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MODELLING LARGE STRESS REVERSALS IN SOFT CLAY

FABRICATION DE MAQUETTES POUR INVERSIONS DE GROSSE TENSION EN ARGILE MOLLE

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A constitutive relationship, known as the CARMEL model, has been developed to predict the behaviour of anisotropically consolidated clay. Changes in induced anisotropy during loading can be modelled by the proposed relationship. This enables it to be used for the prediction of strains resulting from large stress reversals, during which the anisotropy of soil evolves. The model has been used to predict the behaviour of two types of kaolin clay during large reversals of deviatoric stress. Comparisons of observed and predicted behaviour are made. Since the model is based on the principles of Critical State Soil Mechanics a direct comparison with predictions using Modified Cam Clay have been conducted. Results of the comparisons show the CARMEL model provides improved predictions.

INTRODUCTION

Construction activities and the service conditions of structures can sometimes result in zones of the adjacent soil being subjected to large reversals of stress. Such loading can be a single cycle, such as excavation followed by construction, or caused by repeated monotonic loading. To reliably predict the response of soil to stress paths containing large reversals suitable constitutive models are required. Described herein is the application of a constitutive model, based on the concepts of critical state soil mechanics, for the prediction of this type of stress path.

A constitutive model - known as the CARMEL model - (Davies and Newson, 1992) has been developed to describe the stress/strain behaviour of anisotropically consolidated soil. Anisotropic consolidation leads to the formation of an inherent anisotropic fabric and thus an anisotropic stress strain behaviour, e.g. Nadarajah and Parry (1974). The application of a long stress path in which the ratio of deviatoric stress to mean normal effective stress (q/p') is varied can result in a change in the nature of the anisotropy of the soil as induced anisotropy evolves. Stress path triaxial tests conducted to develop the proposed model indicated that for small stress probes there was little evidence of a change in anisotropy, Newson, (1992). However, when large stress paths were applied subsequent stress probes revealed a change in the degree of anisotropy. Similar observations have also been reported by a number of other workers e.g. Stipho (1978). An implication of these observations is that during long loading paths not only does the degree of anisotropy of inherently anisotropic soils change but also inherently isotropic soils can develop anisotropic constitutive behaviour. When attempting to predict a large stress reversal, therefore, the evolution of anisotropy during previous loading paths must be considered. In this paper prediction of the response of both initially isotropic and anisotropic consolidated soils will be considered.

PROPOSED CONSTITUTIVE MODEL

The proposed model is based on the critical state concept for soils, Roscoe, Schofield and Wroth (1958). The major features are an empirical yield locus, a theoretical plastic potential function, originally derived by Dafalias (1987) for an associated anisotropic model, and an isotropic and rotational hardening rule. The yield locus and rotational hardening rule were obtained from stress path triaxial tests conducted by Bondok (1989) and Newson (1992). The experiments revealed non-associated behaviour and the plastic potential function was selected to agree with the observations. Prior to yield the soil is modelled as a linear elastic material.

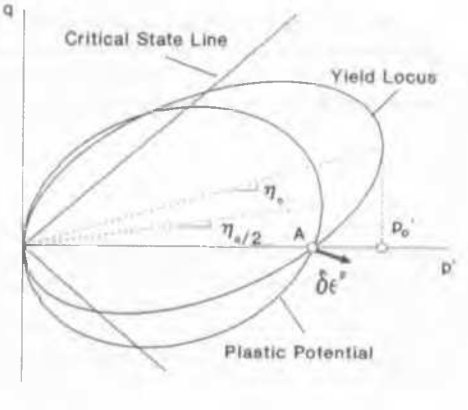

Fig. 1. The CARMEL yield locus and plastic potential

The yield and plastic potential functions are plotted together in Fig. 1. The plastic potential shown in the figure represents yielding at point A; the plastic strain increment vector at that point is also shown. The yield locus is a rotated distorted ellipse orientated around the K_0 consolidation line, given by the function:

$$(1-\eta_o^3/M^3).(q-\eta_o.p')^2-(M-\eta_o)^2(p_o'-p')p'=0 \qquad (1)$$

where $\eta = q_o/p_o'$, which is the gradient of the K_o consolidation line.

Similarly the plastic potential is also a rotated distorted ellipse, but in this case it is orientated around a constant stress ratio line $(\eta = q / p')$ which has a gradient, α_o, half that of the K_o consolidation line. The expression for the plastic potential is:

$$p'^2 - p'.\beta + \left(q^2 - 2.\alpha_o.q.p' - \alpha_o^2.p'.\beta\right) / M^2 = 0 \qquad (2)$$

where $\alpha_o = \eta_o / 2$ and β is the value of p' at the apex of the plastic potential.

