Scale effects in direct shear tests on sand

L'effet d'échelle dans les essais de cisaillement à la boîte dans les sables

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SYNOPSIS: This paper presents the results of laboratory tests using a large direct shear apparatus (1 m x 1 m x 1 m soil samples). The box was fully instrumented with pressure cells in the internal end walls and a photographic technique was used to assess the strains in the sand mass. Two smaller direct shear devices were also employed to study the effect of scale on test results. The results obtained showed that the shear zone thickness at the sample mid-height is scale dependent and that non-uniformities of strain and stress distributions along the central region occur. It was also suggested by the results that non-coaxiality between stresses and strain increments prevailed.

1 INTRODUCTION

For decades the direct shear test has been used as a mean of obtaining strength parameters for soils. Despite this wide utilization, very few attempts to study factors affecting the test results or the test itself have been found in the literature. Recently, the direct shear test has deserved more attention by researchers with the publication of works by Jewell (1980), Dyer (1985), Potts et al (1987) and Palmeira (1987). The simplicity presented by this test, in contrast with the complexities of tests that were intended to substitute it, has kept the direct shear test in use in day to day work in geotechnical engineering.

The direct shear test is specially recommended for testing free draining soils. Results of tests with this apparatus, save for some few exceptions, have been restricted to the use of the standard Casagrande shear box. This paper presents results on the investigation of the behaviour of sand in a large direct shear box. Results obtained in smaller devices are also presented for comparison.

2 DESCRIPTION OF APPARATUS AND SOILS USED IN THIS WORK

A large direct shear box designed for the study of soil samples reinforced by inclusions (Palmeira, 1987) was also employed for the study of unreinforced sand. The box is schematically shown in Figure 1. It allows soil samples with 1 cubic metre (1m x 1m x 1m). The end walls were lubricated with double layers of polythene, grease and oil. A rubber bag filled with water provided the vertical pressure on top of the sample and allowed the measurement of vertical displacement on top by monitoring the outflow of water from the bag. The shear load was applied by a jack connected to an hydraulic system while relative displacements between both halves of the box were obtained by an inductive displacement transducer. Total pressure cells were installed on the side wall of the box which transfer the shear load to the sample, and a

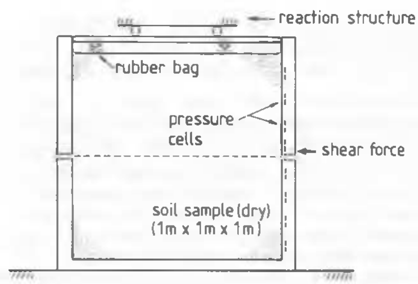

Figure 1. Schematic view of the large shear box.

perspex wall on the front face of the box allowed the measurement of marker displacements using a photographic technique. More details of the equipment can be found in Palmeira (1987).

The other direct shear devices used for the present study were the standard Casagrande shear box, which allows samples of 60 x 60 x 32 mm , and a medium size shear box for soil samples of 252 x 152 x 152 mm, which was initially used by Jewell (1980). The same boundary conditions used in the large shear box were provided for the smaller ones.

Leighton Buzzard sands 7/14, 25/52 and 14/25 were used in the experiments. Only the latter was used in tests with the large shear box. Table 1 summarises the general characteristics of these sand samples in terms of particle size ranges, mean particle diameters (D_{50}) and Relative Density Indices (I_D). All sand samples were prepared by pluviation in order to obtain a dense and uniform sample. All tests performed by the authors were carried out under 30 kPa vertical pressure and 0.5 mm/min testing speed.

3 TEST RESULTS

A series of tests was performed with the three direct shear devices described above using Leighton Buzzard sand 14/25. Table 2 summarises the results obtained in terms of mobilised

Table 1. Main characteristics of Leighton Buzzard sands.

Sand	Particle Size (mm)	D_{50} (mm)	I_D (%)
25/52	0.2 - 0.6	0.4	87
14/25	0.6 - 1.2	0.8	87
7/14	1.2 - 2.0	1.6	86

Table 2. Summary of test results with Leighton Buzzard Sand 14/25.

Shear Box	t (mm)	ϕ_{ds} (deg)	$(d\delta_y/d\delta_x)_{max}$
Small	9 ± 2	50.1	0.306
Medium Size	18 ± 2	50.2	0.319
Large	100 ± 10	49.4	0.311

friction angle on the central plane (ϕ_{ds}), maximum rate of increase of the mean vertical displacement at the top boundary with shear displacement ($d\delta_y/d\delta_x$) and the thickness of the shear zone at mid-height of the sand sample (t). The shear zone thickness was obtained by visual inspection through the perspex wall of the shear boxes (medium size and large shear boxes) and by thin wires placed vertically inside the sample crossing the central plane (all three boxes). Figure 2 presents the test results in a non-conventional form where the shear stress normalised by the vertical stress was plotted against the shear displacement normalised by the shear zone thickness. From these results it can be observed that the shear zone thickness and the post peak behaviour of the sample were significantly affected by the scale of the test. The sample in the large box continues to dilate at large strains while in the smaller boxes the critical state has already been reached.

