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The Use of In-situ Tests in a Study of the Effects of Fissures on the Properties of Stiff Clays

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SUMMARY. - The large variations in the shear strengths and modulii measured in triaxial tests on standard 76 mm long x 38 mm diameter specimens of stiff fissured clay has led to the use of large in-situ tests to measure these properties. The undrained properties have been measured by means of loading tests on plates with diameters of up to 865 mm at various depths in boreholes and effective strength parameters have been determined by in-situ tests using a 610 mm square shear box.

A detailed study has been made of the effects of plate diameter, fissure spacing, degree of confinement of the borehole immediately above the test level, the method of preparing the test surface and the interval of time between excavation and loading the plate.

Effective strength tests have been made in the large shear box using effective normal stresses between 17.5 and 100 kN/m^2 which is the range of particular interest in many engineering applications. In some of the tests pore pressure measurements were made on the plane of shear to check that the rate of shear was sufficiently slow to ensure that the pore pressure remained zero.

Large in-situ tests have provided a better measure of strength and deformation parameters applicable to full-scale conditions for two highly fissured clays. By comparing the results obtained from both field and laboratory tests of various sizes a better understanding of the influence of fissures on the properties of stiff fissured clays has been obtained.

The paper describes these tests, gives typical results to illustrate the influence of fissures and compares the results with laboratory tests. The use and limitations of in-situ tests for determining the full-scale strength applicable to a particular problem are discussed.

I. - INTRODUCTION

The difficulties of sampling and the wide scatter of results obtained from laboratory tests on small samples of stiff fissured clays has raised severe doubts as to the value of present procedures for obtaining the mechanical properties of these clays. During detailed investigations of the London Clay in a deep shaft at Ashford Common (Refs 1 and 2) large variations in strength were measured in triaxial tests on 76 mm high and 38 mm diameter specimens even though the specimens were carefully prepared from hand excavated block samples. These large variations made it almost impossible to decide which values were representative of the large scale strengths of the clay. In-situ loading tests on a 152 mm diameter plate and on a 38 mm diameter cone penetrometer made at various levels in the deep shaft from which the block samples were obtained showed that the shear strength of the clay that was mobilized depended on the size of the test in relation to the spacing of the fissures in the clay. They also suggested that the lower strengths obtained in the

laboratory tests on small specimens were more representative of the large-scale strengths than were the average values. The conclusions drawn from this investigation have led to an increased use of in-situ plate loading tests to estimate the undrained strength of fissured London Clay (Ref 3) for use in the design of piled foundations (Ref 4). These tests, together with loading tests on instrumented piles (Ref 5) confirmed that the large-scale strengths of the fissured London Clay were appreciably lower than the average values given by tests on small specimens. Tests on different sized specimens of London Clay, and Barton Clay which is also highly fissured, showed that the measured strength decreased as the size of the specimen was increased (Refs 6, 7 and 8). As a consequence of these findings the author initiated a study of in-situ tests using different sizes and types of equipment in conjunction with laboratory tests on specimens of various sizes prepared and sampled by the best available techniques. Loading tests on a 865 mm diameter plate installed at various levels in boreholes and in-situ shear tests

using a 610 mm sq shear box formed an important part of the investigations. The present paper describes these tests and gives some typical results and comparisons with the results of laboratory tests. The use and limitations of both in-situ and laboratory tests for determining the strengths applicable to particular problems are discussed.

II. – THE USE OF IN-SITU LOADING TESTS FOR MEASURING THE UNDRAINED PROPERTIES OF STIFF FISSURED CLAYS

(a) Factors Which May Affect the Undrained Properties of Stiff Fissured Clay Estimated From In-Situ Loading Tests

The undrained properties of stiff fissured clay determined from in-situ plate loading tests may be influenced by the following factors:

i) The mineralogical composition, strength, and the type of discontinuities present in the clay. Stiff clays contain numerous discontinuities in the form of bedding surfaces, joints, shear dislocations, and fissures. Even in clays with similar mineralogical properties the discontinuities can vary in size, continuity, inclination and surface roughness with both depth and location.

ii) The forces and restraints imposed on the ground around the test levels by different arrangements adopted for the tests.

iii) Dimensions of the test equipment and in particular the relative dimensions of the loaded plate and the spacing of the fissures in the clay.

iv) The reduction in stress and the accompanying strains which occur in the clay during drilling and insertion of the test equipment.

v) The interval of time between drilling the hole and loading the plate.

vi) The rate of penetration during loading.

The effects of the type of clay and the different structural weaknesses will only become apparent when comparable results are available from tests in a number of clays with widely differing properties.

The effect of forces or restraints imposed on the ground near the test level may vary with the type and structure of the clay. Model studies of deep in-situ loading tests in soft unfissured clay made by the author (Ref 9) showed that the maximum bearing pressure which could be applied to a plate installed in a borehole having a diameter equal to that of the plate was the same for tests made in unlined and lined boreholes irrespective of whether the liner remained stationary or moved down at the same speed as the plate. However, the maximum bearing capacities measured on a plate of a given size decreased rapidly as the ratio of the hole to plate diameter increased from 1.0 to 1.5. At present there is only limited data available from tests in stiff fissured clays. In-situ loading tests in fissured London Clay at Wraysbury near London Airport using 292 mm diameter plates in cased and uncased boreholes gave almost identical results. At another site in London Clay a few tests made on a 292 mm diameter plate pushed from inside a thick, very tight fitting liner gave ultimate bearing pressures of up to 10 to 15 per cent greater than loading tests on plates at the same levels in unlined boreholes.

