The effect of modelling volumetric creep on ground movements

Effet de modéliser le fluage volumétrique sur les prédictions de mouvements du sol

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ABSTRACT: The effect of volumetric creep, defined as continued volumetric straining at constant mean effective stress, has been investigated by associating the change in volumetric strain with a change in preconsolidation pressure. This simple representation has been used in the 3-SKH model (Stallebrass and Taylor, 1997). Analyses are presented simulating both laboratory element tests and a boundary value problem. The results were consistent with general observations of the effects of volumetric creep and provided insight into the consequences of modelling creep in this way for the prediction of ground movements around soil structures.

RÉSUMÉ: L'effet du fluage volumétrique, qui est défini comme une deformation volumétrique continue sous une pression sphérique effective constante, a été étudié en assimilant le changement de deformation volumétrique à un changement de pression de préconsolidation. Cette representation simple a été utilisée dans le modèle 3-SKH (Stallebrass & Taylor, 1997). Les analyses numériques, qui simulent des essays de laboratoire et un problème en place avec conditions aux limites, sont présentées. Les resultants obtenus se sont avérés consistents avec les effets de fluage observés en général, et ont permis de comprendre les consequences de modeliser le fluage de telle façon pour prédire les mouvements de sol autour des structures géotechniques.

1 INTRODUCTION

Over the past ten to fifteen years a number of constitutive models simulating the behaviour of stiff overconsolidated soils have been developed from the results of high quality laboratory testing at small strains. The majority of these models have been created to simulate the behaviour of reconstituted soil samples, thus they may lack the ability to model some of the phenomena associated solely with soils in their natural state in the ground. Consequently these models are still unable to predict the precise patterns of behaviour observed in the field (Addenbrooke et al, 1997). Several workers have identified aspects of behaviour that are particularly important when modelling the response of natural soil (Leroueil and Vaughan, 1990, Cotecchia and Chandler, 1997), including the effects of fabric, bonding, thixotropy and creep. In natural deposits the response of the soil may be affected by more than one of these effects occurring simultaneously. However, this study isolates the influence of volumetric creep which in the field will occur predominantly during the geological history of the soil. A simple representation of volumetric creep has been implemented into an existing soil model, to examine whether it has a major effect on subsequent predictions of ground movements compared to other features of the behaviour of natural soils. It has been assumed that the soil will not undergo any bonding during the period of creep, such that when compressed the state of the soil will follow the normal compression line, rather than yielding to the right of it p'_{cb} in Figure 1. This paper first outlines the experimental characteristics of volumetric creep and then describes the way it has been implemented into the existing soil model before presenting results of both single element and boundary value problem analyses.

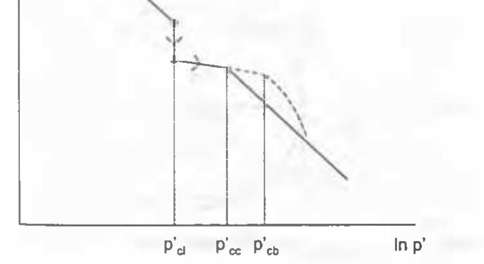

Figure 1. Schematic diagram in volumetric space showing possible state paths for soil subject to ageing effects distinguishing creep and bonding.

2 EXPERIMENTAL CHARACTERISATION

It has been observed that when soil remains at a constant effective stress for a period of time it is likely to demonstrate a stiffer response to further loading (Richardson, 1988). Volumetric creep, which was described by Bjerrum (1967) as "a delayed compression representing the reduction in volume at unchanged effective stresses", has been shown to account for some of this additional stiffness in tests such as those by Bishop (1966), Som (1968) and Bjerrum (1967). Bjerrum divided the compression caused by the application of loading into instant and delayed compression rather than the more conventional primary and secondary compression arguing that creep straining also occurs during primary compression. Mesri and Choi (1985) who analysed settlement and pore pressures under two test embankments concluded that the assumption that creep occurs once primary consolidation has ended realistically describes soft clay consolidation, and for simplicity that is the assumption made in the implementation of creep described here. Irrespective of the precise formulation of the models, it is generally accepted that creep deformations follow a logarithmic relationship of the form

$$\Delta v = C_\alpha \ln(\Delta t / t_0) \tag{1}$$

where Δv is the change in specific volume due to creep, C_α is the secondary compression index, Δt is the time at a constant effective stress, and t_0 is a reference time, which denotes the onset of creep (often the end of primary consolidation).

