In situ testing and its value in characterising the UK National soft clay testbed site, Bothkennar.

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ABSTRACT: Considerable amounts of in situ testing have been undertaken at the Bothkennar soft clay National testbed site in the UK. This has been to both characterise the site and also to undertake studies on the in situ testing methods. The paper covers data from cones and piezocones, various type of pressuremeter, vane tests, Marchetti dilatometer and field geophysics. This paper shows how valuable the in situ testing can be as part of a site characterisation.

1 INTRODUCTION

The Bothkennar National testbed site was purchased in 1989 by the then Science and Engineering Research Council (SERC) to provide facilities for research into the properties of low OCR, high plasticity clays. The purpose of this paper is to collect together and compare some of the data from a variety of in situ tests performed at the site.

2 THE SITE

Bothkennar is located on the River Forth, approximately midway between Edinburgh and Glasgow. The site is a low-lying field bounded on 3 sides by flood embankments. The site was chosen as it was believed to have relatively uniform deposits as a result of the postglacial history of the area (see Nash et al 1992). The lithology of the site comprises a buried gravel (the Bothkennar gravel), above which lies a sequence of micaceous silty clays. These mainly comprise the Claret Beds which form the soft clay sequence and extend up to within 1.5-2m of the ground surface (Paul et al 1992). The sequence is in part overlain by the clayey silts of the Grangemouth Beds and, at the margins of the estuary, is completed by modern intertidal deposits.

Paul et al (1992) suggest that the Claret beds are shallow water (subtidal) marine to intertidal estuarine deposits, laid down under a reducing water depth of less than 20m between 5000 and 3000 years before present (BP). Figure 1a shows the detailed facies profile established by Paul et al as part of their engineering geological study of the site. They identified 3 principal facies types within the sequence:

- a bedded facies, in which the primary sedimentary layering remains visible,
- a mottled facies, in which the bedding has been partially or totally destroyed by bioturbation,
- and a laminated facies in which numerous silt laminae are present at spacing of a few centimetres or less.

The facies were established both from visual appearance of the sediment and from their high resolution bulk density signatures. In this way the profiles of Figure 1b were established for various boreholes. They also established lithological units within the

