IMPACT

Investigation of Extreme Flood Processes and Uncertainty

Final Technical Report – January 2005

Contents:

Final Technical Report

Co-ordinator: Mark Morris, HR Wallingford, UK

Contract No. EVG1-CT-2001-00037
Project website: www.impact-project.net

IMPACT: Investigation of Extreme Flood Processes and Uncertainty

A research project supported by the European Commission under the Fifth Framework Programme and contributing to the implementation of the Generic Activity on Natural and Technological Hazards within the Energy, Environment and Sustainable Development Programme.

Contract No.	EVG1-CT-2001-00037	
EC Project Officer:	Karen Fabbri	Karen.FABBRI@cec.eu.int
	Hans Brelen	Hans.Brelen@cec.eu.int
Project Co-ordinator:	Mark Morris	m.morris@hrwallingford.co.uk

The IMPACT Project was undertaken through a team effort. The project team comprised 11 partners from 10 European Countries as follows:

HR Wallingford Ltd	(UK)
Universität Der Bundeswehr Műnchen	(Germany)
Université Catholique de Louvain	(Belgium)
CEMAGREF	(France)
Università di Trento	(Italy)
University of Zaragoza	(Spain)
CESI	(Italy)
SWECO	(Norway)
Instituto Superior Technico	(Portugal)
Geo Group	(Czech Republic)
H-EURAqua	(Hungary)

The team also acknowledges the financial support offered to some partners by national agencies and the participation of additional individuals and organisations from around the world. In particular, financial support from the UK DEFRA / EA joint flood defence research programme.

Technical collaboration and support is also acknowledged from:

Des Hartford	BC Hydro	Canada
Mikko Huokuna	FEI	Finland
Tai Mai Phat	Hydro Quebec	Canada
Sebastiano Sanna		Italy
Greg Hanson	USDA-ARS	US
Paul Visser	TU Delft	Netherlands
Gurmel Ghataora	Birmingham University	UK
Jean-Robert Courivaud	EDF	France

OVERVIEW

This report comprises the final Technical Report for the IMPACT project. The report has been structured according to project results in the following way:

1. Overview
2. Field and laboratory data
3. Benchmark tests of current models
4. New approaches to breach formation modelling
5. New approaches to flood propagation modelling
6. New approaches to modelling sediment movement under extreme flood conditions
7. Development of a geophysics based approach for the rapid assessment of embankment integrity
8. Assessing modelling uncertainty
9. Site specific case studies
10. Associated project documents

These results are cross cutting in relation to the six project work packages. The contents of this report are based upon material drawn from more detailed reports for each of the work packages. All references may be accessed via these more detailed reports and are not included within this document. A summary of associated IMPACT Project documents is given at the end of this report (Section 10).

KEY MESSAGES

Significant Advances:
The IMPACT Project has allowed significant advances to be made in the understanding and modelling of a range of extreme flood processes including breach formation, flood propagation, sediment movement, modelling uncertainty and embankment integrity assessment. This has placed European researchers, and subsequently European flood modellers, at the forefront of current capabilities in this field.

Best Practice:
Research within the project process areas has identified and advanced current best practice. In particular:

- Breach formation modelling: A range of breach models have been assessed and developed using large scale field and laboratory data. These models offer improved capabilities and reliability in comparison to earlier models and offer the current state of the art for breach modelling. The widely used US NWS model, developed in the 1980's, has now been shown to be obsolete in its approach.
- Flood Propagation modelling: Analysis of different modelling techniques for simulating urban flooding and dam break propagation has highlighted differences between models and modelling approach. Limitations in modelling are found to be constrained by the accuracy of data provided for the models, modelling assumptions (roughness values) and computing power, rather than by the mathematical modelling approaches. Grid resolution should improve further as computing power increases, so allowing wider use of more complex 2D modelling techniques, although research is urgently needed to clarify modelling roughness values for extreme flow conditions.
- Sediment movement: Research has confirmed that sediment movement during extreme floods has a significant effect upon the depth of flood water and on the wave propagation rate. However, the level of understanding of these dynamic processes, and the performance of new models, mean that no tools are readily available for use within the flood risk management community. Further research into this area is required in order to advance knowledge and modelling ability and to allow these important processes to be included within flood risk management assessments.

Quantifying Uncertainties:
A practical approach to assessing the potential magnitude of uncertainty within the flood modelling process was developed and applied to a case study. In practice, this was applied to breach and flood propagation models only; the uncertainty associated with predicting sediment movement was found to be too large to warrant such an assessment. The size of uncertainty in predicted flood water levels for the project case study was found to be quite large – in the order of ~30% of water depth. This has significant implications for end users (e.g. emergency planners, asset managers, development planners etc.) in how they use flood modelling results; end users should accommodate such degrees of uncertainty within their applications.

Integrity Assessment:
A review of geophysical investigation techniques has been undertaken and new technology tested to identify a new approach that would allow the 'rapid', non intrusive integrity assessment of flood defence embankments. Results of a new system are promising and, with further development, may allow integrity assessment of 5-10km of embankment per day compared with the relatively slow and expensive existing approach of isolated sampling.

Added Value of International Collaboration:
The IMPACT Project has proved a successful project for European collaboration – and indeed wider international collaboration. The nature of the science means that the problems faced are similar worldwide. Equally, the high level of expertise required to research and develop capabilities in this field means that there are relatively small numbers of such experts worldwide. Having established key links through the IMPACT project it is recommended that these links are maintained where possible to enhance further research in this specialist area.

Contents list

1. INTRODUCTION

1.1 Overview

The IMPACT project addresses the assessment and reduction of risks from extreme flooding caused by natural events or the failure of dams and flood defence structures. The work programme is divided into five main areas, addressing issues originally identified by the CADAM project (EC FP5 – Concerted Action on Dam break Modelling). Research into the various process areas has been undertaken by groups within the overall project team. Some work package 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.

Results from the five technical work package areas have been structured according to the following deliverables:

- Field and laboratory data
- Benchmark tests of current models
- New approaches to breach formation modelling
- New approaches to flood propagation modelling
- New approaches to modelling sediment movement under extreme flood conditions
- Development of a geophysics based approach for the rapid assessment of embankment integrity
- Assessing modelling uncertainty
- Site specific case studies

1.2 Work Packages

The IMPACT Project research programme comprised 5 technical work packages as follows:

- WP2: Breach formation
- WP3: Flood propagation
- WP4: Sediment movement
- WP5: Uncertainty analysis
- WP6: Geophysics and data collection

1.2.1 WP2: Breach formation

Research here focused on our ability to predict breach formation through a dam or flood defence embankment. The core work linked field and laboratory testing (to collate reliable data sets and understand basic breach formation processes) with numerical model testing, comparison and development. In addition, consideration was given to factors affecting breach location (links via WP6) and also the uncertainty associated with breach modelling was investigated (WP5). A more detailed description of the work plan can be found in the Description of Work (DoW), sections WP2.1-2.4, WP5 and WP6.

Core research work comprised:

- 5 large scale field tests (embankments 4-6m high tested to failure)
- 22 1:10 scale laboratory tests
- Extensive numerical modelling using field and laboratory data leading to model validation and development
- Development of methodology for identifying the relative risk of breach location in linear defences

1.2.2 WP3: Flood propagation

WP3 was devoted to the advancement of the scientific knowledge and understanding, and to the development of predictive tools in the area of the simulation of catastrophic inundation of valleys and urban areas following the failure of a control structure. The scope of work was broadly divided into two areas: *Urban flooding* and *Flood propagation in natural topographies* (flood routing). Both topics have been approached in a similar manner - by means of a combination of desk, experimental, field and computer work.

Desk work comprised conceptual experiment design and model development as well as analysis of laboratory data and simulations output. Experimental work was devoted to understanding flow characteristics and to acquisition of reliable data for model testing and validation. Field data was sought for the same purposes. Computer work comprised programming model developments and performing simulations of selected flood scenarios.

1.2.3 WP4: Sediment movement

The focus of WP4 was to investigate sediment movement during extreme flood conditions and how it may be modelled. Work focussed on movement in the near and far fields, namely movement immediately downstream of a breach or failure (near field) and morphological response including channel widening, braiding etc. (far field). As with other WPs, the approach adopted comprised a mixture of laboratory and numerical modelling, culminating in analysis and application to a case study.

1.2.4 WP5: Uncertainty analysis

The objective of work here was to demonstrate the uncertainty inherent within the flood modelling process and how this may affect end user use of the data. The scope of work included development of an approach to assess modelling uncertainty and application, where possible, to breach, propagation and sediment modelling through use of a case study application. Development of the approach and implications for end users was undertaken through group and end user feedback via the four project workshops. This work package was therefore cross cutting across all of the science process areas.

1.2.5 WP6: Geophysics and data collection

WP6 contained two clear areas of work. The first focussed on the testing and development of geophysical investigation techniques, whilst the second on review, collection and analysis of field data relating to breach formation.

The overall objective of the geophysical work was to establish whether or not an approach for the non intrusive, rapid assessment of embankment integrity could be developed using existing or modified geophysical investigation techniques. This work was undertaken through analysis and comparison of approaches using a series of field trials.

The primary objective of the breach data collection was to try and establish whether or not breach location could be related to soil or other field parameters through collation and analysis of data relating to large numbers of embankment failure in Hungary and the Czech Republic. This component of work relates closely to objectives of WP2 and is reported along with this work in Section 3 of this report.

2. FIELD AND LABORATORY DATA

Since extreme floods occur infrequently, it is difficult to obtain reliable and extensive data sets through which the flood processes may be analysed and models validated. Consequently a core part of the IMPACT project for all of the work packages included collection of field and / or laboratory data.

2.1 WP2: Breach Formation

2.1.1 Objective and approach

Objectives of the modelling work undertaken through WP2 of the IMPACT project were to:

- Establish a better understanding of the embankment breaching process
- Provide data for numerical model validation, calibration and testing, and hence improve modelling tools
- Provide information / data to assess the scaling effect between field and laboratory experiments
- Identify best approach /approaches to simulate breach formation through embankments
- Assess and quantify the level of uncertainty of the current breach modelling techniques

The work divided into 3 clear packages, namely field modelling, laboratory modelling and numerical modelling / analysis (see Figure 2.1).

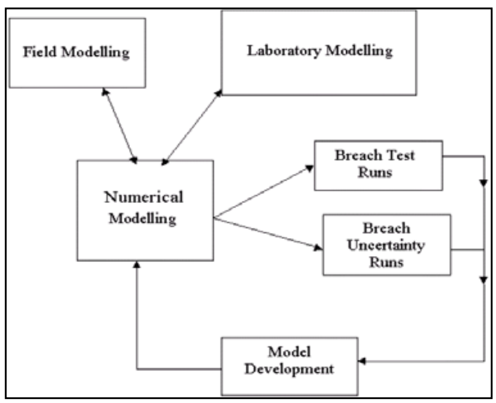


Figure 2.1 Programme of field, laboratory and numerical modelling

2.1.2 Data collected

Extensive sets of field and laboratory data were collected. In Years 1 and 2, five field tests were undertaken in Norway. The five tests were designed to provide large scale data on breach formation processes in homogeneous and composite embankments, failing by overtopping and piping. The five tests comprised:

- 6 m high cohesive embankment / overtopping (25 % clay and less than 15% sand)
- 5 m high non-cohesive embankment / overtopping (less then 5 % fines)
- 6 m Composite embankment / overtopping (Rock fill & Moraine)
- 6 m Composite embankment / piping (Rock fill & Moraine)
- 4.5m Homogeneous embankment / piping (Moraine)

In general, the following data was collected from each field test:

- Water level at locations up and downstream of the embankment
- Flow released from the upper reservoir into the 'test reservoir'
- Pore water pressures in the embankment
- Breach development (time development of breach based upon movement sensors)
- Digital cameras and videos up and downstream monitoring breach development

Figure 2.2 below shows examples of 4 different field tests in progress.

Figure 2.2: Breach development stages (4 different field tests)

A total of 22 laboratory experiments were also undertaken at HR Wallingford in the UK. The overall objective of these tests was to better understand the breach processes in embankments failed by overtopping or piping and identify the important parameters that influenced these processes. These tests were divided into 3 series, as summarised below:

- Series #1: 9 tests Homogeneous embankment; non cohesive material; overtopping failure
- Series #2 8 tests Homogeneous embankment; cohesive material; overtopping failure
- Series #3 5 tests Homogeneous embankment section; cohesive material; piping failure

2.2 WP3: Flood Propagation

2.2.1 Objective and approach

The objectives of collecting data from laboratory experiments and field searches are manifold:

- To gain insight into flow characteristics in extreme flooding conditions, in particular rapid flow effects such as front movement and interactions, flow reversals, interaction with obstacles.
- To obtain well documented data sets that can be reliable used for understanding the flow behaviour and for mathematical model development, testing and validation.
- Learn about real life effects that can not be reproduced at the laboratory scale.

2.2.2 Data collected

Large amounts of data on flood propagation have been accumulated and classified during the course of the project. The type of data consists mainly of water level evolution at selected locations of a physical model or a selected area of a real valley. Water velocities and inundation maps (high water marks) as well as pictures and video sequences have also been collected in relation to the following Deliverables listed in the Description of Work (DoW) project contract document:

- D3.1.2 Laboratory benchmark datasets for urban flood modelling
- D3.1.4 Validation of modelling techniques for urban flooding against field data
- D3.2.2 Flood propagation data from laboratory physical models
- D3.2.4 Validation of modelling techniques for flood propagation in natural topographies

Experimental work in urban flooding was scheduled during Year 1 of the project involving two partners, Université Catholique de Louvain (UCL) and Centro Elettrotecnico Sperimentale Italiano (CESI). Experiments were conducted to determine detailed flow characteristics around buildings and general flow patterns and flood-city interaction in urban areas.

The former were performed by UCL and named as "the isolated building experiment" whereby a severe dam break wave impinged on a model building in a laboratory flume. Measurements of water level evolution at several gauging points together with several stills of surface velocity vectors around the building were obtained for several dam break wave intensities.

The latter conducted by CESI at its Milano facilities dealt with the flooding of a model city in a short reach of the physical model of a river valley (scale 1:100). The experiment was named "the model city flooding experiment". The model city, made up of concrete blocks was instrumented with water depth probes of the conductivity and pressure types. Water depth history at several points located amidst buildings was recorded during the flooding episodes. The experiment consisted of many runs with the original and a modified valley bathymetry, two model city lay outs and several inflow hydrographs of varying intensity. The amount of recorded data is significant.

Experimental work devoted to flood propagation in natural valleys was scheduled during the second half of Year 2 involving UCL and CESI again. The first experiments (UCL) considered Dam break flow over a sill. The propagation of a strong dam break wave along a laboratory flume with a sill in part of its bottom led to a complex set of effects. Of particular interest is the propagation of the wave upslope over a dry bed, then down slope once the crest is surpassed and the multiple reflections at the end of the flume and the sill slopes. Data were obtained with the aid of water depth probes and high speed cameras. The second set of data regard the propagation of a flood along the physical model of a river valley. Several flood intensities were considered. Data collated by CESI from former experiments include water depth history at more than twenty locations along the model obtained by both conductivity and pressure transducer type probes.

2.3 WP4: Sediment Movement

2.3.1 Objective and approach

A series of laboratory experiments were conducted in the laboratories of the UCL (dam-break flow) and UdT (uniform debris flow). Two types of behaviour were considered:

- In the near field, rapid and intense erosion accompanies the development of the dam-break wave. A first stage of work was devoted to the characterisation of the debris flow in uniform conditions, before investigating more in depth the behaviour under dam-break flow conditions (Figure 2.3).
- In the far field, the solid transport remains intense but the dynamic role of the sediments de-creases. On the other hand dramatic geomorphic changes occur in the valley due to sediment de-bulking, bank erosion and debris deposition (Figure 2.4). Later work is devoted to the far-field behaviour.

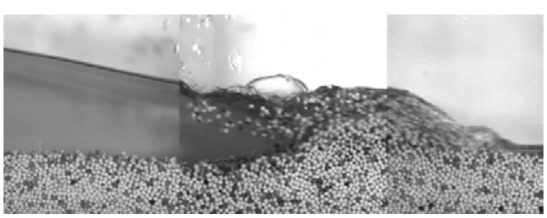


Figure 2.3 Near-field geomorphic flow (UCL)

Figure 2.4 Bank erosion resulting from intermittent block failure

Field data tests were not undertaken, but data from the Lake Ha!Ha! dam-break that occurred in 1996 on a tributary of the Saguenay river in Quebec (Brooks and Lawrence, 1999) was analysed in detail (See Section 8).

The following data sets are available from undertaking laboratory tests:

- Uniform debris flow, to investigate the acting forces and the velocity distribution (UdT)
    - with uniform material (PVC particles)
    - with graded material (PVC particles and sand)
- Dam-break flow to investigate near-field effects: scouring and formation of a debris-flow plug (UCL)
    - with the same bed level upstream and downstream from the dam (Spinewine and Zech, 2002b)
    - with an initial step in the bed level (higher level in the reservoir), described in Spinewine and Zech (2003)
- Dam-break flow in an initially trapezoidal valley to investigate far-field effects: bank erosion and channel widening (UCL), described in le Grelle et al. (2003, 2004)
    - with uniform material (sand)
    - with graded material (sand and coarse gravel)

2.4 WP6: Breach Field Data

2.4.1 Objective and approach

Work under WP6 involved collation of case study data and mass data relating to dike breach and extreme flood events in Hungary and Czech Republic; analysis of the data in relation to identification of factors contributing to breach location.

The methodology of data collation was based on archival investigation and systematization of historical data available in national and county archives and libraries, and in the Museum and Archive of Water Affairs to find traces of the historical records of the old Flood Prevention and Drainage Associations ceased just after World War II, and of the papers, as well as legal and technical regulations of the 19th and early 20th century. The existing regional water directorates were also subject of investigation concerning their collection of old plans and technical papers.

Statistical evaluation of data types, formation of data series, assessment of interdependence of data and homogeneity tests, finally standard statistical analysis of the data series were performed.

2.4.2 Data collected

Data collection was extended to the following main groups of information: -date and location of breach; -breach data; -origin of the flood causing failure; -failure mechanism; -cause of breach; -flood parameters; -data on damages; -embankment parameters; -soil types; -river morphology; -remarks and literature. All together the data collection plan extended to 59 different types of data of every particular dike breach. The actually available data covered finally 51 types as a maximum.

A total of *1,245 breaches were identified* in Hungary. Length of breaches were identified in 559 cases, along the Danube in 78, along the Tisza River in 96 cases, along primary tributaries to these rivers in 290 cases, while along small rivers in 95 cases. Soil types are identified in 72 cases, even if roughly or generalised, due to the in homogeneity of the several times reinforced dikes.

Although *complete data series* of events comprising detailed flood parameters, embankment parameters and soil type characterisation *are too rare*, and in the majority of the cases only partial data are available to this unexpectedly huge amount of breaches, quite a high number of data series could be analysed for different cases. Parameters concerning date, final length, cause, and failure mechanism of breach are best available.

2.5 The Value of Data (potential uses)

A common finding of each of the work packages was that more advances could be made with models if time was available for further analysis of the data sets. Consequently, the field and laboratory data collected under

IMPACT retains considerable value – both in terms of use by other researchers to validate new models and approaches, and use by IMPACT project members for continued analysis and model development.

The nature of the work undertaken through IMPACT makes much of the data quite rare and of significant value to researchers in this field. The availability of high quality, large scale field and detailed laboratory data is rare – particularly for extreme events, where the focus during the event is rarely on data collection.

A common finding of researchers in each of the main process areas was that more could be learnt and further steps in model improvement made through further more detailed analysis of the data sets. The availability of the data means that there is significant value in funding such additional research.

3. BENCHMARK TESTS OF CURRENT MODELS

3.1 WP2: Breach Formation

3.1.1 Objective and test description (overview)

Extensive numerical modelling has been undertaken by selected members of the IMPACT project team and the value of model comparison was enhanced by additional participation from modellers world-wide (See Table 3.1 for details). A significant number of numerical model runs has been undertaken as blind tests to ensure complete objectivity. Blind means that numerical modellers were asked to undertake their work and submit their results before the results from the field and laboratory tests are released. Modellers were then invited to submit further (revised) modelling results after receiving the field or lab test results (Aware testing). Results presented in this paper are blind except for laboratory Series #1 where only aware testing was undertaken due to data processing errors.

