DEVELOPMENT OF NEXT-GENERATION EMBANKMENT DAM BREACH MODELS

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ABSTRACT

The Dam Safety Interest Group (DSIG) of CEA Technologies, Inc. (CEATI) is an international group of dam owners that pursues collaborative research on a wide range of topics. Since 2004 the DSIG has been working to facilitate the development and deployment of a physically-based embankment dam breach model. The group, with assistance from non-CEATI member organizations, has completed a first phase of work which identified promising numerical models presently under development and compiled real-world case study data and large-scale laboratory test data for future use in model validation. In the second phase of the project, the group will evaluate candidate modeling technologies using the assembled data sets and then integrate selected technologies into the HEC-RAS dynamic routing model suite. Parallel work is also underway to evaluate methods for quantifying the erodibility of embankment materials, a key input for a new and improved model. At this time, the models under consideration are primarily capable of analyzing embankments with simple geometries experiencing overtopping flow. In a future third phase, the group plans to pursue capabilities for more complex and varied embankment configurations and for breaches initiated by internal erosion and piping.

INTRODUCTION

Computational tools for routing floods caused by dam failure have been in widespread use since the 1980s, and advanced 2D modeling capabilities and integration with GIS are now common. Most of these tools still rely on simple parametric descriptions of the breach event that initiates the flood wave. A user specifies the ultimate width, depth and shape of the breach and the time required for breach development, and the model simulates the flow through the breach as it enlarges at the specified rate. For concrete dams the breach parameters are often selected based on structural analysis and

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hypotheses of likely structural failure modes. For embankment dams, which in most cases fail by progressive erosion, breach parameters are often obtained from simple regression equations based on dam and reservoir properties. Since actual erosion processes are not modeled, the uncertainty of these breach parameter predictions is large. Factors increasing the uncertainty for embankment dams include inherent variation in the erodibility of embankment materials as a function of soil type and compaction and moisture conditions, and the effects of variability of embankment design, configuration, and geometry. The large uncertainties associated with breach modeling make it difficult to accurately determine the consequences of dam failure and effectively plan for dam-break flooding emergencies.

Models that simulate actual erosion processes to predict breach development in embankment dams have also been available since the 1980s, but have not seen widespread use. Most of these models have been based on primitive simplifications of the erosion and breaching processes that have proven to be inconsistent with subsequent observations of breach mechanics in case studies and laboratory tests. Application of the models has been hindered by a lack of ability to quantify the erodibility of embankment materials, and a shortage of models that effectively incorporate objective measures of erodibility.

Several factors are now driving the need for improved modeling of embankment dam erosion and breach processes. Populations at risk in areas immediately downstream from large dams continue to increase, the significant influence of warning time on flooding lethality has been recognized, and risk assessment procedures are being increasingly used to prioritize dam safety investments. Accurate modeling of erosion and breach processes helps address each of these needs by improving our ability to predict whether progressive erosion will lead to dam failure, and if so to model the dam breach outflow hydrograph and its timing.

The Dam Safety Interest Group (DSIG) of CEA Technologies, Inc. (CEATI) is an international group of dam owners that pursues collaborative research on a wide range of topics. Since 2004, a DSIG working group on embankment dam erosion and breach modeling has been working to facilitate the development and deployment of a physically-based embankment dam breach model. Work is being performed by DSIG-member organizations, interested non member organizations, and contractors. In addition to the in-kind contributions of the working group members, other DSIG-member organizations are sponsoring the work through cash contributions.

PROJECT STATUS: PHASE I – INFORMATION GATHERING

The working group was established and the project initiated in 2004 with a plan to subdivide the work into three phases: information gathering, model development and testing, and model refinement. In Phase I three tasks were undertaken that will provide a foundation for future model development:

1. Develop a database of case studies suitable for use in testing new breach models,

2. Review past and present laboratory testing programs to identify laboratory data sets that could be used for testing of new breach models, and

3. Review computational models for simulating dam breach to identify those models presently under development which could serve as the foundation for a next-generation breach modeling tool, integrated into state-of-the-art dam-break flood modeling software.

