Recent advances in the numerical modelling of embankment dams

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SYNOPSIS. The main concern when designing or analysing embankment dams is usually their stability. However, assessing their deformation is also important. This paper describes the recent use of advanced numerical analysis to predict the latter. Examples of its use in assessing likely movements of six embankment dams constructed in the UK are provided. Various phases in dam life are considered: embankment construction, first reservoir impounding, subsequent reservoir operation and raising the crest level. The use of adequate constitutive laws and, in particular, the importance of modelling the plastic behaviour of embankment fills during loading, unloading and re-loading is clearly demonstrated.

INTRODUCTION

Embankment dams are complex geotechnical structures. The materials involved in their construction vary widely, involving foundations ranging from soft clays to hard rocks and fills ranging from compacted clays to rockfills. In the beginning their design and construction were largely empirical and based on past experience rather than on theory. With no intention of diminishing the important role of experience, the advances made in the theory of soil mechanics, together with the development of advanced numerical analyses in the last 40 years, have made it feasible to predict stresses, strains and displacements in dams during construction, first impounding and subsequent operation.

Many attempts have been made to predict the behaviour of embankment dams. The finite element (FE) method is a powerful tool for such predictions. A large number of FE analyses of actual dams have been reported in the literature and these have been extensively summarised by Duncan (1994).

The FE analysis of stresses and movements in embankment dams is an exceedingly complex problem. The techniques for modelling construction,

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first impounding and subsequent operation are covered in various publications (see e.g. Naylor, 1991). Many factors should be considered, such as construction in layers, the stiffness of the simulated layer, compaction stresses, etc. However, the most influential factor is the modelling of the stress-strain behaviour of the fill by an appropriate constitutive law (Duncan, 1992). A review of the different constitutive laws used in the numerical analysis of embankment dams can be found in various publications (see e.g. Potts & Zdravkovic, 2001). Both elastic and elasto-plastic formulations are available. The former are simpler to use, but the latter are far superior.

All FE analyses reported in this paper were carried out using the computer code ICFEP (Potts & Zdravkovic, 1999). The available space does not allow for a detailed description of the constitutive models used, laboratory testing performed and model parameters derived. However, references are provided wherever appropriate.

ROADFORD DAM

Roadford Dam in Devon is a homogeneous 41m high rockfill dam completed in 1990. Unusually conservative slopes were adopted for this dam (Figure 1) because the Carboniferous rockfill used in dam construction was prone to weathering. An important design feature of the dam was the presence of a less compressible sand-waste fill to reduce differential movements between the asphaltic membrane and the stiff concrete block at the upstream toe.

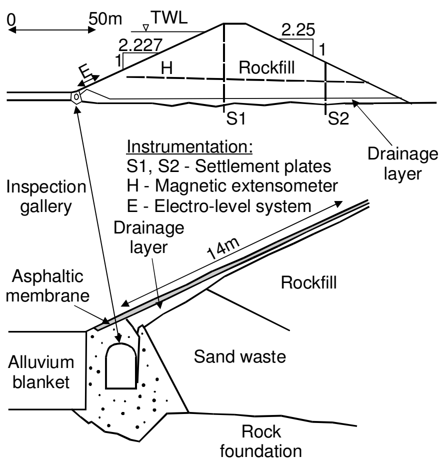


Figure 1. Cross-section of Roadford Dam.

The properties of the rockfill were measured in 250mm diameter triaxial and 1m diameter oedometer equipment by the British Research Establishment (BRE). Results of a suite of drained triaxial tests in compression at different confining stresses are shown in Figure 2. The fill was initially characterised by a relatively simple non-linear elastic perfectly plastic model of the Mohr-Coulomb (MC) type (Figure 2a). As a research exercise (Kovacevic *et al*, 1994), the rockfill behaviour was also predicted (Figures 2b and 2c) by using two more complex elasto-plastic models of the Lade's type (Lade, 1977; Lade & Kim, 1988), both of which account for the plastic behaviour before and after the peak strength of the rockfill is mobilised.

