## Modelling Breach Initiation and Growth

**EXECUTIVE SUMMARY**

**Date**: February 2009  
**Report Number**: T06-08-01  
**Revision Number**: 3_5_P01

**Task Leader**: Mark Morris  
**Partner**: HRW

FLOODsite is co-funded by the European Community  
Sixth Framework Programme for European Research and Technological Development (2002-2006)

FLOODsite is an Integrated Project in the Global Change and Eco-systems Sub-Priority  
Start date March 2004, duration 5 Years

**Document Dissemination Level**

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**Co-ordinator**: HR Wallingford, UK  
**Project Contract No**: GOCE-CT-2004-505420  
**Project website**: www.floodsite.net
DOCUMENT INFORMATION

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<td>Mark Morris</td>
</tr>
<tr>
<td>Contributors</td>
<td>Andreas Kortenhaus and Paul Visser</td>
</tr>
<tr>
<td>Distribution</td>
<td>Public</td>
</tr>
<tr>
<td>Document Reference</td>
<td>T06-08-01</td>
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DOCUMENT HISTORY

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<th>Date</th>
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<td>Initial draft structure and content</td>
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<td>6/02/08</td>
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<td>Andreas Kortenhaus</td>
<td>LWI</td>
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<td>Added comments and content re LWI research</td>
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<td>7/02/08</td>
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<td>HRW</td>
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<td>Revision to include research work and issues from 2008</td>
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<td>3_2_P01</td>
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<td>HRW</td>
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<td>Further refinement, identification of key issues and conclusions</td>
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<td>3_3_P01</td>
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<td>21/12/11</td>
<td>3_5_P01</td>
<td>Paul Samuels</td>
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ACKNOWLEDGEMENT

The work described in this publication was supported by the European Community’s Sixth Framework Programme through the grant to the budget of the Integrated Project FLOODsite, Contract GOCE-CT-2004-505420.

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RELATED DOCUMENTS

The full reports to which this summary relates are available from the FLOODsite Project Website at http://www.floodsite.net/html/search_results.asp?documentType as FLOODsite Report Numbers T06-06-03 and T06-08-02.

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Executive Summary for Task 6

1. Scope of the research in Task 6

1.1 An overview

The timing and rate at which a flood embankment or embankment dam breaches is critical in determining the timing, rate and total volume of flood water that passes along the river valley or spreads into the floodplain. Consequently, the accuracy with which breach initiation and breach growth through an embankment is predicted directly influences the accuracy to which a flood risk analysis may be made and subsequently the confidence to which flood risk management activities may be planned.

In comparison to the uncertainty in prediction of other parts of a flood risk model, for example the modelling of river flows or floodplain inundation, the present degree of uncertainty in predicting breach initiation and formation processes is very high.

Where flow modelling may permit the prediction of flows and levels in a river to within a number of cubic metres per second (cumecs) or centimetres, the typical accuracy of breach modelling is far cruder. For example, at the end of the IMPACT Project (Morris et al., 2005) it was suggested that the accuracy of breach modelling in predicting just the peak discharge of a flood hydrograph arising from flood flow through a breach was perhaps ±30%. The accuracy of predicting the timing (breach initiation), rate and overall growth of a breach was considered to be far worse. The implications of working with this degree of uncertainty vary according to the end application / user of the model predictions. Predictive breach models may be used to support:

- Flood risk assessments
- Asset managers seeking to identify critically important reaches of embankment
- Performance assessments to determine what may be considered as acceptable rates of overflow or overtopping
- Design of emergency repairs to limit and close a breach
- Emergency planners seeking to identify the timing and magnitude of potential flooding and hence appropriate evacuation measures (including the potential failure of fluvial and coastal embankments and embankment dams)
- Assessment of risks arising from the erosion and deposition of soils during a breach event

The key objectives of FLOODsite Task 6 were therefore to improve the understanding of breach initiation and development and hence to improve the accuracy with which breaching processes could be predicted. This was done through a generic approach to:

- Review of existing knowledge; establish current state of the art
- Undertake targeted breach modelling tests (wave induced breach initiation)
- Develop new and improved predictive breach models

This work was undertaken by three project partners, each of whom focussed upon different aspects of the breaching problem. The focus of these three research areas was:

1. To investigate and simulate wave induced breach initiation processes
2. To analyse breach processes in relation to soil state and develop an improved version of the UK HR BREACH model (supporting detailed breach simulation for flood risk analyses)
3. To develop a new, rapid cohesive breach model (building from the earlier Dutch BRES model) in support of breach prediction for system risk modelling

A summary of the scope of research for each area is given in Sections 1.2 - 1.4 below. The work in Task 6 linked with a number of other research tasks in FLOODsite, and projects outside of FLOODsite, as shown in Figure 1-1. In particular, the work linked from Tasks 2 (Hydraulic
loading) and 4 (Failure mechanisms) and fed into Tasks 7 (Reliability analysis) and 8 (Inundation modelling). This reflects the role that breach prediction has at the heart of any flood risk analysis process. Task 2 provides definitions of hydraulic loading on structures (e.g. wave loading) and Task 4 provides knowledge on failure mechanisms for flood defence structures. Breach models are required within Tasks 7 and 8 to provide predictions of breach growth and hence the rate of release of flood water.

**1.2 Scope of work: Wave induced breach initiation**

Wave action and overtopping (rather than overflowing) flow can lead to breach initiation and ultimately failure of the flood embankment, sea dike or dam on the landward side and on the seaward side. Our understanding of this process was limited and no models existed to allow prediction of these failure processes. The effects of wave action and overtopping are worse if the embankment has cracks or fissures which allow the water to ingress into the embankment, or allow the impact of wave forces to propagate into the cracks and remove soil from the cracks.

A programme of research was undertaken to investigate wave induced breach initiation processes, including detailed analysis of wave action on cracked soils and wave action in relation to soil state. Both field and laboratory work were undertaken to investigate and validate these processes, with the

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**Deliverables:**
- Report T06-06-03 – Current state of the art
- Report T06-08-02 – Improved understanding and modelling of breach initiation and growth

**Figure 1-1  Links to and from Task 6 research on modelling breach initiation and growth**
research culminating in the testing to destruction of a large section of real sea dike in the large wave flume (GWK) at Hannover (Figure 1-2).

