Geo-Resilience 2023 Conference, Cardiff, Wales
D.G. Toll & M.G. Winter (Eds)
British Geotechnical Association, London. 2024
https://doi.org/10.53243/Geo-Resilience-2023-2-5

Resilience of Old British Embankment Dams

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Abstract

Many embankment dams with central puddle clay cores have been built in Great Britain 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. A frequently observed increase in settlement rate indicated a possible decrease in their stability. However, the various studies clearly showed that the dams' upstream fill was subject to substantial changes in effective stress and that the strains due to drawdown were not fully recovered during re-impounding resulting in permanent deformation, predominantly settlements. These settlements often meant that the dam freeboard would have become inadequate to meet modern flood safety requirements, and the common solution was dam raising by constructing new fill on the downstream shoulder thereby extending the operational life of the structures and potentially increasing capacity. This paper describes finite element analyses undertaken to gain a further insight into the mechanisms of behaviour during long-term operation and subsequent raising of these dams which turned out to be very resilient earth-fill structures. This work also has implications on the current thoughts related to operation and raising of flood embankments in response to climate changes.

Keywords: Dams, Safety, Deformations, Stability, Analysis

1. Introduction

There are many embankment dams with narrow central cores of puddle clay which have been built in the U.K. since the early 19th century. Often there is little information about how they were built, and their continuing safety is a matter of concern. Detailed inspections of these dams have shown that they developed significant crest settlements during operation. To ensure the safe long-term operation of these structures or to restore the capacity of a reservoir, a solution is to raise the crest of these dams usually by adding 'new' fill on the downstream slope; under some circumstances this approach might also be used to increase the reservoir's capacity.

These settlements could not be accounted for by 'standard' creep theories. The Building Research Establishment 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. Irrecoverable settlements more than 50mm were often reported, although the dams are old and have been subject to repeated drawdown.

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 Finite Element (FE) method of analyses at Imperial College (Kovacevic *et al*, 1997) using the numerical code ICFEP. The main purpose of the analyses was to examine dams' behaviour during the reservoir operation and establish whether the observed movements could be recovered, and their implications for long term stability. A simplified construction history was simulated, involving construction in layers, full consolidation of the core, impounding and the establishment of steady seepage, prior to impositions of the drawdown and re-impounding cycles, and in one case crest raising, described subsequently. No attempt was made to reproduce the historic operational history of the reservoirs.

The fills of these old dams were often placed in relatively thick layers with very limited compaction. Sources of fill were often variable. No records of fill placement were kept. It was not possible to investigate the fill used in the embankment shoulders in detail, and the properties had to be estimated. Old puddle cores were constructed with care, and, of necessity, they were placed at a consistent undrained strength. Some test data were available from drilling, and more specific soil properties could be adopted.

Given that the purpose of the FE analyses was to examine the behaviour during operational cycles of drawdown and impounding, the unload-reload properties, which dominate predictions during reservoir operation, were of particular importance. Figures 1 and 2 show the results of measured (Holton, 1992) and predicted response during cyclic oedometer tests on both puddle clay and typical shoulder fill. Matching of the observed permanent volumetric strains after each cycle of unloading and reloading by the adopted advanced elasto-plastic constitutive models (Kovacevic *et al*, 2011) is quite good, although the first (thereafter 'non-hysteretic') model was not able to capture typically observed hysteretic behaviour (see Figures 1(b) and 2(b)).

