TRANSPORT RESEARCH LABORATORY

Field evaluation of the TRL load cell pressuremeter in Gault Clay

Prepared for Quality Services, Civil Engineering, Department of the Environment, Transport and the Regions

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Executive Summary

In the design of geotechnical structures, a reliable prediction of soil deformation under load is primarily dependent upon the accuracy with which the stress regime in the ground is known. For this reason *insitu* testing using pressuremeters has been increasingly employed to complement laboratory testing at the site investigation stage.

The forerunner of the current self-boring expansion pressuremeter was the load cell pressuremeter. However, past developments tended to concentrate on the expansion pressuremeter because of its ability to give additional data on soil modulus and shear strength parameters, although the load cell pressuremeter is inherently more suitable for *insitu* stress measurements. Recent changes to the load cell pressuremeter carried out by TRL in conjunction with Cambridge Insitu now make this instrument more viable for general use. The primary advantage of the TRL load cell pressuremeter is that complex interpretation of the stress results is unnecessary as the instrument is direct reading. This report describes a field trial of the TRL pressuremeter in Gault Clay.

The design of the self-boring load cell pressuremeter incorporates six ‘null sensing’ load cells and piezometers equi-spaced around its circumference for the measurement of *insitu* lateral stress and porewater pressure respectively.

Field evaluation of the instrument was undertaken at a site in Gault Clay with the results being compared with those from the expansion pressuremeter. Lateral stresses measured after about 1 hour using the load cell pressuremeter and derived from strain measurements using the expansion pressuremeter were found to be broadly comparable. In both cases, stresses were significantly higher than those determined when the load cell pressuremeter readings were given more time to fully stabilise. This finding has implications for the use of all pressuremeters in stiff clays, where over estimation of *insitu* stress has serious cost implications in the design of retaining walls and other below ground structures. However it is only with the continuously monitored load cell pressuremeter that the necessary test duration can be readily established.

1 Introduction

In the design of geotechnical structures, a reliable prediction of soil deformation under load is primarily dependent upon the accuracy with which the stress regime in the ground is known. For this reason *insitu* testing using pressuremeters has been increasingly employed to complement laboratory testing at the site investigation stage. Information on the various types of pressuremeter and their performance is given by Mair and Wood (1987).

Although the development of the self-boring expansion pressuremeter (Camkometer) in the early 1970’s proved a significant advance in measuring *insitu* lateral stress compared to pressuremeters installed in pre-drilled boreholes, reliable interpretation of *insitu* lateral stress from measurements of radial strain remains problematic (Hawkins et al, 1990). A detailed knowledge of the various methods of interpreting the results is necessary and the estimate of *insitu* stress is still somewhat subjective depending on the analytical approach. For this reason the Transport Research Laboratory funded by the Highways Agency developed a new self-boring device known as the TRL load cell pressuremeter (Darley el al, 1996).

The principles of both the self-boring expansion and load cell pressuremeters were first developed by Windle and Wroth (1977), who acknowledged that the latter was potentially better for *insitu* stress determination. However further developments tended to concentrate on the expansion pressuremeter because of its ability to give additional data on soil modulus and shear strength parameters. A detailed description of the design changes to the load cell pressuremeter carried out by TRL in conjunction with Cambridge Insitu which now make this instrument more viable for measuring *insitu* stress have been reported by Darley et al (1996). The primary advantage of the TRL load cell pressuremeter is that, in addition to improved technology, it incorporates six ‘null sensing’ loads cells and six piezometers equi-spaced around its circumference for measuring *insitu* total lateral stress and porewater pressure respectively. Complex interpretation of the stress results is unnecessary as the instrument is direct reading which also means that each test can be continued on site until the instruments are fully stable and any excess porewater pressure generated by the drilling has dissipated.

This report describes the field evaluation of TRL load cell pressuremeter to establish its performance in Gault Clay. The results from the test borehole are compared with those obtained when using the expansion pressuremeter at the same site.

2 Description of the TRL load cell pressuremeter

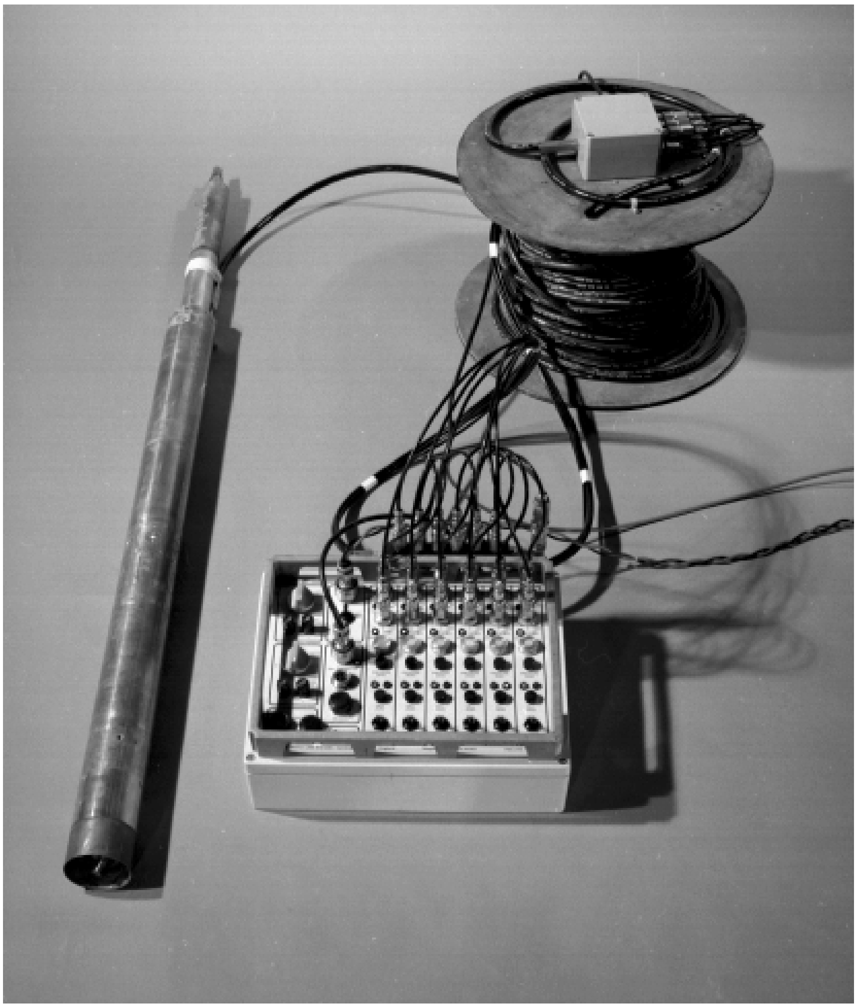
A detailed description of the TRL load cell pressuremeter is reported by Darley et al (1996). The instrument was designed to have the same external dimensions as the expansion pressuremeter (Camkometer) and is operated using the same self-boring principles. However the instrument is designed to continuously measure only total lateral stress and porewater pressure, and no other soil parameters. For this reason the inflatable rubber membrane and the protective steel strips (‘Chinese Lantern’), which are necessary for the expansion pressuremeter, are no longer required with the load cell pressuremeter. This, in itself, is considered to be advantageous in self-boring with minimal insertion disturbance so that the load cells and piezometers incorporated in the pressuremeter are in intimate contact with the ground.

