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# A RING TORSION APPARATUS FOR SIMPLE SHEAR TESTS

## UN APPAREIL A LA TORSION D'EPROUVETTE ANNULAIRE POUR ESSAIS DE CISAILLEMENT SIMPLE

## КОЛЬЦЕВОЙ ПРИБОР ДЛЯ ИСПЫТАНИЯ НА ПРОСТОЙ СРЕЗ

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SYNOPSIS. A new ring torsion apparatus has been designed and built to conduct simple shear tests under nearly plane strain conditions. The unique feature of the apparatus is the sample container consisting of stacks of thin metal disks which offer little resistance to twisting while keeping the radial strain in the sample at a negligible level. The apparatus includes an inertial loading system which facilitates cyclic shear tests under various stress conditions. Some typical results of cyclic drained and cyclic undrained tests on a sand are described to demonstrate the usefulness of the apparatus for obtaining quantitative information of the strength and deformability of soils in simple shear under plane strain conditions.

## INTRODUCTION

The simple shear test has been recognized important for investigating the strength and deformability of soils in connection with plane strain problems (Roscoe, 1970). For an "ideal" simple shear test in which both the stress and strain are kept uniform within a rectangular parallelepiped sample as shown in Fig. 1(a), the following conditions must be satisfied:

1) No change in the width and length of the horizontal cross-section of the sample.

2) No friction on the side faces.

3) Full complementary shear stress on the ends.

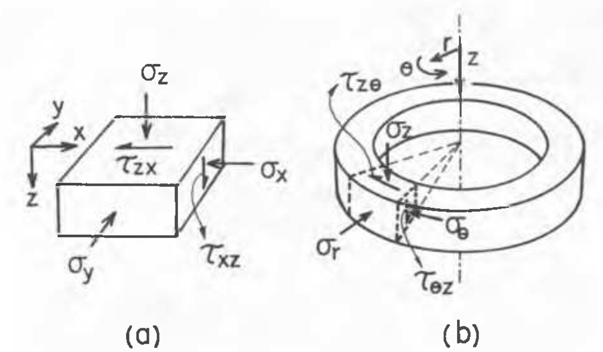



FIG. 1. (a) IDEAL SIMPLE SHEAR TEST; (b) RING TORSION SIMPLE SHEAR TEST

In the simple shear apparatus composed of metal plates (Roscoe et al, 1967; Finn et al, 1971), neither the complete elimination of the unwanted side friction nor the full development of the complementary shear stress has been achieved, resulting in uneven distribution of the boundary stresses. Although Roscoe et al were able to effect a partial development of complementary shear stress by providing two hinged supports for the end flaps diagonally opposite to each other, this scheme fails when the direction of shear stress is reversed (Yoshimi, 1972).

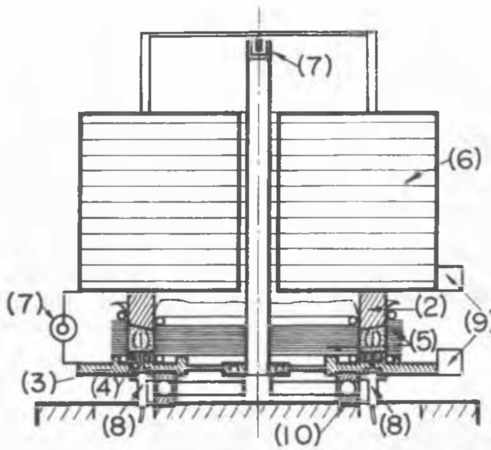
Although Roscoe et al were able to study the magnitudes and directions of the principal stresses and strains in the middle third of their specimen assuming nearly uniform distribution of stresses and strains, a greater degree of uniformity is required for a problem in which local defect governs the result, e.g., the liquefaction of saturated sand under cyclic shear conditions.

The difficulty in developing the complementary shear stress is probably shared by the direct simple shear apparatus using a wire reinforced rubber membrane (Bjerrum and Landva, 1966).

