Centrifuge modelling of clay core earth dam deformations

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Case histories of internal erosion incidents affecting earth dams have revealed that dam core deformation, and subsequent transverse cracking or hydraulic fracture, are influenced by the geometry of a dam's abutments. This paper explores the suitability of using plane strain centrifuge modelling and PIV analysis to study the soil deformation adjacent to different abutments. The work builds on existing numerical and centrifuge studies, and is based on the premise that 2D deformation fields will provide useful insight into the conditions and mechanisms that lead to the initiation of internal erosion. The paper focuses on preliminary tests undertaken on the small scale centrifuge at the University of Sheffield and discusses modelling considerations, particularly regarding the use of PIV analysis for clay slurry. The deformation results show good agreement with case history observations, providing a starting point for further modelling of dam core behaviour using the techniques described.

1 INTRODUCTION

Cross-valley deformation of clay core earth dams is one of the contributing causes of damage to the water-retaining dam core and the initiation of internal erosion. Within the core, deformation and internal stress transfer can lead to the formation of transverse cracks, creating a path for concentrated leak erosion. Furthermore, even if transverse cracks don't develop, internal stress redistribution can result in zones of low total stress within the core which are prone to hydraulic fracturing once reservoir filling takes place (Sherard, 1985).

Once a concentrated leak has developed, the safety of the dam is critically dependent on the presence of suitable filter layers to trap eroded particles and arrest further loss of core material. However, worldwide, many clay core earth dams were constructed prior to the adoption of modern filter design criteria, meaning for many structures a safe outcome in cases of concentrated leak erosion cannot be assured and the consequences of transverse cracking are thus potentially very serious.

The distribution and severity of transverse cracking and low stress zones within a dam core depend on a number of factors; including core material properties, construction method and quality, abutment geometry, and competency of the founding layer. This paper discusses construction-induced deformations arising from consolidation of the clay core in order to understand their potential significance when determining the competency of clay core dams.

2 BACKGROUND

Case study reports indicate that concentrated leak erosion is most likely to occur within the first few years of a dam's service (Sherard, 1985) – i.e. the period when settlement and deformation will still be taking place. In addition, extreme loading events, in particular strong earthquakes, can cause additional deformation and initiation/acceleration of erosion many years after a dam's construction. The Matahina Dam located on the North Island of New Zealand suffered concentrated leak erosion both on first filling, and again 20 years later following the 1987 Edgecumbe earthquake. In both cases, the root cause of the erosion was deformation of the core material adjacent to irregular horizontal 'steps' in the abutments, resulting in transverse cracks developing at depth within the core (Gillon, 1988 & 2012). The Matahina case study highlights the importance of being able to predict the pattern of deformation and development of potential zones of weakness in a dam core.

Previous studies exploring soil deformation adjacent to abutments of various geometries almost exclusively use finite element modelling (FEM), many assuming a symmetrical valley cross-section and plane strain deformation of a longitudinal slice of the dam core. Based on the results of various FEM studies, the influence of abutment slope and irregularity are summarised by Hoeg (1995):

- The primary potential tension zones are located at the crest of the dam near to the abutments,
- Where there is a change in abutment slope, the more abrupt the change, the wider and deeper the primary tension zone and the larger the maximum tension stress,
- Where there is a very abrupt change in slope (for example a horizontal step), a secondary tension zone may develop at depth, just below the step.

Centrifuge tests undertaken by Hou et al. (2010) suggest the same general pattern of surface cracking and tension zones at depth adjacent to abrupt changes in abutment slope. Their tests allowed observation of the crest surface and qualitative post-test observation of movements within the model during excavation, however the tests did not allow the strains within the model to be observed or quantified.

There is therefore potential to complement these existing studies by undertaking physical modelling of idealised dam longitudinal sections, using PIV to capture the magnitude, distribution and development of strains adjacent to different abutments. It is expected that experimental observation of the pattern of deformation in the core adjacent to an abutment will provide valuable insight into the progressive development of zones of weakness within the core, the contributing mechanisms of deformation (i.e. compression and consolidation versus shear deformation and distortion), and will provide data for the calibration of numerical models.

