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Modelling breach initiation and growth

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ABSTRACT: Predicting how a flood defence structure, such as a river or coastal embankment, behaves under varying load conditions is an essential part of undertaking a flood risk assessment. This understanding directly influences the prediction of rate and volume of any flood water that may cross over or through the flood defence structure and impact on the protected area behind. A range of research and model development has been undertaken through Task 6 of the FLOODsite project, building upon earlier work under the IMPACT project and linking with ongoing international initiatives such as the Dam Safety Interest Group breach modelling project. This paper outlines the innovative research undertaken by three organisations within FLOODsite investigating wave induced breach initiation, the influence of soil state and cracking on initiation and improved simulation of the breach initiation and growth stages to support flood risk analyses.

1 INTRODUCTION

Key research efforts within the European Integrated Project FLOODsite (FLOODsite, 2004; www.floodsite.net) are dedicated to enhancing knowledge and ability to predict breach initiation and growth. This work links closely with other FLOODsite initiatives, such as understanding defence structure failure modes (FLOODsite, 2007a) and implementing system risk analyses for river, estuary, and coastal areas.

The research that has been undertaken addresses the important process of wave induced breach initiation and builds upon earlier European research on breach formation under the IMPACT project. The breach formation research also links with an ongoing Canadian / US initiative, facilitated by the Dam Safety Interest Group (DSIG), to review, validate and develop the most promising breach models (worldwide).

This paper provides a brief update on the current state of art for breach modelling and then introduces the wave induced breach initiation research that has been undertaken by the Leichtweiß-Institut of the Technical University Braunschweig (LWI). This research included a review of wave induced breach initiation processes and the development of models to simulate these processes. Development work was supported by small scale laboratory testing, culminating in the large scale testing of a real embankment section in the GWK flume at Hanover.

The paper then outlines the research and development work undertaken by the Delft University of Technology (TUD) and HR Wallingford Ltd. (HRW) on the development of the BRES and HR BREACH predictive breach models. TUD developed a new breach model for predicting breach growth through cohesive embankments, building on the earlier work of Visser (Visser, 1998) and using the IMPACT project data sets. HRW developed a second generation version of the HR BREACH model, again including detailed analysis of the IMPACT project data, but also through close collaboration with the DSIG breach modelling project.

All of the research undertaken follows a common theme towards improved understanding of the complex interactions between geotechnical and hydraulic processes that occur during breach, particularly focussing upon the influence of soil state and vegetation on fundamental processes affecting initiation (such as surface erosion and headcut), as well as growth processes.

The paper presents key findings from the research, demonstrates how the models may be applied and subsequently the route through which this may be used within industry to ensure that the latest and most appropriate techniques are used within flood risk analyses.

2 STATE OF THE ART FOR BREACH MODELLING

Engineers and researchers have strived to predict breach formation processes for many decades. Disturbingly, many observations regarding embankment behaviour and breach processes made decades ago are often reported today as if new phenomena. Bossut & Viallet (1764) even give descriptions of how soil type affects embankment performance and how care should be taken in selecting and placing soils, which would not be out of place today! Breach initiation and formation processes comprise complex interactions between soil and water which requires the integration of science across these disciplines in order to advance our knowledge. Additionally, the development of computing power and numerical modelling over the last two decades offers an increasing range of tools with which complex analyses may be performed. Work by researchers such as Mohamed, 2002, Temple et al, 2005, Zhu, 2006, D'Eliso, 2007 and Stanczak, 2008 demonstrate increasing awareness and integration of science across these disciplines. FLOODsite, 2008a provides an overview of the current position.

Until the last 5–10 years, a majority of attempts to model breach focussed upon the hydraulic processes, predefined erosion patterns and used simple sediment equations for predicting the rate of erosion. The significance of soil state, its effect on soil erodibility and the effect on the overall physical erosion process were not widely appreciated. These factors are now being recognised and investigated, and may help to explain why the accuracy of breach modelling has not progressed faster.

Where researchers have focussed efforts upon investigating one particular type of soil, in one state, and without recognition of the significance of this, it has resulted in the presentation of a model or equation for predicting generic breach which is in fact only really applicable to limited soil type and conditions. Such approaches have led to wider confusion over the accuracy and applicability of breach models as well as breach formation processes.

