In-Situ Testing of Soft Rocks

Essais *in situ* des roches molles

A. C. MEIGH, M.SC.(ENG.), M.I.C.E., *Rock Mechanics Limited, London, Great Britain*
S. W. GREENLAND, A.M.I.C.E., *Rock Mechanics Limited, London, Great Britain*

SUMMARY

This paper compares the results of plate-loading tests and pressuremeter tests in Coal Measure mudstone and sandstone, Keuper marl, and Bunter sandstone. These results are also compared with those obtained from laboratory tests on open-drive samples, drill cores, and hand-cut blocks. From the comparisons made, it can be seen that the pressuremeter tests and plate-loading tests are in good agreement, both in terms of modulus of linear deformation (E) and ultimate bearing capacity. On the other hand, laboratory tests are shown to be subject to the effects of sample disturbance. Comments are made regarding the effect on pressuremeter results of the boring methods used.

SOMMAIRE

Dans cet exposé une comparaison est faite entre des résultats d'essais de charge sur plaque et des essais pressiométriques sur les roches des "Coal Measures," le "Keuper Marl" et le "Bunter Sandstone". Les résultats ont été comparés aussi aux résultats d'essais de laboratoire faits sur des échantillons prélevés par battage, par le forage au diamant et sur des blocs coupés à main. D'après les comparaisons on peut constater une bonne concordance entre les résultats d'essais de charge sur plaques et les essais pressiométriques. Ces résultats sont présentés en fonction du module de déformation linéaire (E) et de la capacité portante. D'autre part on peut constater que les essais de laboratoire donnent des résultats faux à cause du remaniement des échantillons. On donne aussi quelques explications concernant les effets de la méthode de forage sur les résultats des essais pressiométriques.

THE PRINCIPAL SOFT ROCKS involved in foundation engineering in the United Kingdom are the Keuper marl, the Coal Measures, the Bunter sandstone, and the chalk. In such materials open-drive sampling is often attempted, particularly in the upper, more weathered part of the bedrock, but this causes sample disturbance to such an extent that test results are frequently completely misleading (Meigh and Early, 1957). In harder rocks the difficulty is overcome by coring with a diamond drill. In the softer rocks this can also be done, and high core recoveries can be obtained by using large diameter swivel-type, double-tube core barrels, with the most suitable bits for core preservation. Unfortunately some proportion of core can be lost in weaker zones, however, and it is just such zones which may be significant in a particular problem. Even if cores are recovered from weaker zones, their strength may have been reduced by the drilling process, or the fissured and jointed nature of the rock may make it impossible to prepare satisfactory test specimens.

In-situ testing is therefore of major importance in the soft rocks. Vane tests are out of the question, and it has been the authors' experience that static cone tests are generally inapplicable. On the other hand, standard penetration tests have been done on many occasions and can be used as a rough guide to rock strength. The principal *in-situ* test for soft rocks is the plate-loading test, however. More recently the Ménard pressuremeter has been used in soft rocks to measure strength and modulus of linear deformation, and it is the purpose of this paper to present some results obtained in the United Kingdom and to compare them with results of plate-loading tests, and of laboratory tests on specimens obtained by various means.

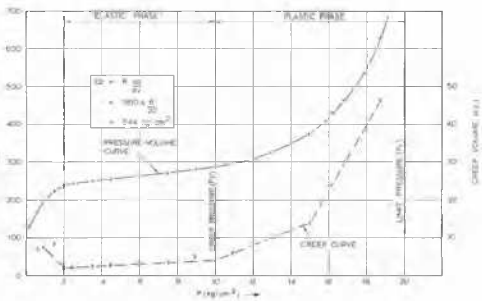

FIG. 1. Typical pressuremeter test curve on silty mudstone of Coal Measures.

THE PRESSUREMETER TEST

The Ménard pressuremeter, a comparatively recent development, performs a load test on the walls of a borehole of small diameter. A direct measurement is made of the ultimate bearing capacity and the modulus (E_p) is derived from the pressure-deformation curve.

A cylindrical metal probe covered with rubber membranes is inserted into the borehole to the test level and is inflated by water under pressure from a surface control apparatus. Pressure-deformation relationships are established by observing the volume of water injected into the probe during incremental pressure increases. A curve of pressure *versus* volume change is then plotted as shown on Fig. 1, from which the pressuremeter parameters are derived. Referring to this curve, there is an initial lead-in phase where the natural earth pressure condition is being restored. This is followed by a phase where the response is linear; from the slope of this line the modulus (E_p) is derived. At higher pressures, the rate of volume change increases rapidly until the limit pressure (P_L) is reached, where the curve becomes asymptotic to the vertical. This gives a direct indication of the ultimate bearing capacity.

