European research on dambreak and extreme flood processes

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SYNOPSIS. Effective risk management for dams requires an understanding of potential hazards and an assessment of the various associated risks. This requires analysis of potential impacts which, in the case of dambreak, requires an ability to reasonably predict conditions that may result through failure or partial failure of a dam. The IMPACT Project focuses research in five areas related to dambreak, namely breach formation, flood propagation, sediment movement, geophysical investigation and assessment of modelling uncertainty. This paper provides an update on this 3-year programme of work with an overview of some initial findings, particularly in relation to work on breach formation.

THE IMPACT PROJECT

The IMPACT Project (Investigation of Extreme Flood Processes and Uncertainty) is a research project running for 3 years from 2001-2004, funded by the European Commission and supported in the UK by Defra and the Environment Agency. The focus of work is directed at four process areas (breach formation, flood propagation, sediment movement, geophysical investigation) and assessment of uncertainty within modelling tools. These research areas were identified during earlier research (Morris, 2000) as areas where predictive ability was relatively poor, and hence 'weak links' in any risk assessment or emergency planning studies.

Programme of work

Research into the various process areas is undertaken by groups within the overall project team. Some work areas interact, but all areas are drawn together through an assessment of modelling uncertainty and a demonstration of modelling capabilities through an overall case study application. The IMPACT project provides support for the dam industry in a number of ways, including:

Long-term benefits and performance of dams. Thomas Telford, London, 2004

- Provision of state of the art summaries for capabilities in breach formation modelling, dambreak prediction (flood routing, sediment movement etc)
- Clarification of the uncertainty within existing and new predictive modelling tools (along with implications for end user applications)
- Demonstration of capabilities for impact assessment (in support of risk management and emergency planning)
- Guidance on future and related research work supporting dambreak assessment, risk analysis and emergency planning

Each work area is briefly outlined below, followed by a focus upon work investigating breach formation. More detailed information on all areas of the project may be found via the project website at www.impact-project.net.

Breach Formation

Existing breach models have significant limitations (Morris & Hassan, 2002). A fundamental problem for improving breach models is a lack of reliable case study data through which failure processes may be understood and model performance assessed. The approach taken under IMPACT was to undertake a programme of field and lab work to collate reliable data. Five field tests were undertaken during 2002 and 2003 using embankments 4-6m high. A series of 22 laboratory tests were undertaken during the same period, the majority at a scale of 1:10 to the field tests. Data collected included detailed photographic records, breach growth rates, flow, water levels etc. In addition, soil parameters such as grading, cohesion, water content, density etc. were taken. Both field and lab data were then used within a programme of numerical modelling to assess existing model performance and to allow development of improved model performance.

Flood Propagation

Work on flood propagation focussed on two different aspects, namely, prediction of flood flow conditions through urban areas and prediction of flood conditions in real topography.

Whilst river modelling has become a routine part of design and analysis of river works, the way in which flooding of urban areas is predicted has not been ‘standardised’. A number of different approaches may be taken, such as simulation of streets as flow channels, simulation of key areas as storage reservoirs or simulation of general flow by increased roughness. The objective of this component of work is to compare various approaches and hence identify differences and perhaps the best approach. This work has been undertaken through analysis of both field and lab data. Physical modelling of flow through urban areas provided base data for model comparison.

Sediment Movement

Under dambreak or extreme flood conditions, significant volumes of sediment may move. In the near field, close to a breach or failed dam, sediment will be entrained and carried with the surging flow. In the far field, the nature of flow and sediment conditions may produce significant changes to the river such as lateral widening, braiding or major changes in course. With respect to dambreak assessment and emergency planning, sediment movement and deposition may significantly affect bed, and hence surface water, levels as well as provide an obstruction for access.

Research is underway through a combination of laboratory modelling and numerical simulation. Initial work is focussing upon developing new relationships for sediment entrainment under extreme and varying conditions. It is noticeable that current approaches for predicting breach growth or sediment movement during dambreak all utilise existing sediment transport equations that are typically based upon long term steady state conditions.