Loading tests on 38 mm diameter probes and on a 152 mm diameter plate at Ashford Common (Ref 2) clearly showed the importance of the size of the test equipment in relation to the spacing of the fissures. The large scatter obtained from loading tests in London Clay on plates with diameters less than 200 mm (Ref 3) also showed the importance of the size of the test equipment. The main purpose of the large-diameter plate tests described in the next section of this paper was to provide a reliable basis for evaluating the results of both smaller in-situ tests and laboratory tests on various sizes of specimens.

Very little data is available on the influence of the interval of time between excavation and loading the clay, but deformation moduli determined from plate loading tests made in the base of the Ashford Common shaft at time intervals from $\frac{1}{2}$ hour to $2\frac{1}{2}$ days after completion of excavation showed an appreciable decrease with time.

No exhaustive series of tests have yet been made to study the effect of the rate of penetration during loading on either the load-settlement curves or the ultimate bearing pressures measured on plates. The limited data available from plate and pile loading tests where rates of loading several times lower and higher than the rate of 2.5 mm/min used in our loading tests were employed suggests that this is a minor factor at these rates of loading. Further investigations are however required, particularly in those clays which expand rapidly when unloaded.

(b) Loading Tests on a 865 mm Diameter Plate in 900 mm Diameter Boreholes

Loading tests on a 865 mm diameter plate in 900 mm diameter boreholes have been made for the purpose of evaluating the reliability of the undrained properties of stiff fissured clay as measured by in-situ and laboratory tests. One of the principle aims was to keep the interval of time between drilling and testing as short as possible. The tests were made in unlined boreholes apart from the short lengths of
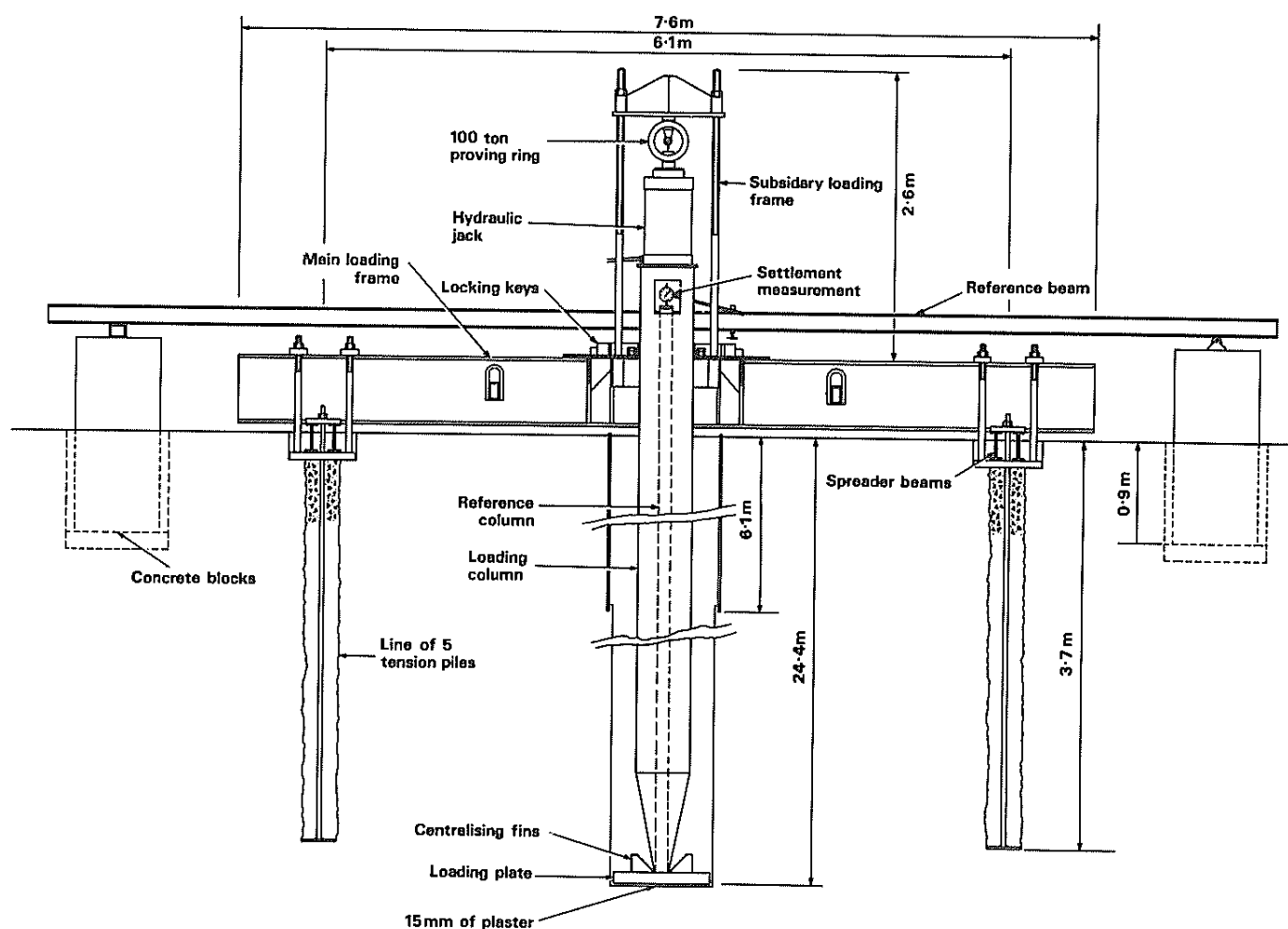
Fig 1   Vertical section through the plate loading test equipment

