RECLAMATION

Managing Water in the West

PAP-1065

Evaluation and Development of Physically-Based Embankment Breach Models

By M.W. Morris, T.L. Wahl, R.D. Tejral, G.J. Hanson, and D.M. Temple

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

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M.W. Morris, M.A.A.M. Hassan
HR Wallingford, Wallingford, United Kingdom

T.L. Wahl
Bureau of Reclamation, Denver, Colorado, USA

R.D. Tejral, G.J. Hanson, D.M. Temple
Agricultural Research Service, Stillwater, Oklahoma, USA

ABSTRACT: The CEATI Dam Safety Interest Group (DSIG) working group on embankment erosion and breach modelling has evaluated three physically-based numerical models used to simulate embankment erosion and breach development. The three models identified by the group were considered to be good candidates for further development and future integration into flood modelling software. The evaluation utilized 7 case studies comprising three large-scale tests carried out in Norway (5- to 6-m high embankments); two large-scale tests from the USA (1.75-m high embankments); and the prototype failures of the Oros (Brazil) and Banqiao (China) dams. The breach models evaluated were SIMBA, HR-BREACH, and FIREBIRD BREACH. Results of the evaluation are presented along with details of the continued development of two of the three models (HR BREACH and SIMBA).

1 INTRODUCTION

In 2004 the Dam Safety Interest Group of CEATI International (an international consortium of electric power generating utilities with common research interests) initiated a new research project aiming to advance the state of practice for computer modelling of embankment dam erosion and breach processes. A working group was formed, composed of representatives from CEATI-member utilities with a strong interest in this topic, including several pursuing dam breach modelling research programs of their own. Other organizations with strong research programs on this topic were also invited to join and participate in the working group. The resulting collaboration has brought together many of the most active researchers and organizations working on dam breach modelling worldwide (Table 1).

The working group has pursued this research using a phased approach. The first phase reviewed historical developments related to physical modeling 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. Summary results from that evaluation effort are discussed in this paper.

The development and integration of next-generation dam breach modelling tools into dynamic flood routing models and the continued improvement of those models going forward is the long-term objective of the CEATI-sponsored project. The models studied thus far are focused primarily on the overtopping[1] failure mode and relatively simple embankment geometries, but development is underway on modules to simulate internal erosion and more complex embankment geometries. These capabilities are expected to continue to improve over time.

Table 1. — Members of the CEATI Working Group, and other project sponsors.

ORGANIZATION	ROLES	Primary Representatives
CEATI International	Technical coordination	Gary Salmon (deceased)
Electricité de France	Assemble case studies of real dam failures. Erodimeter and piping erosion research.	Jean-Robert Courivaud
Hydro Québec / Ecolé Polytechnique Montréal	Review of numerical models for simulating dam breach, development of FIREBIRD BREACH model.	Tai Mai Phat, Réne Kahawita
Bureau of Reclamation	Review of laboratory physical hydraulic modelling programs. Investigation of erodimeters.	Tony Wahl
USDA-Agricultural Research Service	Large-scale laboratory testing and development of SIMBA/WinDAM models. Development and investigation of erodimeters.	Greg Hanson, Ron Tejral, Darrel Temple
HR Wallingford	Small- and large-scale physical model testing (IMPACT project), developers of HR-BREACH model	Mark Morris, Mohamed Hassan
US Army Corps of Engineers	Erodimeter evaluation, breach model evaluation, potential integration of breach modelling technology into HEC-RAS suite	Jeff McClenathan, Johannes Wibowo, Michael Gee
Elforsk, Energo Retea	Numerical breach model evaluation	Ascila Romanas, Fredrik Persson
Ontario Power Generation	Numerical breach model evaluation	Allan Kirkham, Yibing Zhang
Other sponsors: Churchill Falls Hydro, EoN Vasserkraft, Great Lakes Power, Manitoba Hydro, New York Power Authority, Seattle City Light, Scottish & Southern Energy		

[1] In this paper, the term 'overtopping' is used to mean the continuous overflow of water rather than wave overtopping.