Figure 1a shows the instrument and control system, whilst Figure 1b shows a close up of two of the six cell clusters arranged around the circumference of the pressuremeter. The circular ceramic piezometer elements are seen in Figure 1b to the left of the more oval load cell plates. The design of each load cell is based on that of the contact stress transducer (Arthur and Roscoe, 1961) and uses strain gauged pillars to support the cell top plate. Whilst the load cells will measure soil lateral stress directly with no balancing internal gas pressure, the pressure reading would then be subject to error owing to the small movements (0.008mm per MPa of applied pressure) of the top plate developed under load. Carder and Krawczyk (1975) carried out calibrations of a soil pressure cell incorporating the contact stress transducer and showed that significant under-registrations in measured boundary stresses occurred in ‘direct’ mode because differences in stiffness between the cell and the boundary altered the distribution of soil pressure over the cell face.

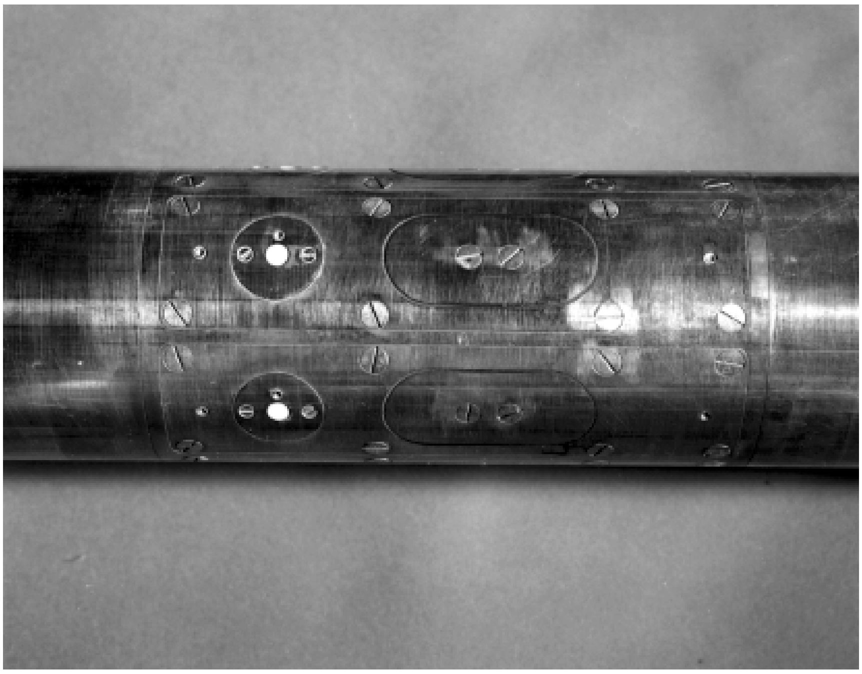
For this reason, the load cells in the pressuremeter were always operated in ‘null sensing’ mode. In this mode, the top plate of each load cell is maintained perfectly flush with the surface of the instrument by applying an internal gas pressure of a known magnitude. As the external soil stress acting on the instrument changes with depth, the internal gas pressure to each individual cell is automatically adjusted by the control system to maintain the load cell output at the bench zero obtained prior to the commencement of drilling. In practice, the response time of the control system is such that small differences from the zero may occur on each load cell. These differences are allowed for by evaluating the external soil pressure on each load cell from the sum of the measured gas pressure and any small differential pressure recorded by the load cell.

The ‘null sensing’ is continuously operated for 24 hours per day, both when drilling and when carrying out a test at a particular depth. The continuous operation of the null sensing system during drilling is advisable to prevent inward displacement of the load cell plate under the soil load; subsequent ‘nulling’ from a displaced position would risk the development of higher soil pressures than exist *insitu*.

The six piezometers incorporated in the instrument have detachable high air entry ceramic elements which need to be de-aired before the instrument is used. A strain gauged diaphragm for the measurement of porewater pressure is included behind the ceramic element of each piezometer. The piezometers are ‘direct’ reading devices and use the same technology as in the self-boring expansion pressuremeter.



(a) Probe and control unit



(b) Close up of two of the six cell clusters

Figure 1 TRL load cell pressuremeter

Before use the pressuremeter was calibrated using an external cylindrical collar which enabled a known pressure to be applied simultaneously to all six cell clusters. Further details of the calibration procedures and a description of the control system and signal conditioning are given by Darley et al (1996).

3 Test procedure for field trials

Trials were carried out in a free field location in Little Eversden, Cambridge, where about 4.5m of gravel overlay stiff over-consolidated Gault Clay. This site was particularly suitable as Cambridge Insitu had carried out earlier tests using the self-boring expansion pressuremeter. The *insitu* lateral stress regime established using the expansion pressuremeter could therefore conveniently be compared with the new data from the load cell pressuremeter.

The test borehole was first established through the gravel into the clay using a shell and auger drilling rig and the 200mm diameter borehole cased with steel duct. Before the load cell pressuremeter was inserted into the borehole it was powered up and, when the outputs had stabilised, a set of zeros was obtained on the various instruments. The pressuremeter was then lowered into the borehole and drilling commenced using a rotary cutter with its tip set at 5mm behind the leading edge of the cutter shoe; water flush was employed to remove the spoil in the usual manner. Self-boring continued until the cell clusters were at the first test depth of 5.9m, when the hydraulic pack driving the rams and rotary cutter was switched off to prevent vibration during the test. As the measured stresses appeared to have stabilised after four hours, the test was terminated and self-boring was then recommenced. It must be noted that the duration of the first test was significantly less than required elsewhere. This was probably because the borehole to 4.7m depth was established some time in advance of the testing and ingress of water had caused softening of the clay immediately below the bottom of the hole.

Tests were carried out at one metre intervals to a final depth of 13.9m. The duration of these tests ranged from 20 to more than 70 hours. The test program took 12 working days to complete and some tests were allowed either to run overnight, or in the case of the tests at 7.9m and 12.9m depth, over a weekend. After testing was completed the pressuremeter was removed from the hole and a second set of zeros taken on all instruments. No significant changes in the zero readings were apparent. Subsequently the pressure calibrations of the instruments were also checked and found to be in good agreement with those obtained before field testing.

Following completion of the testing programme, an inclinometer tube was temporarily installed in the borehole left by the pressuremeter to check its verticality. Figure 2 shows the lateral displacement profile with depth in two mutually perpendicular directions. The results show that the maximum lateral displacement from vertical was less than 80mm over the 14m depth of the borehole. On this basis it was concluded that the borehole was reasonably straight and the possibility of spurious effects due to the pressuremeter going off line could be discounted.

The inclinometer tube was subsequently withdrawn and pneumatic piezometers incorporating high air entry ceramic elements installed at depths of 6.9m, 10.7m and 13m with bentonite seals between them. At this stage the borehole was completely backfilled with bentonite and, after allowing a few weeks for the porewater pressures to equilibrate, readings were taken. The results from the ground piezometers were then compared with those from the piezometers in the load cell pressuremeter.

It became apparent during the first test that one of the piezometers in the pressuremeter was recording pressures well in excess of the other five. The results from this piezometer were therefore omitted when calculating the mean porewater pressure at the various test depths.

