J.M.O.HUGHES, M.E., Ph.D., Senior Lecturer, University of Auckland
C.P.WROTH, M.A., Ph.D., M.I.C.E., Lecturer, University of Cambridge
M.J.PENDER, B.E., Ph.D., Ministry of Works, New Zealand.

A Comparison of the Results of Special Pressuremeter Tests with Conventional Tests on a Deposit of Soft Clay at Canvey Island

SUMMARY A self-boring pressuremeter has been developed to the stage where accurate measurements of properties can be made in situ on soil which has suffered very little disturbance. Results of tests conducted on a deposit of soft estuarine clay are compared with those from vane shear tests, Dutch cone penetrometer tests and undrained triaxial tests.

1. INTRODUCTION

Complete and realistic solutions of boundary value problems in foundation engineering are now possible as a consequence of the advent of finite element computations. But to obtain such solutions it is essential to select appropriate values for the in situ effective stresses, and to describe adequately in mathematical terms the deformation characteristics of the soils in question. Recent research has confirmed the belief that deformation parameters measured on specimens in the laboratory bear little relation to those measured or deduced in situ due to the irreversible effects of sampling disturbance.

To meet this need for accurate in situ measurement of soil properties a family of special instruments has been developed by the Soil Mechanics Group of the University of Cambridge. Because of the initial objective of measuring the in situ lateral stresses and hence evaluating K_o, the first instrument acquired the name of the Camkometer. However the basic concepts of the Camkometer have been steadily adapted and developed so that additional soil parameters can be measured. In particular, a self-boring pressuremeter has been used successfully in a variety of soils, and particularly in soft clay. In this paper results are presented of undrained expansion tests, and they are compared with results from conventional in situ and laboratory tests.

2. ESSENTIAL FEATURES OF THE PRESSUREMETER

The overriding requirement for the family of instruments is that they can be introduced into the ground with the very minimum of disturbance. One successful method of achieving this is to have the instrument, Fig.1, in the shape of a right circular cylinder and to jack it slowly and steadily into the ground, while the soil that enters the open bottom end of the cylinder is removed to the surface. This soil is removed by the action of a rotating cutter and is flushed to the surface by fluid (either water or drilling mud) which is pumped down the inside of the shaft of the cutter and up the annular space between the shaft and the inside of the cylinder.

The degree of disturbance caused by the insertion and operation of the instrument has been observed by Hughes (Ref 1) under carefully controlled laboratory conditions by means of the radiographic technique developed at Cambridge by Arthur, James and Roscoe (Ref 2). The radial displacement of the soil immediately adjacent to the surface of the instrument due to its insertion was measured to be

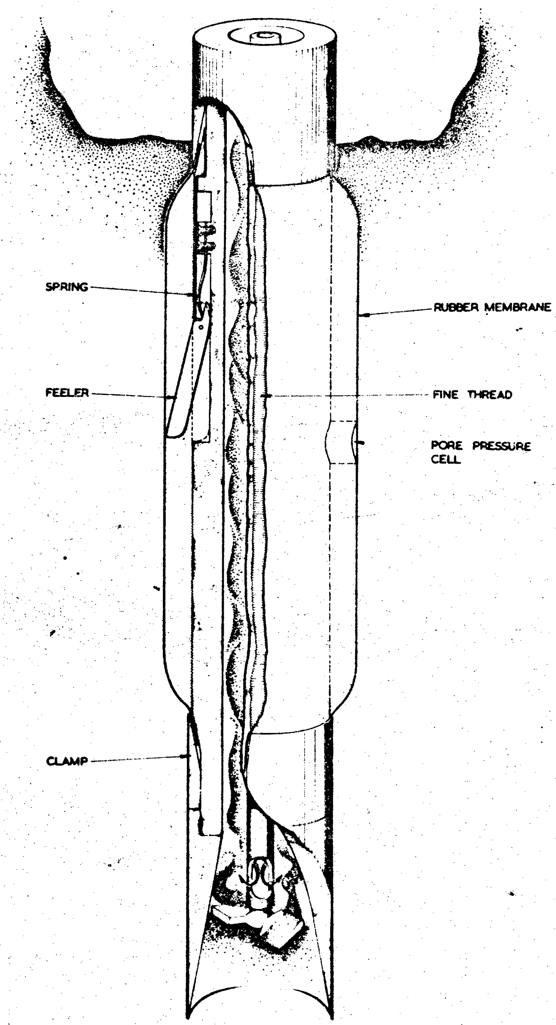

Fig.1 Details of the pressuremeter after insertion with rubber membrane partly expanded.

less than 0.5% of the radius of the instrument.