The three models included in this evaluation are all physically-based, simulating fundamental erosion processes by relating factors causing erosion to factors resisting erosion. The models utilize quantifiable erodibility parameters that can be directly measured or estimated from other soil properties when measurement is not possible. The models are not calibrated to reproduce observed data from specific dam breach case histories or laboratory tests, but rather rely on verification of the basic erosion process models against laboratory tests designed to study the basic processes. The three models all have the capability to simulate erosion and breach of embankments that are primarily composed of cohesive materials, and some also include erosion models focused on non- cohesive soils. The models have varying abilities to analyse embankments with complex internal geometries (i.e., zoned construction). The models all consider erosion caused by overtopping flow, and some have the capability to also consider internal erosion. This evaluation focused only on overtopping. The three models evaluated in this study are:

- SIMBA – SIMplified Breach Analysis – Under development at the USDA-ARS Hydraulic Engineering Research Unit, Stillwater, Oklahoma. (Temple et al. 2005, Hanson et al. 2005a). This is a research-focused model used to analyse data from large-scale laboratory tests for the purpose of developing and refining algorithms needed for the creation of an application-focused model, WinDAM B. The focus of SIMBA is headcut erosion in homogeneous cohesive embankments. The version of the model evaluated here had some optional components disabled or restricted. (WinDAM B Version 1.0 was officially released in August 2011).
- HR-BREACH – Under development at HR Wallingford, UK (Mohamed 2002). This model has been improved through the years in connection with several European Union initiatives related to flood modelling, including CADAM, IMPACT, FLOODsite, and FloodProBE. HR BREACH has a surface erosion component used to simulate erosion of cohesive or non-cohesive materials (but assuming surface erosion for both), an energy-based headcut migration model (although not applied within the CEATI project), and capability to analyse overtopping or piping. The model can also simulate erosion through a structure with a core and surface protection layers of grass or rock.
- FIREBIRD BREACH – Developed at the Polytechnic School of Montreal through a collaboration with Hydro Québec. (Wang and Kahawita 2002). FIREBIRD BREACH models surface erosion only (no specific head cut model), but includes options for zoned embankments and failure due to piping.

In addition to these three models, the NWS-BREACH model (Fread 1988) was also evaluated as a point of comparison, since for many years it has been one of the most widely used process-based dam breach models. NWS-BREACH simulates surface erosion only and allows for failures due to piping. The model also allows for the definition of a zoned embankment, but at each time step computes erosion based on a homogeneous average of soil properties along the length of the breach channel. This is a much simpler implementation than HR BREACH, which computes erosion rates specifically for each zone.

The evaluation process was carried out by assembling a team of evaluators from the participating organizations, including the developers of the various models. The evaluators were educated in the theory, development history, and use of the programs. The various case study data sets were presented, discussed, and reviewed for data accuracy before modelling began. Model evaluators were asked to run each model on the various case studies with at least two sets of input parameters. The parameters used for initial runs comprised a so-called "best estimate" based on the data that would be available for a hypothetical application of the model to prediction of a future breach event (a quasi "blind" run). After this initial run, evaluators were asked to make additional runs in which modelling options and parameters were varied with the objective of matching previously observed behaviour from the real world event or laboratory test. In making these additional runs the evaluators were seeking to evaluate the sensitivity to various parameters and to determine whether observed behaviour could be reproduced with reasonable parameter values and modelling options. Evaluations of sensitivity were carried out subjectively, with the understanding that models should exhibit "appropriate" sensitivity, since laboratory testing has shown that soil erodibility can vary widely (Hanson and Hunt 2007) and does dramatically affect observed breach behaviour (Hanson et al. 2005b).

