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The Shearing Resistance of a Fine Closely Graded Sand

La résistance au cisaillement d'un sable fin à grain uniforme

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Summary

A series of tests to determine the shear strength of a fine sand was made using a triaxial cell machine and a shear box. A number of constant volume (undrained) triaxial tests was also made. These tests show:—

- (1) The compressibilities of the sand wet or air dry are the same.
- (2) The angles of shearing resistance of the sand are the same, wet or air dry, if tested under otherwise the same conditions.
- (3) At a porosity of about 42% the shear box and triaxial give approximately the same angle of ϕ . Below this porosity the shear box gives an angle about 10% higher, and above this porosity it gives an angle about 5% lower.

Introduction

The sand used in the experiments was a closely graded river sand having the grading curve shown in Fig. 1. The average Specific Gravity of the grains was 2.654. Using this value the maximum porosity (dry) (Kolbuszewski, 1948) was 46.8%: in the tests the loosest sample placed was 46.95% and the densest approximately 38%. The grains under the microscope appeared rough, the predominant mineral being colourless quartz.

Compressibility tests under an all-round pressure in the triaxial cell gave the curves shown in Fig. 2. It will be seen that there is no marked difference in the compressibilities of the wet and air dry samples.

The permeability varied from 8×10^{-3} cm/sec at a porosity of 38% to 2×10^{-2} cm/sec at 46%. This high permeability implies that any pore water pressures tending to build up locally during shear will rapidly become uniform throughout the sample; thus a rapid rate of strain could be used in the drained shear tests without the risk of a pore water pressure built up. Similarly in the undrained tests the pore water pressures could be measured at the base of the triaxial specimen with the assumption that the same pressures existed at the failure planes.

Sommaire

Une série d'essais ont été entrepris pour déterminer la résistance au cisaillement d'un sable fin au moyen de l'appareil triaxial et de la boîte de cisaillement. Simultanément des essais triaxiaux à volume constant (non drainés) ont été exécutés. Les résultats indiquent que:

- 1° Les caractéristiques de la compressibilité du sable sont les mêmes, qu'il soit saturé ou sec.
- 2° Les angles de résistance au cisaillement de deux échantillons de sable, l'un saturé, l'autre sec, sont identiques s'ils sont déterminés dans les mêmes conditions.
- 3° Avec une porosité approchant 42% la boîte de cisaillement et l'appareil triaxial indiquent à peu près le même angle ϕ . Au-dessous de ce degré de porosité l'angle indiqué par la boîte de cisaillement est supérieur de 10%, au-dessus de ce degré de porosité il est inférieur de 5%.

The triaxial cell and shear boxes are similar to those described in detail by Skempton and Bishop (1950).

Setting up Triaxial Samples

The general hydraulic arrangement used in the triaxial tests is shown in Fig. 3. By shutting off the appropriate parts of the system three types of test could be carried out as follows:—

- (a) undrained triaxial tests measuring pore water pressures;
- (b) drained triaxial tests measuring volume changes (saturated);
- (c) drained triaxial tests measuring volume changes (air dried).

In the undrained triaxial tests considerable care was taken to ensure that both the hydraulic system and the sample were free of air. This point is of considerable importance, for even a small amount of air can affect the results. The hydraulic system was therefore checked before each test by fitting a sealing bolt at the sample end of the pore water drainage channel. A pressure of 200 lbs./sq.in. was then applied behind the mercury capillary, and if the mercury thread did not advance more than about 5 mm (this was probably due to expansion of the