Also plotted on Fig. 1 is the creep curve, which shows the tendency of the material to deform with time at any given pressure throughout the range of the test. The creep pressure (P_F) is that pressure at which the creep curve makes a definite upward break, and generally agrees closely with the upper limit of the linear phase of the pressure-volume curve.

Fuller details of the apparatus and its theoretical treatment are given by Ménard (1957), and by Gibson and Anderson (1961).

TESTS ON COAL MEASURE ROCKS NEAR WAKEFIELD, YORKS.

In the Wakefield area a site investigation with more than six hundred boreholes was carried out along part of the proposed Sheffield-Leeds Motorway, between Dodworth, near Barnsley, in the south and Stourton, near Leeds, in the north. The route crosses strata of Coal Measures age, composed mainly of silty mudstone and sandstone overlain by soft alluvium and sand and gravel in valley bottoms.

Boring in the overburden was carried out with soft ground boring rigs and this was continued for a short distance in the softer weathered zone of the rock, below which diamond drilling was continued. Pressuremeter tests were carried out at the various bridge sites in order to determine safe bearing pressures for the foundations of these structures. Results of tests in the grey silty mudstone, which was the predominating material, are presented in Fig. 2, and the actual test curve for one test is plotted in Fig. 1. For simplicity, tests in sandstone, coal, and seatearth, and a few tests which showed an increase in modulus with pressure, indicating a closing up of open fissures, have been excluded.

Values of the modulus (E_p) obtained from the pressuremeter tests are plotted against depth below ground level in Fig. 2a. These were from locations where the ground level was relatively high—above 240 feet ND. In Fig. 2b similar results are given for locations at lower ground levels.

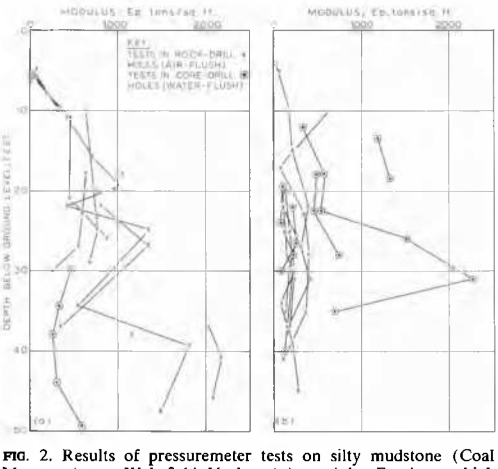

FIG. 2. Results of pressuremeter tests on silty mudstone (Coal Measures) near Wakefield, Yorks.: (a), modulus E_p, sites on high ground; (b), modulus E_p, sites on low ground.

Space limitation prevents the presentation of values of the limit pressure (P_L). For both groups of sites, there are very low values of E_p and P_L near the surface where the rocks are weathered to a stiff clay. (Tests in soft alluvium, sand and gravel overburden, and backfilled open-cast material have been excluded.) Below this there is a marked difference in values for the two groups of locations. Taking the general ranges of values in the zone 20 to 30 feet below ground level gives the following comparison:

	Modulus E_p (tons/sq.ft.)	Limit pressure P_L (tons/sq.ft.)
Higher sites (G.L. > 240 ft ND)	500–1500	20–45
Lower sites (G.L. < 240 ft ND)	100–400	10–30

It may be significant that in the holes on the higher sites, the groundwater level was generally below the depth explored, whereas on the lower sites, groundwater level was generally only 8 to 10 feet below ground level. On these lower sites some holes were put down with a rock drill (wagon drill) using air-flush, and others with a diamond coring drill using water-flush. These have been distinguished on the plot in Fig. 2b, but it is not possible to establish any significant difference in the results obtained in the low sites. On the other hand, the holes on the higher ground were put down by wagon drilling methods, with one exception, and it is interesting to note that in these dry holes the one hole put down with water-flush diamond drilling gave somewhat lower values of E_p than those obtained for the other holes where air-flush methods were employed (Fig. 2a).

