INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The Directional Shearing Cell

La Cellule de Cisaillement Directionnel

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SYNOPSIS This article describes an apparatus capable of applying normal and shear stresses uniformly to four faces of a cubical sample under plane strain testing conditions by means of flexible boundaries. Loose sand samples are prepared by pouring through air to produce a void ratio of 0,72 ± 0,03. Inherent anisotropy is avoided by pouring perpendicular to the plane strain sides. Strain measurements are made from photographs and radiographs taken after each load increment. Results on loose Leighton Buzzard Sand indicates that stress-strain-strength behaviour is not influenced by the direction of the major principal stress (ϕ'=const=40°±1°). This confirms that the edge effects and strain's non-uniformity within the samples are negligible. Failure planes are oriented at $\{45° - 1/4\ (\nu + \phi')\}$ to the major principal stress axis. (Where ν is dilation angle).

INTRODUCTION

The successful prediction of field performance based on laboratory test results requires a judicious duplication of the initial and incremental stresses encountered by various soil elements in the field. Existing stress path methods (Lambe, 1967) account for the changes in magnitude of the stresses. On the other hand, the effect of changes in principal stress directions cannot be determined in the laboratory by means of existing equipment because of the difficulties associated with controlling and changing the principal stress direction. In the conventional triaxial and true triaxial apparatus (Bishop and Henkel, 1975; Ko and Scott, 1967; Dunstan, 1968; Green, 1969 and others) principal directions cannot be changed. The Direct Shear Box (Lambe, 1951) and the Cambridge Simple Shear Apparatus (Roscoe, 1953) allow rotation of major principal stress, but the rotation cannot be controlled. Only the hollow cylinder (Broms and Casbarian, 1965) is capable of controlling rotation but suffers from the non-uniformity of stresses and strains across the sample.

A successful apparatus requires uniform normal and shear stresses to be applied to the sample by means of flexible boundaries in order to allow complete freedom of deformation. Any desired rotation of the major principal stress direction can thus be achieved without sacrificing the uniformity of stresses and strains. At present, the practical complications imposed by such boundary conditions appear to limit it to plane strain conditions. Such an apparatus was developed at University College, London, for testing dense sands. (Arthur et al 1977a, 1977b, 1980). This article describes a Directional Shearing Cell built on the same principles, but capable of testing loose sand to the large strain levels required to reach failure without sacrificing uniformity within the sample. (Until ≈ 16% major principal Strain).

DESCRIPTION OF THE APPARATUS

Fig. 1 shows isometric views of the apparatus. The important feature of this cell is the capability of the boundaries to conform with the changing shape of the sample during testing by adjusting: 1) The location and orientation of the backing plates and hence allowing large strains without stress concentrations at the corners, and 2) The direction of the shearing sheets to keep the shear stress aligned with the sample sides. In addition glass panels inserted in the plane strain sides enable sample deformations to be measured by means of photography. The different components of the cell are described in detail by (Rodriguez del Camino, 1977) and summarized below:

Pressure Bags ②*

Normal stresses are applied to the sample by means of reinforced rubber bags, that can be pressurized with water. Each pressure bag consists of three smaller bags of 107 x 100 x 10 mm each, glued together.