3 MODIFICATIONS TO CONSTITUTIVE MODEL

Ingram (2000) describes the modifications to the 3-SKH Model (Stallebrass & Taylor, 1997) which were necessary to assess the effect of periods of rest on subsequent predicted ground movements. The 3-SKH model (Figure 2) is an elasto-plastic model incorporating yield within a modified Cam clay state boundary surface (Roscoe and Burland, 1968). Two kinematic surfaces, the yield and history surfaces, representing the extent of small strain elasticity and the effect of recent stress history lie inside this surface. They are related to the size of the bounding surface by fixed ratios, and translate to follow the current stress point. This soil model was used since the kinematic surfaces already allow significant improvement in predictions compared to the conventional Cam clay model.

Creep behaviour has been incorporated into the model by simulating the way in which volumetric strain due to creep moves the current state of the soil inside the state boundary surface. A creep equation

$$\varepsilon_v = \psi \ln(\Delta t/t_0) \tag{2}$$

which is of the form proposed by Borja and Kavazanjian (1985) has been used to describe the accumulation of plastic volumetric strains, ε_v, with passing time. This formulation requires a new parameter, ψ, the secondary compression index, to be included in the description of the soil model. The secondary compression index has been used instead of the more common C_α, because it is more consistent with the natural strains that are used in the formulation of the model. The reference time, t_0, is held constant and equal to one minute. This implies that the volume change during creep is not affected by the time to the end of primary consolidation. This is consistent with the simplified approach adopted, and the fact that pore pressure consolidation is not modelled in any of the analyses presented here. The duration of creep straining, Δt, is a variable defined in the input for the analyses in units of minutes. Plastic volumetric strain computed by equation 2, is added in a single increment, which moves the state to a new swelling line or elastic wall, as shown in the v: p' plot in Figure 2. This enlarges the bounding surface which is a projection of the state boundary surface on an elastic wall, such that the preconsolidation pressure increases from p'_{ci} to p'_{cc}. This process is described by the hardening rule for the model, which follows the Cam clay models in linking plastic volumetric strain to a hardening parameter p'_c. As the bounding surface expands, the inner surfaces also increase in size about their centres. The consequences of implementing creep in this way are twofold, firstly, the state of the soil is now within the yield surface so that the small strain stiffness of the soil increases to its maximum value irrespective of recent stress history, although the effect of recent stress history is still preserved through the overall configuration of the surfaces. Secondly, since the elastic shear stiffness is related to overconsolidation ratio in the model (Viggiani and Atkinson, 1995), the initial shear stiffness is increased.

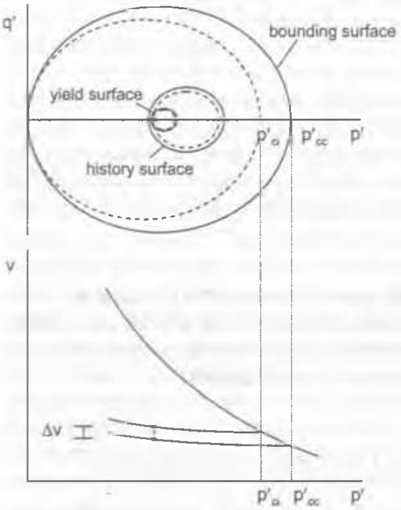

Figure 2. The inclusion of volumetric creep in the 3-SKH model.

4 EVALUATION OF MODELLING OF CREEP

In order to evaluate the effects of incorporating volumetric creep into the 3-SKH model, several finite element analyses modelling a uniform element of soil were undertaken. The first set of analyses, series 1, investigate the interaction between modelling creep and recent stress history. The second set, series 2, look at a stress path more representative of field loading, that is undrained shearing from a one-dimensional overconsolidated state. The parameters used in the model were those derived for London clay, by Stallebrass and Viggiani (1994), or those given in Stallebrass and Taylor (1997) for Speswhite kaolin with the addition of a creep rate ψ calculated by Richardson (1988) assuming a t_0 of one minute from a series of stress path tests on London clay.

