DAM BREACH MODELING – AN OVERVIEW OF ANALYSIS METHODS

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Abstract: The two primary tasks in the analysis of a potential dam failure are the prediction of the reservoir outflow hydrograph and the routing of that hydrograph through the downstream valley to determine dam failure consequences. When populations at risk are located close to a dam, it is important to accurately predict the breach outflow hydrograph and its timing relative to events in the failure process that could trigger the start of evacuation efforts. This paper provides an overview of the methods used to predict breach outflow hydrographs, ranging from simple methods appropriate for appraisal-level estimates to more complex methods for analysis of individual cases. The progression of technology development is followed from methods that predict peak outflow directly to those that predict breach development directly and model the hydraulics analytically, and finally to methods that model erosion processes, breach development and hydraulics in great detail.

INTRODUCTION

Dams are an important part of this nation's infrastructure, providing flood control, water supply, irrigation, hydropower, navigation, and recreation benefits. Despite their many beneficial uses and value, dams also present risks to property and life due to their potential to fail and cause catastrophic flooding. To mitigate these risks, dam owners and regulators carefully analyze and inspect dams to identify potential failure modes and protect against them. Since no program for preventing failure can ever be certain, and because the potential for loadings exceeding design limits can never be eliminated, another essential part of risk mitigation is simulating potential failures and planning for them. These plans can include public education programs, development of warning systems and procedures, and development of effective evacuation procedures. Simulations of dam failure and flooding consequences can also be used by dam owners to prioritize the risks presented by individual dams comprising a dam inventory. This prioritization process facilitates the effective use of financial and human resources to improve public safety and reduce dam failure risk.

The two primary tasks in the analysis of a potential dam failure are the prediction of the reservoir outflow hydrograph and the routing of that hydrograph through the downstream valley to determine dam failure consequences. The routing of large floods is a well developed science, although some areas of uncertainty do remain (e.g., changes in channel roughness due to debris effects, sediment deposition modeling, etc.). Great progress is also being made in this field, as geographic information technology and computing resources continue to improve, making more sophisticated flow modeling possible, and making it easier to integrate flow information with geographic information to simulate dam failure consequences. The greater source of uncertainty in most situations is the prediction of the reservoir outflow hydrograph, especially for embankment dams in which dam failure is usually the end result of a progressive erosion process that is itself very complex and difficult to accurately model. Prediction of the reservoir outflow hydrograph is especially important when the population at risk is located close to the dam, where peak attenuation and other flood routing effects have not yet taken place. As our nation's population continues to grow and urban areas expand into formerly rural areas, this situation is becoming ever more commonplace.

This paper presents an overview of today's typically used methods for predicting dam breach outflow hydrographs, with discussion of the advantages and disadvantages of different approaches for specific applications. The methods presented range from simpler well established methods to more complex approaches now under development.

HISTORY

The 1964 failure of Baldwin Hills Dam, near Los Angeles, California, and the near failure of Lower Van Norman (San Fernando) Dam as a result of an earthquake in 1971 prompted the State of California to enact statutes requiring dam owners to prepare dam failure inundation maps. The need for developing procedures for estimating the breach hydrograph was thus born. Prior to the enactment of the California statutes, very little was published regarding procedures for estimating dam breach outflow hydrographs.

Numerous dam failures that occurred in the U.S. in the 1970's, including Buffalo Creek coal waste dam (West Virginia, 1972), Teton Dam (Idaho, 1976), Laurel Run Dam and Sandy Run Dam (Pennsylvania, 1977), and Kelly Barnes Dam (Georgia, 1977), led to an increasing focus on dam safety, including legislation and executive branch actions (Powers 2005). The Federal Guidelines for Dam Safety, dated June 25, 1979, stated that inundation maps should be prepared, and the 1978 Reclamation Safety of Dams Act set more detailed guidelines for the Bureau of Reclamation, one of the federal government's largest dam-owning agencies. This act authorized Reclamation to preserve the structural stability of its dams and related facilities by performing modifications. Similar legislation has since been passed in countries around the world. In the United States today, most dam safety decisions are driven by the predictions of the probability of dam failure and the magnitude of resulting loss-of-life; property damage is a secondary consideration that does not by itself justify dam modifications.

MODELING STRATEGIES

With the end product of most dam breach analyses being the prediction of flooding conditions and resulting loss of life, the focus of dam breach modeling has traditionally been on the tools that produce the predictions of flood inundation. Until the early 1990s this was most commonly a flood routing model, such as the National Weather Service DAMBRK or FLDWAV model, the NWS Simplified Dam-Break Flood Forecasting Model (SMPDBK), the HEC-RAS model from the U.S. Army Corps of Engineers, or one of several commercial models with similar capabilities. These various models have been designed with interfaces that facilitate several different approaches to the modeling of the breach process, but none of these routing models have specifically attempted to integrate a detailed simulation of the erosion processes that lead to dam breach. Detailed simulation of the breach process has required the use of separate models specifically focused on erosion processes that provide output of breach geometry development over time. There has also been recent development of more sophisticated tools for completing the analysis of flooding consequences; some of these are separate from the routing models, while others are being integrated into them.