No	Organisation	Country	Modeller	Model(s)
1.	HR Wallingford	UK	Mohamed Hassan	HR Breach NWS BREACH
2.	Cemagref	France	Andre Paquier	Simple model
3.	UniBW	Germany	Karl Broich	Deich_P
4.	ARS-USDA	USA	Greg Hanson	SIMBA model
5.	Delft Hydraulics	Holland	Henk Verheij	SOBEK Rural Overland Flow
6.	Ecole Polytechnique de Montreal	Canada	Rene Kahawita	Firebird model

Table 3.1: Researchers who participated in the numerical modelling programme

The following list shows the numerical modelling runs undertaken by the modellers:

Field tests:
- Blind runs: Field test 1,2,3,4 and 5.
- Aware runs: Field tests 3, 4 and 5.

Lab Tests:
- Series #1: Aware runs Lab test 2,4,5,6,7 and 9.
- Series #2: Blind runs Lab test 10,11,12,13,14,15,16 and 17
- Aware runs Lab test 10,11,12,13,14,15,16 and 17

.

Given the large amounts of data collected through the field and laboratory modelling work, it was not practical for all modellers to undertake blind and aware simulations for all data sets. Priorities were placed as follows:

1 Model field test cases
2 Model lab test cases matching field test cases
3 Model other lab test cases

3.1.2 Results and analysis

Extensive data sets have been collected from the numerical modelling exercise. All results have been plotted and an initial review of performance made. A breach modelling workshop was held at HR Wallingford on 21-23 April 2004, where field, lab and numerical modelling data was reviewed. Conclusions from this workshop may be found in the workshop notes, with overall conclusions feeding into Section 4 – new approaches to breach formation modelling.

3.2 WP3: Flood Propagation

Benchmarking of computer models has been a capital task during project duration, and, in particular, the core of tasks leading to deliverables D3.1.3 Urban flood modelling tests against laboratory benchmark configurations, D3.1.4 Validation of modelling techniques for urban flooding against field data, D3.2.4 Validation of modelling techniques for flood propagation in natural topographies. Overall three benchmark campaigns were conducted each one comprising several configurations.

3.2.1 Objective and test description (overview)

The objective of all tests performed is to validate the techniques developed and built into the computer models. This is done by comparison of model output with data either obtained from laboratory experiments or from field observations. The data used are almost exclusively water depth history at different gauging locations although in some tests snapshots of surface velocity vectors have also been used.

3.2.1.1 The isolated building test case

This benchmark was presented by UCL (Soares-Frazao & Zech, 2002) in late 2002 and launched in early 2003. It considers the propagation of a strong dam break wave along a flume that impinges onto a building shaped object as described in The isolated building experiment. The main objective of the benchmark was the assessment of the capabilities of mathematical models to represent the complex flow pattern arising in the interaction of dam break flow and a single building: shock formation, reflection and propagation, unsteady wake and vortex shedding. More than eight teams participated in the benchmark, including partners of IMPACT project (UCL, Cemagref, UDZ) and external teams (National Taiwan University, University of Parma and University of Pavia). It is worth noting that in this benchmark surface velocity measurements were also available for comparison.

3.2.1.2 The model city flooding experiment

The objective of this benchmark was to assess the accuracy and reliability of models in predicting flooding in urban environments. To this end, IMPACT project partners involved (UCL, Cemagref, UDZ) run their models according to the configuration explained in the Model city flooding experiment. A detailed description of the benchmark is given in Alcrudo et al. (2003). The benchmark was presented in the 2nd Impact project workshop in Mo-i-Rana (Norway, November 2002) and launched in early 2003.

3.2.1.3 Other benchmarks

Other validation initiatives have been undertaken within IMPACT project that are not officially considered as benchmarks. In particular, runs have been made to consider model performance in two experimental configurations concerning issues of flow propagation in natural topographies: The Dam break flow over a sill and the physical model of Toce river valley, both described earlier in this report. The runs addressed the ability to model front (shock wave) propagation and wetting and drying of the terrain. They are not considered true benchmarks because no separate blind and aware phases were respected and also because only one or two partners (UDZ and UCL or only UDZ respectively) undertook them, hence a critical comparison between models was not possible. Another benchmarking campaign in the flood propagation area of the IMPACT project is the case study (The Tous Dam break) that will be dealt with later in this report.

3.2.2 Analysis and conclusions

3.2.2.1 The isolated building test case

As it is put forward in Soares-Frazao et al. (2003) the highly unsteady flow pattern arising from the interaction between the dam break wave and the model building is extremely complex. For this reason there were strong fears that it could be adequately modelled. However, overall agreement between experimental and computed water depth history at all gauging points was observed for all models used, although differences between modelling techniques were also noted. It is worth noting that the very simple high friction technique performed as well as the others. This is probably due to the rapid condition of the flow. Of special relevance in computed results were found the mesh resolution and characteristics. Agreement between computed and experimental surface velocities was not so obvious but still acceptable. Average values were reasonably well predicted but rapid time like oscillations were difficult to capture by all models. It can be concluded that complex flood flows can be adequately solved for in the laboratory scale with the techniques developed. A more in depth analysis of benchmark results can be found in Soares-Frazao et al. (2003).

3.2.2.2 The model city flooding experiment

The model city flooding experiment benchmark aims at assessing the capability of present models to reproduce mutual influences between the flow and the buildings in the flooding of a city. The benchmark configuration was devised to test the capability of models to reproduce the complex flow pattern taking place during extreme flooding of a city where interactions between the city structure (streets, crossings …) and the high speed flow, lead to hydraulic jump formation, propagation, reflections and interactions. To this end water depth history measured at some ten gauging points located among the model buildings was compared with computer model predictions. Benchmark results were presented at the 3rd Impact project workshop in Louvain-La-Neuve (Belgium) in November 2003. A detailed analysis of the results can be found in the corresponding technical report (Murillo et al. 2004b). Other reports focus on the modelling efforts made by individual partners: Noel et al. (2003), Mignot and Paquier (2003).

Main conclusions are that the studied configurations were consistently well reproduced by all models and modelling techniques used. Points of concern were boundary conditions (mainly inflow) responsible for a certain advance in flood arrival with respect to experimental data. Main flow features such as primary front formation and reflection at the city water front (first row of buildings), flood progress inside the city, secondary and oblique jumps as well as their interactions, and wakes behind the buildings were satisfactorily reproduced by all models with different degree of detail depending mostly upon mesh resolution.

3.2.3 Other benchmarks

The two other tests considered during Flood propagation Impact project work, Dam break flow over a sill and the physical model of Toce river valley were worked out by only one or two partners with access to experimental data during modelling work and hence can not be considered full benchmarks. The first one addressed the wave propagation over dry bed as well as front propagation up and down slopes and reflections. Modelling work was undertaken by UCL and UDZ. It was expected that all models fitted with modern numerical technology (shock capturing operators, balanced treatment of source terms, wetting and drying logic etc …) performed well in the test as it happened to be the case. Test results can be found in Soares-Frazao et al. (2004) and Murillo et al. (2004a). Tests concerning model performance in the simulation of the flooding of the physical model of Toce river valley were conducted by UDZ showing overall good agreement with experimental data (Murillo et al. 2004a).

The conclusion that can be drawn from these tests is that modelling flood propagation cases with the SWE approximation at the laboratory scale can be accomplished with considerable accuracy at reasonable cost, even if some model assumptions are violated at some locations (for instance buildings).

3.3 WP4: Sediment Movement

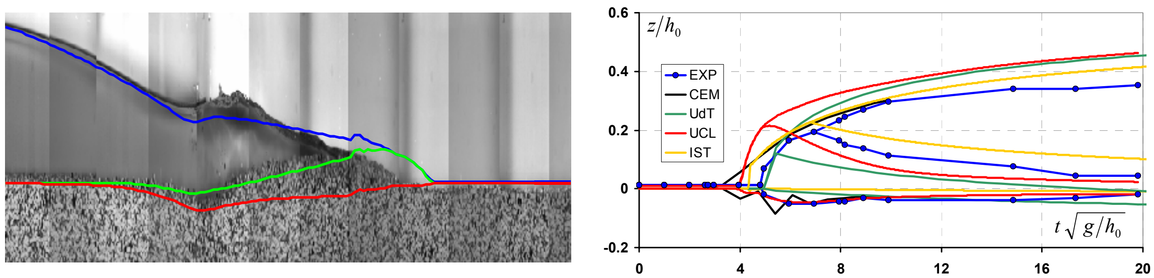
3.3.1 Objectives and approach

Three benchmark sessions were conducted, allowing different modellers to test their models in a blind simulation of experiments performed during the IMPACT project. By comparing the results of such blind simulation, and analysing those at the light of the different mathematical description, knowledge can be gained about advantages and limits of each modelling approach. For each benchmark, the modellers were asked to provide a description of their numerical model, which allowed the in-depth analysis of the results

3.3.2 Results collected

Dam-break flow over an initially flat bed

The benchmark description is given in Spinewine and Zech (2002b). Results were obtained from 4 institutions, members of the IMPACT Sediment Movement group: CEMAGREF, UdT, IST and UCL. Figure 3.1 shows typical results, where the computed results for the bed level, the level of the moving sediment layer and the water level are compared to the experimental ones.

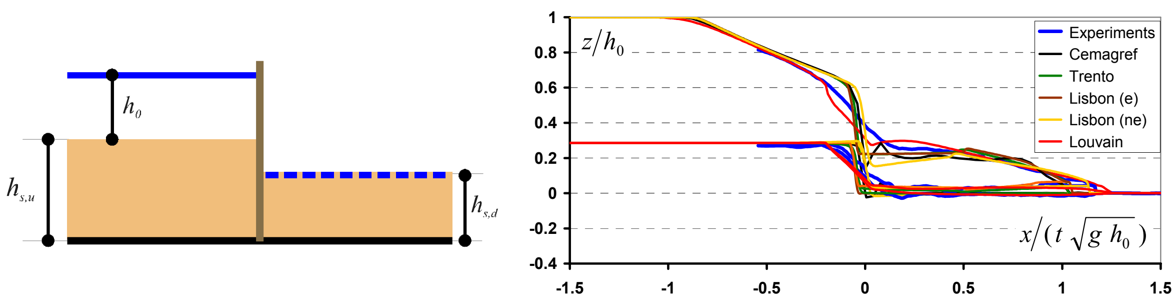


(a) (b)

Figure 3.1 Experimental and numerical results from the benchmark on dam-break wave over an initially flat erodible bed: (a) UCL model, t = 0.6 s (b) all modellers, at $x = 5\ h_0$

Dam-break flow over an initially stepped bed

The benchmark description is given in Spinewine and Zech (2003). Results were obtained from 4 institutions, members of the IMPACT Sediment Movement group: CEMAGREF, UdT, IST and UCL. The comparison of the various models with the experimental data of stepped-bed benchmark is made in Fig. 3.2, which represents the various levels at a given time.



(a) (b)

Figure 3.2 (a) Definition sketch for the stepped-bed benchmark; (b) Comparison between experimental and numerical results from the benchmark at $x = 5\ h_0$. For each set of results, the lower line corresponds to the fixed bed level, the middle line to the moving sediment layer and the upper line to the water surface

Bank erosion induced by a dam-break flow in an initially prismatic valley

The benchmark is represented in Figure 3.3 and described in le Grelle et al. (2003). Results were obtained from 4 institutions, members of the IMPACT Sediment Movement group: CEMAGREF, UdT, IST and UCL (Figure 3.4).

Figure 3.3 Experimental measurement

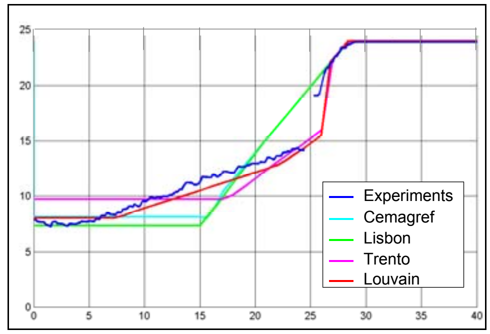


Figure 3.4 : Cross section after 10 s

3.3.3 Analysis and conclusions

Dam-break flow over an initially flat bed and over an initially stepped bed

Regarding the front celerity the results by Trento (UdT) take advantage of the calibration process, which involves these celerity as a calibration parameter. In contrast, their moving sediment layer is underestimated, due to the fact that the concentration of this layer is assumed to be the same as the bed material, which is not the case of the Louvain (UCL) and Lisbon (IST) models: in the reality, the concentration of this moving layer has to decrease to allow the movement of the particles. The erosion due to the front mobilisation only appears in the Louvain and Cemagref (CEM) models. Even though Cemagref's simple model cannot provide any results for the moving sediment layer, it still yields a valuable estimate for the water surface after the shock. The asymmetric treatment of erosion and deposition could explain the success for the UCL model in this regard.

Bank erosion induced by a dam-break flow in an initially prismatic valley

The Cemagref model, where only the bed moves, does not account for the typical widening of the section, which evidences the need of a bank stability criterion. In the Trento model, all the bank material is moved to the bottom without reshaping the bank, which clearly leads to overestimate the bed level. The Lisbon model curiously fails in representing the bank failure whilst such a mechanism would be initiated by the deepening of the bed. The model used by Louvain obviously takes advantage of the definition of an angle of repose for the deposition of the material issued from the bank collapse.

It must be noted than in the experiment, the initial bank angle was greater than the critical one, which emphasises the phenomena. With a flatter slope, the morphological effects would be less important.

4. NEW APPROACHES TO BREACH FORMATION MODELLING

4.1 Objectives and Approach

IMPACT project objectives relating to breach of dams and embankments comprise:

- Advancement of breach modelling (breach formation) capabilities through field, lab and numerical modelling work
- An assessment of breach modelling uncertainty (WP5)
- Investigation of factors leading to breach location (in linear flood defences) (WP2/WP6)

4.2 Analysis and Findings

4.2.1 Breach formation modelling

Breach model performance was assessed and enhanced using the data collected from field and laboratory tests. This data provided:

- Field data from large scale tests covering non cohesive and cohesive embankment failure; embankments comprised homogeneous and composite; failure modes overtopping and piping
- Lab Series 1 data provided knowledge and data relating to overtopping failure of homogeneous, non cohesive embankments. Parameters varied included sediment grading / D_{50}, breach location and embankment geometry
- Lab Series 2 data provided knowledge and data relating to overtopping failure of homogeneous, cohesive embankments. Parameters varied included material type / grading, compaction, water content and geometry
- Lab Series 3 provided knowledge and (limited) data relating to piping failure through embankments.

Whilst it will always be possible to improve predictive models for breach formation, it is also helpful to try and assess the performance of existing models and to give some guidance as to which models may be most appropriate for use (in various conditions).

Based upon a methodology proposed by Hassan (2002), an indicative ranking was obtained for the models that participated in the IMPACT numerical modelling programme. Initial rankings were obtained by combining measures of the accuracy of the predictions of the peak outflow, water level at peak outflow, time to peak, and final breach width (see Tables 4.1-4.4). Note that not all models performed all tests and hence a range of tables is presented showing comparisons of various modelling results (e.g. compare model performance for the same set of tests rather than overall averaged figures). A range of weightings for combining different performance measures (such as peak discharge, breach width etc) are also given. These are relevant if you are looking for model performance related to a specific output such as peak discharge.

Average score - all models (regardless of number of runs)											
Range of Weighting Factors		Peak Outflow / Water Level at Peak Outflow		Peak Outflow / Peak Water Level		Peak Outflow		Time to Peak		Final Breach Width	
PO:1 TP:1 WLP:1 PWL:0 FBW:1		PO:1 TP:0 WLP:1 PWL:0 FBW:0		PO:1 TP:0 WLP:0 PWL:1 FBW:0		PO:1 TP:0 WLP:0 PWL:0 FBW:0		PO:0 TP:1 WLP:0 PWL:0 FBW:0		PO:0 TP:0 WLP:0 PWL:0 FBW:1	
HR BREACH	8.1	Sobek	8.1	HR BREACH	8.6	HR BREACH	8.9	HR BREACH	8.7	Sobek	7.6
Sobek	7.8	HR BREACH	7.9	Sobek	8.2	Sobek	8.3	Cemagref	8.4	HR BREACH	7.1
Cemagref	7.2	Firebird	7.0	DEICH	7.3	DEICH	8.2	Simba	7.9	DEICH	5.0
DEICH	6.9	DEICH	6.8	Cemagref	6.8	Cemagref	8.2	NWS BREACH	7.7	NWS BREACH	4.7
Simba	6.4	Cemagref	6.7	Simba	6.6	Simba	6.6	DEICH	7.5	Simba	3.9
NWS BREACH	5.9	Simba	6.1	Firebird	6.4	NWS BREACH	6.4	Sobek	7.0	Cemagref	2.8
Firebird	4.1	NWS BREACH	5.1	NWS BREACH	6.3	Firebird	4.2	Firebird	5.2	Firebird	0.0

Table 4.1: Overall model performance scores (regardless of number of runs)

Average score – All models that performed all runs					
Range of Weighting Factors	Peak Outflow / Water Level at Peak Outflow	Peak Outflow / Peak Water Level	Peak Outflow	Time to Peak	Final Breach Width
PO:1 TP:1 WLP:1 PWL:0 FBW:1	PO:1 TP:0 WLP:1 PWL:0 FBW:0	PO:1 TP:0 WLP:0 PWL:1 FBW:0	PO:1 TP:0 WLP:0 PWL:0 FBW:0	PO:0 TP:1 WLP:0 PWL:0 FBW:0	PO:0 TP:0 WLP:0 PWL:0 FBW:1
HR BREACH 8.1	HR BREACH 7.9	HR BREACH 8.6	HR BREACH 8.9	HR BREACH 8.7	HR BREACH 7.1
Cemagref 7.2	DEICH 6.8	DEICH 7.3	Cemagref 8.2	Cemagref 8.4	DEICH 5.0
DEICH 6.9	Cemagref 6.7	Cemagref 6.8	DEICH 8.2	NWS BREACH 7.7	NWS BREACH 4.7
NWS BREACH 5.9	NWS BREACH 5.1	NWS BREACH 6.3	NWS BREACH 6.4	DEICH 7.5	Cemagref 2.8

Table 4.2: Overall model performance scores (only models performing all tests)

Average score – Sobek model runs only					
Range of Weighting Factors	Peak Outflow / Water Level at Peak Outflow	Peak Outflow / Peak Water Level	Peak Outflow	Time to Peak	Final Breach Width
PO:1 TP:1 WLP:1 PWL:0 FBW:1	PO:1 TP:0 WLP:1 PWL:0 FBW:0	PO:1 TP:0 WLP:0 PWL:1 FBW:0	PO:1 TP:0 WLP:0 PWL:0 FBW:0	PO:0 TP:1 WLP:0 PWL:0 FBW:0	PO:0 TP:0 WLP:0 PWL:0 FBW:1
HR BREACH 8.3	Sobek 8.1	HR BREACH 8.3	HR BREACH 9.3	HR BREACH 9.0	Sobek 7.6
Sobek 7.8	HR BREACH 8.1	Sobek 8.2	DEICH 8.4	Cemagref 8.5	HR BREACH 6.2
DEICH 7.4	DEICH 7.2	DEICH 7.3	Sobek 8.3	DEICH 8.5	NWS BREACH 5.8
Cemagref 7.0	Cemagref 6.5	Cemagref 6.5	Cemagref 7.7	Sobek 7.0	DEICH 4.8
NWS BREACH 6.0	NWS BREACH 5.5	NWS BREACH 6.3	NWS BREACH 5.4	NWS BREACH 7.0	Cemagref 3.5

Table 4.3: Overall model performance scores (comparing tests completed by Sobek model)

Average score – Simba model runs only					
Range of Weighting Factors	Peak Outflow / Water Level at Peak Outflow	Peak Outflow / Peak Water Level	Peak Outflow	Time to Peak	Final Breach Width
PO:1 TP:1 WLP:1 PWL:0 FBW:1	PO:1 TP:0 WLP:1 PWL:0 FBW:0	PO:1 TP:0 WLP:0 PWL:1 FBW:0	PO:1 TP:0 WLP:0 PWL:0 FBW:0	PO:0 TP:1 WLP:0 PWL:0 FBW:0	PO:0 TP:0 WLP:0 PWL:0 FBW:1
HR BREACH 8.2	HR BREACH 8.3	HR BREACH 8.7	Cemagref 9.2	HR BREACH 8.2	HR BREACH 7.8
Cemagref 6.9	Cemagref 6.7	Cemagref 7.4	HR BREACH 8.6	Simba 7.9	Simba 3.9
Simba 6.4	Simba 6.1	Simba 6.6	DEICH 7.4	Cemagref 7.5	Cemagref 3.5
DEICH 5.0	DEICH 5.0	DEICH 6.2	Simba 6.6	NWS BREACH 6.0	DEICH 2.9
NWS BREACH 4.6	NWS BREACH 4.2	NWS BREACH 5.4	NWS BREACH 6.4	DEICH 5.1	NWS BREACH 0.7

Table 4.4: Overall model performance scores (comparing tests completed by Simba model)

Note: In tables 4.1-4.4 weighting parameters relate to: PO: peak outflow; TP: time to peak outflow; WLP: water level at peak outflow; PWL: peak water level; FBW: final breach width

When reviewing Tables 4.1-4.4 it should also be noted that:

- some models simulate composite structures – others not
- some models (such as Simba) have been developed purely for simulating cohesive embankments
- some models are complex predictive models, whilst others are far simpler

(Details of the nature of each model may be found in the WP2 technical report)

From these tables HR BREACH appears to perform consistently well and NWS BREACH consistently poorly. However, when choosing a model for a given application it is recommended that the following points are considered:

- Do you need to simulate a composite or homogeneous structure?
- Do you need to simulate erosion of cohesive or non-cohesive material? Is head cutting likely to occur?
- Do you need a quick and approximate estimate of peak discharge, or as reliable and detailed estimate of a flood hydrograph as possible?
- Do you need to undertake uncertainty analysis of your simulation? Is Monte Carlo sampling required?
- What is the nature of your embankment? How does this match any data upon which a given breach model or equation may be calibrated?

