DISCUSSION

Determination of liquid limit from equilibrium sediment volume

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The authors present an intriguing insight into the water-holding capacity of clays. They propose a method for determining the liquid limit from equilibrium sediment volume. This is appropriate as the equilibrium sediment state is due to an effective stress level of a definite value of matrix suction. This is borne out of the authors' statement regarding the use of soil moisture tension by Russell & Mickle (1970) as one of the alternative methods for determining the liquid limit. In fact, in the initial period of analysis and use, the liquid limit was regarded mainly as a physical parameter of clays and used primarily for classification of fine-grained soils. However, a significant step towards the use of the liquid limit as an engineering property can be attributed to the work of Skempton (1944) for assessment of the compression index of clays from their liquid limit water content. Nagaraj & Srinivasa Murthy (1983) subsequently examined this from a micromechanistic viewpoint. The liquid limit has the attributes of an engineering parameter reflecting shear strength and compressibility at that water content due to a low but not negligible value of effective stress (Nagaraj *et al.*, 1993). As such, it is a valuable parameter for accessing soil behaviour and the in-situ nature of soil deposits.

The authors' test procedure, which is simple to perform and apparatus-independent, can be used by engineers to determine the equilibrium (taken as 24 h) sediment void ratio e_s from the measured sediment volume, dry weight of the sample, and the measured or assumed specific gravity. Values of e_s can be used as a normalising parameter for grouping soils into different states (e.g. normally or over-consolidated, aged or naturally cemented) with reference to an intrinsic state line (ISL) similar to that developed by Nagaraj *et al.* (1994) and Nagaraj and Miura (2001) using the liquid limit void ratio e_L . Such a framework allows for the assessment of engineering behaviour such as compressibility, shear strength and permeability.

The concept of using e_s as an alternative parameter to e_L in obtaining the reference state of clays was presented by the first discussor and his co-workers in 1984 (Nagaraj *et al.*, 1984). Table 1 summarises data for four Indian soils tested by Nagaraj *et al.* (1984)—three residual soils and one marine soil. The liquid limit values were determined using the fall cone method on oven-dry samples. The liquid limit void ratio was computed as equal to $w_L G$, and the sediment void ratio was determined from the measured 24 h sediment

volume using a procedure similar to that presented by the authors.

The relationship between equilibrium sediment volume and liquid limit void ratio for the data in Table 1 is

$$e_s = 1.76e_L \quad (9)$$

Figure 4(a) plots the one-dimensional compression paths for these four clays starting from a remoulded state. Nagaraj *et al.* (1984) normalised these data by e_L and found a unique relationship of the form (Fig. 4(b))

$$\frac{e}{e_L} = 1.23 - 0.276 \log \sigma'_v \quad (10)$$

with a goodness-of-fit $r^2 = 0.976$ for number of data points $n = 24$.

Normalising the consolidation data by e_s rather than e_L gives the following relationship (Fig. 4(c))

$$\frac{e}{e_s} = 0.69 - 0.149 \log \sigma'_v \quad (11)$$

with $r^2 = 0.980$.

Figure 5(a) plots void ratio against permeability for the four soils listed in Table 1. Again, normalisation by e_L (Fig. 5(b)) produces a unique relationship as presented by Nagaraj *et al.* (1984)

$$\frac{e}{e_L} = 2.23 + 0.204 \log k_v \quad (12)$$

with $n = 24$ and $r^2 = 0.974$. Normalising these data by e_s gives the following relationship (Fig. 5(c))

$$\frac{e}{e_s} = 1.25 + 0.112 \log k_v \quad (13)$$

with $r^2 = 0.980$.

These data show that the liquid limit void ratio as determined by conventional tests and the equilibrium sediment void ratio result in unique relationships between normalised void ratio (e/e_L or e/e_s) and compressibility and permeability. In all cases the resulting equations are linear in semi-log space with very high r^2 values. However, measurement of the equilibrium sediment volume, as proposed by the authors, is simple to perform and apparatus-independent, unlike the traditional liquid limit test equipment and procedures. Thus the equilibrium sediment volume procedure, when coupled with reference states like those presented in Figs 4(c) and 5(c), provide a convenient framework for grouping soils of similar states and behaviour. That is, the

Table 1. Summary of soil properties

Soil	Liquid limit: %	Plastic limit: %	PI: %	Specific gravity, G	Liquid limit void ratio, e_L	Sediment void ratio, e_s
Red soil	50	27	23	2.65	1.32	2.31
Brown soil	62	31	31	2.63	1.62	2.85
Black cotton soil	84	47	37	2.68	2.25	3.96
Marine soil	106	47	59	2.64	2.79	4.92

Fig. 4. Consolidation relationships: (a) void ratio, e ; (b) normalised liquid limit void ratio, e/e_L ; (c) normalised sediment volume void ratio, e/e_s

intrinsic state line framework based on e_L , as originally developed by Nagaraj *et al.* (1984), is readily extended to the use of e_s .

Although the data presented here are limited to four soils, they do span a fairly wide range of void ratios at the liquid limit ($e_L = 1.32$ – 2.79) and at the sediment equilibrium state ($e_s = 2.31$ – 4.92). However, the focus of this discussion is not on the specific relationships suggested but rather on the phenomenological model possible with equilibrium sediment void ratio. The possibility of refining the constants in equa-

Fig. 5. Permeability relationships: (a) void ratio, e ; (b) normalised liquid limit void ratio, e/e_L ; (c) normalised sediment volume void ratio, e/e_s

tions (11) and (13) remains as and when more data become available.

Although the data presented in Table 1 are for oven-dry soils (the tests were conducted in 1984), it is preferred that future sediment volume tests be conducted on samples that are not oven dried. The authors note such a restriction for marine soils, but in fact a variety of other soils can also be adversely influenced by the oven drying process (e.g. Pandian *et al.*, 1993). Thus a prudent approach would be to avoid using oven-dry samples and simply calculate the sediment volume as presented by the authors in equation

(8). This does prolong the test, as the water content of the sample after sedimentation needs to be measured, but it removes any uncertainty about the influence of oven drying.

Authors' reply

The discussers have explained the use of the void ratio at equilibrium sediment volume as a normalising parameter for grouping soils into different states and for the assessment of engineering behaviour such as compressibility, shear strength and permeability. The authors are aware of the contribution of the senior discussor and his co-workers in using the void ratio at liquid limit for the prediction of engineering behaviour of fine-grained soils. Replacing of void ratio at liquid limit by void ratio at equilibrium sediment volume is a simple possibility. The authors, however, do feel that the engineering behaviour of fine-grained soils cannot be so simply predicted with a single parameter, except in ideal situations.

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