Figure 1-2 Testing wave induced breach initiation processes on a section of real coastal embankment

The objective of the large scale testing was to provide quality data on the wave induced failure processes that could be used to refine and validate new models for the prediction of breach initiation from wave action. The overall goal was to produce ‘research models’ that could simulate breach initiation by wave action on both the seaward and landward faces of an embankment.

1.3 Scope of work: Analysis of breach processes in relation to soil state and development of the next generation of the HR BREACH model

Between 1998 and 2001, HR Wallingford developed a first version of the HR BREACH model (Mohamed, 2002). This model predicted breach growth through cohesive and non cohesive materials, combining model simulation of flow, soil erosion and structural behaviour (slope instability) (Figure 1-3).

Figure 1-3 Screen outputs from the HR BREACH model showing the prediction of breach growth at four consecutive stages

As part of the IMPACT Project which ran from 2001-2004 (Morris et al., 2005), a detailed programme of field and laboratory testing was undertaken to collect quality data on breach formation (Figure 1-4). This research highlighted that the prediction of breach formation was very complex and that there
appeared to be different processes (in both flow and soil erosion) depending upon the type of soil used and the stage of breach formation Figure 1-4). The research also highlighted the relative performance and limitations of various breach models at that time.

![Figure 1-4 Stages of breach erosion from the IMPACT project (Field Test#1). Surface erosion (left), head cut formation (centre) and transition from breach initiation to breach formation (right)](image)

The objective of this part of the FLOODsite research on breach modelling was to analyse the IMPACT data (and other related research data) in more detail, and in particular with relation to soil processes and the impact of soil state on erodibility and breach formation.

This research would try to address some of the gaps in knowledge and model performance issues identified during the IMPACT project, and these advances in understanding would then be used to develop an improved and enhanced version of the HR BREACH model. The aim of the improvements was to improve the accuracy and reliability of breach prediction and to extend the range of model applicability towards a wider range of real flood embankment geometries and design.

1.4 Scope of work: Development of a new cohesive breach model and simplified method (BRES)

The BRES model was developed around 1998 (Visser, 1998) at the Technical University of Delft (TUD) for predicting breach growth through non cohesive materials (i.e. sands). This model differed from models such as HR BREACH in that it used a predefined pattern of stages for breach growth and hence did not predict flow and erosion conditions at sections through the embankment (Figure 1-5). This simplified approach meant that the model ran very quickly and could be used without too much difficulty within larger models, such as system risk models.

The objective of this part of the FLOODsite research programme was to develop the BRES model further to include prediction of breach through cohesive materials as well as non cohesive. In particular, data from the IMPACT project would be used to validate processes and model performance (Zhu, 2006).
2. Principal results

The principal results from the FLOODsite Task 6 research programme are presented below:

Section 2.1 Review of existing knowledge and current state of the art
Section 2.2 Wave induced breach initiation
Section 2.3 Analysis of soil state and development of the next generation HR BREACH model
Section 2.4 Development of a new cohesive breach model and simplified method

2.1 Review of existing knowledge and current state of the art

A range of issues were considered as part of the state of the art review. This review was updated throughout the project, hence also providing a state of the art upon project completion in 2009. Key findings are summarised below:

Review of available breach models

FLOODsite Report T06-06-03 (Morris et al., 2009b) provides a comprehensive review of the current state of the art for modelling breach initiation and growth processes. The report draws from detailed reviews undertaken as part of four different PhD studies plus research from the Dam Safety Interest Group (DSIG) breach modelling project (Mohamed, 2002, Zhu, 2006, D'Eliso, 2007, Kahawita, 2007, Stanczak, 2008, Morris, In Prep.)). No existing models simulating breach initiation through wave action were found; a detailed listing of more general breach models and their approach to simulation is given. By far the majority of these existing models are research tools developed at universities of by individuals, rather than commercially available codes to support flood risk management activities.

Definition of breaching processes and relevance to different end users

Breach initiation and formation processes are complex and highly interdependent upon water, soil and structural processes. The significance of soil state (erodibility) in determining which processes occur has been missed by many researchers in the past. Consequently, many processes and models have been presented as 'generic' breach models when in fact they relate to specific types and state of
embankment. It is suggested that this also explains why faster progress has not been made in refining the accuracy of breach models over the past two decades.

A clear summary of processes and their link to soil state is provided within the review.

**Progress and issues regarding integration of breach models into flow models and system risk models**

The demand from industry for the integration of reliable breach models with flow models or system risk models to allow more accurate flood risk analyses to be performed is strong. However, the main limitation faced is balancing modelling speed and accuracy. At the start of the FLOODsite research, no directly integrated models existed and use of slower (i.e. runtime a few minutes) breach models within system risk models was not considered feasible because of this. Consequently, many flood risk assessments and models tended to use very simplistic representations of breach, rather than the current state of art. Hence, whilst the need for more reliable breach models was recognised, these models also need to have very fast run times for use in integrated models.

**Gaps and Shortcomings**

Gaps and shortcomings were identified. These included:

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<td>1. Prior to the FLOODsite research, no models were found that simulated breach initiation from wave action. Consequently, the models produced as part of this research form the first attempt to simulate these processes.</td>
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<td>2. The influence of soil type and state on breaching processes has been recognised. A clear definition of breach growth stages is provided.</td>
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<td>3. A record of historic development of breach models has been provided, however the majority of breach models listed are not commercially available codes. Comparisons from the IMPACT Project and the current DSIG breach modelling project provide the best information on commercially available models. The DSIG project has identified the HR BREACH, SIMBA and FIREBIRD models as having greatest potential for future development and integration into or with industry flow models.</td>
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<td>4. The need for large scale reliable data to understand breaching processes and validate models is clear, however the number of research initiatives that might provide such data is very small. No significant research is underway following the IMPACT project and outside of the FLOODsite work, other than at the USDA-ARS-HERU at Stillwater, Oklahoma. Tests here are typically carried out on embankments ~2m high.</td>
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<td>5. The demand for breach models that can be used within industry is strong. However such breach models need to be both accurate and fast for use within larger system risk and flow models.</td>
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**2.2 Wave induced breach initiation**

The programme of research to look at wave induced breach initiation aimed to investigate and understand the physical processes and then to produce numerical models in the form of research tools (rather than industry models). The research focussed upon breach initiation on the seaward face through wave impact and the landward face through wave overtopping. Initial investigations were undertaken with the support of small scale physical models. The research culminated with the large scale testing of a real dike section, including grass cover (Figure 1-2).

