Damage to soil structure during triaxial testing

Dommages dans la structure du sol pendant les essais triaxiaux

L.A.BRESSANI, Department of Civil Engineering, Imperial College, London, UK
P.R.VAUGHAN, Department of Civil Engineering, Imperial College, London, UK

SYNOPSIS Weakly bonded soil such as residual soil has a brittle structure which may be damaged by disturbance during sampling. It is shown that this structure may also be damaged by laboratory test procedures, including specimen saturation, eccentricity of loading and the adoption of an inappropriate stress path, leading to the inadvertent underestimation of strength and stiffness.

INTRODUCTION

Most residual soils have a weakly bonded structure [Vaughan, 1985 ; Vaughan *et al*, 1988]. This bonding makes them brittle and difficult to sample except by hand excavation. Often they have coarse pores and/or are partly saturated. They then suffer a loss of average effective stress when the average total stress decreases on sampling [unlike a sedimentary clay], and they expand.

The effects of this expansion on structure, strength and stiffness are not yet understood, but there is some evidence that the bond strength and stiffness which are measured in the laboratory are less than those observed in the field [Sandroni, 1985 ; Vaughan *et al*, 1988]. Studies of slope stability in which drained strength has been measured in the laboratory sometimes find that this strength is insufficient to account for observed stability.

The cause of this difference between properties measured in the laboratory and those deduced from field behaviour may be sample disturbance, but testing techniques may also contribute. Comparative laboratory studies are presented here which illustrate the effects of different test techniques. The effects of different techniques of sample saturation, of stress-path and of sample set-up are examined. The conclusions are likely to apply to other weakly bonded soils.

THE MATERIAL USED IN THE EXPERIMENTS

The 'soil' used in this study is an artificial one which simulates the bonded properties of residual soil [Maccarini, 1987 ; Vaughan *et al*, 1988]. It is made by mixing a sand with a wet Kaolin slurry [kb], air drying it so that the clay slurry retreats into the interstices of the sand, and then firing it in an oven. The kaolin then forms a bond between the sand grains. A mixture of quartz sand [qs] and a sand formed by crushing and sieving fired kaolin [ks] may be used to simulate the hard [unweathered] and soft [weathered] grains present in residual soil. Bond strength may be varied according to the firing time and temperature. Dense samples may be made by vibration. Loose samples are made by adding sand made from paraffin wax to the initial mix. When the samples are fired the wax vaporises, giving increased porosity. The material has the advantage over real residual soil that both bond strength and porosity can be varied widely in the same material, with a variation in properties between samples of the same manufacture of only a few percent. However, bonding cannot be introduced under stress, as occurs in geological deposits. All the tests reported were drained and on 38mm dia. specimens.

Yield in weakly bonded materials is seldom abrupt, and definition of yield involves some judgement. There is often an initial slight first yield where some increase in deformation starts, followed by a second more substantial and obvious yield, which is also of more engineering significance [Vaughan *et al*, 1988]. The major second yield is shown here. The nature of the strength and second yield exhibited by a porous residual soil from Basalt [Vaughan *et al*, 1988] is illustrated on Fig 1a, and those from a variant of the artificial soil on Fig 1b. It can be seen that the artificial material shows similar behaviour, strength and yield stress to the natural one.

THE EFFECT OF SATURATION PROCEDURES

The effects were examined of saturating the test specimens [1] by increasing both pore pressure and cell pressure to dissolve pore-air [the back pressure technique], and [2] by flooding them under vacuum. In the latter the dry sample was placed in an air-tight cell, which was evacuated slowly to a 90% vacuum. After 10-15 minutes the cell was flooded slowly with water from the base, the vacuum being maintained. When the cell was full it was kept under vacuum overnight. The vacuum was then slowly reduced to allow any remaining air to dissolve. Saturation of the relatively coarse pored artificial soil was good, a pore pressure response of more than 96% of confining stress being typically observed. The results of three tests, consolidated to an effective stress of 100kPa, on specimens of very porous soil saturated by vacuum are shown as a, b and c on Fig 2. The test results are similar.