The measured settlements near the dam centre line and mid downstream slope during construction are presented in Figure 3. The magnitude of the

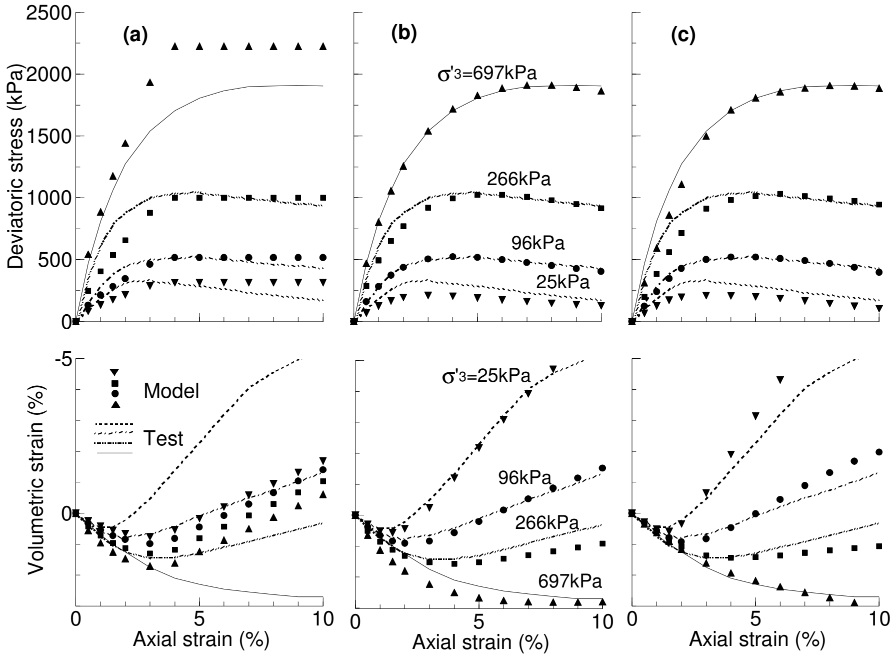


Figure 2. Predicted and measured behaviour in triaxial tests by (a) nonlinear elastic MC and (b) & (c) Lade's elasto-plastic models – Roadford Dam.

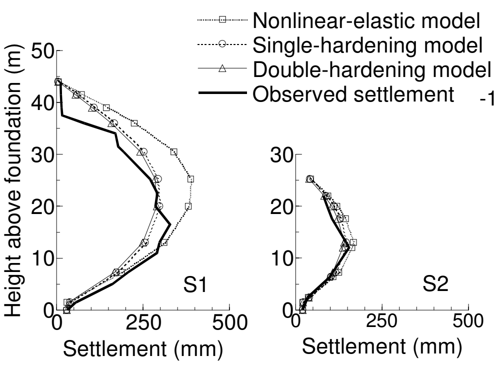


Figure 3. Predicted and observed settlements during construction - Roadford Dam.

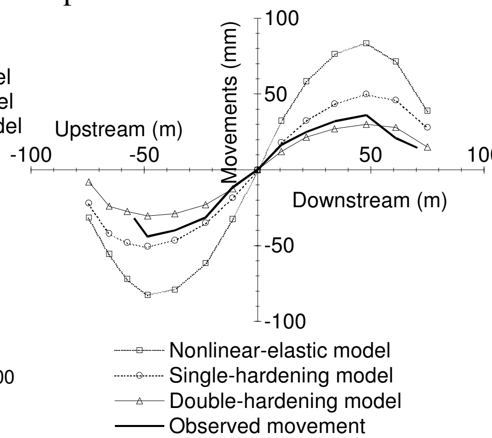


Figure 4. Predicted and observed lateral movements during construction - Roadford Dam.

predicted settlements is in reasonable agreement with the measurements. Whereas the non-linear elastic MC model overpredicted the settlements slightly, the Lade's elasto-plastic models underpredicted them.

The measured and predicted lateral movements along the extensometer H (see Figure 1) are shown in Figure 4. It can be seen that the non-linear elastic MC model overpredicted lateral movements by a factor of two. The prediction could have been improved but only by using soil parameters which no longer fitted the triaxial test results. However, both Lade's elasto-plastic models predicted the horizontal movements reasonably well, so the behaviour of the embankment was recovered from the available laboratory data. The likely cause for the difference between the above predictions is the ability of the Lade's models to account for the plastic strains pre-peak, which are qualitatively quite different from the elastic strains predicted by the non-linear elastic model.

