Field and laboratory measurements of soil stiffness

Mesure sur place et en laboratoire de raideur de sol

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SYNOPSIS A simple and precise method of measuring local axial strains on triaxial samples is described and it is demonstrated that conventional methods of strain measurement can lead to very significant under estimates of soil stiffness. Results of triaxial tests on samples of London Clay show that the undrained stress-strain behaviour is strongly non-linear but not greatly influenced by sampling or stress-path. The undrained stiffnesses at small strains are in good agreement with values obtained from high quality insitu tests and from back-analysis of field measurements. Good agreement is obtained between laboratory determined undrained stress-strain characteristics and insitu stress-strain behaviour deduced from three instrumented loading tests in London Clay.

INTRODUCTION

The back analysis of observed ground movements associated with foundations and excavations in stiff clays often leads to stiffnesses which are more than an order of magnitude greater than values measured in the laboratory. In the past these differences have been attributed to sample disturbance (Marsland 1971) and the choice of inappropriate stress paths (Parry 1979).

Following the work of Costa Filho (1980) a simple, precise method of routinely measuring local strains on samples has recently been developed (Burland and Symes (1982)). Using this technique Jardine et al (1984) have shown that significant errors can result from conventional methods of strain measurement and that at small strains the actual stiffness is frequently much greater than that deduced from external measurements. In this paper the results of a comprehensive series of laboratory tests, using the new techniques, on samples of London Clay are reported. These data are compared with stiffness profiles derived from high quality insitu tests and stress-strain characteristics deduced from field measurements.

LABORATORY MEASUREMENT OF STIFFNESS

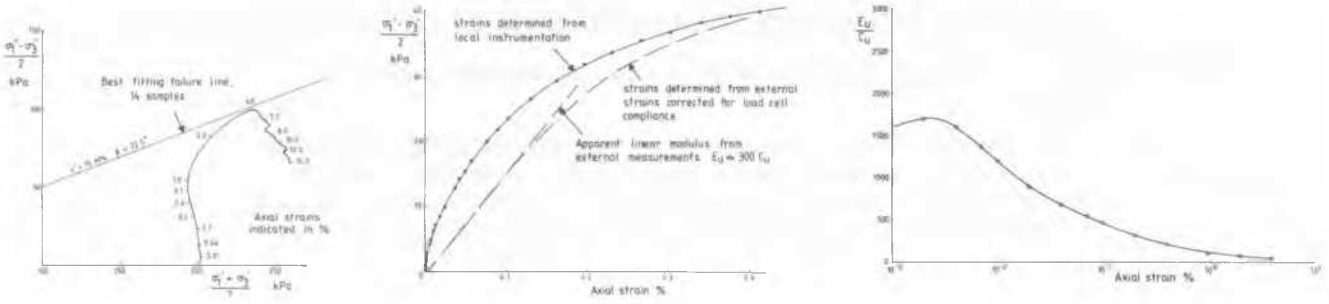
The technique used for measuring the mean local axial strains of triaxial samples makes use of a pair of axial displacement gauges mounted on the specimen. The principle of the gauge is that the relative vertical displacement between two footings bonded to the sample membrane is converted to a rotation by means of a hinged arrangement. The rotation is measured by means of an electrolytic level. The device can resolve to less than 1μm over a range of 15mm, is simple to mount and is not damaged when the sample is taken to failure. A full description of technique is given by Jardine et al (1984).

Two series of triaxial tests have been carried out using the new techniques on undisturbed samples of London Clay from sites at Canons Park in North London and Bell Common in Epping Forest. The samples were obtained by thin walled push sampling and were tested unconsolidated undrained with pore pressure measurement.

The results of a typical test on a sample from Canons Park are given in Figure 1. The observed effective stress path is plotted in Figure 1(a). Values of locally measured axial strain are indicated and it is of considerable practical importance to note that a shear stress equal to a quarter of the failure value is required before a strain of 0.1% is achieved. In Figure 1(b) the stress-strain curves obtained from local and external measurements are compared. It can be seen that the external measurements, which have been corrected for load cell compliance, lead to apparently linear initial stress-strain behaviour. However the local measurements show much stiffer non-linear behaviour.

In Figure 1(c) the results of the internal measurements of stiffness are plotted in terms of E_u/c_u versus log strain where E_u is the secant undrained Young's modulus. The strongly non-linear nature of the sample response is evident with E_u/c_u values decreasing from about 1,700 at 0.003% strain to more commonly accepted values of 100 to 200 at 0.5 to 1.0% strain. It should be noted that the initial linear portion of the externally measured stress strain curve gives an E_u/c_u value of 300 which is approximately six times less than the initial value obtained from internal measurements.