The aim of the small scale tests was the investigation of influences due to boundary conditions such as scaling factor, flume walls, simplified model setup on the breach initiation and breach development. Five tests with overflow conditions, and 16 tests with wave overtopping conditions were conducted.
The overflow experiments were performed in a basin and the wave overtopping tests in a 2m wide wave flume (Geisenhainer et al., 2006).

This research work focussed upon initiation processes through a typical Dutch or German coastal dike. Such a dike comprises an embankment with a sand core, thick clay cover and grass surface protection. Hence some of the processes identified will be generic to failure of any embankment, whilst others will be specific to this form of embankment.

2.2.1 Breaching of coastal dikes initiated from the landward slope

Two models were produced to simulate the breaching process of coastal dikes induced by wave overtopping (Figure 2-1); these were a preliminary model (D'Eliso et al., 2006b) and a detailed model (D'Eliso et al., 2006a). The detailed model extends from the preliminary model.

The dike simulated in both models has a sand core and a clay revetment with a grass cover. The cross-section of the dike is relatively simple (i.e. without toe berms, toe protection or ditches). The model can simulate breach initiation induced by wave overtopping or combined wave overtopping and overflow.

The preliminary model is based on simple formulae and several simplifying assumptions, but still provides an overview of the entire breaching process. The model simulates most of the processes involved in breach initiation. The model is divided into two parts, namely the preliminary flow model and the preliminary morphodynamic model. The flow model describes the hydraulic boundary conditions including wave overtopping and wave overtopping plus overflow. The morphodynamic model describes failure of the grass cover layer, the clay layer and the subsequent development of the full breach. All of these processes are described by simplified approaches within the preliminary model.

The detailed model (D'Eliso et al., 2006a) is based on the preliminary model (D'Eliso et al., 2006b), but with several simplifying assumptions replaced by a more process-oriented description of the entire breaching process. The model includes all processes involved in the breach initiation and growth stages.

Compared to the preliminary model, the detailed model introduces and improves simulation of the following processes:
1. Introduction of new processes
   • Water infiltration in the dike;
   • Scour hole in the clay cover and sand core;
   • Sliding of the cover layer;
2. Improvement of processes already included in the preliminary model
   • Wave overtopping discharge at the dike;
• Incipient breach location;
• Headcut erosion and advance.

2.2.2 Breaching of coastal dikes initiated from the seaward slope

A similar approach was taken for modelling initiation from wave impact as for wave overtopping, in that an initial preliminary model was developed, and subsequently a more detailed model.

The preliminary breaching model for sea dikes (Stanczak et al., 2006) is based on simple empirical formulae, but it provides the information on the whole breaching process, including breach initiation, formation and development. The developed model is divided into five main parts: (i) hydrodynamic module (ii) grass erosion module, (iii) clay erosion module (iv) sand core erosion module (up to the inner slope) and (v) sand core wash-out module (breach widening and deepening) (Figure 2-2).

The aim of the preliminary model was to provide a fast, overall picture of the breaching process, using a minimal amount of basic input data needed:

• dike parameters - geometry and material properties;
• sea state at the toe of the dike - wave height distribution and water level;
• numerical parameters - time step and grid size.

![Figure 2-2 Breach development initiated from the seaward side (Stanczak et al., 2006)](image)

The more detailed model contained a number of refinements and enhancements upon the preliminary model. Since the time to failure of the grass and clay cover layers constitutes a key parameter needed for the estimation of the warning times, focus was put on improvement of the grass and clay erosion prediction within the model, in particular using the knowledge on grass and clay erosion gained from a range of laboratory experiments. New processes that were added or enhanced also included consideration of water infiltration and failure in cracks and the method for predicting sand core erosion.

Both the overtopping and impact models were modular in nature with the focus of model development being to try and validate and then integrated existing knowledge and methods for the various different stages of breach initiation and growth rather than develop new completely new methods and models. The research successfully analysed and combined multiple methods and models to provide initial research models simulating the effects of wave action (Stanczak, 2008).
2.2.3 Large scale wave impact and overtopping tests

A series of large-scale breach tests were performed on a dike section (taken from a coastal embankment) in the GWK flume in Hannover, Germany, in June 2008 (Figure 1-2). The aim of the experiments was the investigation of breach initiation processes from wave impact and overtopping. This work was undertaken in collaboration with the European EroGRASS project (Geisenhainer, 2008).

The FLOODsite dike breach test was the final test within a series of wave impact and wave overtopping experiments. The complete test series was conducted between April and June 2008 and can be divided into four phases. The first phase investigated the influence of the wave impact on the erosion of the grass cover; the second phase addressed the influence of wave overtopping on the initiation of grass cover failure. The investigation of the influence of weak points located on the landward slope on the strength of the grass cover under wave overtopping was undertaken in phase 3 and the final (fourth) phase investigated the process of breach development in the dike.

The tests were conducted in the Large Wave Flume, GWK (Hanover), which is 5m wide, 7m deep and 324m long (Figure 2-3). The maximum water depth for the tests was 5.0m. The wave generator could reproduce regular waves with heights up to $H \approx 2.50\text{m}$ and irregular waves with significant heights up to $H_s \approx 1.5\text{m}$. To avoid side effects from the wave flume on the breach growth process the maximum breach width which could be investigated was 4.0m.