Recognizing that the ends of the shear box were responsible for precluding uniform distribution of stresses and strains in the simple shear test, the present authors have attempted to devise an apparatus in which an endless, i.e., ring-shaped sample was to be subjected to torsion as shown in Fig. 1(b). The object of this paper is to describe two designs of the apparatus, Mark 2 and Mark 3, and to show their applicability to drained and undrained tests on sand.

## THE MARK 2 RING TORSION APPARATUS

As shown in Fig. 2 an annular soil sample, 240 mm ID, 24 mm wide, and 20 to 24 mm high, is subjected to vertical load and torque. The unique feature of the apparatus is the sample container consisting of stacks of thin duralumin disks (0.5 mm thick) whose surfaces are sprayed with dry lubricant. The container is intended to offer little resistance to twisting while keeping the radial strain in the sample at a negligible level.




(1) Sample (2) Loading platen (3) Rotating table (4) Porous bronze base (5) Sample container (6) Weights (7) Displacement transducers (8) Pore pressure transducers (9) Accelerometers (10) Thrust bearing

FIG. 2. MARK 2 RING TORSION APPARATUS

The annular loading platen of brass is beveled in such a way that the height of the sample is proportional to the radius. Except for the curvature effect, therefore, the test is essentially a simple shear test in which the sample is to be subjected to nearly uniform shear stress under nearly plane strain conditions.

The bottom of the loading platen which makes contact with the soil is roughned with conical dents 0.4 mm in diameter spaced at an interval of approximately 0.8 mm. The side walls of the container are lined with rubber membranes 0.5 mm thick.

The vertical load is applied by circular steel weights on the loading platen. Fig. 3 shows three methods of applying torque: (a) the controlled strain test by turning the rotating table while holding the weights, (b) the controlled stress test by hanging two sets of weights over pulleys while holding the rotating table, and (c) the inertial cyclic loading test by twisting the rotating table back and forth. The magnitude of the inertial torque is computed by multiplying the moment of inertia of the weights by the angular acceleration.

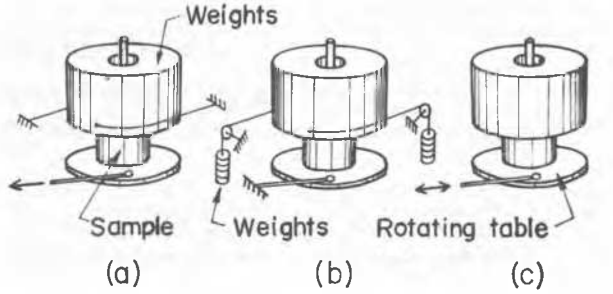



FIG. 3. METHODS OF SHEAR TESTS:
(a) CONTROLLED STRAIN TEST
(b) CONTROLLED STRESS TEST
(c) CYCLIC TEST BY INERTIAL TORQUE

Linear differential transformers are used to measure the settlement and the relative circumferential displacement of the sample. Two pressure transducers are installed below the porous bronze base diametrically opposite to each other. Accelerometers are mounted on the rotating table and the weights to determine the tangential acceleration at the bottom and top of the sample, respectively. The output from all the transducers are recorded simultaneously on an eight-channel oscillograph.

For cyclic shear tests, the rotating table is driven by a horizontal shaking table, which in turn is driven by an electrodynamic vibration exciter capable of producing irregular motions as well as sinusoidal motion in the frequency range from 0 to 80Hz. The exciter is equipped with a gate circuit by which a predetermined amplitude is reached within one cycle, so that the early part of the motion can be clearly defined (Figs. 8 and 10).

For cyclic shear tests in which the shear stress is partially reversed, a nearly constant static shear stress is superposed to the inertial shear stress by means of a pair of long springs attached to the innermost part of the weights as shown in Fig. 4.

Test Procedure: Saturated sand which has been boiled for 30 min. is placed with a spoon in a water-filled mold composed of the inverted loading platen and collapsable side walls as shown in Fig. 5. The sand in the mold is then frozen in such a way that freezing starts at the bottom and progresses upwards in order to avoid expansion of the sample.

After the sample has been frozen solid, the side walls of the mold are removed, and the sample and the loading platen are placed in the annular space between the rubber membranes.