The nature of the models evaluated enables a relatively detailed comparison of simulated and observed behaviour. The models all simulate both the breach initiation and breach formation phases, as described by Wahl (1998). Breach initiation begins with the first flow of water over or through a dam that is sufficient to initiate warning, evacuation, or other heightened awareness of the potential for dam failure. During breach initiation, flow released from the dam increases very slowly, because the zone of active erosion is not located at the point of hydraulic control of the outflow. When active erosion progresses through the dam to the point that it reaches the hydraulic control section, then the breach formation phase begins and flow begins to increase rapidly. Breach formation continues until the breach reaches its maximum size.

Whereas early attempts to predict embankment dam breach parameters focused on just the breach formation phase, these physically based models make it possible to evaluate the ability of the models to simulate both breach initiation and breach formation. Thus, model runs were evaluated for their ability to reproduce the breach initiation time, breach formation time, erosion rates during each phase of breach development, and the complete breach hydrograph (peak flow and duration).

To evaluate the models, they were tested using a set of seven case study dam failures. Two of these dam breaches were real, historic events (Oros Dam-Brazil 1960; Banqiao Dam-China1975), and five were large-scale tests conducted in outdoor laboratory facilities in Norway (Hassan and Morris 2008) and the USA (Hanson et al. 2005b). The laboratory tests, especially those from the USA, provided cases in which erodibility of the embankment soils was very well quantified, test conditions were carefully controlled, and observed erosion and breach development were well documented. The USA tests (1.75-m high embankments) included one case of full breach development and one case in which headcut erosion damage occurred, but breach initiation was not completed. The three tests from Norway (5- to 6-m high embankments) were all cases of full breach development, with differences in soil material (homogeneous clay; gravel dam with moraine core; and homogeneous gravel). Due to the test facility (a reach of a large river below an active storage reservoir), test conditions were more difficult to control, actual behaviour was more difficult to document, and there were some questions about the quality and accuracy of the data made available to the modellers. Erodibility parameters for the embankment materials were less certain than for the USA tests. The two real dam breaches provided an opportunity to test the models on full-scale scenarios, but with typical difficulties estimating soil material properties (especially erodibility), the as built design of the dams and uncertainties about the quality of other input data and actual breach performance data.

The model evaluation results showed that the SIMBA and HR-BREACH models both performed very well on 6 of the 7 test cases. The Banqiao Dam 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 organizational support for continued development since it was first created and the user interface was found to be difficult to use.

Headcut erosion was a dominant feature of most of the case studies. The SIMBA model with its deterministic approach to headcut simulation (Hanson et al. 2001) performed very well and exhibited appropriate sensitivity to soil parameters. Only the surface erosion options in HR BREACH were used for the evaluation runs, since HR BREACH's headcut migration model (developed by Temple et al. 2005) is similar to the SIMBA/WinDAM headcut models. In two of the Norway test cases that included non-cohesive materials, surface erosion was a significant process observed during the tests. Here, the HR-BREACH model performed very well. SIMBA was also able to do a good job on these cases, but required some user judgment regarding how to model the non-cohesive materials.

The Oros case study test highlighted the importance of drowning effects on breach formation. The valley immediately downstream of the Oros Dam poses a tight constriction. Inclusion of this constriction and the subsequent drowning of the breach during the formation process produced prediction results far closer to the observed data than without consideration of drowning effects.

Table 2 summarizes characteristics of the models and highlights their relative strengths.

Sensitivity of the SIMBA and HR-BREACH models to changes in soil erodibility parameters was judged to be appropriate and consistent with observed variations in breach development during the laboratory tests. Some model runs proved to be very sensitive to specific parameters when it affected the relative timing of the peak of the inflow hydrograph and the completion of the breach initiation phase. This is a real phenomenon which is often dramatic when trying to simulate a laboratory test, where the inflow hydrograph may be manipulated significantly during the test.

Table 2. — Breach model characteristics.

