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Behaviour of Bothkennar clay under rotation of principal stresses

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ABSTRACT: Bothkennar is a national UK soft clay research site, located in Scotland, which was chosen as being representative of uniform soft clays. It has been subjected to extensive field and laboratory testing over the last fifteen years, with the majority of the laboratory experiments involving oedometer and triaxial stress path apparatus. Consequently, the undrained shear strength profiles with depth for triaxial compression and extension are well established. This paper presents results from hollow cylinder tests performed on samples of natural Bothkennar clay, with the aim of establishing the undrained strength profile with depth in torsional shearing, as well as the anisotropic characteristics of this clay due to rotation of principal stresses in the ground. The project was sponsored by a one-year Royal Society/NATO post-doctoral Fellowship Programme.

1 INTRODUCTION

The effects of rotating principal stress axes in the ground on soil behaviour have been investigated at Imperial College over the last twenty years. Most of the laboratory experiments have been performed on reconstituted soils (e.g. sands, clays and sand-clay mixtures) in hollow cylinder devices (Symes (1983), Shibuya (1985), Menkiti (1995), Porović (1995), Zdravković (1996)). The results have shown some dramatic changes in strength and stiffness of such soils, when the direction, α, of the major principal stress changes from vertical to horizontal (i.e. from 0^o to 90^o) (Zdravković & Jardine (1997, 2000, 2001), Hight et al. (1997), Jardine et al. (1997), Jardine and Menkiti (1999)). Some of these results have recently been used in advanced finite element analyses to validate anisotropic soil constitutive models, which were then used in analyses of boundary value problems, such as foundations and embankments, to investigate the effects of soil anisotropy on their engineering response (Zdravković et al. (2001, 2002)). The results again showed significant effects of soil anisotropy in reducing the bearing capacity of foundations, or the failure height of embankments.

The investigation of mechanical anisotropy in natural soils has been less intensive, the reason being the difficulty of obtaining multiple good quality undisturbed samples that are large enough to be tested in hollow cylinder apparatus. A set of hollow cylinder experiments on Pentre clay was reported by Porović (1995), while some experiments on London clay were presented by Hight et al. (1997). Further investigation is required into the effects of rotating principal stress axis directions on the stress-strain-strength behaviour of natural soils.

This paper presents results from hollow cylinder tests on samples of natural Bothkennar clay. Bothkennar is a national UK soft clay research site which has been chosen for investigation as being representative of uniform soft clays. It has been subjected to extensive field and laboratory testing over the last fifteen years, with the majority of results being published in a special issue of Geotechnique, Vol. 42, No. 2 (1992). The majority of the laboratory experiments performed to date involved oedometer and triaxial stress path testing of both natural and reconstituted samples. Consequently, the undrained shear strength profiles with depth for triaxial compression and extension are well established.

The site was recently re-visited and high quality undisturbed samples were obtained from different depths, using thin walled piston samplers and Sherbrooke block samplers. These were used for the hollow cylinder experiments reported in this paper. Samples were re-consolidated to in-situ stresses in the way described by Smith et al. (1992) and then subjected to undrained torsional shearing, with the major principal stress axis rotating between 0° and 45°. These experiments add significantly to the characterisation of Bothkennar clay under general shearing conditions.

2 SOIL CONDITIONS

Descriptions of the soil profile at Bothkennar have been presented elsewhere (e.g. Paul et al. (1992), Hight et al. (1992)). Only the main characteristics will be summarised here.

The Bothkennar clay is a clayey silt with an organic content of 3 to 8%. The soil profile can be divided into five lithological units, on the basis of sedimentology and macro-fabric. Grading envelopes are reproduced in Figure 1, while the variation of composition with depth is shown in Figure 2, after Hight et al. (1992).