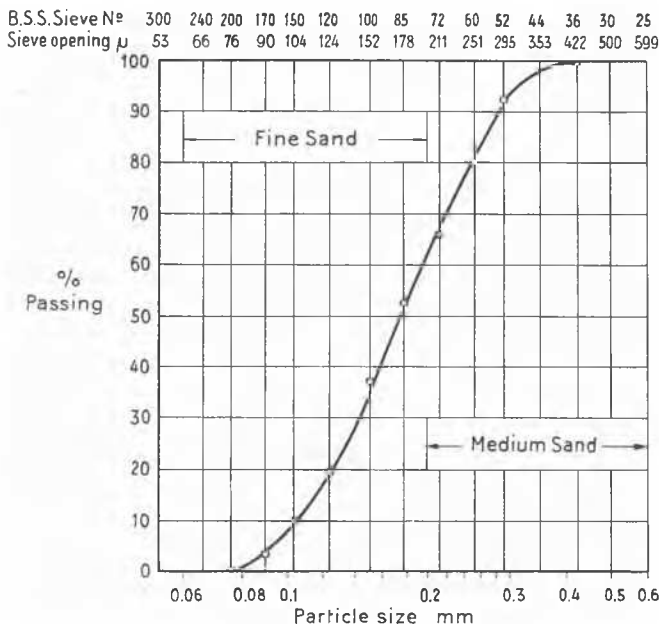


Fig. 1 Grading Curve of Sand Used in Tests
 Analyse granulométrique des sables examinés

system) the hydraulic system was considered air free. The pressure was maintained for 15 minutes to ensure there was no leakage in the system. If a greater movement than this was recorded water was drawn back through the mercury chamber to remove the air bubbles; water was also flushed from the burette into the cell.

The sand was boiled to remove all air: it was then deposited under water into the rubber membrane which was held in position by a split mould.

Before placing the top platten the burette was raised slightly so that the sand just tended to heave. This was sufficient to level the surface but not to segregate the fines, and it got the sand into a very loose state of packing. Where a test at a high porosity was required the top platten was then sealed in position. For a more dense sample the split mould was first tapped, the amount depending on the porosity required.

The burette was then lowered to apply an effective pressure of 1 lb./sq.in. when the sample could stand without support from the mould.

Next the sample dimensions were taken in order to calculate the porosity. The greatest care was taken over this since a small change in porosity can alter the strength very considerably. The height was measured to the nearest $\frac{1}{1000}$ in. by a single reading to the top of a ball bearing placed on the upper platten. Four readings of the diameter were taken, again to the nearest $\frac{1}{1000}$ in. by screwing in two micrometers, rigidly mounted a known distance apart, until they just touched the membrane.

The outside of the cell was then fitted in position and a cell pressure of 2 lbs./sq.in. was applied as the negative pore pressure was removed.

Undrained Triaxial Tests

The cell pressure was then increased until the required consolidation pressure was reached, either 5, 25, or 50 lbs./sq.in. The burette was then sealed off and the cell pressure increased to a further value. This would have tended to consolidate the

sample by expelling water through the capillary, had a corresponding back pressure not been applied by the screw cylinder to the other side of the mercury chamber to maintain the mercury thread in its original position. The pressure applied in the screw cylinder thus gives a direct measure of the pore water pressure within the sample.

As indicated by *Bishop* (1950) the rise in the pore water pressure after consolidation equals the amount of the cell pressure increment since the grains and water may be considered incompressible and no further consolidation is allowed. If the rise in the pore pressure is less than the increase in cell pressure, it may be due to air in the sample, since the volume of the sample would then decrease by compressing the air. Owing to the precautions taken this never occurred to any marked extent, typical readings being as follows:—

Cell Pressure (lbs./sq.in.)	Pore Water Pressure (lbs./sq.in.)
5	0
75	69.8

Apart from air such a difference could also be accounted for by the expansion of the system already referred to. A breakdown of the sand structure due to vibration as the cell pressure was being built up would tend to cause further consolidation by expelling water from the sample, and to prevent this the pore water pressure would have to be increased. If this happened the final pore pressure reading might be 70.2 lbs./sq.in. Care had to be taken to maintain the mercury thread in its exact position after the pressure had been built up, for the sample was left at this stage for 15 min to ensure there was no leakage in the membrane. If through leakage anywhere on the screw cylinder side of the mercury chamber the mercury thread is allowed to fall in the capillary, the sample will consolidate slightly, and when the mercury is restored to its correct posi-