Figure 1 shows the side of a breach through an embankment built from non cohesive material. The sides are vertical; indeed there is an overhang. The material at the foot has fallen after the breach occurred. Early modeller assumptions of trapezoidal breach shape based upon very simple assumptions regarding soil behaviour are wrong.

Similarly, process of breach erosion depends upon the type and state of the soil. Typically erosion falls into two categories: headcut erosion (as shown in Figure 2) or surface erosion. The latter occurs more often in non cohesive materials, such as sand. The former

Figure 1. Breach formation through non cohesive material (showing vertical sides of breach).

Figure 2. Breach formation through headcut (IMPACT project field test #1).

typically occurs in cohesive materials. However, both behaviours can be observed in either types of material, depending on their state (compaction, moisture content etc.).

Figure 3 shows how soil erodibility varies as a function of compaction and moisture content. Relatively small changes in moisture content can result in orders of magnitude differences in erodibility. Such changes in erodibility must have a significant impact on breach initiation and growth processes hence must be considered within the predictive breach models.

There are a range of different breach model types, from non physical empirical models through to physically based, predictive models. Choice of approach in practice is typically driven by the speed of modelling. Simple empirical models offer predictions of potential peak discharge from a breach and are fast to implement (a single equation) but at the cost of very large uncertainty within the prediction. Physically based predictive models may take seconds, minutes or hours to run, but will provide a prediction of the full flood hydrograph with a greater degree of accuracy. Current models for the prediction of flood risk within a system require fast (and hence simplified) models in order for the overall modelling time to be reasonable. Consequently, breach models within such system risk models are typically very simple and contain large uncertainties.

The accuracy of predicting the peak discharge of a flood hydrograph was estimated in the IMPACT project (IMPACT, 2005) to be in the order of ±30% for a physically based, predictive model; errors could be much greater for simple empirical models such as peak discharge equations. Following research under FLOODsite, the accuracy of predictive models has improved to perhaps ±20%. However, accurate prediction of breach initiation timing remains elusive.

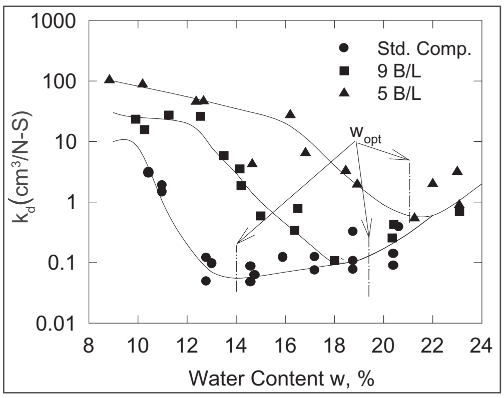

Figure 3. Measured variation of erodibility for a soil over a range of compaction water contents and compaction effort. (Hanson and Hunt, 2006).

As understanding of the complex nature of the breaching process improves, it becomes clear that the complexity of interactions and dependencies upon soil properties, which in turn can vary naturally and as a function of construction and deterioration, suggest that a single prediction of breach for a given scenario may be inappropriate. Instead, use of Monte Carlo sampling to provide an understanding of the potential range of behaviour is likely to be more appropriate. However, such an approach increases modelling time against the current needs to reduce modelling time!

It is with this background that the research work on breach initiation and growth has progressed under FLOODsite. Whilst three organisations have driven the research, this has integrated with previous and ongoing work around the world. The research has comprised small and large scale physical modelling, data analysis and model development, testing and validation. Conclusions from this research have been integrated into breach models and those models are now being used to assist in flood risk assessments. The following sections 3, 4 and 5 of this paper outline the different research programmes.

3 LWI RESEARCH ON WAVE-INDUCED BREACHING

3.1 *Introduction*

Advances on breaching of sea dikes have been made for homogeneous dikes with sand (Visser, 1998) and more recently, with clay (Zhu, 2006). However, based on a complete literature review on wave-induced breaching (Oumeraci et al. 2006), it has been found that a process-oriented prediction of wave-induced breach initiation and development for a real coastal dike built of a sand core, a clay layer, and with grass cover is still not available. Also, existing models for dams or embankments (Morris & Hassan, 2002) are not applicable to such coastal dikes because the physical processes from wave action and the structural layout are different.