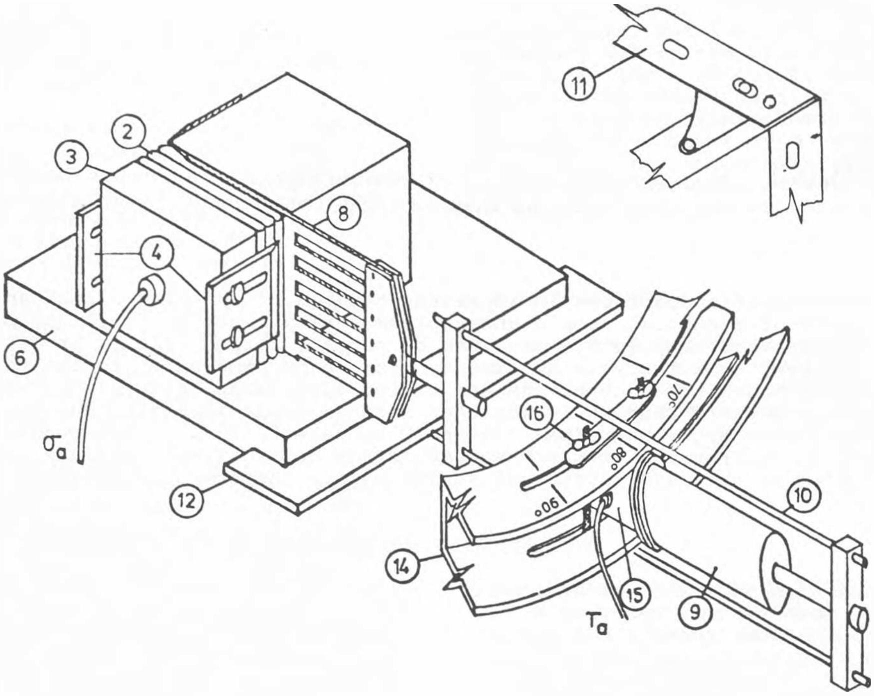
Adjustable Backing Plates ③

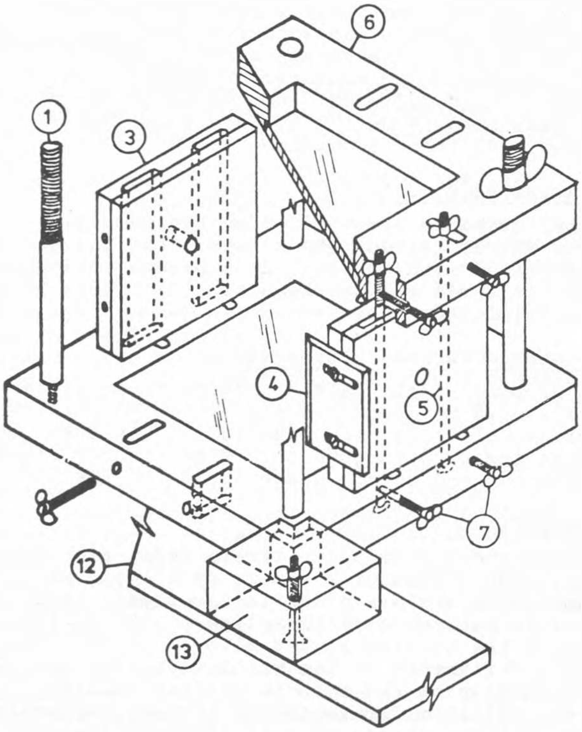
The freedom of the backing plates to move laterally (28 mm) requires each plate to have two vertical slots as shown in Fig. 1. A Steel rod ⑤ is inserted through each slot, and is fixed to the top and bottom plane strain plates.

Plane Strain Sides ⑥

The top and bottom plane strain sides are identical and consist of a square duralluminium frame where a glass plate is inserted. Two slots in each side of the plate at 90° to the ones on the backing plates allow: 1) The insertion and fixation of the steel rods ⑤, and 2) The translation and rotation of the backing plates ③ in order to obtain the desired position. Plane strain is maintained by four adjustable steel rods ① linking the top and bottom plates.

* Encircled numbers refer to numbers on Fig. 1





PART No.	DESCRIPTION
①	Steel rods to maintain plane strain.
②	Pressure bags.
③	Adjustable backing plate.
④	Retaining vanes.
⑤	Steel rods to guide the backing plates.
⑥	Plane strain sides.
⑦	Wing screws to fix the backing plates.
⑧	Shearing sheets.
⑨	Water pressurized cylinders.
⑩	Frame attaching pistons to sheets.
⑪	Steel frame supporting the apparatus.
⑫	Brackets to secure the plane strain box.
⑬	Clamp to prevent movement of box.
⑭	Semi-circular rail to support cylinders.
⑮	System of ball bearing.
⑯	Clamps to prevent movement of cylinders.

