Recent Improvements in Predicting Breach through Flood Embankments and Embankment Dams

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SYNOPSIS. In the past decade a series of national and international initiatives have focused on understanding and improving the reliability of breach prediction. Breach prediction provides underpinning data for many types of flood risk assessment, including, for example, data for a dambreak analysis, a reservoir safety risk assessment, or for emergency planning. However, breach prediction remains one aspect of the overall risk analysis process that contains a high degree of uncertainty compared to other elements of the assessment. Uncertainty in breach prediction typically relates to a lack of understanding of the physical breach processes, the prediction methods available and their use, or misuse, within industry.

This paper provides an overview of current capabilities for predicting breach, from simple rapid methods through to more complex predictive methods. This review draws from experience gained through working on the EU FLOODsite project, the CEATI Dam Safety Interest Group breach modelling project, the more recent FRMRC2 programme and HR Wallingford company research work on breach prediction. The FRMRC2 programme work introduces a new simplified method for the rapid assessment of breach, whilst the HR Wallingford research introduces a new method for predicting breach through zoned embankments or dams.

Examples of where different methods are either appropriate or inappropriate are suggested along with an indication as to the future direction of research and industry model development for breach prediction.

INTRODUCTION

Predicting the way in which a flood embankment breaches is of interest to a range of different people operating within the flood risk and dam safety management sectors. Predictions are used as part of a flood risk assessment, for flood defence scheme design options, emergency planning and emergency response work. This paper provides a brief summary of breaching processes, an overview of recent research supporting the development of models and methods for predicting breach, and key factors affecting how and when different models or methods should be applied.

BREACHING PROCESSES

The way in which a flood embankment or embankment dam breaches depends upon the load conditions, the material that the dam is constructed from, and the state in which that material is. Surface protection measures, such as grass, rock, concrete etc. serve to delay the breaching process. However, the performance of this surface protection is only as good as the weakest point; for example, if gaps in grass cover exist and the embankment is overtopped, then erosion is likely to start at this location and undermine the remaining cover (Figure 1).

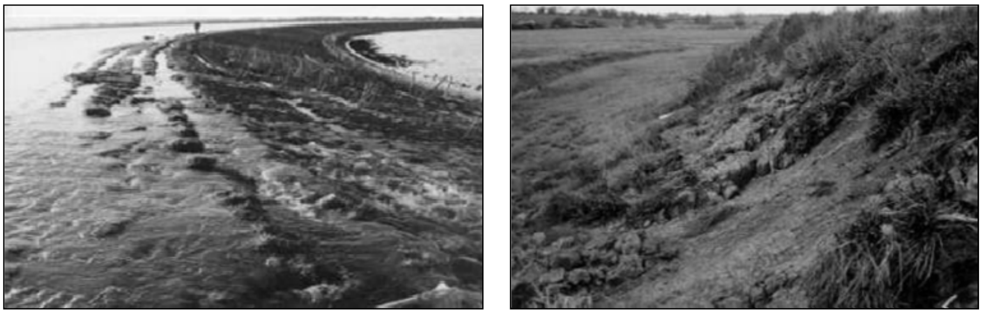

Figure 1. Embankment overflow protected by grass cover (Left); Wave overtopping erosion of a coastal embankment (Right) (Photos from the EU FLOODsite project)

When flood embankments are overtopped by waves or overflowed by water, there are two fundamental erosion processes that tend to occur.

Where the soil is sandy and relatively weak, it can be highly erodible and layers of soil will erode, with the crest and downstream slope eroding down and back respectively. This quickly leads to catastrophic breach. In particular, as the crest of the embankment erodes downwards, the rate of flow across the embankment increases, so also increasing the rate of erosion and breach formation (Figure 2 *Left*). Where the soil is clayey and relatively strong, erosion tends to form headcuts. Headcuts are steps in the downstream face of the embankment. These steps typically start at a weak point in the embankment slope, or near the toe, and progress in size and location backwards into the embankment. The rate of progression depends upon the rate of overflow, the height difference between the cascades formed by the headcut, and the strength (erodibility) of the soil. The advantage of headcut as compared to surface erosion is that catastrophic failure of the dam does not to occur until the headcut cuts back through the crest to the upstream slope, at which point the discharge rapidly increases. Up to this point, the crest remains intact and the breach flow relatively controlled (Figure 2 *Right*).

