturated specimens and in each test the behavior during loading, unloading, reloading and saturation of the specimen was monitored. Volume change, suction and shear stress of the soil specimen during straining of the specimen were recorded. Also the amount of collapse deformation during the saturation process was measured. The apparatus performed successfully and may be useful as an ideal tool for further research on unsaturated soils. One of the main advantages of the proposed simple shear apparatus is that it does not require a reinforced membrane as lateral support is provided via confining pressure. This means that consolidation can be performed at K values other than K_0. The confining pressure can be servo controlled and together with the hydraulic servo control of shear load. The apparatus is capable of performing advanced tests such as zero volume change, constant water content, and collapse tests in a simple shear mode.

REFERENCES

1. Hilf, J. W., An Investigation of Pore Pressure in Compacted Cohesive Soils, Ph.D. Dissertation, Technical Memo., No. 654, U.S. Dep. of Interior, Bureau of Reclamation, Design and Construction Div., Denver, CO, p. 654 (1956).
2. Rahardjo, H., Lim, T. T., Chang, M. F. and Fredlund, D. G., Shear-strength characteristics of a residual soil, *Can. Geotech. J.*, **15**, p.313 (1978).
3. Rahardjo, H., Fredlund, D. G., Consolidation apparatus for testing unsaturated soils, *Geotech. Testing J.*, **19**, No. 4, p. 341 (1996).
4. Gan, K. M., Fredlund, D. G. and Rahardjo, H., Determination of the shear strength parameters of an unsaturated soil using the direct shear test, *Can. Geotech, J.*, **25**, No. 3, p. 500 (1988).
5. Bjerrum, L., and Landva, A., Direct simple shear tests on a Norwegian quick clay, *Geotechnique*, **16**, No. 1, p. 1 (1966).
6. Roscoe, K. H., An Apparatus for the application of simple shear to soil samples, Proceedings, Third Int. Conf. on Soil Mech. and Found. Eng., Zurich, **1**, p. 186 (1953).
7. Casagrande, A. and Rendon, F., Gyratory Shear Apparatus Design, Testing Procedures, Technical Report S-78-15, Corps of Engineers Waterway Experiment Station, Vicksburg, MS (1978).
8. Jaime, A., A two-direction cyclic shear apparatus, Proceedings, Fifth Pan American Conf. on Soil Mech. and Found. Eng., Buenos Aires, Argentina, **II**, p. 395 (1975).
9. Ishihara, K. and Yamazaki, F., Cyclic simple shear tests on saturated sand in multi-directional loading, *Soils and Foundations*, **20**, No. 1 (1980).
10. Budhu, M., Lateral stress observed in two simple shear apparatus, *J. of Geotech. Eng.*, **111**, No. 6, p. 698, (1985).
11. Bounlager, R. W., Chan, C. K., Seed, H. B., Seed, R. B. and Sousa, J. B., A low compliance bi-directional cyclic simple shear apparatus, *Geotech. Testing J.*, **16**, No.1, p.36 (1993).
12. McCarron, W. O., Lawrence, J. C., Werner, R. J., Germaine, J. T. and Cauble, D. F., Cyclic direct simple shear testing of a beaufort sea clay, *Can. Geotech. J.*, **32**, p. 584 (1995).
13. DeGroot, D. J., Germaine, J. T. and Ladd, C. C., The multidirectional direct simple shear apparatus, *Geotech. Testing J.*, **16**, No. 3, p. 283 (1993).
14. DeGroot, D. J., Germaine, J. T. and Ladd, C. C., Effect of nonuniform stresses on measured DSS stress-strain behavior, *J. of Geotech. Eng.*, ASCE, **120**, No. 5, p. 892 (1994).