4 Test results

Figure 3 shows the variation of the measurements with time at each test depth. Total lateral stresses are the means from the six load cells and mean porewater pressures were calculated from the five working piezometers. The effective lateral stress is not measured directly but calculated from the difference between the total stress and porewater pressure.

The pattern of behaviour in terms of total lateral stress measurements is similar for all tests with a significant fall in stress occurring over the first few hours of each test. After this initial reduction, the total lateral stress then slowly stabilises. The overall time necessary for stabilisation appeared to vary with depth. Some tests at shallow depths appeared to fully stabilise after about 4 hours, tests at greater depths appeared to take a much longer time. For example, it is doubtful if the total stress values measured at 11.9m depth were fully stable after 20 hours.

As a component of the total stress is the porewater pressure, it is possible that total stress will only stabilise when any excess porewater pressure induced by the drilling process has dissipated. Inspection of the time plots in Figure 3 tends to confirm that the time taken for total stresses to fully stabilise appears similar to that for the porewater pressures. Further substantiation is obtained from examining the calculated variation of effective lateral stress with time; the time for effective stresses to fully stabilise is generally much less. On this basis the necessary duration of the test at each depth will be dependent upon the rate of porewater pressure dissipation and the permeability of the particular soil strata. At this site, weathering of the Gault Clay is expected to have increased its permeability at shallow depths.

Although the time for full stabilisation of total stresses appears to be related to excess porewater pressure dissipation as described above, the same relation between stresses and porewater pressure does not exist during the first few hours of the test. For example, in Figures 3a and 3b for tests down to a depth of 10.9m, the porewater pressures appear to initially build up rapidly whilst total stresses are falling. For deeper