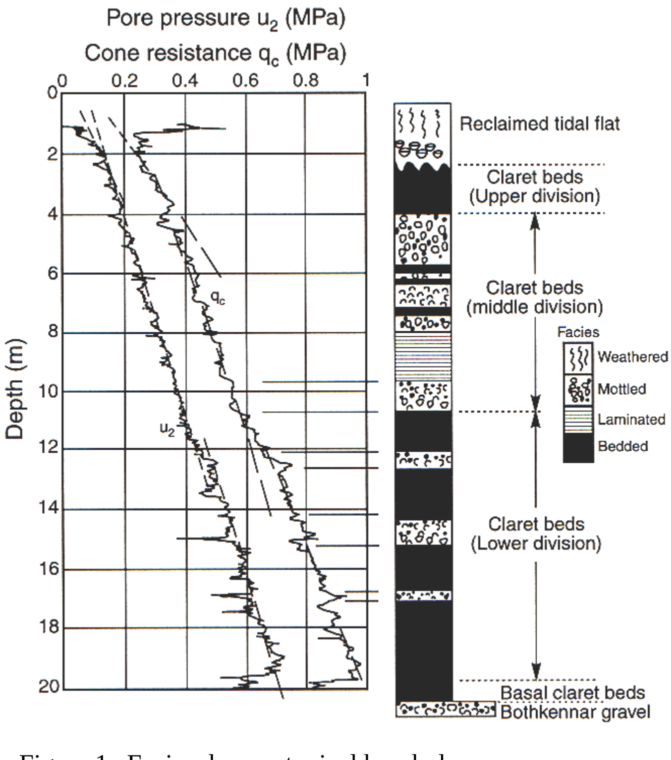


Figure 1a Facies down a typical borehole

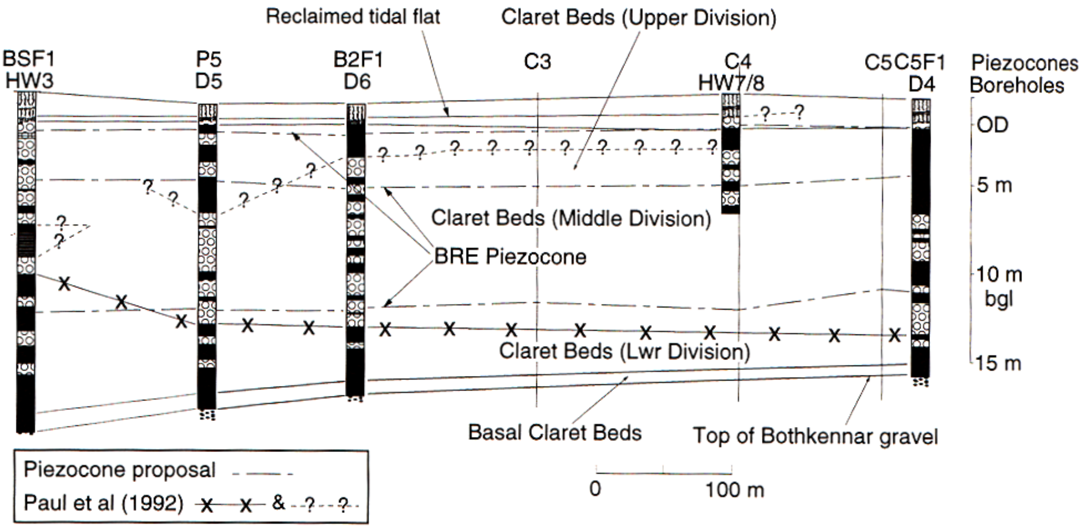


Figure 1b Lithology from a longitudinal section across the site

profile based on sedimentological and water content variations and these are also shown in Figure 1 (Paul 1995 personal communication). The upper, middle and lower divisions of the Claret beds also relate to the dominant types of facies; in the upper and lower the bedded facies and in the middle the mottled facies dominate. They proposed that the laminated bed was a local variation within the middle division. Reference to these detailed sequences will be made later in the paper.

A general soil profile is shown in Figure 2. Detailed considerations of the laboratory test data for the site can be found in Hight et al (1992).

3 THE IN SITU TESTS

Numerous in situ tests have been performed at the site. These have had two main functions, namely:

- To aid the characterisation of the site in terms of variations in the lithology, both laterally and vertically, and to establish geotechnical parameters
- to aid the understanding and interpretation of in situ testing devices

In situ tests so far used on the site include: Cone Penetration (CPT), Piezocone (CPTU), Seismic CPT, Dynamic probing (DP), Cone Pressuremeter (CPM), Self boring pressuremeter (SBP), Menard Pressuremeter (MPM), Marchetti Dilatometer (DMT), Offshore Dilatometer (ODMT), Penetration field vane (VT), Bat Probe, Geophysics – cross hole, downhole, refraction, rayleigh wave, spade and mini cells, in situ permeameters.

Space does not allow a detailed presentation and discussion of all the in situ testing work and so effort will be given to discussing those tests relating to the topics of profiling, strength, deformation and in situ stress state.

3.1 *Lithology.*

The ability of the cone resistance and porewater pressure to respond to changes in material type is not