During insertion of the instrument the inflatable rubber membrane of the pressuremeter is restrained to be the same diameter as the cutting head by the application of an internal suction. After insertion to the required depth (with a greater amount of cover than that shown in the schematic diagram of Fig.1) the membrane can be expanded by an internal pressure ψ controlled by a hand-operated reducing valve from a high pressure cylinder of nitrogen. The pressure is measured both by an electrical transducer within the instrument and by a standard pressure gauge next to the control valve.

The radial expansion of the membrane is monitored by three separate hinged feelers which are kept in contact with the membrane by the action of thin leaf springs. Each spring has mounted on it electrical resistance strain gauges which indicate the movement of the feeler, and hence of the membrane.

An important additional feature of the pressure meter has been the incorporation of two small pore-pressure transducers that are fixed to the rubber membrane and are free to move during expansion. These transducers are in direct contact with the soil as it is deformed.

3. SOIL CONDITIONS AT CANVEY ISLAND

A major oil refinery in the U.K. was proposed for an undeveloped site adjacent to the river Thames at Canvey Island, Essex. Because of the possible economic benefits of founding the large oil storage tanks on the soft ground without the use of piles, special field loading tests were carried out as reported by George and Parry (Ref 3). The opportunity was taken to use the Camkometer at the site, and compare the results with those from conventional tests of good quality.

The site consists of about 8 m of soft clay overlying dense sand. In addition to the routine site investigation two Delft continuous samples were taken at the site of each of two small circular trial embankments before construction. The profile of natural water content and Atterberg limits obtained for the layer of soft clay is shown in Fig.2. Fuller details of the site are given in Ref 3.

4. UNDRAINED EXPANSION TESTS BY PRESSUREMETER

Six undrained expansion tests were carried out at different depths in one vertical profile. The results of test No.5 at a depth of 6.1 m are shown in Fig.3(a). The uppermost curve ABCDEF is the recorded applied pressure ψ plotted against the radial displacement of the membrane, expressed non-dimensionally as a strain ε by dividing by the initial radius of the membrane a_o.

The middle curve AIJ is the effective radial stress σ'_r plus u_o; recorded by the pore-pressure transducer which is so arranged that the diaphragm is acted on internally by the applied pressure $\psi = \sigma_r$ and externally by the pore-pressure u. The point A where the two curves diverge is the start of any excess pore-pressure, and is considered to be the proper datum for the start of the test and to mark the in situ total lateral stress.

Cylindrical polar coordinates are used and the radial displacement of any point is denoted by ξ. Because of axial symmetry the principal stresses acting on an element of soil are $(\sigma_r, \sigma_\theta, \sigma_z)$;

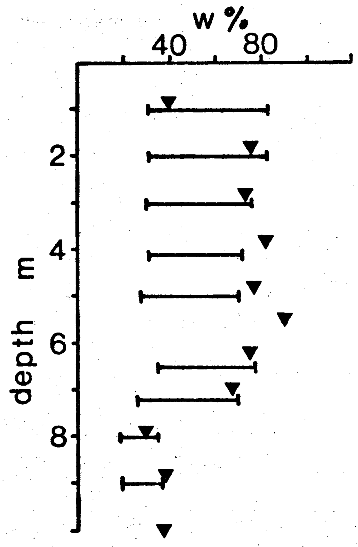

Fig.2 Profile of natural water content and index tests for the soft clay

initially $\sigma_r \equiv \sigma_\theta$ but as expansion of the cavity (of current radius a) occurs, σ_r increases to become the major principal stress and σ_θ reduces to become the minor stress. The current strains (compressive being taken as positive in accordance with normal practice in soil mechanics) are given by $\varepsilon_r = -\frac{d\xi}{dr}$, $-\varepsilon_\theta = \frac{\xi}{r}$ and $\varepsilon_z \equiv 0$ based on the assumption that the deformation is purely radial. Wroth and Hughes (Ref 4) show experimental evidence in support of this assumption for small strains.