Tests d and e were on specimens initially saturated by applying a back pressure. The confining stress and the pore pressure were increased sequentially in small steps of about

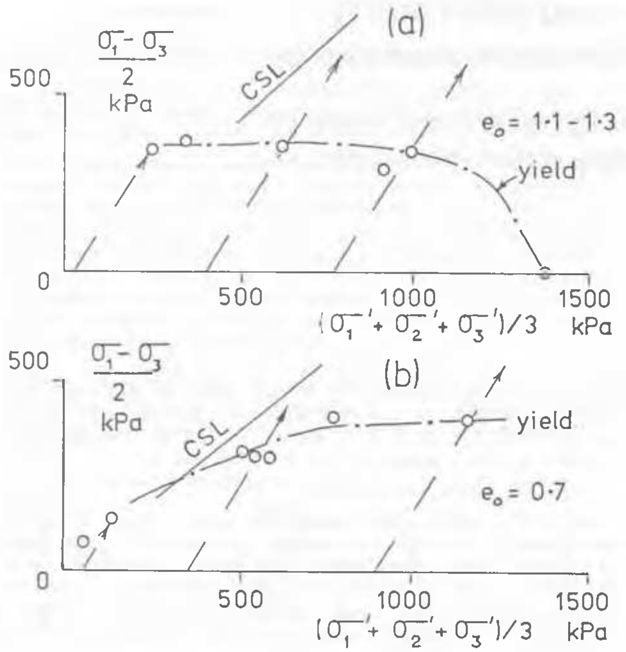

Figure 1. Yield of [a] residual soil from Basalt, [b] artificial soil [57% qs, 30 % ks, 13% kb, fired 500°C for 5 hours]. [After Vaughan *et al*, 1988].

5kPa to a back pressure of 400kPa. Thus the samples were subject to many small loading and unloading cycles of effective stress. They show a yield stress in shear which is about 85% of that shown by the samples saturated by vacuum and not loaded cyclically.

Tests g, h and i [Fig 2] were set up to be saturated under suction, but a leak occurred while the samples were being flooded under vacuum, and air entered the cell. Large and rapid oscillations in pressure occurred, which, since the samples were still partly saturated, resulted in cyclic changes in effective stress, probably of about ±40kPa. The disturbance of the sample caused by these stress changes reduced the yield stress to about 70% of that observed in the samples saturated by vacuum.

Further evidence is provided by five drained triaxial tests on samples made with a lower void ratio [Fig 2]. The samples for tests j, k and l were saturated using the vacuum technique. The results are consistent, showing a variation in yield stress of about ±5%. The sample for test m was loaded isotropically to 60kPa, unloaded to zero, loaded again to 60kPa, unloaded to 25kPa, then reloaded to 60kPa and sheared. The yield stress is substantially reduced. It should be noted that the stress path prior to shearing has gone nowhere near the yield surface determined for this material from tests involving only an increase in stress.

From the above it is clear that quite small cycles of isotropic stress, such as are often applied during conventional sample saturation, can have a considerable effect on the yield stress of weakly bonded soil. Only where continuously variable pressure control is used to elevate both confining stress and back pressure simultaneously can cycles of isotropic stress be wholly avoided. This is only practical when the soil is of relatively high permeability, as is usually the case with residual soil. The success of this technique was demonstrated in one test where both the confining pressure and the pore pressure were increased slowly and together to 350kPa, with the sample then left for three days to enable any remaining air to dissolve. The later process was monitored by the careful measurement of volume change. Only then was the B parameter measured. This sample had a yield stress the same as those saturated by vacuum. Measurement of inflow to the sample is the best way of monitoring saturation when confining stress and pore pressure are elevated together.