lining provided at the top of the boreholes to ensure the safety and efficiency of the operations. A crane-mounted drilling rig of the type used for constructing large bored piles was used to drill the boreholes and to erect the test equipment. A vertical section through the plate loading equipment is shown in Fig 1. The loading frame was designed so that the major part of it could be left in place during drilling and erection of the test equipment. In the particular application illustrated in Fig 1 the reaction was provided by 10 small tension piles which were pulled out by a crane after completion of the tests, but the arrangement is sufficiently flexible to permit other tension pile arrangements. The main reaction frame consisted of two 7 m long 610 mm x 320 mm I-section steel girders spaced 1200 mm apart with a fabricated centre table having a 1200 mm diameter hole. The frame was fixed at ground level to spreader beams connected across the tops of the tension piles. A helical flight auger was used to drill the 900 mm diameter borehole to within about 600 mm of the test level, and a flat-bottomed bucket

auger was used to take out the remainder so as to produce a flat-bottomed hole. Loose and protruding clay was removed from the bottom of the hole by hand for all the tests and for some of the tests additional clay was removed from the bottom using a sharp spade and a hand scraper.

Operations in the bottom of the borehole were carried out from a safety cage fitted with a removable base to allow a man to alight at the bottom of the borehole and work under the protection of the cage. A continuous clean air supply was also provided down the borehole and the operations were generally in accordance with the requirements of British Standard CP 2011:1969.

As soon as the removal of spoil from the base of the borehole was completed, a quantity of high strength gypsum plaster was taken down in the safety cage and spread on the bottom of the borehole to form a layer 15-20 mm thick. The plaster mix used consisted of $2\frac{1}{2}$ parts by weight of Crystacal EN plaster

to 1 part of a 1 per cent K_2SO_4 solution. This gave a mix which could be easily poured up to about 10 minutes after mixing, remained fairly plastic for a further 5 minutes, but reached a strength of about 3000 kN/m^2 in 30 minutes. The loading plate was lowered into the hole by suspending it below the safety cage from where it was guided into position and carefully centralised in the bottom of the borehole. During the lowering operation three guides consisting of steel strip were fixed to the plate to prevent it scraping clay from the side of the borehole, but these were removed when the plate was in position.

The loading column was built up from 1.5 m lengths of screwed 460 mm diameter casing tube and was lowered into the borehole in 6 and 12 m lengths. Each 6 m length was provided with handling lungs that engaged in slots in a small frame supported on the main reaction frame, thus eliminating the need for clamping devices during the fixing of additional 6 m lengths. The bottom end of the loading column was tapered in order to minimise eccentricity of the load transferred to the plate. During the final stages of lowering the column was guided into a central position on the plate by a conical cup welded to the top of the plate.

The settlement of the plate was measured on an independent axial column built up from lengths of 100 mm diameter tube which were fitted with handling lugs and pinned spigot joints to speed erection. With the reference column in position the loading column was capped by a special section incorporating a window giving access to the head of the internal reference column and with a horizontal top plate

Fig 2   Subsidiary loading frame being lowered into position

to carry the jack. A subsidiary loading frame fitted with rollers to keep the top end of the loading column central was then lifted into position, as shown in Fig 2. The loading jack and 100 tonne proving ring were incorporated in this loading frame and arranged to be self-centering on the top of the loading column. The loading frame was held down on to the main frame by four steel locking keys, sliding into key-ways attached to both frames. The complete loading system was designed to provide loads on the plates of up to 150 tonnes.

The dial gauge to measure the settlement of the reference column was attached to a rod which passed through the window of the loading column and was clamped to a 12 m long reference beam. The ends of the reference beam rested on rollers cast into concrete blocks which in turn rested on concrete pad foundations, well removed from the tension piles and the test borehole. This reference beam was left in position throughout all the tests in a particular borehole.

The whole of the arrangements were devised with the intention of keeping the time taken to erect the loading and settlement measuring system to a minimum. The average time between the completion of machine boring and the commencement of a loading test was 140 minutes for the tests in which the loose material only was removed by hand from the test level and 180 minutes where an additional depth of clay was removed from the bottom of the borehole by hand digging, but times as low as 60 minutes were achieved.

During the loading test the jack was extended at a constant rate of 2.5 mm per minute using a multi-speed hydraulic pumping unit which ensured a very smooth penetration, free from pressure pulses.