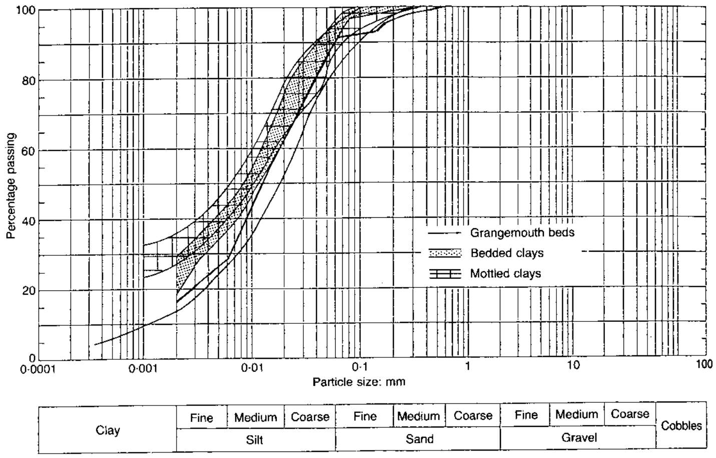

Figure 1: Grading envelopes of Bothkennar clay (after Hight et al. (1992))

The clay is structured as a result of deposition in sheltered water and of subsequent bonding between silt particles. Untreated soil has a plasticity index, PI, of 40% and high compressibility, which is in contrast with the high angles of shearing resistance measured in both triaxial compression and extension (φ' of 37° and 42° respectively). However, after removal of the organic content the plasticity index lies between 18 and 22% and high angles of shearing resistance are a result of the silt content, as well as the angularity of the silt particles. Consequently, a high angle of shearing resistance is also measured in residual conditions ($\varphi'=30^{\circ}$ in a ring shear apparatus).

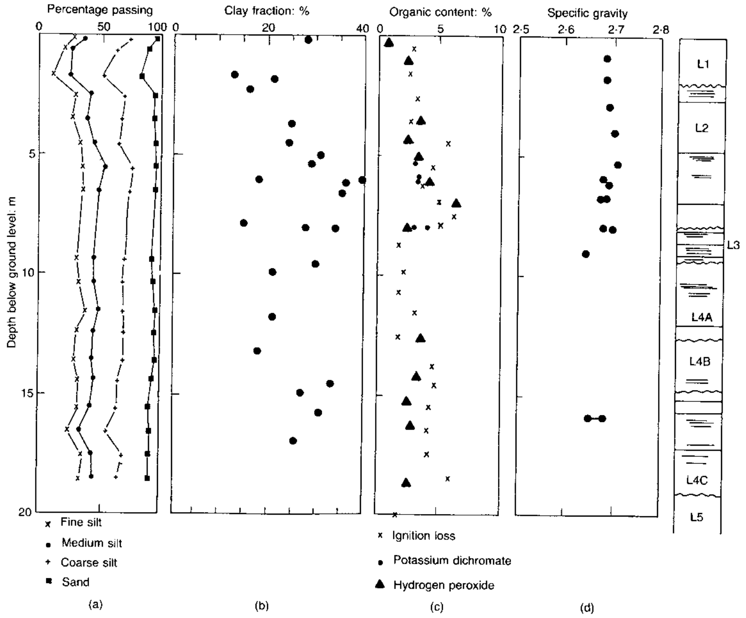

Figure 2: Variation of composition with depth: a) sand and silt content; b) clay fraction; c) organic content; d) specific gravity (after Hight et al. (1992))

The Bothkennar clay has an overconsolidation ratio of approximately 1.5 (Leroueil et al. (1992)), which is thought to be largely an ageing effect since the deposit has been subjected only to minor unloading. Hydrostatic groundwater conditions exist in the clay, with the groundwater level approximately 0.75m below the ground surface.

The structure of the clay is degraded with further disturbances, starting with sampling at the site, and it has been shown at Bothkennar that the Sherbrooke sampler produced the least disturbed material, with the most preserved structure.

3 EXPERIMENTAL SET-UP

The resonant column hollow cylinder apparatus used in this project is described in detail in Porović (1995). It can accommodate two sizes of a hollow cylindrical sample: 71mm inner diameter (ID) by 101mm outer diameter (OD) by 200mm height, or 38mm ID by 71mm OD by 200mm height. The latter size samples were used for the experiments presented here.