4.2.2 Breach modelling uncertainty

An approach combining sensitivity analysis and Monte Carlo sampling has been developed which provides a practical approach to assessing the magnitude of uncertainty within breach modelling. Details of this approach are given under WP5. When applied to the Tous case Study, results suggested that the band of uncertainty around prediction of peak discharge was in the order of ±50%. Previous assessment of model performance against field and laboratory data suggested accuracy in the order of ±30%. Since the laboratory and field tests provided more controlled test conditions, it is reasonable to expect a better order of accuracy in modelling results. Best estimates of peak discharge are therefore likely to be within this range of accuracy.

4.2.3 Breach location

The aim of work here was to investigate potential approaches / methodologies for identifying the relative risk of breach occurring along long lengths of flood defence embankment. This problem may be viewed from a number of perspectives, namely:

- Investigation of physical processes and factors contributing to breach formation through an embankment (and hence identification of key indicators or parameters for inclusion within a model framework or asset inspection / management system)
- Development of a framework for assessment based upon 'available knowledge'
- Assessment of flood risk, regardless of specific breach location (i.e. 'what if' approach to modelling inundation from breach

Physical Factors Affecting Breach Location

Research under IMPACT WP6 includes the collation and analysis of data relating to breach of embankments across Hungary and the Czech Republic. The focus of this work is the collation of embankment condition, material and failure process data to allow identification of key parameters and processes.

Whilst details of a large number of breach events were collated the quality of available data proved to be poor and detailed analysis of any correlation between material properties and breach was not possible. However, correlation between typical breach size and breach location along the river was possible. The collected data base allowed analysis of failures along the Danube River from 77 data series, along the Tisza River using 97 data series, from 288 data related to the tributaries and further 95 of the small rivers of Hungary leading to:

- relations between the length of the breaches vs. height of overflow and of the flow rate of the river;
- relations between the length of the breaches and the location of the breach along the river.
- relation between length of breaches and calendar years of occurrence (the role of time).

Whilst these relations are of value on a local level, further analysis would be required to determine applicability to other catchments.

Framework for Assessment Based Upon Available Knowledge

Work in this area has advanced significantly in the UK through the Defra / EA flood defence research programme. An integrated approach based upon representation of flood defence structures, such as embankments, through the use of fragility curves (load – performance curves) is being developed and will provide a mechanism for identifying the relative risk of
breach formation along linear flood defence embankments.

Assessment of Flood Risk Resulting from Multiple Breach Locations

An investigation of this approach to modelling has been undertaken by Karl Broich (UniBwM). Overview papers are given in the 4th IMPACT workshop notes.

4.3 Key Conclusions and Recommendations for Industry

4.3.1 Understanding the breach formation process

Key processes that were evident from field and laboratory tests include:

- breach side walls are typically vertical during breach development (not trapezoidal as many breach models suggest)
- whilst continuous erosion is likely to occur, lateral erosion is normally through failure of discrete sections of embankment. The size of these discreet sections can vary from small to significant. Removal of this failed material is often very quick and not through steady erosion (i.e. carried out of the breach area by force of flow)
- cohesive material tends to show initial embankment erosion through head cutting (creation of steps) rather than uniform erosion of the face. This may affect the rate at which erosion of the crest / upstream face initiates and hence would be particularly relevant when trying to improve model accuracy in relation to breach initiation and timing
- the rate of breach formation is particularly dependent upon soil properties and embankment condition [e.g. cohesive / non cohesive; compaction; water content].
- Breach location (across an embankment dam for example) significantly affects the formation rate. Where lateral growth is restricted in one direction, erosion rates in the other direction do not compensate.
- Embankment structure is significant. A composite structure (e.g. core and outer layers) will erode differently to a homogeneous embankment. The degree to which the core material dictates the rate of lateral erosion is unclear, but a significant role is thought likely. Interaction between a core structure and supporting fill material dictates the rate of breach growth (in comparison to uniform erosion of a homogeneous embankment).

4.3.1.1 Breach formation modelling

1. Significant progress has been made through the breach formation work within the IMPACT project and considerable amounts of data relating to breach growth have been collected and analysis and review undertaken. Model performance has been assessed - it can be seen that the HR BREACH model performs consistently well, whilst the NWS BREACH model performs consistently worst.

2. Of the models tested, those attempting to predict breach growth through the calculation of discrete failure rather than continuous erosion appeared to perform best. This suggests that the approach of integrating aspects of soil mechanics, structure failure and hydraulics is a reasonable approach.

3. The extensive datasets that have been collected provide the opportunity for further significant advances in modelling capability to be made through further development work based upon observations, processes and problems as well as a more detailed analysis of the data sets.

4. It has been demonstrated under WP5 that the shape of a breach flood hydrograph is important for determining worst flood conditions downstream from a failure. Conditions are dictated by a combination of flood volume and release rate (i.e. flood hydrograph) and topography. This requires the whole breach formation process to be predicted rather than simply an estimate of peak discharge value, which is quite commonly adopted within the dam safety industry.

5. The controlled laboratory and field tests clearly showed the importance of understanding and accounting for soil properties and condition when trying to predict breach growth. Parameters such as cohesion, density and water content significantly affect breach development. Neglecting or oversimplifying these processes can lead to inaccurate simulation of the failure of the embankment. It is clear that many existing models do not include these factors and will therefore struggle to reproduce reliable results for apparently identical embankments, but whose compaction or moisture content varies.

6. Simulation of a composite structure through averaging of soil properties or ignoring potential effects can lead to <u>very large errors</u> (several hundred percent) in breach growth prediction. This approach is used within the NWS BREACH model.

7. The breach formation process is complex, and depends upon a range of parameters including hydraulic loading, and the design and condition of the embankment. Existing numerical models tend to simplify the processes and can help to reinforce misunderstandings as to the real process (e.g. breach shape is

typically with vertical walls, not trapezoidal as often quoted by models. Trapezoidal shapes develop after the breach formation process when embankment material dries and slumps.)

8. The location of a breach is important – even when considering failure of an embankment dam across a valley. An outflow hydrograph obtained with a side breach (i.e. where lateral growth is restricted in one direction) differs from that obtained from a central breach. A number of earlier breach models have been calibrated incorrectly using Teton data. This phenomenon is also significant when considering how to breach a landslide dam.

9. A number of processes were identified in the field and laboratory tests which most models do not currently simulate. These include modelling of the critical flow control point through the breach, breach dimensions, slumping of the upstream face and side face undercutting. In addition most models do not include assessment of soil parameters, slumping of the breach sides, the core structure and head cut processes.

10. Breach models use sediment equations based on existing steady state transport equations. Conditions during the breach formation process are far from steady state, hence these equations are only used in the absence of more reliable equations. Use of different equations for the same embankment loading conditions can give significantly different results.

11. The performance of breach models varies for different conditions, however it could be seen that an accuracy of ~±30% was found for predicting peak discharge values of breach flood hydrographs relating to field and laboratory tests. When applied to the Tous case study, the error band shifted to +50% -20%.

12. A qualitative comparison of scale effects has been made, showing that some features of cohesive and non cohesive behaviour are simulated at the laboratory scale (e.g. head cut, erosion) whilst others were not (e.g. seepage). A more detailed analysis of the data is required to provide a quantitative assessment. In particular, the analysis requires a focus on soil properties and condition parameters.

13. Not many models simulate the pipe formation process although some progress has been made in developing the few that do to incorporate features observed in the field tests.

4.3.1.2 Recommendations for users

1. The availability of models for predicting breach growth is relatively limited. Those models that are available are often limited in their capabilities. Care should be taken to ensure that the user clearly understands what the model predicts and how that prediction is made. Flow modelling packages often claim to incorporate breach models, however in reality these modules simply allow the user to define the rate of potential breach growth and subsequently predict flow through the breach. When choosing a model for a given application it is recommended that the following points are considered:
   - Do you need to simulate a composite or homogeneous structure?
   - Do you need to simulate erosion of cohesive or non-cohesive material? Is head cutting likely to occur?
   - Do you need a quick and approximate estimate of peak discharge, or as reliable and detailed estimate of a flood hydrograph as possible?
   - Do you need to undertake uncertainty analysis of your simulation? Is Monte Carlo sampling required?
   - What is the nature of your embankment? How does this match any data upon which a given breach model or equation may be calibrated?

2. When reviewing model performance (tables) the user should appreciate that:
   - The ranking are indicative
   - The models have been tested against a range of different scenarios
   - Some of the models have been developed for specific applications hence their performance will vary

3. When selecting a breach model there are a number of different types that may be considered. These include peak discharge equations, 1D breach models and 2D breach models. The advantages and disadvantages of using these different approaches are:

   Peak Discharge Equations: These offer a simple estimate of peak discharge – which may not give worst case flood conditions downstream. The equation is empirical and based upon regression on a set of data drawn from historic failures. The user should always ensure that the application matches the data set upon which the discharge equation is based.

   1D Models: These have the advantage of being relatively simple and computationally quick in comparison to 2D models, although the prediction of flow through the breach may not be as accurate as a 2D model. Many earlier models predefine the shape of the breach and rate of growth. Later models allow 'free formation' and incorporate an increasing degree of soil mechanics to allow for embankment conditions and a variety of failure processes. This appears to significantly improve the accuracy of prediction.

   2D Models: Whilst predicting flow through the breach opening more accurately than 1D, most 2D models do not incorporate any routines to take account of the way in which the breach may form (i.e. soil mechanics; slope stability etc). Sole use of standard steady state sediment transport equations to define rate of breach growth is unlikely to produce consistent results.

4. The accuracy of model prediction depends upon the aspect of the model results that the user is interested in. If a model predicts a flood hydrograph, the user may be interested in the time to initiation, volume of flood water, peak discharge etc. The accuracy of current breach models for each of these is approximately:
   - Peak discharge: ~±30%
   - Hydrograph shape (flood volume OK; hydrograph shape poor): poor
   - Time to initiation (rising limb of flood hydrograph): unreliable

   In summary, a user should look for a model which:
   - Simulates physical processes and is not necessarily calibrated to specific past events
   - Incorporates soil parameters / soil failure mechanisms
   - Allows for and simulates real composite structure behaviour
   - Allows selection of different sediment transport equations
   - Allows for the head cut process in cohesive materials
   - Allows for uncertainty within modelling parameters, providing a distribution of potential results

   A few of the models considered within IMPACT offer a high proportion of these features. All models contain significant degrees of uncertainty.

5. A user should be aware of how a model has been developed. A model that is calibrated against a limited number of specific historic events will most likely perform well under similar conditions, but may perform very badly against different conditions. A model that is based upon physical processes and not calibrated to specific events is more likely to perform reasonably over a wider range of conditions (providing conditions are within the scope of the model capabilities).

4.3.2 Key points from WP6: Breach field data analysis

We do believe that the above results give very important data for the industry in their preparatory and emergency management activities. Furthermore:

- To assess potential location of possible breach of flood dikes due to overtopping is possible.

- Methodology to assess potential location of possible breach due to hydraulic failure of the foundation soil in alluvial river valleys is described.
- Relations described between the lengths of the breaches vs. the height of overflow; the flow rate of the river and the location of the breach along the river may be a substantial support in planning and implementing confinement activities, and such data or relations are not provided by any of the work packages of the project.
- Special attention is to be given on the evaluation of flood fighting methods given, especially to those giving examples on wrong interventions to close breaches. Protecting and securing the levee stub is essential in preventing the growing of the length of the breach.

Analysis of the distribution of failure mechanisms for different periods of the time span shows that with the continuous and repeated heightening and reinforcement of the flood embankments, proportion of dike breaches originated from overtopping is decreasing, while that of the subsoil failure is increasing as a result of growing exposure (head) to the foundation soil. Slight increasing in the proportion of failures due to loss of dike stability can also be observed which is contradictory to the increased profiles as a result of reinforcement, but is explained by the growing duration of floods on the one hand and by contour seepages due to inappropriate construction (see below).

Overtopping was the failure mechanism in 73% of the identified cases within the investigated 220 years. The proportion for the past 50 years is 61%, including the 33 dike breaches during the ice jam flood in 1956. Apart from the ice jam flood events, the proportion of overtopping droops back to 46%. Using the same basis of estimation, the proportion of subsoil failures rose from 7% to 25%, while the loss of dike stability slightly increases from 7% to 9%.

Explanation on these facts and the causes can not be directly concluded from the collected data, but from indirect results of the data collation, such as the investigation of old legal and technical regulations, technology descriptions, findings of different soil mechanical surveys that could not numerically expressed.

4.3.2.1 Factors influencing dike failures

Dip in crest level

In case the failure mechanism is overtopping it is evident that the cross sections having height deficiencies in comparison with the forecasted peaking flood crest are seriously prone to damaging, or even breaching in lack of appropriate countermeasures during floods. Maintenance plays an essential role, but it is also vital to have integrated contingency plans including up to date longitudinal profiles of the dikes to enable the designation of emergency heightening activities when flood forecasts are available.

Vegetation

Role of vegetation is important but different in case of different possible failure mechanisms.

In case of *overtopping*, existence of well-maintained healthy and dense grass covers can significantly raise the resistance against and thus delay the beginning of erosion, leading to the development of head cut. Experience shows (see WP6 D6.7 report) that in case of overtopping with even 20-30 cm depth well maintained dikes can ‘survive’ if the staff and material to intervene to raise the height by sandbagging or mud boxing is at the right place in the right time.

Only the above mentioned grass cover is allowed on the surface of the dike and in the maintenance belt of the dikes (designated in 10 m width measured from the toe) to protect slopes from erosion (in case of torrential rivers such protection should be provided by revetment). Vegetations with *penetrative roots* (trees, bushes, shrubs, weed, etc.) can *contribute to saturation* of the dike body, and even to *leakages or piping* if their roots are decayed or rotten.

In Hungary, dike sections prone to *wave erosion* are protected against this phenomenon by special *forest belts* of willow trees in a width of 40-60 m on the water side of the dike, outside the above-mentioned 10 m wide maintenance belt. In case there is no room for such biologic protection, specially designed revetment is used.

High burrowing animal activity that destroys the integrity of the dike body is also dangerous. In this respect the old maintenance guidance documents considered the field mouse, the gopher (ground squirrel) the mole and the fox. Dike guards of ancient times were given special bonus in case of handing tails of gophers and foxes in.

Specific soil types at the base and in the dike body. In case the covering layer (hence likely the dike material itself) consists of organic (peat) or saline or disperse soils, dike is prone to collapse fast. Changing soil or protecting the supporting body by draining are the only solutions.

Specific subsurface soil types. Role in failure and methodology to assess potential location of possible breach due to hydraulic failure of the foundation soil is described in the detailed technical report.

Contour seepage due to inappropriate foundation of dike or that of reinforcements. Such problems are expected to be observed especially along old and reinforced dike sections. In the beginning of dike constructions and reinforcements the work was done manually or by utilising animal power. Lack in previous removal of the humus layers can be observed in soil explorations either at the base and/or at the junctions on the slopes. Critical contour seepages in these boundary layers may lead to slope sliding.

4.4 Key Conclusions and Recommendations for Further Scientific Progress

Whilst significant progress has been made through the IMPACT Project work, the research has highlighted key areas where further improvements may be made. In addition to identifying processes and problems that may be addressed within a further round of model development, the volume of high quality data collected has proved greater than could reasonably be analysed within the IMPACT project. Consequently, more detailed analysis of the data will permit significant further advances in modelling capability.

Key actions required to provide further improvement in model accuracy are:

1. Use of IMPACT data and review of model performance in relation to prediction of breach dimensions. [All models struggle to predict breach dimensions accurately. This aspect is overlooked where the prediction of a breach hydrograph is better. However, this masks an underlying problem that should be addressed before enhancing modelling capabilities further].

2. Use of IMPACT data to review model performance in relation to flow prediction. [Correcting model prediction of breach dimensions (1 above) will affect model prediction of flood flow. This should also be reviewed in light of the nature and position of typical flow control through a breach (i.e. upstream bell mouth type control].

3. Soil parameters and embankment condition greatly affect the rate and nature of breach growth. These aspects require further analysis and integration into breach models. Particularly, the aim to link observation or simple measurement of parameters in the field, to model prediction of failure.

4. The breach growth process (initiation, formation, widening) is controlled by a combination of hydraulic loading and soil mechanics response. Further analysis of failure mechanisms (through in depth analysis of IMPACT data) is recommended in order to allow more appropriate simulation by models. Reliable prediction of the time to initiation, flood hydrograph shape and ultimate breach dimensions all rely on these processes.

5. A more detailed analysis of scale effect between field and laboratory data should be made by analysing the IMPACT data – in particular in relation to soil parameters and embankment conditions (moisture content; compaction).

6. Prediction of pipe formation remains at a relatively basic level. Data collected under IMPACT could help further analysis and model development here.

Key actions relating to breach field data and analysis are:

1. Scientifically accepted archival investigation and systematization of historical data is a very time consuming activity. Much more time allocation is needed for such investigations to explore more specific data. Continuation of data collation is needed to enable better determination of the impacts of different factors to breach formation.

5. NEW APPROACHES TO FLOOD PROPAGATION MODELLING

5.1 Objectives and Approach

The main objective in this work area is to produce more reliable modelling methods for the propagation of catastrophic floods generated by the catastrophic failure of a water control structure. Such floods are commonly much more difficult to simulate than natural river floods due to the presence of rapidly varying flow conditions including mixed, sub, super and transcritical flow, shock propagation, interaction and reflections. Partial objectives of the project in this theme comprise the following:

- To review current modelling techniques of flood propagation in urban areas and through complex valleys
- To produce modelling techniques capable of coping with flow conditions present in floods resulting from failure of a control structure, in particular: Mixed sub, super and transcritical flow, moving shocks and their interaction with obstacles in the flooded area.
- To develop models that can provide a more detailed description of flow processes and characteristics of a flood, particularly in urban areas.
- To produce and demonstrate methods for practical computation and develop guidelines for their use.

The former objectives fall within particular objectives of deliverable D3.1.1, Mathematical modelling techniques for flood propagation in urban areas, and D3.2.1, Advanced mathematical modelling techniques for flood propagation in natural topographies. The adopted strategy is a collaborative development and testing of models, but based upon an individual approach. Each partner involved has developed and applied particular improvements into his computer models or developed additional new models separately from the other partners.

5.2 Analysis and Findings

After a careful literature review (Alcrudo 2002) and discussions between project members the adopted mathematical framework for flood propagation modelling has relied upon the full nonlinear Shallow Water Equations (SWE) in two dimensions (2D). It is clear that with present computational resources and work load allocated within the project a more elaborate mathematical description is yet unfeasible if practical computations are envisaged. This situation is open to change, but not clearly in the near future. Hence, and during project work all developments in modelling technology have been performed within the SWE framework. Computer models in which developments have been worked out and/or tests performed comprise:

- SW2D (Alcrudo and Mulet) and SIBIL (Murillo and Brufau) from University of Zaragoza (Spain)
- RUBBAR2D (Paquier and Mignot) from CEMAGREF (France)
- UCL-2D (Soares-Frazao) from Université Catholique de Louvain (Belgium)
- ONDA2D and FLOOD2D from CESI (Italy)

Additionally a completely new computer code has been written from scratch:

- SWNE (Mulet) at Universidad de Zaragoza (Spain)

5.2.1 Urban flooding

Main issues regarding urban flooding are the flow characteristics and interaction with buildings and the representation of the flow inside the area covered by the city. In order to deal with these, the following approaches have been developed, coded and tested by most partners involved:

- One dimensional city representation as streets
- Building representation as areas of increased friction
- Building representation as abrupt bottom elevations
- Detailed meshing of the city area and representation of buildings as solid walls within a high resolution 2D calculation

The techniques listed were coded into the different models and put to work on the different benchmarks and the flood propagation case study with considerable success.

