Current research in embankment dam engineering at Imperial College London

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This paper gives a short introduction to two research streams in embankment dam engineering underway at Imperial College London. The first is the modelling of embankment dam behaviour during earthquakes and the second is an investigation into the susceptibility of granular filters to internal erosion. The research motivation, methods and expected outcomes of each stream are discussed.

1. Introduction

Imperial College has a strong tradition, spanning nearly six decades, of research into embankment dam behaviour, from Bishop's early work on the stability of embankment slopes (Bishop, 1955) to the post-failure analysis and redesign of Carsington dam (Potts *et al.*, 1990; Skempton and Vaughan, 1993) and Vaughan's research into the 'perfect filter' (Vaughan and Soares, 1982), to more recent analysis and redesign of the main dam embankments at Empingham and at Abberton reservoir (Kovacevic *et al.*, 2007, 2013).

Today, there are two research streams into embankment dam engineering underway in the Department of Civil and Environmental Engineering at Imperial College. In addition to traditional modelling of large-scale embankment dam problems, which is at present focused on their behaviour during earthquakes, investigations are also being made on the susceptibility of granular filters to internal erosion. This paper outlines the research motivation, methods and expected outcomes of each of these two research streams.

2. Particle-scale analysis of granular filters

Filters protecting the core against internal erosion are one of the most critical features in zoned embankment dams. Most embankment dams are constructed using granular filters of sand and gravel. Granular filters are required to be internally stable, meaning that the finer filter particles should not be able to be washed out from between the coarser filter particles (ICOLD, 1994). A feature of internally unstable soils which makes them particularly hazardous is that the finer particles can be eroded at very low hydraulic gradients (Skempton and Brogan, 1994).

Loss of these finer particles can lead to local changes in permeability, settlement and loss of freeboard, the appearance of sinkholes and potential dam failure. For example, the 71 m high Gouhou dam in western China failed on first filling owing to erosion of internally unstable shoulder material, causing 288 casualties (Zhang and Chen, 2006). Figure 1 shows the remnant of the failed dam.

Nowadays simple, conservative filter rules are used to ensure internal stability in new dams, as comprehensively described by the recent ICOLD Bulletin on Internal Erosion (ICOLD, 2013). However, many older dams were constructed before these rules were developed and a more precise set of tools is needed to assess the risks to these structures. To develop such tools it is first necessary to better understand what actually leads a material to be internally unstable.

One of the major obstacles to improving our understanding of internal instability is that mainstream experimental methods, such as permeameters, only allow external measurement of variables such as water pressures and the quantity of eroded material; what is happening in the filter must be deduced from these external observations. For a more scientific assessment of internal instability, two questions must be addressed, both of which require knowledge of the filter structure, as illustrated in Figure 2.

1. Are the finer filter particles free to be moved by seepage flows, or are they held in place by stresses from the coarser particles?
2. If free to move, can the finer particles fit through the pore network between the coarse, load-carrying 'skeleton'?

Two new techniques are employed in the attempt to answer these questions. These methods 'look inside' granular filters

Figure 1. Gouhou dam failure, 1993 (Chang, 2012)

and directly measure the critical characteristics leading to internal instability. The first technique is the discrete element method (DEM), a type of numerical analysis, and the second is micro-computed tomography (micro-CT), an experimental method. Both these techniques operate at a ‘particle-scale’, meaning they generate data which can quantify features of individual filter particles.

2.1 DEM

Like a real soil mass, a DEM model is made up of individual particles which are in contact with one another. DEM models calculate the stresses and displacement of each particle, and hence the soil mass. Figure 3(a) shows a digital image of a DEM model.

DEM can be used to provide two data sets which are useful for assessing internal instability. The first is the geometry of the filter material: particle sizes, locations and which neighbouring particles are in contact with one another. From this information a way has been developed to measure the narrowest ‘throats’ within the network of pore space between the coarser particles, which control whether any finer particles can actually be eroded (Shire *et al.*, 2013). Figure 3(b) shows a digital image

Figure 2. Schematic diagram of prerequisites of internal instability

Figure 3. DEM images (a) internally unstable filter sample; (b) pore-throat measured between DEM particles

of these pore-throats, which are shown as circles between solid particles.

The second data set is the stresses acting on each particle, which the DEM model calculates using simple equations based on Newton’s laws. The particle stresses give a measure of how easily a particle can be moved by a seepage flow through the filter: if fine particles are only under a very low stress, they will be easily erodible (as long as they can also fit through the pore network).