4.1 *Creep and the recent stress history effect*

The first set of analyses followed a pattern similar to a series of tests by Stallebrass (1990) carried out to examine the effects of recent stress history on laboratory samples. The stress path followed enables a variety of histories to be examined in a single test. The soil was modelled as Speswhite kaolin to be consistent with a the test reported by Stallebrass (1990), although little data exists for the creep rate of Speswhite kaolin so the secondary compression index measured by Richardson (1988) for London clay was used in these analyses. The sample was isotropically compressed to 720kPa, and swelled back to 300kPa, the soil was then subjected to a series of stress probes which can be seen in diagrammatic form in Figure 3. The stress probes allow the stressstrain response of the soil to be measured along the same drained constant p' stress path but following different approach paths. The effect of creep on the constant p' path followed in the test was modelled by repeating the test with periods of 1 year and 1000 years of creep inserted before each of the constant p' stages i.e. at stress state A in Figure 3. The period of creep of 1 year was thought to represent the sort of time period achievable in the laboratory using careful testing. The period of 1000 years was used to investigate the logarithmic nature of the creep relationship by allowing creep for a further three log cycles.

Figure 3 also shows a schematic representation of the configuration of the three surfaces defining the 3-SKH model before each of the constant p' excursions. The dotted lines show the original configuration of the surfaces, with the solid lines representing the surfaces after a period of creep has been modelled. Figure 4(a) shows shear stiffness data for the four constant p'

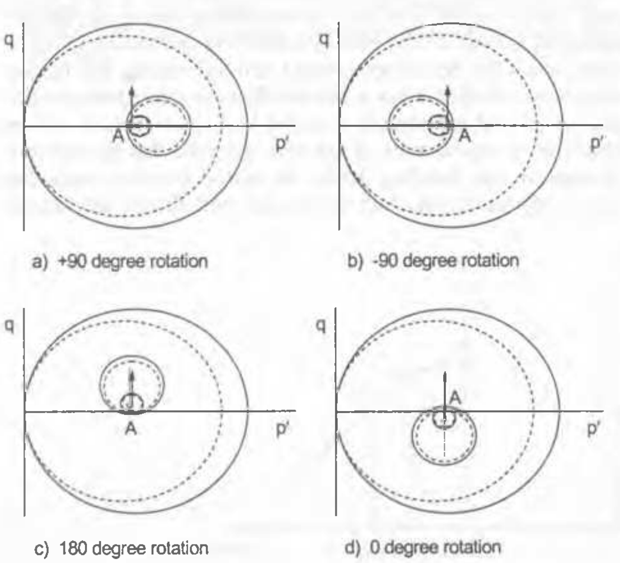

Figure 3. Diagram showing the configuration of the surfaces in the 3-SKH Model after different recent stress histories and volumetric creep.

paths after each of the four different recent stress histories with no creep allowed. The data are plotted as tangent shear stiffness against deviator stress, following Stallebrass (1990) and the predictions follow the pattern observed by Stallebrass. Figure 4(b) shows the same graph plotted for shearing following 1 year of creep. It can be seen that for all the stress paths except the 90° rotation the pattern of behaviour is very similar to the series of tests where there was no creep, but in all cases the initial stiffness is now equal to G'_{ec}, the elastic shear modulus computed by the model. For the 90° rotation tests the initial stiffness increases slightly as the value of G'_{ec} is dependent on R_0, but the decay of stiffness at stress changes less than c.30 kPa is more rapid. The slower decay in stiffness when there is no creep occurs because at the start of shearing the stress state lies on both the kinematic surfaces and these surfaces are configured such that they have to translate during shearing to become aligned with the new stress path direction. For the other recent stress histories, the graphs show that where creep has been allowed stiffnesses are greater both initially and throughout the stress range of the test. The consequences of this on the stress-strain response can be seen in Figure 5 where deviator stress against shear strain is plotted for loading following a 180° rotation. At q = 140 kPa the secant stiffness has increased by almost a factor of 3 after 1000 years of creep. Data for shearing following both the -90° and 0° stress histories show the same type of overall increase in stiffness. The stress-strain response changes less dramatically with creep following the 90° stress history. All paths show some increase in initial stiffness as expected, with the analyses allowing 1000 years of creep predicting initial stiffnesses around 2% higher than for the analyses allowing 1 year of creep The effect of recent stress history is still evident in the predicted stiffness curves where creep was allowed, and this is in agreement with the conclusions drawn by Richardson (1988) that the effects of time and recent stress history are additive.

