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EVALUATION OF NEW MODELS FOR SIMULATING EMBANKMENT DAM BREACH

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Abstract

A consortium of dam owners collaborating through the Dam Safety Interest Group (DSIG) of CEATI, Inc. is evaluating the performance of three embankment dam breach models currently under development. The group is utilizing case-study data from real dam failures and laboratory data from recent large-scale breach tests conducted in USA and Europe. Models are being evaluated for their ability to reproduce observed breach outflow hydrographs and breach geometry, their input data requirements and sensitivity to input data and model parameters, their flexibility for application to a variety of embankment types and failure scenarios, and their overall ease of use and computational requirements. An effort is also underway to evaluate methods for quantifying the erodibility of embankment materials, as erodibility parameters are key inputs to all of the models. The model evaluation process is intended to lead to the selection of modeling technologies that can be integrated with state-of-the-art dam failure flood routing and inundation analysis tools.

Introduction

Computational tools for analyzing floods caused by dam failure have been in widespread use since the 1980s. Advanced 2D modeling capabilities and integration with GIS are now common, allowing for more detailed simulation of inundation effects, property damage, and threats to life. Tools are also under development for making more sophisticated analyses of the movements of people during evacuation efforts to determine ways in which detailed evacuation planning might reduce flooding lethality. An important aspect of the process that has advanced slowly in the past three decades is the simulation of the dam breaching process itself, especially with respect to embankment dams for which the typical failure modes involve progressive erosion. Failures due to either overtopping erosion or internal erosion require significant elapsed time for the breach to open and may lead to the loss of only a portion of the embankment. This is significant because the ultimate breach dimensions and the rate of breach development affect the breach outflow hydrograph, which drives the subsequent analysis of the flooding impacts.

Two relatively simplistic approaches to breach modeling are typical. The first is direct estimation of the breach outflow hydrograph by simple equations (usually derived from regression analysis) that relate the peak outflow discharge and time for breach development to basic reservoir and embankment parameters. Once the peak outflow is estimated, it can be used to complete the analysis of flooding impacts. The second approach is the use of similar regression equations to predict parameters of the breach opening, viz.: size, shape, and rate of development. These breach parameters are then used in a computational model that determines the breach outflow through the parameterized opening using a weir equation and may also simulate the downstream flooding effects.

Both of these approaches have large uncertainty associated with them (Wahl 2004). To improve estimates of breach outflow discharges and flooding consequences, there have been efforts to develop physically-based computational dam breach models that simulate erosion processes and the associated hydraulics in a detailed manner. The first widely recognized model of this type was the National Weather Service (NWS) BREACH model (Fread 1988). This model is able to simulate breaches initiated by overtopping or piping and uses the Meyer-Peter and Müller sediment transport equation as modified by Smart (1984) for steep channels. Flow down the face of the dam is modeled as a quasi-steady uniform flow. Other breach models of this era (see Wahl 1998 for a more detailed discussion) also use sediment transport equations originally developed for riverine environments, and this has come to be seen as a significant shortcoming of all of these models. The NWS-BREACH models and others of its generation have never been widely used, as the extra effort required to apply them has not generally yielded much increased confidence over the simpler regression-based methods.

Recognizing the fact that dam breach erosion processes are fundamentally different from riverine sediment transport processes, the current emphasis of researchers in this area has been to develop a good understanding of the erosion and breach formation mechanics and then build new models upon that foundation. Headcutting has now been recognized as the dominant physical process in the breach of most earthfill embankments, and headcutting is regulated primarily by the process of sediment detachment rather than sediment transport. Several new breach models founded upon these principles are now under development. This paper describes an effort to evaluate three such models to determine their ability to reproduce breach events observed in large-scale physical model tests and real-world case studies.

CEATI Dam Breach Erosion Project

The Dam Safety Interest Group (DSIG) of CEATI International, Inc. (CEATI) is an international group of dam owners that pursues collaborative research on a wide range of dam safety-related 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. Key working group members represent the following organizations:

- Electricité de France
- U.S. Army Corps of Engineers
- Hydro Quebec and contractor Montreal Polytechnic University
- U.S. Bureau of Reclamation
- USDA-Agricultural Research Service (ARS)
- HR Wallingford
- Ontario Power Generation
- Elforsk AB

Phase I

The working group was established and the project initiated in 2004 with a plan to subdivide the work into three phases: information gathering, model evaluation and implementation, and model refinement. The information-gathering phase comprised three tasks:

1. Develop a database of well-documented real-world case studies suitable for use in evaluating and 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 models presently under development that were poised to be next-generation breach modeling tools and could be integrated into state-of-the-art dam-break flood modeling software.