This paper presents the first of a series of centrifuge tests exploring the influence of abutment geometry on the pattern of deformation of earth dam cores. The tests discussed herein focus on deformations that develop during dam construction and post-construction consolidation for a hydraulic fill-type material, and compare steep-sided abutments with and without horizontal steps. The primary objective of these tests was to establish the displacement field through the early stages of clay core consolidation. This would require novel methods to allow particle tracking of clay slurries, but would also allow future dam stability tests to be conducted after inducing the structural weakness arising from dam construction.

3 MODELLING

The focus of this work was on the consolidation deformations immediately following dam construction. As a result, kaolin slurry prepared at a 1:1 clay-water ratio by mass was chosen for the clay core material. Kaolin was selected due to its availability in the laboratory and the high water content was according to standard methods for puddle clay core construction where material must have water content greater than 1.3 times the plastic limit (Reeves et al. 2006). An advantage of using a high water content during the preliminary tests was the large deformations that would be induced during consolidation. Subsequent tests will use lower water contents having verified the modelling techniques.

The use of clay slurry would also restrict the formation of tensile cracks in the clay core, as observed in previous studies. Clays have shown reasonable ductility at high water contents during clay beam fracture tests (Amarasiri et al. 2011) and this was expected to be improved further in the kaolin slurry. These properties allow this study to focus on any localised deformations during consolidation, rather than needing to be concerned over potential fracturing processes.

3.1 *Centrifuge modelling set up*

Centrifuge modelling was conducted in order to allow sufficient consolidation times. The small scale teaching centrifuge at the University of Sheffield (Black 2014) was used due to its simplicity and model dimensions. The small model height ensured consolidation times were minimised during the experiments undertaken, allowing for a fast turnaround of different models.

Figure 1 shows an image of the model container. The internal dimensions of the model were 115 by 140 by 30 mm (height, breadth, thickness). The thickness was restricted to 30 mm to limit the volume of expelled water and prevent the centrifuge running out of balance. All internal edges of the container were sealed and two-way drainage was attained using a porous plastic layer at the model base and allowing water to collect above the top of the clay surface. Significant water depths above the clay surface were reported following all tests.

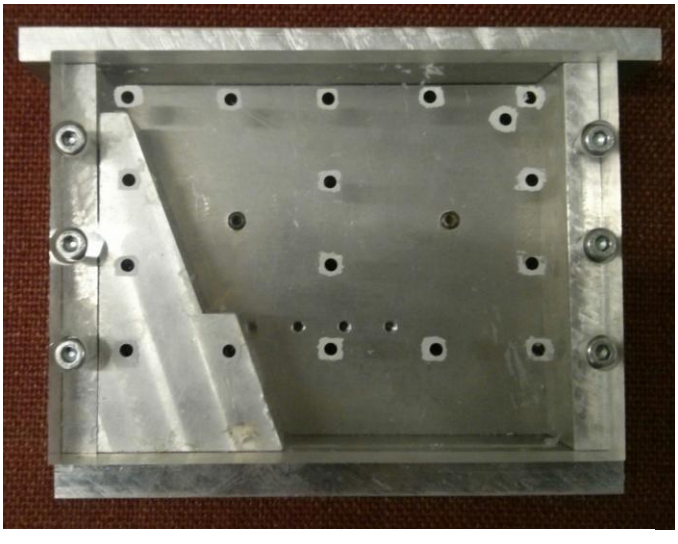

Figure 1. Photograph of centrifuge model container.

The abutments were constructed of solid aluminium inserts spanning the model thickness. These were sealed on all sides to prevent water flowing into the abutments, deliberately restricting water flow towards the base or surface of the model.

Two abutment geometries were tested as illustrated in Figure 2. Each slope had an angle of inclination of 70° and the same toe position in both models, 53 mm from the left hand side of the model. One geometry had a consistent “straight” slope whereas the second had a 10 mm step at the mid height.