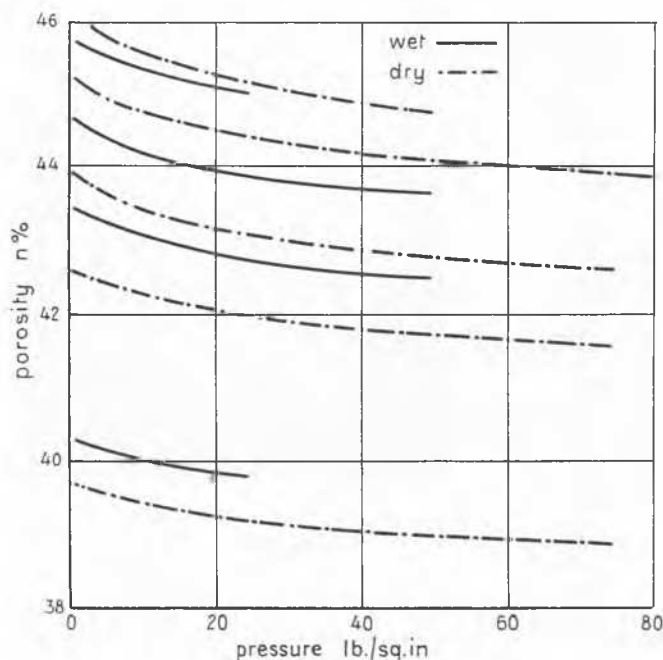


Fig. 2 Compressibility Curves
 Courbes de compressibilité

tion this over-consolidation will be shown up by a rise in pore pressure, e.g. to 70.4 lbs./sq.in.

Vertical strain was then applied to the sample. The effect of this is to re-adjust the positions of the grains relative to one another and each grain may be imagined as slipping into a more comfortable position. There is therefore an initial tendency for the overall volume to decrease (a phenomenon observed in all drained tests); but this is not allowed in the constant volume test, for as the water tends to be pushed out through the capillary the pressure in the screw cylinder is increased to maintain constant the overall volume. The effect of

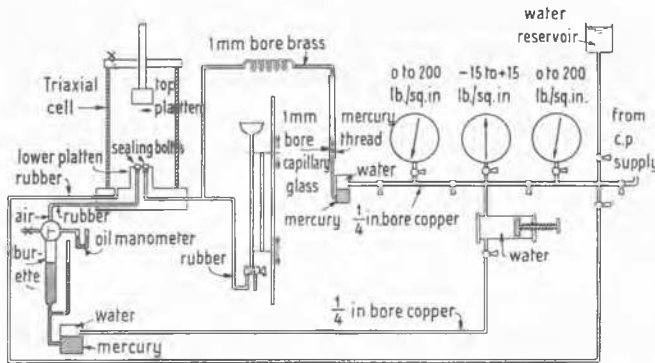


Fig. 3 Hydraulic Lay-out for Triaxial Tests (Diagramatic)
Schéma hydraulique des essais triaxiaux

the initial strain is therefore to reduce the intergranular stress and raise the pore pressure, and in a very loose sample the pore pressure may continue to rise for the greater part of the test. In a more dense sample, however, as the strain proceeds the grains have not the same latitude in which to manoeuvre, and the time comes when instead of attempting to reduce the overall volume the grains climb up on one another and attempt to