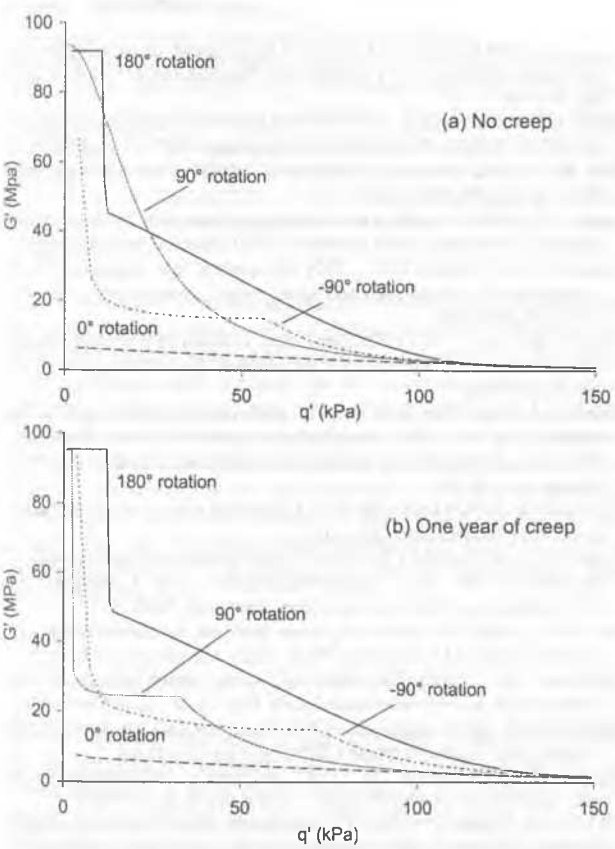

Figure 4. Stiffness curves for a constant p' shearing stage showing the effect of modelling recent stress history and creep.

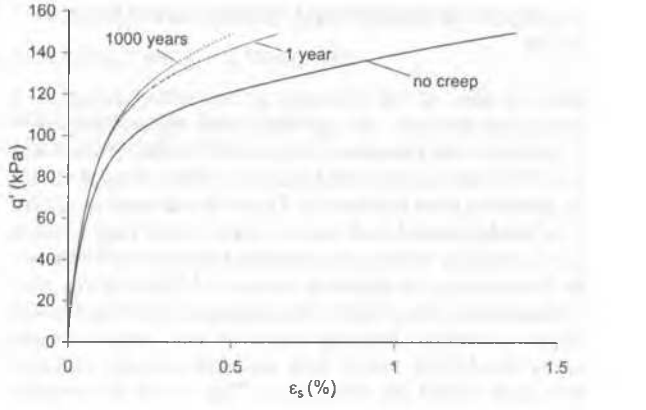

Figure 5. Stress-strain curves for constant p' shearing following 180° rotation, which show the effect of creep.

4.2 *Creep and undrained loading*

In the series 2 analyses the soil, which was modelled as London Clay was one dimensionally compressed to 400kPa, and swelled back to 200kPa, before being sheared undrained. Figure 6 shows the stiffness curves computed during the undrained shearing. The recent stress history for this loading path is approximately a 90° rotation and once again for the analysis where one thousand years of creep has been allowed before shearing, the initial elastic stiffness is higher and the rate of decay of stiffness at small strains is greater leading to lower stiffnesses over the strain range 0.005 - 0.1%. At larger strains the shear stiffness is higher for the analysis where creep was allowed. The slower decay in stiffness when there is no creep occurs for the same reason as described for the drained stress path with this recent stress history. This difference in the way the surfaces translate can also be seen in the shape of the stress paths in Figure 7. At small changes in stress, $\Delta q'$ less than 50 kPa, the shape of the paths, representing the anisotropy created by the recent stress history, varies significantly when there is no creep, but is approximately constant when creep has taken place.