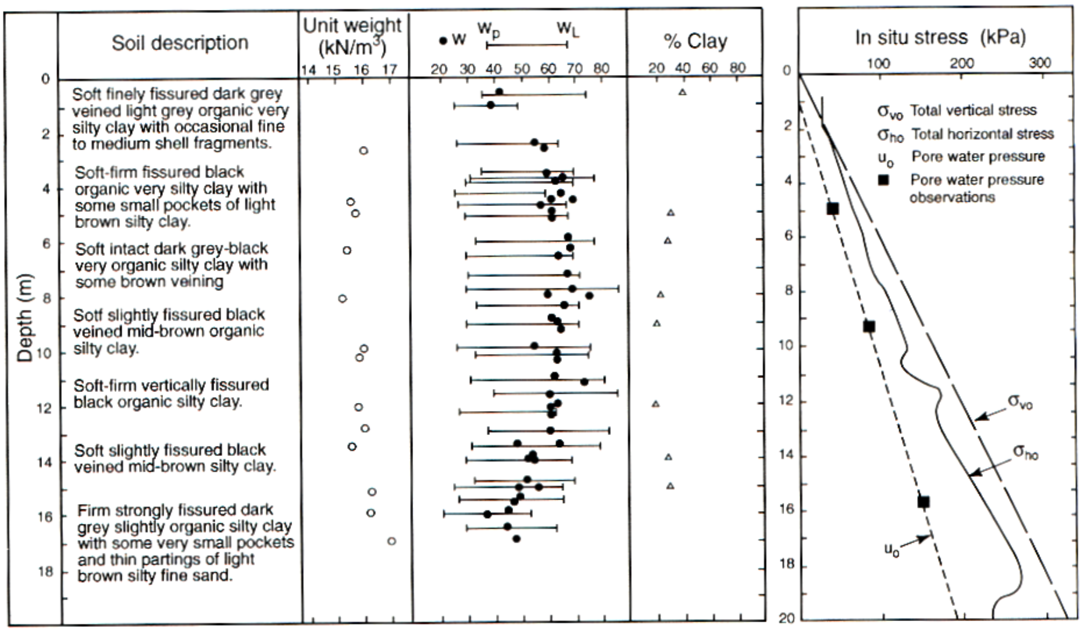


Figure 2 Typical soil profile

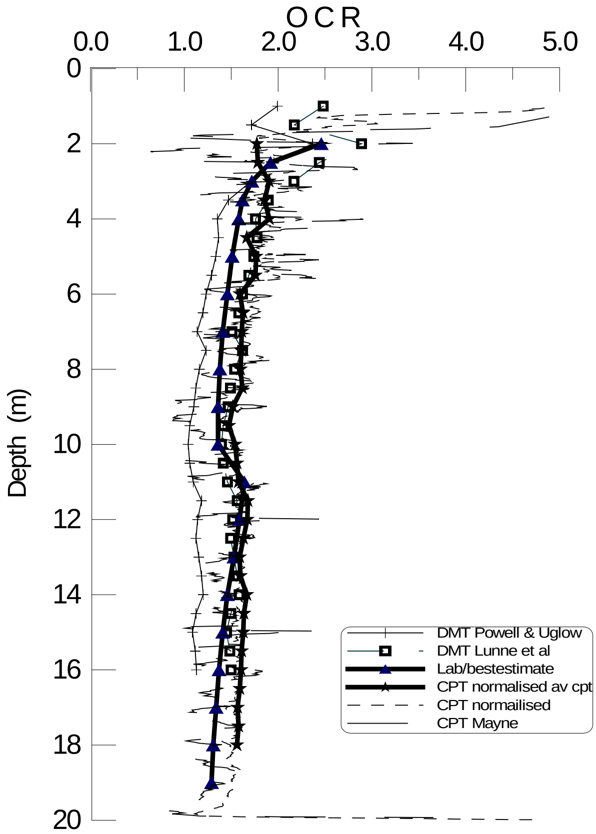


Figure 3 Assessed OCR profiles against depth

restricted to the coarse or obvious stratigraphic changes of soft and stiff layers; it can also be used to detect and map more subtle changes within a deposit. In Figure 1a it can be seen how facies variations down the profile at Bothkennar can be detected by the CPTU. Powell and Quarterman (1995) showed how each facies could be assigned a signature which could then be used to map the variations across the site. At a larger scale the changes in slope of the profiles in Figure 1a can be used to map the lithological units in the deposit and were found to be more reliable than those made by visual description of sample profiles (see Figure 1b).

Of the other in situ tests at Bothkennar only the DMT gives the level of detail (i.e. frequency of reading) that allows any degree of mapping in a deposit of this type. Changes in the slope of the pressure against depth plots allowed a degree of mapping of the major lithological units similar to the CPTU.

3.2 *In situ stresses*

Figure 2 shows the in situ stress based on density measurements for vertical stress, piezometers for pore water pressure and measurements from spade cells and SBP tests for horizontal stress. The SBP and spade cell measurements gave good agreement.

3.3 *Overconsolidation Ratio (OCR)*

The original characterisation of the site relied heavily on sampling and laboratory testing to determine the soil properties. Oedometer tests showed considerable scatter in OCRs and implied an almost constant average value with depth with a wide scatter band (Nash et al 1992). As a result the shape of the best estimate profile was only arrived at with the benefit of guidance from the in situ testing. In Figure 3 the assessed profiles of OCR are presented for DMT and CPTU. The DMT profiles are based on the standard Marchetti correlation and also those of Powell & Uglow (1988) and Lunne et al (1992). It is seen that all three clearly identify the shape of the OCR profile i.e. the two layer effect but with varying degrees of accuracy. The Marchetti values are too high, while the other two methods fall either side of the best estimate. The Powell & Uglow correlation was known to be weak at low OCRs and the adjustments by Lunne et al appear to have improved this defect.