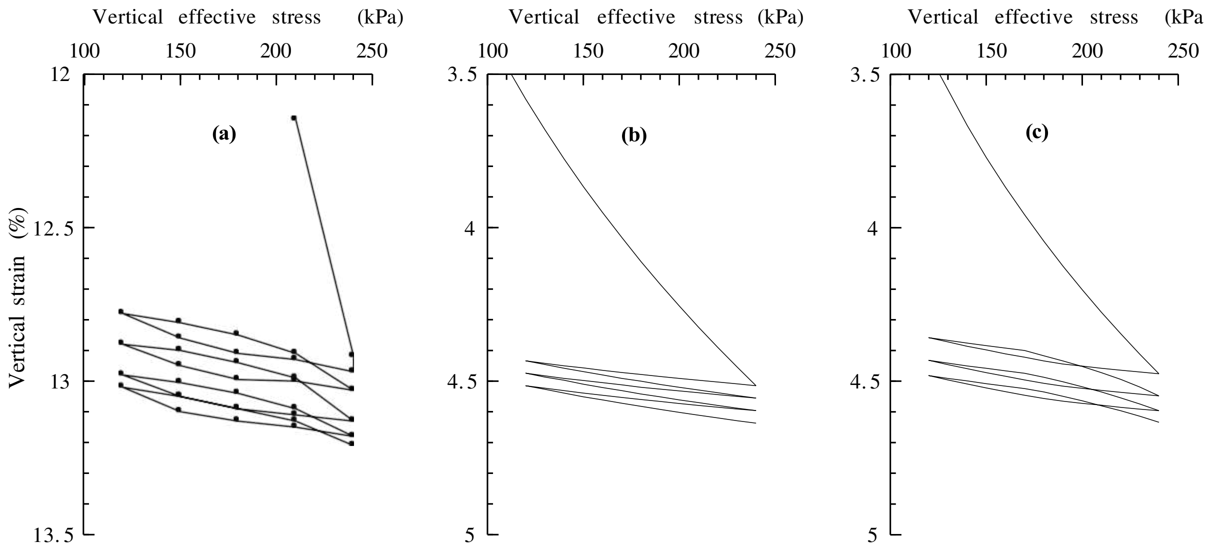

Figure 1: Behaviour of puddle clay during cyclic loading in oedometer test: (a) observed and predicted (b) without hysteretic and (c) with hysteretic behaviour.

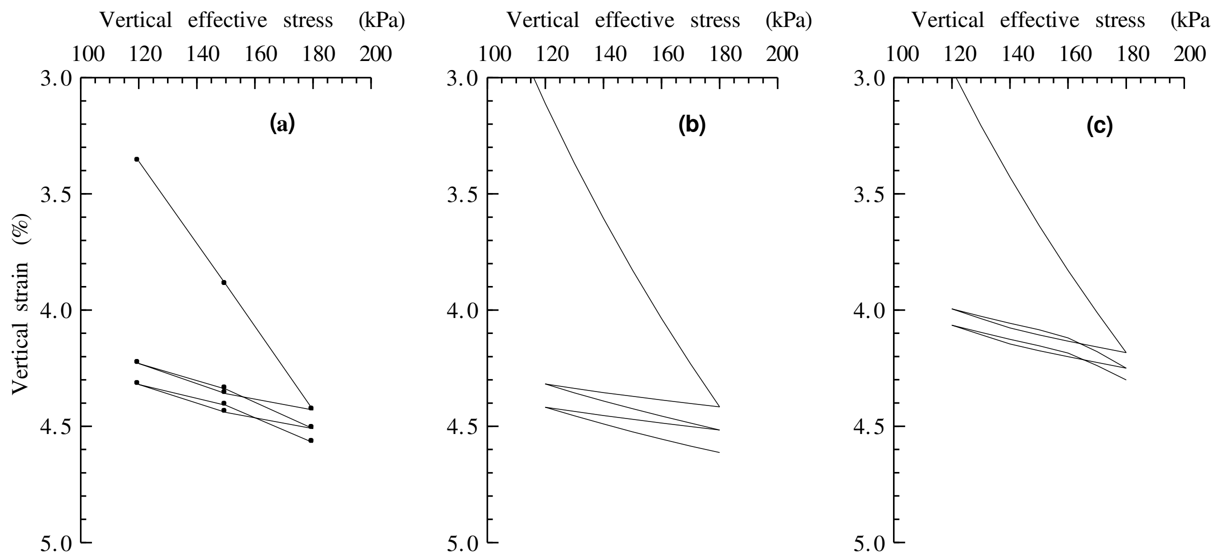

Figure 2: Behaviour of shoulder fill during cyclic loading in oedometer test: a) observed and predicted (b) without hysteretic and (c) with hysteretic behaviour.