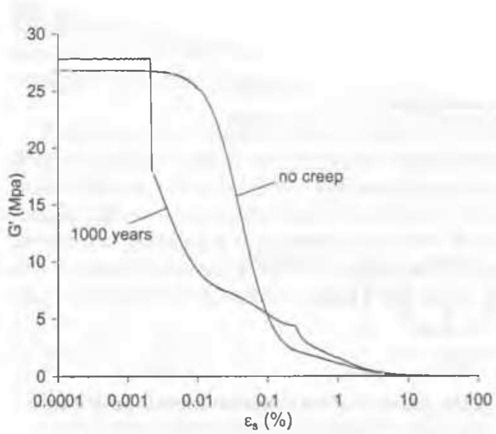

Figure 6. Variation in Secant stiffness during undrained shearing

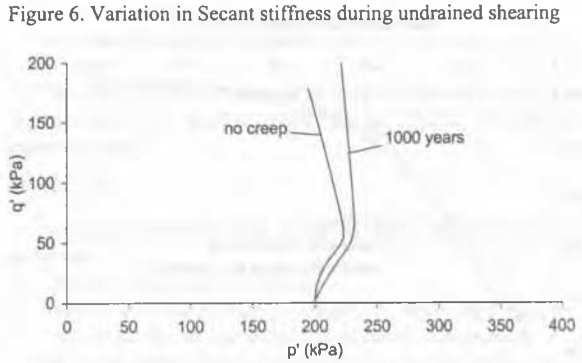

Figure 7. Variation in stress path during undrained shearing

5 INFLUENCE OF CREEP ON A BOUNDARY VALUE PROBLEM

To obtain an idea of the influence of modelling creep on a boundary value problem, the geometry and approximate geological history of the Heathrow Express trial tunnel (Deane and Bassett, 1995) were used as the basis for a finite element analysis. The geometry used is shown in Figure 9 and consists of five metres of made ground and terrace gravel overlying London clay. The geological history was simulated drained by first swelling the London clay to represent erosion of 200m of the clay layer. Subsequently, the effect of the redeposition of the Terrace Gravels was created by building a layer of sand elements modelled using the 3-SKH model with properties similar to those used by Grant (1998) for silica sand. This is not an accurate model of the behaviour of the gravel layer, however it does allow the clay to be reloaded by a layer of drained soil which at low stress levels has a non-linear stress-strain response. The tunnel crown is at a depth of 16m and for simplicity, no distinction was made between the three construction methods used for this tunnel. Excavation was simulated undrained by removing the tunnel elements, replacing them with nodal forces, and reducing these forces by an equal percentage until a volume loss of 1.5% was achieved at the clay/sand interface. Three finite element analyses were carried out, run 1 simulated the tunnel excavation with no creep, run 2 had a period of creep lasting half a million years, ahead of tunnel construction, and run 3 was the same as run 2 with the addition of one million years creep at the end of erosion of the London clay.

The behaviour predicted by the three different analyses is characterised by the surface settlement profiles in Figure 10, settlement profiles at the clay layer follow the same trend, and have not been presented. These settlement profiles are all for the same volume loss and show a narrowing of the trough and greater maximum settlement as the periods over which creep occurs increase. Nevertheless, the predicted change in trough width is small compared to that which would be required to obtain a Gaussian distribution of vertical settlement, which is usually assumed to represent field displacements (O'Reilly and New, 1982). For a tunnel of this depth the point of inflection of the curve, defining the trough width should be c.10m.

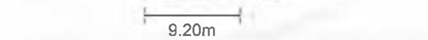

Figure 8. Sketch of the geometry of the Heathrow Express Trial Tunnel

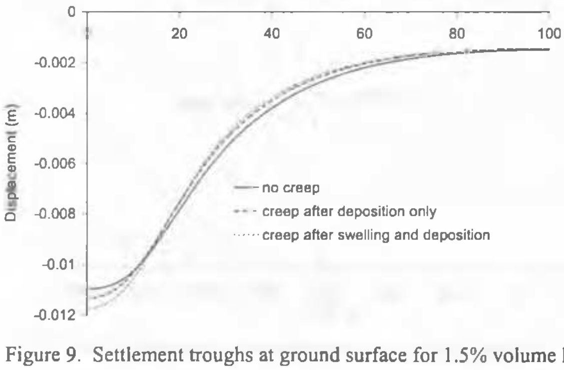

Figure 9. Settlement troughs at ground surface for 1.5% volume loss

6 CONCLUSION

The method used to incorporate simple volumetric creep into analyses carried out using the 3-SKH model enables this model to predict key parts of the expected behaviour. Where creep has been simulated, the model predicts an increase in initial stiffness, which is associated with an increase in apparent preconsolidation pressure. The model also predicts an overall increase in secant stiffness, which is largely independent of recent stress history. Thus the predicted effects of time and recent stress history could be considered additive, which is in agreement with the findings of Richardson (1988). It is difficult to evaluate the detailed features of the predictions made due to the scarcity of data for stiff clays. The inclusion of this simplified representation of volumetric creep has a noticeable but small effect on the predicted settlement profiles at the ground surface for the tunnel problem. It would seem from this preliminary study of the effects of modelling creep, that because the effect of recent stress history is largely unchanged, creep modelled in this way is unlikely to have a significant effect on distributions of movements.

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