Simulation of triaxial test data on Auckland residual soil using a bubble stress-strain model

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ABSTRACT

This paper presents an application of a bubble model (a non-linear multi-surface kinematic hardening soil model), implemented in the *FLAC* software, to simulate the stress-strain behaviour measured in an undrained triaxial compression of Auckland residual clay. The workings of the model are explained in a qualitative manner and the differences between this model and modified Cam clay model are explained. It is shown that the model represents the overall stress-strain behaviour of the soil well. The extent of the small strain elastic behaviour is controlled by the size of the bubble. The results show that the softening just beyond the bubble is too severe and that further work is needed to optimise the selection of values for plastic modulus part of the bubble model.

1 INTRODUCTION

Soil structure interaction modelling requires reliable data on the stiffness properties of the soil which interacts with a foundation. As a first stage in this modelling it is usually assumed that the soil behaves as a linear elastic material. Determination of a representative elastic modulus for the soils at a given site is not a simple task, particularly as the norm is for soil profiles to be layered, often in a complex fashion. Additionally, it is well known that the application of the elastic model to soil stress-strain behaviour is at best simply a convenient approximation. However, one attractive feature of the elastic idealisation is that there exist a large number of solutions to boundary value situations of geotechnical interest; a much-used collection of these is contained in the book by Poulos and Davis (1974). In this sense the elastic model is always a good starting point for considering how a foundation might react to applied loads, while the use of the elastic model is often justified because under serviceability limit state actions foundation response often appears to be linear.

However, it is well known that soil is not a linear elastic material. Consequently, any worthwhile understanding of soil stiffness and soil-structure interaction must account for the real stress–strain behaviour of the soil and represent the nonlinearities in both monotonic and cyclic loading. The quest for such an understanding was a major preoccupation of the geotechnical research community in the second half of the twentieth century; it continues today. Realistic representation of soil stress-strain behaviour carries with it two categories of overhead cost. First, there is additional complexity, things are no longer as simple as they are within the linear elastic framework. Second, values for more soil parameters are required. We indicated above that obtaining accurate values for soil elastic stiffness is not a trivial task; the provision of values for model parameters is even more demanding if we use a realistic soil stress-strain model.

One class of the soil stress-strain-strength models available are those developed within the framework of critical state soil mechanics. A good example is the modified Cam clay model (MCC), originally expounded by Roscoe and Burland (1968) and more recently by Wood (2004). This has been moderately successful at representing the behaviour of soft clays. The

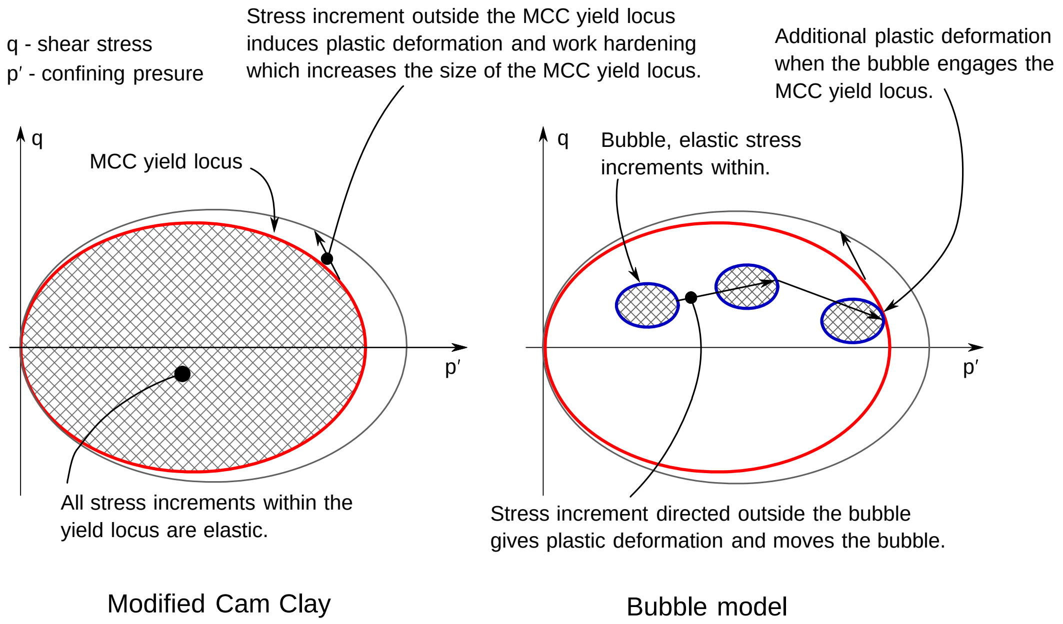

Figure 1: Diagrammatic comparison between the modified Cam clay model and the simplest version of the bubble model.