CEATI-DSIG reports documenting the results obtained from each effort have been produced and should be publicly available by the time of final submission of this manuscript. Overviews of the tasks and the results obtained from them are given below.

Case Study Database of Embankment Dam Breaches

Validation and verification of embankment dam breach models has always been a difficult task. Laboratory data sets are often influenced by scale effects and simplifications that make them inadequate to test the range of possible real-world situations that a model must simulate. On the other hand, real-world case studies are often poorly documented due to a lack of eyewitnesses, variation in how eyewitnesses interpret and relate their observations, haphazard data collection hampered at least initially by a priority focus on rescue and recovery after a failure and a lack of forthright disclosure by parties that may anticipate legal fallout from a failure.

To facilitate future verification and validation of dam breach models, Electricité de France undertook the task of developing a database of high quality real-world dam failure data (Courivaud 2007). The database covers a relative small number of failures, but with an emphasis on obtaining high-quality data, identifying errors in existing databases, and resolving inconsistencies between conflicting accounts of individual failures.

Specific principles guiding development of the database include:

- Case studies must be sufficiently well documented to be used for numerical model testing, e.g. these case studies provide reliable input data and have reliable observations of breach outflow hydrograph that allow comparison with output data from numerical models.
- Verification of data is facilitated for the future by providing the source reference for each item of data—text or numeric.
- The reliability of every item of data contained in the database is rated.
- The database is designed to provide data via a World Wide Web interface.

At this time the database includes 13 case studies of embankment failure by overtopping erosion, with plans to include internal erosion failures in the future. A range of materials is represented, from well compacted embankments with a cohesive core (Oros Dam) to non-compacted hand-made embankments (Machhu 2 Dam). The range of dam heights is 8 to 60 m, and peak breach outflows range from 117 to 78,000 m^3/s.

Dam geometry, reservoir characteristics (area and capacity curves), final breach geometry and breach peak outflow are completely documented with reliable data in most of the 13 cases.

Although gaps and unknowns remain, mainly in dam material characteristics, 7 of the 13 failures are documented well enough to be used as validation test cases for dam breach numerical models. Twelve of the failures are documented sufficiently to be used for testing newly developed empirical breach peak outflow relations.

The greatest need for more and better data for the cases included in the database is in the area of material characteristics and compaction conditions and techniques used during dam construction. Material descriptions and classification information, moisture conditions during compaction and at failure, and descriptions of compaction methods or estimates of compaction energy are needed to allow one to estimate material erodibility.

The assembly of this database has helped to highlight those areas that should receive primary attention when investigating and documenting future dam failures. The data that should be given highest priority include:

- geometry of dam before failure, and geometry of breach immediately after failure,
- data on embankment material characteristics, including conditions during compaction and the techniques used to compact materials; erodibility measurements made during construction, if available,
- erodibility measurements made after failure, using *in situ* techniques or in a laboratory using samples recovered from the body of the dam,
- inflow and outflow data (hydrographs and water level records) and rating tables or curves for spillways and outlets, and
- timeline identifying key points in the breaching process.

Laboratory Embankment Dam Breach Tests

Laboratory testing has long been a key element of efforts to improve our understanding of embankment dam breach processes. The review of literature in this area (Wahl 2007) revealed more than 325 embankment breach tests dating from the end of the 19th century to the present day. Most testing has been focused on simple homogeneous embankments, although there have also been notable efforts to study more complex embankment designs, such as zoned rockfill with interior structural elements. Most studies have focused on overtopping erosion as the initiating mechanism, but internal erosion and piping have been considered in several recent studies. Table 1 provides a summary of the notable embankment dam breach testing programs.

Until recent years, most embankment breach testing has taken place at relatively small scales, with embankment heights of about 0.15 to 1 meters. At this scale, the work has been focused on embankments composed of mostly noncohesive materials, e.g., rockfill dams, sand dikes, and fuse plug embankments. With care, the erosion of these materials can be effectively simulated in small-scale models. The impervious layers in some of these structures (e.g., fuse plugs) can and have been modeled at times. This is possible at small scale because the impervious layers are thin and processes influencing the failure of the impervious elements have been well understood and somewhat isolated from the processes influencing erosion of the non-cohesive material.