The behaviour of three puddle clay core dams is now presented.

2. Ramsden Dams' behaviour

2.1 Ramsden Dam

Ramsden Dam in Figure 3, has a central puddle clay core and concrete filled cut of trench. The embankment shoulders are free draining. It was built between 1879 and 1883. Precise surveying showed that, between 1977 and 1985, the embankment was settling at an average rate of 8mm/year and moving downstream at 3mm/year. The crest had been reconstructed twice prior to 1988, when the reservoir was emptied. It was drawdown again by 6m in 1989.

The observations and predictions (using the 'non-hysteretic' model) of crest movements and settlement in the core over this period are shown in Figure 3. The analysis shows that the large and irrecoverable deformations observed can be reproduced by the numerical analysis assuming soil parameters which are consistent with the actual materials (Figures 2 and 3). The FE analysis shows that the average local safety factor (the ratio of strength mobilised to strength available at the current stress level) at the end of major drawdown is about 1.8. Thus, large irrecoverably deformations occur despite a substantial factor of safety against overall slope failure, and such large movements do not necessarily indicate incipient instability.

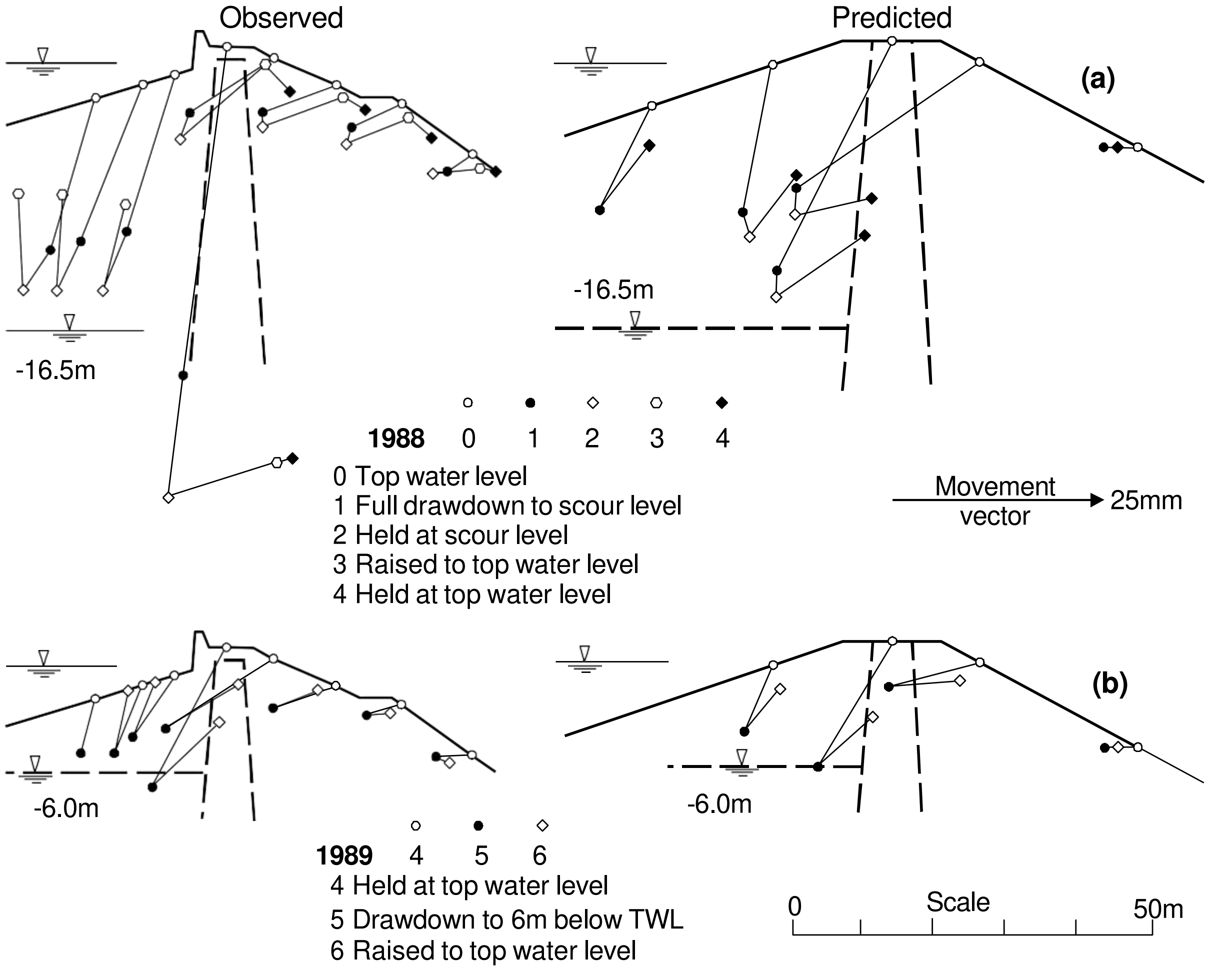

Figure 3: Observed and predicted behaviour of Ramsden Dam during (a) 1988 and (b) 1989 drawdowns.

It should be noted that the irrecoverable movements arise through the difference in elastic properties in unloading and reloading, not through plastic strain (see Figures 1(b) and 2(b)). As such, irrecoverable strains are even predicted for the second smaller drawdown. However, there is an important difference between the deformations predicted by the analysis and those observed. Whereas the analysis predicts an irrecoverable deformation towards upstream of the whole embankment crest due to a drawdown cycle, the observations show irrecoverable spreading of the dam crest, with upstream slope moving upstream and the crest and downstream slope moving downstream. The causes of this difference may well be due to the inability of the used constitutive model to account for the observed hysteretic behaviour in the oedometer tests (see Figures 1(a) and 2(a)), as will be demonstrated in the case of Walshaw Dean Lower Dam below.