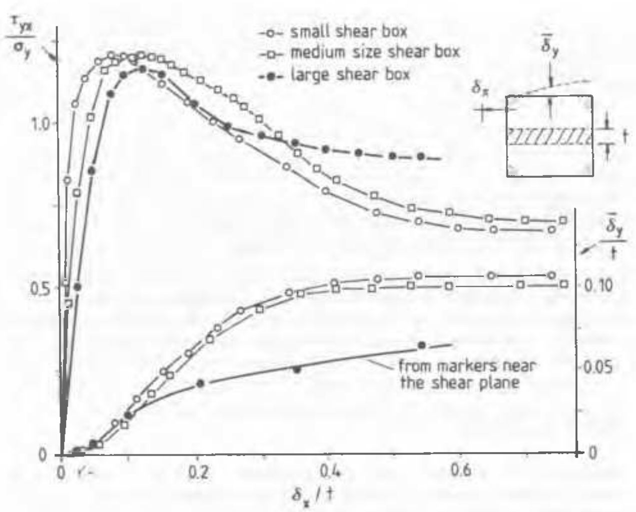

Figure 2. Direct shear test results

The effect of the scale of the test on the shear zone thickness can be observed in Figure 3 where the ratio between the shear zone thickness and the sample height (t/H) is plotted against the sample height to mean particle diameter ratio (H/D_{50}) for several tests with Leighton Buzzard sands. Data found in the literature are also presented in this figure. This form of data presentation produces a consistent pattern showing the increase in the thickness of the shear zone in relation to sample height when the size of the sample decreases in relation to the soil particle size.

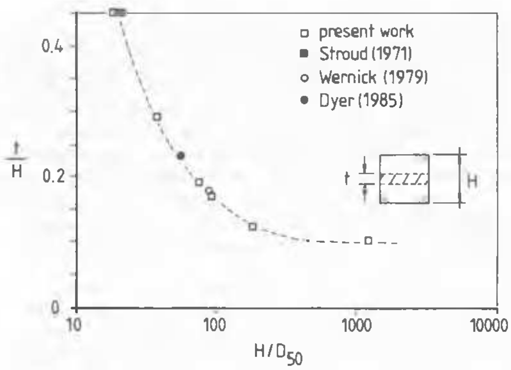

Figure 3. Influence of scale on the shear zone thickness.

Figure 4 presents the horizontal total stress distribution on the side wall of the large shear box which transfer the shear load to the sample, in tests with Leighton Buzzard sand 14/25. A non-linear stress distribution with a considerable increase in the total stress as one approaches the central region of the sample can be observed. This stress distribution allows one to study the forces acting on the soil block formed by the sample top half. These forces are presented in Figure 5. If one assumes a trapezoidal distribution of vertical stresses on the central plane, for the sake of simplicity, the following expressions for the value of the pressures at the ends of the central plane can be derived:

$$\sigma_{yA}/\sigma_y = 1 + 2(3d_p/L - \tan\delta)(\tau_{yx}/\sigma_y)$$
$$\sigma_{yB}/\sigma_y = 1 - 2(3d_p/L - 2\tan\delta)(\tau_{yx}/\sigma_y) \quad (1)$$

Substituting values in expressions (1) one obtains that $\sigma_{yA}/\sigma_{yB} \simeq 2$. This difference in stress levels at the corners of the sample leads to the conclusion that progressive failure must have happened in tests with the large shear box. This was confirmed by the distribution of shear strains along the central region of the sample obtained from the markers movements, which shows higher levels of shear strain at peak stress ratio in regions of lower stress levels and vice-versa, as shown in Figure 6.

The observation of strain patterns in tests with the medium size and the large shear boxes showed that one of the zero extension lines lies

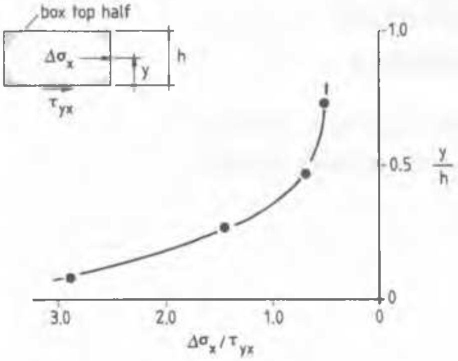

Figure 4. Total stress distribution on the side wall of the large shear box.