Three principal strategies for dam-break flood modeling have emerged since the 1970s. The first strategy was to predict the breach outflow hydrograph directly and then use one of the available routing models to route that flood downstream so that flooding consequences could be determined. The second approach was to parameterize the breach so that its evolution through time could be described in relative simple mathematical terms, allowing the breach outflow hydrograph to be determined by combining the description of the breach development with a weir equation or other appropriate model for simulating the hydraulic performance of the breach opening. Typical breach parameters determined were the maximum breach size, rate of breach development (or total time needed for full breach development), the shape of the breach, and a mathematical model for how enlargement takes place (e.g., linear increase of breach dimensions through time). In this second approach, breach parameters could be determined by several different means externally to the flood routing model, but determination of the breach outflow hydrograph took place in the routing model. The third approach is to use a combined model that simulates specific erosion processes and the associated hydraulics of flow through the developing breach to yield a breach outflow hydrograph. Early models that took this approach were run separately from flood routing models, with the breach outflow hydrograph provided as input to the routing model. There is work being done now to integrate breach modeling and flood routing capabilities into a single model.

The breach modeling strategies described in the previous paragraph are summarized in Table 1, with further subdivisions in the methods shown. This table suggests that there are five different processes by which one can perform the analysis that leads to determination of a breach outflow hydrograph. The remainder of this paper will discuss these five approaches in more detail.

Table 1. — Dam-break flood modeling strategies. The first column indicates different approaches to determining breach parameters and/or the breach outflow hydrograph.

<table>
<tr><td>Regression models for Q_p as function of dam and reservoir properties</td><td rowspan="2">Approximate breach outflow hydrograph by predicting peak outflow and hydrograph shape directly</td><td rowspan="5">Route breach outflow hydrograph to determine flooding consequences</td></tr>
<tr><td>Analytical models to predict Q_p with closed-form equations or charts as functions of dam and reservoir properties</td></tr>
<tr><td>Regression models for breach parameters as function of dam and reservoir properties</td><td rowspan="2">Provide breach parameters as input to routing model, which determines breach outflow hydrograph by the use of hydraulic equations for flow through enlarging breach</td></tr>
<tr><td>Apply erosion model to predict breach evolution and then approximate breach description in a parametric way for input to routing model</td></tr>
<tr><td colspan="2">Process-based erosion and hydraulics models that simultaneously determine breach development and resulting outflow hydrograph</td></tr>
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Regression Models for Peak Outflow: The essential characteristics of the breach outflow hydrograph that affect loss of life in a dam failure event are the magnitude of the peak discharge, which affects inundated area, and the time required for the flow rate to rise to the peak, which relates to available warning time. Wahl (1998) identified ten references in the literature providing thirteen different formulas to directly estimate the peak outflow discharge as a function of dam and/or reservoir properties. Most of the formulas had been developed by regression analysis of case study data from real dam failures. Two of the ten references also provided companion formulas that could be used to estimate a time parameter, and six other references provided formulas for estimating dam failure time and other breach parameters, but not peak outflow. These formulas offer means to estimate the complete breach hydrograph if one assumes a hydrograph shape and knows the volume of water to be released through the breach. The most commonly assumed hydrograph shape is triangular. The most widely applied peak-flow prediction equations have been those of SCS (1981), MacDonald & Langridge-Monopolis (1984), Costa (1985), and Froehlich (1995a). An analysis by Wahl (2004) found the Froehlich (1995a) equation to have the lowest uncertainty of the peak flow prediction equations available at that time. Advantages of this approach are its simplicity and quickness which makes it useful as a screening tool for analyzing large dam inventories and offers a quick way to check the reasonability of results from other methods. Disadvantages of this approach are the fact that none of the equations include factors related to material erodibility, and the time parameters predicted by these equations help define the shape of the hydrograph but do not fully answer the question of how much warning time is available prior to the release of peak outflow. The time parameter predicted by these methods is the rise time of the hydrograph from the end of breach initiation to the time of peak outflow. The end of breach initiation is the time at which erosion through the embankment has progressed to the upstream side of the crest. Prior to this, the time from first overtopping or first observable seepage flow of concern to the end of breach initiation can be lengthy, especially if the embankment is erosion resistant. It is this time that is of most interest from a warning and evacuation standpoint. A recent contribution to the literature on the topic of peak flow prediction equations is Xu & Zhang (2009) who applied a multiparameter nonlinear regression analysis to a very large database of case studies and did evaluate the effects of erodibility, which were very significant.