Table 1. Laboratory embankment breach test programs (from Wahl 2007).

Performing Organization	Test Description or Purpose	Dates	No. of Tests
			Approx. 325
Washington State Univ.	Fuse plug breach - models	1959	10
Washington State Univ.	Fuse plug breach – field-scale	1959	1
Washington State Univ.	Fuse plug breach - sectional (breach initiation phase)	1959	2
Univ. of Windsor, Canada	Fuse plug breach - models	1978	Unknown
China - fuse plugs	Fuse plug breach – field-scale	1970s to 1982	>50
Bureau of Reclamation	Fuse plug breach - model	1985	8
Technical University of Graz	Overtopping breach failure of various configurations of rockfill dams	1982	22
China – rockfill dams	Rockfill dam breach – lab scale	Unknown	Approx. 6-8
Simons, Li & Assoc. for USDOT-FHWA	Highway embankment overtopping - sectional models to develop embankment test methods and tools for predicting erosion damage	1982-1986	35
Simons, Li & Assoc. for USDOT-FHWA	Evaluate embankment damage and protection measures	1985-1988	57
Simons, Li & Assoc. for USDOT-FHWA	Evaluation of articulated concrete block embankment protection systems	1988-1989	17
USBR	Embankment dam overtopping; sectional models to evaluate erosion and protective measures	mid 1980s	9
University of Colorado	Centrifuge testing - feasibility	1983	2
University of Colorado	Prototype test	1983	1
Colorado State University	Overtopping breach failure	1991	2
USDA-ARS-HERU Stillwater, OK	Erosion in cohesive bare-earth and vegetated steep channels	Late 1990s	4
USDA-ARS-HERU Stillwater, OK	Overtopping Breach – cohesive	1999-2001	7
USDA-ARS-HERU Stillwater, OK	Breach widening – cohesive	2003	3
IMPACT-HR Wallingford	Series 1 - Lab-scale overtopping breach of homogeneous noncohesive embankments.		9
IMPACT-HR Wallingford	Series 2 - Lab-scale overtopping breach of homogeneous cohesive embankments.		8
IMPACT-HR Wallingford	Series 3 - Piping initiation and development		5
Norway - IMPACT	Large-scale tests of overtopping of cohesive, noncohesive, and zoned embankments; and piping through cohesive and zoned embankments	2002-2003	5
Norway - Other field tests	Through-flow and breaching of rockfill dams	2002	2
Norway - Lab tests	Through-flow and overtopping of rockfill dams	2002-2003	23
Delft Univ. of Technology – The Netherlands	Breaching of sand dikes	1994, 1996	5
University of Birmingham – Great Britain	Qualititative evaluation of overtopping breach of sand embankments	1998	2
Brno Univ. of Technology – Switzerland	Overtopping breach - Noncohesive	before 2000	1
Univ. of Auckland – New Zealand	Overtopping breach - Noncohesive	Late 1990s	9
Technical University of Lisbon - Portugal	Overtopping breach - rockfill	2001	22
St. Petersburg State Technical Univ. - Russia	Overtopping breach - Noncohesive	2003?	4
Thailand	Overtopping breach - Noncohesive		4
South Africa	Overtopping breach - Noncohesive	before 2005	24
École Polytechnique de Montréal	Overtopping breach - moraine	before 2005	1

Several recent test programs have utilized larger scales, with embankment heights up to several meters. This work has begun to examine breaching of embankments in which the impervious and cohesive materials form the entire dam, or at least a significant portion of it. Headcut erosion and geotechnical stability of slopes and soil masses becomes important, and these processes have been shown to be sensitive to material properties that are difficult to control and scale. Associated work aimed at quantifying erodibility of embankment materials has shown that erodibility can be very sensitive to factors such as moisture content and compaction effort.

The largest test programs in terms of both number and scale of tests have been carried out as part of the European IMPACT project and in the U.S. by the Agricultural Research Service (ARS) (Hanson et al. 2005, Hunt et al. 2005). Each test program has led to development of new numerical models, and the large scale tests should be valuable for all future efforts to develop better dam breach models.