After consolidating the sample under a desired vertical load, the rubber membranes are sealed against the loading platen with rubber rings, and a back pressure is applied to the pore water.

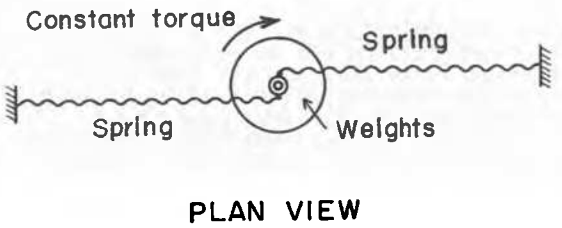



FIG. 4. DIVICE FOR CONSTANT SHEAR

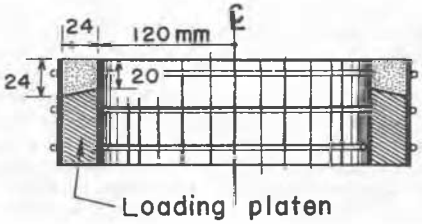



FIG. 5. MOLD FOR FREEZING SAMPLE

THE MARK 3 RING TORSION APPARATUS

The Mark 3 apparatus is the result of the following modifications on the Mark 2 apparatus as shown in Fig. 6:

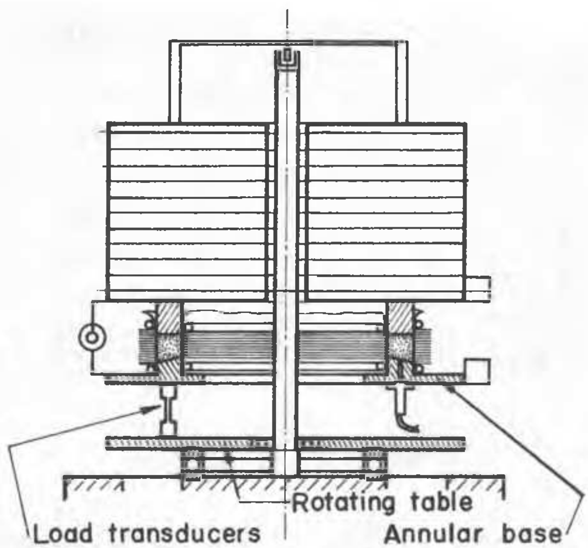



FIG. 6. MARK 3 RING TORSION APPARATUS

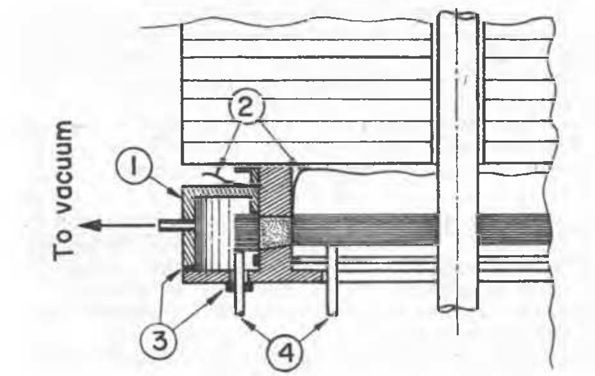
1) Instead of the loading platen, the base is beveled, so that the top surface of the sample is horizontal.

2) The duralumin disks for the sample contai: er are replaced by strainless steel disks of the same thickness (0.5 mm).

3) The thickness of the rubber membranes is reduced to 0.3 mm.

4) The annular base is supported by three transducers which measure the vertical load and the torque at the bottom of the sample, while the sample container is supported independently.

5) To facilitate preparation of samples of loose sand directly in the container, a collapsable vacuum chamber as shown in Fig. 7 is added.




(1) Vacuum chamber (2) Rubber membrane
(3) Gasket (4) Supports for container

FIG. 7. VACUUM CHAMBER FOR OUTER RUBBER MEMBRANE

Test Procedure: After the rubber membranes have been secured on the annular base and the sample container properly positioned, vacuum is applied to the vacuum chamber. Soil sample is then placed in the annular space between the rubber membranes, and the loading platen is placed on the sample. In the case of saturated sand, preboiled sand is placed underwater.