For ease of presentation the stiffness-strain characteristics can be represented by the two parameters $E_{u(0.01)}$, the undrained secant modulus at 0.01% strain, and L, the index of



(a) Undrained stress path. (b) Initial stress-strain behaviour. (c) Stiffness-strain characteristic.

Figure 1. Typical London Clay UU test data (Canons Park 7.3m depth)

linearity defined as $E_{u(0.1)}/E_{u(0.01)}$

COMPARISON OF INSITU AND LABORATORY MEASUREMENTS

Figure 2 shows the results of UU triaxial tests on samples of London Clay from Canons Park, with the soil profile indicated on the same figure. A sharp increase in undrained strength was observed passing from the disturbed to the undisturbed London Clay. There is a corresponding increase in $E_{u(0.01)}$ at around 4.3 metres depth. The values of $E_{u\,(0.01)}$ from Bell Common are also plotted, but with depth defined as distance from the top of the London Clay.

For comparison the distributions of E_u from camkometer and large diameter plate tests carried out nearby at Hendon (Windle and Wroth (1977)) are shown on Figure 2. Also shown is the distribution of E_u with depth obtained from the back analysis of the measured movements of an excavated retaining wall in central London (Cole and Burland (1972)).

The results given in Figure 2 show that the value of $E_{u\,(0.01)}$ is substantially influenced by geological history but does not increase rapidly with depth within the undisturbed London Clay. The values of $E_{u\,(0.01)}$ are considerably larger than apparent values of E_u obtained from high quality insitu tests and field measurements of the settlement of structures. Butler (1975) noted that for foundations on London Clay $E_u \doteq 400 c_u$. These results might be anticipated since the measured boundary displacements for surface loading or pressuremeter tests are strongly influenced by the more highly stressed, lower stiffness, regions. Therefore the back analysis of such measurements using linear elasticity will give stiffnesses which are generally lower than the small strain triaxial values. However the profile of E_u deduced from observations of ground movements around excavations lies closer to the $E_{u\,(0.01)}$ profile. This is thought to result from the weaker influence of locally overstressed zones in such problems (Simpson et al 1979).

It is of considerable interest to note that dynamic values of shear modulus G obtained by Abbiss (1981) using geophysical methods give values of E_u (=3 x G) which are approximately 30% greater than the values of $E_{u(0.01)}$ found in UU tests.

INFLUENCE OF STRESS HISTORY

To investigate the influence of stress history and stress path on undrained stiffness a number of laboratory tests were carried out on reconstituted London Clay. The samples were consolidated one-dimensionally from a slurry and further consolidated and swelled back under K_o conditions to various overconsolidation ratios using a triaxial stress path cell. Undrained compression and extension tests were then carried out.

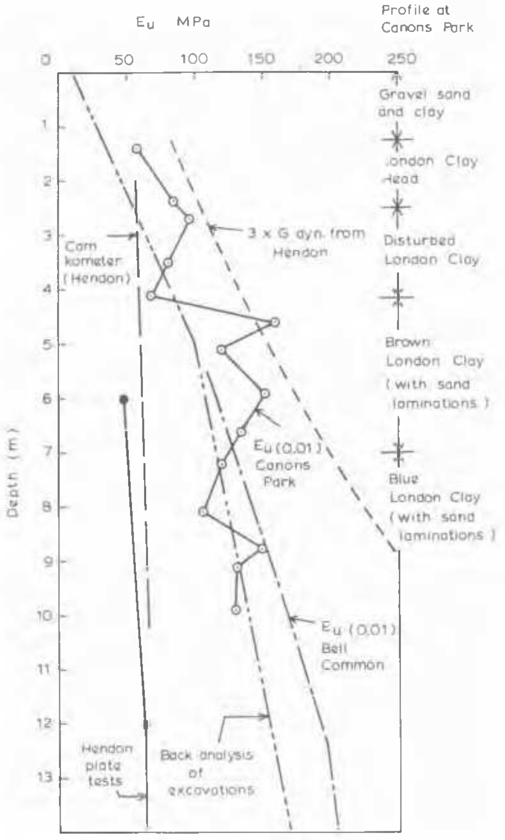
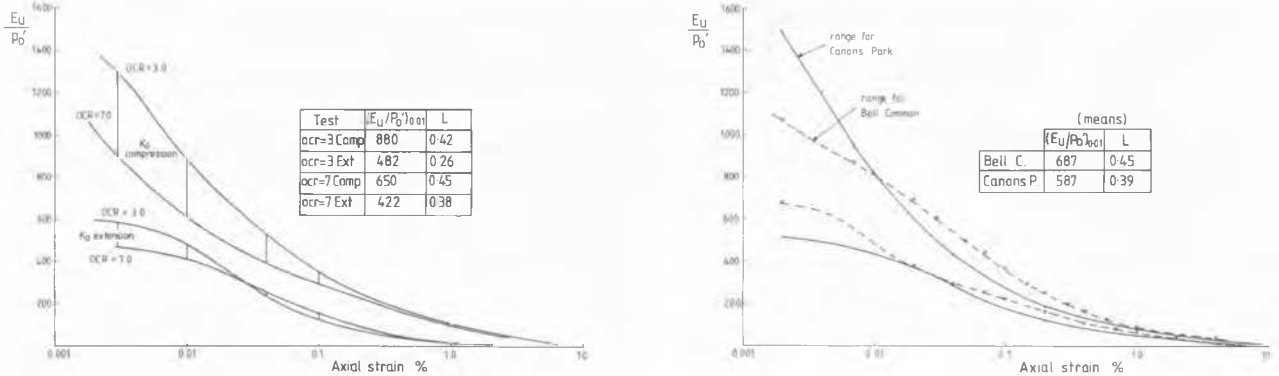