![Cross section of dike model in GWK](image)

The flume model represents a typical sea dike, which can be found on the coast of the German Bight, but also in the Netherlands. The dike consists of a sand core, with a clay revetment and grass cover. The cross section did not include any berms. The seaward slope was 1:4 and the landward slope 1:3. The dike crest was 2.2m wide and the dike crest elevation was 5.8m. The clay cover layer was 0.8m thick; this thickness also includes the grass cover (grass roots). The 0.8m high clay cover consisted of a 0.6m thick clay layer and a 0.2m thick grass layer. The seaward edge of the dike crest was located 187.3m from the wave generator. The grass cover originates from an existing sea dike located near Ribe (Denmark) and considerable care was taken to maintain good quality and uniform cover for the tests.

The entire dike crest was eroded during the testing and the height of the remaining dike body including the remaining grass sods was 4.8m as compared to the original height of 5.8m (Figure 2-4). Large areas of the grass layer on the seaward side were damaged by wave impact. The different stages of breach formation were analysed using video footage from the tests allowing analysis of the erosion process (Figure 2-5).
Overall, the large-scale model tests in the GWK, Hannover were regarded successful. On the one hand, they have clearly shown expected processes such as headcut erosion, undermining of the clay layer, and scour erosion. Detailed analysis will allow for a quantification of these processes so that calibration of any numerical models will be possible. On the other hand, new and less expected results such as the collapse of clay aggregates and big blocks or the damage of the grass cover by breaking waves have also been observed. The former are believed to have considerable effect on the breach development and need to be considered in numerical breach modelling of sand-clay embankments or sea dikes.
2.2.4 Key points identified

Key points which were identified from the research undertaken for wave induced breach initiation were:

1. Two model systems each consisting of a preliminary and detailed (numerical) model are now available for modelling wave induced breach initiation and growth. Both model systems assume a standard sea dike built of a sand core covered by clay and a grass cover. The model systems deliver the time of erosion, breach growth, final breach widths, and the associated hydrograph. Preliminary and detailed models differ in the accuracy of processes considered where the detailed model is more accurate with less uncertainty in the results of final breach parameters.

2. Large-scale model tests have been performed on a near to prototype scale in the large wave flume (GWK) of Hannover. The tests have shown the feasibility of modelling both breach initiation and growth under laboratory conditions.

3. Results of the model tests have shown that expected processes could be reproduced and are now quantifiable for further use in the calibration of numerical models.

4. Additional observations from the model tests include the relevance of damage of the initial grass and clay cover, the damage of grass cover on the seaward side of the dike by wave impacts, and the importance of clay block failure for the overall breach process.

5. Tests under small-scale and large-scale conditions have also shown that any of these tests need very careful preparation and attention to a range of processes and potential limitations. Lessons learned from this experience comprise the limited flume width and hence limitations in the breach growth development, limitations in the wave maker’s ability to generate sufficiently high waves for wave overtopping, construction and maintenance of the grass cover layer, unwanted erosion and piping effects, etc.

2.3 Analysis of soil state and development of the next generation HR BREACH model

The objective of the research work here was to review and improve breach model performance, making particular use of valuable breach data sets and observations collected as part of the IMPACT project research (Morris et al., 2005).

A number of issues relating to breach model performance were identified during FLOODsite. These covered both flow and erosion assumptions within breach models. Given the complex interactions between soil, water and structure that occur during breach formation, the research meant investigation of all aspects of the breach model performance.

2.3.1 Analysis of IMPACT data

The IMPACT field test data provides extensive footage from five different, large scale breach tests. The footage highlights different stages of flow and associated physical processes from breach initiation through to breach growth. The data is unique in that it offers detailed records of breach formation through embankments that are 4-6m high, storing up to 80,000m³ of water, hence observed processes are at near prototype scale for typical flood embankments.

Two lines of investigation were undertaken; firstly, analysis of key physical processes which were then used to validate or steer numerical model development (Morris, 2009). Secondly, an in depth review of data quality, since initial work highlighted some discrepancies in the data sets (Hassan and Morris, 2008). The analysis, recommendations and full data sets have now been placed on the FLOODsite website for public use.
The analysis of IMPACT data confirmed a number of processes, including:

- Flow phases (weir flow $\rightarrow$ converging flow $\rightarrow$ weir flow $\rightarrow$ open channel flow)
- Aggressive erosion of breach sides arising from elongated vortex action as flow converges and drops through the breach (hence non uniform distribution and highly dynamic erosion within the breach)
- Vertical or undercut sides to the breach (Figure 2-6)
- Soil wasting, whereby blocks from the breach sides fail and are removed near instantly (Figure 2-6)

![Figure 2-6 Soil wasting (left) and vertical / undercut sides to the breach (right)](image)

**2.3.2 Analysis and development of model**

Figure 2-7 below provides a schematic showing the technical areas and aspects of the breach model that were investigated and revised.

![Figure 2-7 Schematic plan showing research and development topics for the HR BREACH model](image)

Many of the technical areas shown in Figure 2-7 were interrelated and model testing and development was extensive (Morris et al., 2009a, Morris, *In Prep.*). A summary of the developments that have been made to the HR BREACH model as a result of this research are:
- Refinement of vegetation performance analysis (time of initiation)
- Refinement of modelling tolerances, cross section geometry and flow calculation and critical section identification
- Refinement of section erosion (breach growth) process
- Refinement of flow calculation through addition of variable weir coefficient based upon evolving embankment profile
- Transfer to use of erosion equations, away from sediment equations, and hence allowance for soil wasting, dynamic soil erosion and use of erodibility to reflect soil type and state
- Development of soil zones, allowing modelling of more complex (more realistic) embankment structures
- Refinement of breach side slope stability analysis to better reflect observed physical processes

These refinements resulted in improved performance of the model, and a more flexible approach for simulating breach through real embankments. The introduction of ‘zones’ allows the breach model to simulate erosion through embankments constructed from layers of different materials, or the same materials but with differing erodibility (Figure 2-8). This approach can be used to simulate embankments that have been extended over a long period of time or which, for example, might suffer from fissuring in the outer layers.

![Figure 2-8 Example of zoning introduced into breach model to provide flexibility in representing different (real) embankment structure designs](image)

In parallel with model development, work has also been undertaken to directly integrate the breach model with a flow model (InfoWorksRS). This was achieved in mid 2008, providing the first truly integrated predictive breach and 2D flow model for use in flood risk management practice.