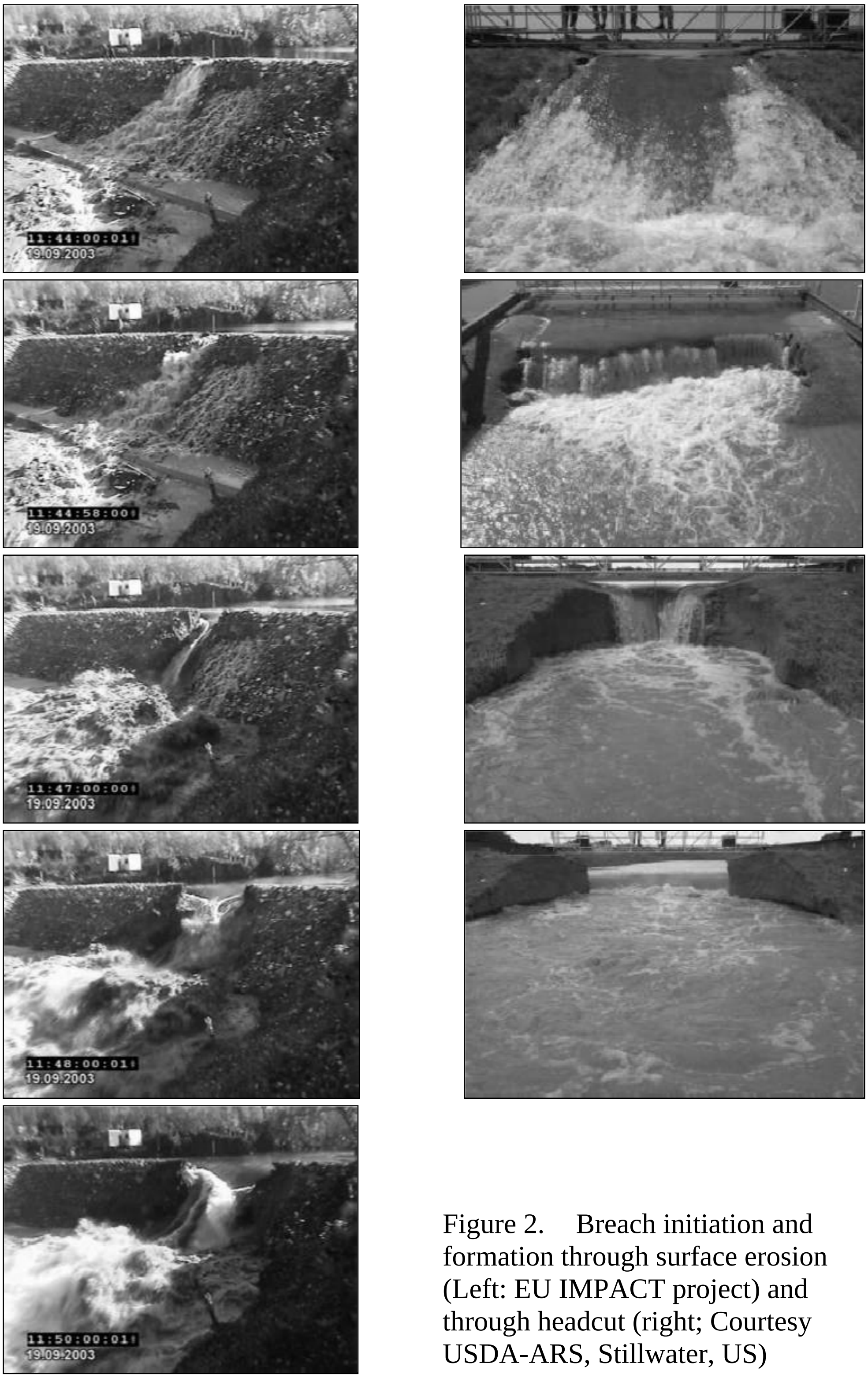

Figure 2. Breach initiation and formation through surface erosion (Left: EU IMPACT project) and through headcut (right; Courtesy USDA-ARS, Stillwater, US)

Where flood embankments or dams have been constructed and extended over long periods of time there may be layers of material within the dam body that erode at different rates, and with different processes. Equally, where structures have been built on or through the dam, these can act to protect against breach or to focus erosion in certain areas leading to breach. An example of this are transition points between defence types (e.g. wall to embankment) where waves may be focussed or seepage flow possible, both of which could initiate breach.