	HR-BREACH	SIMBA / WinDAM	FIREBIRD	NWS-BREACH
Erosion Process Models	Good	Good	Fair	Limited
Surface protection	Vegetation (CIRIA) and rip-rap	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

2 DEVELOPMENT OF THE SIMBA AND WINDAM B MODELS

Over the past 70+ years a large number of embankment dams have been constructed in the United States and elsewhere. The U.S. National Inventory of Dams (NID) lists approximately 80,000 dams with the majority of these being classified as earth embankment dams. The USDA, Natural Resources Conservation Service (NRCS) is listed as involved in more than 23,000 of these dams (Hanson et al., 2008). Changes in watershed conditions both upstream and downstream from these structures, combined with sediment deposition within the flood pool has led to an increased potential for overtopping during extreme events and an associated increased potential for loss of life and property in the downstream floodplain. Due to these concerns the USDA, Agricultural Research Service has been conducting a research program with joint efforts from the Natural Resources Conservation Service (NRCS), and Kansas State University (KSU) to develop new technology and tools for predicting the performance of earthen embankments during overtopping. The initial efforts of this program resulted in the development of a computational research tool SIMBA (SIMplified Breach Analysis) for evaluating algorithms and code for predicting erosion and breach of homogeneous embankment dams. The computational model is the result of research including embankment overtopping tests conducted in the outdoor laboratory. The model is a simplified representation of the observed process of progressive erosion leading to embankment breach. The erosion technology developed in SIMBA has now been incorporated into Windows Dam Analysis Modules (WINDAM B) which is a modular software application being developed for the dam safety profession in response to this need (Hanson et al. 2011).

The SIMBA model used in the DSIG evaluation program was not a full-featured model, but a research tool, which at the time of the evaluations concentrated on processes observed and material properties required for predicting erosion in overtopping of homogeneous embankments. For this reason it did not evaluate failure of vegetation or riprap or handle non-level crest profiles. WinDAM B provides a more complete evaluation including surface protection provided by vegetation and rip-rap.

Idealized three-dimensional shape and growth of breach are determined by coupling a headcut development and advance model with hydraulic calculations based on normal depth flow and unit flow rates. Flow rate is approximated by assuming hydrostatic pressure and an energy coefficient of unity at the point of hydraulic control. The erosion rate is a function of a soil detachment rate coefficient and the excess applied stress.

$$\dot{\varepsilon} = k_d\left(\tau_e - \tau_c\right) \qquad (1)$$

where

= erosion rate, L/T

= coefficient of detachment, $L^2M^{-1}T$

= effective shear stress, $ML^{-1}T^{-2}$

= critical shear stress, $ML^{-1}T^{-2}$

Effective shear stress is assumed to equal gross shear stress, e.g. for normal depth flow on the dam face (= unit weight water, = depth normal to slope, = slope).

The headcut migration model used in the DSIG evaluation is a stress based model. The model is labelled the Hanson/Robinson model (Hanson et al. 2001). This model predicts advance by failure at the headcut face as depicted in Figure 1. The plunging action of the jet increases E_v until the element slides as described by

$$\frac{dX}{dt} = \frac{H_h}{2E_v} k_d\left(\tau_{hf} - \tau_c\right) \qquad (2)$$

where

= headcut height, L,

= undercut distance, L,

= shear stress at headcut face, $ML^{-1}T^{-2}$.

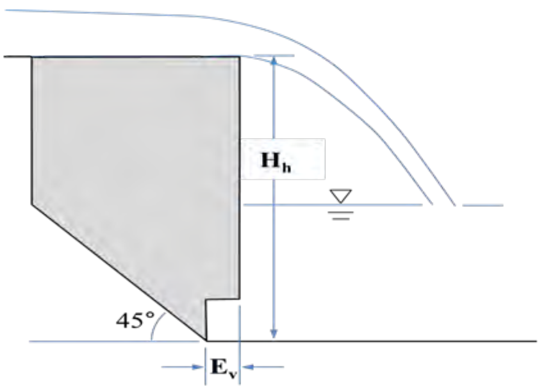

Figure 1 Schematic of headcut failure element, Hanson/Robinson headcut advance model.