Two approaches for assessing the breaching of sea dikes, one from the shoreward side due to wave overtopping and one from the seaward side induced by wave breaking are described in the following, including the initiation of erosion of the protective grass layer and large-scale model tests in a wave flume.

3.2 *Breach initiation*

The preparation of large-scale experiments included a series of small-scale tests on sand dikes in a basin (overflow conditions) and a small-scale wave flume at LWI (wave overtopping conditions). The aim of these test were the investigation of influences due to boundary conditions such as scaling factor, flume walls, simplified model setup on the breach initiation and breach development processes. Five tests with overflow conditions and 16 tests with wave overtopping conditions were conducted (Geisenhainer et al. 2006). An example of the latter is shown in Figure 4.

Additionally, to better understand the initiation of erosion due to wave impacts on the seaward side, systematic erosion tests by falling water jets have been performed (Stanczak et al. 2007). Three types of clay, representing different erosion resistances as well as grass cover of moderate quality have been used in order to gain information on the processes of surface erosion and shear failure within a crack in dike cover subjected to impact pressures. A computer-controlled system has been used to generate impact pressures in the range 12–25 kPa using a mass of water that could be suddenly dropped from a given height.

The conceptual model of Führböter, 1966 on the shear failure of the crack in clay has been compared to the experimental results. It was observed, that the shear failure itself did indeed occur whereas the failure mechanism, however, significantly differed from the predicted one. The tests with the clay samples subjected to a series of impact pressure events provided results which compared well to literature (Torri et al. 1987). The coefficients describing the parameters of the soil and the damping effect of the water layer have been calibrated using the experiments. A new empirical approach to calculate the influence of the root network on the erosion of grass due to impact pressures has been proposed. These results have been used to feed into the breaching model describing the breaching from the seaward side.

3.3 *Breaching model from the shoreward side*

The model consists of a *model system*, which includes (i) a *preliminary model* (level I) and (ii) a *detailed model* (level II) representing the core of a stepwise modular approach for the breaching simulation.

The selected cross-section of the dike is as simple as possible, i.e. without toe berm, toe protection, or ditch. The breaching process is induced by wave overtopping and optionally by combined wave overtopping and overflow (combined flow) on the landward side of the dike. Both models include a series of hydrodynamic and morphodynamic modules (D'Eliso, 2007).

The *preliminary model* uses simple formulae (i) to explore and identify the problems and the most important issues to be improved in the development of the detailed model, (ii) to get familiar with the simulated processes (iii) to start quantifying the uncertainties (D'Eliso et al. 2006). The *detailed model* is based on the level I model, but (i) some simplifying assumptions are removed, (ii) new aspects of the breaching process are simulated, (iii) the uncertainty level is reduced. Model parameters and uncertainties are quantified in both models making use of sensitivity and reliability analysis (Monte Carlo or Latin Hypercube Sampling).

3.4 *Breaching model from the seaward side*

The complete model (Stanczak et al. 2006) consists of a basic preliminary model and a more process-oriented, detailed model.

The *preliminary model* is mostly based on simple empirical formulae, it provides information on the whole breaching process, including breach initiation,

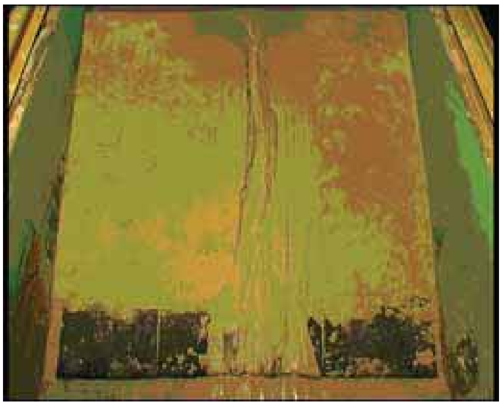

Figure 4. Breach initiation induced by wave overtopping.

Figure 5. Sea dike in the large wave flume of Hanover.

Figure 6. Cross section of the dike model in the large wave flume of Hanover.

formation, and development induced by wave impacts from the seaward side. The *detailed model* is based on the preliminary model but uses advanced numerical tools to predict the hydraulic loading (VOF modelling) and time-dependent steps for the erosion of the seaward side of the dike, and the breaching process itself (Stanczak, 2008).