Brand [1975] investigated the influence of

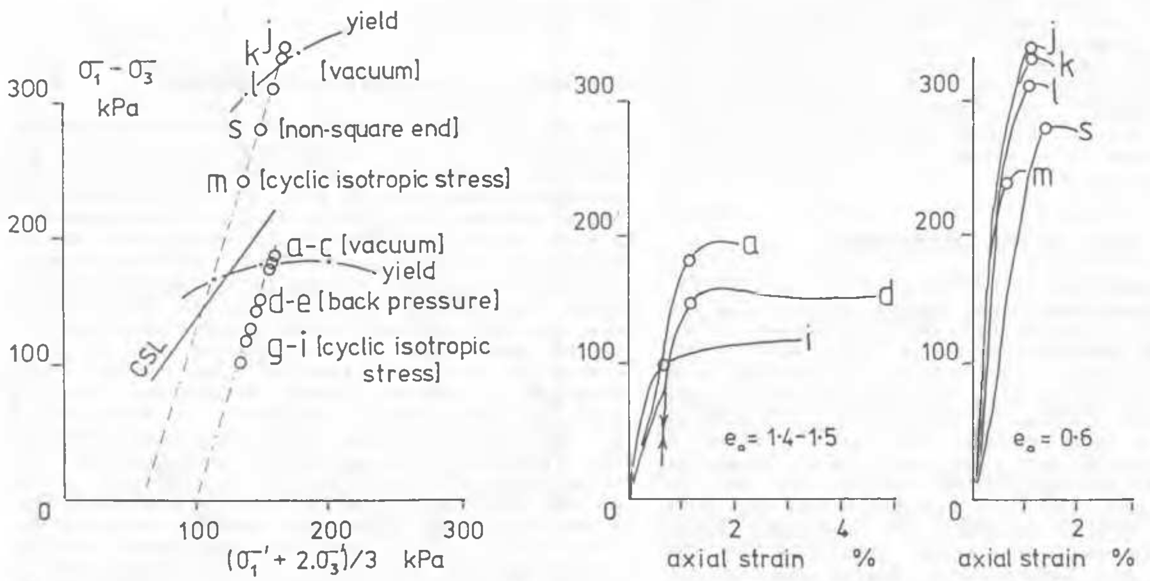

Figure 2. The effect of saturation method and non-square ends on yield and failure of artificial bonded soil. Tests a - i : 57% qs, 30% ks, 13% kb; tests j - m: 87% qs, 13% kb; all fired for 5 hours at 500 °C.

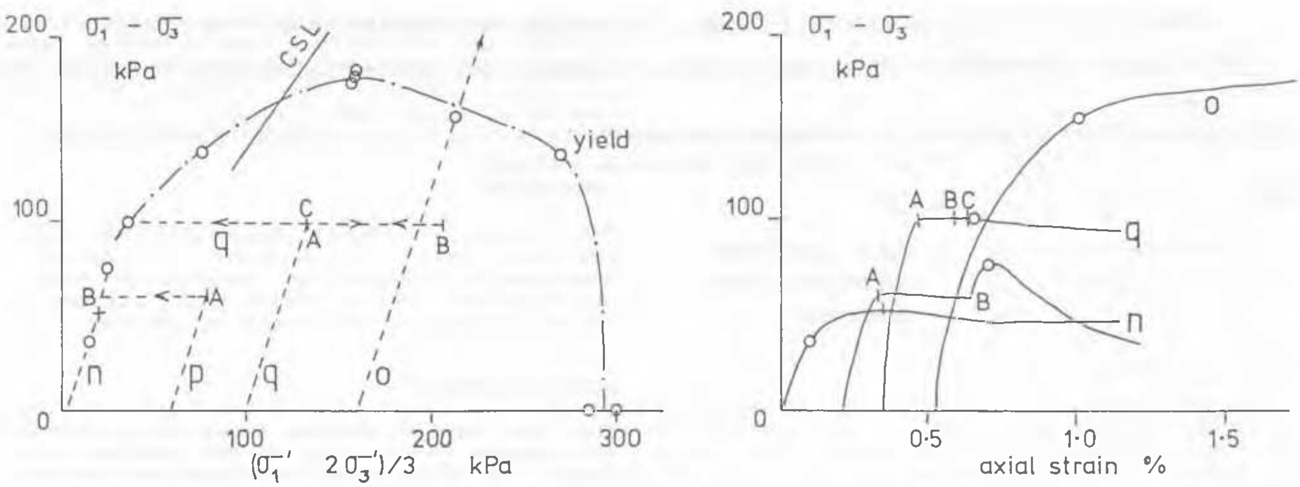

Figure 3. The effect of stress path on yield and failure of artificial bonded soil; 57% qs, 30% ks, 13 % kb, fired for 5 hours at 500°C.

saturation by back pressure on the behaviour of undisturbed samples of soft Bangkok clay. He found that structure was destroyed even when confining stress and pore pressure were increased together. Other similar results have been reported. Dias [1987] found that samples of lateritic soil showed higher strengths when soaked to eliminate initial suctions [giving a degree of saturation of about 85%] than when fully saturated by a back pressure. Soaking generally produces a sample containing only occluded air, when the effective stress is given by the pore water pressure. Thus soaking is sufficient to enable tests to be performed in terms of effective stress. Saturation of residual soils may be best avoided, although this leaves uncertainty in the measurement of volumetric strain through inflow to the sample.