THE IMPORTANCE OF SELECTING THE RIGHT MODELLING APPROACH

A range of different people working within the flood risk and reservoir safety management sectors need to predict how a flood embankment or embankment dam might breach. The way and rate at which a dam breaches affects the timing of the breach, the rate and magnitude that flood water is released, and hence the size of the breach itself. This significantly affects the results of a flood risk assessment and changes the way in which flood events are managed.

Understanding the degree of uncertainty within any breach prediction method that has been used is therefore important information that should be considered alongside any specific breach prediction or assumption. The degree of uncertainty that is acceptable for a prediction depends upon the end use of the data and varies from application to application. Hence, in some situations a simple, but highly uncertain estimate suffices, whilst in others it is more appropriate to reduce uncertainty and give greater information about the range of potential breach scenarios by more detailed modelling. Failing to recognize the degree of uncertainty within breach data that is used in subsequent analyses can undermine the validity of those analyses.

RECENT RESEARCH INITIATIVES SUPPORTING THE DEVELOPMENT OF BREACH MODELS

The following sections provide a summary of different initiatives from the past five years that have supported the development of new or refined methods for predicting breach processes.

The EU FLOODsite Project

The EU FLOODsite project was a large European research project investigating flood risk analysis and management solutions. The project ran for five years (2004-2009) and had a research team of over 250 members, drawn from 15 different countries. The project website (www.floodsite.net) will remain active until ~2030 and permits access to all of the project research. Research under Tasks 4 & 6 addressed flood defence structure failure modes and the prediction of breach initiation and growth. Research here was carried out in parallel with the CEATI DSIG project (see below) and the HR Wallingford breach research programme (see below).

FLOODsite reports T06-06-03 (Morris et al., 2009), T06-08-02 (Morris et al., 2008) and T06-08-11 (Morris, 2009) provide a state of the art review, report on the science of breach initiation and growth and analysis of physical breach processes respectively. The latter provides a frame by frame analysis of video footage of large scale field tests undertaken during the EU IMPACT project (www.impact-project.net).

The CEATI Dam Safety Interest Group Breach Modelling Project

In 2004 the Dam Safety Interest Group of CEATI initiated a new research project aiming to advance the state of practice for computer modelling of embankment dam erosion and breach processes. The longer term objective of the project was to integrate breach models with dynamic flood routing models suitable for industry use. The resulting collaboration brought together many of the most active researchers and organizations working on dam breach modelling worldwide. The working group undertook the research using a phased approach. The first phase reviewed historical developments related to physical modelling of dam breach processes in laboratory environments (Wahl, 2007) and ongoing efforts to develop improved numerical models (Kahawita, 2007). Laboratory test data were compiled, especially results from recent, large-scale physical model tests, and real-world case study dam failure data were also collected (Courivaud, 2007). The review of numerical models identified three computer models that the working group chose to evaluate in a second phase of the project using the assembled laboratory and real-world case study data sets. These three models were the USDA SIMBA (now embedded within WinDAM B) model, the HR Wallingford HR BREACH model and the Polytechnic School of Montreal FIREBIRD BREACH model. All three models are physically-based, simulating fundamental erosion processes by relating factors causing erosion to factors resisting erosion. The models utilise quantifiable erodibility parameters that can be directly measured or estimated from other soil properties when measurement is not possible.

The model evaluation results showed that the SIMBA and HR-BREACH models both performed very well on six of the seven test cases. The Banqiao Dam (7^{th}) case was poorly modelled by all of the programs, and the quality of the input and observed data are questionable for this case. The evaluators were unable to successfully run the FIREBIRD BREACH model on most of the test cases. Compared to the other two models, this model has received substantially less organisational support for continued development since it was first created and the user interface was found to be difficult to use. A summary of conclusions drawn from the performance evaluation is given in Table 1 below.