When applying this model the initial anisotropy need not necessarily result from K_o consolidation; although this would be the most common application in engineering practice. Different forms of anisotropy can be accommodated by change of the value of the parameter η_o to the appropriate constant stress ratio during consolidation. Indeed, if $\eta_o = 0$, which corresponds to isotropic consolidation, the model devolves to Modified Cam Clay.

The evolution of the parameter η_o which defines the rotation of the ellipses, is controlled by the following experimentally derived incremental expression:

$$\delta\eta_o = \pm\left[1 - (\eta_s / M)^2\right].\delta p^*.\exp(\eta_s - \eta_{os}).(1 - \eta_{ko}) \qquad (3)$$

where,

$\delta p^* = \delta(p'/p_o')_{iso}$
η_s = stress ratio at start of increment
η_{os} = rotation of ellipse at start of increment
η_{ko} = rotation of ellipse for one dimensional consolidation

in which $\delta(p'/p_o')_{iso}$ is the change in the ratio of p' to the value of p' at the apex of the ellipse, i.e. p_o', if only isotropic hardening were to occur during an increment of loading. Equation 3 is positive for increase in q and negative for decreases in q. The model is currently formulated in triaxial space and q is negative when lateral stresses are greater than axial stresses.

During anisotropic - or isotropic - normal consolidation (where the stress path is continuously located at the apex of the yield locus) δp^* will be zero. It therefore follows from Eqn. 3 that $\delta\eta_o$ is equal to zero and there is no rotation of the yield locus.

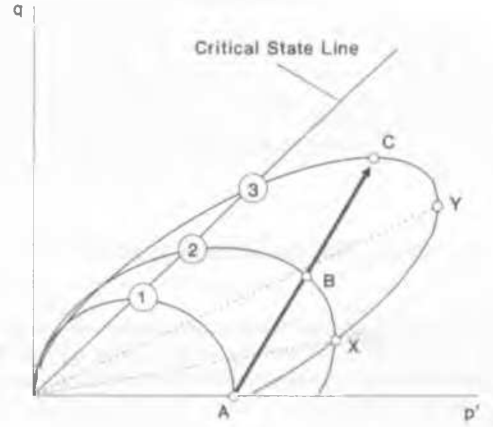

Fig. 2. Evolution of the CARMEL yield locus

Figure 2 shows diagrammatically the simultaneous rotation and expansion of the yield locus during plastic straining. As the stress path moves from point A, which coincides with the apex of the initial yield surface, towards C the yield surface both expands isotropically and rotates such that when at B (locus 2) the apex is at point X and at the end of the stress path (C on locus 3) the apex is at Y. This represent a change in the state of the soil from its initial isotropic state to one of anisotropy.

Based on the original concept of simplicity, the model requires only one independent parameter additional to those of the critical state family of models. In common with earlier models the extra parameter, η_o, has a physical meaning, i.e. the gradient of the K_o consolidation line in q:p' space. The rotation of the plastic potential surface, α_o, is a function of η_o. Due to the double functioned nature of the model it is known as CARMEL, i.e. the *CAR*diff *M*ultiple *EL*lipse model.

PREDICTIONS USING THE PROPOSED MODEL

Presented herein are predictions of triaxial tests conducted on specimens of two types of kaolin clay, viz: "Speswhite" and "P300". The specimens were subjected to large stress reversals resulting from a change in deviatoric stress (q) whilst the mean normal effective stress (p') was held constant. Both compression and extension stages were conducted in each test. Both anisotropically and isotropically consolidated specimens were tested, with loading proceeding with either an increase or decrease in deviatoric stress.

Predictions of these tests using the proposed model are compared with predictions using Modified Cam Clay, Roscoe and Burland (1968), which represents a "benchmark" against which the CARMEL model can be assessed. Both models require the same material parameters, since the CARMEL model is a hybrid of Modified Cam Clay. These were obtained from standard triaxial tests and are presented in Table 1.

Table 1. Soil material parameters

Soil Type	λ	κ	Γ	M	ν	η_{ko}
Spezwhite	0.171	0.030	2.09	0.845	0.3	0.41
P300	0.096	0.022	1.35	0.950	0.3	0.50

Comparisons of the predicted response of the shear and volumetric strains with measured values when specimens of P300 kaolin, isotropically normally consolidated to a mean normal effective stress of 200 kPa, are subjected to large stress reversals (A-B-C) are shown in Figs 3 and 4. In the test shown in Fig 3, I1, the deviatoric stress was first increased to a value of 170 kPa and then loading reversed to a value of -133 kPa. In the second test to be analysed, I2, shown in Fig 4, the deviatoric stress was initially reduced to -170 kPa and loading reversed and the deviator stress taken to a value of 170 kPa.