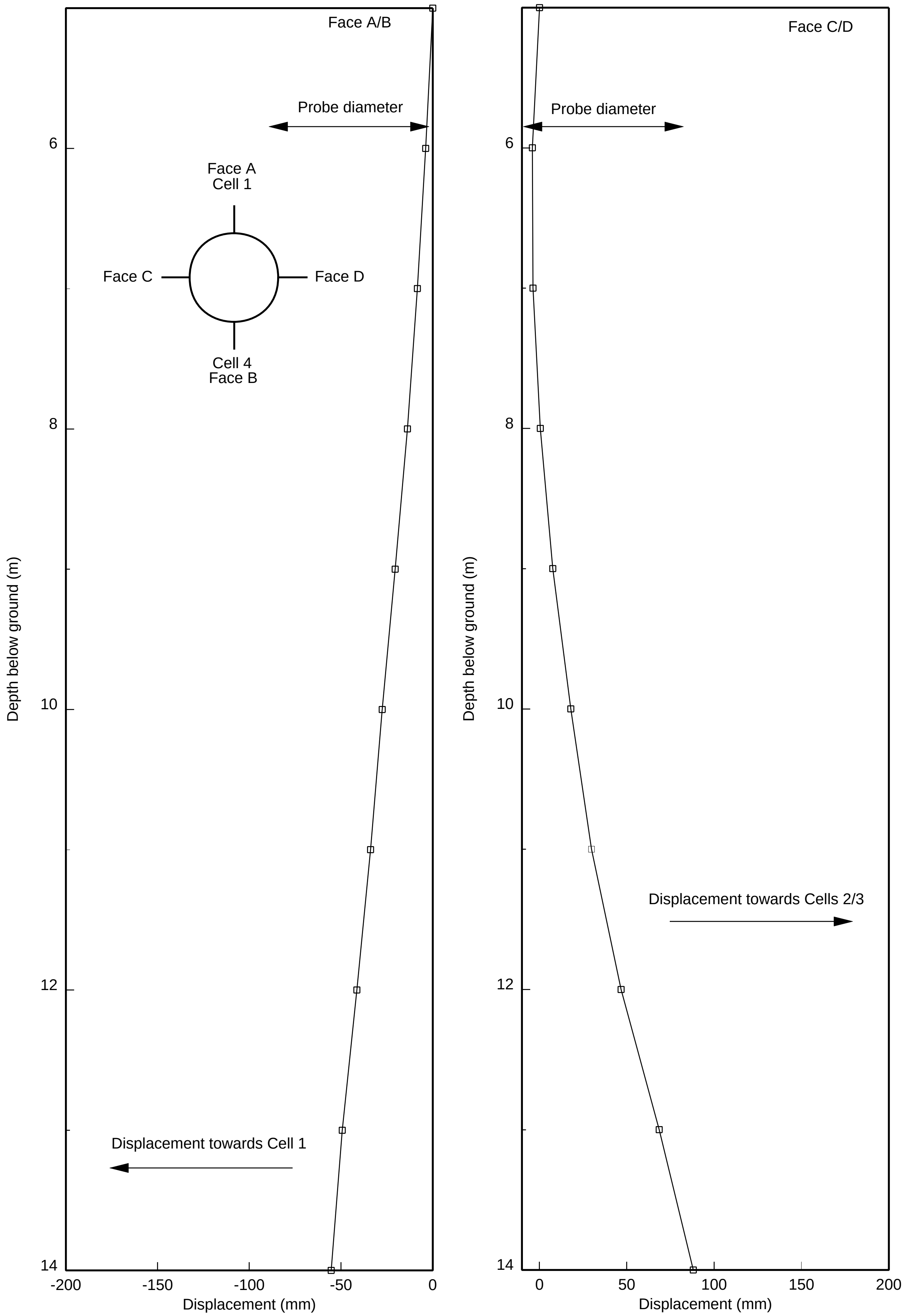


Figure 2 Lateral displacement profiles of test hole

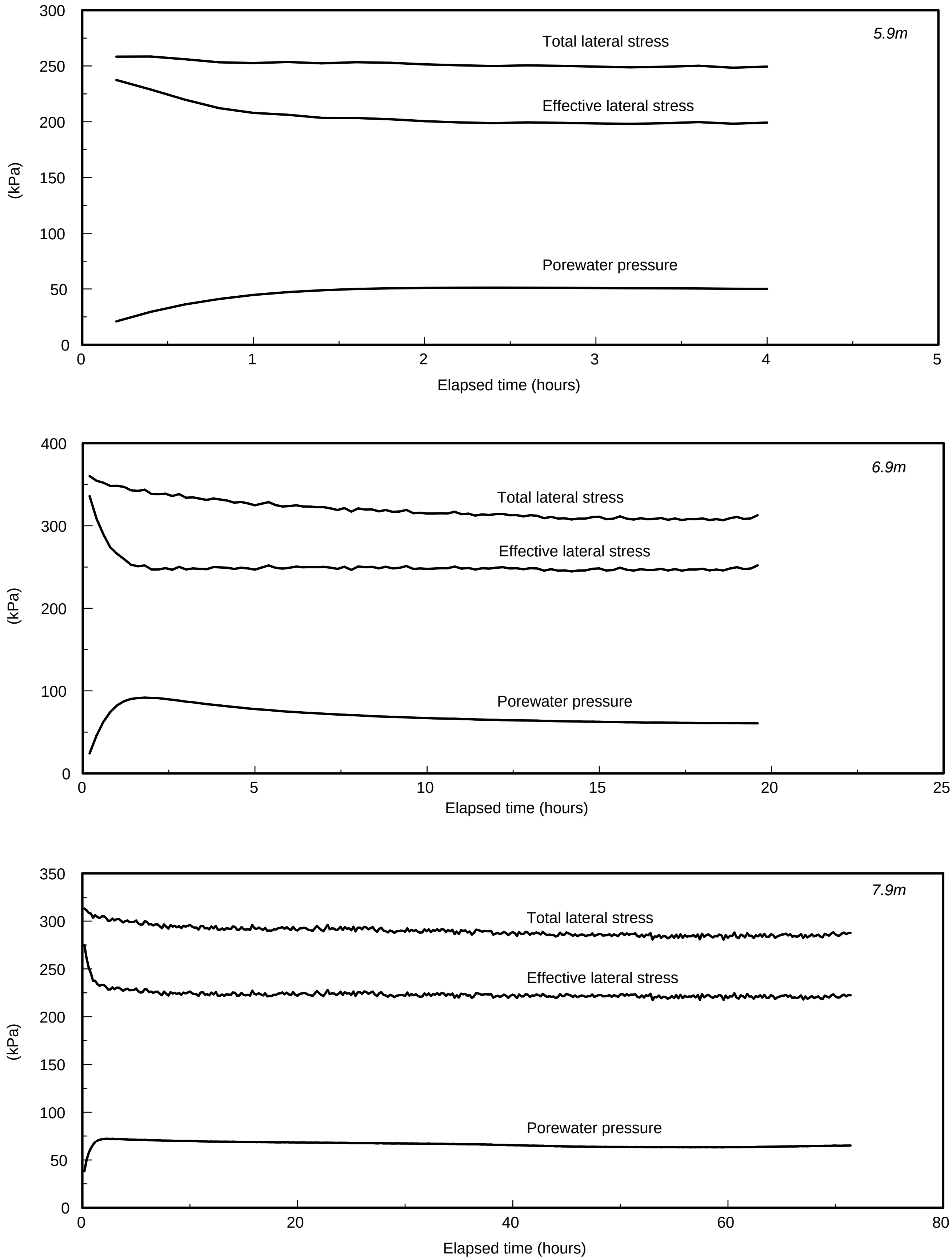


Figure 3(a) Test results at 5.9m, 6.9m, 7.9m below ground level

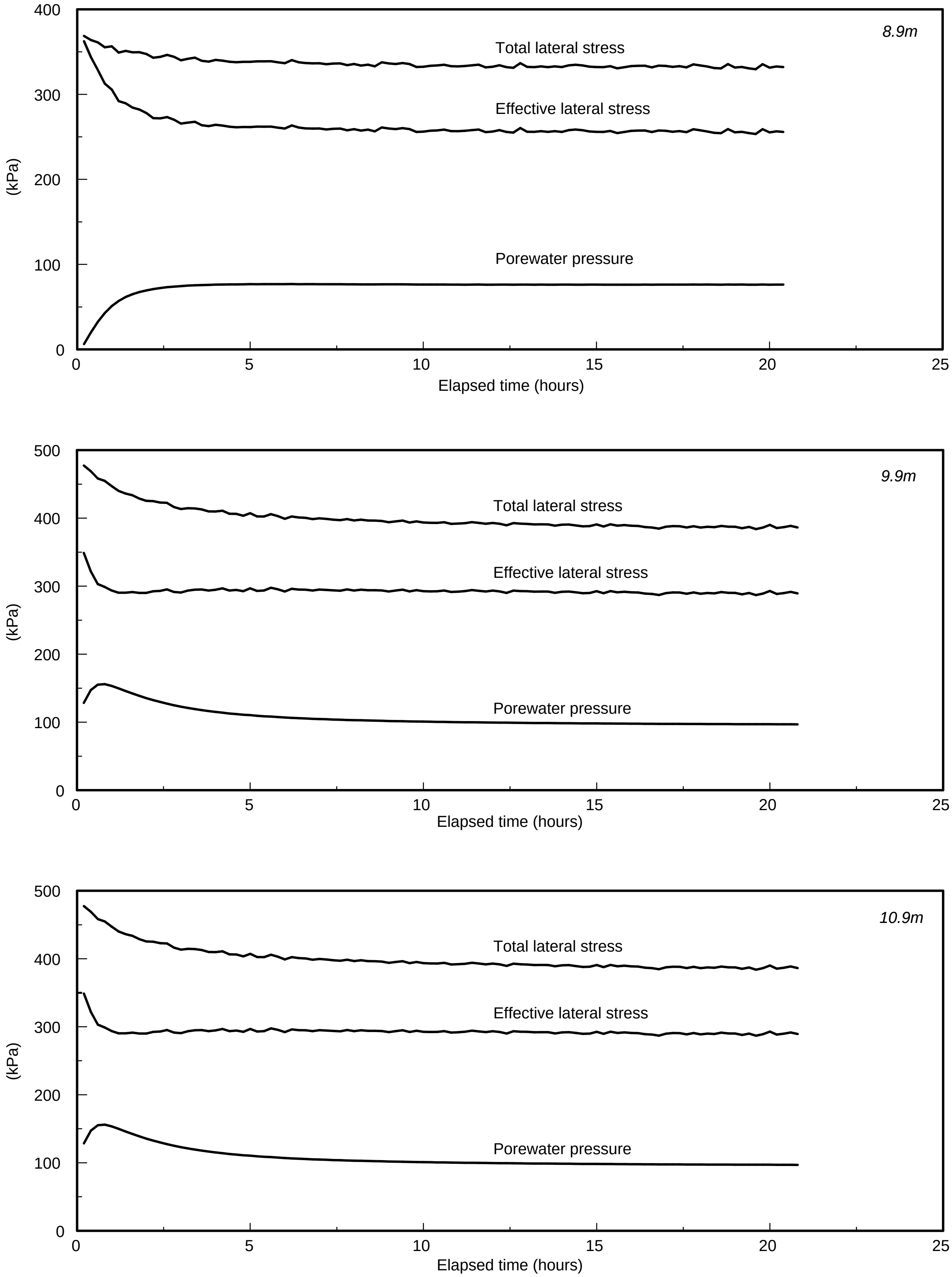


Figure 3(b) Test results at 8.9m, 9.9m, 10.9m below ground level

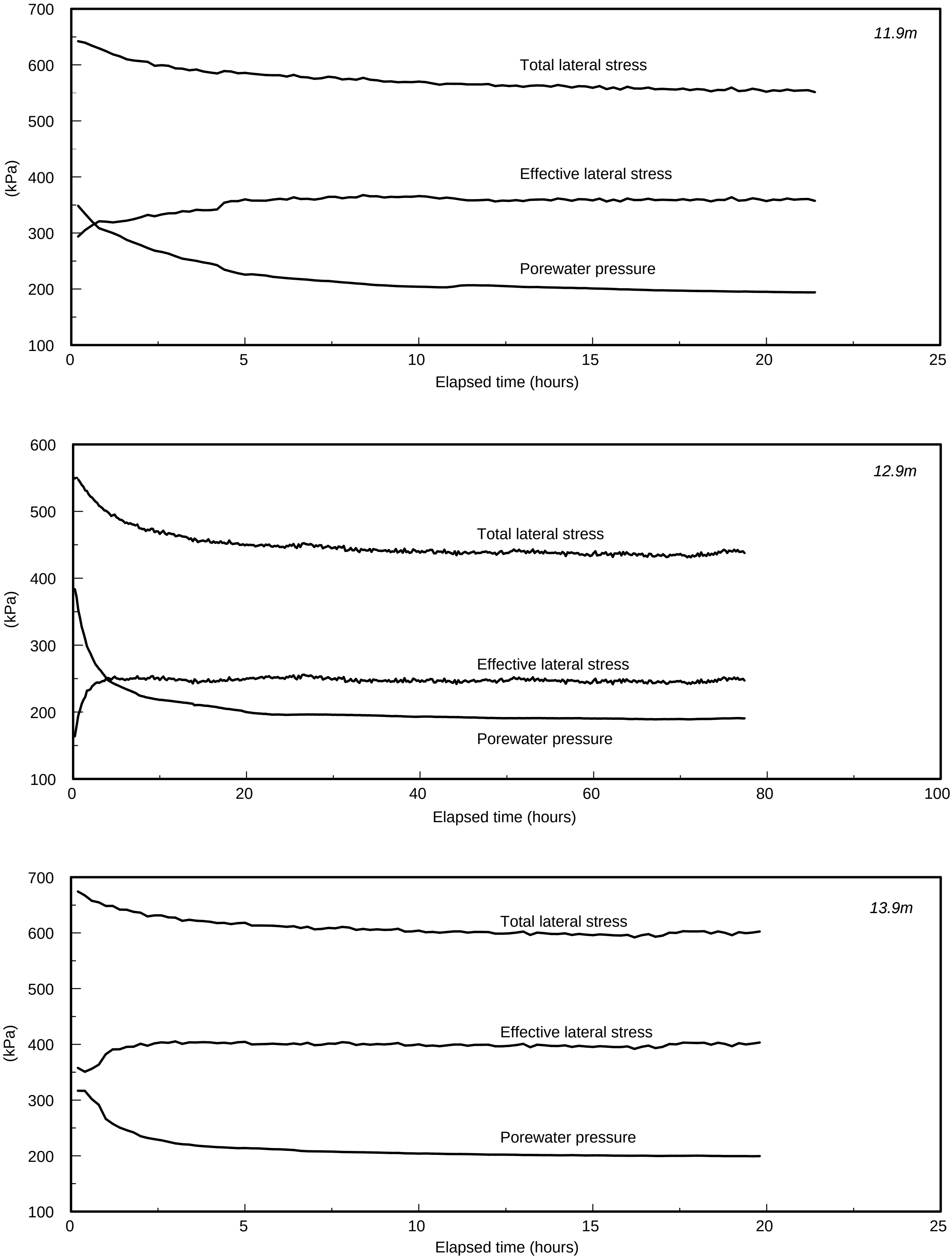


Figure 3(c) Test results at 11.9m, 12.9m, 13.9m below ground level tests (Figure 3c) the converse is observed with high initial porewater pressures and larger reductions in porewater pressure than total stress. These effects are probably caused by a combination of factors which depend on the response time of the piezometer, the rate of dissipation of any excess porewater pressures generated by drilling, together with the permeability of, and presence of fissures in, the surrounding soil. The response time of the piezometers incorporated in the load cell pressuremeter may be retarded, in a similar way to any push-in piezometer, by any smearing with clay during the drilling phase. Although the evidence from these tests suggests that the piezometers read true porewater pressures after a few hours have elapsed, readings taken earlier than this must be treated with caution.

These findings have implications for the use of both load cell and expansion pressuremeters in stiff and impermeable clays. A duration of about 16 hours was recommended by Darley et al (1996) for tests in London Clay to ensure that reasonable stability had been reached for measurements of total lateral stress. Most of the tests in Gault Clay indicated that a similar test period was appropriate. The continuous monitoring capability of the load cell pressuremeter is particularly advantageous in enabling a suitable test duration to be decided on site by observation.

5 Discussion of results

5.1 Magnitude and distribution of lateral stresses

Figure 4 shows the variation of total lateral stress with depth measured by both the TRL load cell pressuremeter and the self-boring expansion pressuremeter (Camkometer). In the case of the load cell pressuremeter, stress values are means from the six load cells as measured one hour after the start of each test and at the end of each test. As the time to the end of each test varied according to when the readings were fully stable, the duration of each test is also indicated in Figure 4.

For the expansion pressuremeter, the *insitu* lateral stress was assessed by examining the stress-strain curves from each of the strain arms to determine the lift-off stresses. Lift-offs were established from the initial discontinuities in the curves after investigation of the 'signature' of each arm (Clarke, 1992). The final values in Figure 4 were the means from the three arms and generally tests were completed during the first hour after drilling to the required depth. The results from the expansion pressuremeter required a significant amount of time to derive and were open to variations of interpretation by different operators carrying out the analysis.

