Breach Parameter Prediction Methods and the Need for and Potential Benefits of Improved Breach Models

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The evolution of hydraulic research related to dam safety that has led the Bureau of Reclamation to its current interest in breach modeling begins with research during the late 70's and early 80's into high capacity spillway alternatives (e.g., labyrinth weirs, fuse plug spillways, high capacity ogee crests) aimed at preventing overtopping and subsequent failure of embankment dams. During the mid-80's we began to consider allowing overtopping while protecting against failure using wedge block systems and other alternatives. This research has also addressed questions of the threshold and likelihood of failure through investigations of the stability of riprap subjected to overtopping flows. Today, Reclamation's focus on risk assessment as a decision-making tool makes questions of failure thresholds, probability, and consequences of failure paramount; our ongoing Dam Foundation Erosion research program addresses the potential for failure of concrete or embankment dams due to erosion of abutments and foundation areas. Our interest in dam breach modeling is a natural extension of this work and the need to consider both the risk and consequences of embankment dam failure. A move toward the use of early warning systems and other non-structural fixes for dam safety deficiencies also makes dam breach modeling of prime importance.

A quick review of the dam break analysis process begins with the final objective of most studies, the prediction of loss-of-life and property damages due to a potential dam failure. In risk assessment studies, estimates of the probability and threshold of failure are also needed. In the most simplistic approach, we must predict the outflow hydrograph, route the flood through the downstream valley to determine inundation levels, flow conditions, and flood arrival times, and then use that information to estimate the consequences. In situations where the population-at-risk is well downstream of the dam, a relatively gross estimate of the outflow hydrograph is sufficient, since routing effects predominate and attenuate even significant differences in the initial outflow hydrograph. DAMBRK and its successor FLDWAV are the most widely used state-of-the-art tools for performing the routing analysis.

Reclamation's interest in breach modeling arises both from an interest in thresholds and probabilities of failure, as well as from situations in which the population-at-risk is located very near the dam, in the near field in which routing effects have not greatly attenuated the flood wave. In this scenario the accurate determination of the outflow hydrograph and its timing are critical to the consequence analysis. Several alternative approaches are available for determining the outflow hydrograph, none of which are yet as fully developed technically as the routing tools mentioned above.

The simplest approach is to predict the outflow hydrograph and its timing using statistical or comparative approaches based on case study data from past dam failures. This approach has relatively low precision due to wide variability in the construction (design features, materials, etc.) of the case study dams documented in the literature, and questionable quality of some of the case study data, specifically breach formation times. A more rigorous approach is to simulate the breach development and then use principles of hydraulics to determine the outflow. This option can be similarly subdivided into statistical approaches and more rigorous physically-based methods.

Statistically-based methods for estimating breach parameters are numerous, but suffer from similar deficiencies as the statistical methods for directly determining breach outflow. If statistical methods are used, ultimate breach parameters are obtained, and the breach is then simulated in the dam-break flood routing model using some type of progressive enlargement of the breach opening, such as a linear increase of breach dimensions during the breach formation time.

There are several physically-based breach models described in the literature. The NWS-BREACH model, developed in the early 1980's, is probably the best known and most widely used, although statistical methods for predicting breach parameters are probably used more commonly than any of the physically-based breach models. The majority of the physically-based models have been used only by their developers. The primary weakness of the available breach models from the standpoint of breach mechanics is their use of tractive stress-based erosion models. Observations of actual dam failures and laboratory tests show that most embankment breaches are dominated by headcutting erosion (at least in the critical initial phase), which has been best modeled in recent years as an energy-dissipation driven process (e.g., ARS's spillway headcut erosion research). This does not inherently mean that the available breach models produce unreasonable results. However, we now know more about the mechanics of embankment failure and the modeling of headcut erosion than we did at the time that NWS-BREACH and other similar models were developed. This presents an opportunity to improve the physical basis of these models and to potentially improve their usefulness.

The primary advantage of a physically-based approach to breach modeling is the opportunity to get much better information about breach timing than can be obtained from the statistical methods. To review, statistical methods are available to predict breach width, breach side slope angles, and breach formation time. Breach depth is usually conservatively assumed to be the full height of the dam. A closer look at the definition of breach formation time is warranted.

