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Predicting Embankment Dam Breach Parameters - A Needs Assessment

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ABSTRACT

Simulation of embankment dam breach events and the resulting floods are crucial to characterizing and reducing threats due to potential dam failures. Development of effective emergency action plans requires accurate prediction of inundation levels and the time of flood wave arrival at a given location. If population centers are located well downstream of a dam, details of the breaching process have little effect on the result; travel time, attenuation, and other routing effects predominate. However, in a growing number of cases, the location of population centers near a dam makes accurate prediction of breach parameters (e.g., breach width, depth, rate of development) crucial to the analysis. If breach parameters cannot be predicted with reasonable accuracy, increased conservatism with associated increased costs may be required. This paper examines existing empirical procedures and numerical models used to predict breach parameters, reviews new technologies relevant to dam breaches, and outlines a program for development of an improved numerical model for the simulation of embankment dam breach events.

BACKGROUND

Today there are numerous tools available for analyzing dam failures and the resulting floods. Wurbs (1987) compared state-of-the-art models, including the National Weather Service (NWS) Dam-Break Flood Forecasting Model (DAMBRK), the U. S. Army Corps of Engineers Hydrologic Engineering Center Flood Hydrograph Package (HEC-1), and the NWS Simplified Dam-Break Flood Forecasting Model (SMPDBK). DAMBRK, the most widely used dam failure analysis model, is being upgraded and will be replaced in the future by FLDWAV (Fread, 1993), which combines capabilities of DAMBRK and the NWS's DWOPER model. FLDWAV's improvements relative to DAMBRK include capability for modeling interconnected river systems, flows over or through levees, automatic Manning roughness calibration, improved numerical stability, and input and output improvements. FLDWAV's treatment of the actual dam-breach process is essentially identical to that of DAMBRK.

The two primary tasks in the hydraulic analysis of a dam breach are the prediction of the reservoir outflow hydrograph and the routing of that hydrograph through the downstream valley. Predicting the outflow hydrograph can be further subdivided into predicting the breach characteristics (e.g., shape, depth, width, rate of breach formation), and routing the reservoir storage and inflow through the breach. DAMBRK, FLDWAV, and other similar models treat the routing tasks—through the breach and through the downstream valley—in much greater detail than the breaching process. In fact, most models do not directly simulate the breach. Rather, the user of the model independently determines the ultimate breach parameters (i.e., dimensions of the fully developed breach), and the time required for breach formation. These parameters are provided as input to the routing model, and the model then simulates the development of the breach in a progressive fashion, usually a linear increase in breach dimensions over the span of the breach formation time. There is presently little research to support or refute the assumption of linear breach development.

Table I. — Embankment breach models (V. Singh and Scarlatos, 1988; Wurbs, 1987).

Model and Year	**Sediment Transport**	**Breach Morphology**	**Parameters**
Cristofano, 1965	Empirical formula	Constant breach width	Angle of repose, others
Harris & Wagner, 1967; BRDAM, 1977	Schoklitsch formula	Parabolic breach shape	Breach dimensions, sediment properties
Lou, 1981; Ponce & Tsivoglou, 1981	Meyer-Peter Müller formula	Regime type relation	Critical shear stress, sediment, tailwater
BREACH, 1985	Meyer-Peter Müller, modified by Smart	Rectangular, triangular, trapezoidal	Critical shear, sediment, tailwater, dry slope stability
BEED, 1985	Einstein-Brown formula	Rectangular or trapezoidal	Sediment, tailwater, saturated slope stability
FLOW SIM 1 and FLOW SIM 2	Linear erosion or Schoklitsch formula	Rectangular, triangular, trapezoidal	Breach dimensions, sediment properties

Ultimate breach parameters are typically estimated using case study-based predictive equations that relate breach parameters to gross characteristics of the dam and reservoir, such as dam height and storage volume (MacDonald and Langridge-Monopolis, 1984; Froehlich, 1987, 1995; Reclamation, 1988; Von Thun and Gillette, 1990). Such relations have high uncertainty due to scatter in the available case study data, especially with respect to breach formation time and breach side slope angles. These relations also are based on a database of dam failure case studies that includes few examples of large dams or large reservoirs.

The National Weather Service BREACH model (Fread, 1985) and other similar numerical models do attempt to simulate the breach formation process in greater detail, but are not widely used at the present time. Table I shows physically-based dam breach models and their characteristics (V. Singh and Scarlatos, 1988; Wurbs, 1987). Several of these models are dependent on calibration coefficients that have not been effectively generalized. The greatest weakness of the existing models is their reliance on tractive-stress based erosion models that do not reflect the predominant mechanisms of headcut erosion, geotechnical slope failure, and lateral embankment erosion observed in case studies and physical model studies.

BREACH PARAMETER DEFINITIONS

Embankment dam breaches are typically assumed to be approximately trapezoidal in shape; the breach geometry can be described in terms of a breach height, average breach width, and breach side slope angle. The slope of the breach invert in the flow direction is assumed to be horizontal. These parameters describe the breach geometry to the extent needed to compute flowrates through the breach, assuming discharge characteristics of a broad-crested weir.

