

DISCUSSION

## Soil stiffness in stress paths relevant to diaphragm walls in clay

W. POWRIE, H. PANTELIDOU and S. E. STALLEBRASS (1998). *Géotechnique* 48, No. 4, 483–494

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The authors report an extensive triaxial testing programme on reconstituted kaolin to investigate the influence of stress paths on the stiffness of soil elements in the vicinity of diaphragm walls. They state that ‘the effect of the recent stress history of the soil on its stress–strain response is now well established’.

In support of this statement, they present data that appear to show that the stiffness of their kaolin, when tested under triaxial conditions, is strongly influenced by a change in stress path direction. Fig. 8 of their paper shows that a specimen that experienced a reversal in total stress path direction (180°) has a normalised stiffness 4–8 times higher than that of specimens that undergo no reversal in total stress path direction. This finding is in broad agreement with results from reconstituted London Clay reported by Atkinson *et al.* (1990), who showed an increase in stiffness of an order of magnitude when comparing the stiffness after a reversal in effective stress path direction with no change in direction.

There is now increasing evidence that these ‘effects of recent stress history’ may be artefacts both of the soil and of the methods used to test it. After completion of a stress excursion in any stress path test it is invariably found that some volumetric and shear strains, however small, continue to occur under a constant effective stress state. If the creep rate is not allowed to decrease sufficiently, strains from creep will be included in strains measured during subsequent stress excursions. When a stress path reversal occurs, the stiffness, will appear to be higher, and when no stress path reversal occurs, the stiffness will appear to be lower. Natural (bonded) intact soils might be expected to undergo less creep at small strains than reconstituted or destructured soils.

The effects of creep on small-strain stiffness measurements have been broadly understood for a number of years. Hight & Higgins (1995), in recommending a shear strain rate of 5%/day for undrained triaxial tests, have suggested that the creep rate prior to shear should be less than 0.05%/day. Similarly, Jardine (1995) has recommended a ratio of creep rate to shear strain rate of less than 1%. Although none of these authors states whether these shear strain rates should be measured locally or externally, it is clearly desirable that both rates should be measured locally, since the use of values from external strain measurement could introduce large errors (by up to a factor of 7, in our experience).

We have recently completed a research project in which we have measured the stiffness of clays and a weak rock at very small strain levels. The work included an investigation on the effect of recent stress history on the stiffness of specimens of Bothkennar clay, obtained using the Sherbrooke sampler (Lefebvre & Poulin, 1979). LVDTs were used as local strain instruments after calibration against a Fabry–Pérot interferometer (Heymann *et al.*, 1997) to an accuracy of better than  $\pm 0.027 \mu\text{m}$  (Heymann, 1998).

For the Bothkennar clay, rest periods of between 1 and 2 days were allowed between completing the incoming stress excursion and commencing with the outgoing stress excursion. The creep rates (measured locally) were less than  $0.3 \mu\text{m}/\text{h}$  when the shear phase commenced. This ensured a ratio of creep rate to shear rate (both measured locally) of less than 0.8%.

Three stress paths were applied in order to investigate the effect of recent stress history on Bothkennar clay (Fig. 12). The direction of the incoming stress path was different, while

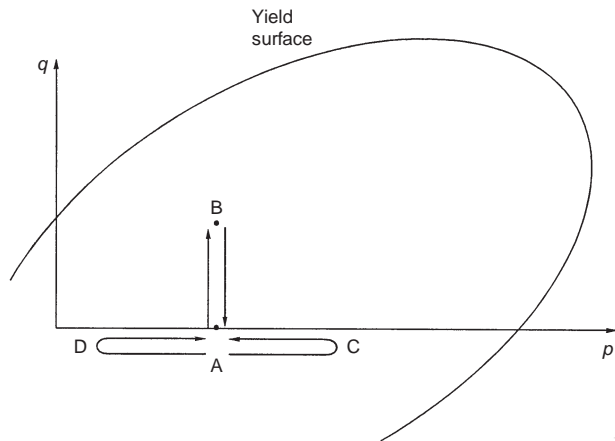


Fig. 12. Stress paths applied to the Bothkennar clay. Incoming stress paths: BA, CA, DA. Outgoing stress path: AB

the direction of the outgoing stress path was identical in each case. The resulting changes in stress path direction were 180°, +90° and –90°. The lengths of the incoming stress paths were 10 kPa, which was significant with respect to the isotropic yield stress of approximately 40 kPa. In addition, the lengths of the first two outgoing stress paths were approximately 9 kPa, which resulted in an axial strain of more than 0.06%. This is well in excess of the strain level of 0.02% required to induce plastic strains in Bothkennar clay (Smith *et al.*, 1992). The stiffness for each outgoing stress path is shown in Fig. 13. It can be seen that the stiffness is almost identical at all strain levels. Hird and Pierpoint (1997) have also recently produced evidence for the Oxford clay that seems to support the idea that recent stress history has little effect on locally measured stiffness, once creep effects are eliminated.

Unfortunately Powrie and his co-authors give no details of their test procedures. We would therefore be grateful if they could present data for the rest periods that they allowed between stress excursions, together with comparisons between the observed rates of strain immediately before and after the start of each final loading stage. Could they say how they accounted for the effects of creep?