Geophysics & Data Collection

This 2-year module of work was added to the IMPACT project through a programme to encourage wider research participation with Eastern European countries. The work comprises two components; firstly review and field testing of different geophysical investigation techniques and secondly collation of historic records of breach formation.

The objective of the geophysical work is to develop an approach for the 'rapid' integrity assessment of linear flood defence embankments. This aims to address the need for techniques that offer more information than visual assessment, but are significantly quicker (and cheaper) than detailed site investigation work. Research is being undertaken through a series of field trial applications in the Czech Republic at sites where embankments have already been repaired and at sites where overtopping and potential breach is known to be a high risk.

The objective of collecting breach data is to create a database of events that includes as much information as possible relating to the failure mechanisms, local conditions, embankment material and local surface materials. Analysis may then be undertaken to identify any correlation between failure mode, location and embankment material, surface geology etc.

Uncertainty Analysis

The objective of work here is to establish the uncertainty that may be present in modelling predictions, and subsequently how this might influence use of the information by the end user. Uncertainty in component model predictions (i.e. breach model, flood propagation model, sediment model etc.) is being established, followed by a combined assessment on an overall case study to demonstrate techniques and conclusions.

Conclusions from the IMPACT Project Research
Conclusions from the IMPACT project research will be presented and discussed in full during a final project workshop, to be held in Zaragoza (Spain) on 27-29th October 2004.

This paper will now focus on work undertaken during Years 1 and 2 of the project within the breach formation theme area.

A FOCUS ON BREACH FORMATION

The objectives of this area of research work were to:

- Collate reliable field and laboratory data demonstrating failure processes for cohesive and non cohesive embankment failure (failure mainly by overtopping, but also through piping)
- Objectively assess existing breach model performance
- Allow further development and validation of breach models to improve performance
- Allow an assessment of the effect of scaling on breach data collection (i.e. field data versus laboratory data)

This was achieved by undertaking 5 field tests (up to 6m high), 22 laboratory tests and an extensive programme of numerical modelling with modellers participating from around the world, as well as within the EC.

Field Work

Five field tests (see Table 1) were undertaken as part of the IMPACT project, although additional tests were also undertaken as part of the Norwegian national research programme.

Table 1. Programme of field tests

Test	Nature	Height	Failure mode
Test #1	Homogeneous, cohesive	6m	Overtopping
Test #2	Homogeneous, non cohesive	5m	Overtopping
Test #3	Composite (Rock fill shoulders and moraine core)	6m	Overtopping
Test #4	Composite (Rock fill shoulders and moraine core)	6m	Piping
Test #5	Homogeneous (moraine)	4m	Piping

Figure 1 shows material gradings for each of the various test materials and Plate 1 shows Field Tests #1 and #5 at various stages of testing.