Soaking of a sample of partly-saturated residual soil will decrease the isotropic effective stress within it. Comparison of the strengths of dry and soaked samples, and those in which suction is varied, indicates that this reduction may be several hundred kPa, depending on the coarseness of the pores of the soil [Ho & Fredlund, 1982 ; Dias & Gonzalez , 1985 ; Dias & Gehling, 1985]. Thus even soaking under constant total stress may cause some damage to soil structure. If so, then the determination of the effective stress within a partly saturated sample by comparison of test results from samples in the natural and in the soaked or saturated state may be in error due to the loss of strength caused by soaking.

THE INFLUENCE OF STRESS PATH

A yield surface may be defined from the results of drained triaxial compression tests, as shown for the high-porosity artificial soil on Fig 3. Yield at low stress occurs only slightly before peak deviator stress is reached [Test n of Fig 3]. At higher stress it occurs well before failure [Test o of Fig 3]. Failure coincides with critical state and the complete destruction of bonding by large strains, although these strains may not be attainable in the triaxial apparatus. The low stress region is important in slope stability, as bonding gives a cohesion intercept to the strength envelope.

It can be seen from Fig 3 that a drained compression test performed at low confining stress approaches the yield/failure envelope obliquely. This is shown by test n [Fig 3], performed at a confining stress of 5kPa. The test shows yield at a deviatoric stress of 35kPa. Strains then increase significantly [although remaining small] until a maximum deviatoric stress of 53kPa is reached.

The stress path from drained compression tests is inappropriate for slope stability problems where failure occurs as a result of delayed swelling or increased pore pressure due to heavy rain [Brenner *et al*, 1985]. The more appropriate stress path is shown by tests p and q, in which a confining stress is first applied, followed by a deviatoric stress which is significantly less than that required to cause yield. The sample is then failed by increasing the pore pressure while maintaining constant deviatoric stress. In the case of test p failure had not occurred as zero confining stress was approached. Failure was induced by completing the test as a vertical drained compression test with σ'_3 = 3kPa. It can be seen that the failure points for all three tests lie on the stress path of a drained compression test at a very low confining stress. Despite this the deviatoric stresses reached at failure increase from 53, to 77, to 91 kPa, depending on the path adopted to reach failure. The equivalent values of c', assuming that φ' = 34°, are 12, 20 and 23kPa.

It might be expected that bond strength would decrease with increasing strain, and that the strength observed in the different tests would vary inversely with the strains at failure. If total axial strains from the beginning of the test are considered [Fig 3], then this does not seem to be the case.

It is also of interest that the effect of cyclic changes of isotropic stress, which cause a marked reduction in strength when a sample is subject to them at zero deviatoric stress, do not seem to have the same influence when they act with a positive deviatoric stress. Test q, which shows the highest strength, was subject to one such cycle.

The coincidence between this data and that from 100mm diameter triaxial tests on weathered

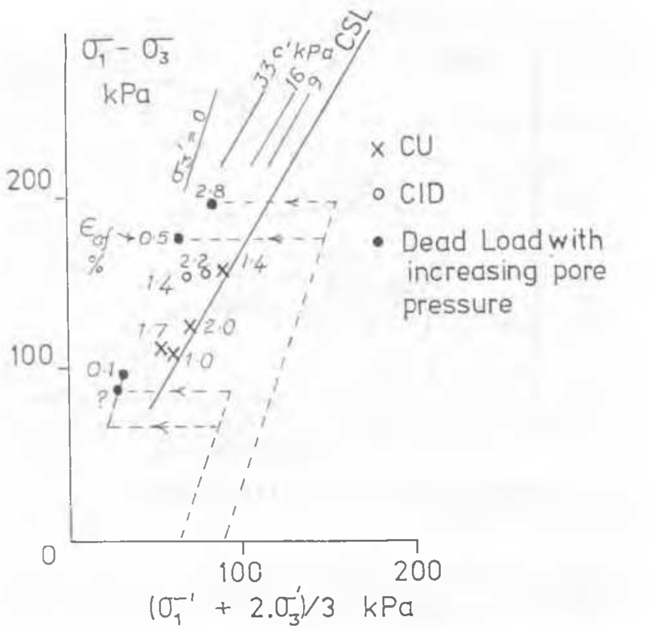

Figure 4. Failure of residual soil from granite in drained [CID], consolidated undrained [CIU], and dead load triaxial tests [Geotechnical Control Office, 1982].

granite from Hong Kong [Geotechnical Control Office, 1982], is shown on Fig 4. Saturated consolidated undrained tests gave the lowest strengths, with a maximum value of c' = 9kPa [with φ' = 42°]. Isotropically consolidated drained tests gave a maximum value of c' = 16kPa, whereas tests in which failure was induced by increasing the pore pressure gave a maximum strength of c' = 33kPa. As with the results on the artificial soil, the results do not correlate with strain at failure, in this case measured from the start of shearing.