Authors' reply

The principal aim of the paper was to compare the rates of mobilization of soil strength with shear strain in stress paths representative of those followed by typical soil elements behind and in front of an embedded diaphragm type retaining wall. The main reasons why a difference might be expected are as follows.

- (a) The soil on one side might start closer to its ultimate (active or passive) state than the soil on the other (Symons, 1991).
- (b) For a given wall rotation, the shear strain in the soil in front of the wall may be greater than the shear strain in the soil behind (Bolton & Powrie, 1988).
- (c) The removal of overburden from the soil remaining in front of the wall during excavation (Symons, 1991).
- (d) During excavation, the soil behind the wall follows a stress path in the opposite direction to that followed during the last stage of wall installation, while the soil in front of the

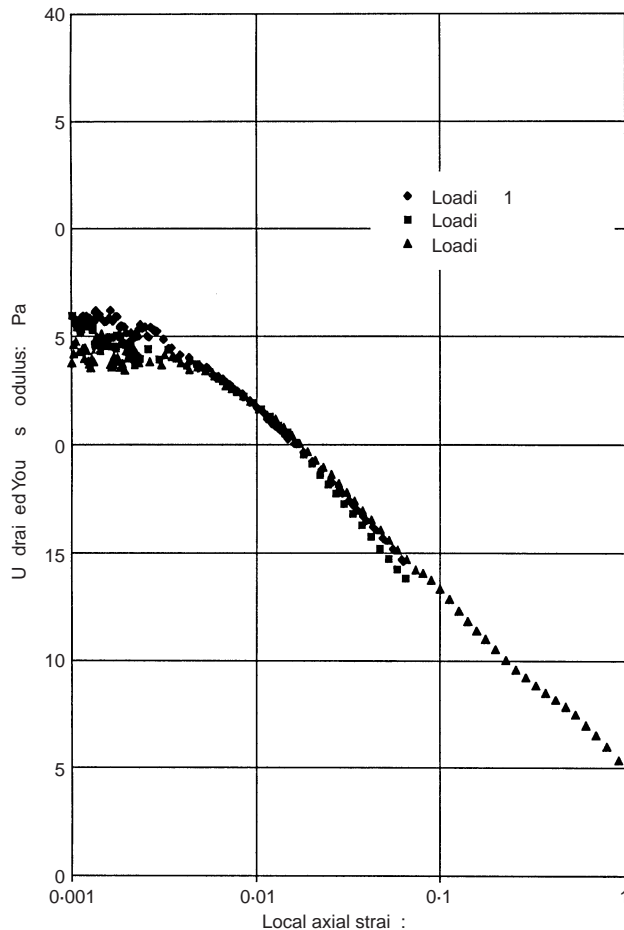


Fig. 13. Undrained secant Young's modulus as a function of the logarithm of strain, for the three stress paths

wall follows a stress path that is almost a continuation of that immediately preceding (this paper).

The rest periods between the stress excursions in the tests reported in this paper were intended broadly to reflect those that would occur during diaphragm wall installation in the field, and were generally of the order of 24 h. As overconsolidated clays generally exhibit much smaller creep rates than a near-normally consolidated clay such as Bothkennar (Jamiolkowski *et al.*, 1979), the effect of creep in our tests can reasonably be considered to be insignificant. In any case, the effects of creep in the laboratory tests would have been similar to those in the field, and cannot in this case be dismissed as an artefact of the testing procedure.

In our tests, we observed significant differences in stiffness over a wide range of strains. As noted by Clayton and Heymann, our tests were in this respect consistent with those reported by Atkinson *et al.* (1990), who found that the effect of recent stress history on measured stiffnesses followed a consistent pattern irrespective of the direction of the 'common path' taken to the datum stress point. Creep depends on stress state rather than on stress increment, so that if the effects attributed to recent stress history had in fact been caused by creep, a difference should have been apparent between, for example, compression and extension.

The results presented by Clayton and Heymann for Bothkennar clay are interesting, and suggest that the behaviour of this material may be dominated by the natural structure for the

relatively small stress changes investigated. Further investigation would be necessary to establish whether an incoming stress path of 10 kPa was in fact sufficient to create a noticeable recent stress history effect. It may be that for this soil it is impossible to assess the effect of recent stress history using multiple stress probes, as probes of sufficient length would affect the structure of the soil. However, from a pragmatic point of view this too would be an effect of recent stress history. In addition, a significant difference in stiffness for variations in stress path rotation of  $180^\circ$  to  $90^\circ$  would not necessarily be expected, even for soils where the effect of recent stress history is important (Stallebrass & Taylor, 1997). In this respect, it would be interesting to see the results of a test on Bothkennar clay in which the stress path AB represented a continuation of the incoming stress path.

In summary, our tests have shown that the response of the soil (in terms of the mobilisation of strength with shear strain) behind an embedded diaphragm type retaining wall will be different from that in front, owing to the different stress paths followed. We believe that the results of our tests are, within the usual constraints of the laboratory testing of soils, representative of what would occur in the field. The data presented by Clayton and Heymann relate to a very different type of soil subjected to different stress paths, and do not alter this conclusion. It is clear, however, that the relationship between the effect of stress path change and soil structure is complex, and requires further attention.

#### CORRIGENDUM

In Fig. 8, the symbols for tests KA1 ( $180^\circ$ ) and M1A ( $0^\circ$ ) have been transposed.

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