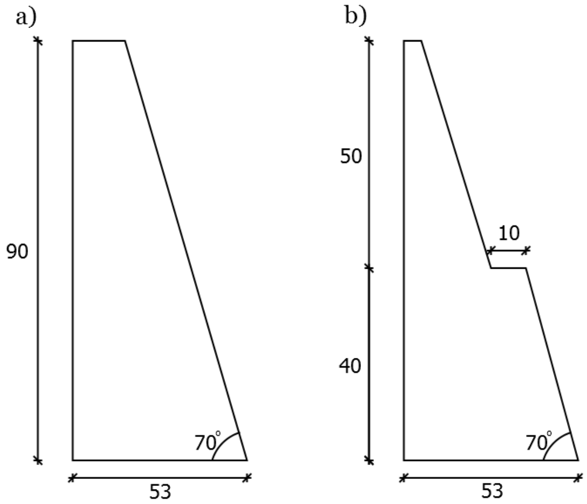

Figure 2. Embankment geometries used during testing (all length dimensions in mm) (a) Straight (b) Stepped.

3.2 *Tracking clay consolidation*

In order to investigate the potential strain localization in the clay core, image tracking was used to monitor deformations during consolidation. To achieve particle image tracking in kaolin models, a floc is frequently added to the soil surface to provide texture for Particle Image Velocimetry (PIV). This is straightforward when using preconsolidated models, but impractical for implementation with a slurry and a different solution was required for this set of experiments. The chosen method was found to be similar to that detailed by Ottolini & Dijkstra (2014).

The model preparation sequence is shown in Figure 3. First, silicon grease was evenly applied to the Perspex window (Fig 3a), before a modelling floc was sprinkled onto the greased surface (Fig 3b). The grease held the floc in position, and allowed the texture of the model to be viewed before adding the clay. This produced well textured images throughout the testing. Figure 3c shows the clay slurry being poured into the box. To prevent disturbing the floc with the clay slurry, the slurry was poured such that it did not smear against the greased and flocced window. Instead, the clay spread out and horizontally contacted the window, pushing the floc against the Perspex. This was continued until the box was full and ready for mounting on the centrifuge (Fig 3d). The centrifuge test immediately followed this preparation sequence, to ensure all models were tested with similar initial conditions.

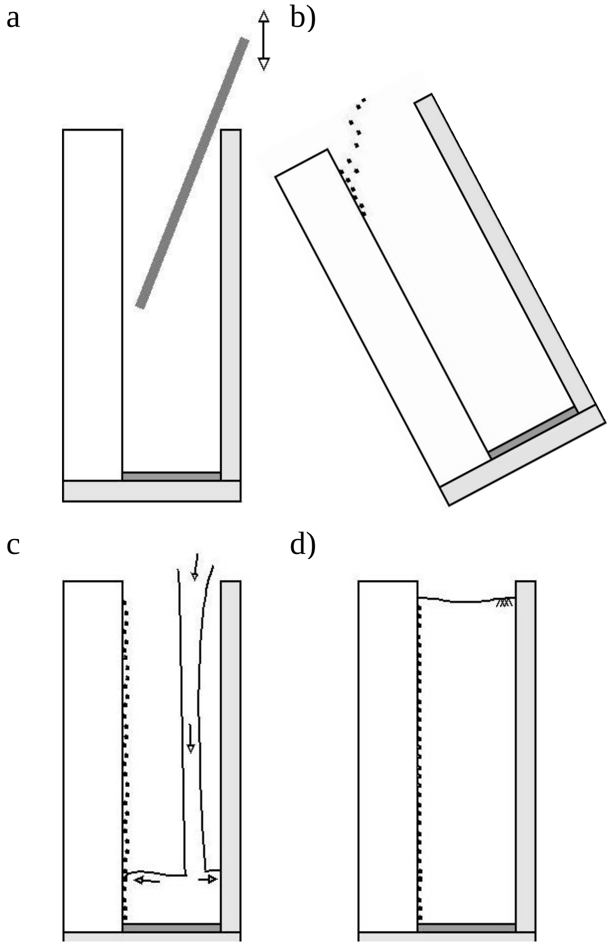

Figure 3. Model preparation sequence. (a) Applying silicon grease to window (b) Sprinkling floc onto window (c) Pouring clay slurry (d) Completing model for test.