Analytical Models to Predict Peak Outflow: Analytical models for peak breach outflow are based not on regression analysis but instead on an equation or set of equations derived from the physics of dam breach erosion and hydraulics. An early example of such a model is the work of Cristofano (1965), which can be argued to be the first physically based dam breach model. The model related the rate of erosion of the breach channel to the discharge through the breach, using an equation that accounted for the shear strength of soil particles and the force of the flowing water. Key assumptions were a trapezoidal breach of constant bottom width, side slopes of the breach determined by the angle of repose of the material, and bottom slope of the breach channel equal to the internal angle of friction. An empirical coefficient was critical to the model's performance (Fread, 1988).

A more recent example of the analytical approach is the model developed by Walder & O'Connor (1997). They developed a mathematical model for peak discharge from an idealized reservoir and breach as a function of a dimensionless parameter combining material erosion rate and reservoir size, a breach shape parameter (width-to-depth ratio), the breach side slope angle, a reservoir shape factor, and the breach depth-to-dam height ratio. They compared their model results to data from case study dam failures (including landslide dams) and identified typical ranges of the key input parameters. After evaluating the influence of the different input parameters and fixing the values of those parameters that had minimal effect on the result, they proposed a set of simplified equations that could be used to compute appraisal-level estimates of peak outflow. The key parameter in the final simplified model was the dimensionless factor based on erosion rate and reservoir size. Advantages of this approach are the fact that it recognizes differences in behavior between small and large reservoirs. Small reservoirs (or those dams that fail very slowly due to erosion-resistant embankments) drain significantly before the breach is fully formed, so the peak outflow occurs while the breach is still forming. Large reservoirs (or dams that fail quickly) maintain their reservoir head until the breach has reached its ultimate size, so the peak flow occurs when the breach is fully formed and is subjected to maximum head. Disadvantages of this technique are that it still does not aid in the determination of the time required for breach initiation, since the analytical model treats only the breach formation process.

Regression Models for Breach Parameters: A first step in subdividing the analysis of a dam breach and its outflow hydrograph to allow more detailed evaluation is to separate the breach formation process from the analysis of flow through the breach. This allows the flow problem to be handled analytically (e.g., treating the breach opening as a weir control), while the breach development problem which is not as well understood is handled with empirical regression models. The regression models are developed using case study dam failure data and predict parameters characterizing the breach development as a function of other dam and reservoir characteristics. This approach saves the dam break model from actually simulating the erosion processes by which the breach develops.

The parameters describing a breach are typically taken to be the breach depth, width, side slope angle and formation time. Breach depth is usually taken to be the dam height and some argue that the breach side slope angle should be taken as vertical for most cases, so breach width and breach formation time are the two parameters of most interest. Numerous investigators have developed regression models to predict these two parameters. Wahl (1998) reviewed the methods available at that time and Wahl (2004) and Froehlich (2008) have considered the uncertainty of breach parameter estimates and found them to be very significant, especially the time parameter. The review by Wahl (2004) found that the best methods of breach width prediction (Reclamation 1988; Von Thun & Gillette 1990; Froehlich 1995b) had uncertainties of about ±1/3 order of magnitude, and the best predictions of breach time (Froehlich 1995b) had uncertainties of about ±2/3 order of magnitude.

Advantages of the breach parameter approach to dam break modeling are that the analyst can exert some control over the breach parameters used in the dam break model, taking into account site specific factors such as an upper limit on breach width due to erosion resistant abutments. Weaknesses of the breach parameter approach are primarily the uncertainties of the predictions, which arise from a multitude of factors.

Erosion Models Leading to Parametric Breach Descriptions: This approach to dam failure analysis uses a dam breach model that simulates specific erosion processes to define the development of the breach. The first widely applied and most well-known model of this type is the National Weather Service BREACH model (Fread 1988). Since the erosion processes are related to the flow through the breach, models of this type by necessity also predict the breach outflow, but they do so without incorporating some of the features of a dam-break flood routing model, such as tailwater effects on the flow through the breach and dynamic effects on the flow within the upstream reservoir (most breach models have used level-pool storage routing through the reservoir). If these effects might be significant, then a hybrid modeling approach is possible. The erosion-based dam breach model is used to simulate the breach development and its results are used to construct a parameterized representation of the breach development process (i.e., to determine ultimate breach width, breach formation time, etc.). These breach parameters are then provided as input to the dam-break flood routing model, which can determine the breach outflow hydrograph itself, accounting for dynamic effects in the reservoir and downstream tailwater effects.

Process-Based Dam Breach Models Integrated with Dam-Break Flood Routing: The next step in the development of dam-break modeling technology is the integration of models that simulate embankment erosion and breach processes with the models used to route the resulting flood and determine downstream consequences. Wahl et al. (2008) described some of the erosion models being considered as part of one such effort. Just as previous advancements in dam-break flood modeling occurred when the process for determining the breach outflow hydrograph was subdivided into breach development and analytical hydraulics, the breach development process is being refined further by subdivision. The models under development now (Mohamed 2002; Temple et al. 2005) recognize different phases in the breaching process and also incorporate quantitative estimates of material erodibility into the modeling of each phase.

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