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The authors have decided to study the influence of microstructure on the time-dependent response of undisturbed and reconstituted London clay using drained and undrained triaxial compression tests (CIU and CID) with step changes in the applied strain rate. The paper presents interesting behaviour, and the authors should be commended for demonstrating the viscous response of London clay.

The primary influence of microstructure on the engineering response of London clay can be seen in Fig. 18(a), which compares the stress–strain response in the undisturbed and reconstituted states. Fig. 18(b) shows similar behaviour from triaxial compression tests on Rosemère clay from Eastern Canada (Philibert, 1976). From Fig. 18, it can be seen that there are similarities in the relative stress–strain response of the two materials, in spite of their vastly different index properties (e.g. $I_1 \approx 0$ compared with $I_1 \approx 1.2$). The stress–strain response of both clays during triaxial compression is characterised by: (a) a peak shear strength followed by post-peak strength reduction with large strain; (b) a predominantly strain-hardening response of the reconstituted or disturbed materials; and (c) at large strain, a post-peak strength of the undisturbed clay that approaches that of the reconstituted and ‘cut’ materials respectively. The difference in behaviour (the shaded areas in Figs 18(a) and 18(b)) is typically attributed to the effects of microstructure or weak bonding between the clay particles and aggregates of clay particles. Such behaviour is analogous to that typically observed in oedometer consolation tests on undisturbed and reconstituted materials (Burland, 1990).

Regarding the time dependence or rate sensitivity of London clay, the authors quantify viscous effects using the jump in deviatoric stress induced immediately after changing the applied strain rate. Although such an approach has merit, the following presents an alternative interpretation of the rate-sensitive response of London clay using the theory of overstress viscoplasticity (Perzyna, 1963). The current authors hope that this alternative interpretation will provide additional insight into the viscous response of undisturbed and reconstituted London clay.

THEORETICAL BACKGROUND

Perzyna (1963) originally proposed the theory of overstress viscoplasticity for the yielding of steel at high temperature. This theory has been subsequently adapted to geological materials by researchers such as Adachi & Oka (1982), Katona & Mulert (1984), Desai & Zhang (1987), and Hinchberger & Rowe (1998). For an elastic-viscoplastic material, the strain-rate tensor can be decomposed into elastic and viscoplastic components as follows:

$$\dot{\epsilon}_y = \dot{\epsilon}^e_y + \dot{\epsilon}^{vp}_y$$  

(1)

At yield or failure, the viscoplastic strain-rate typically dominates (Qu, 2007).

A form of the viscoplastic strain-rate tensor is (Katona & Mulert 1984; Desai & Zhang, 1987)

$$\dot{\epsilon}^{vp}_y = \frac{1}{\mu} \varphi(f) \left[ \frac{\partial f}{\partial \sigma_y} \right] = \frac{1}{\mu} \left[ \frac{q_0}{q_0} - 1 \right] \left[ \frac{\partial f}{\partial \sigma_y} \right]$$  

(2)

where $\mu$ is a viscosity constant with units of inverse time (typically s$^{-1}$); $f$ is the yield function from classical plasticity theory; $\varphi(f)$ is the flow function, which is derived from $f$; and $[\partial f/\partial \sigma_y]$ is the plastic potential, which is derived as a vector of unit length. The Maclaurin brackets $\langle \rangle$ in equation (2) imply $\varphi(f) = 0$ for $f < 0$ and $\varphi(f) = (q/q_0)^N$ for $f \geq 0$.

The flow function $\varphi(f)$ in equation (2) is a power law (Norton, 1929), where $q_0$ represents the long-term strength (reached at very low strain rates), $q$ is the strain-rate-dependent deviator stress at yield, and the term $q/q_0$ is the overstress (e.g. $q/q_0 = 1.1$ implies 10% overstress). An upper-bound estimate of $q_0 = q_0 = 125$ kPa, can be obtained for London clay from the deviator stress reached after 4 days of stress relaxation (see Fig. 3 in the original paper).

Considering axial strain rate only, the viscoplastic strain rate at yield is approximately

$$\dot{\epsilon}^{vp}_{axial} = \frac{1}{\mu} \left[ \frac{q}{q_0} \right] N - 1 \left( \sqrt{2/3} \right)$$  

(3)

where $\sqrt{2/3}$ is an estimate of the plastic potential, $\partial f/\partial \sigma_{11}$, derived assuming constant-volume deformation. Although London clay exhibits dilatant behaviour during the triaxial tests (see the pore pressure response in Fig. 8), the plastic potential has a negligible impact on the following discussion and derivation. Taking the logarithm of equation (3) and rearranging, it can be shown that (Qu & Hinchberger, 2007)

$$\log(q) = \alpha \log(\dot{\epsilon}_{axial}) + A_s$$  

(4)

for $q/q_0 \geq 1.1$. In equation (4), $A_s \cong \log(q_0 \mu\alpha)$ and $\alpha = 1/N$. Leroueil & Marques (1996) and Soga & Mitchell (1996) have used a similar relationship to evaluate the rate sensitivity of various clays.

Thus elastic-viscoplastic constitutive models based on a power law flow function (e.g. Adachi & Oka, 1982; Katona & Mulert, 1984; Desai & Zhang, 1987; Hinchberger, 1996; Hinchberger & Rowe, 1998) imply a linear relationship between $\log(q)$ and $\log(\dot{\epsilon})$ for stress states at yield or failure. In such a theory, the rate sensitivity (variation of $q$ with $\dot{\epsilon}$) at yield or failure is governed by $\alpha$, which is the inverse of the power law exponent $N$. The following is a re-evaluation of the strain-rate effects measured by the authors for London clay using the above theoretical framework.