The documentation for DAMBRK and FLDWAV defines breach formation time as:

> *...the duration of time between the first breaching of the upstream face of the dam until the breach is fully formed. For overtopping failures the beginning of breach formation is after the downstream face of the dam has eroded away and the resulting crevasse has progressed back across the width of the dam crest to reach the upstream face.*

Compilations of case study data from actual dam failures have used this or similar definitions, such as Froehlich (1987, 1995):

> *...the time from beginning of rapid growth of a breach, to the time when significant lateral erosion of the embankment had stopped.*

Other investigators have reported variations of the breach development time, such as MacDonald & Langridge-Monopolis (1984) who reported *maximum development times*. Von Thun, Dewey, and Gillette (1990, 1993) commented on the overall question of breach time parameters, saying:

> *...The determination of breach formation time is quite subjective and would vary from observer to observer. ...This time can begin long after the first overtopping or initial erosion.*

From the standpoint of predicting warning times and loss-of-life, and then designing emergency action plans and warning systems, breach formation time as it is typically defined does not provide sufficient information. The initial phase of breaching erosion leading up to the first compromising of the reservoir volume is not included in the breach formation time. However, it is critical to determining available warning and evacuation time, and research into loss-of-life during dam failure floods shows that relatively small differences in warning time have a dramatic effect on loss-of-life. Thus, to adequately predict loss-of-life for decision making purposes, and then prevent loss-of-life using early warning systems and well executed emergency action plans, we need to have a better understanding of the initiation of breach, prior to the start of the classical *breach formation phase*. To facilitate this, a breach initiation phase needs to be considered, with an associated *breach initiation time* defined as follows:

> *Duration of time, beginning with the first observable flow over or through a dam that might initiate warning, evacuation, or heightened awareness, and ending with the start of the breach formation phase.*

Unfortunately, statistical methods for predicting breach initiation time do not exist in the literature; only breach formation time has been studied in much detail. Furthermore, the case study data on breach formation times are tainted by the subjective nature of the observations. This can be seen when attempting to apply these statistical methods to actual case studies; our ability to accurately match predictions to the observations is quite poor. Because of this, the most promising avenue for determining breach initiation times is the application of a physically-based breach model.

Several technologies have developed in the years since the first development of the NWS-BREACH model that provide an opportunity to make significant improvements upon the NWS-BREACH model. These include:

- Earth spillway headcut erosion technology developed by ARS using field data and tests conducted at the Stillwater hydraulics laboratory.
- Fuse plug embankment research by the Bureau of Reclamation that addresses breach mechanics of zoned embankments and the lateral erosion phase of breach enlargement.
- Research by the Bureau of Reclamation and others that has improved our understanding of the stability of riprap protection on overtopped embankments.
- Ongoing ARS embankment breach research, which is an extension of the past spillway headcut research.

These and other technologies can be used to improve the NWS-BREACH model or develop a new model founded on our improved understanding of embankment breach mechanics. A key component of the development of such a model will be large-scale physical model testing, such as that being conducted here in Stillwater. These tests will further improve our understanding of breach mechanics, and will provide data needed to verify and calibrate numerical models. Based on Reclamation experience in the overtopping protection and dam foundation erosion projects, tests should be sized so that prototype-size earth materials can be used to reduce uncertainty associated with scale effects caused by scaling material properties.

Some desirable features of a new or improved breach model are:

- Good integration with available field data about material properties and dam condition.
- Operation in an interactive, graphical environment that facilitates data input and analysis of model results.
- Good integration with the FLDWAV model; output from the breach model should be formatted in such a way to make it convenient to use as input to a subsequent FLDWAV analysis.

CONCLUSIONS

There is a need for improved physically-based embankment dam breach models, and potential benefits are significant given future focus on risk assessment, emergency action planning, and early warning as decision-making and problem-solving dam safety tools.

The determination of breach initiation time is critical, and is best approached with physically-based models.

Recently developed and still-developing technology provides an excellent opportunity now to improve dam breach modeling tools. Large-scale physical model testing should be a primary component of efforts to develop new or improved dam breach models.

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