Many approaches exist for interpreting the CPTU to OCR (see Lunne et al 1997) but the two that were found to work best here were a method based on the normalised cone resistance and a method based on a combination of cavity expansion and critical state theory (Mayne 1991).

The normalised cone resistance generated OCR profile is based on the relationship:

$$OCR = k\,(q_t - \sigma_{vo})/\,\sigma_{vo}'$$

where k is a constant which typically falls in the range 0.2 to 0.5 (Powell et al 1988 recommend higher values in aged heavily overconsolidated clays). Lunne et al (1997) suggest 0.3 as a starting point with adjustments as data from other sources become available. Leroueil et al (1995) suggest a value of 1/3.6 (0.303) based on several soft clays they investigated. A value of k=0.3 is seen in Figure 3 to slightly over estimate the OCR best estimate but clearly shows the two stage decay in OCR.

The method of Mayne (1991) is somewhat more time consuming in its application needing values of ϕ' down the profile, but is seen to give a good prediction of the profile shape.

3.4 *Coefficient of earth Pressure at rest (K_o)*

Figure 4 shows the derived profiles of K_o from CPTU, DMT and VT. Two methods for determining K_o from the CPTU are those of Kulhawy & Mayne (1990) based on normalised cone resistance (essentially the same as OCR but with k=0.1) and Sully & Campanella (1991) using normalised pore pressure difference (this latter correlation requires the use of a piezocone with at least two pore pressure sensors). In Figure 4 both procedures are seen to give values of K_o very close to the best estimate derived from the in situ stress profile from spade cells and SBP although 0.12 rather than 0.1 has been used in the Kulhawy and Mayne correlation,.

Two profiles from the DMT, one based on Marchetti's original correlation and one on Powell &