2.2 Walshaw Dean Lower Dam

The Walshaw Dean Lower Dam is the lowest in a chain of three dams completed in West Yorkshire between 1901 and 1907. It has a maximum height of 22m and a narrow central puddle clay core 2.6m wide at the top battering with 12 to 1 towards a 3m wide and 20m deep puddle clay filled cut-off trench. The dam showed obvious signs of settlement and it is believed that more than 1m of crest settlement has occurred since the end of construction. A continued rate of settlement of approximately 10mm per year indicates little reduction with time. The dam was heavily instrumented and deformation measurements for three cycles of drawdown and refilling over a three-year period (1990 to1992) were reported (Tedd *et al*, 1997).

A comparison between the predicted and observed movements during 1991 and 1992 drawdowns are presented in Figure 4 (Kovacevic *et al*, 2004). The deformations are smaller than those for Ramsden Dam but are still considerable. The predictions shown in Figure 4(a) were achieved by modelling non-hysteretic behaviour of the fill materials (puddle clay and shoulder fill) with the non-linear elastic unloading moduli being stiffer than the reloading ones (see Figures 1(b) and 2(a)). The agreement between predicted and observed settlement was quite good. However, whereas the magnitude of the horizontal movements during drawdowns was predicted reasonably, net upstream movements were predicted after complete cycles of drawdown and impounding rather than downstream ones as suggested by the measurements. This was also observed in the analysis of Ramsden Dam. Figure 4(b) shows the same predictions using the constitutive model which was able to account for the observed hysteretic behaviour (see Figures 1(c) and 2(c)). Better overall predictions of the horizontal movements have now been achieved.

