DISCUSSION

A constitutive model for partially saturated soils

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Recently we had the opportunity to test the Authors' model in laboratory experiments on a collapsible, non-active undisturbed clay soil, submitted to isotropic stress changes under suction controlled paths (Aguilar, 1990; de Campos, Aguilar & Vargas, 1991). Table 2 presents the model parameters obtained in the experimental programme, which included five suction-controlled triaxial tests.

As exemplified in Figs 26 and 27, the Authors' model was able to predict most of the experimental results quite well. The poorest quantitative comparisons between model and experimental data were related to suction decrease under different levels of constant isotropic stresses p ($= \sigma - u_a$), the experimental collapse deformations being greater than the predicted ones.

A large collapse was observed in one of the tests when the sample was saturated, from its natural stress state, by the application of a small differential water pressure between its bottom and top, while the cell pressure was kept constant. According to the model, this collapse should not occur as the sample was within the assumed initial elastic region.

In our opinion, before questioning the model assumptions, two experimental aspects should be considered

- (a) difficulty in defining the initial stress state of the unsaturated soil, in particular the initial p_0^* (conventional saturated overconsolidation pressure)
- (b) lack of knowledge of the stress path followed by the sample in the conventional saturation process.

As air pressures are not measured, the variation of p is unknown in case (b). (All other wetting paths under constant p steps, followed in the experimental programme, were controlled by known decreases in suction.)

The model parameters r , β and p^c are obtained from

$$\left(\frac{p_0}{p^c}\right) = \left(\frac{p_0^*}{p^c}\right)^{[\lambda(0) - \kappa] / \{[\lambda(0)\{(1-r) \exp(-\beta s) + r\} - \kappa]\}} \quad (48)$$

which is a combination of equations (7) and (12).

An unlimited number of numerical values for these parameters can, in principle, satisfy equation (48). Our experience indicated that p^c is the most sensitive parameter for the definition of the LC yielding surface.

Owing to the importance of the parameter p^c , could the Authors comment further on its definition? Is there any physical meaning behind it (as, for instance, the Hvorslev p_e normalization parameter for overconsolidated saturated soils)?

Fig. 26. Initial yielding surfaces: experimental results and model predictions

Table 2. Model parameters

$\lambda(0)^\dagger$	$\kappa^\dagger$	κ_s	λ_s	p_0^* : kPa	s_0 : kPa	p^c : kPa	r	β : kPa ⁻¹
0.217	0.006	0.008	0.108	80	150	18.1	0.565	0.0215

[†] Average values from isotropic consolidation and confined tests.

Fig. 27. (a) Stress and suction paths followed on experiments and corresponding yielding surfaces; (b) isotropic stress $\times$ volumetric deformations: experimental results and model predictions

Authors' reply

The discussion on some of the points raised is hampered by the lack of more background information on the testing programme carried out.

The Authors share the opinion expressed regarding the difficulties of defining precisely the preconsolidation (or yield) stress p_0^* . This is a general difficulty found in the interpretation of test results under both saturated and unsaturated conditions for many soil types.

The meaning of 'lack of knowledge of the stress path followed by the sample in a conventional saturation process' and 'air pressures are not measured' is not totally clear. If it is the air entrapment phenomenon, which may occur near saturation, which is being referred to, it is agreed that some unknown air pressure may develop within the air bubbles. At this point a transition to a saturated condition takes place. This is a difficult stage for modelling purposes and it is not particularly addressed by the model presented. However, for most of the range before the final saturated condition the permeability of the soil to air allows the easy escape of air from the specimen and, therefore, the air pressure is in general known and equal to the atmospheric value.

The Writers also report the collapse, on wetting, of a sample whose stress state was apparently in the assumed elastic region. As no figures

or data concerning this test are given the Authors cannot comment in detail.

Regarding the apparent freedom in the selection of a combination of model parameters to reproduce a given measured result, it should be stressed that, as discussed in the Paper, the parameters have a physical meaning and they can, in principle, be unambiguously determined from specific tests. For instance, p^c of a given unsaturated specimen is a consolidation net mean stress belonging to its virgin loading curve for which only elastic expansion results when wetted. When $p_0 = p^c$ (equation (48)) all the preconsolidation stresses $p_0(s)$ become equal to p^c . The LC yield curve then becomes a straight line parallel to the s axis at $p_0 = p^c$.

As indicated in the Paper direct physical significance can also be ascribed to parameters β and r ; these also control the shape of the LC yield surface.

The influence of p^c on the shape of the LC yield curves is similar, in quantitative terms, to the variations observed in Fig. 4 for changes in p_0^* .

With regard to the test result plotted in Fig. 27, the calculated value of the virgin compressibility parameter $\lambda(s)$ (for $s = 100$ kPa) is shown as 0.25 (model curve). This value cannot be found from the model parameters reported in Table 2. In fact $\lambda(s)$ (for $s = 100$ kPa) = 0.13. Similarly, a value of

$\kappa = 0.033$ is derived for the model curve in Fig. 27 whereas the value of $\kappa = 0.006$ is reported in Table 1. In view of the shape of the experimental loading curve plotted in Fig. 27 it is surprising that the initial preconsolidation stress p_0 (yield curve LC_0) is located at $p_0 = 200$ kPa (point 7) when the test seems to indicate a much lower value (point 4 of the stress path).

The behaviour of the specimen after the suction cycle applied at $p = 400$ kPa (a sudden increment in the compressibility parameter which varies from 0.15 to 0.45) suggests that the natural soil tested may have cementation bonds between particles which have been destroyed by the plastic strains induced during the previous desiccation. As a result of adopting the modified Cam clay model as the saturated boundary of the model, the particular version presented is not intended for soils exhibiting strong structural effects.

The Authors would like to encourage further applications of the model to the interpretation and prediction of experimental results concerning unsaturated soils of various types and under different stress conditions. In this way the strong points and shortcomings of the model can be identified and appropriate modifications could be obtained.

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