Generally the one hour results from the TRL pressuremeter are in reasonable agreement with those obtained from the self boring expansion pressuremeter, although a larger scatter was obtained with the latter. As would be expected, the results at the end of each load cell pressuremeter tests were less than the one hour results and considered more realistic as the readings were then much closer to equilibrium.

The use of six strain arms in the expansion pressuremeter has already been described by Whittle, Hawkins and Dalton (1995) who reported that a significant variation in the lateral stresses may occur around the instrument. This variation may be due to natural anisotropy in the ground, insertion disturbance perhaps caused by the pressuremeter being deflected from vertical by a hard inclusion, or use of a bent probe or drill string. The use of six load cells in the TRL pressuremeter has the same advantages in permitting an assessment of any inherent anisotropy in the ground and the quality of the pressuremeter test.

Table 1 gives the total stresses measured on individual load cells at the end of each test together with the mean and standard deviation calculated from them. These results are also represented diagrammatically in Figure 5 to illustrate the total lateral stress distributions around the pressuremeter. Some variation in stress around the pressuremeter is apparent with slightly higher stresses being measured on cells 5 and 6 and slightly lower stresses on their diametrically opposite cells 2 and 3. Even if some natural anisotropy were present in the ground, diametrically opposite cells would be expected to record the same values. In this particular instance, the inclinometer measurements in Figure 2 indicate that the pressuremeter borehole was straight and as near vertical as could reasonably be expected. The variation in results may therefore represent the normal scatter which should be expected from the instrument. At this site, free field stresses evaluated from the mean of the six cells were considered realistic.

Table 1 Total lateral stresses measured on each load cell

Test depth (m)	*Total lateral stress (kPa)*							
	Cell 1	*Cell 2*	*Cell 3*	*Cell 4*	*Cell 5*	*Cell 6*	*Mean*	*Standard deviation*
5.9	162	251	212	238	361	271	249	66
6.9	289	297	253	255	372	379	308	56
7.9	270	310	237	177	407	302	284	77
8.9	304	340	288	253	410	389	331	61
9.9	333	318	304	351	446	434	364	61
10.9	379	372	413	358	474	358	392	45
11.9	546	523	516	460	713	561	553	86
12.9	416	299	462	371	552	541	440	98
13.9	634	535	635	494	723	595	603	81

5.2 Magnitude and distribution of porewater pressures

The porewater pressures measured by the piezometers incorporated in the load cell pressuremeter and the three pneumatic piezometers installed in the borehole at the end of the test program are compared in Figure 6. The results from the pneumatic piezometers indicate that a hydrostatic distribution of porewater pressure exists from a water table at about 1m depth below ground level. This correlated well with the depth to water measured in a nearby open borehole.

