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Discussion: Laboratory measurement of strength mobilisation in kaolin: link to stress history

P. J. VARDANEGA*, B. H. LAU*, S. Y. LAM*, S. K. HAIGH*, S. P. G. MADABHUSHI*, M. D. BOLTON* and P. W. MAYNE†

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While Vardanega *et al.* (2012) present an interesting empirical power law relationship for representing the stress–strain response of clays under constant volume, they must take care in the mixing and matching of different strength modes. In particular, the observed increase of normally consolidated undrained shear strength ratio $(c_u/\sigma'_{v0})_{nc}$ with plasticity index (I_p) given by equation (4) was specifically developed on the basis of raw (uncorrected) vane shear strengths measured in the field on natural clays. The general trend for the shear strength ratio from field vane tests (FVTs) varying with I_p is reported by Bjerrum (1972), Larsson (1980), Jamiolkowski *et al.* (1985), Chandler (1988) and Leroueil & Hight (2003), albeit using non-linear relationships such as power law rather than the original linear form.

On the other hand, the general trend for the strength ratio $(c_u/\sigma'_{v0})_{nc}$ from triaxial compression (TC) tests on clays shows essentially no dependence on I_p (Larsson, 1980; Jamiolkowski *et al.*, 1985; Ladd, 1991; Ladd & DeGroot, 2003). As a consequence, this fact led Chandler (1988) to recommend an I_p expression that inter-relates FVT strengths to equivalent TC values.

Figure 9 shows the trends of $(c_u/\sigma'_{v0})_{nc}$ versus I_p using the original FVT dataset of Skempton (1957) and the laboratory dataset from TC, direct simple shear and triaxial extension modes presented by Ladd & DeGroot (2003). While the FVT data show a strong correlation with I_p ($r^2 = 0.946$), the TC data do not ($r^2 = 0.0002$). These trends have been supported by larger datasets including over 200 vane shear test (VST) data and over 200 laboratory strength data (Mayne, 2012).

On the other hand, as per the theoretical link established by critical state soil mechanics, the ratio $(c_u/\sigma'_{v0})_{nc}$ for TC mode increases with the effective stress friction angle ϕ' of the clay, as verified elsewhere (Mayne, 1988, 2012).

AUTHORS' REPLY

We acknowledge the discussor's recent re-evaluation of the variation of undrained strength ratio $(c_u/\sigma'_{v0})_{nc}$ with changes in plasticity index (Mayne, 2012) and his long experience in developing soil parameter correlations and their link to critical state soil mechanics principles (e.g. Mayne, 1980; Kulhawy & Mayne, 1990; Mayne *et al.* 2009). Figure 9 is a provocative reminder of a variety of

influences on the strength of soils other than simply changes in soil mineralogy.

We also recognise that differing test methodologies such as triaxial extension and direct simple shear tests could be used to characterise the normally consolidated behaviour of clay. It should be noted that the undrained strength ratio reported by Vardanega *et al.* (2012) was c_u/p'_0 , consistent with isotropic consolidation to mean effective stress p'_0 . The theoretical and empirical differences between using c_u/p'_0 and c_u/σ'_{v0} in normalising soil test data were well discussed by Wood (1990), who observed that Skempton (1954, 1957) did not distinguish between the two when plotting the FVT data shown Fig. 9, which were used to substantiate the well-known equation (4).

Nevertheless, the strikingly different trend of FVT data in the discussor's Fig. 9 is worthy of reflection. The discussor is right to warn against over-enthusiastic 'mixing and matching' of diverse data from a variety of sources. But, as the discussor will be well aware, any simple relationship between two correlates inevitably masks other sources of variation. In Fig. 9, for example, it seems likely that the FVTs were conducted at an effective stress level at least an order of magnitude smaller than the laboratory tests that provided the remaining data. Highly structured soils might be expected to display larger normalised strengths at small effective stresses, with the ratio decreasing at higher effective stress levels due to destructuration (Baudet & Stallebrass, 2004). Furthermore, active clays of high plasticity will be inherently more likely to develop natural structure than would be the case for low-plasticity clays. Figure 9 may therefore be masking the effects of stress level and destructuration; it is possible that triaxial and direct shear tests conducted on undisturbed samples under low effective confining stresses would show a stronger dependence on plasticity index, similar to the FVTs. This view would seem to coincide with that of Mesri (1975) who used the FVT data from Bjerrum (1973) to derive a strength reduction factor μ that reduces markedly with I_p .

Pragmatically, it should be noted that the range of values quoted by Vardanega *et al.* (2012) for $(c_u/p'_0)_{nc}$ of the kaolin under investigation, 0.19–0.29, does not plot outside the expected range for a soil of plasticity index 33% in Fig. 9.

However, the original point of the letter was to show that the mobilisation strain framework (MSF) as developed by Vardanega & Bolton (2011a, 2011b) can be applied to constant-volume tests on a remoulded soil and that the overconsolidation ratio (OCR) strongly correlates to mobilisation strain ($\gamma_{M=2}$). Normally consolidated kaolin showed a value $\gamma_{M=2} \approx 0.4\%$, whereas overconsolidated kaolin required $\gamma_{M=2} \approx 2\%$ at OCR = 10 (equation (11)). This is almost an order of magnitude increase for a somewhat modest OCR

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*Department of Engineering, University of Cambridge, Cambridge, UK

†Georgia Institute of Technology, Atlanta, GA USA

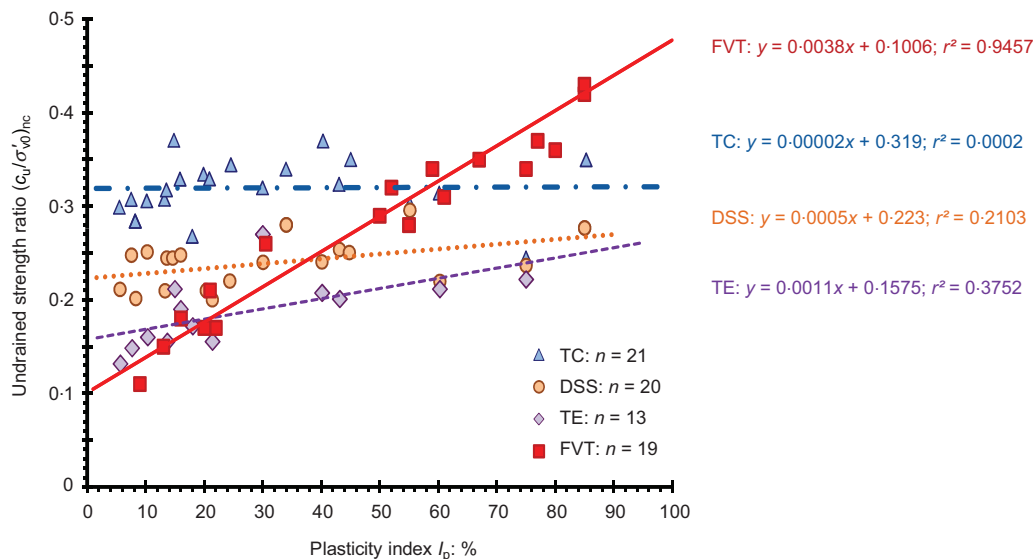


Figure 9. Undrained strength ratio versus plasticity index for field vane test (FVT), triaxial compression (TC), simple shear (DSS) and triaxial extension (TE). FVT data from Skempton (1957) and laboratory data from Ladd & DeGroot (2003)

interval. This conclusion is not altered by the outcomes of the discussion and this reply, and is important for geotechnical engineers who want to simply model the stress–strain behaviour of soils to perform serviceability calculations.

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