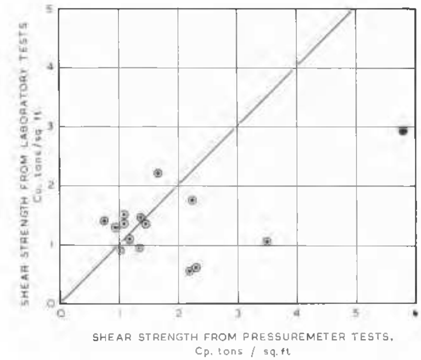

FIG. 3. Comparison of shear strengths from pressuremeter tests with shear strengths from undrained triaxial compression tests.

Where open-drive samples were obtained in the softer materials, undrained triaxial compression tests were done in the laboratory and in Fig. 3 the values of C_u have been compared with values derived from adjacent pressuremeter tests (C_p). There is reasonable agreement for shear strengths below about 1.5 to 2 tons/sq.ft. but above this the laboratory test values are significantly less than the pressuremeter values, demonstrating the effects of sample disturbance.

A certain number of standard penetration tests were carried out in the borings, but it was not possible to arrive at any positive correlation with the pressuremeter results. It could, however, be seen that the weaker silty mudstone

(E_p < 300 tons/sq.ft., P_L < 25 tons/sq. ft.) had N values generally below 100, and that the stronger silty mudstone had N values ranging from 100 to 350.

The results of two plate-loading tests, one at Barugh Green and one at Horbury Road, can be compared with adjacent pressuremeter results. Both tests were made on 12-in. square plates, at approximately 11 feet below ground level with total test duration of some four hours. From the load-settlement curves it is possible to calculate values of modulus using the formula for settlement of a rigid plate

$$\rho = \frac{\pi}{2}[(1 - \mu^2)/E]qR.$$

However the load-settlement relationship is not linear and it is therefore necessary to take a secant modulus at some arbitrary loading.

At Barugh Green where the test was on silty mudstone the modulus is 660 tons/sq.ft. for the loading range 0 to 5 tons/sq.ft., falling to 450 tons/sq.ft. for the range 0 to 10 tons/sq.ft. A pressuremeter test over the relevant depth range gave E_p = 450 tons/sq.ft. which is in reasonable agreement with the plate-loading test. A further pressuremeter test about 4 feet below test plate level gave E_p = 750 tons/sq.ft. The ultimate bearing capacity from the pressuremeter test was P_L = 27.5 tons/sq.ft. whilst the plate had not failed at a loading of 22 tons/sq.ft.; settlement was 0.9 inches.

At Horbury Road the material below the plate was weathered sandstone with bands of soft clayey sandstone. The modulus calculated for the loading range 0–5 tons/sq.ft. is 1,400 tons/sq.ft., but a marked change in slope of the curve beyond this loading causes it to fall to 650 tons/sq.ft. for the range 0–10 tons/sq.ft. A pressuremeter test just below plate level gave E_p = 680 tons/sq.ft. The pressuremeter gave an ultimate pressure of 18 tons/sq.ft. whereas the plate had not failed completely at 25 tons/sq.ft.; settlement was 0.9 inches. This discrepancy is thought to be due to the layered structure, which would also account for the higher value of E, over the 0–5 tons/sq. ft. loading range, compared with E_p.

TESTS IN THE KEUPER MARL AT OLDSBURY, GLOUCESTERSHIRE

The reactors of the nuclear power station at Oldbury are founded in the Keuper marl, which at this site consists of alternating thin layers of sandstone and siltstone, with considerable variations in strength. The upper 5 to 8 feet of the marl is weathered, generally to a stiff clay consistency, and it is overlain by some 13 feet of recent alluvium. Core recovery from diamond drill holes in the marl was variable, 100 per cent being obtained in the stronger layers, falling to 80 to 90 per cent in the weaker layers, and occasionally below 80 per cent, even though large diameter (5-inch) cores were taken.

The weakest material present was a very soft, very closely fissured siltstone, and it was important to measure its strength in connection with the over-all stability of the reactor foundations. This was done by carrying out plate-loading tests located after careful inspection in a number of shafts and pits. Laboratory tests were also carried out on hand-trimmed specimens obtained from blocks cut from trial pits.