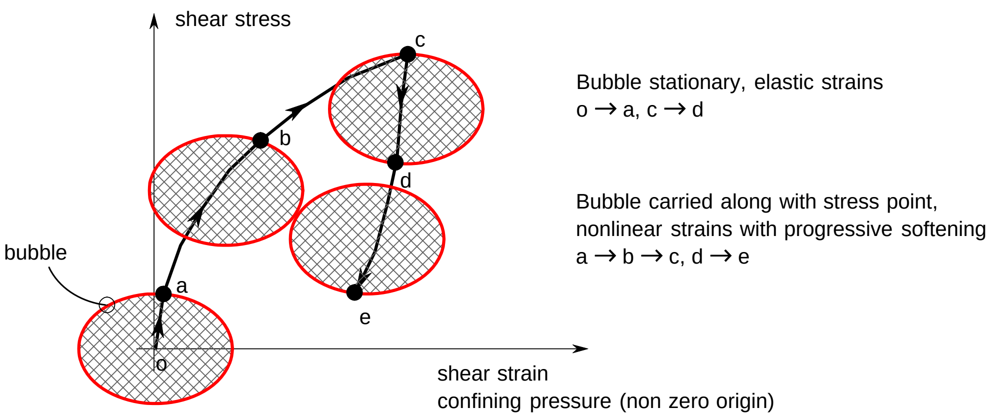

Figure 2: Diagrammatic illustration of how the bubble model represents the nonlinear strains generated during cyclic loading on stiff soil.

model is expressed within the framework of work hardening plasticity. The essence of the model is the existence of three distinct mathematical functions: (i) a yield locus (the boundary between elastic and plastic behaviour, within which the soil is considered to behave elastically – a sort-of generalisation of the preconsolidation concept), (ii) a function that gives the ratio between plastic shear and volumetric strain increments (this is required to handle dilatancy which is a characteristic of soil behaviour that cannot be handled using the elastic model), and (iii) a hardening function (which can be thought of as a function that describes the nonlinear behaviour of the soil modulus). Despite the elegance of the modified Cam clay model, it is severely limited when it comes to describing the stress-strain behaviour of very stiff soils, soils with structure (soils which exhibit sensitivity), and cyclic loading, Pender (1977, 1978 and 1982).

Despite this, the set of concepts embraced within the critical state framework are such that they have continued to inspire soil stress-strain-strength model development; recently steps have been taken to enhance the rigour of these models, for example Collins et al (2007).

One approach to modelling the behaviour of stiff soils is to use a bubble model, the idea of which was first proposed by Al-Tabbaa & Wood (1989). The concept of this, illustrated in the right hand side of Fig. 1, is that within the MCC yield locus elastic deformation is restricted to situations in which the stress state falls within the interior of a small "bubble" yield locus. When the stress state reaches the boundary of the bubble locus plastic deformations are generated and the bubble is carried along with the stress state, i.e. kinematic work hardening occurs. This means that when the stress state engages the boundary of the bubble yield locus there is a gradual decrease in the stiffness of the soil. Alternatively, if the stress state moves back into the interior of the bubble then the deformations revert to elastic. An important feature of the bubble model is the ability to handle cyclic loading within the MCC yield locus. When the shear stress is increasing, the stress state is on the surface of the bubble and the bubble is carried along with the current stress state. When the loading reverses, the stress state moves inside the bubble so that the strain increments become elastic and there is a sudden increase in the soil stiffness. The stress state then moves across the bubble, maintaining elastic behaviour whist inside the bubble, during which the bubble remains stationary. When the stress state engages the other side of the bubble, further nonlinear deformation occurs and the bubble starts to move again. These ideas are illustrated diagrammatically in Fig. 2. When the bubble engages the outer MCC yield locus an additional plastic deformation mechanism comes into play. The equations specifying the behaviour of the bubble model are quite complex, much more complex than those for the MCC model, which in turn are much more complex than the stress-strain equations of an elastic material.

The complexity of the equations means that only numerical solutions are possible, so that the model must be implemented within a finite element or finite difference framework. Ni (2006) implemented the model within the *FLAC* software. The primary purpose of this work was to develop a numerical procedure to handle cyclic loading for soil structure interaction calculations under earthquake excitation. The challenge here is numerical, to handle without the calculations becoming unstable, the sudden change in stiffness when the stress state moves from loading to unloading. In this paper, our objectives are rather more limited and we illustrate some of our experience in applying the model to the simulation of the monotonic loading behaviour of Auckland residual clay determined from laboratory testing on specimens cut from undisturbed block samples.