5.2.2 Flood propagation in natural topographies

This area of work is devoted to cope with the difficulties associated with the propagation of a flood along a real valley where the following problems arise: deviation from the model hydrodynamic assumptions, dominance of source term forcing (bottom slope and friction), abrupt front formation, propagation and interaction, wetting and drying of the terrain, mesh dependence of model output and mesh generation. Also important are the efficiency and speed of resulting models as complexity and size of problems grow.

5.3 Key Conclusions and Recommendations for Industry

Flood propagation models are in use for many years now, and wholly speaking can be considered a mature technology in the sense that they are routinely being used by industry (engineers, consultants, government agencies etc…). However there are still important questions regarding their applicability and range of use: Validity of model equations in certain conditions, convergence of model output to a unique flooding scenario, mesh independence of model output etc … are issues affecting reliability of model predictions.

IMPACT project work in this area has addressed the problem of flood propagation in urban areas and in natural topographies with the aim of developing more capable models and assessing their performance against experimental data. Special emphasis has been placed in comparing model output with data from an actual catastrophic flood. The following are key points arisen during the course of this work:

- The research performed has clearly shown that the models developed can be applied equally well to natural and urban scenarios. The different approaches compared for modelling urban flows all performed reasonably, but performance does depend upon the nature of flow (i.e. slow inundation, fast flowing etc.)
- Models based upon the SWE provide a mathematical framework that is complex enough to represent most physics of actual flood flows while still being computationally tractable. More complex mathematical descriptions do not yet allow practical computations.
- The numerical complexity of state of the art models is high, but this is the price paid to successfully cope with all difficulties encountered when simulating an extreme flood. This complexity pays a penalty in terms of computational resources required to run a simulation.
- Modelling complex extreme floods at the laboratory scale can be accomplished quite successfully. Model results are accurate with low uncertainty and can be obtained in very reasonable times. This situation is in turn a result of: 1) the small scale of the problem and 2) the little or no uncertainty in input data when modelling a laboratory case.
- Application of models to practical extreme floods are much more difficult for a number of factors: 1) The spatial and time scales are several orders of magnitude larger; 2) Data available are not complete or not accurate or both, hence hypothesis must be made (boundary conditions, topography, bed resistance …)
- As a consequence: 1) turnaround times are very long in practical applications, what hinders analysis, model adjustments and quality of predictions; 2) Uncertainty in model output is larger than desired.
- Despite the difficulties listed above models developed and tested during Impact project work can be applied successfully to the prediction of extreme floods as the case study selected.
- With computer technology presently available in engineering environments (high end Pentium IV PCs), current models are viable to simulate a combination of flood duration and area flooded of about 10 square kilometres times day. Larger areas or longer periods of time would result in unacceptably long simulations or too low resolution to yield a local picture of the flow.

5.4 Key Conclusions and Recommendations for Further Scientific Progress

Mathematical models based upon the SWE will continue to dominate the flood prediction landscape in the near future. In order to make their predictions more reliable it is important to clarify the mesh independence issue. This has been done during the IMPACT project for physical model scale experiments where it has been possible to perform simulations beyond the required resolution. However it is not possible to even approximate the asymptotic limit in real cases due to the heavy computational requirements and to the relatively low resolution of the original raw data used. Although this may not be realistic in many practical computations, it is necessary from the research point of view in order to clarify the convergence of all models to a unique solution. Specific actions include:

- Future research efforts should primarily aim at increasing the speed and efficiency of present models while preserving all the built in capabilities and technology (high accuracy, shock capturing operators, proper source term integration, wetting-drying ability, monotonicity, entropic behaviour etc…)
- Although not pertaining properly to modelling technology research should aim also at integration and automation of the modelling pre-process and set up tasks that are intensive resource consuming.
- Although not particularly addressed during Impact project, a means to systematically evaluate bed resistance in flooding environments would very much help problem set up and model predictions.

6. NEW APPROACHES TO MODELLING SEDIMENT MOVEMENT UNDER EXTREME FLOOD CONDITIONS

6.1 Objectives and Approach

The objective is to define a mathematical description for the processes investigated. A literature review was undertaken before trying to extend the available flow description to account for the processes identified in the experiments.

6.2 Analysis and Findings

6.2.1 Uniform debris flow

Some physical similarities between rapid granular flows and gases have led to a great deal of work on adapting kinetic theories to granular materials. All of the models are based on the assumption that particles interact by instantaneous collisions, implying that only binary or two-particle collisions need to be considered.

Jenkins & Hanes (1998) applied kinetic theories to a sheet flow in which the particles are supported by their collisional interactions rather than by the velocity fluctuations of the turbulent fluid. The constitutive relation for the particle pressure is taken to be the quasi-elastic approximation for a dense molecular gas proposed by Chapman & Cowling (1970), describing the variation with concentration of the rate of collisions among the particles.

From experiments, it is possible to derive the particle pressure σ_s and the shear stress τ_s by assuming that the buoyant weight of the grains is entirely supported by collisional granular contacts. The key improvement in the definition of the constitutive relations is to account for an added-mass effect, that is, by replacing the mass density of the sediments ρ_s by:

$$\rho_s' = \rho_s \left(1 + \frac{1 + 2C_s}{2(1 - C_s)} \frac{\rho_w}{\rho_s} \right) \qquad (1)$$

where C_s is the grain concentration. More details can be found in Armanini et al. (2003).

6.2.2 Near-field dam-break flow

6.2.2.1 2D-V level-set model

Considering that the vertical component of the velocity at the first stages of the dam-break flow is not negligible, the initial idea was to develop a 2D-V model to represent what happens in a vertical median plane immediately after the collapse of the dam. The best appropriated model appeared to be a level-set method. This approach relies on the assumption that the flow is subdivided in layers of approximately homogeneous properties, separated by sharp interfaces. The propagating interfaces between the various media (air, water, sediment) correspond to the zero level set of higher dimensional functions Φ, defined as the signed distances to the interface (Sethian, 1999). A Navier-Stokes equation can be developed in terms of vorticity, and thus also in terms of stream functions Ψ, from which the velocity field can be derived. The level-set functions can thus be advected according this velocity field, yielding qualitatively valuable results (Fig. 6.1)

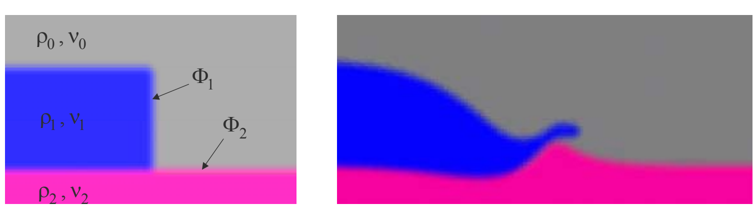


Figure 6.1 Level-set method principle

6.2.2.2 Two-layer shallow-water 1D model

The first developments were presented by Capart (2000). The flow is represented by three layers: (1) the upper layer consisting of clear water of depth h_w, (2) the moving sediment layer h_s and (3) the fixed-bed layer having the bed level z_b as upper limit. In the original model (Capart, 2000), the concentration of sediment was assumed to be constant ($C_s = C_b$) and the upper part of the mixture water / sediment (h_s) was assumed to be in movement with the same uniform velocity as the clear-water layer ($u_s = u_w$). According to those assumptions the shear stress was supposed as continuous along a vertical line. An analytical solutions was derived for this model (Fraccarollo and Capart, 2002), but this, whilst clever, can of course not be used in real-case geometry.
One of the main improvements (Spinewine, 2003; Spinewine and Zech, 2002a) brought to the model is to give new degrees of freedom to the concentrations ($C_s \neq C_b$) and the velocities ($u_s \neq u_w$) between the three layers (Fig. 6.2).

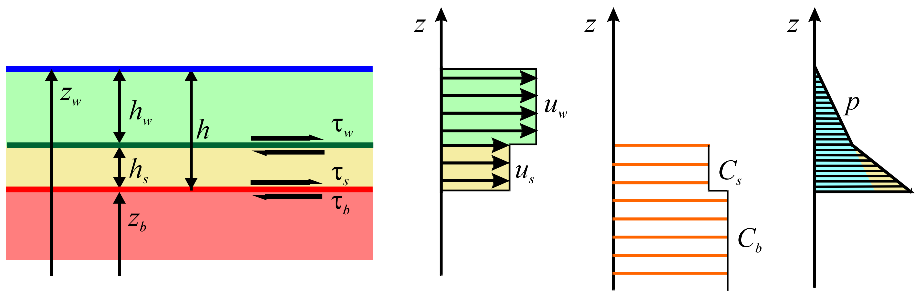


Figure 6.2. Assumptions for mathematical description of near-field flow

The equations obtained from this description are solved by a second-order Godunov finite-volume scheme, where the fluxes are computed using the LHLL Riemann solver (Fraccarollo et al., 2003).

6.2.3 Far-field dam-break flow

6.2.3.1 Two-dimensional model

First, a 2D extension of the model presented for the near field was developed, including a bank erosion mechanism. A detailed description of the method, summarised here, can be found in Spinewine et al. (2002) and Capart and Young (2002). The key idea is that by allowing separate water and fluid-like slurry layers to flow independently, the governing equations are fully equipped to deal with flow slides of bank material slumping into the water stream. Once failure is initiated, the post-failure flow can be captured just like any other pattern of water and sediment motion.

A liquefaction criterion is thus needed to determine when and where portions of the banks are to be transformed from a solid-like to a fluid-like medium. Therefore, the following fundamental mechanism is assumed: activation of a block failure event occurs whenever and wherever the local slope exceeds a *critical* angle α_c. An extended failure surface is then defined as a cone centred on the failure location and sloping outwards at *residual* angle $\alpha_r < \alpha_c$. Finally, sediment material above this cone is assumed to instantaneously liquefy upon failure. In order to account for the observed contrast between submerged and emerged regions, four distinct angles of repose are defined as indicated in Fig. 6.3: angles $\alpha_{c,subm}$ and $\varphi_{r,subm}$ apply to the submerged domain, and $\alpha_{c,em}$ and $\alpha_{r,em}$ to the emerged domain.

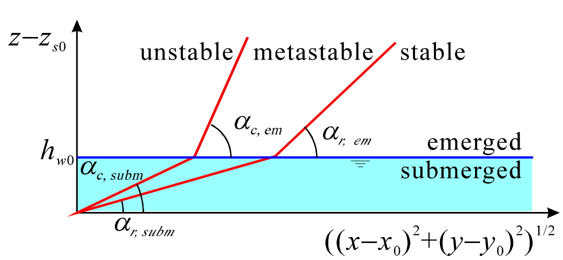


Figure 6.3. Stability diagram for the 2D geostatic failure operator

6.2.3.2 One-dimensional model with global bank failure

The second model selected for coupling with the above bank erosion mechanism is a one-dimensional scheme. It comprises a hydrodynamic finite-volume algorithm and a separate sediment transport routine. The finite-volume scheme, developed with the aim of coping with complex topographies (Soares-Frazão and Zech, 2002), solves the hydrodynamic shallow-water equations while the part of the changes in cross-sectional geometry due to longitudinal sediment transport (bed load) over one computational time step are derived from the Exner continuity equation of the sediment phase. In addition to sediment fluxes at the upstream and downstream faces of a cell, lateral sediment inflow resulting from bank failures is considered as a volume V_s. to be redistributed in the cross section at the end of the computation time step.

A failure is triggered by the submergence of a bank by a rise Δh in water level that destabilises a prismatic portion of material as sketched in Fig. 6.4. In the experiments, the initial bank slope α is less than the stability angle $\alpha_{s,em}$ above the water surface but greater than the stability angle $\alpha_{s,subm}$ below the water surface. Thus the bank becomes unstable as soon as the water rises, and it fails according to the failure angles $\alpha_{f,subm}$ and $\alpha_{f,em}$ corresponding to the submerged and emerged situations, respectively (in practice the failure angles α_f are slightly less than stability angles α_s). The so-eroded volume V_s has now to be redistributed in the cross section.

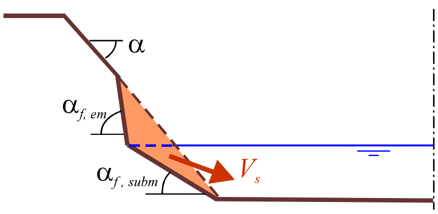


Figure 6.4 Bank failure triggered by the submergence of the bank

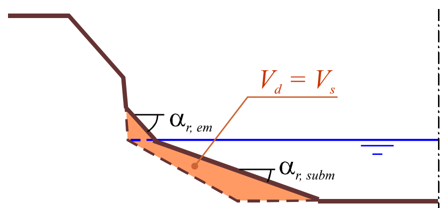


Figure 6.5 Deposition of the material eroded from the banks

The eroded material deposits into the channel as sketched in Fig. 6.5 The submerged portion deposits with an angle $\alpha_{r,subm}$ corresponding to the angle of repose under water while the emerged portion stabilises at an angle $\alpha_{r,em}$ (angle of repose above the water level after the deposition process). All those angles of repose are specific to the material used in the experiments and were measured by means of static and dynamic experiments.

Finally, the numerical 1D model consists in solving in a de-coupled way the three different key steps of the process: (i) the hydrodynamic routing of the water, (ii) the longitudinal sediment transport and the resulting erosion and deposition, and (iii) the bank failures and the resulting morphological changes in the cross-section shape.

6.2.3.3 One-dimensional model with local bank failure

The above scheme appeared to be well adapted to idealised situations, where the cross sections may be defined for instance as rectangles or trapezoids, with a limited number of summits in their polygonal description. For natural rivers the cross sections become too complicated to be described in such a simplified way, and another approach was preferred, inspired by Schmautz and Aufleger (2002) in another context.

The cross-section profile is discretised in little segments, the stability of each of them being checked starting from the side of the valley (Fig. 6.6). If the bank section AB is locally steeper than the critical one (stability angle α_s), the bank portion rotates until reaching the position A'B', corresponding to the convenient angle of repose α_r (emerged or submerged). In return, this new position may aggravate the stability of the adjacent sections (for instance BC has now moved to B'C position). The whole profile has to be browsed several times till all the sections are stable.

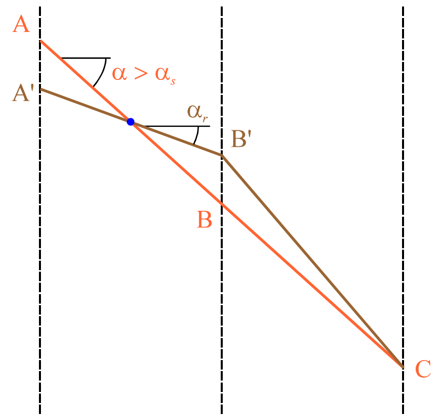


Figure 6.6 Principle of the local bank-failure model

For the longitudinal sediment transport, the following rules are adopted, as well for the global as for the local bank failure model. In case of erosion, according to the Meyer-Peter–Müller formula, the transport is assumed to be proportional to the local value of $(\tau_b - \tau_{b,c})^{3/2}$, where τ_b and $\tau_{b,c}$ are the actual and the critical bed shear stresses, respectively. In case of deposition, the sediment is supposed to deposit uniformly (not horizontally) along the bed, this later being defined as the cross-section elements with a slope less than the submerged angle of repose.

6.3 Key Conclusions and Recommendations for Industry

6.3.1 2D-V model

It rapidly appeared that use of such sophisticated models in real-life cases is nearly impossible. The constraint of the representation of the whole phenomenon along a unique vertical plane is not realistic since most of the real valleys are rather narrow in the vicinity of the dam with significant variations of water depth along the width. The 2D-V approach may thus rather be considered as an interesting step to a fully 3D approach, the later remaining a far objective for the modellers.

6.3.2 1D and 2D-H models

The set of equations describing the movement of sediments under dam-break flow conditions is not yet completely established. It is thus not possible at this stage to develop a commercial package able to solve the problems related to heavy sediment transport following a dam-break event. The current models that include extended possibilities (such as the 2D-H approach described in the previous section) are too slow for practical application.

6.4 Key Conclusions and Recommendations for Further Scientific Progress

6.4.1 2D-V model

The 2D-V approach may be considered as an interesting step to a fully 3D approach, the later remaining a far objective for the modellers.

6.4.2 1D and 2D-H models

A common weakness of all the compared models, at least in the flat-bed benchmark, is that they advance the front too fast. This is originated by the fact that the first stages of the sediment mobilisation are missed since no vertical velocity components are taken into consideration. Another clear conclusion is the difficulty to reproduce the erosive behaviour of saturated debris front, above all if this erosion is followed by a partial re-deposition.

However, the progresses of such modelling, compared to the results available some years ago, is spectacular. A part of this development is issued from new measurement techniques based on digital imaging, that have made possible the observation in real time of the velocity field, as well in the liquid phase as in the solid-transport layer.

The two-layer 1D approach, and its extension in a 2D-H model, seems the most interesting and promising approach. Efforts should tend towards the description of the bank failure operator, including the triggering of a bank failure. This could be achieved by adding considerations issued from soil mechanics. From the numerical model point of view, efforts should be made to allow for computations to run in a reasonable time.

7. DEVELOPMENT OF A GEOPHYSICS BASED APPROACH FOR THE RAPID ASSESSMENT OF EMBANKMENT INTEGRITY

7.1 Objectives and Approach

The main objective of this work package was the review and test application of geophysical monitoring techniques aimed at identifying an approach for the non intrusive, rapid assessment of embankment (dam and flood defence) integrity.

This work was undertaken by the monitoring of in situ embankment conditions at pilot sites at Spluchov and Jilesovice on the Odra River, Czech Republic. Different geophysical applications were trialled and optimal methods and determination of basic entry geophysical and geotechnical parameters undertaken.

Works proceeded in 3 phases, as outlined below:

Phase 1: Determination of optimal geophysical methods as well as parameters observed for monitoring. *Geophysical parameters monitored:*
- volume density (for determination of density model of the given sector of the embankment)
- seismic velocity
- seismic models of elasticity
- porosity
- structure of the embankment
- layering of the embankment (for determination of resistance model of the dam)
- natural electric potential in the space of the dam (identification of places of leakage)

Geophysical methods used:
- Geoelectric methods
- Geological radar
- Seismic methods
- Gravimetry
- Magnetometometry

Phase 2: Monitoring of selected geophysical and geotechnical parameters for WP2.1 test case (Velky Belcicky pond, Czech Republic) - analysis of acquired results.

Phase 3: determination of dependence of modelling results on geophysical measurement in-situ and recommendations for use / implementation of such methods within industry.

7.2 Analysis and Findings

The testing of geophysical approaches (Deliverables D6.2 and D6.4 of WP6) according to the three phases of work proceeded as follows:
- the first stage was performed in April 2003 at increased water discharge and at increased moisture of dam material after snow melting (see IMPACT WP6 Stage Report D6.2.A)
- the second stage was performed in September 2003 at low water level after the extremely dry summer (see IMPACT WP6 Stage Report D6.2.B)
- the third stage was measured at occasional flood level, in Spring (March - April) 2004, during summer snow melting, increased water passage, and increased humidity of the embankment's material. (See IMPACT WP6 Stage Report D6.2.C).

The performance of different approaches is outlined in the detailed supporting reports. During the 3rd stage measurements, attention was focused on testing of the electromagnetic method for measurement of resistivity (respectively resistance), i.e. the method CM and GEM-2. These methods showed promise and could become a basic method for the fast database measurements. During the 3rd stage we had used the modern multi-frequency instrument GEM-2 developed by the company Geophex (USA). The advantage of the multi-frequency variant is that the apparatus can measure at several selected frequencies of excitation electromagnetic field, at the same time. By changing the frequency we can change the depth reach of the measurement. In optimal case a simple conductivity or resistance embankment cross section could be arranged, in future. It will significantly improve preciseness of interpretation of performed measurements under the keeping of high productivity of measurement. Thus, it will enable e.g. evaluation, if anomaly in conductivity (e.g. leakage or a porous section) is present in the embankment body or at an earth plane.

7.3 Recommended Methodology

Deliverable D6.4 of the WP6 has been written as a guide methodology for the use of geophysical methods and is aimed at embankment owners and managers. The testing of geophysical methods for embankment assessment and maintenance was conducted with two main goals in mind:

1. to check the usability of specific geophysical methods for a current state description and detection of defects in existing embankments
2. to provide integration of different geophysical methods into the process of regular asset maintenance and check of the embankment condition.