In both tests I1 and I2 for much of the first loading increment (A-B) predictions of the shear strain show very good correlation with the observed data. However, towards the end of the increments, when substantial plastic strains have developed, in test I1 both models overpredict shear strains - with CARMEL producing slightly closer comparisons. In test I2 CARMEL underpredicts the observed behaviour whilst Modified Cam Clay predicts substantially greater shear strains than those observed. Predictions of the subsequent reversal of deviatoric stresses (B-C) indicate that whereas the CARMEL model shows plastic yielding occurs during this increment

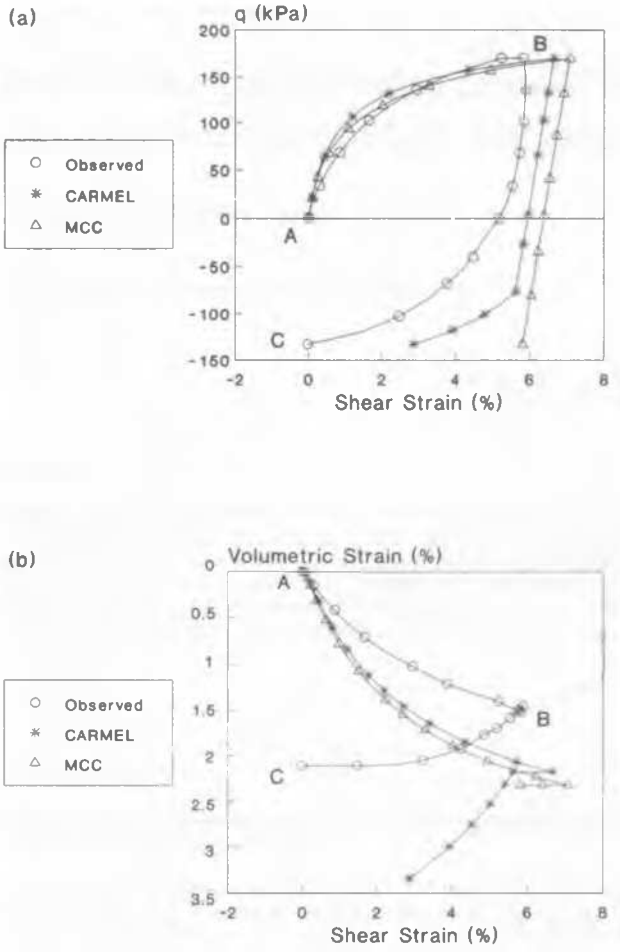

Fig. 3. Observed and predicted behaviour - test I1

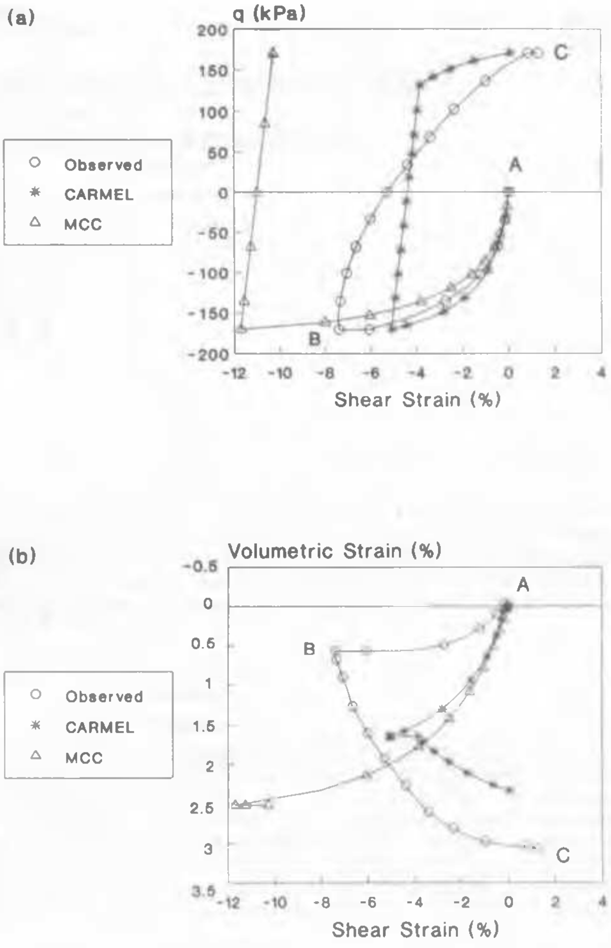

Fig. 4. Observed and predicted behaviour - test I2

Modified Cam Clay behaves elastically throughout. The resulting shear strains agree more closely with the experimental observations which indicate plastic yielding. The explanation for this is that whilst during the first loading increment the Modified Cam Clay yield surface expanded to increase the elastic domain substantially, the CARMEL yield locus evolved by both isotropic and rotational hardening and as a consequence ensured a smaller region of elasticity.