2 WHAT CAN THE BUBBLE MODEL DO?

The main features of soil behaviour that the bubble model can handle are:

- Nonlinear stress-strain behaviour within the MCC yield locus (Fig. 2),
- Cyclic loading, which is nonlinear because the shear stiffness in unloading is very different from that in loading (Fig. 2),
- Dilatant stress-strain behaviour (an aspect of soil behaviour that cannot be captured by the elastic model),
- Collapsing soil structure, i.e. sensitivity (this capability of the model is not discussed herein).

3 SELECTION OF SOIL PARAMETERS

Table 1 summarises the set of parameters and initial conditions required for the bubble model. The parameters are divided into three groups. First, the initial state of the soil, second the parameters needed for the modified Cam clay model, and third the additional parameters needed for the bubble model. The parameters for the MCC model can be obtained from standard laboratory tests. At present there is no standard way of obtaining the parameters for the bubble part of the model. Herein values for these parameters have been obtained by trial and error calculations. The parameters in Table 1 are for the version of the bubble model which applies to nonstructured soil. For soil with sensitivity, values for two additional parameters are required.

Table 1: Bubble model parameters and initial conditions

Initial state of the soil: void ratio, effective confining pressure, shear stress
Parameters for the modified Cam clay model: constant volume friction angle, compression index, swelling index, overconsolidation ratio, shear modulus, Poisson's ratio for the soil particle skeleton
Additional parameters for the bubble model: size of the bubble relative the MCC yield locus, two parameters which control the magnitude of the plastic strain increments associated with the bubble.

4 *FLAC* MODELLING

Triaxial tests on especially instrumented specimens were undertaken to measure the complete stress-strain curve for soil obtained as block samples from a site near where Hillcrest Road crosses the extension of SH1 in the hills behind Orewa. The specimen was 75 mm in diameter and 150 mm in height. The triaxial specimen was saturated and then consolidated to an effective consolidation pressure of 65 kPa under a shear stress of a few kPa. The elastic bulk modulus for stresses inside the bubble was set at 84 MPa, the elastic shear modulus was calculated from this using the Poisson's ratio value of 0.25. The small strain stress-strain behaviour of the specimen was measured with LVDT displacement transducers attached directly to the specimen within the triaxial cell, more details are given by Kikkawa et al (2008).

Having obtained stress-strain data for the specimen, the *FLAC 5.0* implementation of the bubble model was used to simulate the observed behaviour. A single axisymmetric element was subject to strain-controlled loading with an incremental displacement of 10^{-5} mm ($\approx 10^{-5}$ % axial strain) for each step. The use of such small displacement steps was to ensure that the small strain behaviour was captured, particularly for strain less than about 10^{-3} %.

Figure 3 shows the measured and simulated stress-strain responses up to a maximum axial strain of 10%. The response is broadly satisfactory, the main difference being the disparity at the larger strain behaviour where the model has zero hardening after axial strains of about 2.5% in contrast to the gradual increase in shear stress with increasing strain exhibited by the measured response. The plots in Fig. 3 suggest that the small strain behaviour is modelled reasonably well. Figure 4 shows the simulation and test results up to 1% axial strain. From this there appears to be a good match up to a shear stress of a few kPa, after which the modelled curve is too soft. However, the strains measured by the displacement transducer outside the triaxial are quite close to the simulated values (confirming that external measurement of displacement is not satisfactory for capturing small strain soil behaviour). This figure reveals that the fine detail of the stress-strain modelling at small strains does not live up to the expectation of Fig. 3.

Figure 5 replots the stress-strain curve in terms of secant modulus (the slope of the line between the start of the stress-strain curve and the current point) against the logarithm of the axial strain up to an axial strain of 1%. The secant modulus was calculated from the strains measured with the on-specimen LVDT displacement transducers. It is apparent that the simulated modulus is constant up to an axial strain of about 3×10^{-3} %, which corresponds with the actual behaviour of the specimen; the extent of this plateau is controlled by the size of the bubble. The size of the bubble was arrived at after some trial and error calculations. However, once the stress state moves beyond the bubble it is clear that the softening proceeds too rapidly. In other words, we