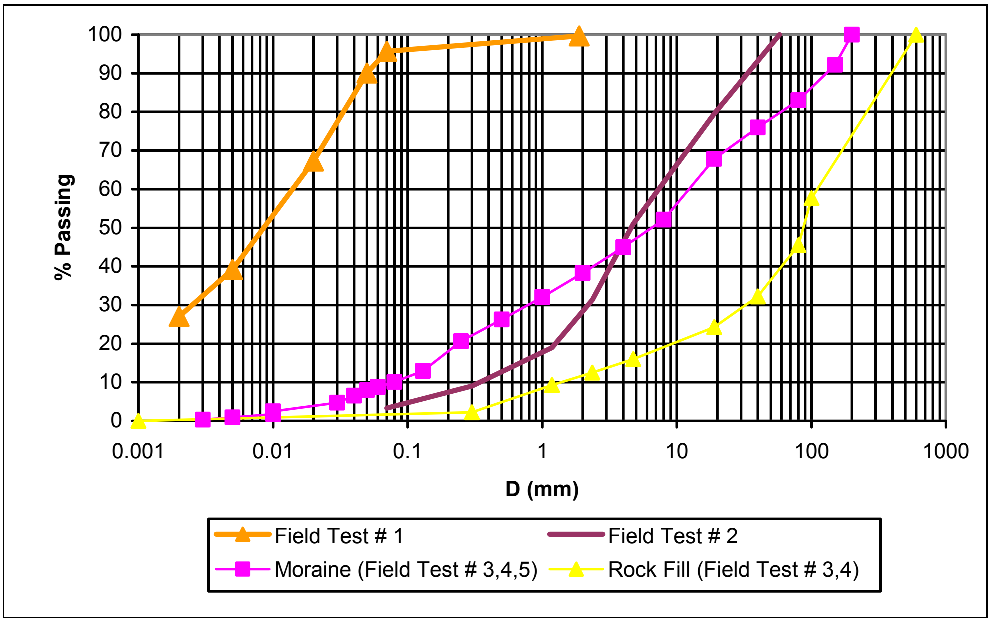

Figure 1 Materials used for the five field tests

Plate 1 Field Test #1 (left) and Field Test #5 (right)

In order to help understand the process of breach formation, a range of data was collected during the tests including water levels, flows and soil properties. Monitoring the rate of breach growth was assisted by the use of movement sensors that were buried within the body of the dam. These sensors recorded the time at which movement occurred, so by recording where the sensors were buried, it was possible to recreate a picture of the breach growth pattern after the failure had occurred.

Initial Findings of Field Work

Whilst data is still being analysed at the time of writing, some initial observations may be made:

Breach Growth & Discharge

Many existing breach models predict discharge by assuming that supercritical flow occurs within the main body of the breach. Flow can then be calculated using a weir equation and the width of the breach. It can be seen from Plate 2 (Field Test #1) that this is not always the case. In this photo it can be seen that the flow through the breach is controlled by a curved weir created by erosion of the upstream embankment face. This ‘control section’ gives weir flow over a length significantly greater than the breach width.

Plate 2: Weir control section

Lateral Erosion of Embankments

Many existing models assume a uniform and sometimes predefined distribution of erosion of material in order to predict breach growth (e.g. uniform growth of a trapezoidal section). It can be seen from Plate 3 below that lateral growth occurs through erosion of material at the base and sides of the breach with discreet failures of the side slopes leading to growth. Note also in this photo that whilst erosion is occurring at the sides, as indicated by coloured water, the flow through the centre is relatively clear, suggesting minimal sediment transport. Most existing models that calculate sediment transport assume a uniform load.

Plate 3: Lateral erosion of embankments (muddy water adjacent to eroding banks; clear water in centre)

Pipe Formation – Effects of Arching

Plate 1(right) shows pipe formation through a moraine embankment. Even after significant erosion has taken place, the crest of the embankment shows little sign of distress and no subsidence. Throughout growth of the pipe the load of the material above the hole has been distributed across the bank through an arching effect. Reliable prediction of breach growth through pipe formation requires a clear understanding and assessment of this process.

<u>Laboratory Work</u>

A series of tests were undertaken in parallel to field tests in the modelling laboratories at Wallingford. The majority of these tests were designed to reproduce and also extend the range of tests undertaken in Norway. This permitted an analysis of scale effect between field and laboratory experiments (1:10 scale factor), and created a wider range of data sets with which to analyse breach growth and assess model performance.

Two main series of overtopping tests were undertaken using the large 'flood channel facility' at Wallingford. The first series (2002) simulated breach growth through overtopping of non-cohesive material. This related to field test #2. Following an analysis of potential scaling mechanisms, the material used was also scaled at 1:10. In order to create a material with properties matching the material used in field test #2, but at a scale of 1:10, it was necessary to mix 4 different sands. The second series (2003) was undertaken to investigate beach formation through cohesive material. Failure was again by overtopping. The behaviour of cohesive material cannot be scaled exactly without also scaling other loads such as gravity. This option was not available to us (i.e. use of a large centrifuge) hence it was decided that tests would be undertaken using material similar to that used for field test #1 and any scale effects carefully considered. For example, analysis of material condition and hydraulic loading allowed an assessment of the scaling of critical shear stress and material erodibility.