3.5 *Large-scale model tests*

Large-scale model tests have been performed at the large wave flume in Hanover where a section of real sea dike has been loaded by waves with heights of up to about 1.5 m. The dike was built of a sand core, a clay layer and a protective grass cover which was taken from an existing sea dike in Denmark (Figure 5).

The cross section of this dike is given in Figure 6, analysis of the tests was still ongoing at the time when this paper was written but the tests have shown that the resistance of the grass cover against erosion and hence against breaching is considerably larger than initially expected.

4 TUD RESEARCH ON BREACH MODELLING

4.1 *Introduction*

The TU Delft breach model BRES (Dutch for breach) has two versions, one for sand dikes (Visser, 1998) and one for clay dikes (Zhu, 2006), with the latter being developed within FLOODsite. The main limitations of the present version of BRES are: 1. it is a model for homogeneous dikes (constructed with sand, or clay, or a mixture of sand, silt and clay), 2. effects of waves are neglected, 3. it is assumed that the transport through the breach of sediment picked up from the breach bed is dominated by suspended load transport (rather than by bed load transport).

The BRES model is a semi-hydrodynamic, parametric 2D breach growth model. It is semi-hydrodynamic since: 1. broad-crested weir formulae are used to calculate the discharge through the breach and the flow velocities in the breach in the final stages of the breach growth process, 2. an analytical approximate solution of the Bélanger equation is used to calculate the flow velocities on the inner slope of the breach in the first stages of the breaching process. It is a parametric 2D breach model since the model is based on the five stage breaching development process as observed in the field and in the laboratory (Visser, 1998).

4.2 *Breach development process*

In the BRES model it is assumed that failure of the embankment has resulted in a small initial breach with a trapezoidal cross-section at the top of the dike, through which the flow of water starts the breach erosion process (at time $t = t_0$). In general five stages (see Figure 7) can be distinguished in the process of breach development, both for sand dikes (as described by Visser, 1998) and clay dikes (see Zhu, 2006). In stages I and II ($t_0 < t \leq t_2$), the breach eats into the dike, decreasing gradually the width and the height of the dike in the breach. In stage III ($t_2 < t \leq t_3$) the breach growth accelerates, and consequently also the discharge through the breach. After the wash-out of the dike in the breach at the end of stage III, the breach grows further in stage IV ($t_3 < t \leq t_4$), mainly laterally. In stage V ($t_4 < t \leq t_5$) backwater in the polder decelerates the flow in the breach, and consequently also the increase of the breach width. A rising backwater ultimately stops the flow of water through the breach.

In stage I ($t_0 < t \leq t_1$), erosion occurs along the inner slope of the dike and, depending on the flow velocity, possibly also along the dike crest. The flow along the inner slopes accelerates, consequently the erosion along this slope increases, steepening the slope until a critical slope angle is achieved at $t = t_1$. This critical gradient is held later on by the inner slope throughout stages II and III. In sand dikes the breach erosion process in stages I, II and III is dominated by shear erosion (see Visser, 1998), which leads to a gradual and relatively uniform retreat of the inner slope. However, in clay-dikes, when the inner slope of the dike has been steepened to the critical gradient, the steep slope acts as a headcut. Headcut erosion, including flow shear erosion, fluidization of the headcut slope surface, impinging jet scour of the dike foundation and discrete

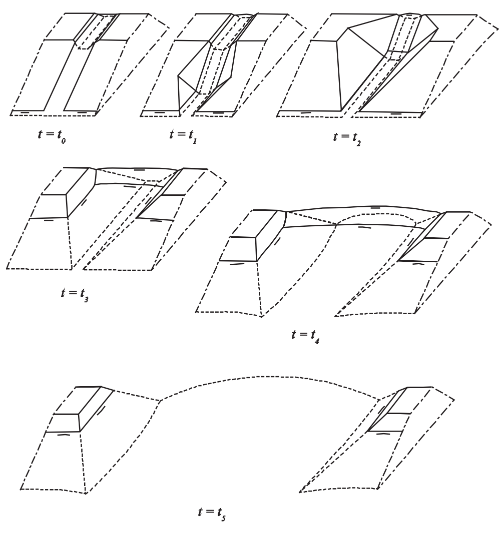

Figure 7. Five-step breach development process.

soil mechanical slope mass failure from the headcut dominates the breach development in clay-dikes in the first three stages (see Zhu, 2006). In principle, in stages I and II the breach develops mainly vertically with only ignorable widening, for both sand-dikes and clay-dikes. Practically, widening of the breach starts at the beginning of stage III at $t = t_3$.