After consolidating the sample under a desired vertical stress, the vacuum is turned off, and the vacuum chamber is removed. For undrained tests, the rubber membranes are sealed against the loading platen with rubber rings, and a back pressure is applied to the pore water.

EXAMINATION OF ERRORS

Vertical Stress: The total friction between the rubber membranes and the container walls can be determined by comparing the vertical load applied on the top of the sample and the load at the bottom measured by the load transducers of the Mark 3 apparatus. When the sand of Table 1 was compacted to a midium density and subjected to a load of 199 kg for an average vertical stress of 1.00 $kg/cm^2$, the total friction was approximately 2.5 per cent of the applied load. The friction corresponds to a coefficient of friction of approximately 0.028 which is about one quarter of that reported by Roscoe et al (1967) when their shear box was lined with plate glass. The relatively small friction can be attributed to the fact that the container is slightly compressible in the vertical direction.

Although there is no direct confirmation, the distribution of the vertical stress within the sample is probably not very far from uniform because of the lateral confinement and of the small vertical friction.

Table 1. Properties of the Tested Sand from Niigata

| | |
|---|---|
| 10 % Size | 0.25 mm |
| Uniformity Coefficient | 1.9 |
| Specific Gravity of Solids | 2.671 |
| Maximum Void Ratio | 1.007 |
| Minimum Void Ratio | 0.590 |

Circumferential Shear Stress on the Horizontal Surface: If there is difference between the torque applied at the top of the sample and that measured at the bottom, it will represent a variation in the shear stress on the horizontal plane. When the sand of Table 1 was placed dry in the container, the difference in the torque was less than 4 per cent for both the static and inertial loading.

Shear Strain: Static drained tests were conducted on the sand of Table 1 to estimate the magnitude and distribution of the shear strain in the sample. Because no direct observation of the sample was possible, the displacement of the exterior wall of the container was assumed to be proportional to the deformation of the sample, which was equivalent to assuming that the slippage between the wall and the rubber membrane was negligible compared to that between adjacent disks of the container.

A multi-exposure technique was used to record the deformation of the container wall on photographic film which was then observed under a microscope. The test results indicated that until failure was imminent the exterior wall deformed uniformly, and that the shear strain in the sample was equal to the apparent shear strain computed from the tangential displacement of the loading platen with respect to the base, implying no slippage at the top and bottom of the sample.

Because the shear stress within the sample is uniform, the uniform shear deformation implies that the sample is uniform throughout the thickness. Thus the observation of the shear deformation can be used to check the uniformity of a sample.

Effect of Centrifugal Force: When the tangential acceleration is zero the radial acceleration takes a maximum value. The centrifugal force on the sample is counteracted partly by a radial shear stress on the top and bottom, $\tau_{zr}$, and partly by a change in the lateral stress on the side walls, $\Delta\sigma_r$.

Although the determination of the relative magnitude of $\tau_{zr}$ and $\Delta\sigma_r$ is a statically indeterminate problem, one can readily estimate the maximum possible value of each by ignoring the other. Both $\tau_{zr}/\tau_{z\theta}$ and $\Delta\sigma_r/\sigma_r$ (see Fig. 1b for notation), which are proportional to the maximum angular amplitude and inversely proportional to the vertical stress, amount to only a fraction of one per cent if the vertical stress and frequency exceed 0.2 $kg/cm^2$ and 2 Hz, respectively.

## DRAINED CYCLIC SHEAR TESTS ON DRY SAND USING THE MARK 3 APPARATUS

A series of cyclic shear tests were performed on the sand of Table 1 prepared air dry at the initial relative densities of 30 ± 5 per cent. Sinusoidal vibration at a frequency of 4 Hz was applied to the rotating table for approximately 30 sec. Fig. 8 shows a typical oscillograph record. The secant shear modulus defined as the ratio between the shear stress amplitude and the shear strain amplitude is plotted in Fig. 9 against the shear strain amplitude for the first, 10th, and 100th cycles.