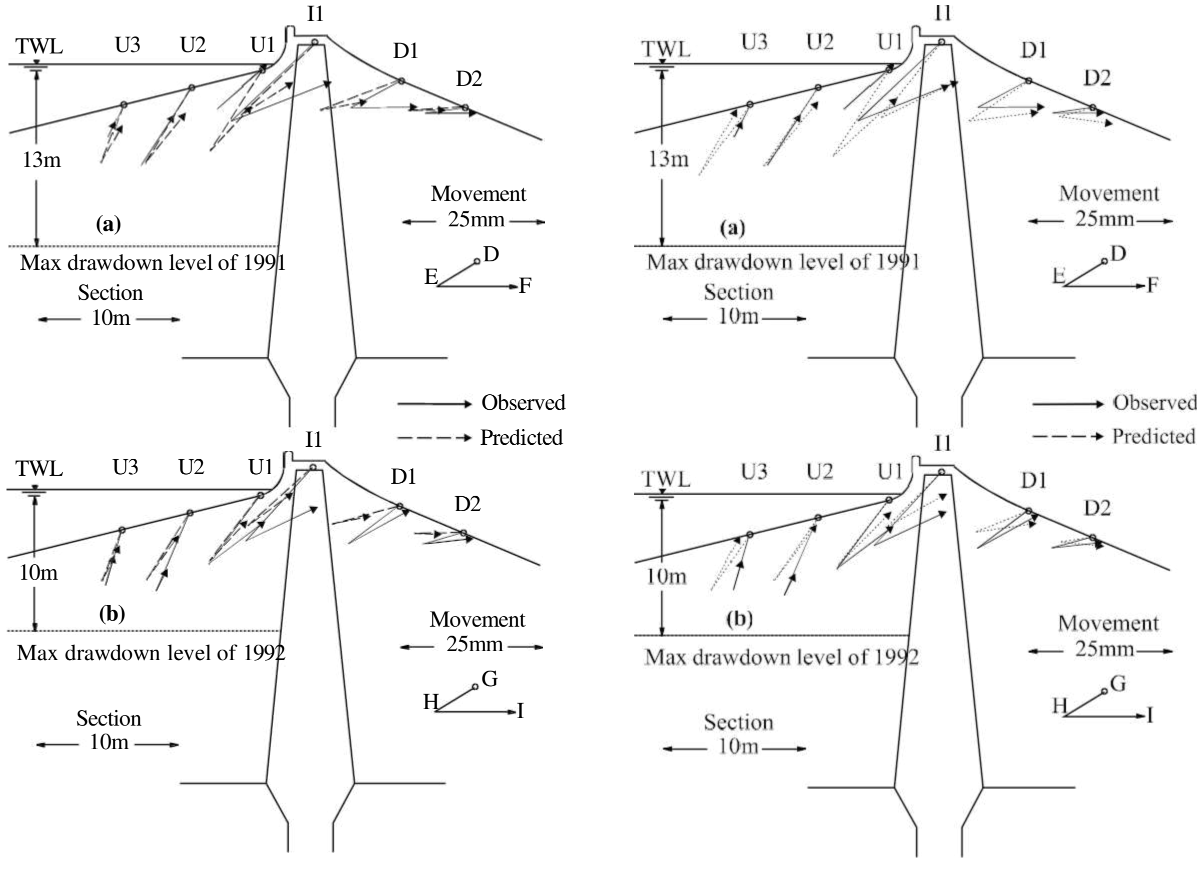

Figure 4: Observed and predicted behaviour during 1991 and 1992 drawdowns using advance constitutive models (a) without hysteretic and (b) with hysteretic behaviour.

The comparison between observed and predicted horizontal (+ve downstream) and vertical movements at the crest for the three drawdowns are shown in Figure 5. The settlements are reasonable predicted by the different constitutive models used (Figure 5(c)). However, whereas the 'non-hysteretic' constitutive model predicted a net upstream horizontal movement after each cycle, the constitutive model which was able to account for the hysteretic behaviour successfully caught the observed movement downstream (Figure 5(b)). It appears therefore that an overall downstream movement of the dam crest is a consequence of the hysteretic behaviour during cycles of unloading and reloading as was suspected during the analysis of Ramsden Dam.