Review of the data produced by the large laboratory testing efforts has helped develop a wish list of priorities for similar work in the future. These include:

- more effort devoted to documenting test embankment construction methods and compaction, and measuring *in situ* material erodibility,
- greater detail in records of the temporal development of breach size and breach channel profiles, to facilitate validation and testing of numerical models,
- more studies of piping-initiated failures,
- laboratory breach tests of zoned embankments, and
- greater attention to slope stability and slope failure processes in the context of dam breach development.

Review of Numerical Models for Embankment Dam Breaching

The third component of the first phase of the project was a review of the state-of-the-art in numerical modeling of dam breach processes. This task was undertaken by Hydro Québec through an association with Montréal Polytechnic. Kahawita (2007) reviewed past and present models for simulating breach formation and grouped them into four general types:

- models that directly predict breach outflow using regression equations (empirical models)
- models that predict breach geometry and the outflow hydrograph using greatly simplified physically-based equations (analytical models)
- models that predict breach outflow analytically using estimates of breach size, shape, and development rate that are obtained from regression equations (parametric models)

- models that simulate basic erosion processes and breach mechanics with a minimum of simplifying assumptions (physically-based models).

The most widely used methods today are still parametric, making use of breach parameter estimates derived from regression equations that do not directly simulate erosion processes. However, the focus of most research and development efforts is on the physically based models.

Kahawita (2007) further subdivided the physically-based models into two groups. The first group of models subdivides the breaching process into phases in which different flow and erosion mechanics are predominant. The individual phases are then modeled semi-empirically using equations whose coefficients, exponents, etc. (i.e., parameters) have been determined empirically from laboratory or real-world data. The second group of models attempts to simulate hydraulic conditions and erosion processes with fundamental differential equations that are intended to accurately describe interactions between hydraulic and erosion processes; in other words they result from a physically based mathematical formulation.

Three physically-based models were deemed to have potential for further development into a next-generation embankment breach modeling tool. The models are:

- SIMBA – Under development at the USDA-ARS Hydraulic Engineering Research Unit, Stillwater, Oklahoma. (Temple et al. 2005, Hanson et al. 2005)

- HR-BREACH – Under development at HR Wallingford, Great Britain. (Mohammed 2002, Mohamed et al. 2002)

- FIREBIRD BREACH – Under development at Montréal Polytechnic. (Wang and Kahawita 2002, Wang et al. 2006)

The SIMBA (SIMplified Breach Analysis) model and the HR-BREACH model are both in the first subcategory of physically-based models, while FIREBIRD BREACH is in the second subcategory. All three models can make use of measured soil erodibility parameters, which sets them apart from most previous embankment dam breach models. SIMBA was originally developed to analyze laboratory dam breach experiments, and thus has simplifications and capabilities that are specific to that purpose. ARS is working to incorporate the SIMBA technology into a larger suite of dam analysis tools targeted at application to the large inventory of dams constructed by the USDA for flood control and watershed protection (Temple et al. 2006). HR-BREACH has been developed for direct application to dam safety, emergency management and flood risk management needs. It was also used as a tool for analyzing dam breach experiments, especially those conducted under the IMPACT project. FIREBIRD BREACH has thus far been developed mostly as a research tool for studying the ability of different sediment transport models to simulate dam breach processes.

A summary of basic characteristics of the current models is presented in the table below:

Model	Embankment types	Erosion modes	Erosion processes
SIMBA	Homogeneous cohesive	Overtopping	Headcut formation, deepening, and upstream advancement; lateral widening
HR-BREACH	Homogeneous cohesive, or simple composite embankments with noncohesive zones, surface protection (grass or rock) and cohesive core	Overtopping, piping	Variety of sediment transport / erosion equations and multiple methods for application. Discrete breach growth using bending, shear, sliding and overturning failure of soil masses
FIREBIRD BREACH	Homogeneous, cohesive or noncohesive	Overtopping	Coupled equations for hydraulics and sediment transport

An important consideration is the fact that overtopping erosion is the primary mechanism simulated by each of these models. Basic research on internal erosion is underway at this time, but the most useful tools produced so far have been aimed at predicting the rate of development of internal erosion, with a focus on providing estimates of warning time. Few simulation models have yet been developed that attempt to model the complete breach process initiating from an internal erosion failure. This is expected to be a long-term future focus of the CEATI-DSIG project.