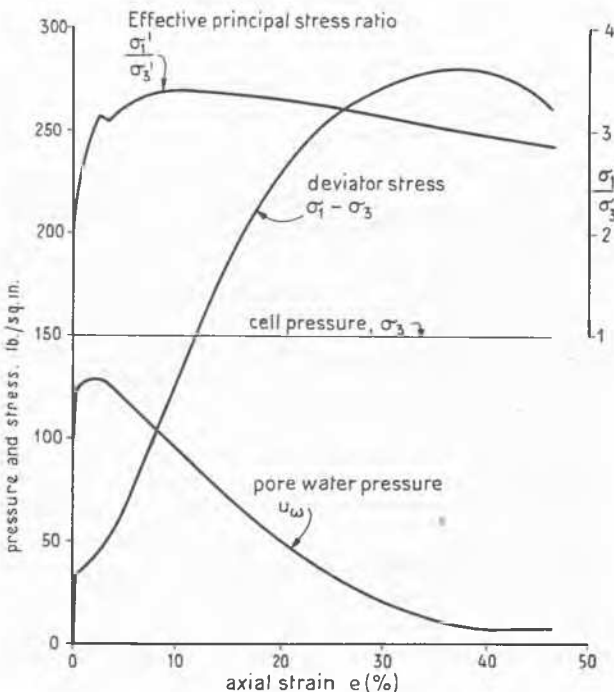


Fig. 4 Readings Taken in Constant Volume Test ($n = 43.5\%$)
Lectures au cours d'un essai triaxial à volume constant non drainé ($n = 43.5\%$)

increase it. This is resisted by decreasing the pressure in the screw cylinder, so that the effect of the further strain is to lower the pore water pressure.

When the pore pressure becomes constant the test is completed. The procedure was then to reduce the cell pressure until the pore water pressure was -1 lb./sq.in., to lower the burette, and to open the valve connecting it to the sample. Then the burette was quickly raised and the sample simultaneously removed from the lower platten. The system was then sealed off, ready for the next test, and the sand was carefully recovered and weighed.

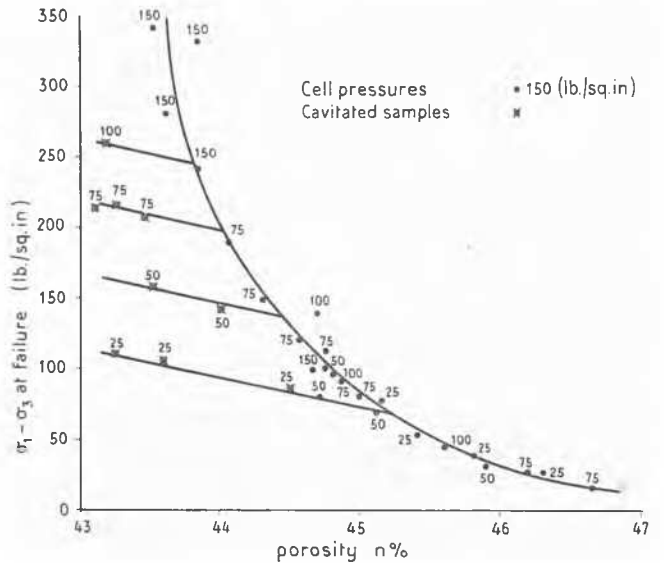


Fig. 5 Relationship between $(\sigma_1 - \sigma_3)_f$ and n for Constant Volume Tests
Rapport entre $(\sigma_1 - \sigma_3)_f$ et n pour essais triaxiaux à volume constant non drainés

Drained Triaxial Tests

Wet. Exactly the same procedure in setting up was followed, consolidation pressures of 5, 25, 50 and 75 lbs./sq.in. being used. After consolidation the connection to the micro-burette was left open so that the pore pressure remained at zero throughout the test and volume changes were read directly off the burette.

As observed above, under strain the sample initially decreases in volume, dense samples subsequently showing an increase.

Air Dry. For these tests the wet channel was sealed off and the dry channel used. The samples were placed in a similar way. Mercury was then pushed up the burette while its top cock was open to atmospheric pressure; this was then closed and the mercury was lowered to place the sample under an effective stress. After the cell pressure had been applied the air in the burette was maintained at atmospheric pressure by adjusting the mercury to keep the sensitive oil manometer balanced. Thus changes of the sample volume were read directly off the burette.

Mechanism of Failure

When a shearing stress is applied to a body on a plane surface the full shearing resistance is reached as soon as the body commences to slide. If the plane is not horizontal the measured

resistance includes the work done in changing the level of the body. Similarly in these shear tests the resistance includes the external work done in changing the volume against the cell pressure. Where the volume is maintained constant no external work can be done.