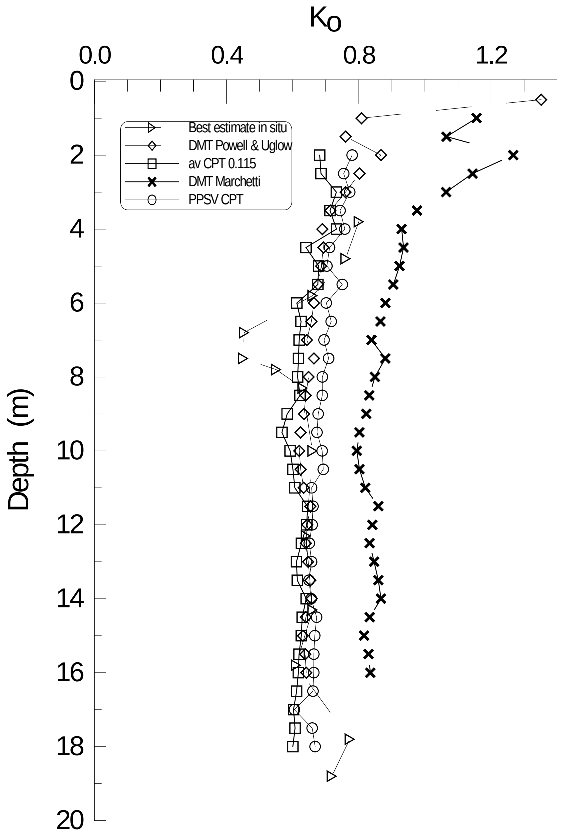


Figure 4 Interpreted K_o against depth

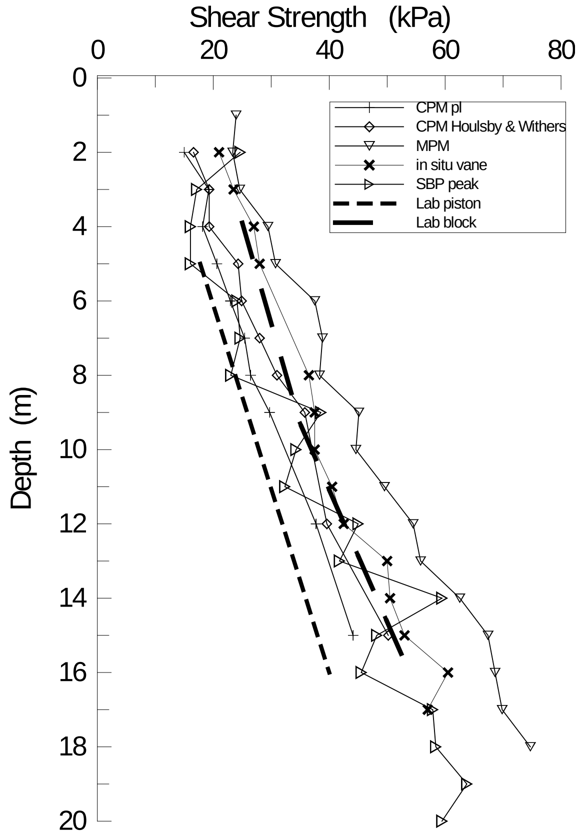


Figure 5a Shear strengths from Pressuremeter tests

Uglow (1988) (see also Lunne et al 1990) are shown. As with OCR the Marchetti values are seen to be too high but the Powell & Uglow correlation is seen to perform well and possibly better than the CPTU data at shallow depths.

The method of Aas et al (1986) for determining K_o from vane test results and triaxial data has also been used and data are shown in Figure 4. The requirement for vane and consolidated undrained triaxial data makes this method more cumbersome but the results look encouraging.

3.5 *Shear strength (s_u)*

Shear strength can be determined from many of the in situ test methods used. However, it must be remembered that it is not a unique value at any one depth but will vary with orientation, test method etc. Some of the devices have methods of interpretation based on theory (VT, pressuremeters etc) whilst others rely on empirical correlations (DMT, CPT etc) which will themselves rely on the type of test used in gathering the source data for the correlation.

Figures 5a, b show the shear strengths derived from the in situ tests and also the best estimate lines for laboratory triaxial tests both standard piston samples and high quality block samples (see Hight et al 1992).

Figure 5a shows the results from CPM, MPM and SBP tests using various methods of analysis, namely:

SBP – derived from the deduced stress-strain curve,

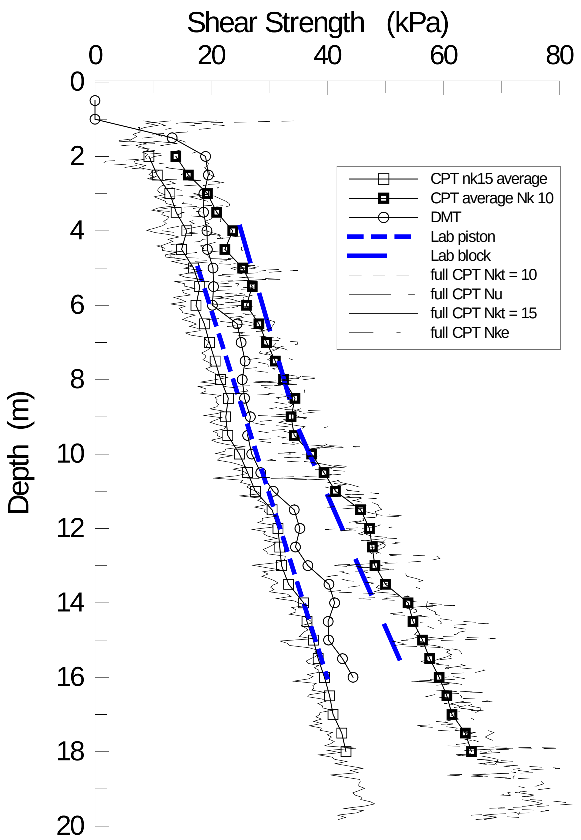
CPM – derived from the Houlsby & Withers (1988) analysis and a limit pressure approach (see Powell & Shields 1995)

MPM – derived from the Menard (1955) approach using limit pressure.

Also included are the results from field vane tests.