For the undrained condition of no volume change all displacements and strains can be expressed in terms of the coordinate r and the displacement of the wall of the cavity ξ_a: this means that the strain ε defined by ξ_a/a_o (i.e. the current displacement of the wall divided by the initial radius a_o) can be used as the basic strain parameter. Moreover at the wall of the cavity $\varepsilon = \varepsilon_r = -\varepsilon_\theta$ so long as there is no volume change.

Jezequel et al (Ref 5), Ladanyi (Ref 6) and Palmer (Ref 7) have separately shown that the shear stress at the wall of the cavity $\frac{1}{2}(\sigma_r - \sigma_\theta)$ is given for small strains by

$$\tfrac{1}{2}(\sigma_r - \sigma_\theta) \simeq \varepsilon \frac{d\psi}{d\varepsilon} = \varepsilon \frac{d\sigma_r}{d\varepsilon} \qquad (1)$$

This analysis has been applied graphically to the results of Fig.3(a). At a typical point E the tangent to the curve is drawn and its intersection G with the ψ-axis is found. The difference in the ordinates of E and G is equal to $\varepsilon(d\psi/d\varepsilon)$ and this can be plotted as the point H to mark the current value of shear stress. The dimension EH is plotted directly below in Fig.3(b). The locus of points such as H is the value of $\frac{1}{2}(\sigma_r + \sigma_\theta)$ and must be a smooth curve; this fact helps to iron out scatter in the derived stress-strain curve.

The resulting stress-strain curve of Fig.3(b) indicates the initial shear modulus and the sensitivity of the soil as well as its undrained strength.