(c)   Typical Results From Loading Tests on 865 mm Diameter Plates and Comparison with Laboratory Tests

Bearing pressure - settlement curves obtained on 865 mm diameter plates using this equipment in unlined boreholes in London Clay at Hendon are compared in Fig 3 with similar tests on 292 mm diameter plates in 300 mm diameter boreholes. The tests on the 865 mm diameter plate gave load settlement curves with reasonably well-defined maximas while the tests on the smaller plates seldom attained maximum values. The large plate tests did not show any obvious bedding errors that were common in the smaller tests made in boreholes that were too small to permit access for cleaning the test surface by hand. In the large tests, where additional clay was dug from the base of the borehole by hand, there was no sign of initial concavity in the load settlement curve commonly recorded in plate tests of all diameters and usually attributed to the closing up of surface fissures in the clay caused by the
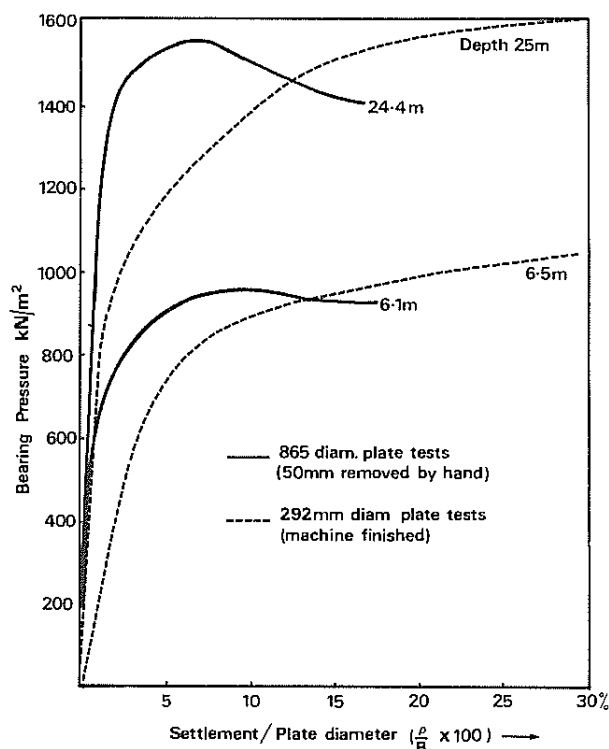
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Fig 3 Typical load settlement curves obtained
from loading tests on 292 and 865 mm
diameter plates in London Clay at
Hendon

tearing action of the auger. Initial concavity in
the load settlement curves did however occur in a
few of the large diameter tests in which only the
loose clay was removed from the base of the bore-
hole prior to setting the plate on plaster.

Shear strengths calculated from the 865 mm
diameter plate tests in London Clay using a bear-
ing capacity factor N_c of 9.25 (which value is based
on results of model tests by the author (Ref 9) and
on plasticity theory (Ref 10) have given very repro-
ducible results, see Fig 2 of reference 11). The
shear strength of London Clay calculated from 865
mm diameter plate tests made in London Clay at
Chelsea are compared in Fig 4 with triaxial tests
on 38 mm and 98 mm diameter specimens and
with laboratory penetration tests in which a 5.5 mm
loading plate was used. At this particular site the
average spacing of the fissures increased from
about 15 mm at a depth of 4 m to about 100 mm at
a depth of 15 m. The surface of many of the
fissures were very curved and the lumps of clay
between the fissures were interlocked to a con-
siderable extent. Some idea of the extent of the
interlocking can be obtained from the fact that it
was safe to work in a deep unlined borehole for at
least 9 days as against a maximum of 2-3 days at
other sites in fissured London Clay. This pro-

nounced interlocking of the clay probably accounted
for the high strength measured on both 38 and 98
mm diameter specimens as compared with the
strengths calculated from the plate tests. At this
site the strength measured on both the 38 and 98 mm
diameter specimens from a depth of about 15 m
were about 1.75 times those calculated from the
plate tests. Comparable figures from tests at a
similar depth made at another site in London Clay
(briefly reported in Ref 11) were 1.1 for tests on
the 98 mm diameter specimens and 1.35 for tests
on 38 mm diameter specimens.

The results of the 5.5 mm diameter penetra-
tion tests provided an approximate measure of the
strength of the 'intact' clay within the lumps
between the fissures. At the site in Chelsea the
shear strengths calculated from the penetrometer
tests increased from about twice to more than four
times the large-scale strength of the clay as de-
termined by the large in-situ test between depths of
5 and 15 m. The large difference between the labo-
ratory and the large-scale in-situ strength values
have clearly shown the fallacy of using strengths
from laboratory tests on small specimens for
design purposes.

Load tests on 140 mm, 292 mm and 865 mm
diameter plates in London Clay at Hendon showed
that the bearing pressures on 292 mm diameter
plates at a settlement equal to 15 per cent of the
plate diameter were in reasonable agreement with
the maxima measured on the 865 mm diameter
plates. Tests on 140 mm diameter plates gave
very erratic results which could not be satisfactorily
interpreted.