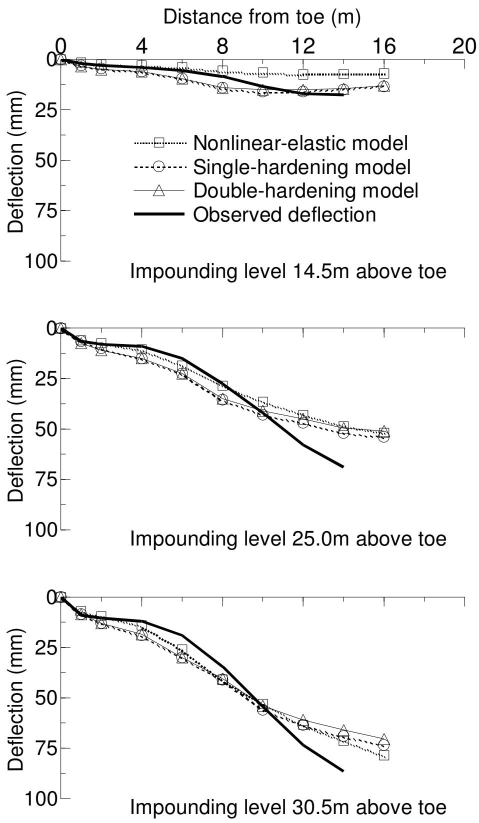


Figure 5. Predicted and observed deflections during first impounding - Roadford Dam.

Measured membrane deflections at three reservoir impounding levels are shown in Figure 5 where they are compared with the predictions given by the various models considered. There is no doubt that the FE analyses were useful in confirming the effectiveness of the sand-waste fill in reducing differential movements at the upstream toe of the dam.

WINSCAR DAM

A similar exercise has been carried out on the 53m high Winscar Dam (Kovacevic *et al*, 2002), which was the first dam in the UK to use an upstream asphaltic concrete membrane as the watertight element. Three horizontal plate gauges were installed in the 50m high section of the dam during construction at positions A, B and C as indicated in Figure 6.

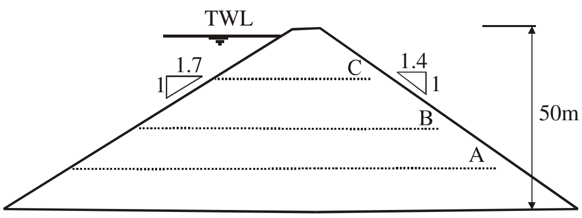


Figure 6. Cross-section of Winsacr Dam.

A comparison of the predicted and observed movements at the end of construction is shown in Figure 7. The first prediction was made by Penman & Charles (1985) using a 'simple' linear elastic FE analysis. The second prediction was obtained using the Lade's (1977) elasto-plastic model. The FE analyses using the two different constitutive models underestimated the dam movements during construction. This was particularly so at the higher dam elevations where the large observed settlements may well be due to creep in the sandstone rockfill (Penman & Charles, 1985)

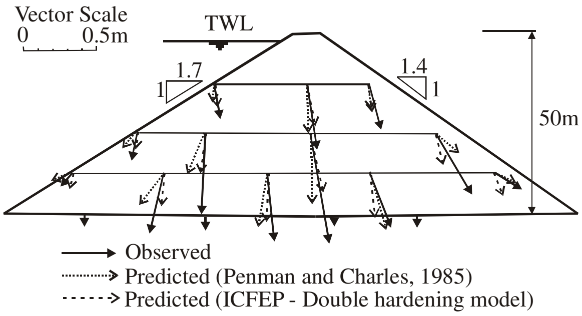
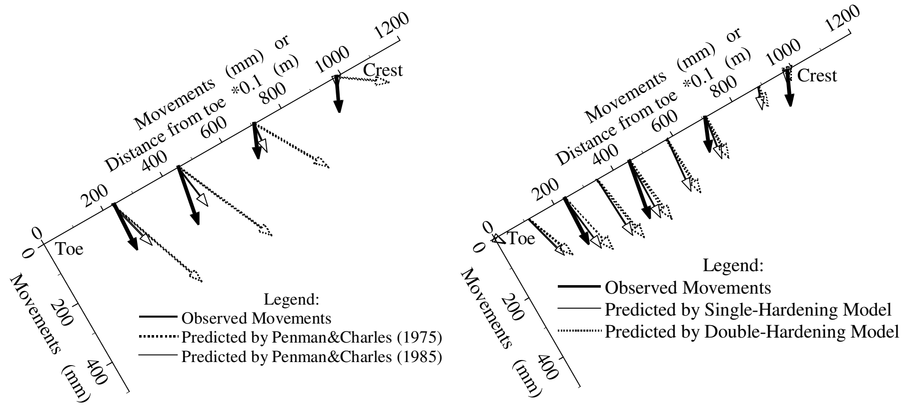


Figure 7. Comparison of predicted and observed movements during construction of Winscar Dam.