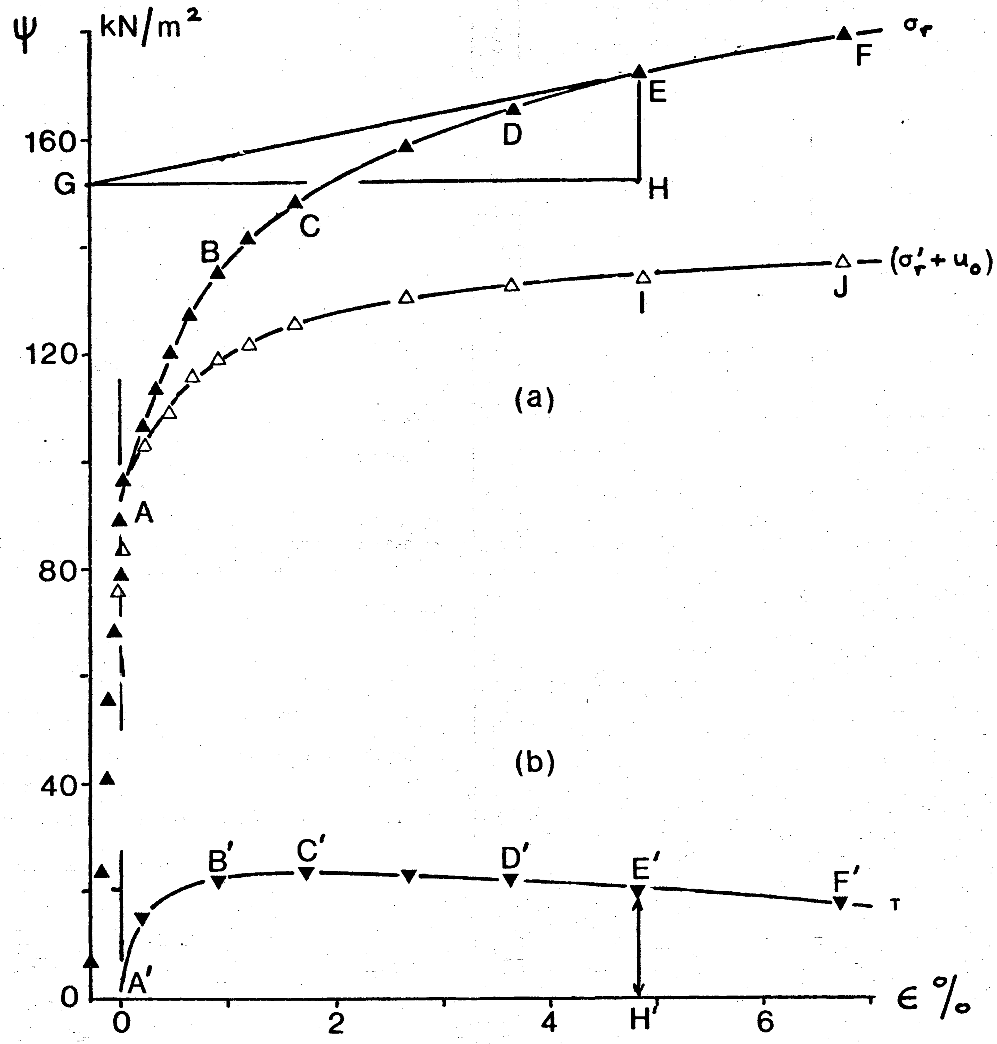

Fig.3 Results of undrained expansion test No.5 at a depth of 6.1 m

5. UNDRAINED SHEAR STRENGTHS

The undrained shear strengths obtained from the pressuremeter tests are plotted against depth in Fig.4(a). The test at a depth of 2.4 m is excluded because it was not continued to sufficient strain to reach a peak in the derived stress-strain curve, and it is thought to have been carried out too slowly so that some drainage occurred. The test at a depth of 5.2 m was in a thin layer of peat within the 8 m deposit of soft clay.

Values of shear strength obtained from the vane shear tests are plotted to the same scale but separately (for purposes of clarity) in Fig.4(b). The mean line for the pressuremeter tests of Fig.4(a) has been repeated in Fig.4(b) and indicates consistently higher strengths than those from the vane shear test. This pattern has been confirmed for other deposits of soft clay in the U.K., Norway and Sweden. It is suggested that the higher strengths obtained by the self-boring pressuremeter may be due to (i) the greater disturbance caused by insertion of the vane and (ii) strain rate effects. In order to prevent drainage the pressuremeter test has to be conducted fast with correspondingly high rates of strain, of the order of 0.6% per minute, for the soil adjacent to the membrane. It is only possible to compute a rate of relative displacement (and not of strain) for the vane test so that no direct comparison can be made.

Results of Dutch cone tests, based on a value of N_c of 9, and of unconsolidated undrained triaxial tests are shown in Fig.4(c). It is notable that in comparison with the results from the Camkometer and the vane, there is much greater scatter for both the cone and triaxial tests, and that the average values of strength are lower. However the strengths are not strictly comparable because of the different orientations of the possible failure planes in the various tests, so that if there is any anisotropy of strength the effects will be included in the results.

6. IN SITU STRESSES

The point A in Fig.3(a) is considered to give an accurate indication of the value of the in situ total lateral stress σ_h, because it marks the instant at which deformation of the soil commences. It indicates both the change in response of the system in the total applied stress-strain curve ABCDEF and the initiation of excess pore-pressures. (The small amount of deformation that is recorded before point