The mean results from the five working piezometers measured at the end of each pressuremeter test showed very close agreement with the pneumatic piezometer profile up to a depth of 10.9m. The three tests below 10.9m however indicate mean porewater pressures around the probe which are about 65kPa in excess of the

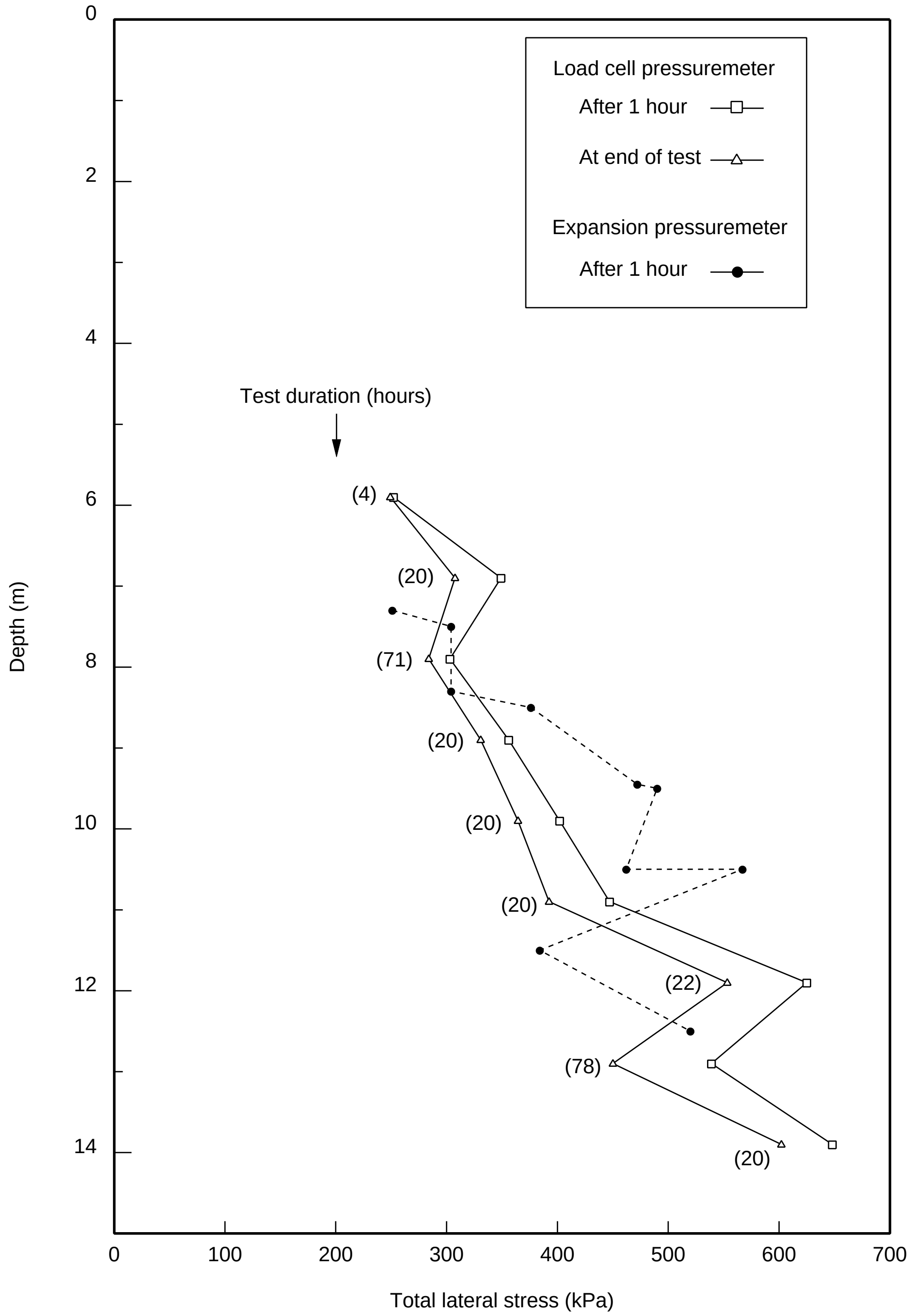


Figure 4 Profiles of lateral stress with depth

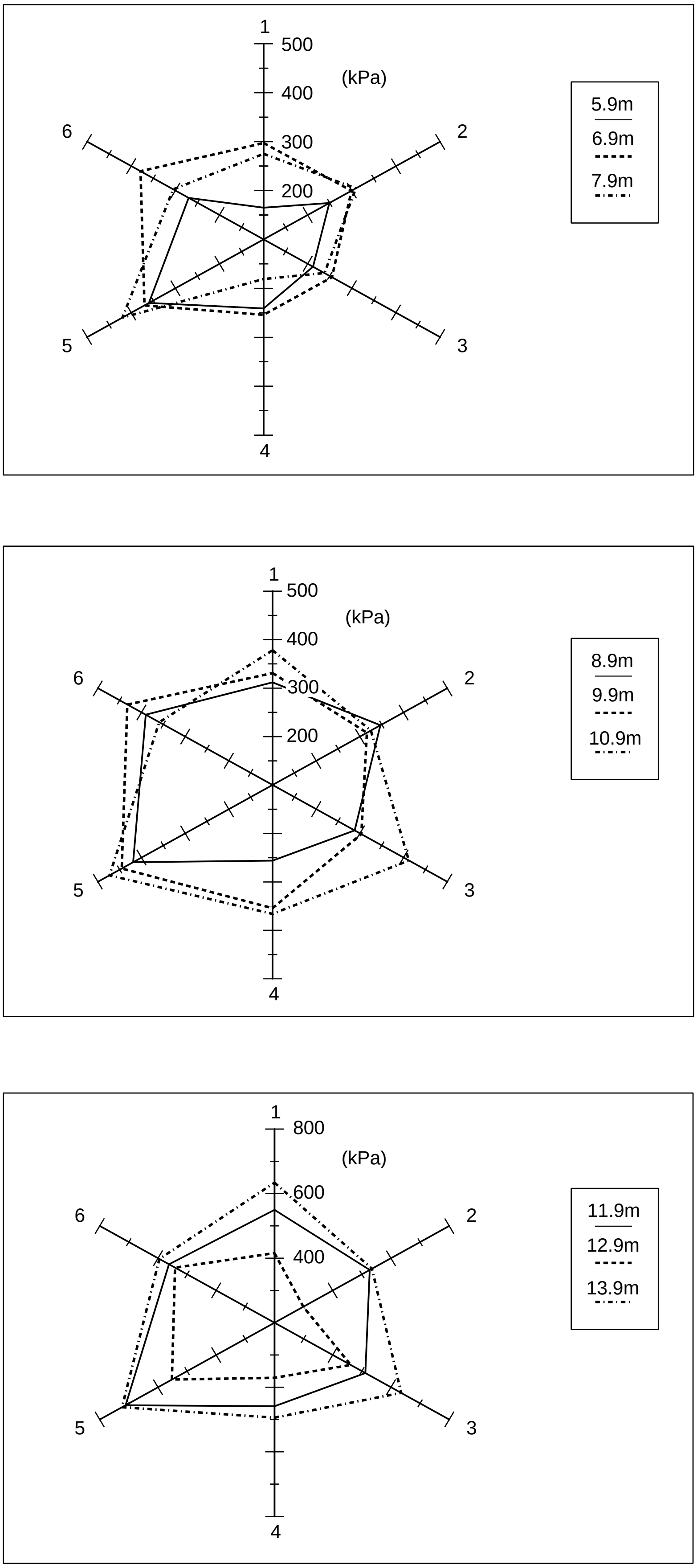


Figure 5 Total lateral stress distribution around the probe

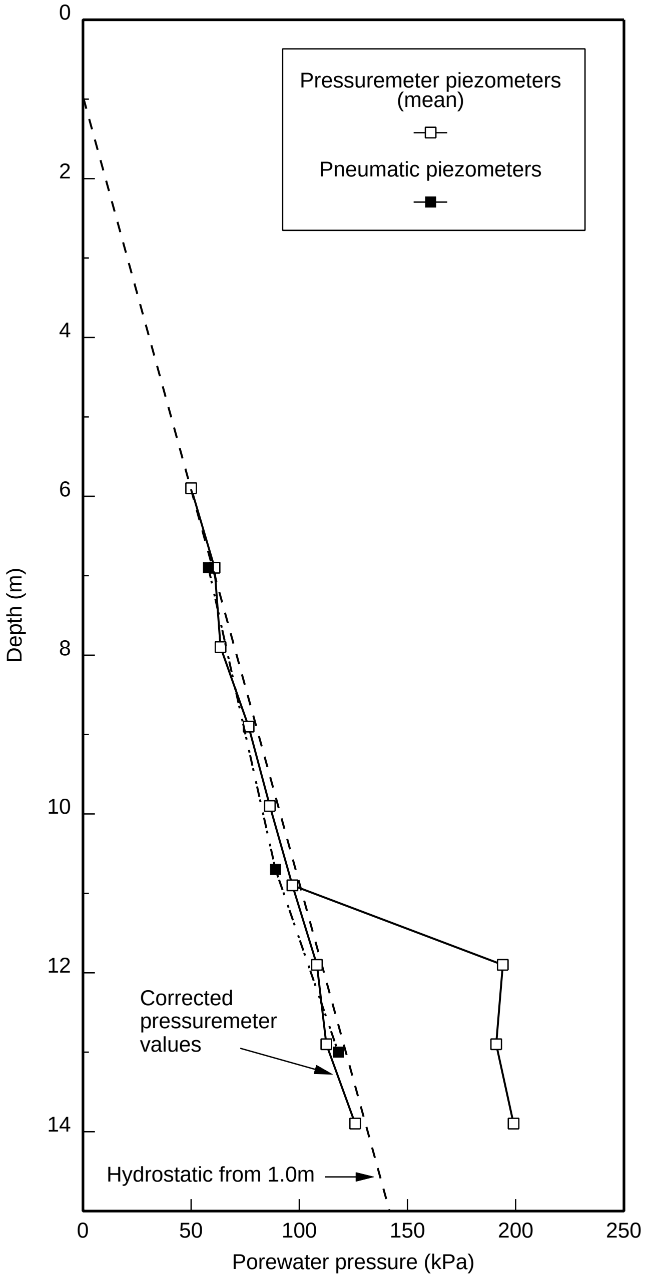


Figure 6 Profiles of porewater pressure with depth

calculated hydrostatic values. At these depths particularly high porewater pressures were recorded by piezometers 4,5 and 6: a corrected plot is shown in Figure 6 which ignores these high values. Whether this behaviour is due to the existence of a very impermeable layer in the Gault Clay at this depth or clay smear affecting the piezometer performance is not clear. Both of these effects might have been overcome if an even longer test duration of approaching a week had been used at these depths. However, if a similar error occurred in the total stress measurements, it would still be within the standard deviation on the stress results given in Table 1.