A comparison of the predicted and observed deflections of the upstream membrane during reservoir impounding is shown in Figure 8. Predictions presented in Figure 8a were made by Penman & Charles (1985). Initially, they significantly over predicted the membrane movements. Subsequently, they modified the model parameters in their analysis to simulate the stress changes during reservoir impounding more closely and, as a result, smaller and more realistic membrane movements were obtained. However, the 'new' parameters could



a) predictions by Penman & Charles (1975, 1985)

b) predictions by ICFEP using Lade's elasto-plastic models

Figure 8. Predicted and observed movements of upstream membrane during reservoir impounding of Winscar Dam.

not recover the observed movements during dam construction any longer. No such 'problems' were encountered in the ICFEP analysis using the Lade's elasto plastic constitutive models (Figure 8b) which were able to predict reasonably well dam movements during both construction and reservoir impounding without adjusting the input parameters derived from available laboratory tests.

OLD EMBANKMENT DAMS

There are a large number of embankment dams with narrow central cores of puddle clay which have been built in the U.K. since the early 19th century. Detailed inspections of these dams have shown that they developed significant crest settlements during operation. These settlements could not be accounted for by 'standard' creep theories. The BRE undertook a detailed programme of field observation of their behaviour under operational cycles of reservoir drawdown and impounding (Tedd *et al*, 1997). It was concluded that the dams upstream fill was subject to substantial increases and decreases of effective stress and that the strains due to drawdown were not fully recovered during re-impounding resulting in permanent deformation, predominantly settlements.

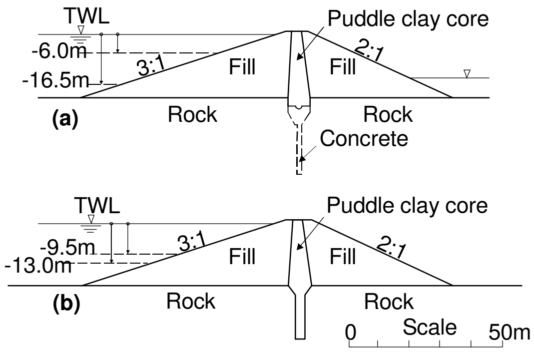


Figure 9. Cross-sections of (a) Ramsden and (b) Walshaw Dean Lower Dam.

To gain further insight into the mechanism of their behaviour during operational cycles of drawdown and re-impounding, several old dams were analysed by the FE method of analyses at Imperial College (Kovacevic *et al*, 1997). Results are now presented for two puddle clay core dams, whose sections are presented in Figure 9.

Ramsden Dam

The 25 high Ramsden Dam has a central puddle clay core and a concrete filled cut-off trench. It was analysed using one of the Lade's elasto plastic models (Lade & Kim, 1988), given its success in reproducing the rockfill behaviour both during dam construction and first reservoir impounding. The laboratory test data on the various materials involved were provided by Horton (1992). The results of cyclic loading in an oedometer test on the dam shoulder fill are presented in Figure 10a. In order to account for the observed permanent deformation after each operational cycle of draw-down and re-impounding, the non-linear elastic moduli in the Lade's model during unloading were made to be stiffer than during re-loading (Figure 10b).

The predictions were in reasonable agreement with observations during two reservoir draw-downs, particularly the smaller second one (Figure 11). However, the analysis showed that there was a tendency for the predicted permanent displacements to be towards upstream, rather than downstream as the observations suggest. It was suspected that a part of the problem was in the inability of the Lades's elasto plastic models to account for the hysteretic behaviour during unloading/ re-loading cycles. Models accounting for the observed hysteretic behaviour exist, and the ‘bubble’ model due to Al-Tabbaa & Wood (1989) successfully predict the observed fill behaviour in the oedometer test as shown in Figure 10c.

