PROGRESSIVE FAILURE OF A TAILINGS DAM: POST-FAILURE PHASE

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Abstract

As explained in a companion paper, the onset of failure of a tailings dam triggered liquefaction of the stored tailings and, with it, a large increase in the forces acting on the dam. The foundation was still only partially consolidated under the loads and its strength was locally deteriorated by strain softening to different degrees. At this point, the solution obtained with ABAQUS/Standard had to be transported to ABAQUS/Explicit for analysis of the ensuing fast dynamic phenomena. The migration imposes very substantial changes in approach:

- the type and order of elements varies, with unavoidable inconsistencies with respect to localization in a strain softening material

- a coupled effective stress analysis must be converted into a total stress analysis, affecting stress fields, boundary conditions, material behaviour, etc

- a Mohr-Coulomb criterion must be converted into a von Mises one while preserving the strength characteristics, which depend on the preexisting effective pressures and the softening already caused by past deformations at each location

The obvious difficulties of the above requirements were successfully overcome and very satisfactory post-liquefaction analyses were carried out, which allowed conducting accurate interpretations of the dam failure and validating the causal theories and mechanisms.

Introduction

As mentioned in a companion paper (Martí et al, 2001), the failure of a tailings dam resulted in the uncontrolled release of several million cubic metres of tailings and tailings water. This led to the contamination of rivers and land surfaces, caused interruption of the mining operations and required adopting a series of costly mitigation and remediation measures. The present paper, as well as its companion, describe some specific aspects of the extensive forensic investigations undertaken, with special emphasis on numerical modelling.

The basic description of the problem was already given in the companion paper (Martí et al, 2001) and will not be repeated here. This description covers the dam and the foundation materials, together with their mechanical and hydraulic characteristics, as well as the sequence of construction up to the activation of a kinematically viable failure surface. At this point, when the dam is no longer stable and starts moving, the companion paper stops and the present one takes over.

The calculations in the companion paper were carried out with ABAQUS/Standard (HKS, 1998a). Key aspects in those calculations were:

- reproducing the construction sequence
- conducting coupled calculations, dealing in separate yet compatible ways with the pore pressures and associated water flow on one side, and with the effective stresses and ground deformations on the other

- accounting for the stress dependent plasticity of all materials and, very specially, for the strain softening of the foundation clays, which plays a key role in the timing and geometry of the failure.

Initial conditions: the failure event

The progressive buildup of the dam and filling of the pond led to a gradual increase on the demands exerted on the dam foundation. The brittleness of the foundation material caused the peak strength to be reached in certain areas, thus decreasing the available strength towards a residual value. Eventually, a situation was reached when an increment in demand could not be supported: all points along a kinematically viable surface were at peak or decreasing strengths. The dam then started to slide along that surface, encountering a progressively decreasing resistance; any strength, higher than residual, along the failure surface decreased towards the residual value.

Behind the dam, the loose structure of the tailings was in a state of equilibrium: water pressures were hydrostatic and the horizontal effective stresses had approximately their at-rest values (about 40% of the vertical stresses). The movement of the dam caused them to liquefy, thus becoming a fluid for some time (much longer than required to complete the failure). In this state, water and tailings become a single liquid, with a density of about 3 Mg/m^3. As a consequence, the horizontal forces on the dam increase by 65%. The vertical distributions of horizontal stresses applied to the dam, before and after the occurrence of liquefaction, are plotted in Fig.1

An already failing dam, suddenly subjected to a 65% increase in horizontal demands, accelerates rapidly. Inertia forces, negligible up to that point, are now an unavoidable component of the calculations. On the other hand, a coupled analysis, necessary up to failure, is no longer required: the process is now far too fast and the effective pressures lack enough time to evolve. As a consequence, ABAQUS/Standard is no longer needed and ABAQUS/Explicit is required.

Migration from Standard to Explicit

In reading the respective manuals, it is clear that HKS has intended to provide for smooth migrations when a problem needs to go from Standard to Explicit. This has been achieved, albeit only for simple problems. In the present case, the migration is anything but smooth. The difficulties are serious and hard to overcome in respect of the two key issues governing this problem: pore pressures and brittleness.

a) *Pore pressures*

No coupled calculations are possible with Explicit, which is tolerable since it is rare for a fast problem to require them; indeed, this applies even in the present case. However, the starting conditions come from Standard, with which the prior coupled calculation had been conducted. A procedure had to be created to combine effective stresses and pore pressures, in order to re-pose the problem in a total stress formulation.

Another difficulty arises because the elements used in Standard (CPE4P) do not exist in Explicit, where CPE4R elements must be used. Gauss points are obviously different and, again, no preset procedures exist for this adaptation.

Densities will now be bulk densities, which are the ones governing inertial effects when the ground accelerates. But the preexisting levels of effective pressures will have to be remembered throughout the explicit calculations, since strengths will depend on them and not on the total pressures that Explicit will handle thereafter. This is discussed further in the next paragraph, together with the brittleness aspects.

b) *Brittleness*

The foregoing problems are only worsened by the strain softening aspects of the clay behaviour. As a function of some measures of plastic strain, the cohesive and frictional parts of the strength are deteriorating. The peak, theoretically possible, strength was different at each Gauss point depending on its effective stress level. The currently available strength is furthermore a function of how much the cohesive and frictional components have deteriorated by past straining; this information is also associated to Gauss points.