The average factor of safety of the upstream slope from the FE analysis after the second and largest drawdown was predicted to be about 1.7, and conclusions are as for Ramsden Dam. It should be noted that for both dams the observed long term irrecoverable movements can be accounted for without assuming any component of creep (time dependent strain at constant effective stress). They are due to stress changes during operational cycles of drawdown and re-impounding and non-recoverable unload/reload moduli.

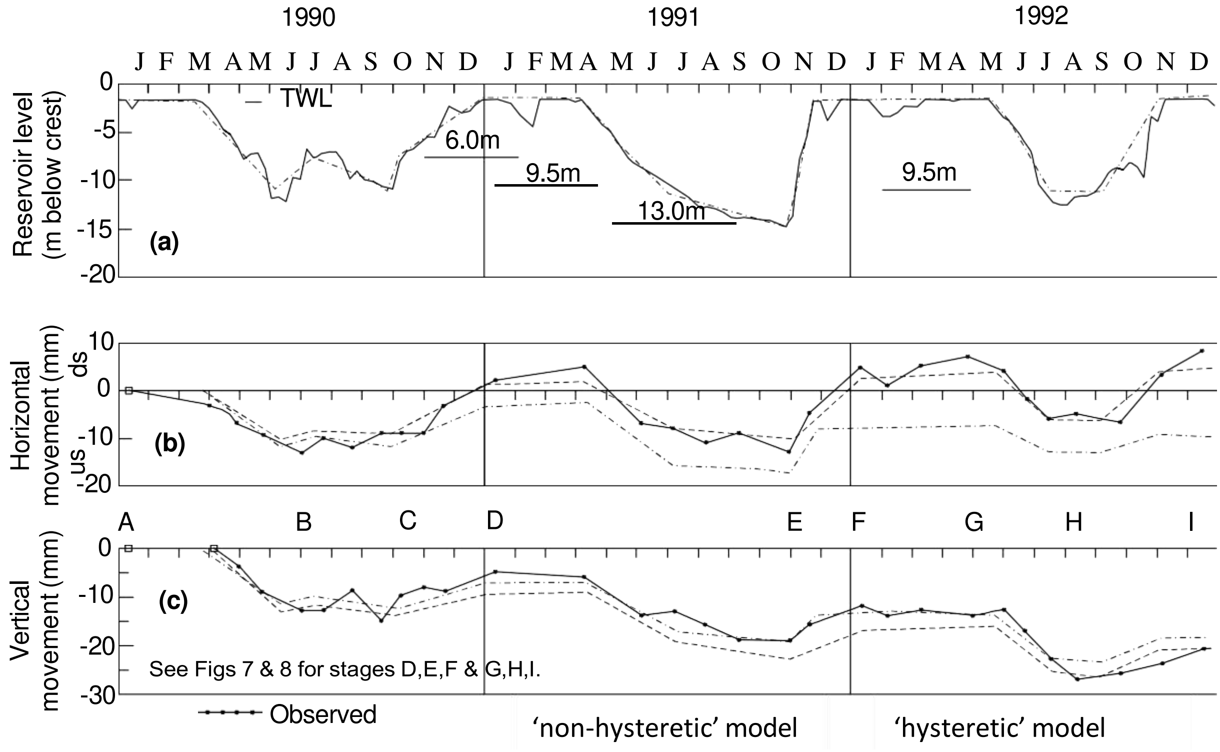

Figure 5: Observed and predicted displacements of the crest during three drawdowns.

2.3 Ladybower Dam

Ladybower Dam is located on the River Derwent in Derbyshire, UK. It was brought into operation in 1943 and finally filled in 1946 (Hill, 1949; Vaughan et al, 2000; Macdonald at al, 2004). It has a plastic puddle clay core of the kind used in Britain from the middle of the 19th century (the same as Ramsden Dam and Walshaw Dean Lower Dam). It is the highest British dam of this type (43m) and one of the last to be built. The crest width of the original dam was 3m and the puddle clay core side batters were 1H:12V. The clay was from a borrow pit in a local clayey colluvium, placed in thin layers. The fill was of colluvium from sandstone and siltstone and the weathered upper layer of the same rock, excavated from the sides of the valley upstream of the dam. It was tipped in layers up to about 3m thick, without compaction. Thinner layers of more select fill were placed against the core. The section of the original dam at maximum height is shown on Figure 6.