The apparatus is capable of applying the same inner and outer cell pressures ($p_{\mathrm{i}} = p_{\mathrm{o}}$), an axial load and a torque to a sample. This combination of loads enables the rotation of principal stresses in a sample, as well as the application of an intermediate principal stress that is different from a minor principal stress (i.e. $\sigma_2' \neq \sigma_3'$). The latter effect can be expressed through the magnitude of the parameter b, which is defined as equal to $(\sigma_2' - \sigma_3')/(\sigma_1' - \sigma_3')$. In triaxial compression b=0, while in triaxial extension b=1. Because the inner and outer cell pressures are the same, the rotation of principal stresses and the value of b change simultaneously, following a relationship $b=\sin^2\alpha$, where α is the inclination of the direction of the major principal stress to the vertical. Therefore it is not possible in this apparatus to apply to a sample a particular value of b and investigate the effect of changing α, or vice versa.

A Hardin oscillator is placed at the top of the sample, however it has not been utilised for the experiments presented here.

4 TESTING PROCEDURES

In total eight Sherbrooke samples of Bothkennar clay from different depths were tested during this project in the hollow cylinder apparatus described above. Five of them subjected to pure torsional shearing are reported here and they are summarised in Table 1. The first step in testing procedure involved sample preparation. A cylindrical sample was first trimmed from a block. Afterwards a procedure described by Porović (1995) was used to drill the central 38mm hole through the sample.

Sample	BH1	BH2	BH3	BH4	BH5
Depth	4.5	6.15	6.5	7.2	8.4

Table 1: Summary of samples tested in torsional shearing

Once placed in the apparatus, the sample was subjected to initial saturation under a back pressure of about 250kPa. Each of the samples was then reconsolidated to the estimated in-situ stress conditions. This involved initial K_o consolidation and swelling, following the procedure established by Smith et al. (1992). After this, the drainage of a sample was closed off and a sample subjected to undrained torsional shearing, with a strain rate of 5%/day. After each stage of the effective stress path, a sufficient period of time was allowed for creep. The criterion adopted for the commencement of the next stage of the stress path was when a volumetric strain rate of 0.05%/day or less was achieved during the creep period. The average duration of each test was four weeks.

5 RESULTS

The effective stress paths followed by all five samples are shown in Figure 3, as a deviator (q) vs. mean effective stress (p') diagram. Apart from sample BH1, they all show a nearly vertical increase in deviator stress from the initial conditions, generating positive pore pressures until failure is reached. Sample BH1, which was from the shallowest depth, appears to be anomalous for this lightly overconsolidated clay, showing dilatant behaviour and generation of negative pore pressures to failure. The effective stress paths are also not very brittle, which is in contrast to those observed in triaxial compression tests (Hight et al. (1992)).

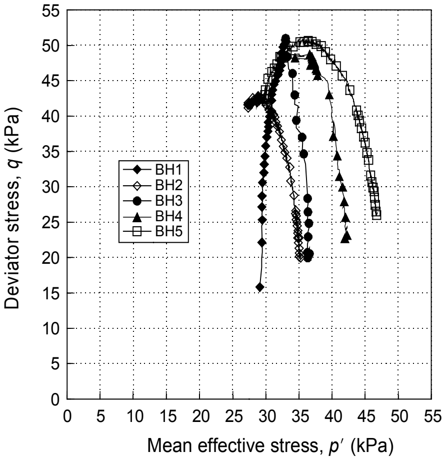

Figure 3:Effective stress paths from undrained torsional shear tests

Figure 4 shows the progression of principal stress rotation in samples, during the application of torsional shear stress to failure. The maximum inclination of the major principal stress, *α*, achieved at failure is between 30° and 35°. In a similar way Figure 5 shows the variation of *b* vs. the applied torsional shear stress, from the onset of shearing to failure. The maximum value of *b* is between 0.25 and 0.35 for all samples.