Another consideration is the fact that the three models were all initially developed for application to homogeneous embankments and are just now beginning to allow some analysis of composite geometries (zoned embankments). Further development of these capabilities is also expected to be a long-term goal of the project.

PHASE II – MODEL EVALUATION AND INTEGRATION

The objectives of the second phase of the CEATI-DSIG project are to evaluate the three numerical models identified in the first phase of the project, by testing their performance against real-world case studies and large-scale laboratory tests. Based on this evaluation, we plan to identify those technologies that are best-suited to integration with existing state-of-the-art flood routing models, and then work to integrate physically-based embankment dam erosion and breach modeling capability into the HEC-RAS modeling suite. We also plan to facilitate the integration of these technologies into commercially available flood routing software, especially those tools that are already used by CEATI-DSIG members.

A parallel activity during phase II of the project is an effort to evaluate methods for quantifying erodibility of cohesive embankment materials. All three of the models we will be evaluating make use of erodibility parameters, specifically a critical shear stress needed to initiate erosion, and a rate parameter that expresses the rate of erosion per unit of applied excess stress. Parameter values can be crudely estimated from basic physical properties of embankment materials, but erodibility is a complex problem and experience from laboratory and field studies suggests that direct measurement of erodibility parameters is extremely valuable.

Numerical Model Evaluation

The numerical model evaluation task is making use of seven data sets selected from the laboratory and case study data investigated in phase I of the project:

- 2 case studies of real-world failures
    - Oros Dam (Brazil)
    - Banqiao Dam (China)
- 2 dam overtopping breach tests at Agricultural Research Service laboratory, Stillwater, Oklahoma
    - Homogeneous embankment constructed from silty sand
    - Homogeneous clay-loam dam (eroded but not completely breached)
- 3 dam overtopping breach tests conducted in Norway for the IMPACT project
    - Moraine-core rockfill dam
    - Homogeneous gravel dam
    - Homogeneous clay dam

Evaluation runs of the models will be made in concert by representatives of CEATI-DSIG member organizations and the developers of the models. Specific evaluation criteria are still under development, but evaluations will focus on the ability of each model to predict the development of the breach geometry over time and the resulting outflow hydrograph. To the extent that the observed data allows, we hope to evaluate the ability of each model to reproduce the time duration of two important phases of the breach process: initial overtopping until erosion through the crest (breach initiation), and from first erosion through the crest until the development of the maximum breach dimensions. Of course, the different laboratory tests and case studies offer varied combinations of observed parameters, so the evaluation criteria will be tailored to some degree to each data set.

Methods for Quantifying Erodibility

Laboratory testing has shown that the erosion of cohesive materials typical of those found in embankment dams is an extremely complex phenomenon. Factors such as material dry density, compaction water content, in situ water content, water and soil chemistry, and of course soil type all affect erodibility, often dramatically. Hanson and Hunt (2006) showed that relatively small changes in compaction energy and compaction water content can change the rate of soil detachment by one to two orders of magnitude. This makes it imperative to actually measure erodibility in some objective way, whenever possible. This need applies to research and laboratory testing, evaluation of case studies, and future application of any model.

Most existing dam breach models in use today do not incorporate parameters that directly indicated material erodibility. Many models do accept input of material size parameters or other material properties that are then related to erodibility through erosion or sediment transport equations, but the large number of factors that determine erodibility makes the use of these equations a form of crude estimation, at best.

The dam breach models under consideration for this project utilize erodibility parameters that can be measured with field and laboratory test devices. The two tests that have received the most interest so far for the study of overtopping erosion and internal erosion are the submerged jet erosion test (JET) (Hanson and Cook 2004) and the hole erosion test (HET) (Wan and Fell 2004), respectively. These two tests are relatively straightforward to perform and yield estimates of the critical shear stress and erosion rate coefficient for a tested material. The JET can be performed in the laboratory, or in the field as an in situ test, when the surface of interest can be exposed for testing. The HET is performed only in the laboratory, but can make use of tube samples to determine erodibility of relatively undisturbed materials.