### 2.3.3 International collaboration and evaluation

As part of the research programme, strong links were established with the CEATI facilitated Dam Safety Interest Group (DSIG) project on breach modelling. Participants in this project were dam owners with an interest in evaluating and developing a breach model for use within industry. Key goals of the DSIG project were to review breach models internationally, review and collect high quality data sets for model testing / validation, identify the three most promising models for evaluation, undertake a programme of model testing and evaluation and subsequently develop the chosen model for industry use, including probable integration into HEC RAS software.

The HR BREACH model was identified as one of the three breach models for closer evaluation. The value to FLOODsite of participation here was the technical feedback and evaluation of model performance and modelling issues by a team of leading international researchers (Wahl et al., 2008). Results from the DSIG project are expected to be available towards the end of 2009.
2.3.4 Key points identified

Key points which were identified from the research undertaken on the IMPACT data and the HR BREACH model were:

1. Analysis of the large scale field test data from the IMPACT project allowed identification of key physical processes including both flow and erosion processes linked to soil type and state. Confirmation of these processes has helped to refine methods used for numerical models and focus needs for future research.
2. A new version of the HR BREACH model has been developed. All key process areas within the model have been refined, including prediction of flow, erosion, soil wasting and the performance of vegetation.
3. A significant step has been taken towards breach simulation of ‘real’ structures by introducing soil zones into the model, allowing representation of embankments and dams constructed from many permutations of different soil type or state (e.g. layered or zoned embankments).
4. The HR BREACH model has been integrated directly with the InfoWorksRS flow modelling package providing the first truly integrated predictive breach and 2D flow model for use in flood risk management practice.
5. The research highlighted gaps and limitations in knowledge in a number of areas. In particular, dependence on the performance of vegetation and soil erodibility where guidance and base data on performance is limited, and the challenges posed for predicting breach through real, complex and composite structures. A shortage of reliable data and the complex nature of the processes emphasises the need for the collection of reliable, large scale test or case study data.

2.4 Development of a new cohesive breach model and simplified method (BRES)

A new BRES model has been produced (Zhu, 2006). The original BRES model (Visser, 1998) simulated breach growth through sand dikes; the new model simulates breach growth through clay dikes. The model differs from the HR BREACH model in a number of ways:

- The model simulates breach growth according to a series of five predefined stages of erosion
- The model does not calculate flow and erosion at cross sections (as with HR BREACH) but calculates times for development of erosion through the various predefined phases (similar to SIMBA). Consequently the model takes only a few seconds to run, rather than tens of seconds to minutes required by HR BREACH
- BRES has been calibrated against specific sets of test data, and validated against several others

The new BRES model is based on the five-stage breach development process as described by (Visser, 1998) (Figure 1-5). For the final two stages three breach types are distinguished in the model, depending on the erodibility of the base of the dike, the presence of a solid toe protection on the outer slope and the presence and erodibility of a high foreland.

The BRES model now has two versions, one for sand-dikes (Visser, 1998) and one for clay-dikes as developed under FLOODsite (Zhu, 2006). Erosion for clay dikes is predicted with the frequently used excess shear stress equation representing the detachment process of cohesive sediment: 

\[ E = M (\tau_b - \tau_c) \]

where \( E \) is the erosion rate (m/s), \( M \) is a soil-dependent coefficient describing the soil erodibility (s-m²/kg), \( \tau_b \) is the bed shear stress (N/m²), and \( \tau_c \) is the critical shear stress for erosion of the soil (N/m²), see Zhu et al. (2005b) and Zhu (2006). The erosion at a headcut during the breach growth process of clay-dikes, including the impinging jet scour of the dike foundation (if any), headcut undermining and discrete slope mass failure, etc, is simulated through the mathematical model developed by Zhu et al. (2005a), see also Zhu et al. (2005b) and Zhu (2006).
A 2D laboratory experiment was performed in 2005 in a 35.5 m long, 0.80 m wide and 0.85 m deep flume of the Laboratory of Fluid Mechanics of Delft University of Technology. The aim of this experiment was to observe the breach erosion process in clay-dikes during Stages I, II and III. The small-scale dike had a height of 75 cm, a width of 40 cm and a length of the crest of 60 cm. The inclination of both slopes was 1:2.

Water level measurements were undertaken with wave height probes in four locations (three upstream and one downstream from the dike). Flow velocity measurements were undertaken using electromagnetic flow velocity meters in two locations upstream of the breach and at one location downstream from the breach. The breach development was both video-taped (through the glass-wall) and photographed (from above and through the glass-wall).

In this experiment five tests were done, one with a small-scale sand-dike and four with clay-dikes constructed from different mixtures of fine sand, silt and clay. Much attention was paid to get a good quality mix of the sand-silt-clay mixture (Zhu, 2006).

The model version for clay-dikes has been calibrated with the data of two 2D TUD laboratory tests and two 3D EC IMPACT Project (Investigation of Extreme Flood Processes and Uncertainty) laboratory tests on clay-dike breaching (Zhu, 2006). The model predictions are in good agreement with the experimental data. Validation of the model with the data of the other two 2D TUD clay-dike laboratory tests yields reasonable agreement between the model predictions and the experimental data (Figure 2-9 (Zhu, 2006)). Finally, the model has been applied to a prototype dike failure in China (1998). The predicted final breach width of 274 m was about 40% smaller than the observed 390 m. The predicted $5.6 \times 10^8 \text{ m}^3$ of diverted floodwater volume is close to the investigation-based estimation of $5.2 \times 10^8 \text{ m}^3$.

![Figure 2-9 Comparison of predicted and measured breach flow rate for Test T3 of the TUD laboratory clay-dike experiment](image)
2.4.1 **Key points identified**

Key points which could be identified from the research on the BRES model, were:

1. Considering the process of breach development in homogeneous dikes, and after the breach initiation stage, five stages can generally be distinguished, both in dikes constructed with non-cohesive material (sand) and dikes constructed with cohesive material (clay or cohesive soil mixtures). However, the processes observed in these stages differ according to the soil type and state.

2. Headcut erosion plays a very important role in the process of breach development in dikes constructed from cohesive soil (or more generally, soil in situ with a low erodibility).