Table 1. Breach model characteristics

	HR-BREACH	SIMBA / WinDAM	FIREBIRD	NWS-BREACH
Erosion Process Models	Good	Good	Fair	Limited
Surface protection	Vegetation (CIRIA) and riprap	Vegetation, riprap in WinDAM	Limited	Yes
Headcut erosion	Good	**Best**	No	No
Stress-based	—	Yes	—	—
Energy-based	Yes	Yes (in WinDAM)	—	—
Surface erosion	Yes	No	Yes	Yes
Mass-wasting / soil-wasting	Stress-based bank failures and arch failure	Bank failures implicit	Some	Some
Effects of Submergence	Yes	Yes (in WinDAM)	No	Yes
Piping progression	Yes	In development	Some	Yes
Data Input Guidance	Good	Good	Limited	Limited
Ease of Use	Good	Good	Difficult	Difficult
Computational Efficiency	Good	Good	Fair	Good
Documentation	**Excellent**	**Excellent**	Limited	Good
Organizational Support for Continued Development	Good	Good	Weak	None
Embankment Geometry Options	**Simple Zoning**	Homogeneous, (Zoned in future)	Simple Zoning	Primitive Zoning

<u>USDA Simba and WinDAM B Models</u>

A long and continuing programme of research has been undertaken at the US Department of Agriculture Hydraulic Engineering Research Unit in Stillwater, Oklahoma looking at soil erosion for earthen dams and subsequently developing the SIMBA breach model. The SIMBA model simulates the progression of a headcut through an embankment dam or flood embankment. The modelling process assumes a predefined failure process (rather than free format erosion) and hence takes only seconds to run. The breaching process is appropriate for predicting breach growth through less erodible materials where the headcut process (rather than surface erosion) would dominate. The SIMBA model does not simulate the effects of grass and rock cover but has now been meshed into the WinDAM B software which provides a framework for modelling dam breach which includes the performance of grass cover, spillway etc. Details of this public domain software can be found at http://go.usa.gov/8Oq.

HR BREACH - HR Wallingford Model Development

The HR BREACH model was originally developed by Mohamed Hassan (Mohamed, 2002) as part of an HR Wallingford research programme. The model predicts the breach growth through an embankment by considering the flow, erosion and stability conditions at sections through the embankment. The model simulates overflow failure through either surface erosion or headcut erosion (the latter using headcut processes as defined by Temple (Temple et al., 2005)). Alternatively, failure through pipe formation can be simulated. In addition to the breach formation process, the model predicts breach initiation, including erosion of grass or rock cover. For the performance of grass cover, either the CIRIA 116 report performance curves can be used (Hewlett et al., 1987) or the earlier Technical Note 71 performance curves (Whitehead et al., 1976) which provide a better representation of grass performance without any added safety factors (Morris et al., 2010, Morris et al., 2012).

The model does not predefine the failure process for surface erosion failure. The model predicts flow conditions at each section and allows erosion to develop according to these flow conditions. The breach shape is not predefined, and as erosion undercuts the sides of the breach, block failure is allowed to occur and hence the breach widens.

Unlike earlier versions of the model, the model now uses an erosion equation rather than a sediment transport equation to predict the erosion processes (Morris, In Prep) (Equation 1). This equation relates the rate of erosion (E) to the shear stress (τ) relative to a critical shear stress (τ_c) and the soil erodibility (K_d). Empirical coefficients (a, b) are taken as 1.

$$E = K_d b(\tau - \tau_c)^a \qquad (1)$$

The use of an erosion equation such as this is more appropriate than using a sediment transport equation since the conditions within a breach are dynamic, highly dependent upon the soil erodibility, and no equilibrium transport conditions are achieved along the breach geometry. The erodibility of a material depends upon its state as well as its type; a highly compacted material with optimum moisture content will be far more resistant to erosion than a saturated poorly compacted material.