The HET simulates flow through a developing defect in a soil mass. A 6 mm diameter hole is pre-drilled through the centerline axis of a soil specimen in a standard Proctor mold or Shelby tube. The specimen is installed into a test apparatus in which water flows through the hole under a constant hydraulic gradient that can be increased incrementally until progressive erosion is produced. Once erosion is observed, the test is continued at a constant hydraulic gradient for as long as 45 minutes. Measurements of the increasing flow rate during the test and the initial and final diameter of the erosion hole are used to estimate the erosion rate and the applied hydraulic stress. The critical shear stress and an erosion rate coefficient are determined for a detachment-driven erosion equation describing the growth of the erosion hole:

$$\dot{m} = C_e\left(\tau - \tau_c\right)$$

where $\dot{m}$ is the rate of mass removal per unit of surface area (kg/s/m^2), τ and τ_c are the applied shear stress and critical shear stress for soil detachment, respectively, and C_e is the coefficient of soil erosion. The coefficient of soil erosion varies over several orders of magnitude in soils of interest in embankment dams.

The JET simulates erosion produced by an impinging jet, such as might occur at the base of a headcut. The soil surface is eroded by a submerged jet, which is produced by a 6.35 mm (¼ inch) diameter nozzle initially positioned between 6 and 30 nozzle diameters from the soil surface. The starting nozzle position and test head may be adjusted to vary the stress applied to the soil sample. Scour of the soil surface beneath the jet is measured over time using a point gage aligned with the axis of the jet. The jet is typically oriented vertically, but can also be positioned at an angle when performing an *in situ* test of an inclined soil surface. The JET also determines the critical shear stress and a detachment rate coefficient, which has typically been expressed on a volumetric basis, rather than on a mass basis as with the HET.

In theory, these two tests measure essentially the same thing, but they apply stress to the soil in fundamentally different ways. Thus, there is a pressing need to understand how the tests perform relative to one another, both to facilitate current research and development and also to facilitate future application of new dam breach models. If the tests correlate well with one another, users would have the freedom to choose either test for future applications; if they do not correlate well, we need to understand the differences between them. For these purposes, a study has been initiated in which the HET and JET methods will be further investigated, with three primary objectives:

1. Improve our understanding of basic assumptions made during the analysis of HET data

2. Investigate potential improvements and simplifications to the procedures for interpreting HET data, and

3. Compare the erodibility parameters obtained with the HET and JET methods on samples prepared in parallel under similar conditions.

Integrating Breach Modeling Capability with Dynamic Routing

Specifics of how breach modeling capability will be integrated with dynamic flood routing models have not yet been determined, but several objectives have been established:

- Integration with HEC-RAS modeling suite, which is freely available and would thus make the technology accessible by the largest number of potential users
- Facilitate integration with commercially available modeling tools
- Capability to perform breach modeling analysis independently or semi-independently from a complete dynamic flood routing study, to allow computationally efficient sensitivity testing and uncertainty analysis of dam breach modeling

In the near future, these objectives may be best satisfied by a loose integration, in which an independent dam breach model is designed to produce output that can be easily incorporated into a flood routing analysis. The disadvantage to this approach will be the lack of a feedback link to allow the flood routing analysis to affect the dam breach process (via tailwater influences). A tighter integration of dam breach modeling capabilities with flood routing tools will make it easier to incorporate this feedback, but may also require greater development effort and may make the use of the dam breach analysis tool more complex.

SUMMARY AND FUTURE PLANS

The CEATI-DSIG working group on dam erosion and breach modeling has completed a first phase of work which identified numerical models presently under development to simulate embankment dam erosion and breach, and compiled real-world case study data and large-scale laboratory test data for future use in model validation. In the second phase of the project, now underway, the group will evaluate candidate modeling technologies using the assembled data sets and then integrate selected technologies into the HEC-RAS dynamic routing model suite. Parallel work is presently underway to evaluate methods for quantifying the erodibility of embankment materials, a key input for a new and improved model. At this time, the models under consideration are primarily capable of analyzing embankments with simple geometries experiencing overtopping flow. In a future third phase, the group plans to pursue capabilities for more complex and varied embankment configurations and for breaches initiated by internal erosion and piping.

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