Dounias, G. T., Potts, D. M. and Vaughan, P. R. (1998). *Géotechnique* **48**, No. 2, 299–300

DISCUSSION

Analysis of progressive failure and cracking in old British dams

G. T. DOUNIAS, D. M. POTTS and P. R. VAUGHAN (1996). *Géotechnique* **46**, No. 4, 621–640.

D. J. Naylor, *University of Wales, Swansea*

The paper addresses the challenging problem of modelling the complex stress changes that will have occurred in old British dams. Certain conclusions are drawn about the vulnerability of these dams to cracking due to hydraulic fracture. Collapse settlement will have been a significant factor here, but it appears not to have been included in the modelling.

The 'traditional dam' used as a basis for the studies had shoulders described as consisting of 'loose dumped Carboniferous mudstone'. In the case of the Dale Dyke dam, the material in the lower half of the shoulders is described as 'shale' and that in the upper half as 'rubble stone and shale'. Clearly, on account of both the poor quality of the rock fill and its lack of compaction, there would have been significant collapse settlement in the upstream shoulder of such a dam on first impounding, and perhaps later (except for the Dale Dyke dam where there was no 'later') in the downstream shoulder due to rain percolation.

The writer has been involved in the modelling of collapse settlement using finite element techniques, and is aware that this can be beneficial. In the case of central clay core dams it can reduce the arching from core to shoulders described in the paper. This would counter the stress reduction in the core at the end of impounding due to the arching, thereby making it safer against hydraulic fracture, at least in the medium term. The Beliche dam in Southern Portugal was designed to take advantage of this by the use of light compaction and relatively poor quality rockfill in the shoulders adjacent to the central core (Naylor *et al*., 1997). There is, however, the possibility in soft clay core dams that collapse settlement in the shoulders *before* significant consolidation of the core has occurred may result in a temporary reduction in the factor of safety due to reverse arching (i.e. from the shoulders to the core). Cox (1995) and Naylor (1989) have suggested that a mechanism on these lines may have been a contributory factor in the Carsington dam failure.

Had collapse settlement been included in the analyses it seems likely that σ_3 in the clay core at the end of impounding would have been higher than obtained in the paper. What the effect would have been after a few drawdown cycles is not clear to the writer. The authors' findings (Fig. 15 in particular) indicate that the effect of a number of drawdown cycles is beneficial in that σ_3 slightly increases. The question then arises of whether this reassuring finding would be reversed had collapse settlement been included in the modelling. In other words: Would repeated drawdown–impounding cycles undo the beneficial effect of the collapse settlement during the first impounding? Perhaps the authors could comment on this and on the general issue of the role of collapse settlement in such analyses.

Authors' reply

The mechanism of collapse in embankment fills is an awkward one to model numerically as it does not operate according to the principle of effective stress in a continuum. Collapse when a fill wets occurs because the lumps of which it consists weaken. While the volume of the individual lumps may increase as they swell, the deformation at the contacts between lumps can give a net contraction of the whole mass of fill. The lumps can weaken through mineralogical effects, as in hard crystalline rock, or by effective stress effects in lumps of stiff clay and weak rock. If a fill is placed dry, loaded, and then wetted followed by collapse, the total strain is roughly the same as it would have been if the fill has been placed 'wet' under the same load at the same dry unit weight. Thus collapse affects the sequence of movement rather than the total movement.

The authors did not model collapse in the analyses presented in the paper. They doubt if collapse was a major influence on the behaviour of old British dams built in wet upland areas. Even with small dams, fills were built relatively slowly, typically at, say, 1·5 m/month. Under British conditions of low evaporation, the weather would add water at a rate sufficient to give an increase in water content of about 3%. The materials used would have been dug slowly from shallow depths and would not have had a water deficiency when placed. However, collapse has been noticed recently in modern compacted fill from mudrock placed rapidly without watering in dry summer weather, at both the original Carsington dam (Skempton & Vaughan, 1995) and at the Roadford dam (Vaughan, 1994). Thus it is of interest to consider the possible effects of such a collapse if it were to occur.

If such collapse did occur, it would cause yield and settlement of the fill. Maswoswe *et al*. (1992) have reported stress paths measured in a K_0 stress path triaxial cell during the collapse of a loose lumpy clay fill at constant major principal total stress. The minor principal stress increased. In a dam, collapse would occur at near-constant stress, and volumetric contraction and shear yield should occur. The inclusion of collapse in the modelling would give less shoulder settlement during construction, with more arching, and more settlement after construction and during impounding with less arching or even negative arching. The effect on stress changes and cracking of the two stages would tend to cancel. Thus the authors would not expect much difference in the predictions of cracking if collapse had been modelled, provided that the total strains after collapse were the same as those obtained using their model without collapse. However, resolution of the question requires the use of more sophisticated models that include collapse of the kind developed by Naylor.

The difference assumed between the stiffness of the shoulders and the core probably has more influence on cracking than does collapse. The difference assumed in the paper ($\times 2.67$) may well be less than actually existed. Tests by Holton (1992) suggest this. Arching may thus have been underestimated.

REFERENCES

Cox, D. W. (1995). The failure of Carsington Dam. Discussion. *Géotechnique* **45**, No. 4, 721–724.

Holton, J. R. (1992). In-service deformations of a puddle clay core dam. Dams & reservoirs. *J. Br. Dams Soc*. **2**, No. 1, 12–18.

Maswoswe, J., Burland, J. B. & Vaughan, P. R. (1992). Stress path method of predicting compacted soil collapse. *Proc. 7th. Int. Conf. Expansive Soils, Dallas*, **1**, 61–68.

Naylor, D. J. (1989). Discussion. *Clay barriers for embankment dams*, pp. 169–171, London: Thomas Telford.

Naylor, D. J., Maranha das Neves, J. R. & Veiga Pinto, A. A. (1997). A back analysis of Beliche Dam. *Géotechnique*. **47**, No. 2, 221 –233.

Skempton, A. W. & Vaughan, P. R. (1995). The failure of Carsington Dam. Reply to discussion. *Géotechnique* **43**, No. 1, 151–173; **45**, No. 4, 719–740.

Vaughan, P. R. (1994). Criteria for the use of weak and weathered rock for embankment fill, and its compaction control. *Proc. 13th Int. Conf. Soil. Mech. Foundn Engng, Delhi*, **6**, 195–206.