Soil type and condition also affect the nature of the breach erosion process (Morris, In Prep). An erosion resistant soil, such as a strong clay, is likely to erode through headcut processes whilst a weaker, erodible material, such as a poorly compacted or sandy soil, is more likely to erode through surface erosion processes. Variations in soil type and condition within the same embankment or dam can mean that both processes occur during breach formation (Morris, 2009). Where soil erodibility is not known, then judgement can be used to estimate the likely range of values and a sensitivity analysis is undertaken for breach prediction, or direct measurement in the field or laboratory is undertaken (Hanson and Hunt, 2006).

A significant development of the model during the last few years has been to introduce the ability to simulate breach growth through zones of different material (Morris, In Prep). A range of generic zone configurations are permitted (Figure 3).

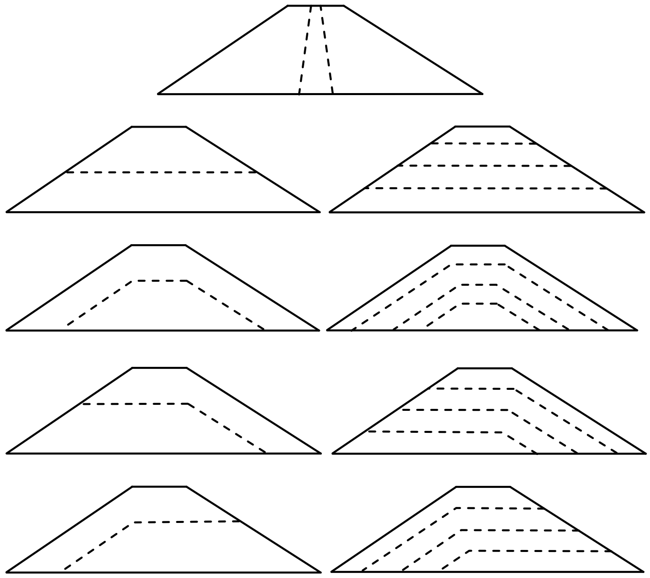

Figure 3. Zoned approach to breach modelling (Morris, In Prep)

The effect of different rates of erosion, resulting from different layers of material within the embankment body, is quite pronounced, changing the shape, magnitude and duration of the potential flood hydrograph. Hence, where it is known that an embankment or dam has been extended using different material or a different state of material, or that zones of different material have been designed within the dam, a zoned approach to modelling provides a more accurate prediction of failure conditions than the assumption that the soil is homogeneous.

Flood Risk Management Research Consortium Programme (FRMRC2) – Simplified Breach Prediction (AREBA Model)

The Flood Risk Management Research Consortium (FRMRC2) undertook a programme of research into different aspects of flood risk management which completed at the end of 2011 (see www.floodrisk.org.uk). One of the modules of research (WP4.4) was to produce a simplified method for the rapid prediction of breach. The goal here was to produce a model or method which could be used within system flood risk models, where large numbers of predictions are required in a short time.

A new breach model called AREBA was developed (van Damme et al., 2011). This model adopts a similar approach to SIMBA in predefining the way in which breach formation occurs, but allows the user to simulate erosion through surface erosion, headcut, or internal erosion (pipe formation) so covering the three main processes causing breach. For surface erosion, the model predefines the way in which erosion cuts back both the downstream face and the crest of the dam (Figure 4 *Left*). For headcut erosion, the model assumes similar processes to those simulated by the USDA SIMBA model (Figure 4 *Right*). For pipe formation the model replicates the process simulated by the HR BREACH model including failure of the material above the pipe as the pipe diameter grows. The model also includes for the effects of surface grass cover (using the Technical Note 71 performance curves).