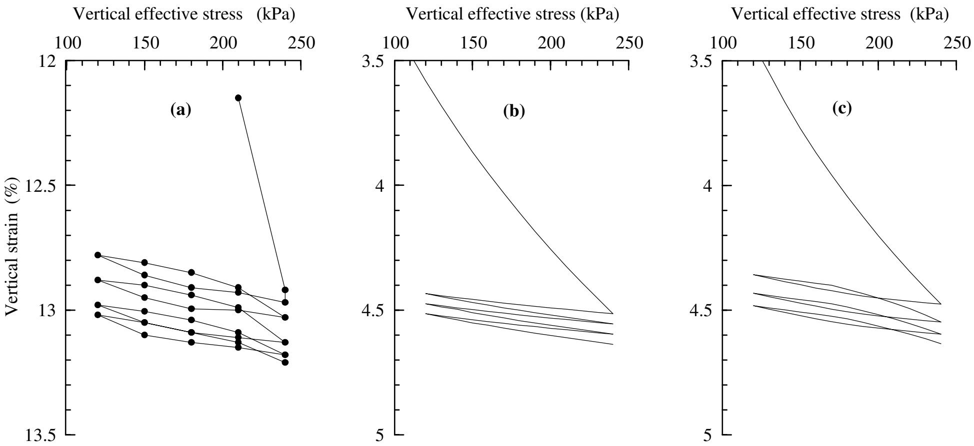


Figure 10. Behaviour of shoulder fill during cyclic loading in oedometer test: (a) observed and predicted by (b) Lade’s and (c) ‘bubble’ model.

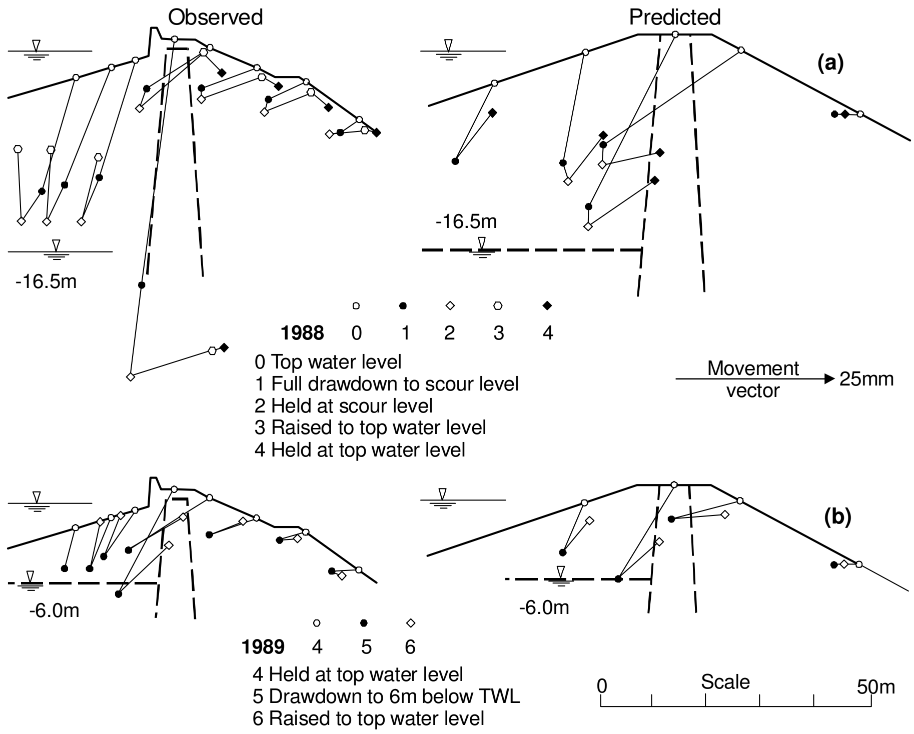


Figure 11. Observed and predicted behaviour of Ramsden Dam during (a) 1988 and (b) 1989 drawdowns – Lade’s (1988) model.

Walshaw Dean Lower Dam

Walshaw Dean Lower Dam is the lowest in a chain of three dams completed in West Yorkshire at the turn of the last century. It has a maximum height of 22mm, free draining rockfill shells, a narrow central puddle clay core and a 20m deep puddle clay filled cut-off trench (see Figure 9b).