In addition to providing better measures of the
large-scale strengths of fissured clays the large
in-situ plate tests also gave moduli nearer the
values deduced from movements of foundations and
excavations. The values of the secant moduli at
half the ultimate load calculated from the load
settlement curves obtained in tests on 865 mm dia-
meter plates in which 50 to 75 mm of clay was
removed by hand digging were appreciably greater
than values measured in triaxial tests on speci-
mens obtained by carefully pushing in the thin-walled
sampling tubes. Values of E calculated from
smaller plate tests, where it was not possible to
prepare the test surface by hand, were appreciably
lower than those calculated from the large tests.

III.- LARGE IN-SITU SHEAR BOX TESTS TO
DETERMINE THE EFFECTIVE STRESS
PARAMETERS OF STIFF FISSURED CLAYS

In order to investigate the stability of excava-
tions and earth retaining structures reliable shear
strength parameters in terms of effective stresses
are required. The results from large in-situ plate
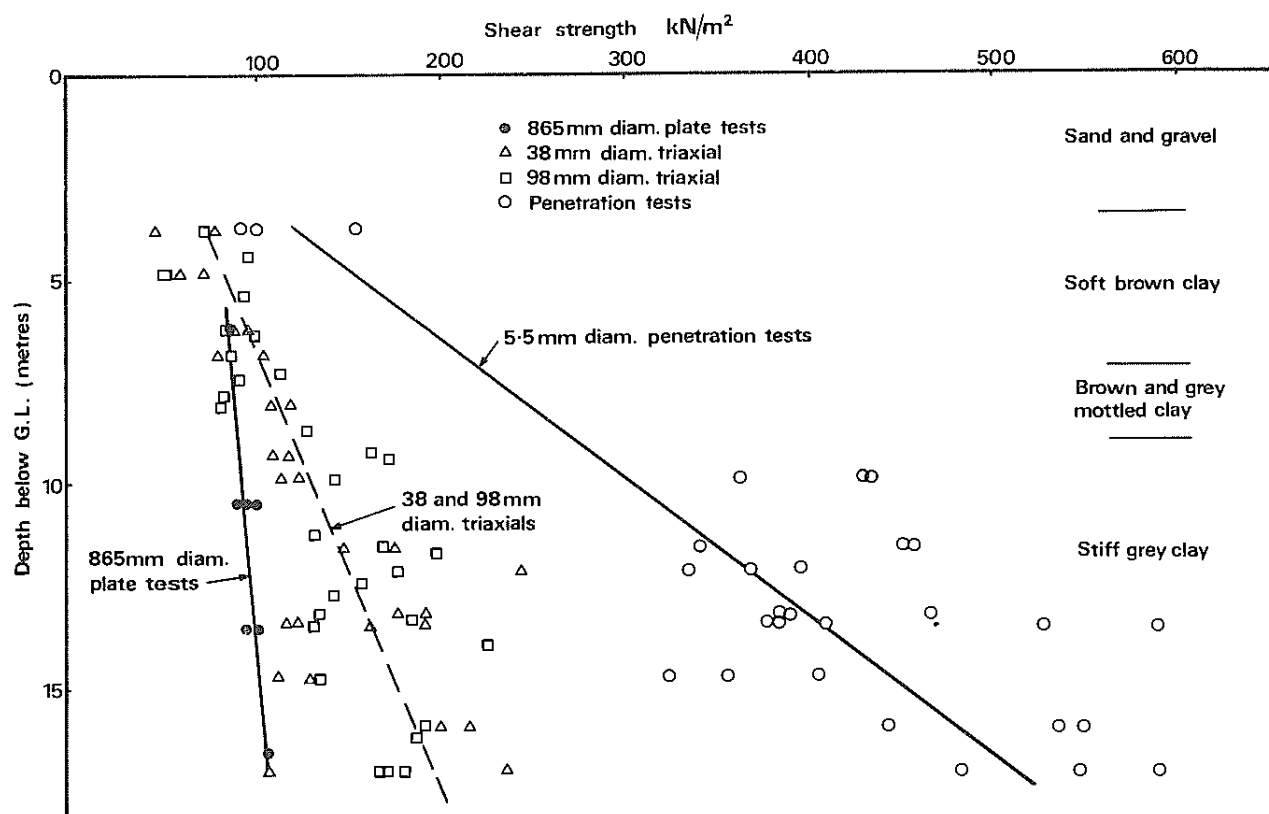tests given in the first part of this paper have

Fig 4 Comparison of shear strengths estimated from 865 mm diameter plate tests and laboratory tests on 38 mm and 98 mm diameter specimens in London Clay at Chelsea

shown that laboratory tests on small samples gave higher undrained shear strengths than those determined by large in-situ plate tests. Since this difference was largely attributed to the fact that the proportion of the shear planes which passed through hard intact clay between the fissures was larger in the laboratory than in the field tests it followed that effective stress parameters determined from tests on small laboratory specimens were also suspect. During the early stages of construction of a large power station at Fawley, Hampshire, tests on 150 mm high x 75 mm diameter specimens of stiff fissured Barton Clay gave an effective strength envelope which was appreciably lower than the envelope from tests on 76 mm high x 38 mm diameter specimens carried out as part of the original site investigation. In order to check this discrepancy and obtain more reliable stress parameters a number of large in-situ shear tests using a 610 mm square shear box were made.