Past research has been focused on the use of a single time parameter, termed the *breach formation time* or *time of failure*. Definitions of these terms have varied in the case study investigations, and the case study data exhibit large scatter, perhaps due to variable interpretations of breach formation time among dam failure eyewitnesses. DAMBRK's definition for the time parameter is:

> *The time of failure as used in DAMBRK is 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.*

The second part of this definition describes a breach initiation phase that precedes the breach formation phase. For purposes of estimating available warning and evacuation time in the event of a dam failure, the *breach initiation time* should be defined as follows:

> *The breach initiation time begins with the first flow over or through a dam that is of enough significance to warrant warning, evacuation, or heightened awareness of the potential for dam failure, and ends at the start of the breach formation phase.*

There is presently little guidance for the prediction of breach initiation times, and breach initiation time is not a factor in the DAMBRK analysis. However, it is likely that the breach initiation phase could be of significant duration in many cases (e.g., dams overtopped by only a small amount, flow over resistant abutment areas, etc.), and even if the breach initiation phase is short, it can still have a significant impact on loss-of-life from a dam failure. BREACH and other similar models do simulate the breach initiation phase, but their accuracy is questionable because they do not simulate headcutting and other observed embankment erosion mechanisms.

IMPORTANCE OF BREACH PARAMETERS

Variation of breach parameters can affect peak discharge and inundation levels, as well as warning and evacuation time. The effect on peak discharges was examined by K. Singh and Snorrason (1984). For small reservoirs (those which experience significant drawdown before the breach is fully developed), changes in breach formation time can dramatically affect peak outflow. Variations of breach width can also produce large changes in peak outflow, especially for large reservoirs. Variations of breach height have a relatively small effect on peak outflow.

Petrascheck and Sydler (1984) demonstrated the sensitivity of peak flow, inundation levels, and flood arrival time to changes in breach width and breach formation time. For locations near a dam, both parameters can have a dramatic influence. For locations well downstream of a dam, timing of the flood wave peak can change significantly with changes in breach formation time, but peak discharge and inundation levels are insensitive to changes in breach parameters.

Warning and evacuation time can dramatically influence the loss-of-life from dam failure. When establishing hazard classifications, preparing emergency action plans, or designing early warning systems, good estimates of warning time are crucial. Warning time is the sum of the breach initiation time, breach formation time, and flood wave travel time from the dam to a population center. Case history-based procedures developed by the Bureau of Reclamation indicate that loss-of-life can vary from 0.02% of the population-at-risk with more than 90 minutes of warning time, to 50% of the population-at-risk when warning time is less than 15 minutes (Brown and Graham, 1988). More recent work by DeKay and McClelland (1991) shows similar extreme sensitivity to warning time.

EMPIRICAL BREACH PARAMETER PREDICTION EQUATIONS

A review of literature performed by this author (Wahl, 1996), revealed numerous breach parameter prediction equations developed since about 1984. Individual equations have been based on analyses of case study compilations, generally comprising about 20 to 60 dams. The database compiled by this author contains 108 dam failures, and was used to analyze and compare the various prediction equations. Figure 1 shows predicted and observed breach widths using three of the available breach-width prediction equations, for subsets of this database (those dams for which enough information was available to apply the equations).

There are some dramatic prediction errors evident with all three relations. Figure 2 compares predicted and observed breach formation times, using several available prediction equations. Again, large prediction errors are evident. It is also significant to note the large variation of reported breach formation times for some dams. This is evidence of potential problems in distinguishing between breach initiation and breach formation phases.

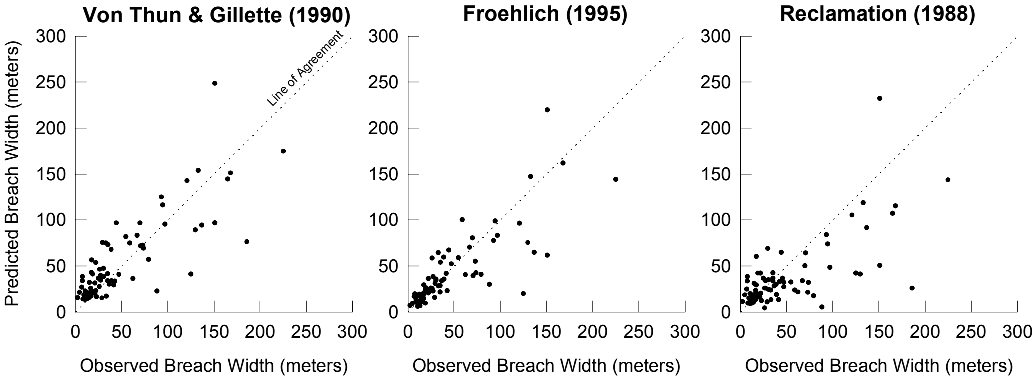


Figure 1. — Comparison of breach width prediction equations to case study data.