A four-stage process of breach development for cohesive materials was documented by Hanson et al. (2005b). When overtopped, a dam may undergo: 1) headcut development at downstream edge of crest, 2) headcut advance into and through the crest to the upstream edge, 3) crest is lowered through further headcut advance upstream of crest, and 4) breach widening. Unique to each stage is a combination of governing stress, and down cutting, advance and widening behaviours as summarized in Table 3.

Table 3 Four stages of cohesive embankment failure as modelled in the DSIG evaluation of SIMBA is summarized by down cutting, advance and widening rates, governing stress, and condition for stage initiation. Advance rates for plunging stress at headcut face are for Hanson/Robinson model.

Stage	Downcutting rate dY/dt	Advance rate dX/dt	Widening rate dW/dt	Governing Stress	Stage Begins When
1. Headcut formation	$k_d(\tau - \tau_c)$	—	$1.4k_d(\tau - \tau_c)$	Normal depth flow on d/s slope	$\tau_e > \tau_c$
2. Headcut advance	$k_d(\tau - \tau_c)$	$\frac{Hk_d(\tau - \tau_c)}{2E_v}$	$k_d(\tau - \tau_c)$	Plunging at headcut face	Eroded depth > critical flow depth
3. Breach formation	Greater of $k_d(\tau - \tau_c)$ or (dX/dt)/Z * See above.	Greater of $\frac{Hk_d(\tau - \tau_c)}{2E_v}$ or $Zk_d(\tau - \tau_c)$ *	$1.4k_d(\tau - \tau_c)$ See above.	Plunging at headcut face Greater of critical depth or tailwater el. flow at crest	Headcut advances past u/s crest
4. Breach widening	—	—	$1.4k_d(\tau - \tau_c)$	Greater of critical depth or tailwater el. flow at crest	Headcut advances to u/s toe

* Z is cotangent of angle between upstream dam face and horizontal.

During stages 1 and 2, no lowering of the crest takes place. Stage 1 is characterized by down cutting and widening of the headcut driven by normal depth flow on the slope as computed by Manning's formula with = 0.02.

When the depth of headcut exceeds the critical flow depth, stage 2 is initiated with headcut advancing into the crest fuelled by the stress due to a plunging jet at the base of headcut; the advance rate is determined by the headcut advance model. Widening and down cutting continue, and submergence may reduce the rates. In addition when the computed value of E_v in Stage 2 and 3 corresponding to failure approaches zero this implies that the headcut height is unstable as a vertical face. Physical observations of headcut advance under these conditions are extremely limited, but the expected mode would be cascading flow down the unstable near-vertical face. Therefore, the headcut advance model as implemented assumes an upper limit on the headcut advance rate equal to the rate associated with normal depth erosion on a ½ to 1 slope. The ½ to 1 slope is based on the erosion feature created in the failure process described in Figure 1. It is recognized that this assumption represents only an approximation of the physics and actual geometry for high headcuts.

As the headcut passes the upstream crest, the hydraulic control begins to be lowered. The advance rate may be a function of plunging stress (as in stage 2) or may now be governed by vertical lowering of the crest due to critical depth flow. Whilst either of these could result in crest lowering faster than down cutting of the headcut, computationally the headcut height is not allowed to decrease until the bases of the headcut and the dam coincide.

In stage 4, the breach can only widen. For stages 3 and 4, submergence is addressed by computing depth at crest as the greater of that associated with tail water elevation or critical depth.

The algorithms developed and evaluated in SIMBA have now been incorporated into WinDAM B, which combines the erosion processes discussed above with other modules that evaluate the surface protection provided by vegetation or rock riprap. Hydraulic computations within WINDAM B further enhance the ability to consider flow concentrations over non-level dam crest profiles with weir coefficients user-defined or determined from cross section. Additionally flow may be routed through multiple spillways, which also may be evaluated for failure potential.

In addition to the stress based Hanson model included in the DSIG evaluation version of SIMBA, an energy-based Temple/Hanson headcut advance model (Temple et al. 2005) is available within WinDAM B for evaluation of headcut advance in stage 2 and 3:

$$\frac{dX}{dt} = C\left(qH_h\right)^{1/3} \qquad (3)$$

where
 = advance rate coefficient, $T^{-2/3}$, and
 = unit discharge, L^2T^{-1}.