On centrifuge spin up, the floc was pushed against the Perspex window by the clay pressure. The coloration of the floc and model also changed during this stage, suggesting that the clay was able to fill any small gaps between the edge of any floc particles and the greased window. Nevertheless, this effect produced sufficient texture to be accurately tracked using particle image velocimetry.

The accuracy of the tracking was supported by the consistent vertical displacement across the model width, especially in the free-field on the right hand side of the model. Additional model height measurements were taken at the sample preparation immediately before spin-up and then immediately after spin-down. These measurements compared favourably to the PIV results, providing further confidence in the chosen methodology.

3.3 *Particle Image Velocimetry*

Images were captured using a GoPro^{TM} camera during the centrifuge tests at a rate of one frame per minute. GoPro cameras are increasingly popular due to their small form factor and survival abilities onboard the centrifuge, but the fisheye lens leads to distorted images, especially when using a small stand-off distance between the camera and object. Given the focus of this work was to capture the strain localization within a consolidating clay core dam, no further attention will be given to assessing the effects of image distortion on the results.

The PIV analysis was completed using the algorithms developed by Stanier et al. (2015). The regression methods used by the PIV routines analysed the large deformations, particularly at the clay surface which settled as much as 30 mm according to pre- and post- test direct measurements of the model.

3.4 *Modelling parameters*

All centrifuge tests were conducted at 70g radial acceleration. Therefore the model represented a prototype dam of approximately 10 m height featuring a 0.7 m wide horizontal step in the abutment. This geometry provides the opportunity to study local deformations in clay consolidating around a rigid abutment upon a rigid base layer. The step width is arbitrary at this stage of the work, but the results showed that the step was sufficient to cause a strain localization in the clay core, warranting further study of this phenomenon.

The centrifuge tests were run for at least 3 hours, representing 1.7 years at prototype scale. This time period does not allow for full dam consolidation but provides results for this preliminary study into the deformations around the abutments. It is reasonable to expect that increasing the consolidation period would only increase the deformations observed in this study, and so increase the extent of the differential settlements.

Approximate settlement calculations using kaolin compressibility properties from Atkinson (1987) predicted 30 mm settlement on the free field side of the container. This compares to the 20 mm settlement observed during a typical 3 hour experiment, suggesting a final consolidation ratio of 67 %.

4 RESULTS

A set of PIV results from two representative tests are presented in this paper, one for the straight abutment and another for the stepped geometry. Both tests were conducted by filling the model container with slurry and accelerating the centrifuge to 70g for three hours. All results plotted show a proportion of the model height and width within the bounds of the control markers. All displacements are given at model scale for this preliminary study.

Figure 4 shows the final horizontal displacements following three hours of consolidation time for both the straight and stepped geometries. Both show a peak in horizontal movement near the surface around X ≈ 40 mm. This is a reasonable finding, given the rigid container boundary on the right hand side of the model restricting any horizontal displacement to zero, which is adequately represented in both cases.