The breach development in stages IV and V depends on the erodibility of the foundation of the dike, and on the stability of the toe protection on the outer slope of the dike (if any) or the height and erodibility of the foreland in cases where the dike foundation has low resistance against erosion. Hence, three types of breaches (Types A, B, and C) can be distinguished in stages IV and V, depending on these geometrical and structural conditions (see Visser, 1998, and Zhu, 2006. Generally, the dominating mechanisms of breach erosion in stages IV and V are the flow shear erosion along the side-slopes of the breach and the resultant discrete soil mechanical breach side-slope instability.

4.3 *Calibration and verification*

The model version for sand-dikes has been calibrated with the data of the Zwin'94 field experiment and validated against the data of a laboratory experiment (see Visser, 1998). The agreement of the model predictions with the data of these two experiments is good (see Figures 8 and 9). The confrontation of the model with the failure of the Noord Dike in Papendrecht (a sand dike) in the Netherlands during the 1953 storm surge indicates that the final breach width of 110 m was present after about 2.5 hr, which is more or less in agreement with a rough eye-witness report (see Visser, 1998).

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

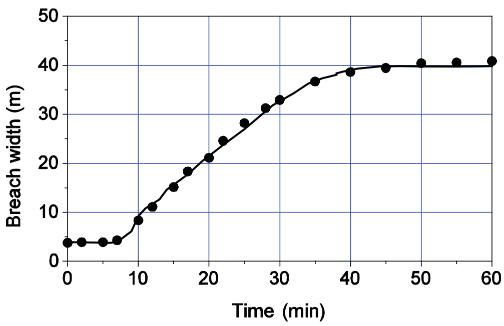

Figure 8. Comparison of predicted (solid line) and observed (dots) breach width at the dike crest for the Zwin'94 sand-dike field experiment.

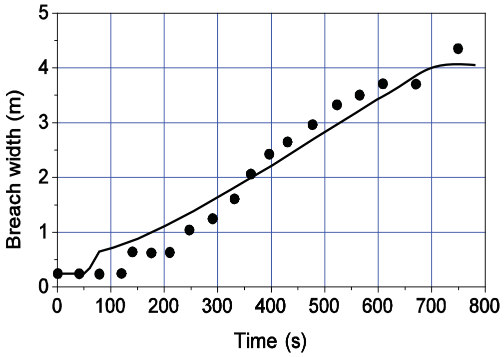

Figure 9. Comparison of predicted (solid line) and observed (dots) breach width at the dike crest for the laboratory sand-dike experiment.

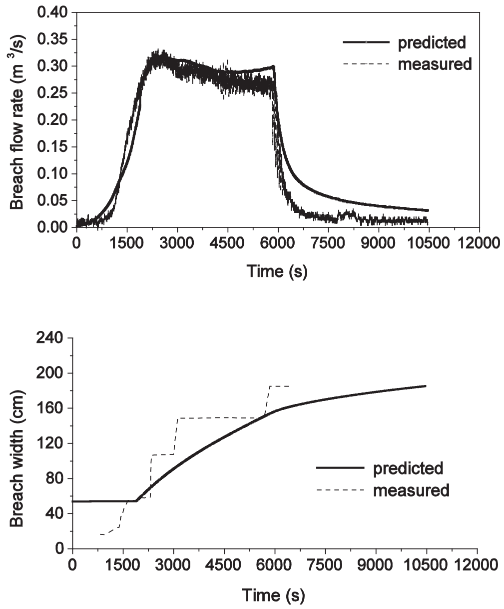

Figure 10. Comparison of predicted and measured breach flow rate (upper panel) and breach width increase (lower panel for test no. 10 of the EC IMPACT Project laboratory clay-dike experiment.

clay dike breaching (see Zhu, 2006). The model predictions are in good agreement with the experimental data (Figure 10). Validation of the model with the data of the other two 2D DUT clay dike laboratory tests yields reasonable agreement between the model predictions and the experimental data. Finally, the model has been confronted with a prototype dike failure in China in 1998 (see Zhu, 2006). The predicted final breach width of 274 m is about 39.7% smaller than the observed 390 m. The predicted 5.6×10^8 m^3 of diverted floodwater volume is rather close to the investigation-based estimation of 5.2×10^8 m^3.