Unfortunately, none of these things are directly accesible in Explicit: different elements, different Gauss points, different constitutive laws, no field variables, etc. Progressing beyond this point required several exercises in ingenuity.

Strategy adopted

In order to overcome the above difficulties, the strategy finally adopted essentially consisted in constructing 360 material models for the foundation clays. These 360 material models are all of the same type (von Mises with strain softening), but their parameters arise from discretizing into ranges the two key variables influencing the strength. Preexisting levels of effective pressures were discretized into 30 bands. Past straining and associated deteriorations were discretized into

12 bands. The combination of both discretizations gave rise to the 360 material models used for representing the foundation clays and accounting for their past deformation history.

The mesh used in the Explicit calculations can be seen in Fig. 2. It is identical to that used in the Standard calculations with two differences. First, the type of elements is different. Second, the tailings and alluvial upstream of the dam have been removed and replaced by the forces that they were exerting on the rest of the materials; this allows increasing the horizontal components of the forces on the dam upstream face to simulate the effects of tailings liquefaction and to observe the resulting evolution of the failure.

This process has been repeated with every result from Standard that predicted well the timing of the failure. The new type of calculation is needed because the greatly increased forces, acting on an already destabilised dam, may (and actually do) generate different failure surfaces from the one initially activated.

Results

A few results are included here for better visualisation. Liquefaction was assumed to develop gradually over 3 s. All plots shown indicate actual displacements after 5 s (2 s after complete liquefaction). Typical dam displacements at that time are around 7 m; incidentally, the final displacements that the dam actually underwent reached up to 60 m along a 700 m section.

Fig. 3 shows a typical result in a case in which a realistically brittle behaviour is assigned to the foundation clays. As can be seen, the failure surface is fairly planar and shallow. The obvious lack of smoothness in the effective strain contours arises because of the discrete jumps in material properties between neighbouring elements, as created by the discretization of strength properties into the 360 material models mentioned earlier.

Fig. 4 presents the type of failure surface triggered when the material is less brittle or when no strength deterioration is assumed to have taken place during the past history of the dam (i.e.: the failure is developed in a "virgin" material).

As a curiosity, because it is of lesser interest here, once it starts, the dam has very few means of stopping. In the real situation, it stopped after a displacement of about 60 m. Even after that displacement, the buildup of a passive wedge ahead of the dam contributes little to its arrest. On the other hand, the liquefied tailings behind the dam are obviously perfectly capable of accompanying its displacement, thus ensuring that their pressures are maintained on the dam. Also, with a large tailings pond, it takes a long time before the level of the stored materials decreases; the rate of materials escaping through the breach is small compared to the capacity of the pond. The actual displacement was kept to 60 m because the volume of initially liquefied tailings was relatively small; their level lowered substantially behind the displacing dam, as they occupied the progressively widening trench being left behind the dam as it moved.

Conclusions

The solution of a problem, which had to be initiated with ABAQUS/Standard, was continued to completion with ABAQUS/Explicit. The work conducted allows proposing the following conclusions:

a) The migration from Standard to Explicit can generate almost unsurmountable difficulties when dealing with reasonably complex problems.

b) Different elements (and Gauss points), different material laws (unavailability of Mohr-Coulomb in this case) and a different solution procedure (no coupled solution available) make the migration hard and very laborious.

c) No automatic procedures exist for migrating from an effective to a total stress analysis, which is a requirement imposed by the migration.

d) The problems are severely worsened when, as in this case, strengths depend on the preexisting effective pressures and on the accumulated deformations at each point.

e) The above difficulties were overcome by constructing a series of 360 material models for the clays, covering the appropriate ranges of effective pressures and strain degradation. The procedure was laborious and complicated but appeared to work well.

References

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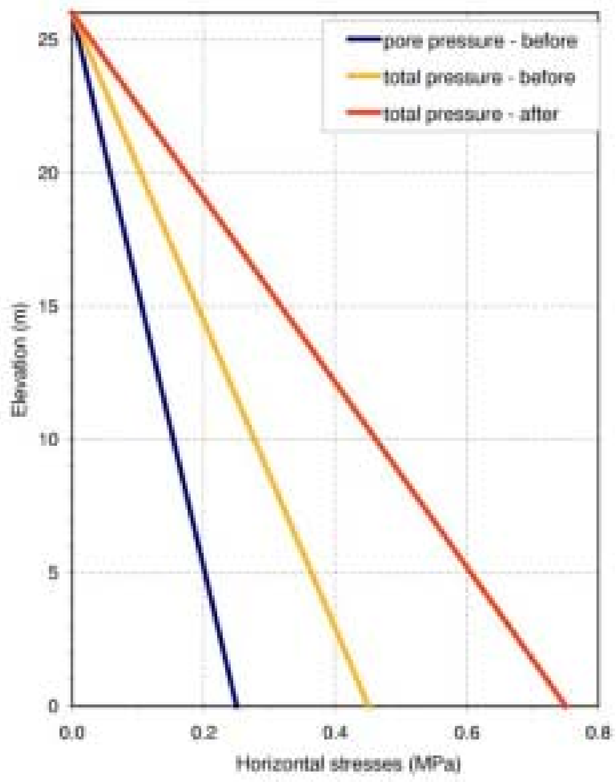