The geophysical methods are based on measurement of physical parameters of the embankment material and seat rock. Interpretation of the acquired data enables identification of the shape and physical condition of individual structures and geological layers within the embankment and to define local non-homogeneity of the material (e.g. cavities, embankment places etc.) Different geophysical methods allow collection of different physical data. Table 7.1 below contains an overview of the basic methods. This chart also includes a list of observed physical parameters for individual methods and evaluation of their suitability for embankment survey / investigation. Terms under the 'usability evaluation' have the following meanings:

"Recommended" methods - basic methods for embankments survey
"Suitable" methods - methods commonly used for the embankment survey
"Conditional" methods - method used exceptionally for special purposes

Table 7.1: Basic geophysical methods overview

Geophysical method	**Observed physical parameters**	**Embankment survey usability evaluation**
Geoelectric methods	Specific electric resistance Conductivity Electric potential	Recommended
GPR – geological radar	Relative permittivity Specific electric resistance	Suitable
Seismic methods	Elastic waves diffusion velocity Elastic waves frequency	Suitable
Gravimetry	Gravitation acceleration Specific volume weight	Suitable
Thermometry	Temperature Temperature flow	Suitable
Magnetometometry	Magnetic susceptibility Magnetisation	Conditional
Radiometry	α, β, γ activity radio nuclides content	Conditional

The most fundamental aspect for successful geophysical methods application in embankment survey and check proved to be the correct definition of the required tasks and exact description of what kind of results can the geophysical methods offer. This helps to avoid misunderstanding both at the side of the embankment owners / managers and geophysics engineers. Embankment destruction (defects) during floods usually developed in a very short time. Mostly it is overtopping, piping, internal erosion, suffosion and slope deformation. During the flood the defected section is usually obvious and the final development of the fault is usually a matter of several hours or days at most.

When analysing older defects it is mostly possible to find “hidden” defects causes which developed continually or had existed even before the embankment construction. It can be both a natural condition (e.g. the embankment construction on the covered old river bed filled with permeable sediments) and the construction faults and unsuitable material used for the embankment construction. Extensive effect is often brought about by repeated water attacks of regular floods which wash the seat rock material or the embankment body material or lead to gradual embankment slope deformation. In this relation we can talk about pre-breach defects formation (see Fig 7.1). “Hidden” causes of defects (faults) creation are often present years before the final destruction. Localisation, condition and development of these “hidden” causes of the embankment defects development is the area where geophysical methods can be useful and can bring valuable information.

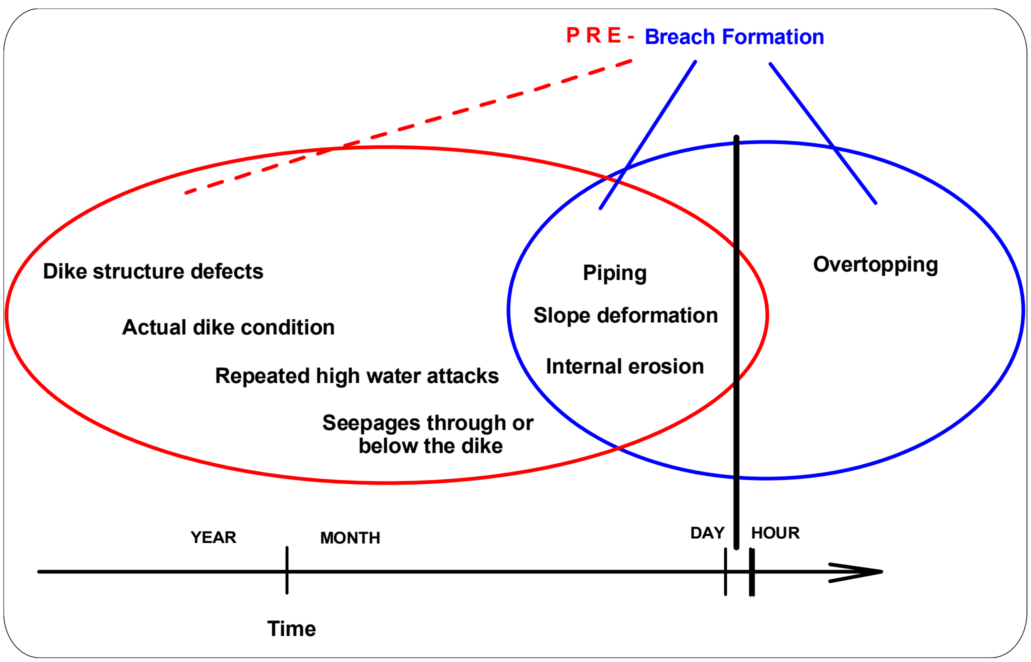


Figure 7.1: Time aspect in relation to breach formation and their “hidden” causes

7.4 Key Conclusions and Recommendations for Industry

Findings from the WP6-geophysics/monitoring programme work have lead to a better understanding of the processes which occur in the event of embankment breach and identification of the dependence between such breaches and the geological bedrock, hydrogeological, geodetic, geotechnical and physical situation, construction of the embankments, their historical development and properties of these waterworks. The geophysical methods of monitoring have a significant importance mainly in the areas, where the data on the bedrock, construction of the water-management works, utilized materials, etc., are incomplete or inaccurate.

Assessment of asset condition is a significant problem for water authorities across Europe. Many countries have tens of thousands of kilometers of flood defences, however there is now a clear, simple and efficient technique for determining the quality of these defences through this work within WP6 of the IMPACT Project . The WP6 geophysics work addresses directly this issue and potentially offers a solution or guidance towards a solution. Improving our ability to reliably determine the condition of an embankment will directly improve our ability to predict and hence manage flood risk. The use of geophysical methods within the construction of the safety new water management works will be applied mainly among the following groups of users:

- owners of the water management works: to assess potential risks from failure and sediment movement
- authorities and emergency planning bodies, water companies
- ministries (for Regional Development, of the Environment, of the Agriculture, etc.): for strategic planning of activities
- commercial application in designing the water management works

Based on embankment geophysical measurements analysis and discussion with representatives of embankment owners / managers it is possible to claim that within the duties of the embankment check and maintenance there are **3 basic task types which can be effectively solved using geophysical methods.** The first task involves long embankment sections survey, second covers the detailed survey of short problem parts and the third method's purpose is to supply data for a geotechnical description of embankment material. These task type definitions are important because under optimal conditions each task will be handled using a different set of geophysical methods and the survey results will bring different type and level of information.

Long Embankment Section Survey

Long embankment section survey is appropriate in case the river basin contains great number of older embankments with missing basic documentation. Usually there is no available information about material used for the embankment construction, their basic structure, previous defects and revisions scope. Besides there is a substantial risk that the construction work is of low quality (e.g. non-homogenous, low quality material). The need of this basic information usually surfaces after strong floods when larger number of defects occurs and the caretaker has to suggest the necessary reconstruction scope. The required extent of embankment survey can vary from dozens to hundreds km of embankments.

Detailed Survey Of Short Problem Embankment Sections

Detailed survey of short problem embankment sections has been the most often required type of geophysical measurement. The survey is carried out in case of the need of detailed description of the scope and the source of known eroded section. It can be the place of repeated leakage under or through the embankment, the place of embankment slopes deformation, the place of technical infrastructure location etc. The problem section is usually about hundred metres long.

The Embankment Material Geotechnical Characteristics Survey

The survey aimed at finding out geotechnical characteristics of embankment material serves as an important foundation for designing larger embankment reconstruction. From geotechnical point of view the reconstructed section should resemble original embankments so that there are no sharp transitions at the boundary. Geophysical measurement can be designed in the form of more or less spot tests or as profile tests. As a basis it is necessary to use methods offering such parameters which can be transformed to geotechnical quantities (volume weight, seismic modules of elasticity, seismic modules of sheer).

Geophysical methods can also be used for time efficient and cheep quality check of construction work of new and reconstructed embankments. It especially applies to the embankments where geotechnical tests proving the construction work quality were not carried out at the time of construction.

7.5 Key Conclusions and Recommendations for Further Scientific Progress

We suggest using the results of the accomplished research as the basis for the database of repeated check measurements which has become common part of embankments check and maintenance. Repeated measurements bring new type of information: thanks to the analysis of the repeated measurements we can detect the anomalies which change through the time and which usually correspond with eroded sections with leakage. This can be called geophysical monitoring of the embankments.

The main conclusion of the WP6 of the IMPACT project is the suggestion of the methodology of geophysical measurements for dike / embankment inspections and maintenance = Geophysical Monitoring System = GMS: This system is formed by 3 parts serving as methodologies for 3 basic tasks described in chapter No. 3.

1. *quick testing measurement* – quick and inexpensive measurement for basic assessment of dike structure and homogeneity. This methodology is also a basis for repeated monitoring measurements.
2. *diagnostic measurement* – detailed measurement performed in disturbed (inhomogeneous) segments for the detection of hidden dike defects
3. *measurement of geotechnical condition* - geophysical measurement for the monitoring of geomechanical properties of disturbed dike segments.

The **GMS system** benefits are in a possibility of objective assessment of dike homogeneity and condition. Geophysical methods so are an advisable complement to the existing methods of inspection (visual inspection, analyses of airborne and satellite photographs).

Quick testing measurement is based on the application of electromagnetic conductometry (EFM method). The use of multi-frequency instrumentation (for example GEM-2, which was originally developed for military purposes) allows us to reach very good results at high productivity. Diagnostic measurement particularly exploits the multielectrode resistivity method with high density of measurement (MEM) in combination with GPR, seismic method or microgravimetry. In the measurement of geotechnical parameters of the dike/embankment materials we use seismic methods and gravimetry.

For the following scientific progress we recommend to use the methodologies of particular types of measurement for the real monitoring issues and testing of the new methodology. Mainly the GEM-2 apparatus improve and use would be developed.

8. ASSESSING MODELLING UNCERTAINTY

8.1 Objectives and Approach

8.1.1 Objectives

The objective of this part of the IMPACT project was to identify and emphasise the uncertainty associated with the various components of the flood prediction process; namely breach formation, flood routing and sediment transport. The effect that uncertainty in each of these predictions has on the overall flood prediction process was then demonstrated through application to case study data. The focus of work under IMPACT WP5 was to:

a) Investigate uncertainty within modelling predictions for predicting breach formation, flood propagation and sediment transport
b) Demonstrate how uncertainty within each of these modelling approaches may contribute towards overall uncertainty within the prediction of specific conditions (such as flood water level at a specific location)
c) Consider the implications of uncertainty in specific flood conditions (such as water level, time of flood arrival etc.) for end users of the information (such as emergency planners).

The scope of work under IMPACT did not allow for an investigation of uncertainty in the impact of flooding or in the assessment and management of flood risk. The assessment of modelling uncertainty provides essential information upon which a later assessment of the uncertainty in risk may be developed through further research.

8.1.2 Approach

The direction of analysis and development of approach was undertaken with the key aim of meeting the needs of industry. To help ensure that this was achieved, discussion sessions were held during the various IMPACT workshops to gain feedback. Key issues that arose during development of approach included:

- The need to refine the focus of work (address model process uncertainty only)
- To adopt a rigorous statistical approach or something less rigorous, but more practicable?
- The extent to which expert judgement could and should be integrated?
- The extent to which consistent approaches may be applied across all science process areas (i.e. speed of models; maturity of scientific knowledge)
- The way in which the different needs of various end user applications of results may be met

The methodology eventually developed and applied:

- Focussed only on modelling uncertainty
- Adopted a less rigorous, but more practicable approach
- Integrated expert judgement, but at the cost of a less rigorous approach
- Allowed for different levels of analysis between model types (i.e. breach and propagation models)

8.2 Analysis and Findings

8.2.1 Analysis: Development of approach

As analysis of the issues involved progressed, it became clear that the differences in scientific understanding and modelling ability between breach and flood propagation as compared to sediment processes were significant to the point that it would exclude assessment of sediment uncertainty from the methodology. Two case studies were therefore used to develop and apply methods: the Tous case Study to demonstrate application of uncertainty analysis to breach and flood propagation methods; the Lake Ha! Ha! Case study to demonstrate extreme natural processes relating to sediment movement. More details regarding sediments processes are given in section 8.2.1.1 below.

Considering a methodology for assessing uncertainty within breach and propagation models, two basic approaches were adopted, namely sensitivity analysis and Monte Carlo analysis. However, whilst a breach formation model may be able to run hundreds or thousands of simulations within a period of hours, it is unrealistic to assume that a complex 2D flood propagation model could undertake a similar process without undertaking weeks or months of analysis. A compromise solution was adopted for IMPACT that combines sensitivity analysis, Monte Carlo simulation and expert judgement. Whilst this approach may provide an estimate of uncertainty which contains a degree of subjectivity (expert judgement) it also provides a mechanism that is achieved relatively simply and provides a quick indication of potential uncertainty.

The process adopted comprised a combination of sensitivity analysis and Monte Carlo simulation, combined with (subjective) assumptions regarding upper and lower case scenarios.

Sensitivity Analyses

The uncertainty of various modelling parameters is examined here by first selecting some representative values for each parameter (e.g. the upper, most likely, and lower values). The modeller then runs the model using these values for each parameter. The output from the model for values other than the most likely value can then be compared with the output of the most likely value or a range is assigned to this model output in relation with the range of the input parameter. This comparison gives an indication of the uncertainty in output derived from each of the input parameters.

The advantages offered by this approach are that it is simple, quick and the relative importance of parameters can be identified. The disadvantages of this approach are that only a small number of values for each input parameter may be tested. The selection of the representative values of a parameter is, to some extent, a subjective process.

Monte Carlo Analysis

In this approach, an appropriate probability distribution is selected for each input parameter examined in the model (an example is given in Figure 8.1 for C_d). A number of runs are then undertaken by changing the values of all of the input parameters based upon their probability distribution. The values of the output parameter are then ranked and the distribution of results is plotted. Confidence limits may be assigned to this distribution (usually 5% and 95 % limits are selected). The range between these limits is then a quantified range for the uncertainty of the output parameter.

Under this approach, the output inherently combines the uncertainty of the full range of input parameters. Regardless of whether one or n parameters are considered, no further analysis of output is required to find the overall range of uncertainty. This is advantageous, if the model can be run repeatedly within a reasonable time frame.

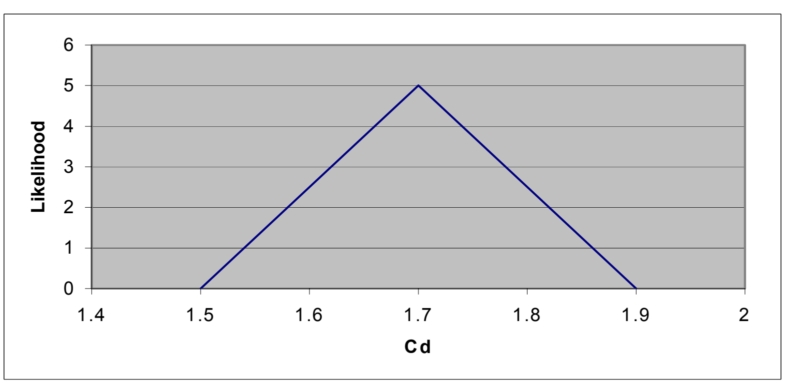


Figure 8.1: Example triangular probability distribution of C_d

Figure 8.2 shows an example of this approach where 1000 runs were undertaken, leading to the distribution shown. Taking the confidence limits as 5% and 95%, the range of uncertainty would be 55-180 m^3/s with a likely peak outflow of 120 m^3/s (at 50%). This translates to – 65 m^3/s to + 60 m^3/s uncertainty in the peak outflow generated from all of the selected input parameters.

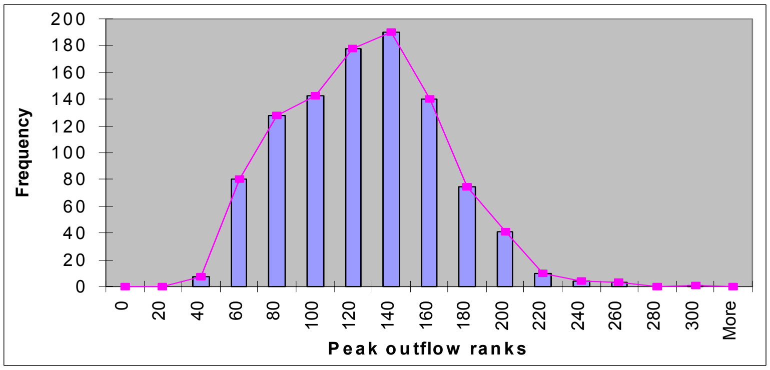


Figure 8.2: Peak outflow distribution based on the Monte Carlo analysis approach

The advantages of this approach are that a wider range of data is tested giving a better indication of uncertainty in comparison to a simple sensitivity analysis. In addition, a probability distribution is produced for the output parameters (e.g. Peak outflow) which also shows any non linearity of response. The main disadvantages of this approach are that the relative importance of each input parameter is not identified and a greater number of model runs is required in comparison to the simple sensitivity analysis approach (i.e. long run time).

With the pros and cons of each approach in mind, the approach adopted by IMPACT was to:

1. Assess breach model uncertainty via sensitivity analysis and Monte Carlo simulation
2. Extract representative flood hydrographs from the breach model analyses representing 'upper', 'mid' and 'lower' scenarios for use in flood propagation
3. Assess flood propagation models through sensitivity analysis only
4. Either select flood propagation model parameters to match upper, mid and lower scenarios for running with upper, mid and lower scenario breach hydrographs – ending with three sets of model predictions

or

Select upper, mid and lower scenario parameters for application to each of the 3 breach hydrographs, resulting in 9 sets of model predictions, from which representative upper, mid and lower conditions may be extracted (see Figure 8.3)

8.2.1.1 Analysis: Considering sediments

Floods from dam or dike failures induce severe soil movements in various forms. Other natural hazards also induce similar phenomena: glacial-lake outburst floods and landslides resulting in an impulse wave in the dam reservoir or in the formation of natural dams subject to major failure risk. In some cases, the volume of entrained material can reach the same order of magnitude (up to millions of cubic meters) as the initial volume of water released from the failed dam or embankment. The risks and uncertainty associated with sediment movement are therefore substantial.

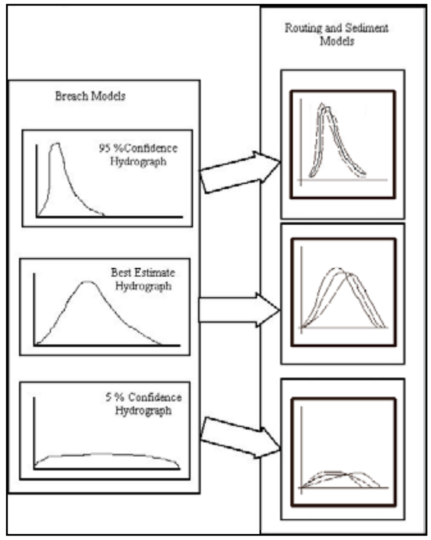


Figure 8.3: Linking uncertainty analysis between models

Extreme flood flows, such as dam break flow, can generate intense erosion and solid transport, resulting in dramatic and rapid evolution of the valley geometry. Both change in valley geometry and the volume of entrained sediment strongly affect the behaviour of flood wave propagation, and thus flood water levels and peak flood arrival time, which are fundamental parameters required for flood risk assessment and emergency planning. This means that uncertainties affecting the prediction of sediment movement may critically affect the whole prediction process. To evidence such an effect, a comparison was made between a wave on a fixed frictionless bed and the same wave on mobile sediments (Fig. 8.4).

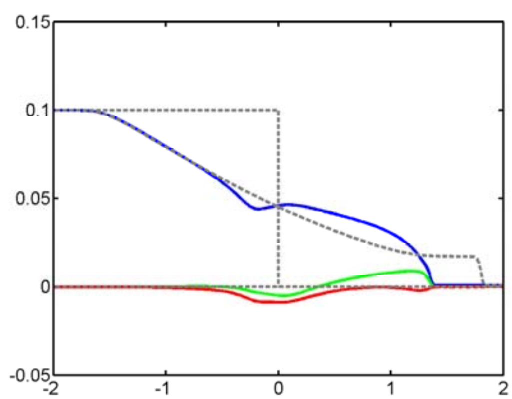


Figure 8.4. Comparison between dam-break wave
on fixed (dotted lines) and mobile bed (solid lines) at $t = 1.5$ s

It clearly appears that the mobilisation of the sediments diverts a part of the available potential energy, in such a way that the wave front is notably delayed, which is an advantage in term of alert and emergency planning for the downstream population. But the water depth is appreciably amplified behind this front, at least in the near field, increasing the endangered area and the associated risk for people living in the vicinity of the collapsed dam. This is consistent with field observations of a ‘wall of water’ forming the front of the propagation wave.