It can be seen that the pressuremeter and vane data fall between the two laboratory lines, the exception being the vane and MPM results. Whilst the both the CPM and MPM interpretations use a limit pressure approach the MPM uses the Menard derived factor of 5.5 on the Menard limit pressure and the CPM uses 6.18 (Marsland & Randolph 1977) on the infinite expansion limit pressure. Generally the Menard limit pressure would be lower than the infinite expansion one and this would result in the derived shear strengths from the two devices being similar. However at Bothkennar the limit pressures from all three pressuremeters were very similar with the MPM tending to be slightly higher and therefore the lower factor results in a higher strength. The more erratic strength profile from the SBP is the result of the varying disturbance effects on individual tests giving slightly different stress-strain curves but they still fall between the two laboratory curves. The CPM data shows strengths from the limit pressure approach tend to the piston sample results and those from the Houlsby and Withers analysis tend to the block samples are does the vane data.

In Figure 5b the strength derived from the DMT and CPTU are shown and for clarity only average data sets are presented; generally the results at any one depth with any one testing device were remarka-



bly consistent. The DMT derived strengths are seen to fall close to the piston sample line as do the CPTU estimates using a typical cone factor N_{kt} of 15 based on plasticity index and scale effects (Powell & Quarterman 1988). Recently Karlsrud et al (1996) used CAUC triaxial tests on high quality block samples to obtain reference s_u values on a range of soils to derive N_{kt}, N_{ke}, and $N_{\Delta u}$ values (see Lunne et al 1997) for the derivation of shear strength from CPTU. In Figure 5b the resulting profiles using these factors are presented; remarkable agreement between the 3 methods of calculation is seen and they fall close to the block sample strength line. The results of Figure 5b should not be totally surprising as the database of information used to establish the DMT and older CPTU correlations were based on standard sampling and laboratory testing techniques and so their agreement with the piston sample data might be expected. The work of Karlsrud et al using higher quality samples allows correlations to the peak strengths observed in these better quality samples.

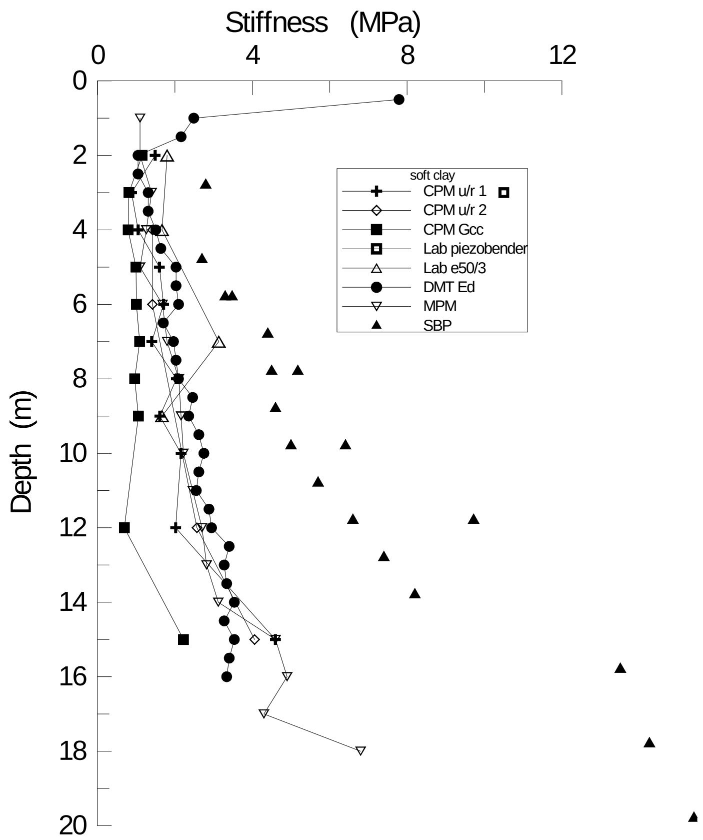


Figure Figure 6a Stiffnesses from in situ tests

3.6 *Stiffness*

Figures 6a, b show stiffness assessments in terms of shear modulus from the various in situ tests. It is now well known that shear modulus varies with shear strain level as well as orientation (anisotropy); however data from in situ tests are still often presented as a depth profile without reference to the strain level. The methods of assessing stiffnesses were:

SBP - unload/reload loops
CPM - unload/reload loops and Houlsby and Withers G_{cc}
MPM - standard Menard interpretation,
DMT – Marchetti E_D, and scaled to G_o
Geophysics – field and laboratory
Laboratory triaxial $E_{50}/3$

It can be seen in figure 6a that, whilst the CPM G_{cc} from Houlsby and Withers analysis forms the lower bound, other assessments fall surprising close to each other and all show a gradual increase with depth; the exception are the results from the SBP which form an upper bound. These higher values from the SBP cannot be explained by strain level as Powell & Shields (1995) showed that the results from CPM and SBP formed two distinct degradation curves when plotted against strain level. They suggested that this was the result of greater 'disturbance' caused by the large strains induced by the CPM insertion causing breakdown of the cemented structure of the Bothkennar clay. Similar behaviour was not found in other deposits.

