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Uncertainties in dam failure modelling with the US NWS BREACH Model

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UNCERTAINTIES IN DAM FAILURE MODELLING WITH THE US NWS BREACH MODEL

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Abstract

This paper draws together experience from using the US NWS BREACH model to simulate dam failure. Several deficiencies in the model have been identified which can lead to substantial uncertainty in prediction of the outflow hydrograph from the dam. There appears to be inconsistency in the transition from piping to overtopping failure and the model can produce unusual hydrograph shapes. The implications for practical application are that flood hazard areas identified by hydrodynamic modelling of the dam breach wave may be significantly in error, particularly in the critical zone close to the dam where risk to life is greatest.

1. Introduction

During the 1980s, Danny Fread of the National Weather Services (NWS) in the US developed the DAMBRK model, and along with this the NWS BREACH model. The BREACH model has been widely used around the world, including the UK, because of its simple construction and availability within the public domain. In the UK, it was introduced with the DAMBRK UK modelling package, which is a modified version of the DAMBRK model for simulation of conditions encountered in the UK. BREACH is a physically based mathematical model for predicting the outflow hydrograph from breaching of an embankment dam. The dam may be man-made or a natural dam formed by a landslide. It can be homogenous or consist of two materials. The model is based on the principles of hydraulics, sediment transport, soil mechanics, the geometric and mathematical properties of the dam, and the reservoir characteristics. Recent research indicates that there may be a number of problems associated with this model since under some conditions the model gives inconsistent results. This phenomena has been confirmed by a number of users across Europe (Morris [1]). Modelling results are typically used for risk management and emergency planning; consequently an error in prediction may lead to inappropriate planning and management. In this paper a description of the model and the results of some test cases are given, followed by a review of the assumptions used in constructing the model and the possible consequences of the model uncertainties.

2. Model description

2.1 Breach Morphology:

In the BREACH model, the breach geometry is defined by two rules. The first rule assumes an initial rectangular shape for breach initiation. The following relation governs the width of the breach:

$$B_o = B_r y \qquad (1)$$

Where:
B_o : Width of the breach.
B_r : Factor based on optimum channel hydraulic efficiency.
Y : Depth of flow in the breach channel.

The parameter B_r is a factor based on optimum channel hydraulic efficiency. It has a value of 2.0 for overtopping failure and 1.0 for piping failure. For failure of man-made dams, the model assumes critical depth at the entrance to the breach channel, whilst for failure of a natural dam (e.g. landslides), the water depth in the breach channel is assumed to be the normal uniform depth rather then the critical depth. That is based on the assumption of a relatively long breach channel length through a natural dam as compared to that through a man-made dam (Fread [2]).

The second rule defining breach growth is derived from the stability of soil slopes (Spangler [3]). The initial rectangular shaped channel changes to a trapezoidal channel when the channel sides collapse, forming an angle α with the vertical. The collapse occurs when the depth of the channel reaches a critical depth, H', that can be expressed as follows:

$$H' = \frac{4C\cos\phi\sin\theta}{\gamma\left[1-\cos(\theta-\phi)\right]} \qquad (2)$$

Where:
C : Soil cohesion (Ib/ft^2).
ϕ : Soil internal angel of friction.
γ : Unit Weight (Ib/ft^3).
θ : Side slope angle with the horizontal before failure (i.e. $\theta_{initial} = 90^o$). After the first collapse $\theta_n = 0.5(\theta_{n-1}+\phi)$. Where n is the collapse counter.

Then the width can be calculated using equation 1 assuming that B_o is the bottom width.

2.2 Hydraulics of Flow over the Dam:

For an overtopping failure, the reservoir water level must exceed the top of the dam before any erosion occurs. Erosion is then assumed to occur only along the downstream face of the dam. Flow into the downstream breach channel is calculated using a broad crested weir formula as follows:

$$Q_b = 3B_o(H-H_c)^{1.5} \qquad (3)$$

Where:
Q_b : Flow into the breach channel (cfs).
B_o : Instantaneous width of the breach (ft).
H : Water level at the dam (ft).
H_c : Breach base level (ft).