At a later date, pressuremeter tests were carried out in 2½-inch diameter rock drill holes (air-flush). These were part of a research programme and were required primarily to compare the settlements obtained by calculations based on the pressuremeter results with those based on data from the original investigation and with observed settlements of the reactors. These settlements are now being recorded and the results of the comparisons will be presented later. The pressuremeter tests encountered certain difficulties, and in many tests the probe burst before the limit pressure was reached. This work was done at an early stage in the development of pressuremeter testing in rocks in this country. Recent improvements in the sheath material have overcome such difficulties. However, in all cases sufficient of the curve was obtained to define the modulus, E_p, which below the weathered zone ranged in value from 200 to 2,700 tons/sq.ft.

It is also possible to compare one of the pressuremeter test results with the results of a 12-inch diameter plate-loading test carried out at the upper surface of a 6½-inch-thick layer of very soft very closely fissured siltstone, and with results of undrained triaxial compression tests. The plate sustained a loading of 15.9 tons/sq.ft. with a settlement of 0.31 inches, but "ran-away" under a loading of 20.9 tons/sq.ft. From the test it was estimated that the shear strength was about 2.85 tons/sq.ft. The pressuremeter test was terminated at a loading of 15 tons/sq.ft. before the limit pressure was reached, but it was estimated from the P_F value and from the shape of the curve that the limit pressure was in the range 16–20 tons/sq.ft. which is in reasonable agreement with the plate-loading test result. The shear strength calculated from this test is between 2.4 and 3.1 tons/sq.ft., say about 2.75 tons/sq.ft.

Undrained triaxial compression tests were carried out on hand-trimmed specimens obtained from six blocks cut from just below plate test level. The tests indicated shear strengths ranging between 0.97 tons/sq.ft. and 2.5 tons/sq.ft. The lowest result could be disregarded as there was clear evidence that this specimen was badly disturbed. The wide range of the results strongly indicated that some of the other specimens were also disturbed. The average of the three higher results gave a shear strength of 2.3 tons/sq.ft. compared with 2.85 tons/sq.ft. for the plate-loading tests and about 2.75 tons/sq.ft. for the pressuremeter test.

In considering the laboratory test results it should be emphasized that these specimens were prepared with great care, by hand-trimming, from carefully cut blocks. It is abundantly clear that tests on drill cores or open-drive samples would be seriously misleading.

TESTS IN BUNTER SANDSTONE AT DARESBURY, CHESHIRE

A preliminary site investigation by diamond drilling was carried out at Daresbury for a new laboratory for the National Institute for Research in Nuclear Sciences and the University of Liverpool, the most important feature of which is to be a large synchrotron. Settlement criteria were severe and it was therefore decided to supplement the preliminary investigation by *in-situ* testing and laboratory testing of drill cores, to determine values of the modulus. The *in-situ* tests consisted of pressuremeter tests and loading tests on plates 1 ft, 2 ft, and 3 ft in diameter. The laboratory tests were unconfined compression tests using electrical resistance strain gauges cemented to the specimens for strain measurement.

Bedrock is Bunter sandstone, overlain by a thin layer of topsoil and sand, which is weathered sandstone. The sandstone is fine- to medium-grained and there is considerable variation in its strength, from very weakly cemented to medium hard. Within medium-hard zones are interspersed zones of weaker cementing, often associated with steep cross-stratification and close bedding. The groundwater level is below the depth of exploration. The values of modulus obtained from the field and laboratory tests are plotted against datum level in Fig. 4.

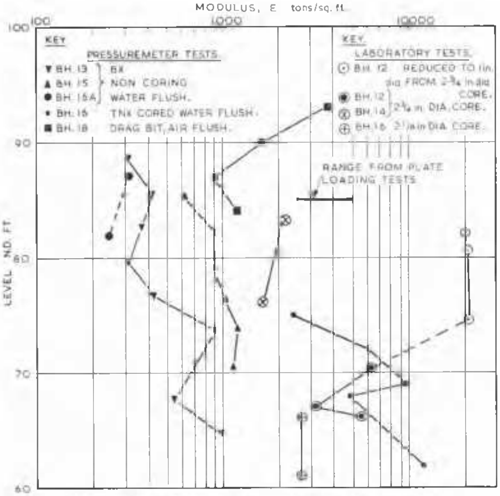

FIG. 4. Comparison of tests of Bunter sandstone.