(a) Details of Large In-Situ Shear Box and
     Method of Test

A diagrammatic section through the shear box and loading arrangements are shown in Fig 5. In plan the shear box was square with sides having an internal length of 610 mm. It was constructed in two halves, each suitably reinforced to form rigid units which could be bolted together to facilitate installation. The lower half of the box was made of perforated sheet steel, fitted at the lower end with a sharpened cutting edge. When making a test a level surface was prepared by hand digging in undisturbed clay 75 to 100 mm above the proposed level of shear. An outline of the box was marked on the prepared surface and a shallow trench about 100 mm deep was carefully dug from around the outside leaving an undisturbed pedestal of clay a little larger than the inside dimensions of the box. The box was then placed centrally over the pedestal of undisturbed clay and pushed down evenly using a heavy concrete block suspended from a crane. The trench around the box was deepened in small stages and the box was pushed down each time until the horizontal joint between the two halves of the box was 75 to 100 mm below the level of the prepared surface. The trench around the lower half of the box was filled with a gravel filter up to the top of the lower half of the box to provide drainage during the consolidation and shearing stages. The area around the shear box was kept flooded up to the level of the shear plane throughout the test. A porous concrete block and piston were placed on the clay surface in the top half of the box. A ballast tank was used to apply a vertical load to the piston through a ball-seating fixed to the centre of the piston and the clay inside the shear box was allowed to come to equilibrium under each applied load. When consolidation or expansion was complete, the bolts connecting the two halves of the box were
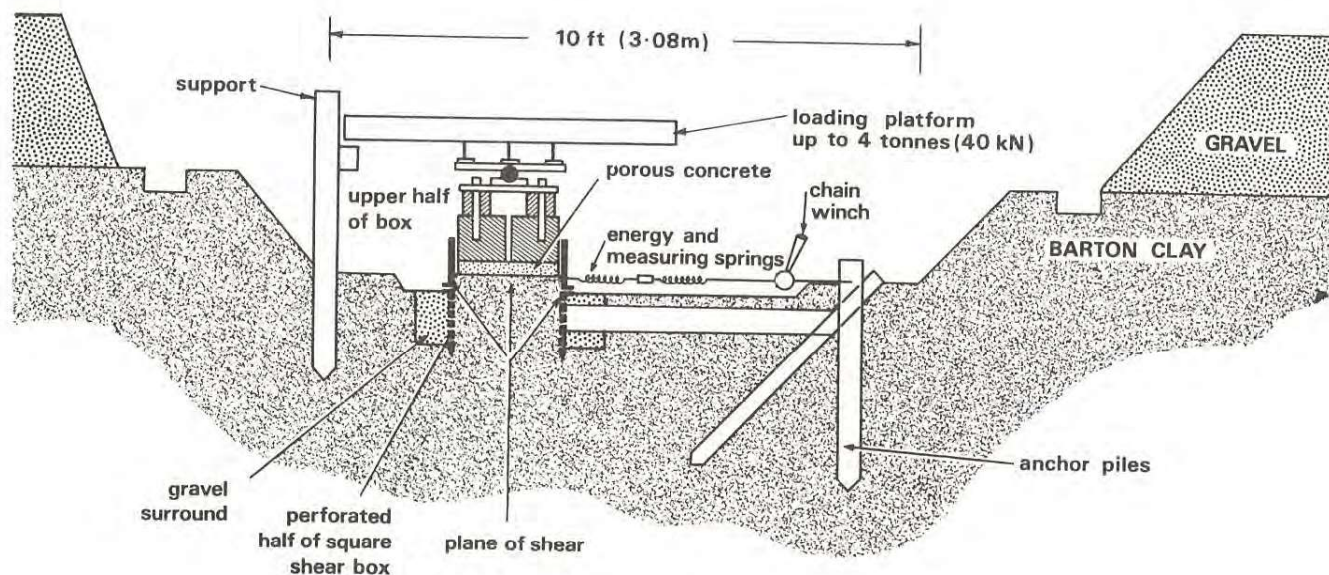
Fig 5   Diagrammatic section of in-situ shear box and loading arrangements

removed and the top half of the box lifted, relative to the clay and the lower half of the box, by means of jacking screws to give a gap of 1 to 2 mm. Horizontal shear loads were applied to the clay between the two halves of the box by means of a winch used in conjunction with calibrated springs. By adjusting the winch 2 to 3 times a day it was possible to maintain horizontal loads to within 0.1 tonnes. The vertical settlement of the piston was measured relative to an external reference frame and horizontal displacements between the two halves of the box were measured directly on targets fastened to the two halves. In order to check that the application of the shear load was sufficiently slow to enable drainage to take place within the clay, pore water pressure measurements were made in some of the tests using small piezometers installed in the centre of the pedestal of clay on the plane of separation of the two halves of the box. The use of hydraulic equipment to provide a constant rate of strain was considered but the test arrangement described above was chosen because of its simplicity, robust nature, and the need for easy recording by site personnel.