These three tasks were completed in 2007 and a Phase II project was then initiated.

Phase II

The objectives of Phase II are threefold:

1. The evaluation of three candidate numerical models identified in Phase I. These models each have desirable characteristics for future use that include erosion and headcut models that use quantifiable erodibility parameters, straightforward internal numerical solution techniques, potential to model both overtopping and piping failure modes and homogeneous or zoned embankments, and a good balance between realistic erosion mechanics and workable input-data requirements.
2. Investigation of alternative means for measuring the erodibility parameters of embankment materials which will be needed for future implementation of new breach models.
3. Integration of next-generation dam breach modeling technologies into existing flood-routing tools being used to analyze dam-break consequences.

The work on item 2 was performed in 2007 and 2008, while the first task, model evaluation, is being carried out at this time, during the summer of 2009. The third task will follow completion of the model evaluation work. The remainder of this paper will focus on a discussion of the model evaluation process and some of the challenges that are being encountered there. Detailed information about the results of the investigation of erodibility measurement methods are given in a companion paper (Wahl et al. 2009) and in Wahl et al. (2008).

Numerical Model Evaluation

The three numerical models that are being evaluated are:

- SIMBA – SIMplified Breach Analysis – 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)

All three of these 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 that will be applied 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 European 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 given in Table 1.

Table 1. — Characteristics of dam breach models.

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

Overtopping erosion is the primary condition simulated by each of these models, although HR-BREACH does include a piping erosion capability. Research on internal erosion is continuing at this time we expect piping erosion capabilities to be further developed in the future. Also, all three of these models were 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 a long-term goal of the CEATI project.

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

Primary performance measures for the evaluation work are the degree to which the models reproduce the observed characteristics of the breach and the resulting breach outflow hydrographs. To the extent that the observed data allows, we hope to evaluate the ability of each model to predict 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 (breach formation). Although these particular case studies and laboratory tests were selected from a population of hundreds of alternatives, and they provide some of the best available data for our purposes, there are still issues that must be addressed in using the data and evaluating the model results.

The two real-world case studies have issues that are common with most real-world case study data.

- Information about the construction of the dam and its state at the time of failure are sometimes unreliable.
    - Oros Dam failed during original construction, and emergency efforts were made to quickly build the embankment higher to prevent failure. The exact configuration of the embankment at failure and the quality of the final construction (and hence the material erodibility) are somewhat uncertain.
    - Banqiao Dam was constructed by manual labor and compacted by foot traffic. The erodibility is somewhat uncertain, but likely high.
- Observations of the failure sequence and eyewitness reports are sometimes unreliable and conflicting with regard to how quickly failure occurred. Different eyewitnesses have different perspectives and interpretations of what they observe.
- Measurements or post-failure determination of breach outflow discharges are often uncertain. Reservoir water surface data sometimes are inconsistent with reported outflow discharges.
- Post-failure reports of the size of the breach opening can be unreliable, especially when access to the site is poor in the aftermath of the flooding and measurements are not made until some time after the failure when the breach opening may have enlarged or changed as a result of continued flow through the breach or weathering effects (sloughing of side slopes).

Similarly, the laboratory test data can be affected by undesirable situations that make the cases difficult to model or make it difficult to discriminate between good and poor performance of a numerical model. Model scale can be a significant issue with respect to how materials behave at the reduced scale and with respect to changes in reservoir dynamics. In both the ARS and Norwegian tests, the sizes of the upstream reservoirs were insufficient to accurately represent a prototype reservoir. In the ARS tests this was overcome by providing a large inflow to the model basin and bypassing most of the flow over a long-crested side weir until the breach grew to a size that would allow it to convey all of the flow. In the Norwegian tests, a very large reservoir with a regulated outlet was available a short distance upstream from the site, so the test was performed without a side weir, but the inflows to the model were adjusted in attempts to maintain a constant head on the embankment as the breach occurred. This proved to be a difficult task, as the travel time from the upstream reservoir to the test site made it difficult to match the reservoir releases to the needed inflows. At times, more water was provided to the test site than necessary. This accelerated the breach processes in unrealistic ways at times, and sometimes produced artificially large outflow rates even before the embankments were breached. One Norwegian test also suffered from an apparent freezing of the embankment that extended the breach initiation phase of the process. For these reasons, some case studies do not offer an opportunity to evaluate all aspects of model performance. These are challenges that will have to be dealt with in the evaluation process.

In addition to quantitative comparisons of model predictions and observed performance from the lab tests and case studies, we will be evaluating subjective characteristics of the models. These include ease of use, sensitivity to specific input parameters, consistency of results for different situations, and input data requirements.

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