The distribution of porewater pressure around the probe at the end of each test is shown in Figure 7. Also shown are the calculated hydrostatic values assuming the water table is 1m below ground surface. Good correlation was obtained between measured and predicted values at depths of up to 10.9m and, with the exception of piezometer 2 which was suspect, little variation in readings occurred around the circumference of the pressuremeter. The porewater pressures recorded by piezometers 1 and 3 remained close to hydrostatic, whilst those for piezometers 4, 5 and 6 all rose sharply below 10.9m depth. This suggests clay smear on these piezometers is a more likely cause then the presence of a very impermeable layer.

6 Conclusions

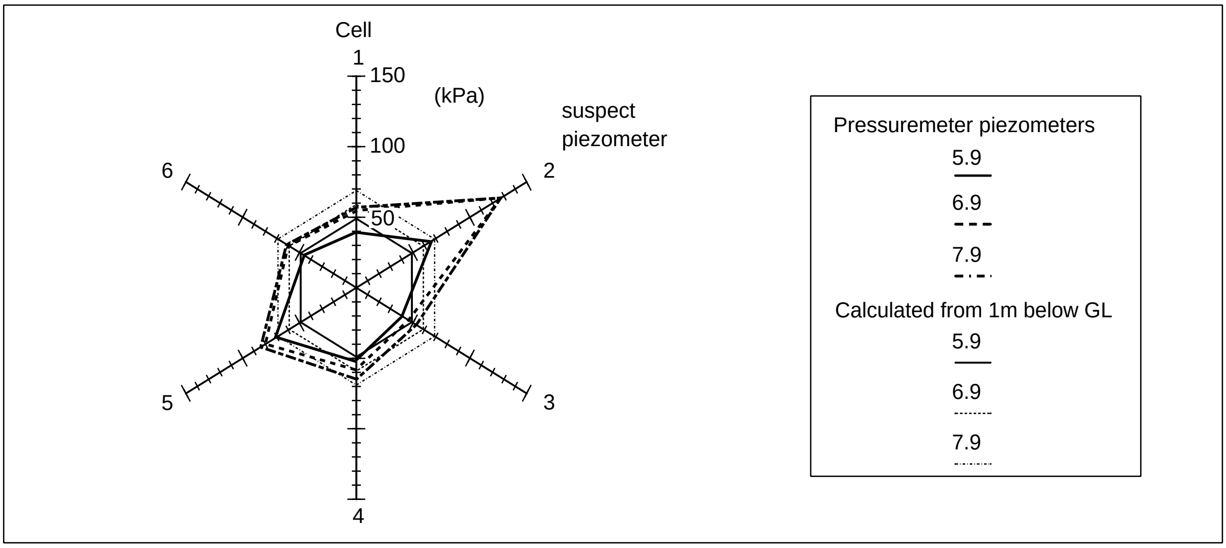
A field evaluation of the TRL load cell pressuremeter has been carried out to assess its performance in Gault Clay. The study is a sequel to the preliminary evaluation carried out in London Clay in 1996 following the design and construction of the instrument. The particular features of this self-boring pressuremeter are the use of six ‘null sensing’ load cells and six piezometers equi-spaced around its circumference for the measurement of *insitu* total lateral stress and porewater pressure respectively. The instrument also gives a direct reading of total stresses and, unlike the expansion pressuremeter, the results do not have to be derived from strain arm data by a skilled analyst. The following conclusions were reached from the study.