2.2 Micro-CT scanning

A major drawback of the DEM is that it requires a very large computer capacity. In order to reduce the computational

requirement, soil particles must be idealised as perfect spheres (even with spherical particles, large models can still take several weeks to produce).

Therefore micro-CT is also used, which provides a non-destructive way to take high-quality images of the internal structure of a real filter material. The micro-CT used here is essentially the same as X-ray CT (CAT) scans, which are commonly carried out in hospitals. A micro-CT scanner takes X-rays images at many angles and combines the resulting two-dimensional (2D) images to form an accurate three-dimensional (3D) image. As the images contrast materials of differing density, the boundary between filter particles and pore-space can be easily identified.

The major difference between medical CT and geosciences micro-CT is that, with no fears of giving the test subjects radiation poisoning, much higher radiation levels can be used. This gives a much better image resolution than is possible in medical applications. Typically, features which are just a fraction of a millimetre can be made out, compared to a few millimetres for medical applications. Figure 4 shows a micro-CT image of sand taken from Fonseca (2011). Information about the geometry of the sample can be retrieved from the 3D image, producing a similar data set to the DEM model: particle locations, sizes and contacts between neighbouring particles. However, a micro-CT image is unable to provide information about particle stresses.

2.3 Research outcomes

A drawback of existing filter rules is that they only take account of the particle size distribution (PSD) and they ignore the bulk material density (i.e. level of compaction), stress level and particle shape. DEM and micro-CT are currently being used to

Figure 4. Micro-CT image of Reigate sand (Fonseca, 2011)

analyse a range of different filter PSDs at a range of densities and overall stress levels. At first the generated pore-scale data are used to determine which existing filter rules have the best scientific basis and will therefore be the most accurate across a wide range of practical applications. Initial results have found good, but not perfect, correlations between a widely used filter rule and the DEM data (Shire and O'Sullivan, 2013). Next, micro-CT data, which are more realistic but harder to analyse, will be assessed in a similar way, allowing some of the idealisations of the DEM model to be identified.

Finally, the most important factors which are not considered in the existing filter rules will be identified, and ways will be proposed in which these can be accounted for. In order for the findings to be used practically with confidence, the results will be validated against high-quality laboratory testing using more established, mainstream methods, such as the permeameter tests of Moffat and Fannin (2011).

3. Modelling the seismic behaviour of dams

Earthquakes are one of the most dangerous and complex threats to embankment dams. They can cause slope failure or excessive deformations owing to high-intensity cyclic ground shaking, and large pore water pressures can be generated, leading to reduced earthfill strength and possible liquefaction. Earthquake loading on dams is extremely complicated: shear waves of many different amplitudes, frequencies and directions of propagation pass through the embankment and the soil responds to these in a highly non-linear manner. This makes it difficult to analyse how an embankment dam will respond during an earthquake of a given magnitude.

The finite-element method (FEM) is the most advanced analysis tool available for practical use in geotechnics. Used properly it can accurately model many aspects of embankment dam behaviour, for example hydraulic fracture of clay cores and progressive failure of embankment slopes (Dounias *et al.*, 1996; Kovacevic *et al.*, 2008). However, owing to its complex, dynamic nature, the modelling of seismic events with FEM is not well established.

Previous researchers at Imperial College have developed FEM models which are able to capture the seismic response of soils, for example Taborda (2011). These are now being applied to the elasto-plastic seismic analysis of dams and are being extended to include advanced features such as modelling the reservoir hydrodynamic pressures (Pelecanos *et al.*, 2013) and the dynamic interaction between the reservoir and dam. Multiple shear-wave directions will be also allowed (instead of the standard assumption that all waves propagate horizontally).

The refined models are being implemented in Imperial College's bespoke geotechnical FEM code, ICFEP (Potts and

Zdravković, 1999). The current authors are attempting to validate them against two well-documented case studies

- La Villita dam, Mexico: a 60 m high zoned earthfill dam which has experienced deformation, but not failure, from six major earthquakes (Pelecanos *et al.*, 2012)
- Yele dam, China: a 125 m high rockfill dam with an asphaltic concrete core, which is located about 250 km from the epicentre of the 2008 Wenchuan earthquake.

So far, significant progress has been made in back analysing the dams (reproducing the earthquake accelerations and displacements from field monitoring data). Once the FEM models have been validated and further refined, it will be possible to realistically model embankment dam response during test earthquakes, including predicting the most likely failure mechanisms for earthquakes of magnitudes well above those previously experienced by the dams. Such analysis will greatly aid risk assessment of existing dams as well as design and construction of new dams.

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