Figure 2. Comparison of laboratory $Eu_{0.01}$ values with insitu data.

Jardine et al (1984) have shown that the non-dimensional ratio E_u/Po' is less sensitive to OCR and generally more satisfactory than E_u/c_u (P_o' is the initial mean effective stress). Figure 3(a) shows characteristics of $E_u/p'o$ versus log strain for the tests on reconstituted London Clay. It can be seen that E_u/p'_o for extension is generally about 50% of that for



Test	$(E_u/P_o')_{0.01}$	L
ocr=3 Comp	880	0·42
ocr=3 Ext	482	0 26
ocr=7 Comp	650	0·45
ocr=7 Ext	422	0 38

	$(E_u/P_o')_{0.01}$	L
Bell C.	687	0·45
Canons P.	587	0·39

(a) Reconsituted London Clay, K_o consolidated. (b) Intact London Clay, summary of UU tests.

Figure 3. Laboratory stiffness-strain characteristics.

compression.

Figure 3(b) shows the envelopes of E_u/p'_o for the UU tests on high quality samples from Canons Park and Bell Common. Although the scatter is somewhat larger, the agreement with the tests on the reconstituted material is remarkably good. In general the values of E_u for a UU test fall between the corresponding values for K_o compression and K_o extension tests on reconstituted material. Thus the influence of sampling and stress history is not as dominant as has previously been thought.

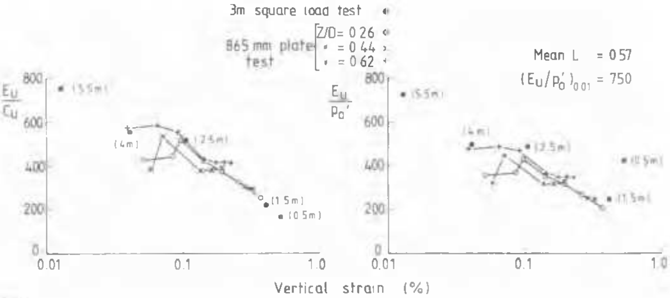
FIELD MEASUREMENTS OF STRESS-STRAIN BEHAVIOUR

As mentioned previously, when the stress-strain properties are non-linear, back-analysis of measured boundary displacements leads to values of E_u which are lower than the small strain laboratory values. The direct measurement of insitu stress-strain behaviour is greatly facilitated when local strains are measured. In this section an analysis of data from three such field tests on London Clay is presented.

Marsland and Eason (1973) present the results of a plate loading test in which displacements of the ground were measured at various depths during loading at a constant rate of penetration of 2.5 per minute. The plate was 865mm diameter and the test was carried out at a site in Central London at the base of a 900mm diameter 17.5m deep shaft. The results allow the direct calculation of average strains for three levels beneath the plate for various applied loads. The secant Young's modulus E_u corresponding to each value of strain can be evaluated using elastic theory to obtain the stress changes. At this site the average laboratory undrained strength C_u was 200kN/m^2. Figure 4(a) shows of plot of E_u/c_u vs log vertical strain for the three levels. It is estimated that at a depth of 17.5m on this site, which is overlain by about 7m of gravel and soft clay, the value of K_o is about 1.5 giving $p_o' = 240$kN/m^2. Figure 4(b) shows a plot of E_u/p_o' vs long vertical strain.