MECHANICS OF EMBANKMENT BREACH

Laboratory testing and field observations of embankment dam failures have shown that headcutting is the predominant mode of failure for cohesive embankments or rockfill embankments with a cohesive core (Dodge, 1988; Powledge et al., 1989). In overtopping failures, headcutting typically initiates near the toe of the dam and advances upstream until the crest of the dam is breached; in some cases a headcut may initiate at the knickpoint present at the downstream edge of the crest. As the headcut advances upstream it will widen and assume a semi-circular shape which improves stability of the headcut through arching of the soil mass. In some cases, multiple stairstep headcuts form on the downstream face of the dam.

Headcut initiation takes place when the protective cover on an embankment fails, allowing localized erosion that creates an overfall. Factors affecting the initiation of headcutting include embankment slope, vegetation type and quality or riprap type and size, cover discontinuities, flow concentrations, flow velocities, and unit discharges. Headcut initiation can be modeled using tractive stress-based approaches (Temple and Hanson, 1994).

The key erosion zone once a headcut has formed is at the base of the headcut overfall. As material is eroded from this area, support for the above soil mass is removed, leading to sudden collapse of the soil block. Tailwater conditions at the base of the overfall and aeration of the nappe are key factors in headcut advance. The Agricultural Research Service has developed empirically-based procedures for estimating headcut advance rates in earth spillways, using a model that compares energy dissipation rate at an overfall to a headcut erodibility index for the material (Temple and Moore, 1994). These procedures are being incorporated into the SITES model used by the Natural Resources Conservation Service for design and analysis of earth spillways (Temple et al., 1994). These procedures have not yet been applied to steep slopes or breaching of earth embankments, but do hold promise for such applications.

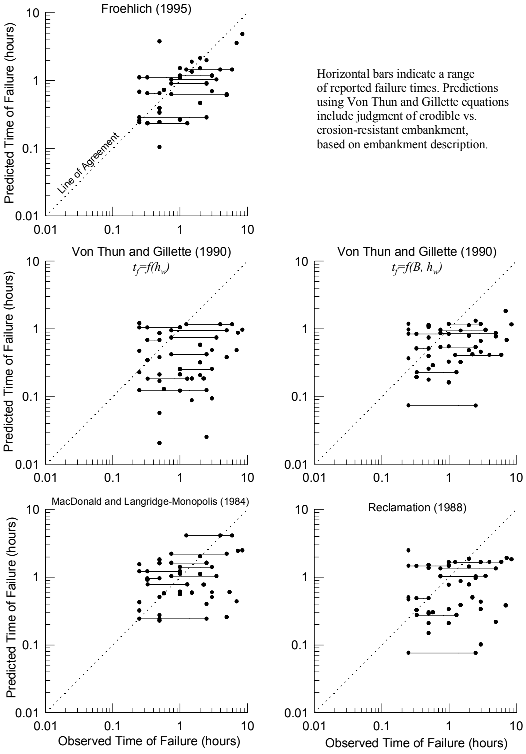
A NEW BREACH MODEL

Clearly, when population centers are close to a dam, accurate prediction of breach parameters is necessary to make reliable estimates of warning and evacuation time, peak outflow and inundation zones, and loss-of-life. Available models cannot fully address the needs for many of these cases. Great benefit could be obtained from development of an improved breach simulation model that is based on the observed erosion mechanics. The model should address the following issues:

- For a given set of conditions, will a dam breach?
- How much time is required to initiate a breach?
- How will the breach develop once it is initiated? Define the geometry of the breach during its development. Define total time for breach development and ultimate breach geometry.

Reclamation is now pursuing a cooperative effort with several agencies to develop such a model. The initial focus will be on the more tractable problem of breaches caused by overtopping, although the model should eventually be applicable to more complex piping and seepage-induced failures. Initial efforts will be focused on the breach initiation phase of the problem. Recent research by Reclamation and others has improved the capability to assess riprap stability, erosion of vegetated surfaces, and headcut advance. Work on a generalized numerical model with unsteady flow and sediment transport capability will also be pursued. This will provide the basis for development of a more specialized dam breach model.

Recent advances in technology for analyzing headcut erosion, riprap stability, erosion of vegetated surfaces, and high energy erosion of resistant earth materials have all come about through extensive large-scale physical modeling efforts and collection of case study data from prototype structures. Similarly, large-scale physical modeling will be required to address complicating factors in embankment breaching processes, such as:



Horizontal bars indicate a range of reported failure times. Predictions using Von Thun and Gillette equations include judgment of erodible vs. erosion-resistant embankment, based on embankment description.

Figure 2. — Predicted vs. observed breach formation times using several prediction equations.

- Variable embankment and foundation configurations, materials, and densities of fill
- Effect of discontinuities, singularities, and flow concentrations
- Presence and depth of tailwater on the downstream slope
- Unique embankment features such as toe drains, blanket drains, erodible filter zones, etc.

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