In the near field (close to embankment or dam breach), rapid and intense erosion accompanies the development of the flood wave. A debris-flow front develops, and the behaviour is different to standard flood flow behaviour. Inertial effects and bulking of the sediments may play a significant role. Most of the processes involved in this kind of phenomenon are uncertain and research is currently at the stage of understanding the processes and developing basic concepts.

Similarly, for the far field, extreme floods leading to erosion and deposition of large volumes of sediment result in morphological change, including the creation of new channels and flood routes. Modelling of steady state sediment movement can be achieved, but extreme flood conditions are far from this type of scenario. There are so many stochastic phenomena involved that the cascade of events becomes unpredictable, forming a kind of uncertainty tree that is difficult to manage. As an example, one key parameter in the modelling process is bed material. This material is heterogeneous, and consists of soils and rocks in an unpredictable arrangement. This single parameter poses a significant challenge for detailed modelling!

In terms to the contribution that 'sediments' make to uncertainty within the overall prediction of flood risk it may therefore be concluded that it will be significant, but that our understanding of the processes and ability to reliably model these is at a level where no predictive assessment may yet be made.

8.2.2 Findings: Application of approach

8.2.2.1 Findings: Application of approach for breach modelling

Breach modelling for the Tous Case study was undertaken by three organisations. Each organisation used 1D models for the simulations. Each produced a range of results based upon Monte Carlo analysis of varying key parameters within their models. The number of runs undertaken by each partner varies, but the results provided give a typical representation of what might be expected when analysing such a situation. Figure 8.5 shows results from each organisation plotted together, along with the given outflow hydrograph for the Tous Dam.

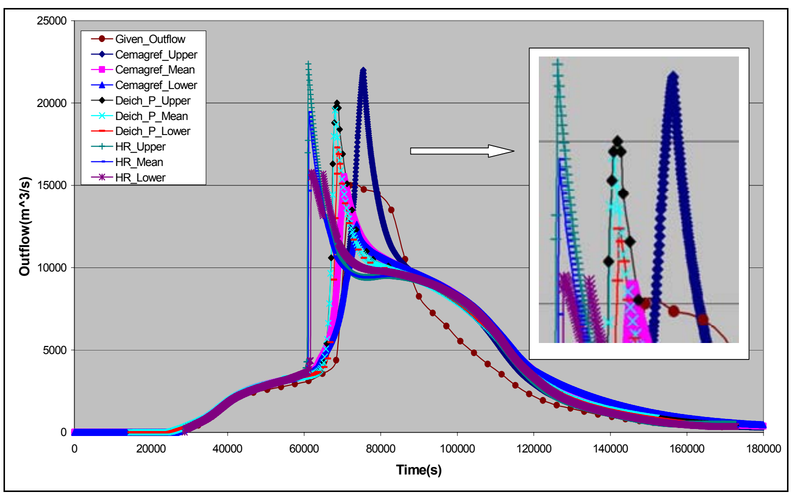


Figure 8.5: Comparison of Tous Breach Modelling Data

Representative hydrographs (upper, mid and lower: Figure 8.6) were then selected on the following basis:

- All modelling results were considered. There was no basis for confirming whether one set of modelling results was better or worse than another. The selection detailed below combines results from all partners and also covers the upper and lower bounds of the modelling results.
- Upper: The upper HR Wallingford estimate provides a result that offers approximately the highest and earliest peak discharge. This will likely lead to worst case conditions downstream.
- Mid: The lower band of UniBwM results offers a hydrograph that was placed mid way between peak and lower estimates, both in terms of timing and flow.

- Lower: The Cemagref lower estimate provides the lowest peak discharge and slowest hydrograph. This will likely lead to the least extreme conditions downstream.

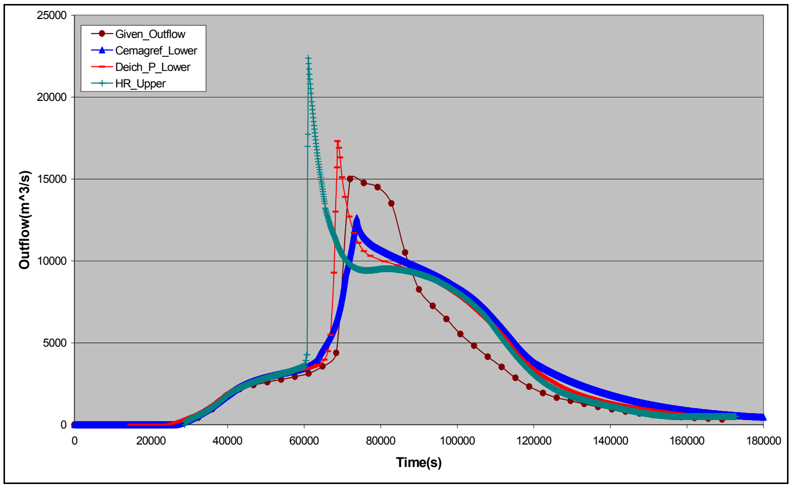


Figure 8.6: Tous Breach Modelling Data: Selected Upper, Mid and Lower hydrographs

Issues raised

The analysis process (of HR Wallingford) highlighted two interesting features of the breach modelling process:

<u>Modeller Assumptions</u>

During the modelling process the Tous Dam failure was also simulated whilst assuming two different sediment transport (cohesive and non cohesive), and a homogeneous embankment comprising either 100% core material type or 100% shoulder material type. This type of assumption has to be made when a breach model can only simulate a homogeneous, rather than composite structure. Figure 8.7 shows a comparison of results for the outflow hydrograph plotted against given case study and the HR BREACH composite modelling results. The predicted hydrographs show a very wide range of scatter, with one peak discharge greater than 300% of the given data. This suggests that the practice of averaging soil properties for composite structures and simulating failure as though it were an homogeneous embankment could lead to significant errors in predictions.

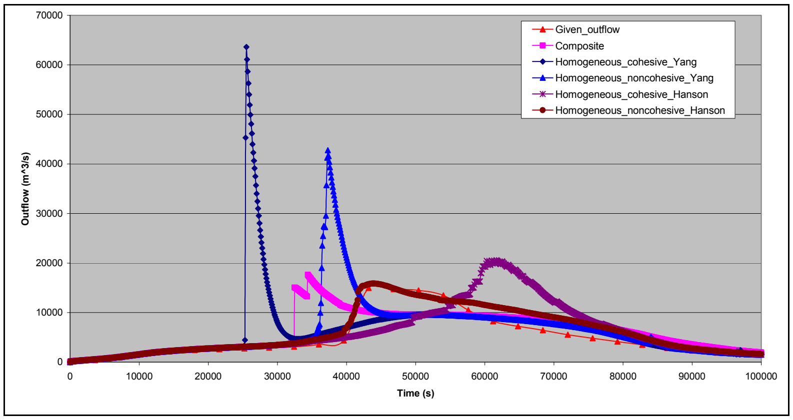


Figure 8.7: A comparison of outflow hydrographs assuming homogeneous embankment and core or shoulder soil properties

<u>To Fail or not to Fail?</u>

Figure 8.8 shows the Monte Carlo analysis distribution generated by the HR BREACH model. The bar to the left of the graph represents model simulations where the dam has not failed. This is a legitimate result of the modelling; no one can be certain as to how certain failure was under the given load conditions. For the analyses undertaken within IMPACT, these scenarios have been ignored. However, for a general risk analysis it would be important to consider the implications of non failure of the embankment or dam. For this analysis ~900 out of ~1600 runs suggested no failure.

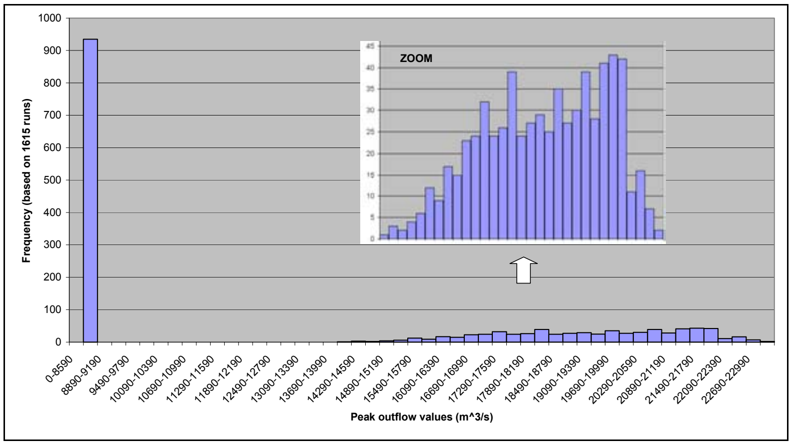


Figure 8.8: MC distribution from HR BREACH Tous analysis

8.2.2.2 Findings: Application of approach for propagation modelling

Flood propagation modelling was undertaken using the breach modelling hydrographs (upper, mid, lower) as upstream boundary conditions. Three models (all 2D) were applied as summarized in Table 8.1.

INSTITUTION	NUMBER OF CELLS	CITY MODEL
CEMAGREF	2611	Vertical walls
UCL	60911	Vertical walls
UDZ-1 (Alcrudo & Mulet)	~ 20000	Vertical walls

Table 8.1 Institutions reporting results for the hydrograph uncertainty analysis.

Note: 'Vertical walls' in Table 8 refers to the method of simulating the urban area – in this case, by creating a 2D ground model incorporating the buildings.

Before considering numerical modelling results it is interesting to make a comparison between model interpolations for predicting the ground level at control points. These differences are not negligible and cause discrepancies in the results if we compare them in terms of water depth. The numerical interpolations for the different control points can be seen in Figure 8.9 below.

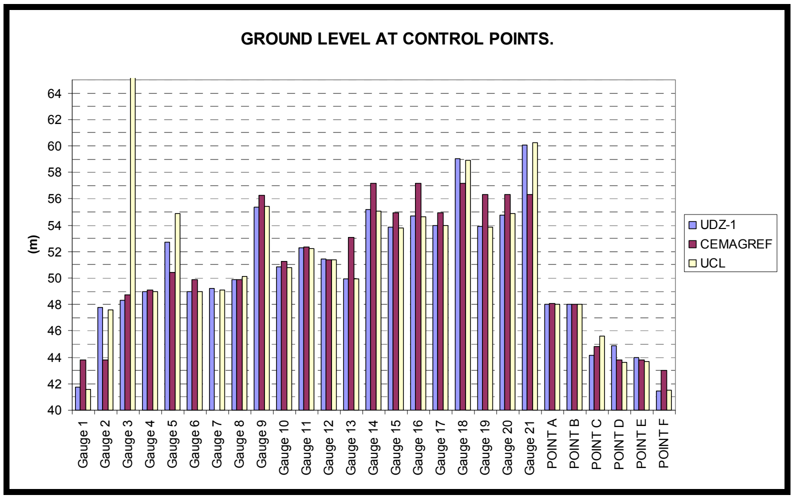


Figure 8.9 Comparison for the ground interpolation between institutions.

Differences in modelled ground level mean that differences in modelled water level are already guaranteed, before we even consider the accuracy of different hydraulic modelling approaches and potential variation in modelling parameters.

Initial model runs were undertaken using the upper, mid and lower breach hydrographs but assuming fixed model parameters (roughness etc.). This provides data that allows a direct comparison of model performance, as shown, for example, by Figure 8.10.

This shows a variation of peak levels of 2-3m as a function of the different breach inflow hydrographs, but also a variation of up to 3m between different model predictions. These differences naturally vary from location to location but a similar analysis may be undertaken at each point to gain an overall indication of where uncertainty lies. Table 8.2 shows a summary, for 7 selected locations, of overall uncertainty (i.e. hydrograph + model differences) and the uncertainty arising just between models.

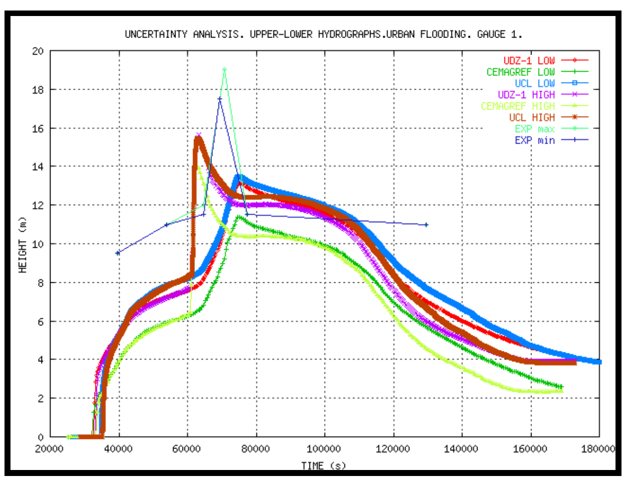


Figure 8.10 Hydrograph uncertainty results for the gauge 1

	Overall Uncertainty		Uncertainty between Models for a given Hydrograph
	Water depth	Water elevation	Water Elevation
Urban	~ 7 m	~ 2-3 m	~ 1 m
Valley			
A	~ 9 m	~ 9 m	~ 5 m
B	~ 6 m	~ 6 m	~ 3 m
C	~ 4 m	~ 3 m	~ 1 m
D	~ 4 m	~ 4 m	~ 1 m
E	~ 4 m	~ 3 m	~ 1 m
F	~ 3 m	~ 2 m	~ 1 m

Table 8.2 Inflow hydrograph uncertainty analysis results.

Having highlighted differences between model performance, both in terms of ground model generation and hydraulic calculation, and the effect of different inflow conditions, the modellers then focussed on analysis of ‘upper and lower’ propagation model scenarios (i.e. the approach shown schematically in Figure 8.3).

Six scenarios were modelled, using two different modelling approaches. Tables 8.3 and 8.4 summarise these approaches.

Case	Hydrograph	Valley Friction (Manning)	Cultivated Zone Friction (Manning)
Lower – Prop Lower	Lower	0.025	0.025
Lower – Prop Medium	Lower	0.035	0.05
Lower – Prop Upper	Lower	0.045	0.1
Upper – Prop Lower	Upper	0.025	0.025
Upper – Prop Medium	Upper	0.035	0.05
Upper – Prop Upper	Upper	0.045	0.1

Table 8.3 Propagation modelling scenarios

INSTITUTION	NUMBER OF CELLS	CITY MODEL
CEMAGREF	2611	Vertical walls
UDZ-1 (Alcrudo & Mulet)	~ 20000	Not included

Table 8.4 Institutions reporting results for the additional uncertainty analysis.

With detailed modelling results from each of the two models for six scenarios covering the case study area it was then possible to extract and compare data at selected locations. Figure 8.11 below shows an example of peak water levels predicted at a given location for the various scenarios. This level varies by some 5m between extreme lower and upper scenarios.

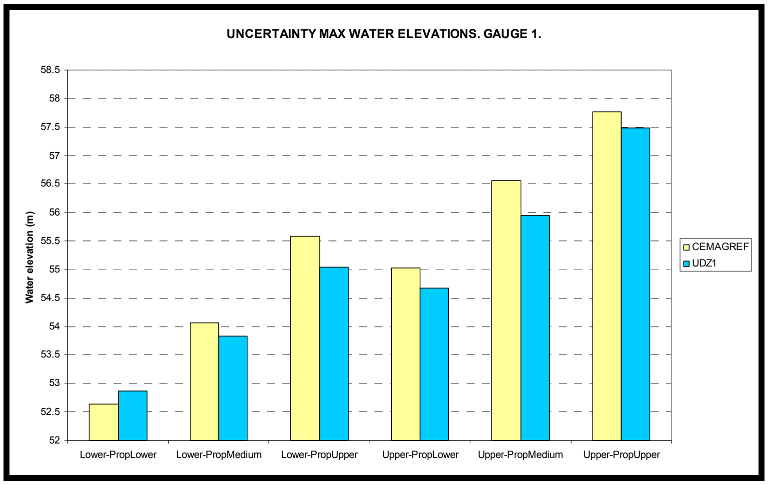


Figure 8.11 Maximum water elevations for gauge 1

Analysis of the modelling data then allows a breakdown of the sources of uncertainty within the overall modelling results. Figures 8.12-8.15 show total uncertainty for 7 selected gauging points followed by uncertainty contributions (for the same points) due to variation in the inflow hydrograph, uncertainty in the friction distribution and uncertainty due to differences between models used.

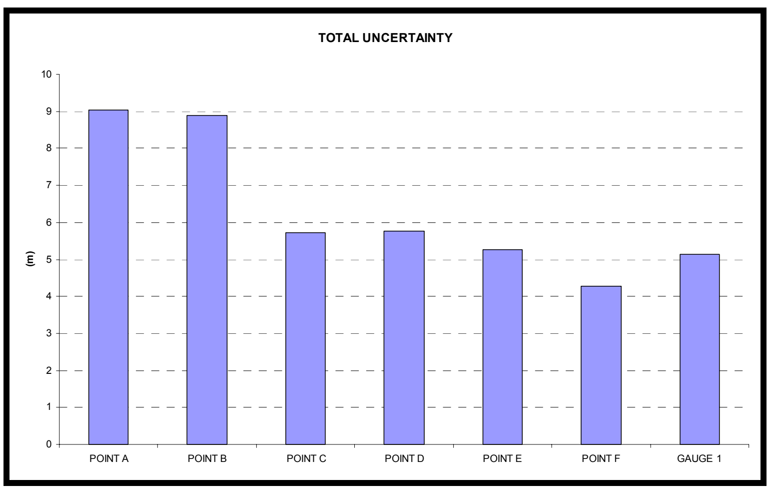


Figure 8.12 Total uncertainty values for each gauging point.

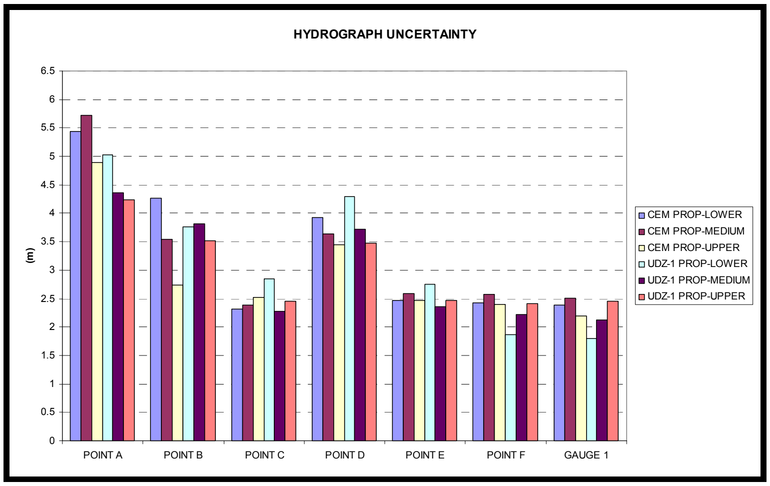


Figure 8.13 Uncertainty due to the inflow hydrograph.

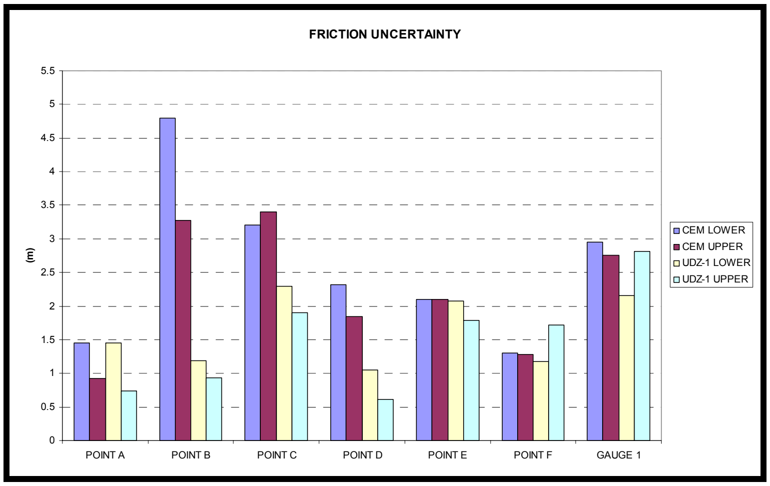


Figure 8.14 Uncertainty due to the friction distribution.