(b)   Typical Results Obtained from Large
      In-Situ Shear Box Tests

Tests using this equipment were made in highly fissured Barton Clay at Fawley near Southampton (Ref 8). The tests were made in the upper 1.5 to 3 m of the unweathered clay, 14 to 17 m below ground level. At this level the clay contained about 70 per cent of particles less than 2 μ

and had average liquid and plastic limits of 80 and 32 per cent respectively. When excavated the hard highly fissured clay fell apart into separate irregular shaped lumps that had dimensions of from 10 to 100 mm; those shown in Fig 6 being typical. The moisture content of the clay in the centre of the lumps was approximately equal to the plastic limit, while the moisture content near the surface of the lumps was 1 to 2 per cent higher. Comparison of the results of small laboratory penetration tests and undrained triaxial tests on 125 mm diameter specimens indicated that the strength of the intact clay within the lumps was about 4 times the bulk strength of the clay in-situ.

Six tests were made using different vertical loads to give normal effective pressures between 17 and 100 kN/m^2. Prior to shearing, the clay was allowed to come to equilibrium under the selected vertical load for about 7 days by which time the rate of vertical movement had become negligible. The horizontal shear load was then applied in small increments at regular intervals so that in test No 1, 2 and 6 the peak stress was reached in 5 to 8 days. In order to check any possible effects of the rate of application of the load, the rate of shearing in test No 3 was much slower, so that the maximum shear stress was reached in 39 days. Additional confirmation that the rate of shearing was sufficiently slow to allow almost complete drainage in the fissures was provided by pore water pressure measurements made at the centre of the clay under test on the plane of separation of the two halves of the box in test 5(a) and in a duplicate test 5(b) in which
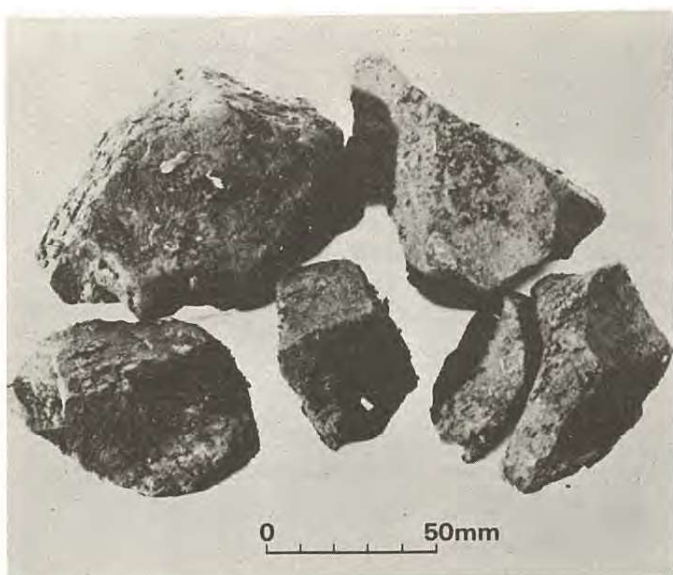
Fig 6   Typical intact lumps of Barton Clay
from shear box test No 3

Fig 7   Shear stress -displacement curves
obtained from tests on Barton Clay
using the large in-situ shear box

the sample was sheared at a much faster rate, the maximum shear stress being reached in 4 hours. In both these tests the pore water pressure increased as the shear load was applied until half the maximum shear stress was reached and then dropped steadily to give pore water pressures around zero at the maximum shear stress and pore suctions after failure. In the quick test the pore water pressure reached a maximum of 11 per cent of the shear load as against 8 per cent for the test loaded at the standard rate. The most significant difference between the two tests occurred after the maximum shear stress had been reached and by the end of the test the pore water suction in the quick test exceeded the shear stress while in the standard test it was only about 11 per cent of the shear stress. Shear stress-displacement curves obtained using the large in-situ shear box are shown in Fig 7. The peak and minimum post-peak values from these tests are plotted in Fig 8 together with the upper and lower limits of the peak strengths on 75 to 125 mm diameter specimens and residual strengths obtained by reversal tests in 60 mm square shear boxes. The peak shear strength measured by the in-situ shear box lies within the range of those measured in triaxial tests on 75 and 125 mm diameter specimens. However, under the lowest normal effective stresses the maximums obtained from the in-situ shear tests tend to the lower limit of those measured in the triaxial tests. The most significant feature of the results obtained from large in-situ shear tests was the very small cohesion intercept and the relatively large angle of internal friction under low stresses. In the case of the Barton Clay the peak values lay close to a straight line giving a c' of
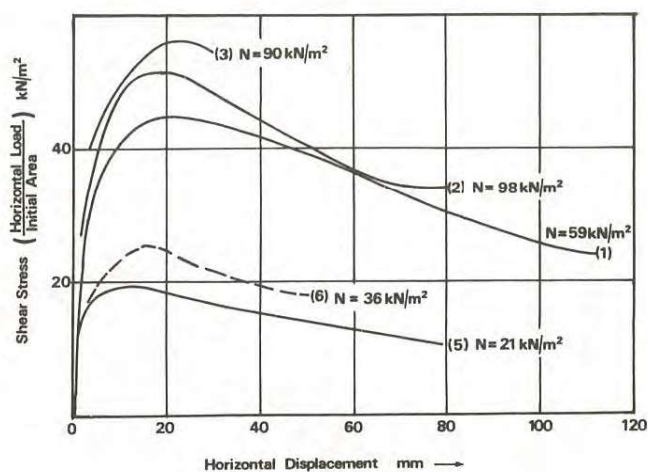
8.3 kN/m^2 and angle of internal friction of ϕ' of $27°$. The results of these large in-situ shear tests show that under low effective stresses fissured clays behave like a granular material composed of interlocking lumps of clay which have an intact strength of 4 to 5 times the strength of the clay in the mass.