INTERPRETATION OF RATE EFFECTS

Figure 18(a) shows the deviator stress $q$ against axial strain response reported by the authors. The data are replotted in Fig. 19 using a semi-log scale. From Fig. 19 it
can be seen that there is relatively uniform variation of \( \log(q) \) with axial strain, although rate effects appear to be less pronounced for the reconstituted material at axial strains in excess of about 5%.

Extracting deviator stress against axial strain rate from Figs 18(a) and 19, a series of essentially parallel linear lines can be obtained in \( \log(q) - \log(\dot{\varepsilon}) \) space. Fig. 20 summarises the \( \log(q) - \log(\dot{\varepsilon}) \) data extracted from undrained triaxial compression tests on undisturbed London clay at axial strains of 1%, 1.5%, 2%, 2.5%, 3%, 4% and 4.5%. Fig. 21 shows similar data for the reconstituted material at axial strains of 1%, 2%, 3%, 4% and 5%. The slope \( \alpha \) of the lines in Figs 20 and 21 represents the rate sensitivity of London clay. When compared in Fig. 22, the data suggest that the mean value of \( \alpha \) is about 0.023 \( (N = 44) \), and that both the undisturbed and reconstituted materials have essen-
tially the same rate sensitivity. Furthermore, the rate-sensitivity parameter \( \alpha \), estimated from drained triaxial tests on intact material (see Fig. 9 in the original paper) is also plotted in Fig. 5. It can be seen that the rate-sensitivity parameter estimated from CID triaxial tests is the same as that deduced from the CIU tests. Thus the rate sensitivity is identical for both drained and undrained triaxial compression, and for the intact and remoulded materials.

For comparative purposes, Fig. 23 shows the results of step tests on Belfast and Winnipeg clay (Graham et al., 1983). The strain-rate parameter \( \alpha \) is plotted in Fig. 24 for both clays. From Fig. 24 it can be seen that \( \alpha \) varies from 0.035 to 0.041 (24 \( \leq N \leq 29 \)) for Belfast clay, and from 0.033 to 0.036 (28 \( \leq N \leq 30 \)) for Winnipeg clay. Both clays are more rate sensitive than London clay. In addition, Belfast and Winnipeg clay do not show reduced rate sensitivity with continued straining (or destructuration) after reaching the peak strength, even for axial strains in excess of 15%. In contrast, the rate sensitivity of London clay diminishes with large axial strains in excess of about 5%; however, additional testing is required to confirm this behaviour.

SUMMARY

From the above discussion and interpretation, it can be concluded that the rate sensitivity of undisturbed London clay is the same as that of the reconstituted material. Thus the structure of London clay appears to have a negligible impact on its rate sensitivity, whereas the primary influence of structure appears to be exhibited by the shaded areas in Figs 18(a) and 19. The above interpretation has utilised a power law in conjunction with Perzyna’s theory of overstress viscoplasticity (Perzyna, 1963), and clearly other interpretations are possible. However, the writers hope that this discussion provides an alternative perspective to that of the authors for consideration.
Authors' reply
The authors would like to thank the discussers for their interest in our work, and their suggestions for interpreting it within different frameworks. The comparison they show between the viscous behaviours of different clays provides a valuable set of data to add to the existing database for structured clays. The discussers propose an alternative method of quantifying viscous effects (the effects of changing strain rate on the stress–strain curve) by using a relationship between log(q) and log(strain rate). The values of q used in that relationship are determined as the value of q obtained from the extrapolated curves for a given strain rate. The double logarithm relation usually ensures that the data approximately fit a straight line, so that a gradient $\alpha$ can be determined for a given soil. This approach presupposes that the soil behaves in an isotach manner, with a unique relationship between strain rate and stress. This is applicable to many soft soils and soft rocks; however, from our results it is clear that reconstituted London clay, like many other soils listed in our paper, does not follow an isotach behaviour (see Figs 3 and 7 of the paper for example), particularly the normally consolidated reconstituted soil. On increasing the strain rate, the soil experiences a temporary jump in deviatoric stress to a peak, and after peak the stress–strain response strain-softens to join a curve representative of the persistent effects of strain-rate change. For soils with an isotach behaviour there is no overshooting, and the immediate peak stresses coincide with the persistent curves, so that a unique stress–strain curve can be defined for a given strain rate (for example intact London clay, in Fig. 10 of the paper; Winnipeg clay and Belfast clay, as pointed out by the discussers). Fig. 25 shows stress jumps during undrained shearing of normally consolidated and overconsolidated London clay, measured from the peak reached immediately after a change in strain rate and from the extrapolated persistent stress–strain curve. The data show that the jumps do not coincide, indicating a non-isotach behaviour. In addition, the effects of strain rate change become more temporary towards failure, and more typical of TESRA behaviour. The discussers assume a direct link between the values of $\alpha$ they found for the undisturbed and reconstituted clay, and the effects of structure on the viscous behaviour of London clay, and conclude from their analysis that the natural structure of London clay has no effect on its viscous behaviour. We believe that the only conclusion that can be drawn from their re-interpretation is that the value of $\alpha$, which represents the persistent effect of strain-rate change, is not affected by structure. Since the proposed method cannot describe whether the behaviour is more typical of isotach or TESRA soils, it cannot capture all possible effects of structure on the viscous behaviour.

Fig. 24. Parameter $\alpha$ measured for Belfast clay and Winnipeg clay

Fig. 25. Influence of stress level on viscous stress jump during undrained shearing of: (a) NC-reconstituted London clay for strain-rate change of $18\times$; (b) OC-reconstituted London clay for strain-rate change of $70\times$
REFERENCES