3. For the modelling of breach growth in dikes, the key problem is the description of the rate of erosion of dike material by the flow. Existing formulas for the erosion of non-cohesive sediment are valid for flow velocities of up to about 2 m/s, while the flow velocities in dike breach can increase to about 10 m/s. Further, **widely applicable** descriptions for the erosion rate of cohesive soils do not exist at all.

4. The lack of widely usable erosion formulas could be addressed if good data sets from prototype or large scale dike breaches covering a range of designs, soil type and soil state were available. Unfortunately these data sets do not exist, hence need to be collected.

5. In spite of the problems indicated above, application of the BRES model to two prototype breaches (one in a sand-dike, and one in a cohesive soil dike) has resulted in reasonable agreement. A larger degree of uncertainty might be expected when applied to different styles of dike and soil type and state, supporting the need for the collation of data from a wider range of large scale or prototype tests with which to refine the performance of breach models.

### 3. **Relevance to practice**

A significant programme of research relating to breach initiation and growth prediction has been completed under FLOODsite. This covers a state of the art review, fundamental process research and breach model testing and development. All of the findings are explained in two key reports, referenced below. Examples of model simulations, access to models and access to all reports can be found via the project website at [www.floodsite.net](http://www.floodsite.net).

The two key documents that explain this research and the findings are:

- Report T06-06-03 Breach processes: A state of the art review. (Morris et al., 2009b)
- Report T06-08-02 Modelling breach initiation and growth (Morris et al., 2009a)

A short summary of the work can also be found in:

- FLOODsite Fact Sheet T06-08-13 - Breach initiation and growth, Predictive models

#### 3.1 **Key issues for practice**

The work has highlighted a range of issues in relation to the prediction of breach in practice. These are summarised in the following sections.

3.1.1 **Current practice: Recognising the significance of breach prediction within a flood risk analysis**

Current industry practice for breach prediction varies significantly between authorities and countries. The range of approaches varies from, effectively guesswork through to detailed numerical modelling.
Intermediate approaches include the use of simple discharge or breach dimension equations or simple parametric models.

It should be recognised that in any flood risk analysis where breaching of defences occurs, the prediction of breach growth will most likely significantly affect the volume and rate of release of flood water. Consequently, the accuracy with which the breach initiation and growth process is predicted may significantly affect the rate and extent of inundation.

3.1.2 Matching approach to end user needs
Of greater concern than the approach used is a tendency for there to be a relatively poor appreciation of the accuracy of approach being adopted and the implications that this may have for any particular end use or application of the results. The practitioner needs to:

- Be aware of the importance that the breach prediction plays within the overall risk analysis
- Be aware of any assumptions or limitations in the approach adopted
- Appreciate the uncertainties within any prediction being made
- Be clear on why the data is needed, how it will be used and hence the significance that uncertainty in the prediction may have for the end user or application

3.1.3 Choosing the right model for predicting initiation and growth
A comprehensive state of the art review has been undertaken (Morris et al., 2009b) listing the historic development of breach models and defining the different types of model that are available. Types available are broadly:

- Non-physically based, empirical models (e.g. peak discharge or beach width/depth equations)
- Semi-physically based, analytical and parametric models (e.g. user defined breach final dimensions)
- Physically based models (i.e. simulating the failure of embankments based on the processes observed during failure, such as the flow regimes, erosion and instability processes)

The simpler the model, the greater the uncertainty and the more limited the information provided. For example, peak discharge equations will offer an estimate of peak breach discharge based purely on dam height and volume of water stored. However, there will be considerable uncertainty in this estimate and the method offers no information regarding rate and timing of breach growth, hence no detail of the actual flood hydrograph. Conversely, physically based models will require much more information about the embankment geometry and soil state, but in turn will provide an independent estimate of breach growth and the outflow hydrograph.

The current state of knowledge means that it is now relatively simple to apply a physically based model for breach prediction. Simpler approaches should only be used as indicators of possible conditions and not used where potential loss of life or significant damages are to be estimated (Froehlich, 1995a, Froehlich, 1995b).

3.1.4 Available models for predicting breach initiation and growth
There are a wide number of non-physically based, empirical models available for use and guidance on performance can be found from Wahl (Wahl, 2004).

There are fewer semi-physically based models, and these are often found within commercial flow modelling packages. However, these still typically require the user to define the breach growth rate or end dimensions.

The number of commercially available physically based models is even fewer. Many models have been produced as part of research work, but few transfer through to wider industry use. The HR BREACH model has been developed as part of the FLOODsite work and is available for use in flood risk management practice within the InfoWorksRS flow package (www.wallingfordsoftware.com).
This comprises the first physically based, predictive breach model integrated within a dynamic 1D/2D flow model.

The Dam Safety Interest Group project on breach modelling is scheduled to conclude in late 2009 and aims to facilitate transfer of a breach model (HR BREACH, SIMBA or FIREBIRD) into wider industry use, perhaps through integration into HEC software.

At present, the results of the FLOODsite research on wave induced breaching remain at a research level with the goal that wave induced processes are introduced into commercial models in the near future.

3.1.5 Limitations and accuracy of breach models

Whilst there remains a significant degree of uncertainty within breach model predictions, the models do provide a far more reliable estimate of likely breach conditions than would be achieved by using very simple equations or guesswork.

The uncertainty within simple equations could range as high as orders of magnitude, because of the way in which these equations are developed. Uncertainty is often further increased because simple equations only provide specific point values - for example, of peak discharge or breach dimensions. The user must then build a flood hydrograph using these values; errors in the shape of the hydrograph reflect errors in the rate of release of flood water and hence affect the accuracy of any subsequent flood risk assessment.

The accuracy of predictive breach models is not as high as, for example, flow models. The difficulty arises from trying to predict the complex interactions between soil, water and structure. Under the IMPACT project it was suggested that model accuracy was perhaps ±30% in predicting peak discharge; after FLOODsite we might revise this figure to ±20-25%. However, we do also have a greater understanding of the processes that are likely to occur hence can look at a range of possible scenarios with greater confidence.

Whilst physically based models require the user to provide a range of data on soil type and state as well as embankment geometry, the accuracy of prediction from such a model will be better using parameters that, in the absence of recommended or measured data, are based upon judgement as compared to using a simpler empirical model that requires less data.