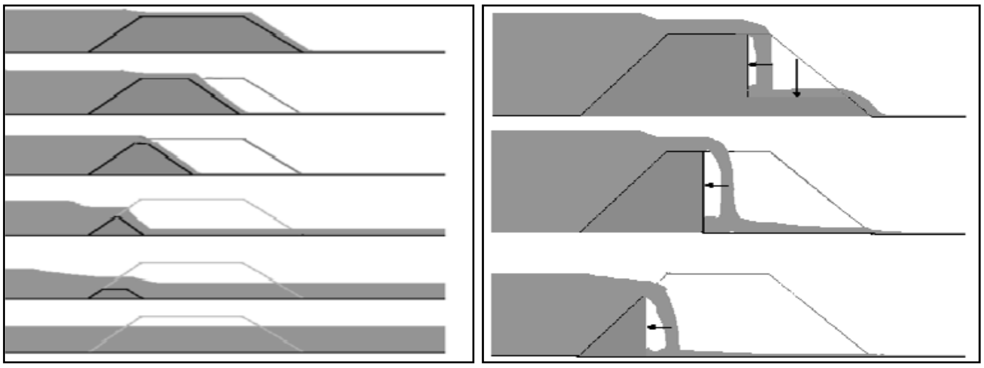

Figure 4. Embankment breach initiation and formation through overflow surface erosion (left) and overflow headcut (right)

As with the HR BREACH and SIMBA models, AREBA also uses an erosion equation that requires the user to provide a value of soil erodibility.

For each of the three failure modes, AREBA uses analytical equations to describe the erosion rates, and flow through the breach. The non-grid based approach gives the model its high run speed (less than 1s). The high run speed makes it easy for the user to simulate a range of potential breach scenarios based upon different input values, and hence gain a better understanding of what might happen at a particular location. As a simplified model, however, it does not simulate breach through more complex or composite structures; the model simulates on the basis of a regular shaped, homogeneous earth flood embankment.

APPLICATION OF DIFFERENT METHODS

There are a variety of different models (or methods) for predicting breach conditions. These may be broadly categorised as:

- Non-physically based, empirical models
- Semi-physically based, analytical and parametric models
- Physically based models

Examples of non physically based or empirical models include peak discharge equations, such as those reviewed by Wahl (Wahl, 2004). These potentially contain very large degrees of uncertainty within the prediction. Semi physically based models include models where simple representation of physical processes are included (Walder and O'Connor, 1997). An option here is also for the user to define the rate or size of breach growth from which the model then predicts the rate of outflow. Again, these models contain a large degree of uncertainty. Physically based models include models such as SIMBA, WinDam B, AREBA and HR BREACH, between which there are varying degrees of flexibility and hence uncertainty, but less so than for the simpler prediction approaches.

Given this range of approaches, which might also include the basic option of judgement (i.e. predict a breach size based upon historic data), the key to selecting the most appropriate model or method is in recognizing what aspects of breach prediction are important for a particular study and what degree of uncertainty is acceptable. Different end users will require different information such as peak discharge, flood hydrograph shape, breach width, time to failure etc. and not all of these parameters are provided by the various methods. Where possible, it is best to undertake analysis which provides a picture of how the embankment or dam might fail; this entails consideration of uncertainty within the load conditions as well as the embankment soil.

FUTURE DIRECTION FOR BREACH PREDICTION

The range of breach prediction methods, from simple equations to complex predictive models, has been developed to meet different end user needs. However, as computing power continues to advance, the ability to apply ever more complex models in very short times allows the user to quickly apply a model for a range of conditions in order to understand more about the flood embankment or dam and how it might fail. The AREBA model provides an excellent example of this, whereby the user can simulate a range of failure processes in a fraction of a second and hence gain a far better understanding of what might occur than, say, through the use of peak discharge equations. It is likely that the use of such a model will supersede the use of regression equations in the coming years.

Development of the HR BREACH model to allow simulation of breach through zones of material has shown the importance of taking material changes into account. In practice, many flood embankments and embankment dams are constructed from zones of material, either from their original design or as a result of later modifications. Hence, where an embankment is zoned, such an analysis provides a more reliable prediction of the potential breaching process.

The CEATI project has highlighted the relative strengths of the SIMBA and HR BREACH models recognising that whilst each model simulates different erosion processes (i.e. headcut and surface erosion), each provides a useful tool for predicting aspects of breach formation. In the future we can expect to see models integrating both of these physical processes automatically within the overall breach simulation. The SIMBA model has also been integrated within the WinDAM B software. Development of SIMBA, and hence WinDAM B, now continues with a focus on improving the simulation of internal erosion. This builds from current research on internal erosion processes (Benahmed and Philippe, 2012).