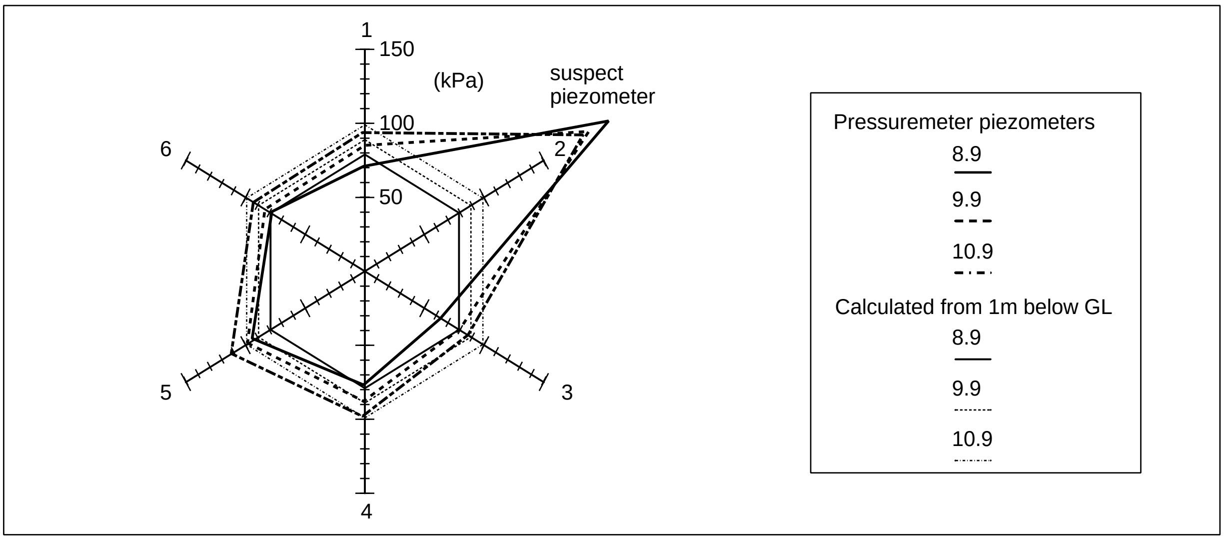
i As the load cell pressuremeter is direct reading, the stresses and porewater pressures can be continuously monitoring on site until they are fully stable. The previous recommendation of a minimum duration of 16 hours for tests in London Clay (Darley et al, 1996) were also found to be generally appropriate for the over-consolidated Gault Clay.

ii Lateral stresses measured after about 1 hour using the load cell pressuremeter and derived from strain measurements using the expansion pressuremeter were found to be broadly comparable. In both cases, stresses were significantly higher than those determined when the load cell pressuremeter readings were given more time to fully stabilise. This finding has implications for the use of all pressuremeters in stiff clays, where over estimation of *insitu* stress has serious cost implications in the design of retaining walls and other below ground structures. However it is only with the continuously monitored load cell pressuremeter that the necessary test duration can be readily established.

iii The value of having six measurement points equi-spaced around the pressuremeter circumference has been previously demonstrated for the expansion pressuremeter (Whittle et al, 1995) and is substantiated by this study using the load cell pressuremeter. The use of six cell clusters not only gives some redundancy in the event of one of the instruments failing but also permits an assessment to be made of any inherent anisotropy in the ground and the quality of the pressuremeter test.

iv Installation of pneumatic piezometers in the borehole following completion of pressuremeter testing provides a low cost method of validating the results from the piezometers incorporated in the instrument. At this site, porewater pressures measured using these two methods





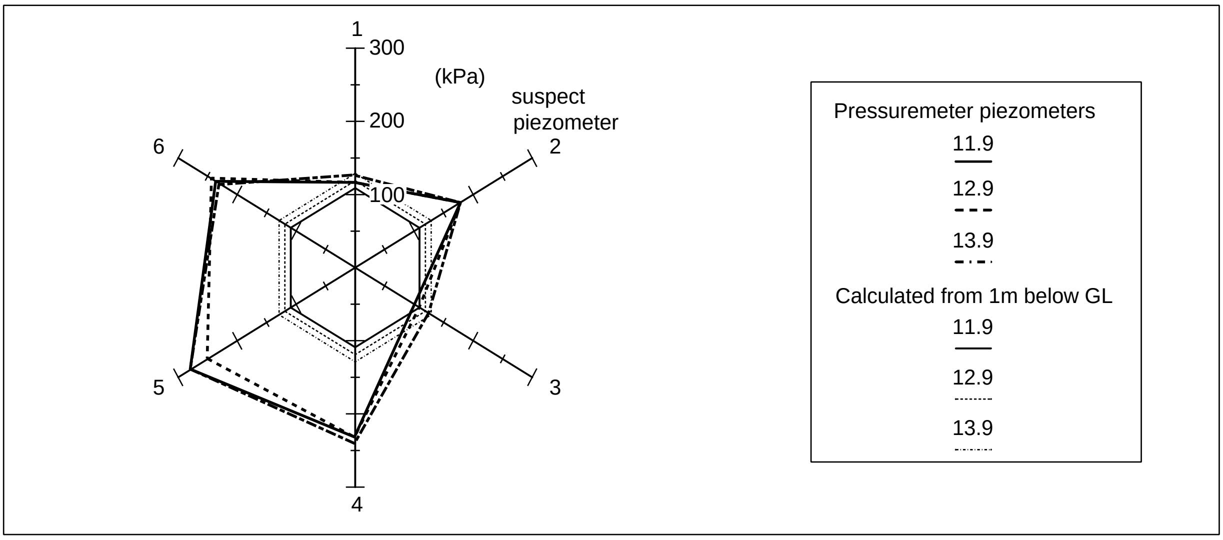


Figure 7 Porewater pressure distribution around the probe

were in close agreement down to a depth of 10.9m. Below this depth, mean porewater pressures from the pressuremeter were in excess of those measured by the pneumatic piezometers; this may have been caused by clay smear on some of the piezometers. This effect might have been overcome if an even longer test duration of approaching a week had been used at these depths.

v Generally the TRL load cell pressuremeter has performed effectively and reliably in both the trials in London Clay and Gault Clay. It appears to represent a significant advance in the measurement of *insitu* lateral stress in stiff over-consolidated clays.

vi When specifying the use of self-boring pressuremeters to determine *insitu* lateral stresses in stiff clays, the following should be borne in mind.

a If using the self-boring expansion pressuremeter, on site evaluation of the porewater pressures from piezometer data is advisable to ascertain that values are reasonably stable prior to carrying out a stress-strain test at each depth. If using the load cell pressuremeter, total lateral stresses can be directly monitored until they have stabilised. In both cases, if tests are carried out before equilibrium has been reached, an upper bound value of total lateral stress can be determined by subtracting any positive excess porewater pressures caused by the drilling.

b In stiff and impermeable clays, a duration of 16 hours may be necessary for stresses around the pressuremeter to have fully stabilised.

vii Use of the new pressuremeter, at site investigation stage, is strongly recommended for those geotechnical designs which are particularly sensitive to the *insitu* stress regime such as the design of retaining walls, cut-and-cover and bored tunnels, and piled foundations. Accurate measurements may significantly reduce construction costs in such cases.

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Thanks are also due to Mr J C P Dalton and his colleagues at Cambridge Insitu for permission to carry out the trial in the grounds at Little Eversden and their co-operation during the study.

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Abstract

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