3.1.6 Recognising the significance of soil state

A key factor that affects model predictions is soil erodibility. This reflects the type and state of the embankment soil, hence it is natural that such a parameter would significantly affect the rate at which a breach might form through the soil. Currently, there is no simple equation for the prediction of soil erodibility, hence values must be sought based either on judgement or field or laboratory testing of the soil.

A (limited) range of different erodibility testing equipment are currently in use and research continues investigating consistency of results between different methods. Whilst this research continues, it is better to apply erodibility equations using guidance or measurements from related measurement equipment and / or researchers. Research at the US Department of Agriculture, Agricultural Research Service, Hydraulic Engineering Research Unit at Stillwater, Oklahoma, US continues to be a leading research centre in this area linking soil erodibility measurement with erosion equations (Hanson and Cook, 2004).
3.1.7 **Key points identified**

Key points which were identified relating to practice were:

- **1.** The prediction of breach initiation and growth is often a critical stage of a flood risk assessment that can significantly affect the overall results of the flood risk assessment. It is therefore important to ensure that an appropriate method or model is selected for application.

- **2.** A model or modelling approach should be selected that is consistent with the required accuracy and resolution of the overall flood risk assessment (i.e. an approach that provides data to an accuracy and resolution that meets specific end user / application needs).

- **3.** There are a large number of non physically based, empirical models freely available but far fewer physically based predictive models. The simplicity of the non physically based empirical models is attractive, however, the magnitude of uncertainty (error) in application can be extremely high (order of magnitude). Use of a physically based, predictive model will provide a more refined estimate of flood hydrograph even if the required data (soil parameters etc.) are based upon judgement rather than direct measurements.

- **4.** Different breach processes occur with different soil types and state (erodibility). Equally, different breach models simulate different breaching processes. It is important to ensure that the type and range of conditions that you wish to simulate can be reproduced by the chosen breach model. Predictive breach models currently simulate surface erosion and headcut erosion processes; research under FLOODsite has improved these capabilities and also provided research tools for predicting wave induced breach initiation.

- **5.** The accuracy of breach models will continue to improve as knowledge regarding vegetation cover, soil state and erodibility improves. This is the current focus of research relating to breach growth, breach initiation and seepage / pipe formation.

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4. **Remaining gaps in knowledge**

During the course of our research the following issues or gaps in knowledge were identified:

4.1 **Extension and uptake of knowledge on wave induced methods into practice**

The FLOODsite research here has improved our knowledge of breach initiation processes arising from wave action. The work has produced initial models for simulation; however these models remain at a research level. The science embedded within these models needs to be integrated into commercial breach models that are more widely available for industry use. Wave induced breach is of relevance to all coastal and exposed fluvial embankments as well as embankment dams.

The FLOODsite research has investigated processes in relation to a typical Dutch or German dike, which is different to, say, typical French or UK dikes. Consequently, some refinement of the approach would be required to produce a generic method suitable for use within a general industry model. Some further investigation of wave processes and refinement of the modelling approach is also required.

4.2 **Linking the prediction of wave action and fissure growth to embankment performance**

Research here has improved our understanding of how cracks exposed to wave action can propagate, resulting in embankment failure. This research needs to be extended to cover a wider range of conditions (soil types, state, crack sizes etc.) and also consideration of other ‘point defects’ such as animal burrows, eroded / dead grass patches etc. This research also needs to be linked with current
research on embankment fissuring (the cause of fissuring) and these jointly related to methods of embankment inspection, assessment and performance evaluation (i.e. performance or fragility curves).

4.3 **Understanding, measuring and predicting soil erodibility**

The research into soil state and erodibility demonstrates the importance of these factors on the rate of breach initiation and growth. However, current methods for identifying soil erodibility are via ‘jet testing’ equipment on a soil by soil basis or simply by judgement. A number of jet or erosion testing methods exist, but results between these approaches are not consistent.

Three approaches would help to provide improved guidance on potential erodibility of embankments:

- Undertake erodibility testing of typical soils in various states so as to develop a database of ‘base values’ and hence provide indicative values of erodibility for embankments made from different soils, in different regions. This might be undertaken at a regional, national or international level.
- A review and comparison of erodibility measuring testing techniques is required to improve understanding of erodibility and to see whether data from the various centres of research and testing might be pooled.
- Research to identify a framework of parameters / measures that would acceptably describe soil erodibility. This would subsequently allow field testing procedures to be identified (for example, perhaps CPT tests) that would link routine asset management, inspection and survey to the provision of parameter measurements that could then be used directly within breach modelling as part of a flood risk assessment.

4.4 **Improved understanding and guidance on the performance of vegetation**

Research into the performance of grass in preventing breach initiation has highlighted the limited data sets upon which guidance appears to be based (Young, 2005, Rocca and Morris, 2008, Morris, in prep.). An example of a useful guide, widely applied within industry, but based upon limited data is the CIRIA Report 116 (Hewlett et al., 1985). The original CIRIA analysis and design work is now 20 years old, but still used to support detailed design (in the UK).

With the likelihood of increased frequency of extreme events, the need for embankments to withstand greater magnitude, duration and more frequent overtopping and overflowing is likely. Two initiatives are proposed here to improve the reliability of design guidance:

- Review, revise and extend guidance through meshing and analysis of combined international data on grass performance. This could be undertaken at a national or international level.
- Application of the wave overtopping simulator (van der Meer, 2006a, van der Meer, 2006b) to a wide range of embankment and vegetation types. This would provide immediate guidance on site specific embankment performance that would be of direct use to the asset manager as well as in ‘calibrating’ embankment fragility curves. Particular analysis should also be undertaken to compare overtopping and overflowing erosion processes, improve design / performance guidance and hence breach model predictions.

4.5 **Impacts of climate change**

The importance of soil erodibility and vegetation on breach initiation and growth processes has been recognised. Changes in the climate will affect the embankment soil state (moisture content, fissuring etc.) as well as vegetation state and type. These changes will therefore also affect soil erodibility. Depending upon the specific changes, this effect might increase or decrease erodibility.
Research is required to assess what changes might occur and whether these pose a significant threat to the continued performance of different flood embankment designs across Europe.