Fig. 1 Horizontal stresses before and after liquefaction

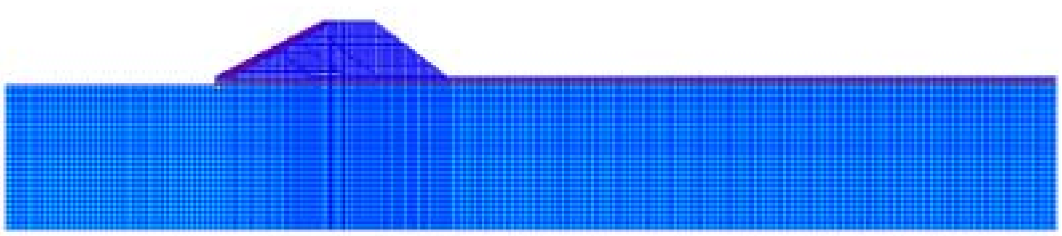

Fig. 2 Mesh used in explicit calculations

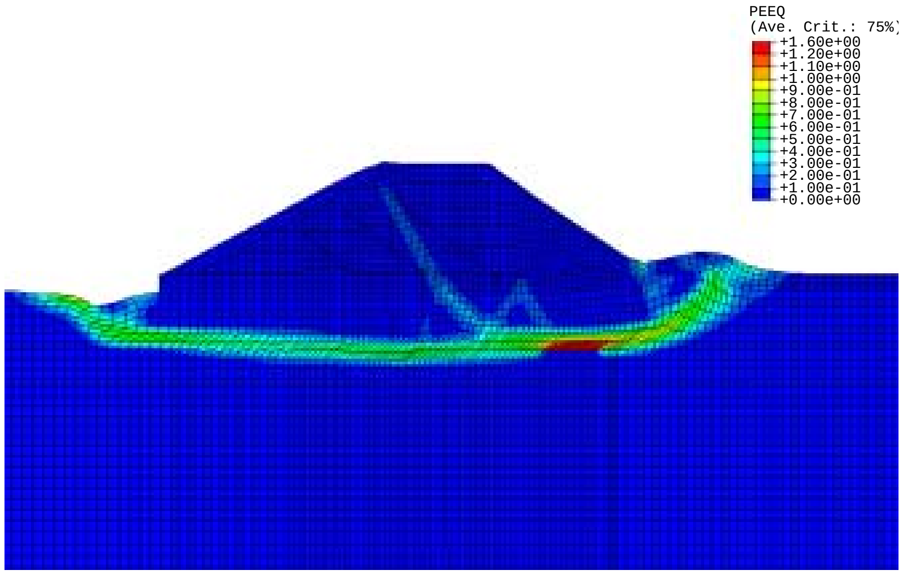

Fig. 3 Displacing dam with plastic strains

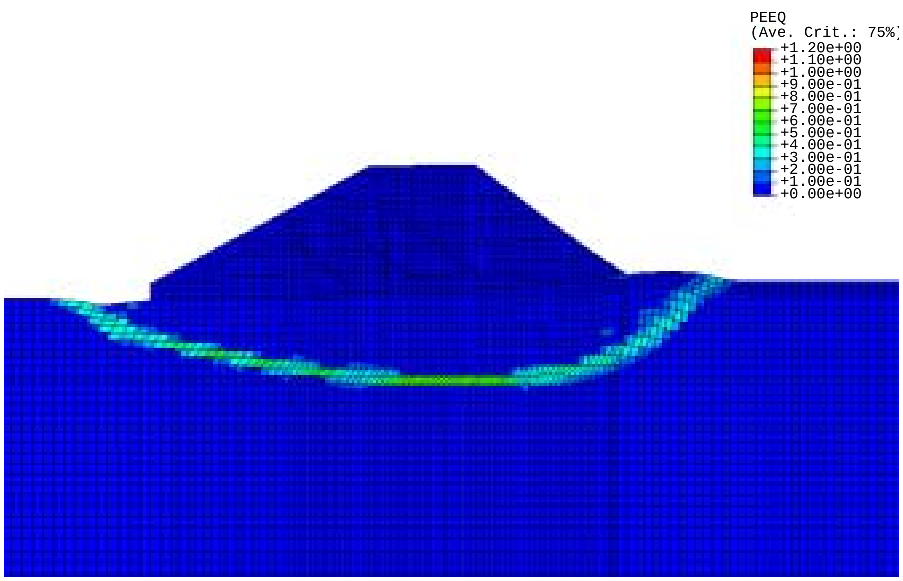

Fig. 4 Plastic strains without deterioration during construction