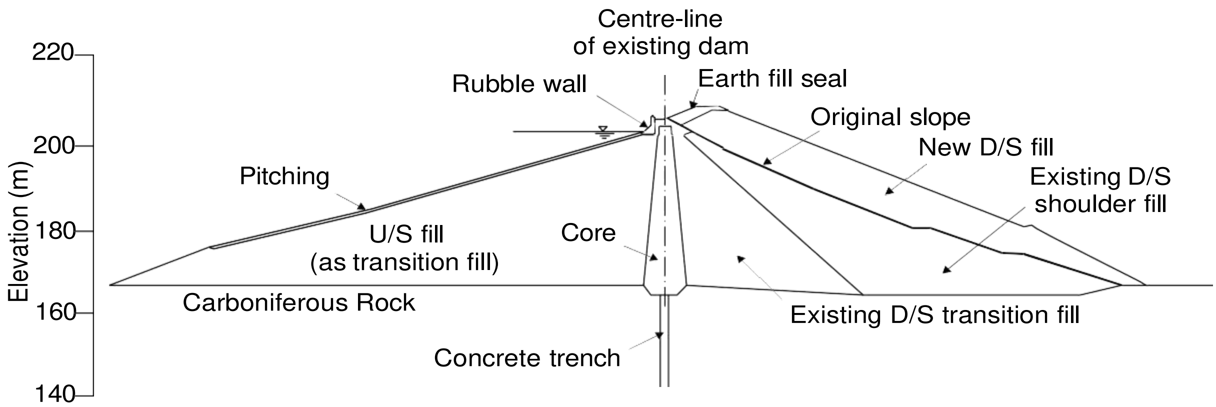

Figure 6: Typical cross-section of original and reconstructed Ladybower Dam.

The designated reservoir water level was raised by 1.5m when the dam was half complete. The base was not widened and raising was achieved by steepening the downstream upper slope, narrowing the crest and constructing a high 'dry-stone' rubble wave wall to form a near vertical upstream face from just below top water level.

Since construction the crest of the dam has settled significantly, by at least 1.5m. The crest was raised on three occasions in the past to maintain freeboard. A major reassessment was made in 1986. At this time the settlement showed an approximately linear relationship with the logarithm of time. It was attributed to creep and the relationship was used to predict future settlement over 50 years. The crest was reconstructed to accommodate this. Unfortunately, very shortly after the reconstruction was completed, the settlement rate increased. Such an increase in the rate of settlement could have indicated a decrease in stability thereby reducing the design life of the structure.

It was decided to analyse the Ladybower Dam section using the same procedures as for the analyses of other old British embankment dams. Both the original dam and its raising were analysed (Kovacevic et al, 2009). Soil properties were taken partly from tests performed in 1986 and partly from precedent. It was expected that this would provide an independent check on the cause of settlement, verify the stability of the reconstruction, and enable a settlement prediction to be made for the modified section. It would also provide a check on general and local stability and predictions of the movements of the dam as the downstream fill was placed, for comparison with observations.

Following the previous experience, the unload/re-load behaviour was simulated as before using non-linear elasticity with increased stiffness on unloading. However, as in the case of the old puddle core dams, the predicted permanent deformations were quite strongly towards the upstream. While no measurements of horizontal movement had been made, sighting along the crest suggested that the movement had been slightly toward the downstream. This disparity between predicted direction of movement and measurement was more pronounced than that found before (see Figures 4 and 5). Thus, it was decided to re-analyse the Ladybower Dam using the advanced constitutive model which accounts for the hysteretic behaviour as before.