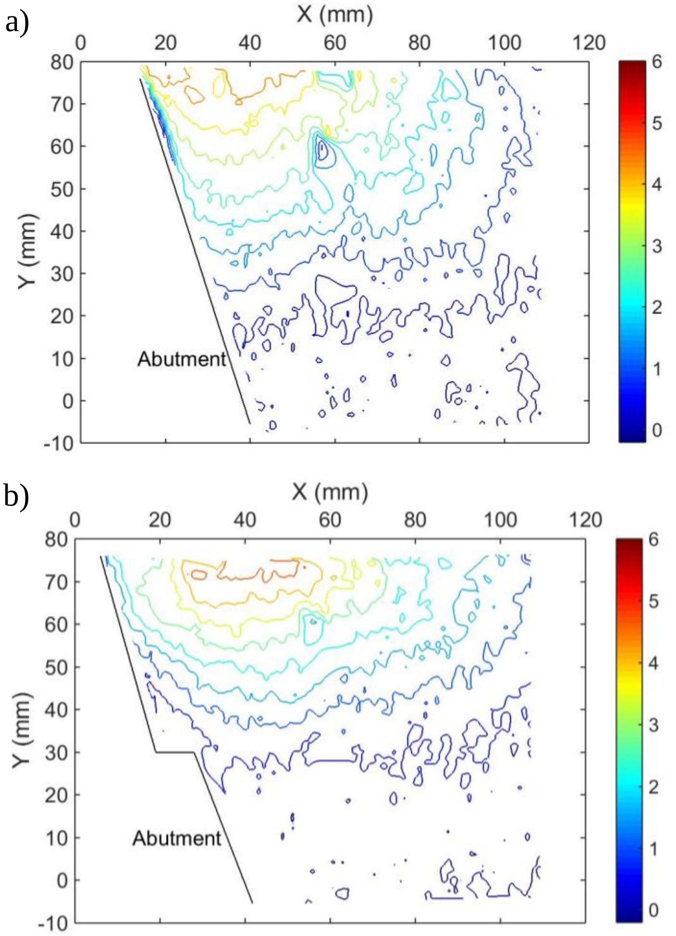

Figure 4. Horizontal displacement contour plot following 3 hours consolidation (a) straight abutment (b) stepped abutment

A larger difference can be seen near the abutment. In the straight case, significant horizontal movements continue to be present close to the abutment whereas in the stepped case this peak in movement is within the model to the right of the abutment step. This result suggests a region of extension between 20 mm < X < 35 mm corroborating the results of Hoeg (1995) and others who reported similar extension around this region in their FEM studies.

The extension region is also affected by shearing between the clay directly above the step and that in the full depth region of the dam. For this, the vertical displacement is plotted in Figures 5 and 6 for the straight and stepped geometries respectively. Subfigures a-c show the displacement that takes place in the hour immediately before.

The figures highlight the success of the modelling technique. In the full depth region of clay, the contours are broadly horizontal, showing equal displacement towards the model base for each hour. As each hour occurs, displacement at the bottom of the model reduces, whilst that at the top increases as per consolidation theory as the excess pore water pressures near the base drainage layer dissipate quickly. The horizontal contours also show the consistency in tracking of the consolidating clay slurry via the floc method described earlier in this paper.