Figure 2 shows the grading curves for both cohesive and non-cohesive tests and Plate 4 examples of each laboratory test.

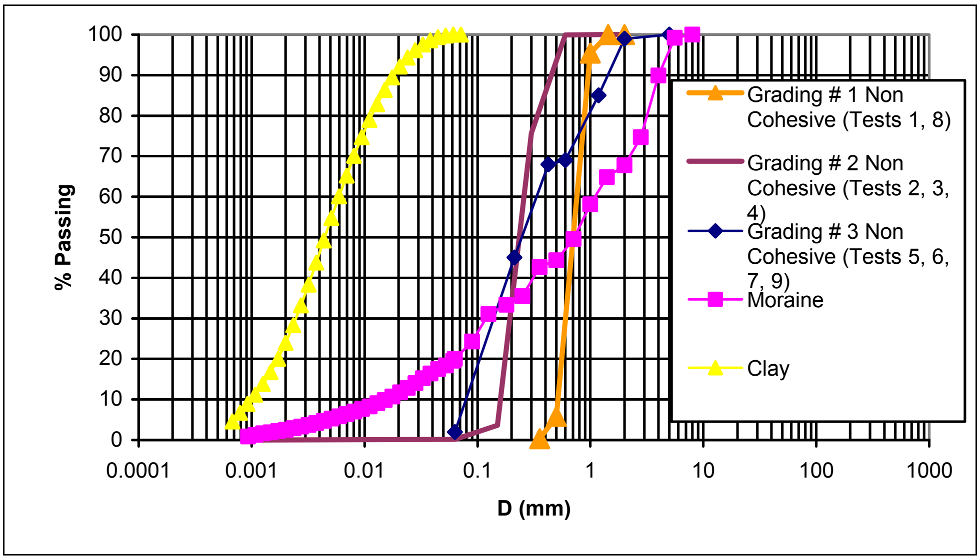

Figure 2 Materials used for cohesive and non-cohesive laboratory tests

Plate 4 Laboratory test of breach formation through overtopping

Table 2 provides a summary of the tests undertaken. Parameters that were varied for the non-cohesive tests included geometry and material grading distribution around a constant D_{50} size. Parameters varied for the cohesive tests included geometry, compaction and moisture content.

Table 2 Objective of laboratory tests

Test	Nature / purpose of test
Non-Cohesive tests; 0.5m high; material gradings 1, 2 or 3:	
#1	Facility set-up / trial
#2	Scale of Field Test #2, but uniform material grading based upon D_{50}
#3	Repeatability of Test #2
#4	As Test #2, but breach initiation adjacent to side of flume
#5	Direct replication of Field Test #2
#6	As Test #5, but embankment face at 1:2 instead of 1:1.7
#7	As Test #5, but embankment crest width 0.3m instead of 0.2m
#8	As Test #2 but larger D_{50} for uniform grading of material
#9	As Test #5 but seepage allowed to develop prior to testing
Cohesive tests; 0.6m high; material clay or moraine:	
#10	Scale of Field Test#1
#11	Repeatability of Test #10
#12	As Test #10, but constructed with half compaction effort
#13	As Test #10, but constructed to optimum moisture content
#14	Continuation of Test #13
#15	As Test #10 but 1:1 gradient for downstream slope
#16	As Test #10 but 1:3 gradient for downstream slope
#17	As Test #10 but using moraine material

In addition to these 17 tests, a further 5 tests on pipe formation were undertaken. Two of these tests were to aid development of an appropriate failure mechanism to ensure that failure of the piping field tests occurred within a reasonable period of time. The remaining three were testing of pipe formation through 3 samples of real embankment (~1m^3) taken from the Thorngumbald Managed Retreat Site on the River Humber. This work was undertaken by Birmingham University and was also consistent with recommended R&D work under the EA / Defra *Reducing the Risk of Embankment Failure under Extreme Conditions* project.