4.4 *Discussion*

After suitable calibrations, the agreement of the predictions of both the sand dike and the clay dike version of the model with the relevant data are fairly good. However, it should be emphasised that the version for clay dikes does not have a general, widely applicable description for the erosion rate of soil, simply because such a description does not exist as yet. This model version also needs further calibration and verification with good prototype data; these data are unfortunately not available.

A strong feature of the BRES model, due to its parametric character, is its computational time of only a few seconds. So, it can be applied in (inundation) studies in which many breach calculations have to be done (for instance Monte Carlo simulations).

5 HRW RESEARCH ON BREACH MODELLING

5.1 *Introduction*

The objective of research undertaken by HR Wallingford under Task 6 of FLOODsite was to improve understanding of breach initiation and formation processes, to implement this knowledge through an improved version of the HR BREACH model and to make this improved model available for use within industry.

Research and development of the HR BREACH model started in 1998, with the model code being initially developed by 2002 (Mohamed, 2002). The model simulated breach formation using 1D flow and pseudo 2D section modelling. The model simulated breach growth by allowing the breach to form to a shape dictated by a combination of geotechnical, hydraulic and structural analyses.

Between 2001 and 2004, the European IMPACT Project (IMPACT, 2005) included a significant programme of research on breach. Part of this work included field and laboratory testing to collate reliable data sets (IMPACT, 2004; Morris et al, 2005). Whilst this work provided valuable data, and allowed the identification of key processes, detailed analysis and implementation within models was not possible. Hence, research under FLOODsite Task 6 makes use of the data produced within IMPACT to support the next stage of breach model development.

5.2 *Review of IMPACT Project data*

A formal review of the IMPACT data was undertaken. This developed into two distinct aspects of work; firstly, analysis of the extensive video and photo footage and secondly a detailed investigation into data quality.

The breach field test data from IMPACT offers a unique opportunity to study breach processes at large scale. In comparison to flood embankments, these are at prototype scale since the test embankments were built ranging between 4–6 m high. The test site allowed for storage behind the embankment of between 50–100,000 m^3 of water, with the option for additional water to be released from an upstream reservoir. During IMPACT, a series of 5 tests were undertaken. Additional tests were undertaken as part of a Norwegian national research project. The video and photo footage of these tests allowed key processes to be observed. These processes included:

– Different phases of breach flow from initial weir flow, through converging flow (Figure 11) ultimately to open channel flow
– Erosion processes ranging from surface erosion and headcut formation through to vortex action undercutting breach sides and soil wasting through mass failures and wash out.
– Larger scale features such as mass movement of the embankment, tension cracking in the crest, pipe formation and migration and arching across pipes.
– Additionally, freezing conditions also influenced some tests and provide a unique insight into how soil state affects breach formation.

Analysis of these processes was used to guide refinement and development of the breach model A detailed investigation into data quality was undertaken since initial inspection of the data highlighted some inconsistencies. This investigation exposed a number of problems with the data sets provided from Norway, suggesting that some of the data used during the IMPACT project is now considered incorrect (FLOODsite, 2008b). Corrected data has been used for model development within FLOODsite.

5.3 *Collaboration with the Dam Safety Interest Group Project*

To strengthen the research and model testing and development programme, links were established with a parallel project on breach modelling, within the CEATI facilitated Dam Safety Interest Group (DSIG). The DSIG comprises an international group of dam owner/operator organisations who collaborate on research projects of direct interest to the group. The DSIG project has three main goals:

1. to review current breach models and identify the most promising models for further study.
2. to review and collate data sets from failures, field and laboratory research that can be used to test and validate breach model performance.

3. to undertake model evaluation of the three most promising models. Evaluation by different members of the group to assess accuracy, usability and suitability for subsequent uptake within industry and potential integration into flow models such as HEC RAS.

