Session report: dams, embankments and slope stability

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This session report discusses 13 papers that were presented at the 8th International Conference on Physical Modelling in Geotechnics 2014 in the session 'Dams, Embankments and Slope Protection'. It concentrates on whether scaling is possible and what the consequences of scaling are in the various papers. Some tests do not really appear to be scaled model tests, because it is difficult to define a prototype that behaves as the model. However, such models can still be useful to study mechanisms that are relevant in prototype.

1. Introduction

The 8th International Conference on Physical Modelling in Geotechnics 2014 (ICPMG 2014) attracted papers from over a wide range of modelling applications. The 13 papers of this session (references in *italic*) described tests in beam centrifuges, a drum centrifuge, 1g model tests and large-scale model tests. Some of these large-scale tests resemble field tests rather than model tests.

An overview such as this has the problem of how to group the papers: by topic, country of the author or kind of model test. All these groupings are possible. In this overview, however, another point of view is taken. This is inspired by one of the papers (Koelewijn *et al.*, 2014). This paper presented six tests in three different set-ups, all on a (nearly) 1:1 scale and it is argued that these tests cannot be performed on a smaller scale. Since most of the other tests described in the remaining 12 papers were performed on a smaller scale, it is interesting to investigate as to what are the consequences of the scaling. First the arguments of Koelewijn *et al.* (2014) will be discussed, to investigate later whether or not these arguments are valid for other tests.

2. Applications in which scale-model tests are difficult

The tests in the paper by Koelewijn *et al.* (2014) are wave overtopping tests on a slope with vegetation. This may be difficult in a small-scale test, although Takahashi *et al.* (2014) showed that it is not impossible to make scale models of vegetation and test its influence. A second model described by Koelewijn *et al.* is of macro-stability. Craig (2014) and Zaytsev (2014) showed that this can be tested in a model even with reinforcement measures. The 'classical' centrifuge model tests described by Craig (2014) are important tests in the development of

physical modelling. Zaytsev (2014) described tests on the reinforcement of railway embankments and showed that reinforcement of the soil next to the embankment with four rows of piles can be very efficient at reducing horizontal settlements.

For layers of peat, as present in the model described by Koelewijn *et al.* (2014), which include reed and wood, it may become more difficult to make a centrifuge model. Other arguments played a role in the tests described by Koelewijn *et al.* (2014). One is that for non-specialists a 1:1 scale model is more convincing than a centimetres-high centrifuge model. The question can be raised if that justifies very expensive 1:1 scale tests.

The last four tests described by Koelewijn *et al.* were all on piping. It is known that scaling is an issue in piping experiments (Bezuijen and Steedman, 2010) and thus experiments on a larger scale have to be performed to construct a model with similar piping properties as can be expected in the field. However, another approach is also possible, as shown by Van Beek *et al.* (2014). They performed small-scale model tests, knowing that these would not result in the same critical gradients as reality, but by simulating the flow in these tests they have tried to find the mechanisms that govern piping.

3. Combination of models

Tamate *et al.* (2014) described a 50g centrifuge model to investigate the stability and failure of slopes due to earthquakes. To know in detail what triggers the failure and if failure can be foreseen by certain preliminary events that normally preceded failure, a 1:1 model was made in which the damage caused by the earthquake was included in the model. In this way, there was no need to give an earthquake loading on the large model.

It was found that enlargement of cracks in the upper part of the slope preceded failure.

Askarinejad *et al.* (2014) described another combination of models. A centrifuge model was built to explain the results of a field test. The effect of the bedrock shape and the drainage properties could be studied in detail in a centrifuge model with known boundary conditions. The influence of a buttress in the bedrock was studied in the centrifuge by performing experiments with and without a buttress. This is, of course, difficult in a field test. How the buttress influences the slope failure could also be simulated by a numerical model. This is thus an example where a small-scale test is a valuable addition to a prototype test, and it allows better analysis of the results of the prototype test.

4. Is there a prototype?

The idea of a model test is that there is also a prototype. Nowadays that is not strictly necessary, because a physical model is also in itself a realisation and it can be used to compare results – for example, with the results of numerical calculations. However, often attempts are made to make links between a physical model and an existing or a possible field situation. For the paper by Detert *et al.* (2014) this is questionable. They present an interesting new solution to building a dam on soft soil, using high-strength geotextile. However, looking at their results it is not clear what geotextile strength is necessary to make a prototype of their model.