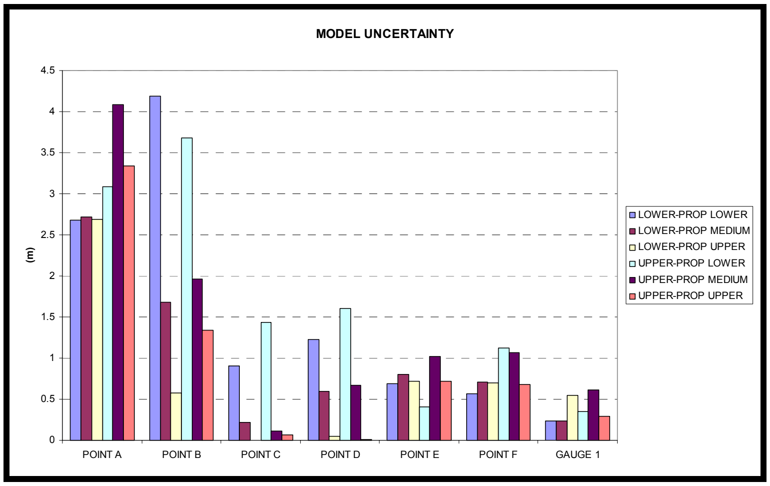


Figure 8.15 Uncertainty due to the model used.

It appeared that the most influencing parameter in water elevation prediction is the bed roughness and its distribution, especially around the town area. The uncertainty in this input is unfortunately large in most practical applications, which translates into considerable uncertainty in model output. Second important factor is the inflow hydrograph intensity to which about 2.5m of water depth uncertainty can be attributed in the town. The bathymetry combined with the computational mesh is the next source of uncertainty in this study. The influence of these two is mixed and difficult to isolate due to the interpolation process needed to construct the discretised model of the valley. Put in other words, differences in output produced by different bathymetric data can also be partially attributable to differences arisen in the interpolation process. Finally uncertainties introduced by different flood propagation models or modellers are less important than the others listed.

Overall uncertainty figures in water elevation can be as high as five meters in the town area and as much as nine meters in the river bed. The explanation for this is the very large range of input data, comprising inflow hydrographs with peak discharges between 12000m^3/s and 22000m^3/s and Manning's friction coefficients ranging from 0.025 and 0.045 in the main valley plus 0.025 and 0.1 in the cultivated zones close to the town. In the runs made during this study the effects of bathymetric interpolations in conjunction with the coarse mesh used by one partner has a considerable impact on the uncertainty of the results, particularly close to the dam. All these factors are added together to yield the figures mentioned above.

8.3 Key Conclusions and Recommendations for Industry and for Further Scientific Progress

8.3.1 General issues

- The proposed approach combining sensitivity analysis, Monte Carlo analysis and upper, mid, lower sampling provides a relatively simple method for indicating (modelling) uncertainty within the modelling results which combines analysis and judgement to give indicative (not rigorous) results

- It was established that the complexity of development and analysis work required to develop a fully rigorous method for assessing modelling uncertainty, and for linking uncertainty between models, was such that this could not be achieved within the programme specified under IMPACT. [This is now being addressed within the FLOODsite project (www.floodsite.net)].

- The different nature of models, and in particular run time, limits the extent to which Monte Carlo analyses can be undertaken. Monte Carlo analysis is currently feasible for breach modelling (where models run in seconds or minutes), but impracticable (at current computer power levels) for detailed propagation modelling (where models run in hours or days). The value of rapid propagation models, where accuracy is offset against speed, should be assessed.

- The magnitude of uncertainty within the predicted water levels for the Tous case study is very high – most likely considerably higher than many people would imagine. This is the result of the combination of multiple factors contributing to overall uncertainty within the predictions. Whilst this is one particular test case, there is little chance to avoid the addition of similar uncertainties when looking at other scenarios. If uncertainty figures are to be reduced by a significant amount, then a very considerable research effort in this area will be needed. To this end, 1) the uncertain inputs have to be investigated in depth in order to hold their span much tighter than presently and 2) the convergence, particularly concerning mesh dependence, of flood propagation models must be more firmly assessed and established and 3) methods for reliably predicting friction values for extreme floods are required.

8.3.2 Breach modelling

- Understanding model sensitivity to different parameters is an essential basic step within uncertainty analysis. Breach models are highly dependent upon selection of an appropriate sediment transport equation.

- Monte Carlo (MC) analysis allows visualisation of the outputs from a model, giving a greater insight into likely breach mechanisms and / or constraints of the model. For the Tous case study, MC analysis highlighted the fact that as some parameters were varied, failure was predicted not to occur. This is a very real possibility, although it is impossible to say how far beyond the point of failure the hydraulic loading pushed the Tous structure during the real event.

- An initial analysis suggests that simulation of composite structures by averaging soil parameters and assuming a homogeneous embankment could result in very significant modelling errors

- Modeller best estimates (i.e. expert judgement) typically gives a better result than 'blind' acceptance of a mid value for different parameters

- Breach modelling results showed a variation around the field data of approximately +50% -20%.

- Breach modelling results all showed a similar hydrograph shape which was different to that observed in the field. Modelling results tended to show a high peak with a rapid drop down whereas the field data suggests a much flatter peak, suggesting prolonged high discharge flow. This is likely to be a function of the breach growth process interacting with the dam core and overflow structures.

8.3.3 Flow modelling

- Uncertainty in valley topography can lead to significant differences in water level. For the Tous case, two topographies were modelled. It is unclear what topography really existed prior to the failure event, and even with this knowledge, the movement of sediment during an event could result in a transition of conditions from one (fixed bed) scenario to another. Topography and potential sediment movement are therefore important factors to consider within a dam break analysis.

- Provided a well documented situation is being modelled the single factor most affecting output (water elevation) is bed friction and its distribution in and around the sensitive areas. The second important factor among those considered is inflow hydrograph into the flood propagation model.

- Modelling mesh density (or section spacing) is important. Of the three 2D models applied to the Tous case study, the number of cells (mesh density) varied significantly from ~2600, ~20000 and ~60000. Ground levels, represented by these meshes, varied, with differences of several metres in some locations (including some locations within the urban areas). Errors in ground level of several metres in zones where flow depth may also be several metres are fundamental. Greatest differences were between the coarser mesh model and the other two, as might be expected.

- The magnitude of variation in predicting water level reduces as you progress away from the dam (as the flood hydrograph attenuates).

- The magnitude of uncertainty in predictions of water levels within the urban areas is large. Variation seems typically in the order of ± 30-50%, even with flood depths of 5-10m. Variation of this magnitude might be expected within the valley nearer the dam, but is surprising at this downstream, urban location.

- Uncertainty in predicting water level may be allocated between differences in model prediction, differences arising from the input hydrographs (i.e. the breach modelling range of predictions) and differences due to assumed friction values along the valley.

  Initially ignoring friction (all assuming similar friction values) differences between propagation model results accounted for perhaps ~1/3 of the overall uncertainty – i.e. 2/3 of the uncertainty may be attributed (in this case) to uncertainty in breach outflow hydrograph.

- Subsequently analysing uncertainty as a function of the influence of the hydrograph, model type and assumed friction range it could be see that:
    - total range of uncertainty varied in magnitude from 9m (~40% water depth; point A) to 4m (~35% water depth; point F)
    - hydrograph uncertainty contributed ~50% of the uncertainty; friction ~25-40%; model type ~10-25%

  For this case study the predictions were therefore most susceptible to variation in the outflow hydrograph, followed by selection of appropriate valley and urban area friction parameters. Choice of model type (between those tested) had the smallest effect. For flood propagation, the single most important factor is therefore choice of friction value.

- These figures are understandable in light of the very large range in input data; the inflow hydrograph peak discharge ranges from 12,000 to 22,000 m^3/s and the Manning's roughness coefficients from 0.025 to 0.1 in some areas. Whilst wide ranging, these are realistically the best estimates that can currently be made under these circumstances.

- The influence of friction parameter was less influenced by distance away from the dam – i.e. choice of friction had a significant and more consistent effect on prediction of local water levels. Output model variation with friction is more noticeable in places close to the areas where high friction values and important variations in these are assigned. In this case study this happens in the surroundings of Sumacárcel where the orange tree orchards were located, hence the direct impact in inundation levels in the town.

8.3.4 Sediment modelling

Most of the processes involved in this kind of phenomenon are uncertain. Also the data needed for such a modelling are commonly difficult to get. The material constituting the reservoir bottom is not uniform, its thickness is not well known and it typically accretes with time. The material of the valley bed downstream from the dam is also heterogeneous: it consists of soils and rocks in an unpredictable arrangement. Measurement of this is tedious, difficult and expensive.

That means that, at the moment, no standard procedure can be recommended to take into account the sediment influence on the dam-break wave. That also means that the end-users have to be conscious of the limits of their models regarding this point.

The models are based on an idealisation of the dam break. The problem is represented in a vertical plane and the dam is supposed to instantaneously disappear without lateral effects. Only the valley-bed material is taken into account in the near-field solid transport, neglecting the material issued of the breaching itself. At the current stage of the models, the bed mobilisation modelling is not yet coupled with the breaching modelling. The models are promising for idealised situations but are still far to represent the real-life situations.

For the far field, the point is to represent the valley evolution, with a succession of erosion and deposition supplied by the upstream solid transport and by the bank collapses. A part of the morphologic evolution may be modelled, above all locally, but for a reach of a few kilometres, there are so many stochastic phenomena involved that the cascade of events becomes unpredictable, forming a kind of uncertainty tree that is difficult to manage.

8.3.5 Implications for end users

The uncertainty analysis programme of work was developed during the project with a significant input from research team members and end users at each of the workshops. During the first two workshops, inputs were primarily focussed around methods of analysis and the general direction of work. During the third workshop preliminary results of the methodology were becoming available. However at the 4th workshop team members and end users were able to see the full extent of the modelling capabilities and uncertainty analysis undertaken, leading to specific end results. Considerable discussion was held relating to both the overall results of the project and the implications of the project findings. Key points for end user application are outlined below:

1 Different end users;

There are many different end users, each with different perspectives (Politician to Commercial Client) and it is recognised that 'one solution' does not meet all needs. Equally, modelling work may be undertaken in a variety of ways to focus outputs on specific aspects. It is important that the end user clearly identified why any analysis is being undertaken and how it would be used; equally for the modeller to understand this.

Blind use of modelling data for a wide range of applications can lead to errors. A simple example would be use of a simple 1D river model created for detailed local modelling of natural flood conditions for use as a dam break model. To the end user, both applications are to predict flood levels in the same area, however model construction and results would be significantly different for each application. For consistency, identical topographic and hydraulic loading data may be used, but model construction and analysis may be different.

2 Understanding the relative importance of different modelling processes:

Users should appreciate the importance of different 'components' of the flood modelling process (i.e. breach, sediments and propagation) and also the fact that the maturity of science for each of these areas is different. As such, the degree of uncertainty contributed by each process is different. The importance of this will depend upon the particular application, where proximity to the dam, topography and nature of bed material will dictate the relative importance of each 'component'.

3 Sediments:

IMPACT research confirms that sediment movement does have a noticeable impact on both predicted water levels and predicted time of flood arrival. However, scientific understanding and modelling capability are currently in their infancy and unable to match abilities in terms of breach and propagation modelling.

4 Uncertainty in model predictions:

Uncertainty within model predictions is actually quite high. The main contributors being uncertainty in the breach process and assumed roughness values. Predicted water levels may vary by as much as ±50%; timing of flood arrival may also vary significantly.

When using flood modelling results to assess potential impacts or plan emergency actions, this range of uncertainty should therefore be built into the analysis. For example, the impact of flooding may vary significantly if levels vary by ±50%, but a probability of such variation may be assumed, so allowing, for example, cost benefit analysis to be undertaken.

When using results for emergency planning, a flexible approach is required whereby plans allow for significant variation of conditions in the field. This is essential if the lives of members of the emergency services are not to be put at undue risk and maximum impact is made in the field.

Given the degree of potential uncertainty, there would be value in establishing early indicators in a catchment of the magnitude and likely behaviour of an event. For example, peak water levels or flood extents at a location higher along a valley may allow refinement of the prediction of likely inundation further down the valley. The value of such an approach would depend greatly upon the size of the catchment, speed of inundation, speed of response and ability to analyse and advise within a very tight schedule. This may not be feasible where timing from failure to inundation is minutes, but could help considerably where hours or days are available.

5 Understanding models:

A huge number of different models exist worldwide for analysing breach formation, flood propagation and sediment movement. The capabilities and accuracy of these models can vary significantly. End users should be aware of the capabilities of models, why they have been selected for use and how the modelling results will be used. It is essential that the degree of accuracy and uncertainty is consistent with end use and, of course, the cost of the analysis.

Faced with the question of whether or not to undertake detailed analysis, the end user can consider two scenarios: a wrong decision that means money was spent and subsequently found to be unnecessary is unfortunate; a wrong decision where money was not spent and subsequently found to be needing is unacceptable.

6 Evaluating experts and models:

How does an end user evaluate an expert / model when they are not calibrated?
The end user is placed in a difficult position of needing to evaluate the performance of a range of models for which there is little data to calibrate against. Logically, use by an 'expert' is then deemed the best approach, but equally how do you validate an expert?

The only approach that can be taken is to try and assess the relative performance of models, an absolute measure of uncertainty (objective of IMPACT) and to gauge expert capabilities through a combination of industry and scientific experience and the nature of proposed approach. Whilst the IMPACT project does not (and can not) provide specific answers to these questions, it does provide examples and indicative measures of performance that may be used to gauge standards.

7 Choosing modelling approach- Peak discharge; hydrograph shape; sensitivity and MC analysis:

The breach and propagation modelling has highlighted the need to always question and confirm the modelling approach before undertaking a study. The Tous case study demonstrates that adoption of a breach hydrograph with the highest peak discharge does not lead to worst case water levels downstream; instead a lower peaked but longer duration hydrograph gives worst conditions.

This observation is not new; logic dictates that flood conditions are dependent upon flood volume, speed of release and local topography. However, a tendency within the dam safety industry to select peak discharge as a measure of potential worst case scenarios (e.g. use of peak discharge equations) can lead to false impressions. Modelling using the full predicted hydrograph (shape) for a range of conditions is the only reliable way to assess potential flood conditions. Use of model sensitivity analysis and Monte Carlo analysis where practicable provides a far greater degree of understanding.

8 End users taking a conservative approach?:

There is a natural tendency for end users to adopt a conservative approach to safety when faced with uncertainty in model predictions. This is logical, but depending upon the particular issue, conservative assumptions may not always be consistent. For example, when faced with planning emergency evacuation for an area, the planner needs to assess likely inundation depths and likely time of arrival of the flood wave. Where sediment is involved, the effect may be to delay arrival of the flood wave, but also to increase the magnitude of the wave. These two effects are inconsistent in terms of a simple conservative approach. The planner therefore needs to appreciate uncertainty in different parameters which may be linked, but each offsetting the other.

9 Next steps towards improved modelling:

To improve modelling capability within each of the three component areas will require a different approach for each:

Flood propagation: Scientifically mature; awaiting increased computing power to improve resolution of modelling grids rather than further refinement of numerical modelling approaches. Timescale: ~5 yrs.

Breach formation: Significant further advances in modelling capability can be made by further analysis of existing and complimentary datasets and by further integration of soil mechanics and hydraulic theory. Timescale: immediate opportunity.

Sediments: Our ability to accurately model the complex sediment processes is relatively poor. Understanding of these processes is improving, but considerable further research into basic processes is required before models can be developed that have the same magnitude of reliability as current breach and propagation models. Timescale: → 10 years

10 Funding improvements:

Many end users (governments and individuals alike) are moving towards a risk based approach for assessing and managing flood risk. Within such an approach the consequences of dyke or dam failure may be assessed, and the balance between strengthening and mitigation of consequences may be made. Equally, the contribution that modelling makes within this process may be clearly identified and the effect of modelling uncertainty determined which in turn allows assessment and justification of funding for research to improve and refine modelling capabilities.

With the huge numbers of flood control and defence assets worldwide, and the potential assets at risk in the event of a failure, the figures will justify significant effort in this area. It would also be preferable for such an investment to be made based upon a logical assessment of conditions rather than in response to a periodic failure of key infrastructure, as so often happens. In addition, with identical problems faced by dam owners and flood defence managers worldwide, it is logical to collaborate and integrate such research initiatives wherever possible, making use of international experts from a range of technical disciplines.

9. SITE SPECIFIC CASE STUDIES

9.1 Overview

It had originally been the intention to use a single case study to develop, apply and highlight modelling capabilities – and in particular to show the degree of uncertainty within modelling results, and how this may (should) affect end user applications. In the event, it proved extremely difficult to locate a case study suitable for all science areas (i.e. breach, sediment movement and flood propagation). Equally, it soon became clear that the level of scientific understanding and modelling capability for sediment analysis was significantly different to that for breach and flood propagation. Consequently, two case studies were selected. The first – Tous Case Study – was used to develop and apply breach and flood propagation models, including an assessment of modelling uncertainty. The second – Lake Ha!Ha! Case Study – was used to highlight key sediment processes and to assess preliminary model performance.

In both cases significant amounts of field data were collated and processed. In both cases, the original IPR for the data remains with the source organisations. Members of the IMPACT project were allowed access to this data for use in analysis within the IMPACT project only. Any further use / analysis by third parties will require authorisation from the original source authorities.

9.2 Specific Knowledge from the Tous Dam Study

The failure of Tous Dam near the central eastern coast of Spain was selected as the Impact project case study for work concerning breach formation, flood propagation and uncertainty. Data concerning the Tous Dam case study were collected from March 2003 to January 2004 with considerable difficulties due to confidentiality and sensitivity issues (the case had only recently and finally been settled in court).

The case study concerns the burst of Tous Dam after several hours of overtopping due to extraordinary heavy rain fall in the area on 19-20 October 1982 that filled Tous Reservoir with more than its rated capacity. The subsequent flood afflicted a large area and about one hundred thousand people had to be evacuated. Only a short reach of the river downstream of the dam was studied, including the town of Sumacárcel (population 2000) the first urban area hit by the flood. The case study, including data collected, are described in detail in reports referenced as Alcrudo and Mulet (2003 and 2004) and Mulet and Alcrudo (2004a, 2004b). A brief summary is given below.

A search for a catastrophic flooding event after failure of a water control structure was initiated at early stages of the project. Of particular importance was the need for city flooding data. This task was considered essential for successful completion of deliverables D3.1.4 and D3.2.4. It also has impacts on other work packages (notably WP4, Sediment transport, and WP5, Uncertainty). This task demanded considerable work input from several partners since it proved difficult to find a suitable scenario. After several candidates were considered, a late decision was made in favour of Tous Dam break that led to catastrophic flooding of a large area in the South Eastern coast of Spain in 1982 including the town of Sumacárcel.

Data sought comprised topography, dam construction plans and materials and hydraulic and hydrologic information. Topographic data collected include high resolution maps (scale 1:500, 1m spacing elevation levels) and digital terrain models (DTM's) of the area at the time of the catastrophe and also current; high resolution aerial photogrammetic pictures in electronic format; extensive photo and video footage of the area and town, including Tous Reservoir. Tous Dam data included construction plans and materials used, including an approximate grading. A large amount of hydraulic information of the event was gathered and collated. This includes high water marks (envelope of water elevation) along the considered valley reach; inflow and outflow hydrographs into and out of Tous Reservoir; rainfall distribution and intensity; timing of the flood; characteristics of the flood inside the town of Sumacárcel, including water elevation at many locations and rough timing. Eye witnesses of the tragedy were interviewed and photos and videos recorded showing the effects of the flood in the town of Sumacárcel.

Modelling work (flood propagation and breach formation) lasted until the 4th and last project workshop held in Zaragoza (Spain) were results were presented. Impact members participating in this task are UCL, CEMAGREF, CESI and UDZ as regards flood propagation. HR Wallingford and Universität des Bundeswehr München (UniBwM) participated additionally in breach formation work.

Several important issues have arisen during Impact work in Tous Dam case study. First of all the check list needed to make up a viable case study is long and difficult to complete:

- Data collection: An extremely important task often hindered by the fact that circumstances associated with any catastrophe do not help data collection and recording.
- Data understanding and collation: Collected data are often incomplete, contradictory or difficult if not impossible to understand in some instances. A considerable amount of work must be put to clarify and collate data in order to make up the case.
- Preparing a model of the event: Mesh the area, translate actual conditions at the boundaries into model boundary conditions (a task difficult in many cases because the flow conditions at the boundaries of the computational domain are not known) assess the relative importance of different parameters.
- Running the model is very difficult in these cases because often time and space-like scales make the problem computationally too big, hence too long to run in reasonable wall times with currently available computers. Flood propagation simulations took days or even weeks because of the need to resolve the flow in the streets of the town while the duration of the flood was two days of actual time.
- Analysis and interpretation of model output can be a difficult and lengthy task due to the large volume of data generated.