The HR BREACH model was selected as one of the three models for detailed evaluation. Evaluation is underway at the time of writing this paper, using seven different breach data sets comprising data from the IMPACT project, USDA-ARS research embankments and the Oros and Banquio dam failures. Conclusions from the evaluation are anticipated towards the end of 2008.

5.4 *HR BREACH model development*

A very extensive programme of model testing, refinement and development has been undertaken. This programme of work has included significant revisions to the flow and erosion processes within HR BREACH, along with additional functionality in both the range of structure types that may be simulated as well as the ability to include varying erodibility for given soils.

Investigation into model performance and sensitivity of different parameters demonstrated the complex interactions that occur within breach prediction. The interdependency of flow, sediment erosion and breach side stability mean that changes to any of these processes can result in a different path for breach development. This reflects the nature of breach formation in reality, as well as within the model.

Flow calculation within the model has been refined through the use of variable weir discharge coefficients and different phases of breach flow, rather than using a simple weir equation with fixed discharge coefficient. Weir discharge can vary by up to 50% as a function of the approach flow conditions and weir shape. During breach formation, the 'weir' shape evolves, hence it is natural that the weir discharge should also change. Whilst retaining a simple weir flow calculation for modelling speed, the accuracy of flow prediction can be improved by using a variable discharge coefficient in this way. Researchers, such as Ackers et al (1978), offer guidance on how discharge varies with weir shape (Figure 12).

Additional research into breach flow was also undertaken using data from laboratory tests (by USDA-ARS) where discharge was measured for hundreds of different (fixed) breach geometries (Figure 13). This allowed the performance of weir equations for different flow conditions and breach geometries to be assessed. Comparison with CFD (FLOW3D) predictions made

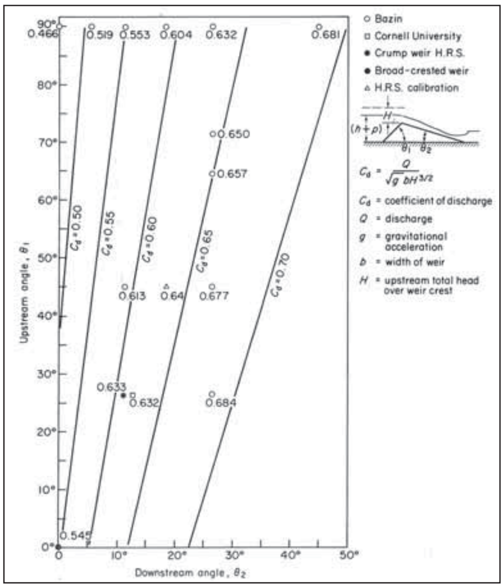

Figure 12. Approximate coefficients of discharge for triangular-profile weirs (Ackers et al, 1978).

Figure 11. Converging flow dropping through a breach immediately after erosion through the upstream crest.

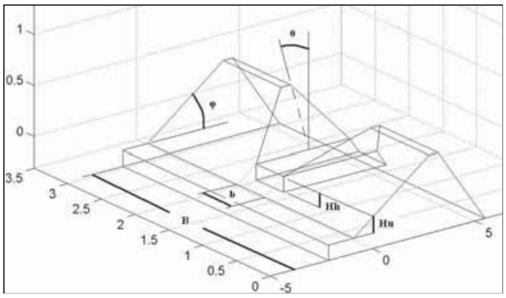

Figure 13. Breach geometry for investigation of breach flow (USDA-ARS research facility Stillwater, Oklahoma).

by Electricité de France on the same data set, allows an appreciation of the accuracy of flow prediction arising from simple or complex methods of modelling. This aspect of the research was continuing at the time of writing this paper.

Research into soil processes and the impact of soil state on erodibility has led us to refine the approach for sediment erosion prediction away from the use of equilibrium sediment transport equations and instead focusing upon sediment erosion equations of the form given in equation 1. This form requires the value of erodibility to be measured or estimated, but unlike the equilibrium equations allows for variations in soil state to influence the rate of breach growth.

$$\dot{\varepsilon} = k_d(\tau - \tau_c) \quad (1)$$

Where:
$\dot{\varepsilon}$ rate of soil detachment (mass/time)
k_d detachment rate coefficient (erodibility)
τ applied shear stress
τ_c critical shear stress.