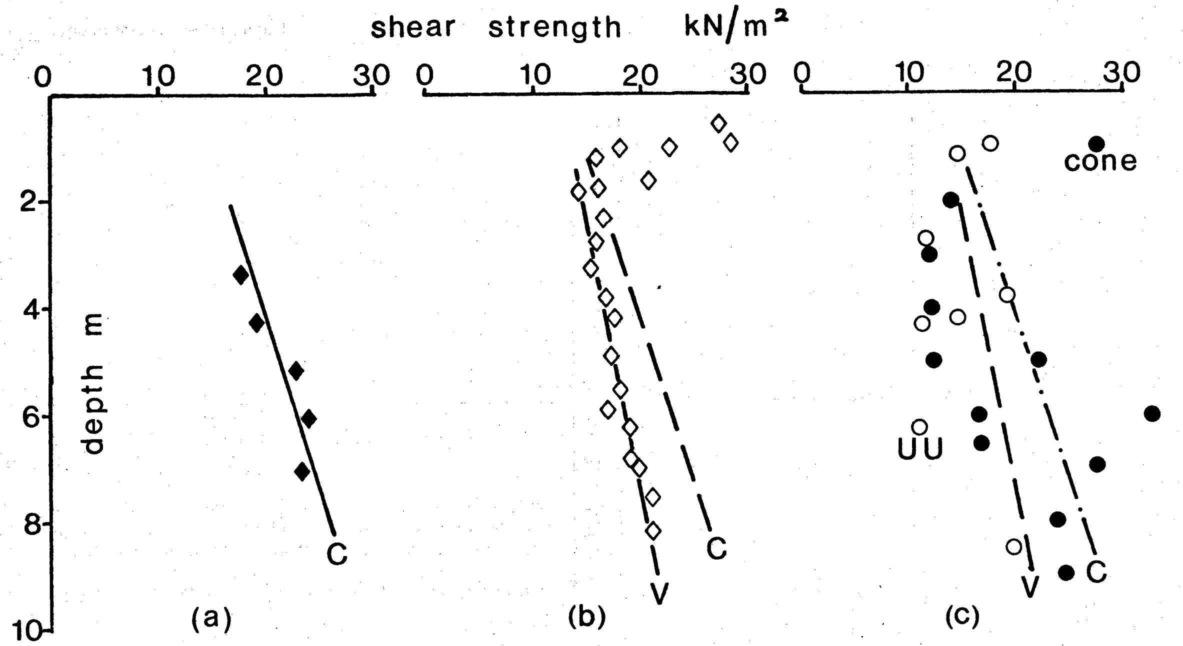

Fig.4 Profiles of undrained strength obtained from (a) Camkometer (b) vane and (c) Dutch cone and triaxial tests.

A is reached is due to the small degree of flexibility in the measuring system and compression of the rubber membrane.)

The pore-pressure transducers allow a measurement to be made of the initial pore-pressure u_o which exists in the ground before the expansion test is started (and after equilibrium has been re-established at the end of the drilling operation). The values obtained during the test programme are plotted in Fig.5(a), and they provide a valuable check on the accuracy and reliability of the transducers.

For each test the in situ lateral effective stress σ_h' has been calculated from the observed values of σ_h and u_o, and the results are plotted in Fig.5(b). Estimates of the total overburden pressure have been made in the usual manner, and used to derive the values of the coefficient of lateral earth pressure K_o shown in Fig.5(c). These values of K_o confirm that the clay is normally consolidated with an average value of K_o of about 0.62.