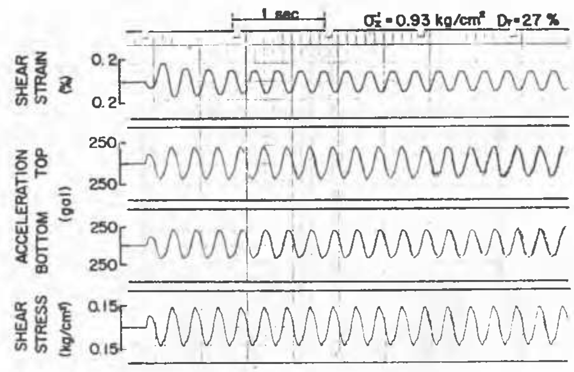



FIG. 8. TYPICAL DRAINED CYCLIC SHEAR TEST ON SAND

It is evident in Fig. 9 that the greater the shear strain, the more pronounced is the stiffening effect during cyclic shear.

The data for the tenth cycle are in good agreement with the curve determined by the method proposed by Seed and Idriss (1970), but are higher than the curve extrapolated from the simple shear test data on a uniform angular quartz sand by Silver and Seed (1971) who used the type of apparatus reported by Bjerrum and Landva (1966).

## UNDRAINED CYCLIC SHEAR TESTS ON SATURATED SAND USING THE MARK 2 APPARATUS

A series of undrained cyclic shear tests were conducted on saturated sand of Table 1 prepared by the freezing method mentioned before and normally consolidated. Extreme care was taken to achieve full saturation and uniform distribution of density. Fig. 10 shows the oscillograph record of a typical test conducted at the initial effective vertical stress of 1.0 kg/cm$^2$ with a back pressure of 0.3 kg/cm$^2$, and at a frequency of 4 Hz.

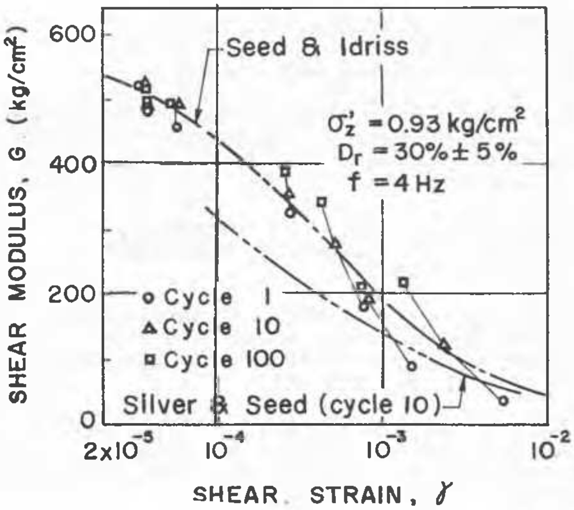



**FIG. 9. SHEAR MODULUS VS. SHEAR STRAIN FOR CYCLIC SHEAR TESTS ON SAND**

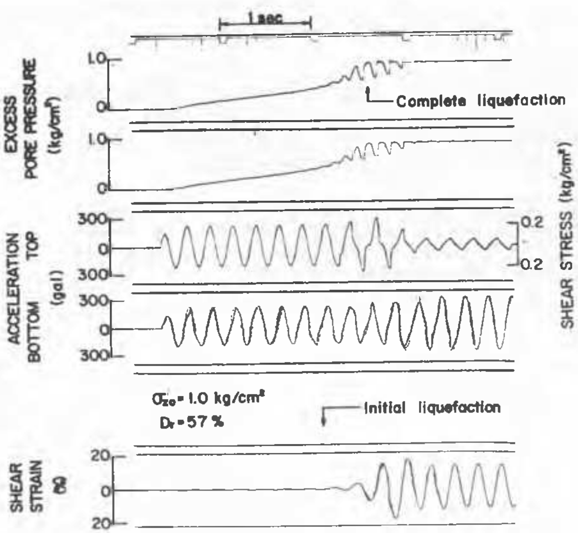



FIG. 10. TYPICAL UNDRAINED CYCLIC SHEAR TESTS ON SAND

During the first seven cycles the pore water pressure increased smoothly while the strain remained negligibly small. The pore water pressure began to fluctuate during the eighth cycle (initial liquefaction), and reached the maximum value equal to the vertical stress (complete liquefaction).