It is clear that stress path can have a marked influence on the strength observed at low effective stresses in weakly bonded materials, even when the path does not approach yield prior to failure.

THE INFLUENCE OF CONFORMITY OF THE ENDS OF THE SAMPLE

In the ideal triaxial test the top cap is horizontal and centred on the loading ram. In reality, it often tilts, and, depending on the type of fitting used, the loading ram applies lateral and rotational constraint, resulting in non-uniform loading of the sample. This can cause progressive failure within a brittle sample, and prevent the full effect of a bonded structure from being measured.

The effect is illustrated by test S on Fig 3. The sample was loaded with the flat base of the load cell in direct contact with the top cap. This tilted by 8° during consolidation. During shearing the load was transferred to the edge of the top cap, giving extreme eccentric loading. The yield stress was reduced by some 20% as a result. It is probable that the most effective arrangement is a semi-spherical end to the loading ram, bearing on a rough flat surface to the top cap. Non-uniform loading during initial centring and rotational constraint during shear are then avoided. The effects of lateral constraint during shear remain.

CONCLUSION

The strength of weakly bonded material such as residual soil is strongly influenced by experimental laboratory techniques such as method of saturation, stress path followed prior to failure and non-uniformity of loading.

ACKNOWLEDGEMENTS

The first author has been supported by CAPES and the Federal University of Rio Grande do Sul, Brazil. Dr M Maccarini developed the artificial material used, and kindly provided data for incorporation in this paper.

REFERENCES

Brand, E.W. [1975]. Back pressure effects on the undrained strength characteristics of soft clay. Soils & Foundations. **15**, 3-16.

Brenner, R.P., Tam, H.K. & Brand, E.W. [1985]. Field stress path simulation of rain-induced slope failure. Proc.11th.Int.Conf.Soil Mech.& Found.Engg., San Francisco. **2**, 991-6.

Dias, R.D. [1987]. Application of pedology and geotechnics on design of power line foundations. Ph.D. Thesis, COPPE, UFRJ, Brazil [in Portuguese].

Dias, R.D. & Gehling, W.Y.Y. [1985]. Influence of the macrostructure originating from pedologic process on the mechanical behaviour of lateritic porous soils in southern Bazil. Proc. 1st Int.Conf. Geomech. Tropical Lateritic & Saprolitic Soils, Brasilia. **1**, 255-268.

Dias, R.D. & Gonsalez, M.D.[1985]. Stress-strain -strength behaviour of a Brazillian Amazon yellow latosol. Proc.1st.Int.Conf. Geomech. Tropical Lateritic & Saprolitic Soils, Brasilia. **1**, 239-253.

Geotechnical Control Office [1982]. Mid Levels Study - Report on Geology, Hydrology and Soil Properties. Geotechnical Control Office, Public Works Dept., Hong Kong.

Ho, D.Y.F. & Fredlund, D.G. [1982]. Increase in strength due to suction for two Hong-Kong soils. Proc.Conf.Engg. & Construction in Tropical Residual Soils, Hawaii. ASCE. 263-295.

Maccarini, M.M. [1987]. Laboratory studies of a weakly bonded artificial soil. Ph.D. Thesis, University of London.

Sandroni, S.S. [1985]. Discussion. Proc.1st.Int. Conf.Geomech.Tropical Lateritic & Saprolitic Soils, Brasilia. **3**, 290-296.

Vaughan, P.R. [1985]. Mechanical & Hydraulic Properties of in-situ residual soils. Proc.1st.Int.Conf.Geomech.Tropical Lateritic & Saprolitic Soils, Brasilia. **3**, 231-263.

Vaughan, P.R., Maccarini, M. & Mokhtar, S.M. [1988]. Indexing the engineering properties of residual soil. Quart. Journal Engg.Geol. **21**, 69-84.