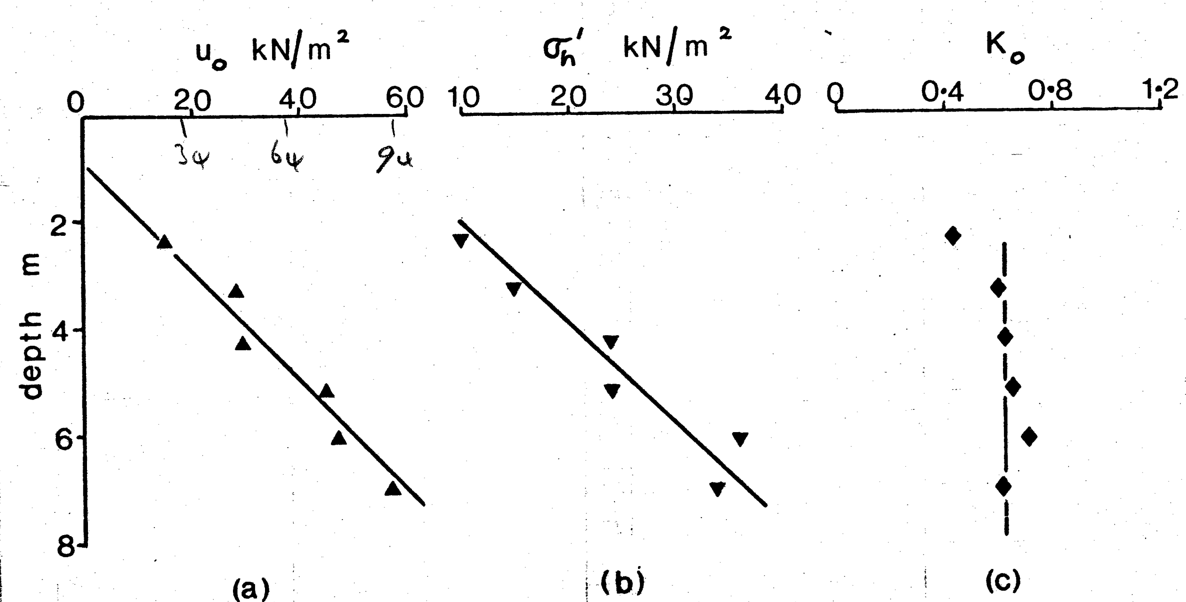

Fig.5 Profiles of in situ stresses

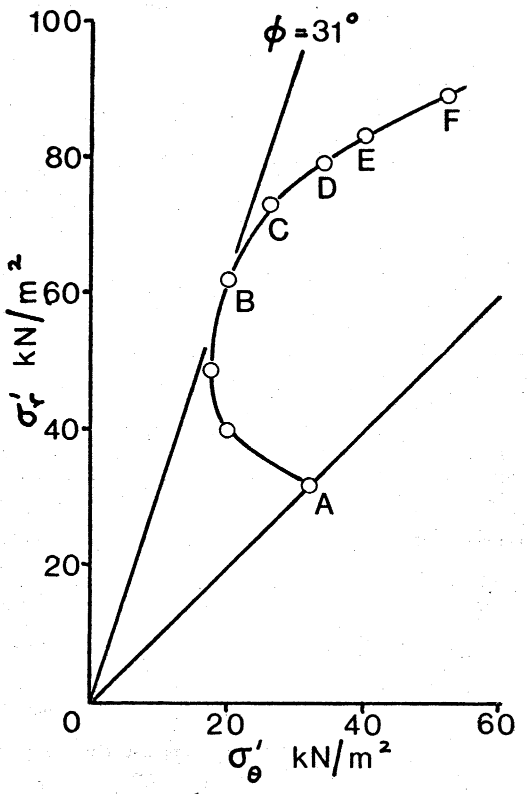

Fig.6 Effective stress path for undrained expansion test No.5

7. EFFECTIVE STRESS PATHS

Knowledge of the effective radial stress σ_r' by means of the pore-pressure transducer, throughout the test (curve AIJ of Fig.3(a)) together with the shear stress makes it possible for the minor effective stress σ_θ' to be calculated. This has been done for several stages of the test given in Fig.3, and the resulting effective stress path experienced by the clay as it is deformed in undrained conditions is shown in Fig.6.

8. CONCLUSIONS

The Camkometer, a self-boring pressuremeter, has been used extensively in deposits of soft clay for the accurate measurements in situ of various soil properties. Results are quoted of a series of undrained expansion tests in a soft clay at Canvey Island, Essex, U.K. The tests can be interpreted to give a complete undrained stress-strain curve (indicating values of shear strength, initial shear modulus and sensitivity) and the in situ lateral stresses. In partic‘‘ar the strengths have been compared with those ‘..om vane, Dutch cone and unconsolidated undrained triaxial tests and are shown to be consistently greater and with less scatter. Measurement of the pore-pressures during the test allows the effective stress path to be plotted.

9. ACKNOWLEDGMENTS

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