SIMBA continues to evolve; it is now being used to consider the problem of internal erosion. Experiments conducted in the outdoor laboratory indicate headcut initiating at the outlet is part of the process of internal erosion in addition to erosion along the length of the internal conduit. These processes are both modelled with the conduit simplified as rectangular and horizontal. It is anticipated that concepts being tested now will be incorporated into WinDAM before the end of 2012.

3 DEVELOPMENT OF HR BREACH

The HR BREACH model was originally developed by Mohamed Hassan (Mohamed, 2002) as part of an HR Wallingford research programme. The model predicts the growth of breach through an embankment by considering the flow and erosion conditions at sections through the embankment. The model can simulate overtopping or piping failure. For overtopping failure, either surface erosion or headcut can be simulated, although the latter reproduces processes as defined by Temple et al (2005) for the SIMBA model. The surface erosion processes were used for model evaluation within the DSIG project.

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).

Earlier versions of the model used sediment transport equations to predict erosion at each section; more recent versions have adopted a form of the detachment-based erosion equation (1) listed above. This more accurately reflects the dynamic nature of breach erosion and allows soil erodibility rather than soil type to dictate how the breach evolves. Hence, by integrating soil erodibility into the breach process, both soil type and soil state are considered. 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 undertaken for breach prediction, or direct measurement in the field or laboratory undertaken (Hanson and Hunt, 2006).

In 2008 the HR BREACH model was integrated within the InfoWorksRS flow modelling package. By coding the breach model as a ‘breach unit’ which operates at a time step level, the flow model can interactively simulate breach formation and associated flows within a reservoir and / or river system, in 1D or 2D, with multiple simultaneous breach predictions at any given time. This level of integration ensures that any potential drowning effects on the breaching processes are taken into consideration; as shown within the CEATI study, drowning can significantly affect breach growth and hence the breach flood hydrograph.

A significant development of the HR BREACH 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 2). Each zone may reflect different material, or simply the same material but in a different state. The key parameter representing the material is the soil erodibility.

The effect of different rates of erosion, resulting from different layers of material within the embankment body, can be quite pronounced, changing the shape, magnitude and duration of the potential flood hydrograph. Figure 3 shows plots of the breach formation process through an embankment with two equal width layers of soil with different erodibility. The progression shown in the left column is where the upper layer is more erodible than the lower layer; the right column shows the formation process with the upper layer being less erodible than the lower layer. The less erodible upper layer delays erosion of the crest and hence produces a later release of flood water, as compared to the scenario with a more erodible upper layer.

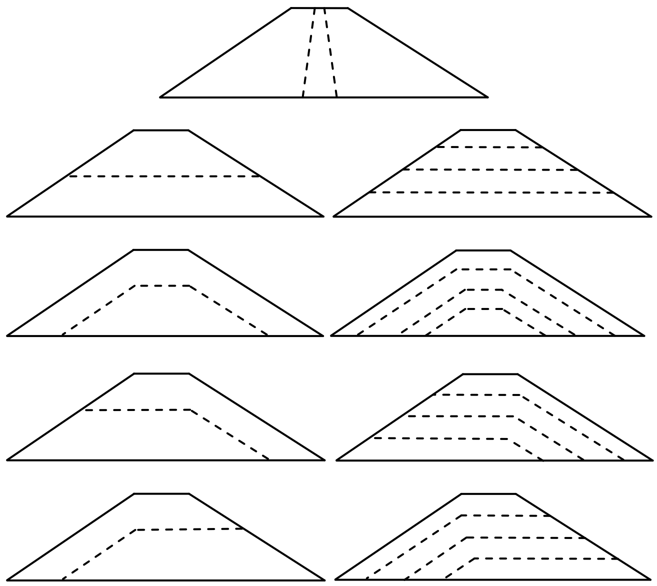

Figure 2 Zoned approach to breach modelling (Morris, In Prep).