Shear in a granular material is progressive since not all the grains move the instant that shear is commenced. The full internal friction is not mobilised until all the grains are just moving. In a dense sample this soon happens, but the shearing resistance nevertheless continues to rise after this point until the rate of change of volume increase is a maximum. In the constant volume test it is probable that dilatancy occurs on the failure planes owing to the non-uniformity of stresses at larger strains; but an overall volume change, and therefore external work, is prevented by controlling the pore water pressure to keep the volume constant. When the pore pressure ceases to fall the maximum strength has been reached. If, however, the pore pressure approaches zero absolute pressure (-14.7 lbs./sq.in. approx.) the free water boils and no further increase in strength will occur.

In the constant volume test the pore water pressure at the start of the test depends on the amount the cell pressure has been increased over the consolidation pressure. For dense samples a large increase, i.e. a high cell pressure, must be allowed if the sample is to mobilise its full strength by avoid-

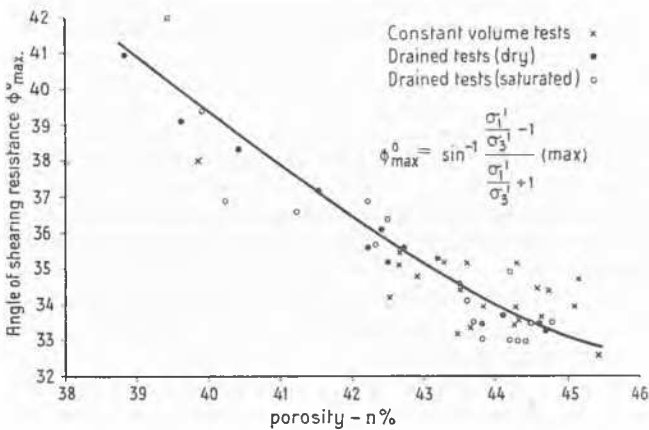


Fig. 6 Change of ϕ with Porosity, Triaxial Tests
Variation de ϕ en fonction de la porosité, essais triaxiaux

ing cavitation. This was demonstrated by consolidating a sample to 5 lbs./sq.in. and raising the cell pressure to 75 lbs./sq.in. (the pore pressure was then 70 lbs./sq.in.). Under strain the pore pressure first rose to 72.8 lbs./sq.in. and then fell until it reached about -14 lbs./sq.in. At this point the full strength appeared to have been mobilised, but by increasing the cell pressure to 100 lbs./sq.in. the pore water pressure was correspondingly increased to 11 lbs./sq.in. and the strength again increased until the pore pressure had dropped to 5 lbs./sq.in. when the full strength had been obtained. A further increase in cell pressure brought no further increase in strength.

Triaxial Results

Fig. 4 shows a typical set of results for a constant volume test. The principal stress difference ($\sigma_1 - \sigma_3$) at failure is a measure of the strength of the sample. Fig. 5 shows this stress plotted against porosity (after consolidation) for the constant volume tests. Apart from the dense range where the samples



Fig. 7 Sample with a Single Failure Plane
Echantillon présentant une surface unique de rupture



Fig. 8 Sample with Multiple Failure Planes
Echantillon présentant plusieurs surfaces de rupture

have cavitated it will be seen that the strength is independent of the cell pressure used, that is to say, if *Mohr* circles are plotted with respect to total stresses at failure for any given porosity, the envelope will exhibit no increase of τ for increasing σ ; the sand behaves like a $\phi = 0$ material. Since

porosity after consolidation is used in this plot the effect of consolidation pressure appears to be unimportant (for this sand, at any rate).