For piping failure, the reservoir water level must be greater than the centre line elevation at which piping is assumed to start. Flow into the pipe is calculated by an orifice flow formula as follows:

$$Q_b = 0.98A\sqrt{2g(H-H_p)} \qquad (4)$$

Where:
H_p : Piping level (ft).
H : Water level at the dam (ft).
A : Pipe cross sectional area (ft^2).
g : Acceleration of gravity (ft/s^2)

2.3 Erosion and Sedimentation:

Fread [2] used the Meyer-Peter-Muller equation, which was modified by Smart [4] for steep slopes, to compute the rate at which the breach is formed. Erosion is assumed to occur equally along the bottom and sides of the breach channel, except when the sides of the channel collapse. Thereupon, the breach base is assumed not to erode downwards until the volume of collapsed material has been removed (at the current rate of transport). Should the breach erode downward to the original valley floor, then further downward erosion is stopped. However, the sides of the breach may continue to erode laterally.

2.4 Geo-mechanics of the Breach Slopes:

The BREACH model includes two routines to deal with sudden enlargement of the breach due to instability of slopes or failure of a portion of the upper dam body. The first module was explained in the breach morphology section above. The second is explained below.

During an overtopping failure, it is possible that the breach could be enlarged suddenly by collapse of the upper portion of the dam. This mode of failure is due to the pressure of water on the upstream face exceeding the stabilising forces of soil shear and cohesion. When such a collapse occurs, erosion of the breach channel ceases until the volume of the collapsed wedge is transported through the breach channel at the same transport rate as prior to collapse. During simulation of piping failure, as the top elevation of the pipe erodes vertically upward, the flow prediction changes from orifice control to weir control when the reservoir water elevation falls below the top level of the pipe. The remaining material above the top of the pipe and below the top of the dam is then assumed to collapse and is transported along the breach channel at the same rate of transport before further erosion occurs.

3. Application of the model

3.1 Fread's Verification

During development of the BREACH model, data from the failure of three earth dams was used to verify modelling parameters and assumptions. The first data was from the piping failure of Teton dam. The timing, shape, and magnitude of the outflow hydrograph compared reasonably with (estimated) actual values (See Figure 1). The final dimensions of the breach were reasonably predicted as well. The final predicted depth was exactly the same as the estimated actual depth (base of the dam) and the difference in width was less than 3 percent.

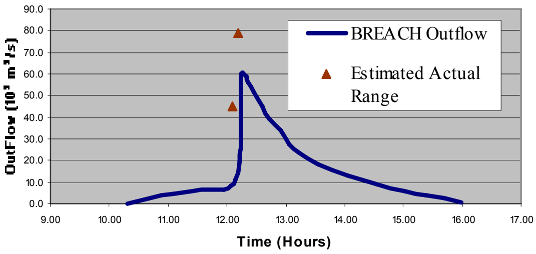

Figure 1 Predicted outflow vs. the estimated actual range for Teton dam

The second data was from the overtopping failure of the Huaccoto landslide in Peru. The timing of the peak outflow and its magnitude are very similar to the observed values (See Figure 2). The final dimensions of the breach were reasonably predicted as well. The difference in depth was lass than 3 percent. However, the difference in width was about 15 percent. The model gave similar results and accuracy when applied to the third data set for the piping failure of the Lawn Lake dam in Colorado.

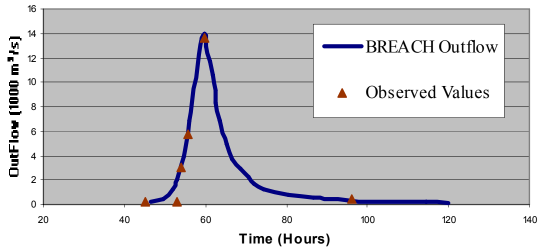

Figure 2 Predicted outflow vs. the observed values for the Huaccoto dam

3.2 Testing on European Structures

As part of a confidential dambreak study, Mohamed [5] used the BREACH model to predict the outflow hydrograph for an earth embankment dam in the UK.