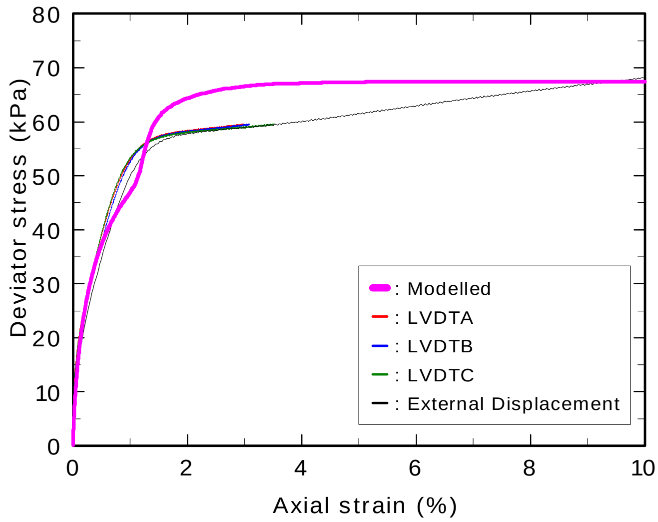

Figure 3: Measured and simulated stress-strain behaviour

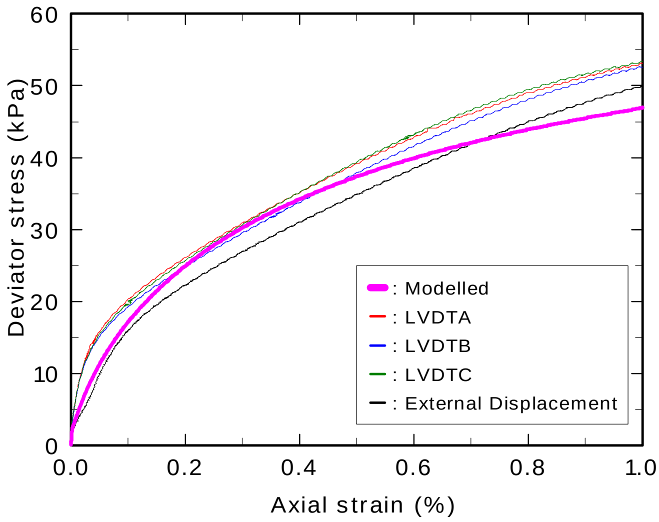

Figure 4: Measured and simulated stress-strain behaviour (small strain)

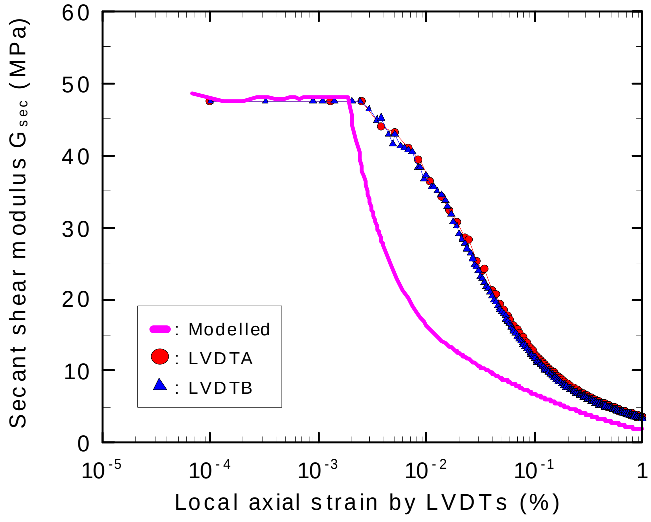

Figure 5: Secant shear modulus from measured and simulated stress-strain data

need to do further work on estimating values for the bubble parameters that control the plastic strains within the MCC yield locus.

In summary then, although Fig. 3 indicates a reasonable match between the measured and simulated stress-strain curves, a more detailed look at the small strain region shows that modelling this correctly is quite demanding. So identification of the small strain behaviour of soil is challenging not only for experimental measurement but also for numerical simulation.

5 CONCLUSIONS

We have reached the following conclusions:

- The paper illustrates the numerical implementation in *FLAC* of one approach to overcoming a long-standing limitation of the modified Cam clay model, namely the representation of inelastic strains within the MCC yield locus,
- Figure 3 shows that a reasonable match has been achieved between the overall measured and simulated axial strains,
- Figure 5 indicates that a bubble of appropriate size is able to represent the elastic region of the soil behaviour, but the calculated secant modulus degrades too rapidly once the bubble is engaged by the stress point,
- Clearly, more work is required to develop an effective way of processing soil test data to find parameter values for the inelastic part of the bubble model.

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