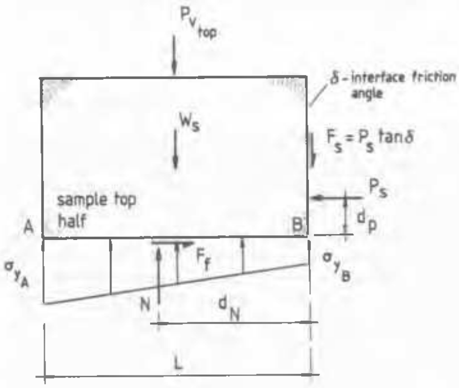

Figure 5. Forces on the sample top half.

horizontally in the central region of the sample. The strain patterns in both boxes also revealed approximately the same value of dilation angle for Leighton Buzzard sand 14/25 of about 24 degrees. This value is close to the value obtained by Stroud (1971) using a simple shear device. The assumption of coaxiality between strain increments and stresses would yield a plane strain friction angle of 57.1^{o}. This value is much higher than the 49.4^{o} value obtained for the friction angle in the direct shear box with flexible top boundary based on the assumption of maximum obliquity. Actually, the latter value is close to the plane strain friction angle obtained by other authors using the same sand under the same operational conditions in other plane strain devices (Stroud 1971 and Arthur et al 1977). Recent discussions on the friction angle obtained in direct shear tests can be found in Jewell (1988).

The assumption of maximum obliquity is reinforced if one takes into account the horizontal stress to shear stress ratio in the central region of the sample at peak. From the Mohr circles of stresses and strain increments one has:

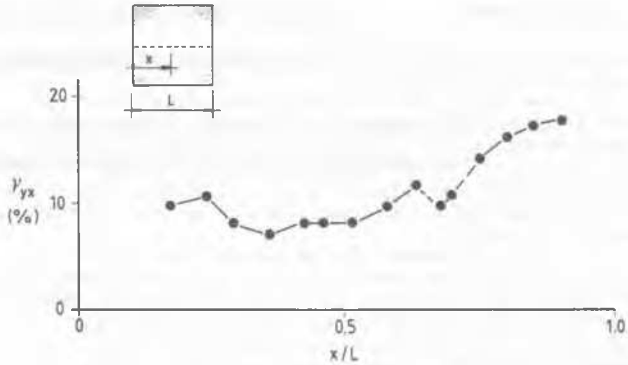

Figure 6. Shear strain distribution in the central region of the soil sample in the large shear box.

Maximum Obliquity Concept:

$$\sigma_x/\tau_{yx} = 2\tan\phi + 1/\tan\phi$$

Coaxiality Concept: (2)

$$\sigma_x/\tau_{yx} = 2\tan\psi + 1/\tan\phi$$

where: ψ = soil dilation angle and ϕ = soil friction angle.

Evaluating expressions (2), one obtains 3.2 and 1.7 for the horizontal stress to shear stress ratio at peak by the maximum obliquity and coaxiality concepts, respectively. The value 3.2 is close to the value measured by the pressure cells on the side wall of the shear box, close to the central plane (see Figure 4). However, further investigation is needed to check to what extent pressures measured at the boundaries of the box can be extended to the interior of the sample mass.

The balance of energy dissipated during the test ($\dot{E}$) was assessed rewriting Taylor's energy correction (Taylor, 1948) as a flow rule given by the sum of the stress ratio and the vertical strain increment to shear strain increment ratio (Wroth 1958 and Stroud 1971):

$$\frac{\dot{E}}{\sigma_y\dot{\gamma}_{yx}} = \frac{\tau_{yx}}{\sigma_y} + \frac{\dot{\varepsilon}_y}{\dot{\gamma}_{yx}} = \text{Constant} \qquad (3)$$

From strain measurements in the central region of the sample during tests with the medium size and large shear boxes, approximately the same value of 0.72 for $\dot{E}$ in tests with Leighton Buzzard sand 14/25 was obtained for both scales. This suggests that as far as energy dissipated during the test is concerned the sand sample presents a unique behaviour, independent of the scale of the test. This value of $\dot{E}$ yields a critical state friction angle of approximately 35.8^{o}, if the maximum obliquity criterion is assumed. This value is close to the usual 35^{o} obtained for the critical state friction angle for Leighton Buzzard sand 14/25 by other researchers (Stroud, 1971).

4 CONCLUSIONS

The main conclusions of the present study are summarised as follows:

(1) The scale of the test did not affect the value of friction angle, dilation angle and maximum vertical to shear displacement ratio; the dilation angle obtained from internal strain measurements was significantly greater than the value obtained from measurements at the top of the soil sample.

(2) The thickness of the shear zone at the sample mid-height was significantly affected by the scale of the test as well as the post peak behaviour presented by the sample. A unique behaviour for the sand was observed when the energy involved in the test was taken into account.

(3) The results obtained suggest that progressive failure occurred and non-coaxiality between stresses and strain increments prevailed.

(4) Despite being an old testing technique, the direct shear box can still provide the geotechnical engineer with important data on the strength of granular materials for ordinary geotechnical works, in view of the cost and difficulties for the prectical application of more sophisticated testing devices.

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