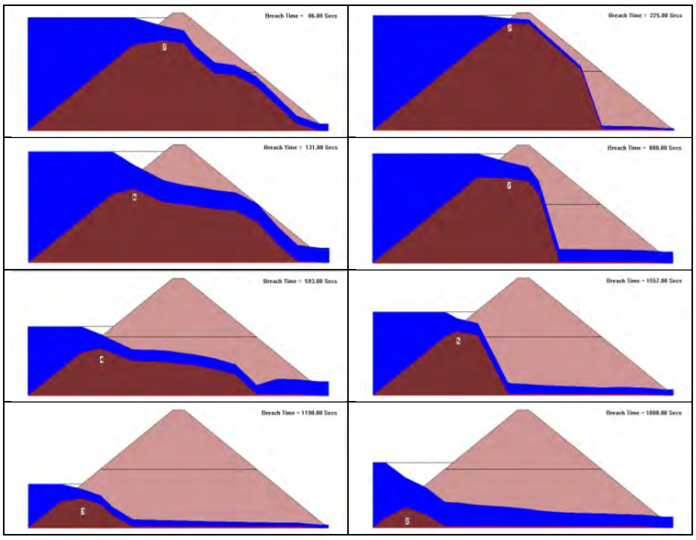

Figure 3 Impact on breach formation process of two soil layers with differing erodibility. Left column shows formation with a more erodible upper layer; right column shows formation with a less erodible upper layer (Morris, In Prep).

Research has also highlighted the importance of soil erodibility in relation to the reservoir surface area (or upstream stage-volume relationship). Where the erosion rate is slow and the reservoir surface area is relatively small, the reservoir can drain at the same rate as the breach invert erodes, resulting in a slow, low-peak breach flood hydrograph. Where the erosion rate is faster and the reservoir surface area is large, the breach invert level erodes at a rate faster than the reservoir draw down. This results in a rapid, higher-peaked breach flood hydrograph. Aspects of this behaviour can be seen in the example shown in Figure 3 where the head of water on the breach invert for the first two stages is greater for the case with a more erodible upper layer (left side images) than the case with a less erodible upper layer (right side images). This phenomenon is then reversed for the last two stages.

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 modelling approach that allows the effects of soil zoning will provide a more accurate prediction of failure conditions than the assumption that the soil is homogeneous. Such a model also allows the effects of designing higher or lower erodibility layers into a dam or flood embankment to be assessed. The deliberate inclusion of a higher erodibility layer would create a fuse plug design, whilst inclusion of a lower erodibility layer would provide greater standards of resistance without the need for construction of the whole dam or embankment from that material (for example, as with the design of typical Dutch or German coastal dikes).

Development of the HR BREACH model continues through various research programmes (such as the EU IMPACT, FLOODsite and FloodProBE projects), and including the HR Wallingford company research programme, in order to maintain a continuously evolving breach model from which different tools may be developed or assessed for industry use. For example, in parallel with development of the zoned approach described above, the model was also used to assist in the development of a rapid, simplified breach model via the UK FRMRC2 research programme. This research produced the AREBA model (van Damme et al., 2011) which simulates breach through simple homogeneous structures in a fraction of a second. Hence, the AREBA model (www.floodrisk.org.uk) provides a tool for use in system flood risk analysis or as an initial rapid assessment of breach, whilst the HR BREACH model (www.hrwallingford.com) provides a tool for more detailed analysis of breach on more complex structures.

4 CONCLUSIONS

The CEATI-DSIG evaluation of numeric breach models showed that the SIMBA/WinDAM and HR BREACH models are each capable of producing realistic embankment erosion and breach simulations. There is significant commonality between the erosion models in each package, and a few differences that are advantageous for some specific embankment types. The development of both models is continuing separately and over time they are expected to share more capabilities (e.g., zoned embankment analysis and piping failures). There is also the potential for creation of a model combining the best features of both programs, and integration of dam breach modelling modules into larger flood modelling packages.