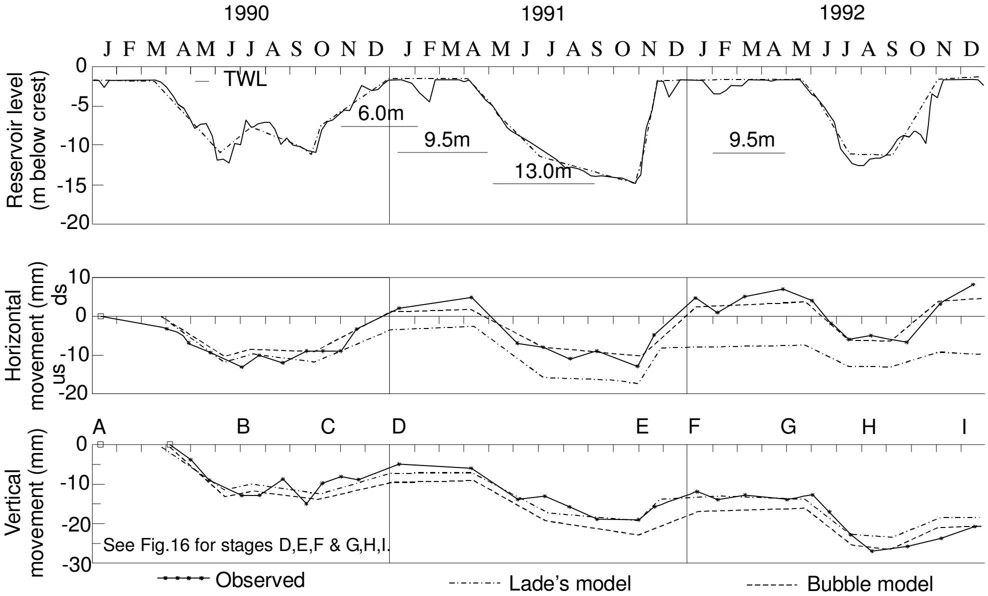


Figure 12. Observed and predicted displacements of the crest during three drawdowns – Walshaw Dean Lower Dam.

The dam was analysed using both Lade's (1988) and 'bubble' models. The measured horizontal and vertical displacements at the dam crest are compared with those predicted by the two models in Figure 12. It can be seen that while the settlements were reasonable predicted by both models, only the 'bubble' model successfully predicted the observed movements downstream. Thus, it appears that an overall downstream movement of the dam crest is a result of the plastic behaviour during unloading/ re-loading loops which the Lade's model cannot account for.

LADYBOWER DAM

FE analyses have been utilised more recently in the design and reconstruction of Ladybower Dam (Vaughan *et al*, 2000). This is a 43m high dam built in Derbyshire during the Second World War. It is one of the last puddle clay core dams constructed in Britain and certainly it is the highest one. The dam settled significantly, at least 1.5m to date. The narrow crest was raised on three occasions to maintain freeboard, steepening further the already steep downstream upper slope. The apparent increase in settlement rate due to rigorous reservoir operation in the last 20 years meant that the freeboard would have become inadequate to meet modern flood safety requirements. Studies showed that the best solution was to raise the dam again by constructing new fill on the downstream shoulder (Figure 13).

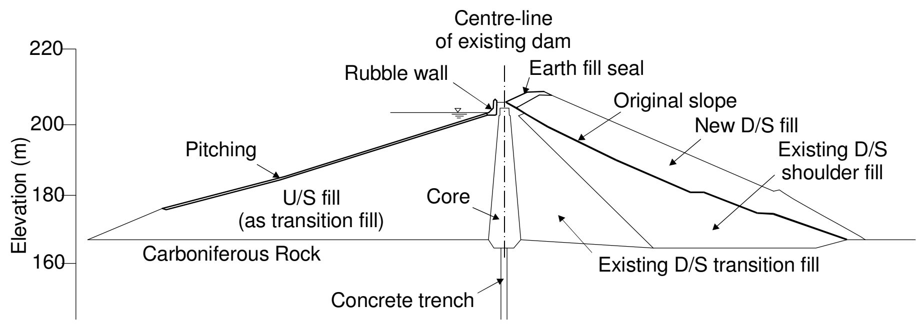


Figure 13. Typical cross-section of old and reconstructed Ladybower Dam.

Before doing so, it was decided to analyse the Ladybower dam using the same procedures as used before for the BRE study. Both the original dam and its raising were analysed. This provided an independent check on the cause of settlement for the original section, verified the stability of the reconstruction, and enabled a settlement prediction to be made for the modified section. However, it also provided predictions of the movements of the existing dam as the new downstream fill was placed, for comparison with observations.

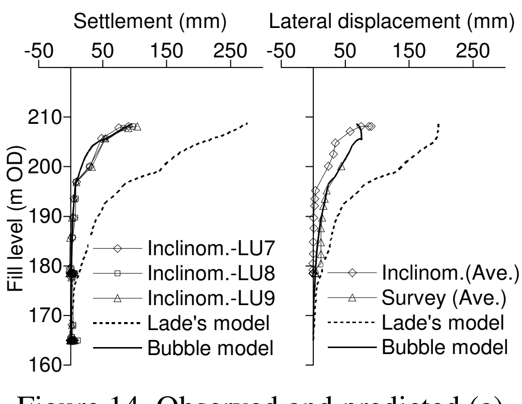


Figure 14. Observed and predicted (a) settlements and (b) lateral displacements at 'old' dam centerline - Reconstructed Ladybower Dam.