Recently a loading test was carried out on London Clay at Bracknell. The test consisted of loading a 3m square area at ground level to an average pressure of 110kpa with settlements measured at depths of 0, 1, 2, 3 and 5 metres beneath the centre. The average strains between each level were evaluated three hours after loading and the corresponding values of E_u were calculated using elastic theory. In Figure 4(a) the values of E_u/c_u for each level can be seen to agree with the results obtained from the deep plate test. At this site the London Clay extends to the surface and a value of $K_o = 2.5$ has been assumed in order to obtain values of p_o'. In Figure 4(b) the values of E_u/p_o' are plotted and reasonable agreement is again obtained with the plate test. The high value for 0.5m depth is thought to be due to surface desiccation.

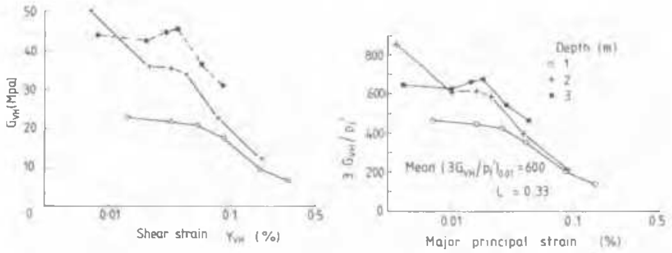
Comparison of the E_u/p_o' values in Figure 4(b) from the loading tests with laboratory values (Figure 3(b) shows that they are about 20% greater than the mean values from the UU tests. However, the values of E_u/p_o' from the anisotropically consolidated compression tests agree well with the values from the field loading tests, but have smaller values of L.



(a) Normalised by Cu. (b) Normalised by p'_o

Figure 4. Field stiffness-strain characteristics from loading tests.

Field data from a completely different type of loading is given by the measurement of vertical shear strains at three depths close to an instrumented jacked-in-place tubular steel pile at Hendon presented by Cooke, Price and Tarr (1979). Since the shear stresses transferred to the ground were accurately measured the data can be used to determine directly the relationship between shear stress τ_{VH} and shear strain γ_{VH} for the London Clay. In Figure 5(a) the relationships between secant G_{VH} and log γ_{VH} are plotted for the three instrumented levels remote from the pile tip. The marked non-linearity of the stress-strain relationships is evident and is similar in form to the laboratory results given in Figure 3.



(a) Measured data (b) Normalized by p '.

Figure 5. Field stiffness-strain characteristics from pile loading test.

In order to carry out a more quantitative comparison of the results from the pile test with the triaxial and other tests, certain assumptions have to be made. The process of jacking the pile into the ground increases the mean effective stresses from p_o' to p_i'. Using the modified Cam Clay model and expanding cavity theory to simulate pile installation, Randolph et al (1979) calculate that, close to the shaft of a driven pile, p_i' at the end of consolidation is approximately 3.5 times the initial undrained strength C_{uo}. For undrained plane strain the major principal strain $\epsilon_1 = \gamma_{vh}/2$ and for an isotropic material $E_u = 3G_{vH}$. In Figure 5(b) the values of $3G_{VH}/p_i'$ are plotted against $\log \epsilon_1$. The values agree remarkably well with the results obtained from the anisotropically consolidated compression tests given in Figure 3(a).

CONCLUSIONS

1. A simple, precise technique of routinely measuring local strains on triaxial samples has been developed which is accurate to about 2×10^{-5} strain.
2. Using the technique it has been shown that conventional laboratory methods of measuring soil stiffness can lead to very significant errors.
3. A series of tests on samples of London Clay using the new technique show that the undrained stress-strain behaviour is strongly non-linear having E_u/p_o' values which decrease from about 800 at 0.01% strain to about 300 at 0.1% strain. Values of stiffness obtained from high quality insitu tests and field measurements fall within this range.
4. Tests on reconstituted samples of London Clay show that stress relief due to sampling and applied stress path do not have a dominant influence on measured stiffness.
5. The analysis of the data from three field loading tests on London Clay, in which local strains within the soil mass have been measured, give non-linear stress-strain properties which agree remarkably well with those determined from triaxial tests.

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