When the results are considered using effective stresses the relationship shown in Fig. 6 can be obtained. The angle ϕ may be calculated either from the principal stress difference or from the ratio. In a drained test the two methods give an identical result, but in an undrained test the principal stress ratio reaches its peak before the principal stress difference is a maximum, and gives a higher value of ϕ . Thus if ϕ is calculated at the maximum principal stress difference, it is found that the value from drained tests are a few degrees higher than those from un-

Setting up Shear Box Samples

The procedure was to place the inner shear box in position in the machine, and to take depth readings on each corner of the lower porous plate using a 2-inch travel $1/1000$ in. dial gauge, and the edge of the outer box as datum. This necessitated only two settings of the dial gauge as the whole box could be moved on its ball bearing runners. The sand was then poured in dry from a funnel, the surface levelled off, the grid and porous plate placed in position, and four further height measurements made. Samples to be tested wet were then flooded by filling the outer box with water. The porosity was calculated after consolidation.

Shear Box Test Results

These are plotted in Fig. 9. The scatter is considerable and other than broad deductions cannot be drawn from them. However, it is apparent that for the shear box also the angle ϕ for wet and dry samples (either air or oven dried) is of the same order.

Comparison of Results

Fig. 9 shows also the $\phi-n$ line taken from Fig. 6. From this it can be seen that at a medium porosity the shear box gives angle ϕ the same order as that given by the triaxial. Denser samples give a higher angle in the shear box, looser samples a lower angle.

Conclusions

- (1) The compressibility characteristics of the sand are the same, wet or dry.
- (2) The angle ϕ of the two samples of the sand, one wet and the other air dry, are the same if tested under the same conditions.
- (3) Drained tests in the triaxial show less scatter than those in the shear box. Undrained tests in the triaxial show more scatter than drained tests.
- (4) At a medium porosity the shear box and triaxial give much the same angle of ϕ . Dense samples in the shear box give an angle about 10% higher than the triaxial; loose samples an angle about 5% lower.

Acknowledgment

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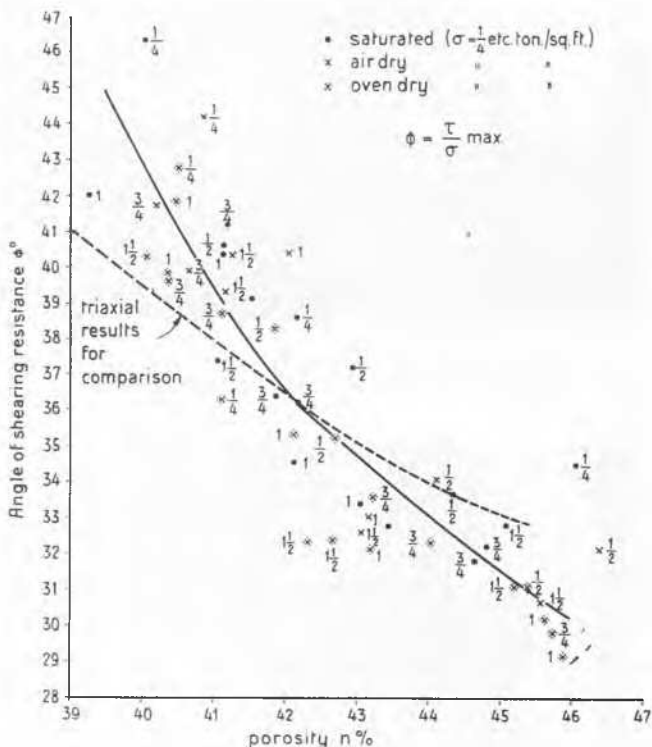


Fig. 9 Change of ϕ with Porosity, Shear Box Tests
Variation de ϕ en fonction de la porosité. Essais dans la boîte de cisaillement

drained tests. When compared on the basis of the maximum principal stress ratios they appear to give about the same values.

Before the technique of sample preparation had been perfected many of the samples failed pronouncedly on a single failure plane (Fig. 7). The samples failed at a lower strain than those having multiple failure planes (Fig. 8) and they all had a lower strength. Apart from this the main factor affecting strength appeared to be the porosity after consolidation.

The results of the drained tests showed no appreciable difference in the angle ϕ for wet and air dry tests.