Fig. 1 Isometric Views Of Part Assembled Box

Shearing Sheets ⑧

The shearing sheets (Arthur et al, 1977a, 1980) described here for completeness,are designed to apply a uniform shear stress over the vertical face of the sample. This uniform shear combined with a uniform normal stress should result in uniformity of stresses throughout the sample. In order to provide a uniform normal stress, the sheets have to be flexible, and to provide shear stress they need to be rigid in the shearing direction. Furthermore, to provide the uniform shear stress they need to transmit numerous shear forces of equal magnitude at different points on the face of the sample. The adopted design shown in Fig. 2 consists therefore of: 1) An outer set of inextensible heavily reinforced rubber pulling sheets to transmit the force supplied by the pressurized cylinders ⑨ , 2) A series of unreinforced rubber strips, greased with a special silicone lubricant (Arthur and Dalili, 1979), are glued to the outer reinforced rubber sheets, transmitting shearing forces to a thin unreinforced square inner rubber sleeve. The large flexibility of the rubber strips, elastic at strains in excess of 300%, provide a reasonable uniform distribution of shear stress along each strip, and 3) An inner rubber sleeve whose dimensions are equal to the sides of the sample. This inner sleeve is thoroughly cleaned and then placed in contact with the sample membrane, so it serves to transmit shear directly to the sample (traction rubber to rubber) and as a barrier to prevent grease penetrating to areas where traction is needed.

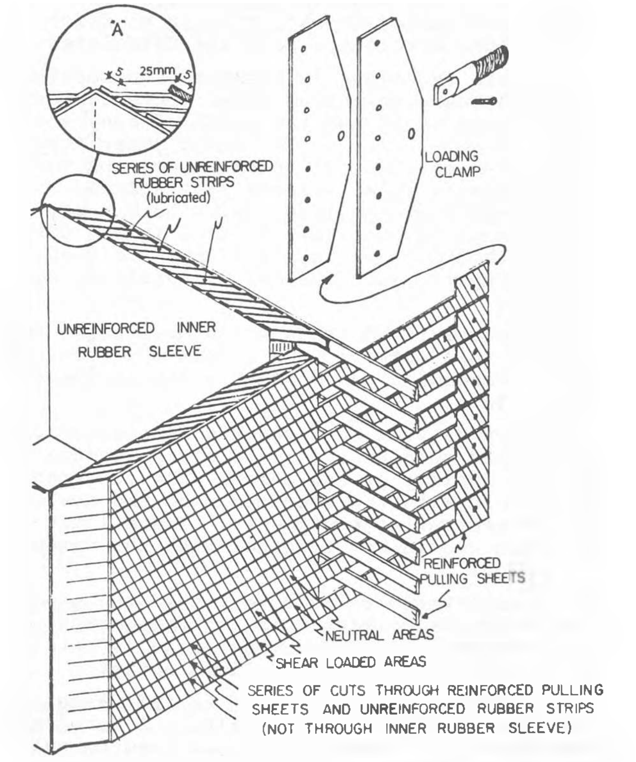


Fig. 2 Shearing Sheets

The description presented so far would apply only if one face of the sample is sheared. However, shear stresses must act along all four faces of the sample, thus pulling sheets must intersect each other. This is achieved by cutting away alternate widths of the reinforced pulling sheets at 6 mm intervals (See Fig. 2). With the shearing sheets cut in this manner the shear force is equally distributed over the sample. The unreinforced and reinforced rubber strips in the neutral areas are left in position so that the normal stress can be transmitted uniformly across the shearing sheets to the sample. These neutral areas also help to stabilize the loaded strips by keeping them in position.

Water Pressurized Cylinders ⑨

The shear force is applied to the shearing sheets by means of frame ⑩ attached to a piston, as shown in Fig. 1. The piston is encased in an acrylic cylincer with an internal length of 136 mm. The piston is loaded bv pumping water into the cylinder.

Support Of The Apparatus ⑪

The shearing cell is supported by a steel frame ⑪ as shown in Fig. 3.

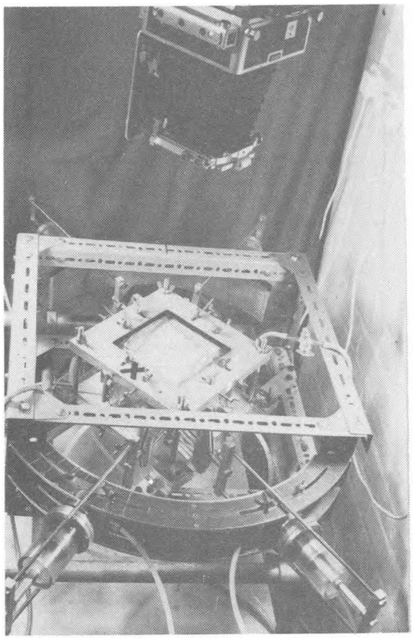


Fig. 3 Overall View Of Apparatus

The plane strain box is fitted into two brackets ⑫ which secure it to the frame. When the box is inserted between these brackets, movement is prevented by means of clamp ⑬ screwed against each corner of the box.