Moreover, in model tests on static liquefaction it can be questioned whether there is a prototype. As in the piping tests, in these tests there are severe scaling issues. The onset of static liquefaction will occur when, during shearing and consequently contracting of a loose-packed sand body, the pore pressure generation is larger than the dissipation. In a centrifuge, the dissipation is N times higher than in the prototype. Claims that static liquefaction is achieved in a model test ($1g$ or Ng) must always raise some suspicion. Creating static liquefaction is very difficult in each kind of model. Increasing the water table in a slope to create instability will lead to an increase in pore pressures, but this does not mean that there is really a static liquefaction. For example, Take (2014) reported on centrifuge tests by Zhang and Ng (2003), who claim to have created static liquefaction. However, looking at the density of the sand (a 'relative compaction density' of 80% after some compaction in the centrifuge) and at the pore pressures during the experiment, this is probably not the case. The characteristic course of the pore pressure during liquefaction is a very fast increase and a slow decrease. During the fast increase of pore pressure, the grains of the sand lose contact and there is some settlement to a lower porosity. This is, for example, reported by Bezuijen and Mastbergen (1988) in $1g$ experiments where

Figure 1. Static liquefaction in a $1g$ test (modified after Bezuijen and Mastbergen (1988))

porosity and pore pressure were measured simultaneously (Figure 1). In these experiments, the relative density was close to zero. The actual course of the pore pressures in time is difficult to determine in the experiment by Zhang and Ng, due to the relative low sampling rate, but they found a different distribution of pore pressures than expected during liquefaction. The experiment of Zhang and Ng as shown in the paper by Take (2014) indicates once more that the sampling rate should be adapted to the time scale of the expected phenomena.

5. Modelling for a project

Most of the studies described so far are for research. Zeping *et al.* (2014) described centrifuge model tests to be used directly in a project. A rock-fill dam had to be built in a steep valley and there were questions on arching effects and differential settlements. It appeared that filling of the reservoir behind the dam led to significant differential settlements and quite high compressive stresses (15–20 MPa) in the diaphragm wall. In this case, the physical modelling tests certainly helped to optimise the details of the dam project.

6. Seismic tests

Sawamura *et al.* (2014) and Dafni and Wartman (2014) reported on seismic model tests.

Sawamura *et al.* (2014) tested the influence of an earthquake on a culvert in the longitudinal direction. The results of this study can be summarised as 'let it go'. With connections between culverts, significant compressive and tensile forces were measured during dynamic loading. When each culvert was separated, the culverts behaved independently and hardly any tensile force was generated. The same result was obtained for the connection between the wall and the culvert. For the situations tested, the permanent deformation after the test was more or less comparable with or without connections.

Dafni and Wartman (2014) tested the dynamic response of slopes and found, by modelling of models, that the ground motion at the crest is frequency specific and depends on the slope height and ground motion wavelength. In general, they concluded that 'physical modelling in the centrifuge proves to be a useful tool for fundamentally understanding dynamic slope response and specifically topographic effects provide that dense instrumentation can be employed'.

In both papers, it is an advantage that the results could be obtained from small-scale tests, since this gave the possibility of reproducible boundary conditions.

7. Piled embankments

Girout *et al.* (2014) showed centrifuge experiments on piled embankments. An impressive set-up was created in which the vertical load on an embankment with up to 60 piles could be tested. The results were compared with the German Earth structures with geosynthetic reinforcement (EBGEO) recommendations and with Plaxis numerical calculations. The authors followed a well-known procedure: one parameter, in these tests, the maximum deflection of the geotextile between the piles, is taken and the result of that parameter in the test is compared with the results of calculations. It is implicitly assumed that as the maximum deflection is the same then the loading on the geotextile is also the same. However, this is not the case for piled embankments. Van Eekelen *et al.* (2012) have shown that the vertical load distribution on the geotextile reinforcement can be determined from the shape of the geotextile deformation between the piles. A different distribution of the deflections means a different loading, although the maximum deflection is the same. The distribution of the deflection is not measured in the model tests of Girout *et al.* (2014), but it is a result for the two calculation models used (see Figure 2).

Figure 2. Results of Plaxis calculations compared with EBGEO assuming the same maximum deflection

In Figure 2, it is assumed that the maximum deflection is the same in the two calculation models and the shape of the geotextile is calculated for EBGEO and determined for Plaxis from figure 9 of Girout *et al.* (2014). It is clear that the shape of the deformation is quite different. With the same maximum deformation, the total loading on the geotextile will be more than twice as large for the Plaxis calculation compared with the EBGEO calculation. The example shows that comparing a single parameter from a model test with a calculation result (or results from two different calculations) is not sufficient to know whether there is agreement; it is also necessary to know what mechanism occurs. Here, interpretation of a small-scale model centrifuge test may be difficult, because it is difficult to measure the deformation of the geotextile on different locations in such a test.

8. Conclusions

Most papers in this session on embankments showed that interesting results can still be obtained by doing small-scale model tests and centrifuge tests. Sometimes small-scale tests are even preferable to large-scale tests, because a better control of the boundary conditions is possible. The scaling rules indicate where problems with scaled model tests can be expected. For the papers described here, this is the case with the piping experiments and liquefaction experiments. Moreover, it is still possible to use small-scale model tests – not as a representation of the field situation, but as a test on its own to study the relevant mechanism.

It is probably more difficult than in the old days, reported by Craig (2014), when some clay and a centrifuge were enough to reach interesting results. Nowadays, more complicated set-ups and more instrumentation are often necessary.