The Tous case study proved that present high resolution models are not practical for simulating large areas within reasonable time periods. A limit for their application is simulation of flooding over approximately 10 square kilometres per day. Longer durations or larger areas would make the simulation with present models unacceptably long or model resolution too low for having a local representation of the flood. Also, if an accurate representation of an urban flood is needed, it is likely that the most efficient technique be a detailed meshing of the affected city or town, despite the difficulties and high work load associated with efficient meshing of complex domains. The bottom elevation technique leads to further increases in the size of the computational mesh, and the high friction approximation may not work well in low speed flow floods that can easily happen inside a city. It is not surprising that, of the five teams that conducted modelling on the Tous case study, all worked out successfully the detailed meshing approach, while only two tackled it by means of the bottom elevation technique, of which just one was able to fully reproduce the flooding of the town. Finally, only one team modelled the case with the high friction technique that was not able to reproduce the observed flooding of the town.

Analysis of model results also showed that although the Tous Dam break was indeed an extreme flood event with submersion levels on the order of meters and reaching tens of meters in some places, the town of Sumacárcel itself was not subject to the impact of an inertial flood. The geographical configuration of the area (and perhaps lessons learned by historic dwellers of the site) led to a town that is actually sheltered from the direct impact of the flood wave. Further, and despite the failure of Tous Dam, the flood wave generated was not an abrupt front. From this view point the case study was not ideally configured for the project as originally expected. However it was proven that methods specifically designed to model extreme flood events performed accurately and equally well in less demanding conditions.

9.3 Specific Knowledge from the Lake Ha!Ha! Study

In July 1996, the collapse of a secondary dam along the Lake Ha!Ha! reservoir resulted in a severe dam-break wave with spectacular morphological changes in the 30 km long river, till the confluence with the Saguenay River in the Ha!Ha! Bay (Fig. 9.1).

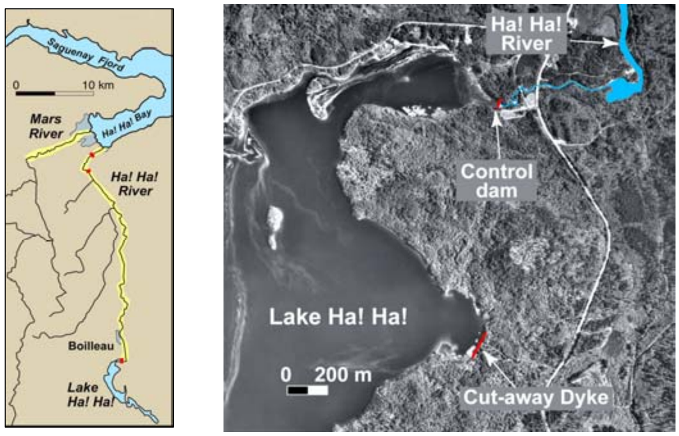


Figure 9.1 Lake Ha!Ha! (Brooks, 2003)

Practically all the typical features of severe morphological evolution could be observed consequently to the disaster: large deposition areas, in which the river has to reconstruct its path (Fig. 9.2a), large-scale widening (Fig. 9.2b), sometimes blocked by the presence of bed-rock sills and banks (Fig. 9.2c), changes in bed profile, changes in path, etc.

(a) Deposition (b) Widening (c) Bed-rock effect

Figure 9.2 Typical morphological evolutions after the Lake Ha!Ha! dam-break wave (Brooks 2003)

A huge effort to interpret the available data was carried out by the Geological Survey of Canada, the University of Quebec, the National Taiwan University and the Catholic University of Louvain (Capart et al., 2003) to produce a usable data set, probably one of the best available for model validation in real-life situations.

After data collation, the real-case study involves:

- Data interpretation
- Posing reasonable assumptions to incorporate in numerical model:
    - Defining a mesh: 1D / 2D?
    - Boundary conditions? Not always physical with available data
- Solve the problem (run the computations)
- Critical analysis of results, assessing value and “reality” of results

Field data
For the Lake Ha!Ha! dam break, extensive data is available for the pre- and post-flood situation. The data was processed by UCL in association with the National Taiwan University, the University of Quebec, and the Geological Survey Canada, owner of the data. The data set comprises a complete DTM (30 km reach) of the pre- and post-flood situation, as well as the reconstructed outflow hydrograph from the dike breach.

Figure 9.3 shows the evolution of the bed profile in the vicinity of a large-scale avulsion. The initial river profile was controlled by a non-erodible rock area explaining the chute in the green profile of Fig. 9.3 Due to an overtopping of a depressed point of the bank line, the river diverted its course. The bed-rock area was bypassed, inducing a severe regressive erosion.

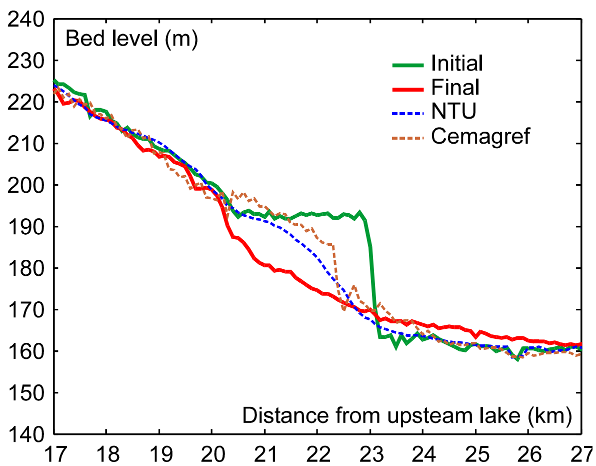


Figure 9.3 Bed profile of the Ha!Ha! River before and after the dam break. Comparison with numerical models

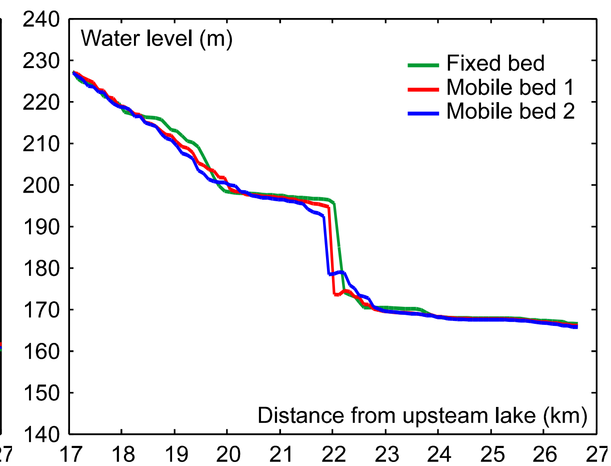


Figure 9.4 Water profile of the Ha!Ha! River near the flood peak (July 20, 19:30). Cemagref numerical model: comparison between fixed and mobile bed (2 approaches)

Although the 1D Cemagref model does not rely on sophisticated description of the moving sediment (Exner equation with solid transport from common formulae), the resulting bed profile evolves in the right direction, nevertheless with some numerical instabilities. Some differences can be linked with the location of rocks and the fact that the computation was stopped after two days, thus before the completion of the erosion process.

Figure 9.4 shows the water profile along the same reach of the river as in Figure 9.3. It evidences the role of bed mobility and morphological changes. The water elevation is obtained from two different calculations with the Cemagref model for mobile bed and compared with a fixed-bed approach (El Kadi and Paquier, 2004). At some locations, the mobility of the bed induces a drop or a rise of the water level up to 5 metres (see, for instance, km 21 and 22 on figure 9.4).

The diffusion-advection model used by the National Taiwan University is two-dimensional and anisotropic, but it relies on rather simple assumptions, which nevertheless appear as very efficient for the particular application of the Lake Ha!Ha! case. The landscape evolution is described by diffusion along slopes according to local gradients. No explicit hydrodynamic computations are required: the water table is horizontal in depressions and the depth is zero everywhere else.

Such an approach provides impressive results at least in some reaches, for instance in the upper reach of the river (Fig. 9.5). The 2D model seems able to capture the erosion zone just downstream the failed dam, and also the main deposition zones. The 1D model also predicts some deposition features, and, to a limited extent, some punctual results in the scouring zone. The widening of some sections is also qualitatively represented.

It is interesting to observe that in a complex case as the Lake Ha!Ha! only the simplest approaches succeeded to give some results, while sophisticated models did not cope with the huge amount of required data.

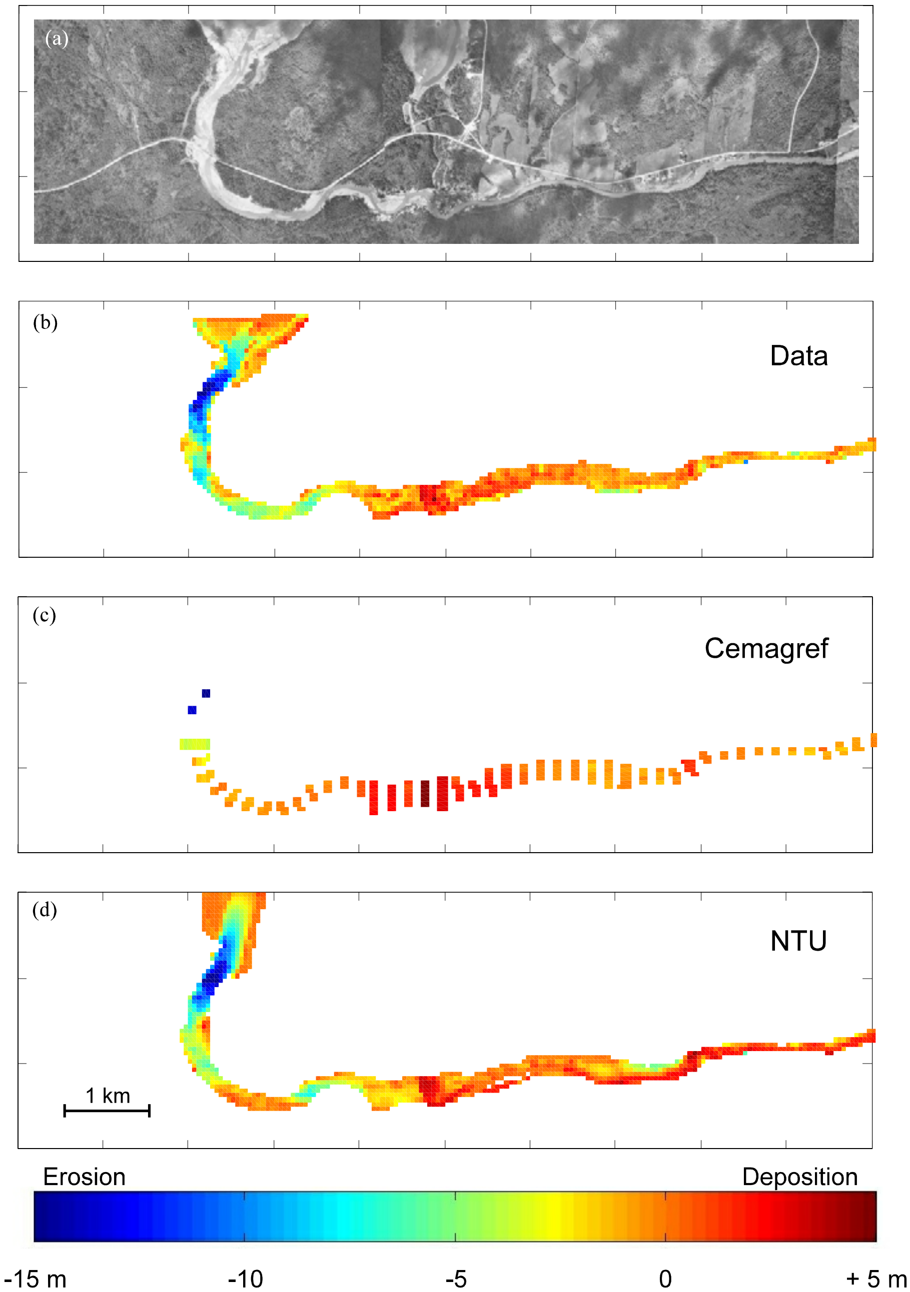


Figure 9.5 Erosion / deposition in the upstream reach of Ha!Ha! River.
(a) Picture of the river after the dam break
(b) Erosion / deposition surveyed after the catastrophe
(c) Numerical modelling result from the Cemagref model
(d) Numerical modelling result from the NTU model

10. ASSOCIATED IMPACT PROJECT DOCUMENTS

Final Report   Annex II, Part A   WP2: Breach Formation

Item	*Description*	*Linked Deliverables*	*Filename*
I	WP2: Technical Summary Report	All: D2.1.1 / D2.1.2 / D2.1.3 / D2.1.4 / D2.1.5 D2.2.1 / D2.2.2 / D2.2.3 D2.3.1 / D2.3.2 D2.4.1	WP2_10Summary_v3_0.doc
II	WP2: Detailed Technical Report	All: D2.1.1 / D2.1.2 / D2.1.3 / D2.1.4 / D2.1.5 D2.2.1 / D2.2.2 / D2.2.3 D2.3.1 / D2.3.2	WP2 technical_Report V9_2.doc
III	Summary of breach formation field tests	D2.1.1 / D2.1.2 / D2.1.3 / D2.1.4 / D2.1.5	Impact_kav.doc
IV	Summary of breach formation field and laboratory data	D2.1.1 / D2.1.2 / D2.1.3 / D2.1.4 / D2.1.5 D2.2.1 / D2.2.2 / D2.2.3	Technical summary V3.doc
V	Description of Deich_P breach model	D2.3.2	IMPACT-36Month_Report-UniBwM-wp23-appendix-1-1_description.pdf
VI	Modelling notes for Deich_P	D2.3.2	IMPACT-36Month_Report-UniBwM-wp23-appendix-1-2_notes.pdf
VII	Cemagref: Advances in breach modelling (Rupro)	D2.3.2	cemagrefbreachglobaloct2004.doc
VIII	Methodology for predicting breach location	D2.4.1	IMPACT-36Month_Report-UniBwM-wp24-annex-3_location.pdf
IX	Identifying potential breach location	D2.4.1	BreachLocationReport_v3_1.doc

Final Report   Annex II, Part B   WP3: Flood Propagation

Item	*Description*	*Linked Deliverables*	*Filename*
I	WP3: Technical Summary Report	All: D3.1.1 / D3.1.2 / D3.1.3 / D3.1.4 / D3.2.1 / D3.2.2 / D3.2.3 / D3.2.4	WP3_10Summary_v1_0.doc
II	Modelling flood propagation in urban areas	D3.1.1	Modelling techniques for urban flooding.pdf
III	Dambreak flow – isolated building test case	D3.1.2	Isolated Building.pdf
IV	Dambreak flow – model city experiment	D3.1.2	Model City Flooding Experiment.pdf
V	Dambreak flow around obstacles	D3.1.2	RF Soares et al Obstacle B1-226.pdf
VI	The model city benchmark tests – analysis of modellers results and conclusions	D3.1.3	THE MODEL CITY BENCHMARK.pdf
VII	Isolated building benchmark tests – analysis of results	D3.1.3	Isolated building benchmark.pdf

VIII	UCL computations for the isolated building and model city benchmarks	D3.1.3	03-11-07 IMPACT Noel print.pdf
IX	Cemagref computations for the model city benchmark test	D3.1.3	Cemagref_City_model_Description_file.doc
X	Modelling flood propagation in natural topographies	D3.2.1	Modelling techniques flood prop natural topographies.pdf
XI	Flood propagation modelling by Cemagref	D3.2.1	WP3_Cem_report.doc
XII	Dambreak flow over bed obstructions	D3.2.2	Bump River Flow final.pdf
XIII	Flood flow modelling over natural topographies – physical modelling	D3.2.3	Consideration_of_model_performance.pdf
XIV	UCL modelling of the Tous Case Study	D3.1.4 / D3.2.4	#6-1_Soares_Zech_Tous1-13.pdf Report runs UCL.doc
XV	Cemagref modelling of the Tous Case Study	D3.1.4 / D3.2.4	CS_Cem_report.pdf
XVI	Cemagref: Potential case study - Nimes	D3.1.4 / D3.2.4	02-05-16 IMPACT Paquier #1.DOC
XVII	The Tous dam break case study	D3.1.4 / D3.2.4	Tous_dam_break_case_study.pdf
XVIII	Zaragoza modelling of the Tous dam break	D3.1.4 / D3.2.4	Tous case study - UDZ_1.pdf
XIX	Zaragoza modelling of the Tous dam break – focus on topography and mesh simulation	D3.1.4 / D3.2.4	Tous case study- UDZ_2.pdf
XX	Tous case study – analysis of modelling results	D3.1.4 / D3.2.4	Validation of modelling techniques-Tous case study.pdf
XXI	CESI modelling work for flood propagation in natural topographies	D3.1.4 / D3.2.4	IMPACT-Technical Report CESI.doc

Final Report Annex II, Part C WP4: Sediment Movement

Item	*Description*	*Linked Deliverables*	*Filename*
I	WP4: Technical Summary Report	All: D4.1.1 / D4.1.2 / D4.1.3 D4.2.1 / D4.2.2 / D4.2.3	Impact WP4 final report 10 pages.doc
II	WP4: Detailed technical report	All: D4.1.1 / D4.1.2 / D4.1.3 D4.2.1 / D4.2.2 / D4.2.3	Impact WP4 final report.doc
III	University of Trento – detailed research report supporting WP4	All: D4.1.1 / D4.1.2 / D4.1.3 D4.2.1 / D4.2.2 / D4.2.3	Final_UdT_draft.pdf

Final Report Annex II, Part D WP5: Uncertainty

Item	*Description*	*Linked Deliverables*	*Filename*
I	WP5: Technical Summary Report	All deliverables: D5.1.1 / D5.1.2 / D5.1.3 / D5.1.4 / D5.1.5	WP5_10Summary_v1_2.doc

II	WP5 Detailed technical report	All deliverables: D5.1.1 / D5.1.2 / D5.1.3 / D5.1.4 / D5.1.5	WP5 technical_Report V1_2.doc
III	Uncertainty analysis undertaken using Deich_P breach model	D5.1.2 / D5.1.3 / D5.1.4 /	IMPACT-36Month_Report-UniBwM-wp51-annex-3_breach-analysis.pdf
IV	Uncertainty analysis of flood propagation modelling for the Tous case study	D5.1.4	Tous_Flood_Prop_Uncertainty.pdf
V	Cemagref modelling for the uncertainty analysis of the Tous case study	D5.1.4	UN_Cem_report.pdf

Final Report Annex II, Part E1 WP6: Geophysics

Item	*Description*	*Linked Deliverables*	*Filename*
I	WP6: Technical Summary Report	D6.1 / D6.2 / D6.3 / D6.4	WP6_10SummaryPartGeo_v1_0.doc
II	Review of geophysical monitoring methods and techniques	D6.1	IMPACT-D6.1_Report.doc
III	Implementation of monitoring programme on embankment dam: summary and analysis of data	D6.2.1	IMPACT-D621_final_TEXT and_A.pdf IMPACT-D6.2.A_AnnexB.doc IMPACT-D621_final_C.pdf IMPACT-D621_final_D4compr.pdf
IV	Implementation of monitoring programme on embankment dam: summary and analysis of data	D6.2	IMPACT-D6.2.B.doc IMPACT-D6.2.B_AnnexB.doc IMPACT-D6.2.B_AnnexC.doc IMPACT-D6.2.B_AnnexD.doc
V	Implementation of monitoring programme on embankment dam: summary and analysis of data	D6.2	D6.2.C_final.doc
VI	Implementation of monitoring programme on embankment dam: summary and analysis of data	D6.3	IMPACT-D6.3attach.doc
VII	Conclusions and recommendations	D6.4	D-6.4_Final.doc

Final Report Annex II, Part E2 WP6: Data Collection (Breach Formation)

Item	*Description*	*Linked Deliverables*	*Filename*
I	WP6: Technical Summary Report		WP6_10SummaryPartBreach_v1_0.doc
II	Sample of breach event database listing	D6.5	D6_5Cover.doc IMPACT Breach Data base 2005-01-15.pdf
III	Detailed technical report on analysis of database data	D6.6	IMPACT DTReport EURAQ 2005-01-15.pdf
IV	Case study data relating to extreme events in Hungary	D6.7	IMPACT D6.7 report cover.pdf D6.7 Surány, 1991 .pdf D6.7 The Körös Valley Flood of 1980 final.pdf D6.7 Gyula 1 1995 .pdf D6.7 The March 2001 flood final.pdf