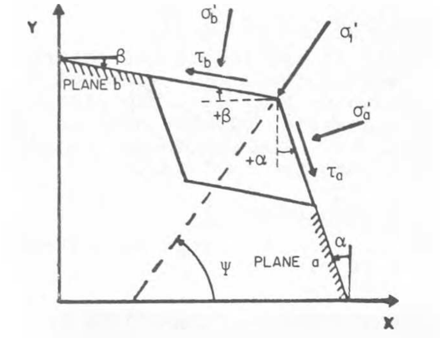
At each end of the steel frame is fixed a semicircular guide rail ⑭ necessary to move the shearing cylinder as the sample changes shape. Clamps ⑯ prevent movement of the cylinders once they have been aligned with the sample sides.

The whole apparatus is mounted on a tubular frame which also incorporates an adjustable support for the camera to allow it to be centered vertically over the sample. The testing apparatus was built at the workshop of the University College, London.

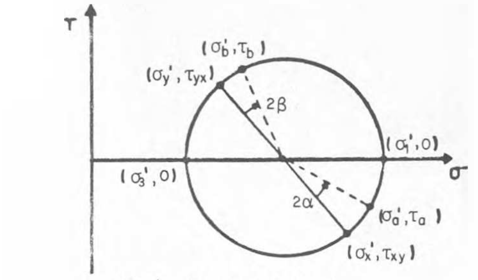
EXPERIMENTAL PROCEDURE

It is only possible to vary the direction of the principal stresses between 0° and 90°, or 90° and 180° once the shearing sheets have been placed around the sample.

Fig. 4 shows a cubical sample with the associated stresses, and Mohr's circle of the stress before and after sample deformation.



CUBICAL SAMPLE WITH ASSOCIATE STRESSES



MOHR'S CIRCLE OF STRESSES

Fig. 4

Sample Preparation

A cubical sample of sand is enclosed in a thin unreinforced rubber membrane (Menzies and Phillips, 1972) containing a grid of perpendicular lines. Two acrylic prisms are glued to diagonally opposite edges of the rubber membrane where the interleaving shearing sheets cross. The set of shearing sheets are placed around the four faces of the sample during an initial negative pressure. The sheets and the sample membrane faces are cleaned thoroughly to provide traction. The four normal pressure bags are well greased, with the special silicone lubricant, and then placed around the sample. The sample is placed between two well lubricated plates which maintain plane strain. The shearing sheets are connected to the water pressurized cylinders, and the sample is then ready to be tested.

Calculations Of Stresses

Generally a test, or part of a test, entails applying a principal stress in a constant direction Ψ. Normally the minor principal stress is held constant (at 14 kN/m^2) and an increase of stress ratio applied, sufficiently to give a small increment of strain. The sample sides will then change in direction by angles α and β. In order to maintain the major principal stress direction constant, angles α and β have to be measured, and the new stresses associated with an increased stress ratio applied parallel and normal to the sample faces. The stresses which then have to be applied to the sample faces are:

$$\sigma_a' = \left|\frac{\sigma_1'/\sigma_3' + 1}{2}\right| \sigma_3' + \left|\frac{\sigma_1'/\sigma_3' - 1}{2}\right| \sigma_3' \cos 2(\Psi - \beta)$$

$$\sigma_b' = \left|\frac{\sigma_1'/\sigma_3' + 1}{2}\right| \sigma_3' - \left|\frac{\sigma_1'/\sigma_3' - 1}{2}\right| \sigma_3' \cos 2(\Psi + \beta)$$

$$\tau_a = \left|\frac{\sigma_1'/\sigma_3' - 1}{2}\right| \sigma_3' \operatorname{sen} 2(\Psi - \alpha)$$

$$\tau_b = \left|\frac{\sigma_1'/\sigma_3' - 1}{2}\right| \sigma_3' \operatorname{sen} 2(\Psi + \beta)$$

These are presented on the Mohr circle of stress in Fig. 4. It should be noted that generally (for Ψ ≠ 45°) $^{\tau}$a and $^{\tau}$b will be of different magnitudes as α and β differ. The angles α and β are measured with a protractor using the sides of the window frame on the top plane strain plate as the coordinate axes. It is essential to apply stresses related to external exes, as sample rotation cannot be measured during a test.