IV. - CONCLUSIONS AND GENERAL OBSERVA-
TIONS ON THE USE AND LIMITATIONS OF
IN-SITU TESTS FOR MEASURING THE
PROPERTIES OF STIFF FISSURED CLAYS

Large in-situ tests of the type described in this paper have shown the important influence which fissures have on the properties of fissured clays. They have led to a better understanding of the behaviour of these clays and have provided strength and deformation parameters more applicable to engineering design than those measured in laboratory tests on 'undisturbed' samples.

Comparison of the results of large in-situ plate tests and laboratory tests have shown that even in the same type of clay the relationships between various tests vary with depth, location, and differences in the fissure structure. They have shown the fallacy and dangers of applying correction factors of the type suggested in References 5 and 12, to results of laboratory tests in order to predict the large-scale behaviour of stiff fissured clays. The same conclusions apply to small in-situ tests such as the Dutch cone (Ref 13), which in general provide a measure of the strength of the clay in the intact lumps between the fissures and the use of these tests to predict the large-scale strength is not recommended.
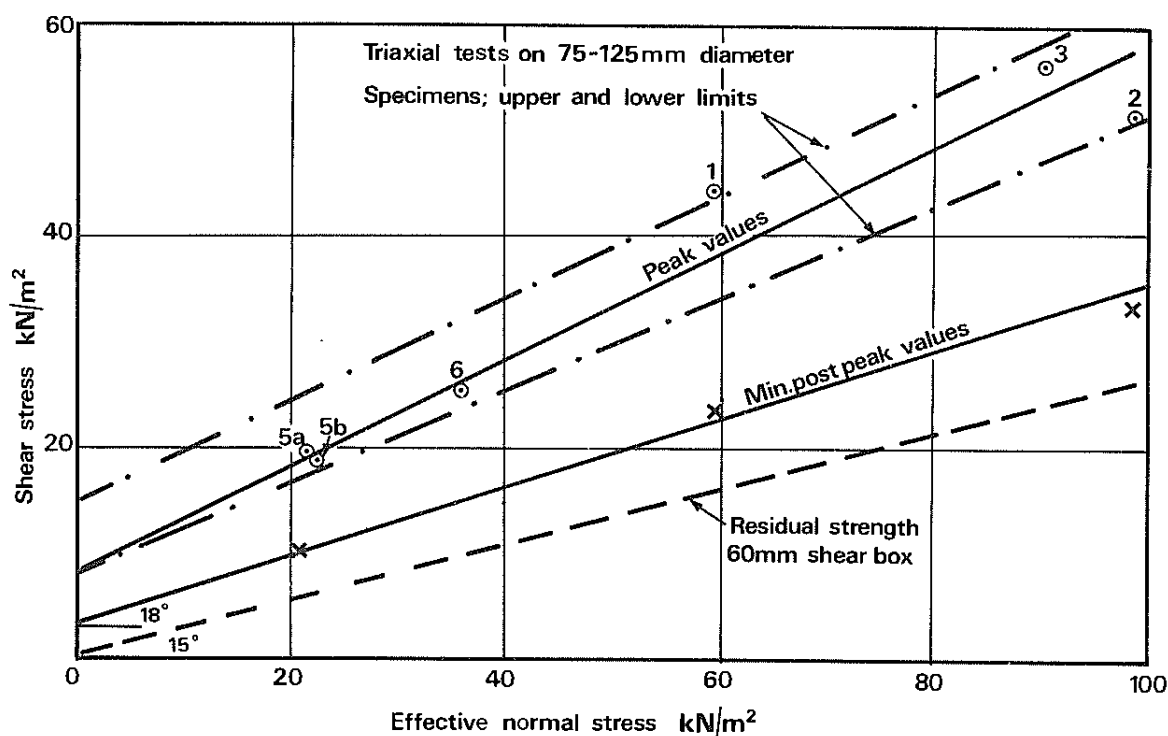
Fig 8   Results of in-situ shear tests expressed in terms of effective stresses

To obtain reproducible and reliable estimates of the modulii of stiff fissured clays it is necessary to make loading tests in boreholes which are sufficiently large to enable a man to remove loosened clay from the test level.   The effects of drilling the boreholes and the interval of time between excavation and testing require further investigation.   Even though in the present tests this interval has been reduced to a few hours some reduction of the modulii and to a smaller extent of the shear strength due to the opening of the fissures in the clay was inevitable. This effect was probably greatest in tests made at the deeper levels and may have accounted for the very small increase in both strength and modulii with depth which was obtained from the tests below about 20 m.   More tests are required in which different periods of time are allowed between excavation and testing, and in which strains are measured in the clay below the loaded area.   Ideally such tests should include measurements of strains occurring during excavation or drilling.

The complex nature and variability of fissured clays make it necessary to consider each clay individually.   New problems are bound to arise when the techniques described in this paper are used to measure the properties of harder clays than those already tested, but even so they should provide a more reasonable measure of the large-scale properties than laboratory or small in-situ tests.

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