Observed settlements and lateral displacements along the axis of the original dam are plotted against the level (height) of the new fill in Figure 14. The observed movements only started to develop after 30m of fill had been placed. However, rather unexpectedly, the axis of the original dam moved down-stream, being dragged down by the new fill. The 'before-the-event' prediction using one of the Lade's models over predicted the observed movements by a factor of 3. The 'after-the-event' prediction by the 'bubble' model was quite reasonable (Vaughan *et al*, 2004). Although this was a surprising result, bearing in mind that the parameters for both models were derived using the same available laboratory tests, it proved that the 'bubble' model can be successfully used in characterising the behaviour of dams during various phases of their life, such as construction, first reservoir filling, operational cycles of draw-dawn and re-impounding and also crest raising.

TRIAL BANK AT EMPINGHAM DAM

The examples of FE analyses of embankment dams presented so far involved the modelling of free draining rockfill materials (with the exception of the puddle clays in the case of the old dams). Thus, it was decided to test the capabilities of the ‘bubble’ model in characterizing the behaviour of modern, compacted clay fills (and even of in-situ clays in a dams’ foundation) which, because of their low permeability, behave largely in an undrained manner, at least during dam construction.

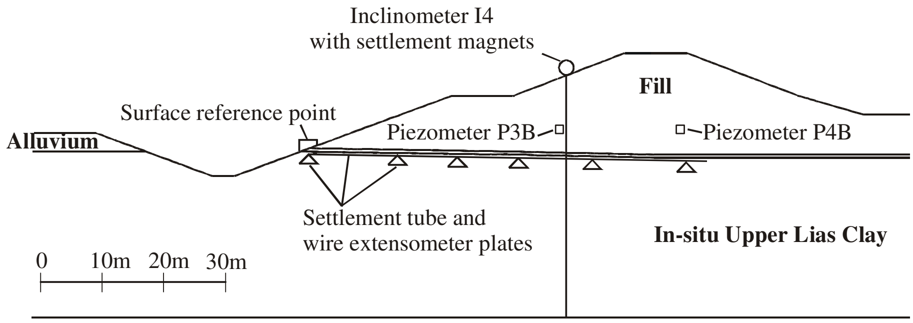


Figure 15. Section of trial bank analysed with installed instrumentation.

The 20m high instrumented trial bank (Figure 15) was built inside the footprint of Empingham Dam to examine and prove the strength of the stiff plastic Upper Lias clay (ULC) in the dam foundation (Bridle *et al*, 1990). The FE analyses using the ‘bubble’ model to characterise the behaviour of both the in-situ ULC and the fill derived from it were reported by Kovacevic *et al* (2007).

The model parameters for the ULC in the foundation were estimated from slow undrained triaxial tests on 260mm diameter samples. The results of two such tests involving post-peak unload/ re-load loops are shown in Figure 16 where they are compared with predictions from the ‘bubble’ model. The model cannot allow for strain-softening due to dislocation, shear surface formation and particle orientation at large strains; however, it accounts for pre- and post-peak plasticity, and the observed non-linearity of the stress-strain response during initial loading and subsequent unloading/ re-loading is predicted reasonably well.

The results obtained during undrained triaxial compression tests on the 100mm diameter field compacted samples of the ULC are shown in Figure 17, where they are compared with the predictions from the ‘bubble’ model. The matching of the observed behaviour is reasonable. In particular, the compressibility of the pore fluid was introduced in the model resulting in a realistic pore water pressure response and agreement with the volumetric strain changes observed in the laboratory tests.

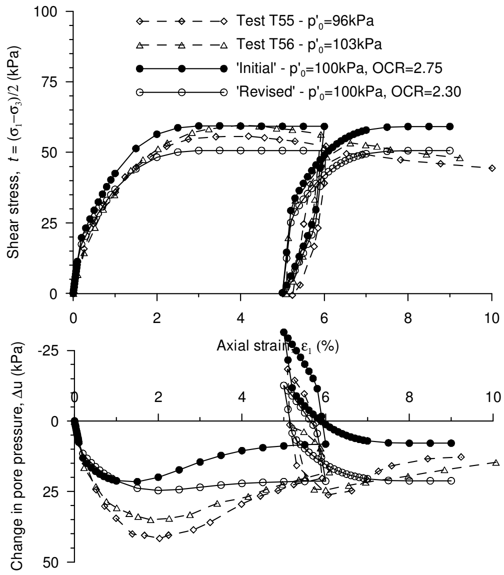


Figure 16. Observed and predicted behaviour of the in-situ ULC in undrained triaxial compression test.