Measurement Of Strains

The procedure of determining strain from the coordinates of an array of lead shots embeded in soil is now widely accepted in soil mechanics research (Roscoe, Arthur, and James, 1963). Radiographs of the lead shot array are taken after each load increment, and strains at different locations within the soil are calculated.

Although this technique is extremely successful, the initial costs for x-ray tubes and accessory equipment puts it beyond the reach of many soil mechnics' laboratories. In recent years some work has been carried out using photograph methods to measure local strains (Butterfield Harkness, and Andrawes,1970) Using both x-ray and photohraphy showed that strains in the directional Shearing Cell are uniform, and that the photographic technique may successfully be used alone.

The photogrammetric methods which have been used throughout this work provide simple and accurate means for recording and measuring displacements within a plane.

The accuracy of such measurements depends on various factors such as the scale of the photograph, the quality of the camera, the alignment of the camera with the specimen, and the accuracy of the meassuring equipment. These limitations were considered together with the human error factor.

A stereocomparator was used to record the coordinates of the markers from the photographs. The accuracy of this instrument is $\pm 4.10^{-6}$ mts. Normally markers were placed 15 mm apart.

All the above errors were found to influence calculations by 0.2% liner strain. A computer program based on (James, 1972) was used to calculate the strains.

EXPERIMENTAL RESULTS

It was considered possible that the shearing sheets between the normal pressure bag and the sample could have an influence upon the stress distribution applied to the sample. This factor could easily be checked in $\Psi = 0°$ tests by comparing the results from two tests, one in which the shearing sheets were included and one in which they were absent. The data indicated that the presence of the shearing sheets did not represent a noticeable influence on the sand behaviour.

Monotonic Loading Tests

Tests were done in which the direction of the major principal stress was maintained constant for each test and the sample loaded monotonically to failure. The major principal stress direction varied from 0° to 45°, which is equivalent to tests from 90° to 45°. (Fig. 5a).

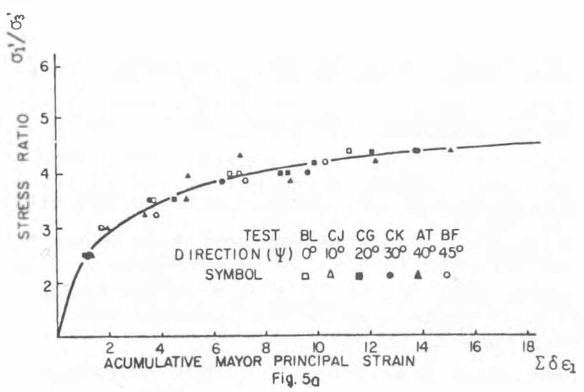


Fig. 5a

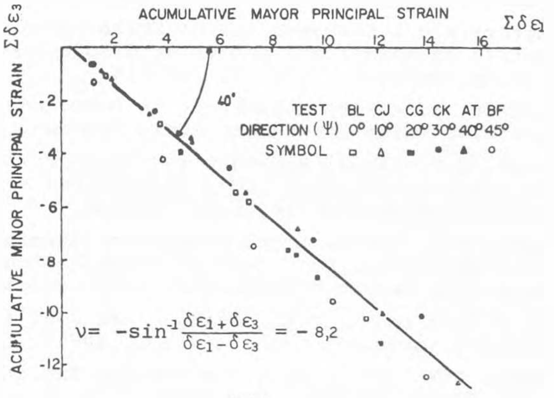


Fig 5b

Fig. 5 Monotonic Loading Tests ($45° \geqslant \Psi \geqslant 0°$)

Stress-strain relationships are plotted using axes of stress ratio versus accumulative major principal strain increments. A unique line was found to represent the whole range of tests.

Comparisons can be made between tests with the major principal stress directions at 0° and 45°. In the first case the sample faces differ in length as strain develop, whereas in the second case all four faces strain equally. Both of these tests fall on one unique stress-strain curve. The test results also show that all equipment limitations are negligible for strains up to 16%.

Fig. 5b presents accumulative manor principal strain increments. All the data again give one unique line, which is linear and defined by the equation:

$$\delta \varepsilon_3 = 0.84 \ \delta \varepsilon_1 .$$

Orientation Of Rupture Layers

Samples were loaded in the Directional Shearing Cell until failure planes developed. Thereafter, photographs and radiographs were taken of each sample so that the orientation of the failure planes could be detected. A positive of a radiograph of a failure sample ($\Psi = 30°$) is shown in Fig. 6a.