Because of the inertial loading system, the motion of the weights underwent a 180-degree phase change as the sand lost its stiffness to transmit shear stress, and the pore water pressure ceased to fluctuate after the complete liquefaction

The fact that the shear strain trace showed no zero shift up to the initial liquefaction may indicate that no slippage occurred at the top and bottom of the sample.

In Fig. 11 is plotted the ratio between the shear stress amplitude and the initial effective vertical stress, $\tau_d/\sigma'_{zo}$, against the number of cycles to initial liquefaction, $n_l$. The data which covered a range in the relative densities from 45 to 65 per cent are corrected to the relative density of 50 per cent assuming that $\tau_d/\sigma'_{zo}$ is proportional to the relative density.

The data are in good agreement with the curve which Seed and Peacock (1971) has suggested as "estimated field behavior" for uniform medium sands on the basis of detailed studies of the previous test results including the simple shear test data of Finn et al (1971).

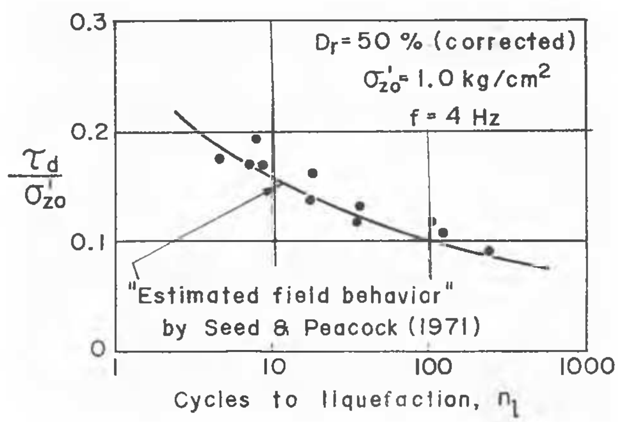



FIG. 11. SHEAR STRESS REQUIRED TO CAUSE LIQUEFACTION IN CYCLIC SIMPLE SHEAR TESTS

It must be pointed out that unlike the previous simple shear tests the present test data require no corrections concerning the initial principal stress ratio or the sample preparation procedure.

ADVANTAGES AND LIMITATIONS OF THE APPARATUS

Advantages: It has been observed during the drained and undrained tests on sand that the new apparatus satisfactorily performed the functions expected in the design. Some of the advantages of the apparatus are listed below:

1) Essentially a simple shear test could be carried out under nearly plane strain conditions with nearly uniform stresses and strains, although the distribution of the vertical stress was not confirmed directly.

2) The inertial loading system for cyclic tests is particularly advantageous for simulating seismic conditions in the field, and it is expected that the apparatus will contribute to obtaining more reliable quantitative information on the strength and stress-strain relationship of various soils under varied cyclic loading conditions.

Limitations: The apparatus is still in an early stage of development and has the following limitations:

1) The radial and circumferential normal stresses during shear are unknown, although their initial values may be estimated indirectly from $K_0$ consolidation tests in the triaxial cell.

2) The relatively large size (28.8 cm in diameter) and the annular shape make it difficult to prepare an undisturbed sample, although the method used by Bishop et al (1971) may be applicable to a cohesive soil if a block sample is available.

3) The relatively large volume (440 $cm^3$) makes it difficult to obtain even a disturbed sample from a boring if the stratum is thin.

4) Considerable skill is required to prepare a uniform sample and to seal the rubber membranes.

CONCLUSIONS

1) With the new ring torsion apparatus, it is possible to conduct simple shear tests under nearly plane strain conditions.

2) With proper care in preparation of a uniform sample, the probable variation in the stresses and strains within the sample is less than a few per cent.

3) With the inertial loading system the apparatus is suitable for conducting cyclic shear tests with partial or complete reversal of shear stress with frequencies up to 80 Hz.

4) Thus, the apparatus provides a direct and reliable means for obtaining quantitative information on the strength and deformability of soils in simple shear and plane strain under various loading conditions.

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