<u>Initial Findings of Laboratory Work</u>

Whilst data is still being analysed at the time of writing, some initial observations may be made:

Headcut Erosion
Erosion of cohesive and non-cohesive embankments occurs in a different way. Cohesive material tends to erode via a series of steps – called head cutting. This was clearly seen in the field tests, but was also reproduced in the laboratory, suggesting that this process was not affected by scaling at 1:10 (see Plate 4 (left)).

Soil Properties, Condition and Seepage
The effect upon the rate of breach formation of variation in soil properties and / or condition was quite noticeable and in particular, the effects of variation in moisture content for cohesive materials. Changing the moisture content of the cohesive material from 20% to 30% (near optimum) changed the erodibility rate of the material by a factor of 12. This effect was significantly smaller when working with non-cohesive material, where allowing seepage through the bank to establish prior to testing appeared to have a minimal effect upon the eventual rate of breach growth.

Material Grading & Compaction
Many existing models represent embankment material by a single D_{50} value. Tests using different material grades, but each with the same D_{50} value, showed different behaviour, with, as might be expected, a wider grading material offering greater resistance to breaching. Also of significance is the degree of material compaction (or density). In one test, halving the compaction effort resulted in a significant change to the rate of breach formation. Specifically the rate of down cutting increased by x2.5, lateral widening increased by x5 and headcut erosion increased by x1.6.

Numerical Modelling and Analysis
A fundamental objective of the field and laboratory research work was to collect reliable data with which to validate and further develop numerical models for predicting breach formation. At the time of writing, model performance was being assessed through a controlled programme of testing such that field or lab data was only released after initial modelling predictions had been collated. This ‘blind’ and ‘aware’ approach to modelling ensured complete objectivity in the assessment of performance.

Whilst some initial results have been assessed, the extent of model performance assessment is not sufficient to allow reporting here. However, full results from this analysis work will be reported later during 2004 and posted via the project website (www.impact-project.net).

BREACH FORMATION: MIDTERM CONCLUSIONS AND OBSERVATIONS

The most striking observation (based upon the field and laboratory test data) is the clear relationship between the breach formation process and the embankment material properties and condition. Whilst this may seem obvious, it is a fact that many existing predictive breach models ignore such information and endeavour to predict the failure process based upon geometry, limited soil property information and hydraulic loading conditions. Whilst tests show that variations in material grading, compaction and moisture content (for example) can affect the rate of material erosion and hence breach growth by factors of more than x10. Where models fail to include even the most basic of soil properties or conditions, then the potential accuracy of their predictions will be significantly constrained.

Failure to account for the way in which breach growth develops will also limit modelling accuracy. For example, it is clear that rockfill embankments behave differently to non or low cohesive earthfill embankments which in turn behave differently to cohesive embankments. This difference applies particularly to the way in which the breach initiates. Most existing models make broad assumptions as to the way in which erosion occurs so as to provide an average rate of formation and hence discharge. Whilst this may be a valid approach for a specific material type and condition (against which the model has to be calibrated), this will lead to inaccuracies when routinely applied as a single solution or model applicable to all materials and conditions.

Future Direction of research

An extensive analysis of breach model performance is currently underway and should be completed by June 2004. This work will also link with an assessment of modeling uncertainty in order to provide the 'end user' with guidance on both the performance / accuracy of breach models, as well as the range of uncertainty that might be reasonable to expect within a model prediction.

In the longer term, it is clear that in order to improve our ability to predict breach growth we will require a much closer integration of soil mechanics and hydraulics analysis. Critical soil parameters that have the most influence upon the initiation and growth of a breach will need to be identified, along with methods for measuring or monitoring these parameters in the field.

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IMPACT Project workshop proceedings:

Workshop #1	16-17 May 2002	Wallingford, UK
Workshop #2	12-13 September 2002	Mo-I-Rana, Norway
Workshop #3	6-7 November 2003	Louvain-la-Neuve, Belgium

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