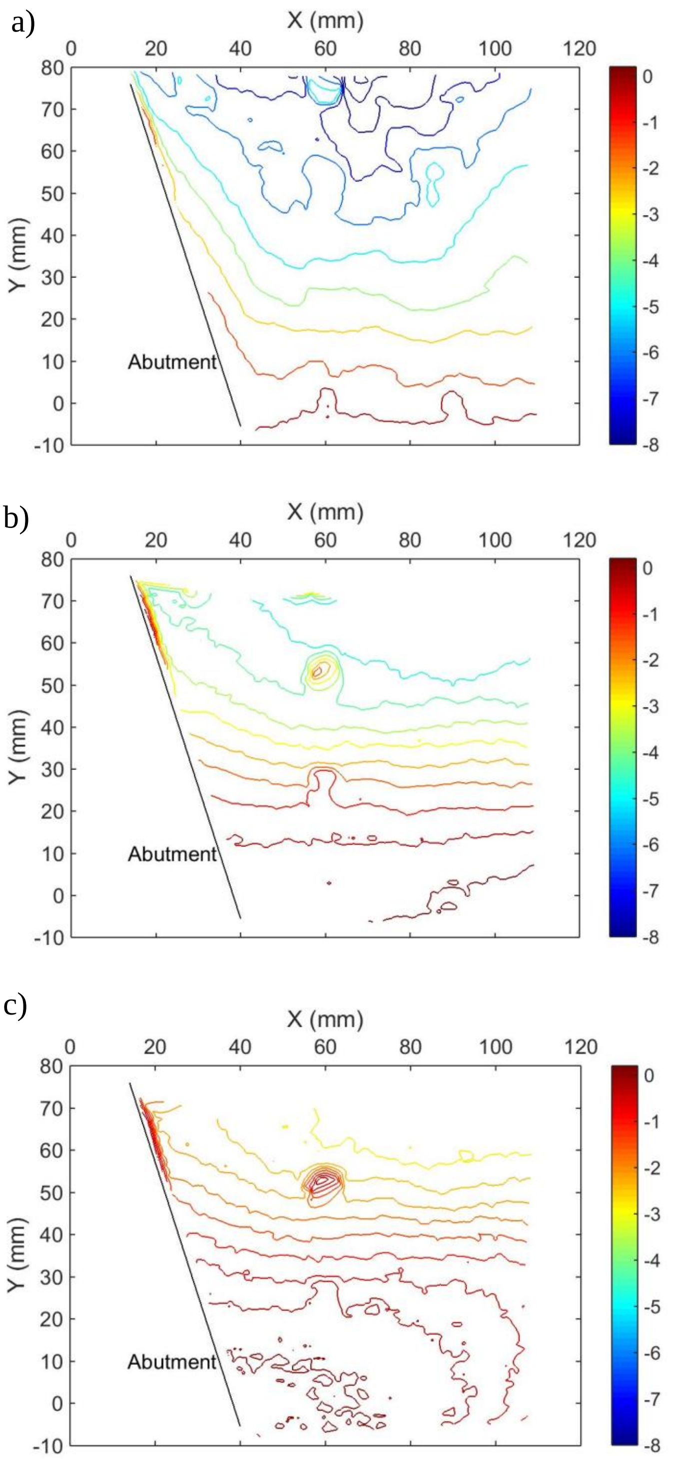

Figure 5. Displacement contour plots for the straight abutment over the (a) First hour (b) Second hour (c) Third hour.

Further comparison of the two geometries show the increased levels of distortion around the abutment step compared to the smoother response seen in the straight case. This can be seen in Figures 6a-c at X ≈ 30 mm throughout the clay depth where the displacement contours become vertical in the model. These results suggest a large region of shear distortion is present in the stepped abutment case, which occurs throughout the experiment and is likely to continue beyond the three hours of testing conducted for this paper.