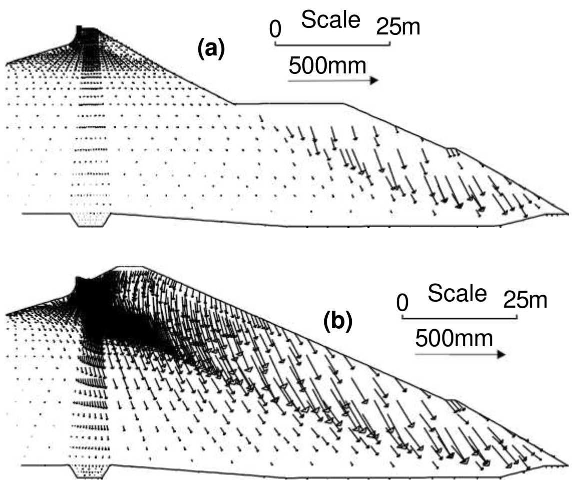

Figure 7: Predicted displacement vectors during reconstruction of Ladybower Dam when 'new' fill is (a) halfway up and (b) complete.

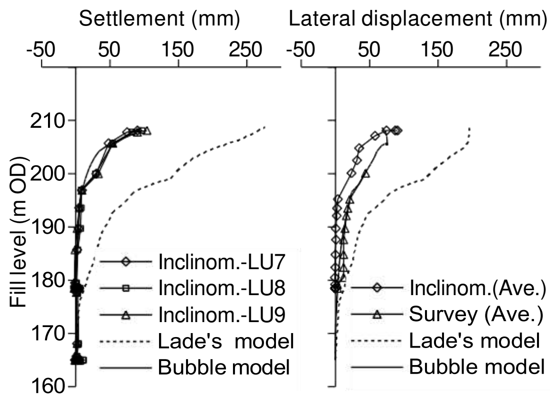

Figure 8: Observed and predicted (a) settlements and (b) lateral displacements at 'old' dam centreline during reconstruction of Ladybower Dam.

The analyses using the two different constitutive models predicted significant movement of the original dam crest. Perhaps surprisingly, the slope of the original dam moved downstream, being dragged down by the new fill. The displacement vectors, predicted by the second model, when the new fill was part way up and when it was complete are shown on Figure 7. The displacements of the original crest are plotted against the rising fill height in Figure 8. The observed movements only started to develop when the fill level reached the elevation of 195m (i.e. after 30m of fill had been placed). The 'Class A' prediction (Lambe, 1973) using the first ('non-hysteretic') model overpredicted the observed movements by a factor of 3. The 'after-the-event' prediction by the second ('hysteretic') model was quite reasonable. This was a surprising result bearing in mind that the parameters for both models were derived using the same laboratory tests.

3. Conclusions

Old British embankment dams with central puddle clay cores and free draining shoulders have suffered from large post construction settlement over the years. Investigation into their settlement records indicates that the settlement is significantly greater than that predicted from conventional consolidation and creep theories. Ongoing settlement can be an indication of potential instability or result in the reduction in a reservoir's capacity. In order restore the capacity of a reservoir or ensure that the structure remains stable, raising of embankments is often considered.

Analyses have been undertaken which show that quite large and non-recoverable movements could have occurred during operational cycles of drawdown and re-impounding of old dams despite a substantial factor of safety against overall slope failure, and such large movements do not necessarily indicate incipient instability.

In order to model the observed tendency for the permanent crest displacement to be towards downstream, it is necessary to account for the soil hysteretic behaviour typically observed in laboratory tests during cycles of unloading and re-loading.

It has been demonstrated that FE analysis is a useful method for interpreting existing field records of old embankment dams. However, it is unlikely to be accurate if used without calibration against field monitoring data.

The approach described in this paper can be particularly useful in estimating the effects of crest reconstruction of old embankment dams. They provide an independent check on the cause of settlement, verify the stability of the reconstruction, and enable a settlement prediction to be made for the modified (raised) section. They can also provide a check on general and local stability and predictions of the movements of the dam as the downstream fill is placed, for comparison with observations.

The results of the analyses are therefore significant in terms of the resilience of earth structures. Although this study relates to embankment dams, the results are equally applicable to flood embankments and the resilience of these structures in the light of climate change.

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