Volumetric strains were less well predicted by both models. During initial stages of the first loading increment both models predict similar behaviour. In test I1 the similarity in predictions was continued to the end of the increment but in test I2 Modified Cam Clay predicted greater volumetric strains. As has been indicated above, the Modified Cam Clay predictions do not include any yielding during the stress reversal hence no volume changes were predicted for the reversal stage. In contrast CARMEL predictions show volumetric strains continuing to increase following stress reversal. Although for both tests predicted and observed values are not in close agreement the experimental trends are correctly predicted by the CARMEL model.

The results of a large stress reversal test conducted on a specimen of anisotropically consolidated Speswhite kaolin clay are shown together with predictions in Fig 5. In this test, A1, following anisotropic consolidation to a stress state of $p' = 396$ kPa and $q = 162$ kPa the stresses were reduced to $p' = 365$ kPa and $q = 150$ kPa resulting in a lightly overconsolidated specimen. Loading proceeded under constant p' conditions by reducing the deviatoric stress (A-B) to $q = -75$ kPa which was followed by a reversal in stress to $q = 300$ kPa.

Comparison of the predicted and measured values of shear stress reveal that the CARMEL model predicted the initial hysteretic unload/reload loop whilst Modified Cam Clay did not. This was because the value of q at point B, Fig 5(a), remained within the original Modified Cam Clay yield locus but lay outside that for the CARMEL model. Because the initial unload/reload loop lay within the Modified Cam Clay yield surface no volumetric strains were predicted by this model for this stage of the test. Volumetric strains were predicted by CARMEL following the trends of the experimental behaviour. On reaching the stress state at the start of loading, $q = 150$ kPa, (point A) the prediction using Modified Cam Clay indicated yield of the specimen. Isotropic hardening in the CARMEL prediction results in a slightly higher yield point of $q = 200$kPa during the reloading stage.

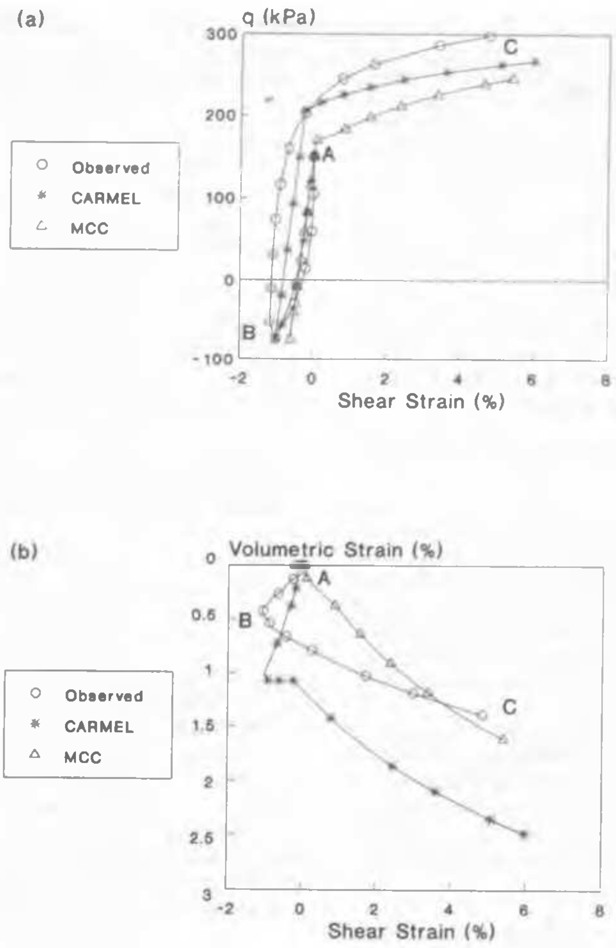

Fig. 5. Observed and predicted behaviour - test A1

CONCLUSIONS

A model has been proposed which can represent the major features of the stress strain behaviour of both isotropically and anisotropically consolidated clay subjected to large deviatoric stress reversals. Predictions using the model have correctly indicated the onset of yielding and the development of the associated irrecoverable strains during large stress reversals. By contrast, in predictions using Modified Cam Clay - a model developed for isotropic soil - the formation of yield loci during initial loading results in the requirement for greater reversals in stress to be applied before yield occurs than was observed experimentally.

Predictions of shear strains using the CARMEL model are generally close to observed values. Although modelling the general trends of the development of volumetric strains very well, the predicted magnitudes were less accurate. This highlights the complex nature of the coupling between isotropic and rotational hardening in the evolution of the yield locus and hence the plastic strain increment vector direction - since the orientation of the plastic potential is a function of the yield locus orientation.

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