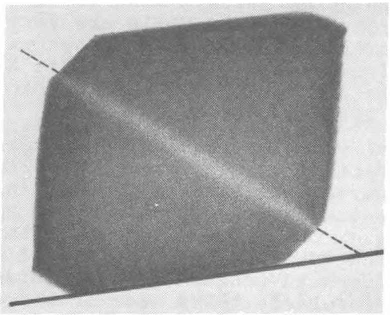


Fig. 6a Radiograph

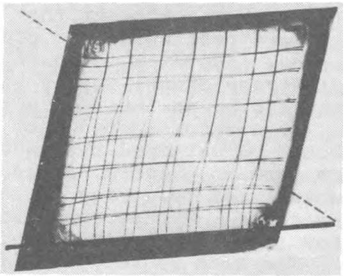


Fig. 6b Photograph

Fig. 6 Failed Sample

The failure plane is associated with the lighter region in the figure. It was also possible to detect failure planes using photography. The failure plane can easily be seen when two photographs, one prior to and one after slip occurs, are superimposed. Fig. 6b shows such a superposition. Both illustrations in Fig. 6 are from the same test, and it can be seen that both methods give failure planes with the same orientation.

RELIABILITY OF RESULTS

The following is a summary of the checks and precautions taken throughout this work to obviate the possibility of errors:

1. Samples were prepared perpendicular to the plane strain sides. Homogeneity of the samples was checked using radiography and also by determining the void ratio of discrete units which had been solidified using a soap grouting technique (Assadi, 1975). The void of the samples were filled with a hot liquid soap solution (1000 cc of water, 120 grams of Lauric acid and 34 grams of sodium hydroxide)

After 2-3 hours of cooling, the soap had solidified and it was possible to cut the sample into small cubes. The void ratio of each unit was calculated, and found to be 0,72 ± 0,03 throughout the sample.

2. The strength and the stress-strain relationship for all tests in which the major principal stress direction was maintained constant up to failure, gave a unique stress-strain curve irrespective of the values of Ψ. Confirmation of this stress-strain relationship was obtained by comparing with results from Stroud, (1971).

   The angle of friction for both dense and loose Leighton Buzzard sand obtained in the Directional Shearing Cells are very close to those obtained from other apparatus at similar stress levels, (Stroud, 1971; Assadi, 1975; Arthur et al, 1977a,b; and Rodriguez del C, 1977).

3. Internal checks were made to decide whether the effect of unloading samples after reaching a certain stress ratio could influence the resulting stress-strain curve upon reloading. Checks were made by unloading and reloading with the major principal stress direction held constant. The stress-strain curves for these tests were identical to those in which the samples were not unloaded.

4. The apparatus was designed with the aim of applying both normal and shear stresses as uniformly as possible over all the surface of the sample. It was thought that flexible boundaries were best suited to produce uniform stresses. However, a check on the uniformity of stress cannot easily be made directly, therefore, an indirect approach was adopted. It was considered that if uniform strains could be obtained throughout an initially homogeneous uniform sample, then uniform stresses must be acting on the sample to produce them. Photographs and computer output show that the strain is uniform up to failure. The high degree of uniformity of strains indicates that the sample was free of extraneous apparatus interference, and that the stresses applied through the flexible boundaries ensure a uniform stress distribution.

It was considered that the above checks were sufficient to show that the stress-strain results were authentic.

CONCLUSIONS

An apparatus capable of applying normal and shear stresses uniformly to each of the four sides of a cubical sample under plane strain conditions was developed. It allows freedom of sample deformation up to 16% major principal strain. The stresses are applied via flexible boundaries. The working range of the apparatus is limited to 150 kN/m^2.

Loose dry samples of Leighton Buzzard Sand prepared by pouring through air were tested. The pluviation produced a void ratio of 0,72 ± 0,03. Strain measurements were made with an accuracy of ± 0,2% from photographs taken after each loading increment.

The friction angle was measured to be $\phi' = \text{const.} = 40° \pm 1°$. The orientation of the failure planes for tests in the Directional Shearing Cell were compared with failure planes from other flexible boundary apparatus. For both loose and dense samples the orientation of the failure planes were in all cases found to be very near to $\pm \left[45° - 1/4\ (\nu + \phi') \right]$.

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