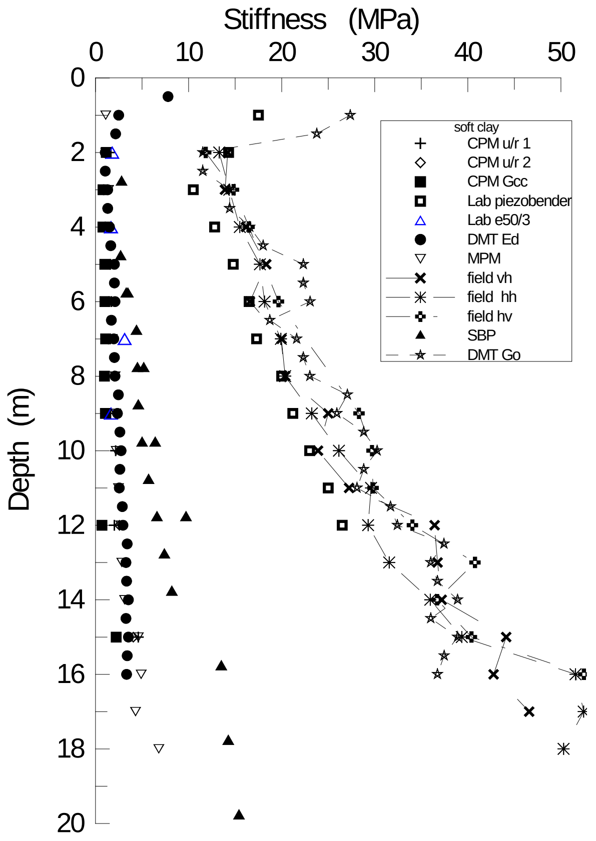


Figure 6b Stiffnesses from in situ and Geophysical tests

In Figure 6b the small strain stiffnesses from field geophysics and laboratory piezobender tests are show. There is a general tendency for the field tests to show signs of stiffness anisotropy ($G_{hh} \neq G_{hv} \neq G_{vh}$) but very little in this normally consolidated deposit. Tanaka & Tanaka (1998) suggested that in soft clays Go could be related to dilatometer E_D simply by a factor of 7.5; in Figure 6b a factor of 11 has been used and shows remarkable agreement with the field data. The laboratory piezobender tests fall below the field data forming a lower bound which is consistent with other soft clay data presented by Butcher & Powell (2001). The combining of various shear modulus assessments to form a general degradation curve with shear strain has proved rather difficult for Bothkennar compared to other sites (see Butcher & Powell 2001) and it is suggested that this could well be the result of disturbance that is induced to varying degrees by intrusive tests or sampling.

4 CONCLUSIONS

Data have been presented from a variety of in situ tests on a well documented testbed site. The ability of all devices to give meaningful data has been shown. Those devices such as the CPTU and DMT have been shown to be particularly powerful in establishing detailed profiles of lithology, in situ stress (via K_o, or OCR), shear strength and to a lesser extent stiffness. It was these two devices that had previously shown variations in the profiles for K_o and OCR that allowed scatter in laboratory data to be more clearly interpreted into the lithology now established. Derivations of shear strength are only valid for the methods used in establishing the original correlation databases. It is important to know what you are correlating with.

Pressuremeter testing using a variety of devices has been shown to give assessments of stiffness and strength. Differences between the devices result from differences in the methods of interpretation and/or, for the present deposit, differences in the disturbance caused to the structured clay. All devices gave consistent profiles.

Following established procedures but using the most up to date methods of interpretation can yield most useful information. There is the potential for more detailed profile information, with reduced scatter and the elimination/reduction of costly sampling and testing.

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