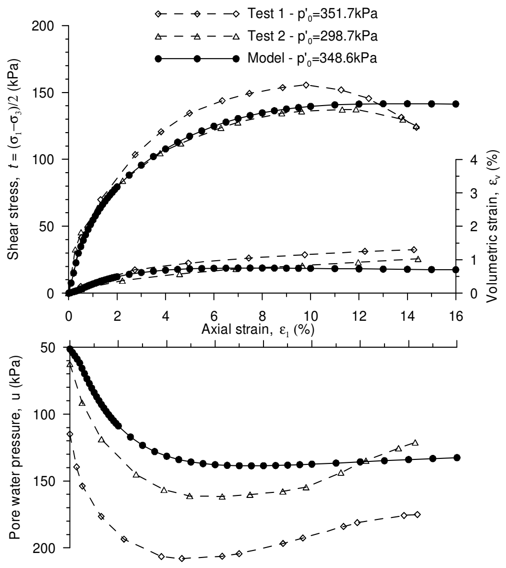


Figure 17. Observed and predicted behaviour of the ULC fill in undrained triaxial compression test.

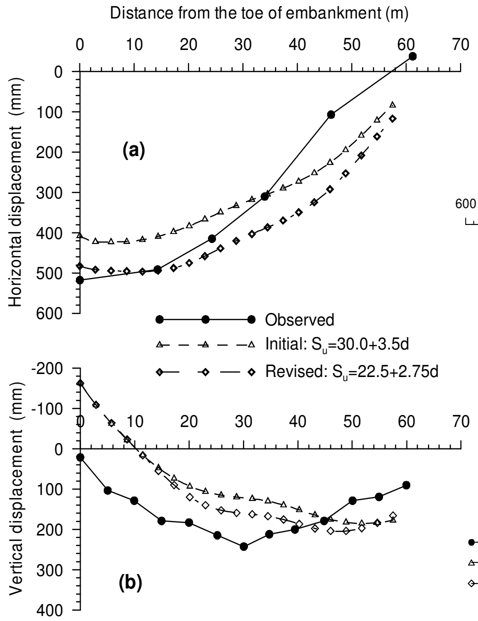


Figure 18. Observed and predicted (a) horizontal and (b) vertical displacements along the top of foundation.

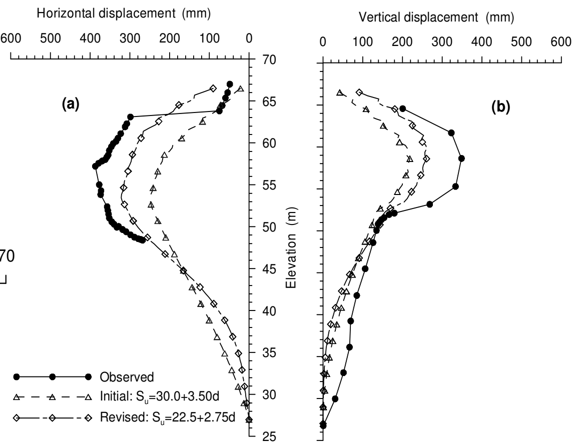


Figure 19. Measured and predicted (a) horizontal and (b) vertical deformations at the end of construction - Inclinometer I4.

The horizontal and vertical displacements at the top of the foundation (along the extensometer and settlement tube in Figure 15) upon completion of the trial bank are shown in Figures 18a and 18b respectively. The horizontal and vertical displacements measured by inclinometer I4 with the corresponding settlement magnets (see Figure 15) are presented in Figures 19a and 19b for the same stage of the analysis. Although the 'revised' analysis, which modelled a lower initial undrained shear strength (S_u) profile of the ULC in the foundation, gave better predictions of the observed trial bank behaviour, the 'bubble' model proved to be successful in characterising the behaviour of the ULC in both the foundation and the fill derived from it.

CONCLUSION

Embankment dams are important geotechnical structures which have often been analysed using advanced numerical analyses. However, to obtain predictions of deformation which agree well with those observed in the field, it is necessary to characterise the behaviour of the various fill (and foundation) materials using advanced constitutive models based on elasto-plastic theory. It has been shown that such models with their parameters derived from the available laboratory test data are capable of reproducing the full range of the observed behaviour of six embankment dams constructed in the UK.

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