A limitation of many breach models is their ability to integrate the simulation of overall embankment stability (leading to breach initiation) and specific breaching processes (given breach initiation). Currently, dams or embankments might be analysed for overall geotechnical stability or for breach, but not the two simultaneously. In practice, the two processes are highly interdependent. Simulating these combined processes is the next challenge for breach modelling.

REFERENCES

Benahmed, N. and Philippe, P. (2012) *Comprehensive report on Action 3.1.1: Internal erosion, FloodProBE Report WP03-01-12-05*, FloodProBE Project, www.floodprobe.eu

Courivaud, J.-R. (2007) *Analysis of the dam breaching database, CEATI Report No. T032700-0207B,* Dam Safety Interest Group (DSIG), Canada. Technologies, C.

Hanson, G.J. and Hunt, S.L. (2006) 'Determining the erodibility of compacted soils for embankment dams', *26th USSD Annual Meeting and Conference*, San Antonio, Texas, USA, 30th April - 3rd May, 2006.

Hewlett, H.W.M., Boorman, L.A. and Bramley, M.E. (1987) *Design of reinforced grass waterways, CIRIA Report 116*, CIRIA, London, UK.

Kahawita, R. (2007) *Dam breach modelling - a literature review of numerical models, CEATI Report No. T032700-0207C,* CEA Technologies (CEATI), Canada. CEATI.

Mohamed, M.A.A. (2002) *Embankment breach formation and modelling methods,* The Open University, England, UK

Morris, M.W. (2009) *Breach Initiation and Growth: Physical Processes, FLOODsite Report T06-08-11*, UK. FLOODsite. www.floodsite.net

Morris, M.W. (In Prep) *Breaching of earth embankments and dams*, The Open University, England., UK. PhD. Subject to examination.

Morris, M.W., Boorman, L.A. and Simm, J.D. (2010) 'Just how important is grass cover?', *British Dam Society 16th Biennial Conference*, University of Strathclyde, Scotland,23-26th June 2010.

Morris, M.W., Hassan, M.A.A.M. and Escarameia, M. (2012) *The performance of vegetation on flood embankments, FloodProBE Report WP03-01-10-06,* UK. EU FloodProBE Project www.floodprobe.eu.

Morris, M.W., Kortenhaus, A., Visser, P.J. and Hassan, M.A.A.M. (2009) *Breaching processes: A state of the art review*, *FLOODsite Report T06-06-03, First.* UK. FLOODsite (www.floodsite.net). www.floodsite.net

Morris, M.W., Kortenhaus, A., Visser, P.J., Hassan, M.A.A.M., Geisenhainer, P. and Zhu, Y.H. (2008) 'Modelling breach initiation and growth', In: Samuels, P. G., Huntington, S. W., Allsop, N. W. H. A. and Harrop, J. eds. *FLOODrisk 2008: Flood risk management, research and practice*, Oxford, UK2008. Taylor and Francis.

Temple, D.M., Hanson, G.J., Neilsen, M.L. and Cook, K.R. (2005) 'Simplified breach analysis model for homogeneous embankments: Part 1, Background and model components', *25th Annual USSD Conference*, Salt Lake City, Utah, USA, 6-10 June 2005, 2005.

van Damme, M., Morris, M.W. and Hassan, M.A.A.M. (2011) *A new approach to rapid assessment of breach driven embankment failures*, www.floodrisk.org.uk FRMRC2.

Wahl, T.L. (2004) 'Uncertainty of prediction of embankment dam breach parameters', *Journal of Hydraulic Engineering*, Vol. 130 (No. 5), pp. pp. 389-397.

Wahl, T.L. (2007) *Laboratory investigation of embankment dam erosion and breach processes*, CEA Technologies (CEATI), Canada. CEATI.

Walder, J.S. and O'Connor, J.E. (1997) 'Methods for predicting peak discharge caused by failure of natural or constructed earthen dams', *Water Resources Research*, Vol. 33 (No. 10), pp. pp. 2337-2348.

Whitehead, E., Schiele, M. and Bull, W. (1976) *A guide to the use of grass in hydraulic engineering practice, Technical Note 71*, London, UK. CIRIA.