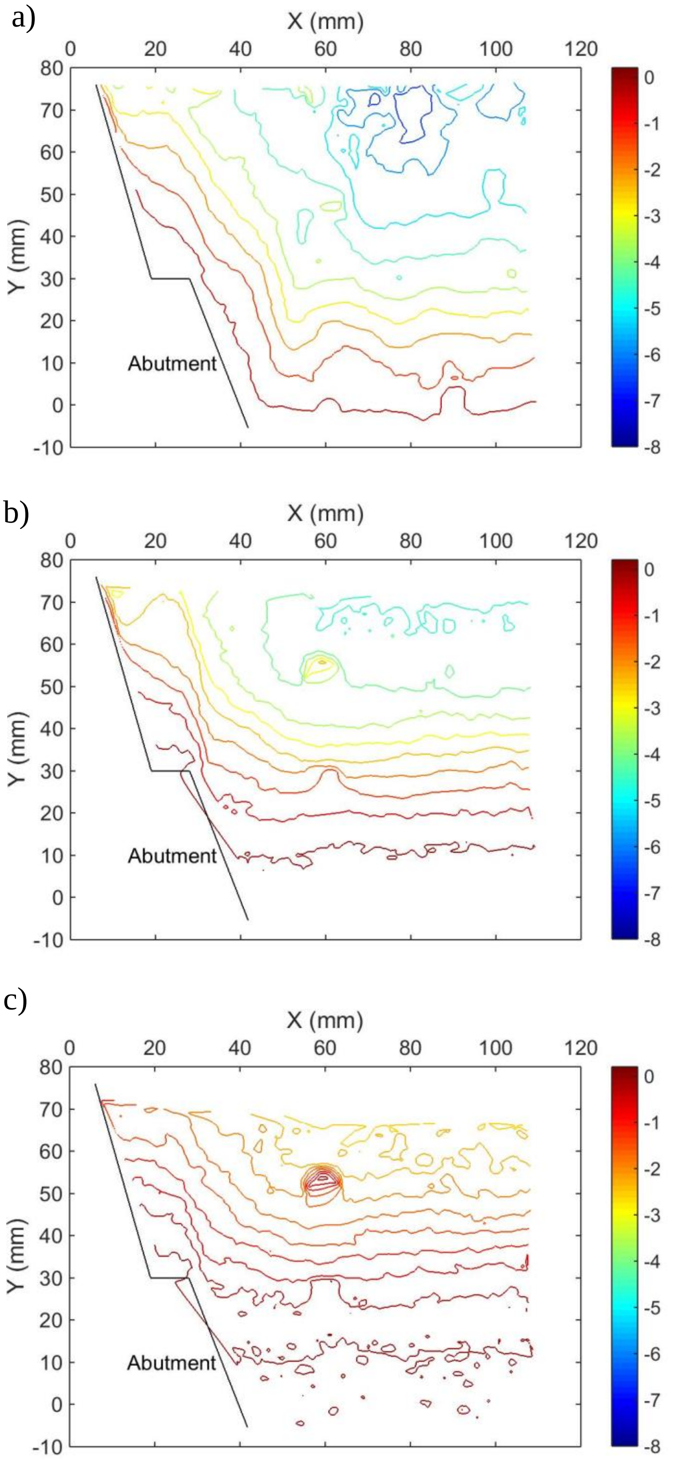

Figure 6. Displacement contour plots for the stepped abutment over the (a) First hour (b) Second hour (c) Third hour.

5 DISCUSSION

The results from these experiments highlight the issues facing earth dam clay cores when constructed around steep and stepped abutments. The horizontal extension region in Figure 4b agrees with previous studies investigating the potential for dam cores to form transverse cracks due to deformations induced by soft foundations or abrupt changes in abutment geometry. This agreement confirms that the modelling techniques based on a kaolin slurry for this paper were representative of dam construction and that strains can be adequately tracked in future work.

The confirmation of a significant region of shear distortion is important for future work. Despite the positive effect of clay consolidation increasing the shear strength throughout the clay core, this region of distortion may provide a weak point prone to hydraulic fracture or to further deformation should any significant loading occur: this loading could be from dam heightening work or via loads imposed by earthquake excitations as seen in the Matahina Dam (Gillon, 2012). In this case, the Matahina Dam suffered internal erosion following the 1987 Edgecumbe earthquake due to piping in the clay core near the dam's left abutment. The piping occurred in a very similar position and orientation with respect to a step in the abutment as observed in the centrifuge experiments reported here. Furthermore, this was the same location with respect to the abutment step where internal erosion developed in the Matahina dam's right abutment 20 years earlier when the reservoir was first filled.

The apparent agreement between the centrifuge results and case history observations is encouraging. Extension of this work is planned to further investigate the region of shear distortion, determine the properties of the disturbed soil, and evaluate the implications of pre-existing shear zones on seismic deformations. The eventual aim of this programme of work is to inform future dam construction, the assessment of existing dams in seismic regions, and the design of remediation measures against earthquake-related internal erosion.

6 CONCLUSIONS

This paper has described preliminary centrifuge tests designed to model the deformation of earth dam core material adjacent to abutments of different geometry. The main objective of these tests was to evaluate the suitability of PIV-based analysis for capturing the deformation of clay slurries undergoing consolidation and shear displacements, and hence establish a basis for further physical modelling of dam core deformation to investigate the conditions leading to internal erosion through concentrated leaks in the core.

The modified technique of applying floc to the pre-greased box window prior to deposition of the clay slurry proved effective in generating suitable texture for successful PIV analysis. The floc appeared to follow the deformation of the soil, as confirmed by the plots of soil displacement away from the abutment, which conformed to the expected vertical consolidation-dominated deformation.

The displacement contours close to the abutment revealed a clear effect of the horizontal step on the pattern of soil deformation, with the step resulting in a zone of significant shear developing within the soil. This zone was oriented vertically and extended from the edge of the step upwards to the soil surface, coinciding with a zone of horizontal extension in the surface soil. The deformation results show good agreement with case history observations, providing a starting point for further modelling of dam core behaviour using the techniques described.

7 ACKNOWLEDGEMENTS

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