Three of the holes for pressuremeter tests (boreholes 13, 15, and 16A) were put down using a BX-size non-coring diamond bit, with water-flush, and it is to be noted that these gave significantly lower values of modulus than the tests in the remaining two holes: borehole 18, in which a drag bit was used with air-flush, and borehole 16 in which a thin-walled diamond coring bit (NX size) was used, with water-flush. On the other hand, an examination of cores showed a considerable natural variation in rock strengths, and this can be seen in the differing results between boreholes 13 and 15 which were put down by identical methods. Furthermore, the boreholes giving higher results, 16 and 18, were on the lower part of the site, where ground level is some 8–10 feet lower. Nevertheless, it would appear that the non-coring technique, with a substantial water flow impinging directly onto the sides of the hole, leads to lower modulus values than the air-flush or the water-flush used for coring.

In the laboratory tests, an important difference can be noted between the whole cores tested (2⅝-inch and 2¾-inch diameters) and the specimens obtained by reducing cores in the laboratory from 2¾-inch to 1-inch diameters (2 inches long). The small cores have a significantly higher modulus which can be regarded as an upper limit for the sandstone between bedding planes. Another factor was that the very weakly cemented sandstone could not be used for laboratory testing as it did not survive facing-up with a diamond saw. Hence the samples tested are representative only of the better material.

The plate-loading tests were done with cyclic loading, but for comparison with the other tests only the first cycles have been considered. These showed a modulus increasing slightly with plate size and ranging between 2,500 and 5,000 tons/sq.ft. This range is plotted on Fig. 4.

Considering the Daresbury results as a whole, it can be seen that there is good agreement between the plate-loading tests values of modulus and the pressuremeter tests in boreholes 16 and 18 (i.e., those in which non-coring with water-flush was not used). There is good agreement also with the laboratory test values, with the exception of the small test specimens from the upper part of borehole 12 which, as already explained, represents an upper limit for sandstone between bedding planes. However, since the laboratory tests are representative of the better materials, there is an indication that the specimens are disturbed to some extent.

CONCLUSIONS

In the paper, results of pressuremeter tests in Coal Measure rocks, Keuper marl, and Bunter sandstone have been presented for the first time. From a study of these results and from the comparisons made with results of plate-loading tests and laboratory tests, the authors have come to the following conclusions.

The laboratory test results on silty mudstone of the Coal Measures from the Wakefield area confirm that, with open-drive sampling, serious disturbance occurs above a certain shear strength value. Experience at Daresbury indicates that in closely fissured and closely bedded rocks, laboratory tests on drill cores are weighted in favour of the stronger materials present, but that even in the somewhat stronger materials disturbance occurs during coring and specimen preparation. This leads to uncertainties about the significance of the laboratory test results. The laboratory tests on specimens of very closely fissured siltstone of the Keuper marl from Oldbury show that even with hand-trimming of specimens from hand-cut blocks serious disturbance occurs.

Just as it is necessary to consider the effects of sample disturbance in boring and drilling, it is also necessary to consider the effects of the method of boring and drilling on the material surrounding the hole, which is tested by the pressuremeter. There is a clear indication that in Bunter sandstone above the water table poor results are obtained using non-coring diamond bits with water-flush. However, if suitable methods are chosen, disturbance does not appear to be significant.

Pressuremeter tests in Coal Measure mudstone and sandstone, Keuper marl, and Bunter sandstone gave results which agreed well with plate-loading tests, in terms of ultimate bearing capacity.

There was also reasonable correspondence between the modulus values, with the pressuremeter values falling in the lower part of the range of plate-loading test values. However, strict correspondence is not necessarily to be expected; the relationship between the moduli for the two tests is complex, and a discussion of this aspect is outside the scope of this paper.

ACKNOWLEDGMENTS

This paper is presented by permission of the Directors of Soil Mechanics Limited. The authors wish to thank the following for permission to quote the results of investigations carried out for them: The County Engineer and Surveyor, West Riding of Yorkshire County Council; Central Electricity Generating Board; Sir Robert McAlpine & Sons Limited; The National Institute for Research in Nuclear Sciences and the University of Liverpool.

REFERENCES

GIBSON, R. E., and W. F. ANDERSON (1961). In-situ measurement of soil properties with the pressuremeter. *Civil Engineering and Public Works Rev.*, Vol. 56, p. 615.

MEIGH, A. C., and K. R. EARLY (1957). Some physical and engineering properties of chalk. *Proc. Fourth International Conference of Soil Mechanics and Foundation Engineering* (London), Vol. I, p. 68.

MÉNARD, L. (1957). Mésures in-situ des propriétés physiques des sols. *Annales des Ponts et Chaussées*, 127e année (3), p. 358.