The role of grass in protecting against surface erosion and hence breach initiation has also been investigated and the validity of the CIRIA grass performance design curves (CIRIA, 1987) is being assessed.

Finally, a significant enhancement to the model has been the inclusion of zoning within the model to allow the simulation of varying erodibility within the soil. This approach allows, for example, the effects of different soil layers, or same soils—different states—to be investigated. This might reflect how an embankment has been raised and extended over a period of decades or centuries and equally, how consolidation of soils might have occurred within a large embankment dam. The option to include a crest layer zone has also been included to allow simulation of the effects of fissuring. Current research (Dyer et al, 2007) suggests that fissuring may typically extend to depths of 5–600 mm in an embankment and can allow direct ingress of water from wave overtopping or intense rainfall into the embankment soil structure. In turn, this may rapidly affect the soil erodibility and hence change the way in which a breach through the embankment might develop. More erodible crest material is very significant for breach initiation, since this controls the rate of overflow which drives breach formation.

5.5 *Breach and flow model integration*

In parallel with breach model process developments, work has also been undertaken to integrate the beach model inside a flow model. Specifically, a version of the HR BREACH model has been integrated into a new 2D version of the InfoWorks RS flow modelling package (Figure 14). By integrating the breach model

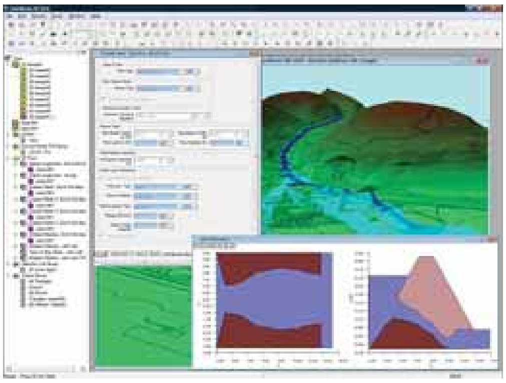

Figure 14. Breach simulation within InfoWorks RS 2D.

as a spill unit, the modeller can use the breach model to either define boundary flow conditions, such as a dam break or breach releasing flood water, or to predict the breach of flood embankments within the flow model simulation. Multiple breach locations can be simulated within the same flow model.

6 CONCLUSIONS

The FLOODsite project has facilitated research into breach initiation and growth processes, as well as the improvement of predictive models. Fundamental science has helped drive model development, and integration of models into commercial flow modelling packages means that this science is becoming more widely available for industry use.

Key advances have been made in:

- Understanding and basic simulation of wave induced breach initiation processes.
- Understanding of soil state influence on breaching processes.
- Improvement of physically based predictive breach models, including refinement of flow and erosion methods and inclusion of potential to simulate variable erodibility.
- Full integration of a predictive breach model inside a 1D-2D flow modelling package.

As with any research programme, increasing knowledge and awareness of processes also highlights gaps in knowledge. Key gaps and hence future direction for breach research includes:

- Data—the complexity of breaching processes means that there are many combinations of soil and structure type, state and loading that may significantly affect the breaching process. Large scale data is required to reproduce these processes and allow model development and validation;

– Natural variability—the state and condition of vegetation cover and soil can vary significantly, as a function of climatic conditions as well as natural variation. The bounds and implications of such variability on breaching processes needs to be determined; the performance of vegetation plays a significant role in determining the timing of initiation stages—a better understanding of vegetation performance is required to improve the reliability of breach initiation timing prediction.
– Erodibility—with many researchers basing model predictions upon a simple measure of soil erodibility, it strengthens the need to understand more about factors affecting erodibility, the collation of base data values for different soils and states, and the suitability of this measure for predicting breach through non cohesive materials.
– Three dimensional effects—to date, most, if not all, models consider breach in 2D. However, breach often initiates where hydraulic loading is focussed, for example when waves are funnelled to a particular point, or where transitions between different structure types are poorly designed resulting in local turbulence. A greater understanding of 3D initiation processes is required.
– Real structures—most models also predict breach through a simple or idealised embankment shape. Real embankments or dams are often constructed and perhaps extended at a later date; they are often not simple in profile. Models need to be able to simulate conditions of breaching through these real structures.

All of the FLOODsite reports referenced in this paper may be accessed online through www.FLOODsite.net

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