5 ACKNOWLEDGMENTS

Whilst this paper has been produced by six authors, a wider team of researchers has been involved with this work. In particular, the authors would like to acknowledge the contributions of:

- Paul Samuels from HR Wallingford and Gurmel Ghataora from the University of Birmingham in the UK for assistance in developing the HR BREACH model and participation in the CEATI project
- Jean-Robert Courivaud (EDF, France), Michael Gee (HEC, USA), Johannes Wibowo (USACE, USA) and Rene Kahawita (Ecole Polytechnique Montréal, Canada) for their particular inputs to the CEATI project

Aspects of the work described in this publication and undertaken by HR Wallingford were 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.

REFERENCES

Courivaud, Jean-Robert, 2007. *Analysis of the dam breaching database.* CEATI International, Dam Safety Interest Group, CEATI Report No. T032700-0207B, 79 pp.

Fread, D.L., 1988 (revised 1991), *BREACH: An Erosion Model for Earthen Dam Failures*, National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

Hanson, G. J., Robinson, K. M., Cook, K. R. 2001. *Prediction of headcut migration using a deterministic approach*. Trans. ASAE Vol.44(3):525-531.

Hanson, G. J., D. M. Temple, M. Morris, M. Hassan, and K. Cook. 2005a. *Simplified breach analysis model for homogeneous embankments: Part II, Parameter inputs and variable scale model comparisons*. Proceedings of 2005 U.S. Society on Dams Annual Meeting and Conference, Salt Lake City, Utah. p. 163-174.

Hanson, G. J., Cook, K. R., Hunt, S. L., 2005b. *Physical modeling of overtopping erosion and breach formation of cohesive embankments*. Trans. ASAE Vol 48(5):1783-1794.

Hanson, G. J., Caldwell, L., Lobrecht, M., McCook, D., Hunt, S. L., Temple, D., 2007. *A look at the engineering challenges of the USDA Small Watershed Program*. ASABE. Trans. Vol. 50(5):1677-1682.

Hanson, G.J., and Hunt, S.L., 2007. *Lessons learned using laboratory jet method to measure soil erodibility of compacted soils.* Applied Engineering in Agriculture, 23(3):305-312.

Hanson, G. J., Temple, D. M., Hunt, S. L., Tejral, R. D., 2011. *Development and characterization of soil material parameters for embankment breach*. ASABE Applied Engineering in Agriculture Vol. 27(4):587-595.

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.
Hassan, M., and Morris, M.W. 2008. *IMPACT Project Field Tests Data Analysis*, Report No. T04-08-04.
Hewlett, H.W.M., Boorman, L.A. and Bramley, M.E. (1987) *Design of reinforced grass waterways, CIRIA Report 116*, CIRIA, London, UK.
Kahawita, René, 2007. *Dam breach modeling – a literature review of numerical models.* CEATI International, Dam Safety Interest Group, CEATI Report No. T032700-0207C, 68 pp.
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. Pending 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.
Temple, D. M., Hanson, G. J., Neilsen, M. L., Cook, K. R. 2005. *Simplified Breach Analysis model for Homogeneous Embankments: Part 1, Background and Model Components.* USSD Technologies to Enhance Dam Safety and the Environment, 25th Annual USSD Conference, Salt Lake City, Utah, June 6-10th 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., 1998, *Prediction of embankment dam breach parameters: a literature review and needs assessment.* Dam Safety Research Report DSO-98-004, U.S. Dept. of the Interior, Bureau of Reclamation, Denver, Colorado, July 1998.
Wahl, T. L.**,** 2007. *Laboratory investigations of embankment dam erosion and breach processes.* CEATI International, Dam Safety Interest Group, CEATI Report No. T032700-0207A, 60 pp.
Wang, P. and Kahawita, R., 2002. *Modelling the hydraulics and erosion process in breach formation due to overtopping*. Proceedings of the Symposium held in Monte Verita, Switzerland. Sedimentation and Sediment Transport. Edited by A. Gyr and W. Kinzelbach. September 2002.
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.