4.6 Predicting the performance of real structures

Research under the FLOODsite Pilot Sites has identified the wide range of real structures that exist (Kortenhaus, 2006). These ‘real structures’ are typically more complex than the simple cases for which predictive breach models or limit state equations apply. Research and development work is required to extend the capabilities of predictive breach models to more directly address real structures. This should include, for example:

- Ability to predict initiation and growth through embankments that have developed historically in stages such that different soil types, layers etc. have resulted (and hence different rates of erodibility exist)
- Ability to predict initiation and growth where there is (potentially complex) interaction between hard and soft structures, such as embankments with sheet piling toe defences or cut-off walls, or with concrete wave walls or crest structures.

The question of predicting breach location also commonly arises. In practice, breach location is dictated by a combination of factors including:

- Embankment geometry (i.e. low spots along crest focussing overtopping or overflow)
- Quality of grass cover or surface protection (i.e. weak spots focussing erosion)
- Quality of design and construction of transitions between embankments and hard structures (i.e. weak spots focussing erosion)

With greater confidence in predicting each of these processes (as a result of the specific research recommendations) will come greater confidence in being able to predict breach location.

Where multiple breaches start to develop in one area, the eventual number of full breaches will be dependent upon the rate of soil erosion at each location, the predicted breach geometry and availability of flood water to erode the breach (i.e. where multiple breaches initiate they typically merge into fewer larger breaches or cease erosion as flood levels subside, often as a result of another breach resulting in catastrophic failure elsewhere along the defence). Again, greater ability to predict individual breach initiation and growth will result in a greater confidence at predicting multiple breach locations.

4.7 Transitions between structures

Early breach models typically assumed that breach initiation had already occurred and subsequently modelled breach growth. Recent developments focussing on breach initiation begin to allow modellers to simulate the initiation process – for example, simulating overflow across grass cover which may or may not lead to breach. The recent flooding of New Orleans highlighted a common cause of defence asset failure as being at the transition point between structures. Action is needed to:

- Investigate basic flow, erosion and failure processes that occur at structure transitions. Limit state equations may be produced to enhance the record of potential failure modes for flood defence structures used within system risk models (Allsop et al., 2007)
- Extend breach models to simulate more complex (real) structures, including initiation processes at transitions

4.8 Differences between coastal, fluvial and reservoir breach initiation and growth processes

To date most breach modelling research has focussed upon the development of a generic breach model that can be applied to any situation. In recent years there has been recognition of fundamental
differences in processes as a result of soil type (i.e. headcut or surface erosion) and within FLOODsite, research on wave induced breach. It is recognised that there are substantially different hydraulic load conditions between coastal, fluvial and reservoir embankments and these may alter the way in which breach initiates and grows. For example, breach growth through a river flood embankment will be affected when river flow velocities are high as compared, say, to breach through a reservoir embankment where approach flow conditions are steady. Action is needed to:

- Investigate different hydraulic load conditions that embankments may be exposed to and identify how breach initiation and growth processes are affected by these variations. This is likely to require large scale model testing.
- Develop predictive breach models to simulate different processes accordingly.

4.9 **Simplified methods**
The research here has advanced knowledge and performance for detailed predictive models. However, the level of science currently being applied for breach initiation and prediction in system models has lagged behind. Limitations in computing power mean that system models cannot directly integrate complex predictive models, hence simplified approaches are required. These simplified approaches should build on, or use, the science and knowledge developed for the predictive models, so as to provide more accurate, but simple methods for predicting breach initiation and growth within system risk models, for a wide range of structure types.

4.10 **More complex (2D/3D) predictive models**
Recent advances in breach modelling have identified some of the key and complex soil and hydraulic processes that take place. As numerical models advance, the opportunity to simulate some of these processes more accurately with 2D or even 3D codes becomes feasible. By developing such models, uncertainties introduced by simplifications created through the use of 1D or 2D models are removed, so improving model performance and allowing any remaining areas of uncertainty to be focussed upon. Action is needed to:

- Build upon knowledge created from research under the FLOODsite project to develop models with better 2D representation of flow and soil processes. In particular, refine simulation of:
  - Wave loading processes (2D → 3D)
  - Flow conditions approaching and through the breach (1D → 2D)
  - Soil erosion and soil wasting (Pseudo 2D → Pseudo 3D)

4.11 **Integrated breach modelling including probabilistic approaches**
As with system risk models, there is a growing trend to try and link or integrated predictive models, such as hydrologic and flow models, and now breach models. Whilst integration of predictive breach and dynamic flow models allows the user to simulate the effects of breach growth more accurately, the simulation does provide a single prediction of events which are subject to considerable uncertainty. The complex interactions between soil, water and structure during breach initiation and growth lend themselves towards a more probabilistic analysis approach. However, integrating models and including a measure of uncertainty is a formidable challenge.

Action is needed to

- Encourage breach model integration with flow models, either by direct integration or via modelling systems such as OpenMI
- Investigate and develop systems within predictive breach models to better account for parameter and simulation uncertainty and ways in which this information may be presented to and used by different linked models and / or the end user.
4.12 Collection of large or prototype scale test data

Breach initiation and formation processes combine complex interactions between hydraulic, soil and structural processes. This makes accurate modelling at reduced scales very difficult. Consequently, high quality data that truly reflects processes that occur in real structures and which can be used for detailed model development and validation is difficult and/or expensive to obtain.

Gaps in large scale, quality data reflecting different stages of initiation and growth should be identified and research coordinated to collect and use such data.

Four approaches might be taken to provide more reliable data from large scale tests. These approaches could be undertaken at an international level in order to combine the very specialist expertise in this field from around the world:

1. Establish a (funded) forensics team that is able to respond quickly to extreme flood or failure events and hence to access and collect data from real events.
2. Facilitate access to a programme of tests in large scale test facilities or using the Norwegian test facilities as developed and used within the European IMPACT project
3. Apply the wave overtopping simulator to a redundant embankment from breach initiation through to failure
4. Provide a central record and access to data from ongoing national research projects relating to embankment breach and performance
5. References