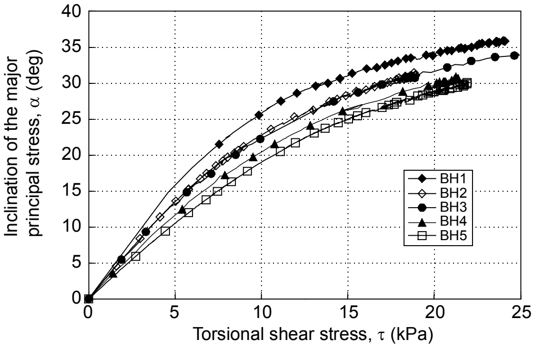

Figure 4: Variation of *α* with torsional shear stress

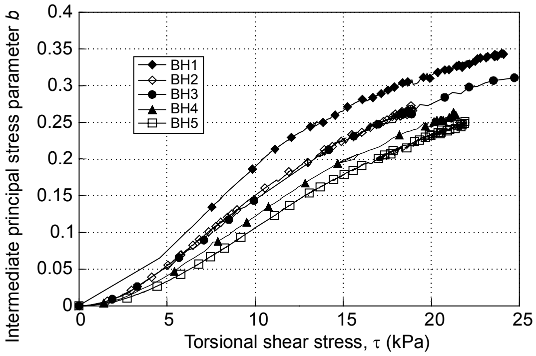

Figure 5: Variation of *b* with torsional shear stress

The undrained strength profile, S_u, in torsional shearing from the above experiments is shown in Figure 6, together with the profiles in triaxial compression and extension, obtained from Hight et al. (1992). All three profiles are different and consequently the undrained strength appears to be anisotropic, as in triaxial compression α=0°, in torsional shearing $\alpha \approx 33°$, while in triaxial extension α=90°. However, in all three cases *b* is also different (0, ≈0.3 and 1 respectively), and hence the differences in S_u cannot be attributed to the effect of principal stress rotation only.

The angle of shearing resistance, *φ′*, at failure from all five samples was on average 40°±1, which is similar to the values measured in triaxial compression and extension (37° and 42° respectively).

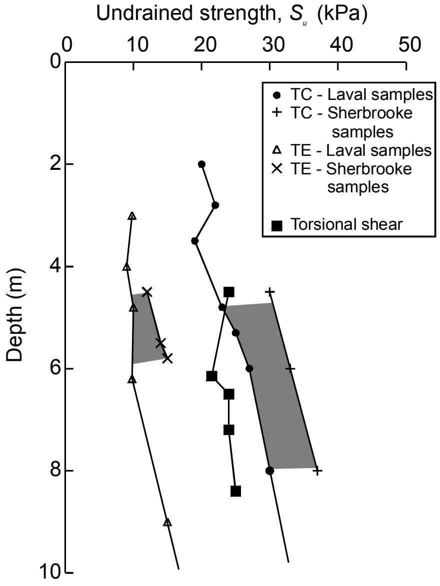

Figure 6: Profiles of undrained strength with depth;
triaxial compression (TC) and extension (TE) after Hight (1992)

6 CONCLUSIONS

A limited set of torsional shear hollow cylinder experiments was performed on high quality Sherbrooke samples of Bothkennar clay, taken at a number of different depths. The aim of the project was to profile the undrained strength of Bothkennar clay.

The test results showed that torsional shear stress paths were less brittle than those observed in triaxial compression. All samples failed when the inclination of the major principal stress reached, on average, 33° and the undrained strength profile in torsional shearing plots between that in triaxial compression and triaxial extension. It is on average about 20% smaller than the compression profile. However, the true effect of strength anisotropy due to rotation of principal stresses is masked by different b values existing for the three profiles.

The angle of shearing resistance from torsional shear tests is similar to the values obtained in triaxial compression and extension, and therefore appears to be unaffected by either α or b for this particular clay.

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