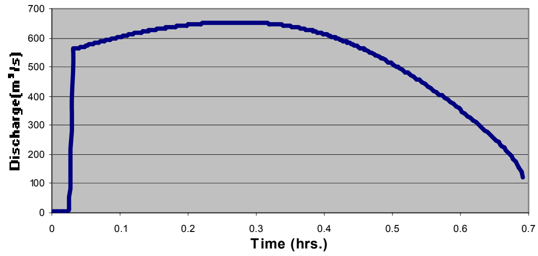

Figure 3 Predicted outflow hydrograph

Figure 3 shows the outflow hydrograph predicted using the BREACH model. It can be seen that the hydrograph shows a sudden rise in flow that indicates an instantaneous failure of the dam. Instantaneous failure is not a realistic mode of failure for earth dams if they fail due to overtopping, unless slope or core instability occurs. The BREACH model does not include any component to deal with core instability and there was no slope instability at this time during the simulation.

Within the EC Concerted Action on Dam Break Modelling project (CADAM), Mohamed [6]also used the BREACH model to simulate failure mechanisms for two test cases, comprising field and laboratory failure of an earth embankment dam through overtopping.

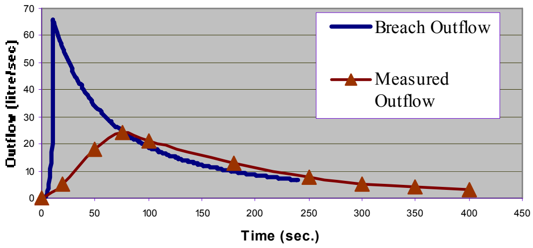

Figure 4 CADAM test case 1

Figure 4 shows a comparison between the measured outflow and the predicted outflow using BREACH for the CADAM test case 1. The timing and shape of the hydrographs are completely different. Also, the sudden increase in outflow indicates an instantaneous dam failure, which did not occur in the physical modelling experiment.

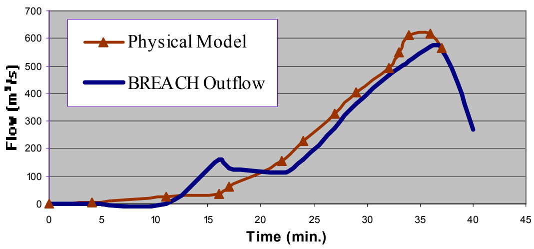

Figure 5 CADAM test case 2

Figure 5 shows a comparison between the measured and predicted outflow using BREACH, for the CADAM test case 2. The timing and shape of the predicted outflow hydrograph compared well with the measured outflow hydrograph. However, the final predicted breach dimensions were different to those measured in the physical model. The difference in top width was about 60%.

To check how the breach model simulates piping failure and how it changes from piping to overtopping failure when the material above the pipe collapses suddenly, a hypothetical failure was assumed as shown in Figure 6 below.

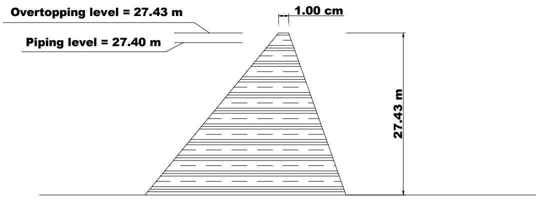

Figure 6 Hypothetical test dimensions

The modelling input data was identical for both tests. One test assumed failure by overtopping and the other by piping, with a pipe initiation at a level less than 3 cms from the assumed overtopping level. The outflow hydrographs for the two cases should be similar since the material above the pipe should rapidly collapse and the piping failure simulation should quickly transform to an overtopping failure simulation.

Figure 7 shows the outflow hydrographs for both the piping and overtopping failure simulations. The two hydrographs are completely different in terms of shape, time to peak, and the peak discharge itself. Even if the initiation time of piping is excluded from analysis of the hydrographs, the two hydrographs are still significantly different. It is also noticeable that the volumes of the predicted flood hydrographs are different for each case.

In an attempt to find out the reason behind these unexpected results, the source code of the program was checked within the context of this study. It was subsequently found that the program simulates breach growth after failure of a pipe in a different way to 'overtopping' breach growth. The same subroutines are not used. This might be the reason for the strange results obtained in the last case study and these problems were reported to Dr Fread at the US NWS.

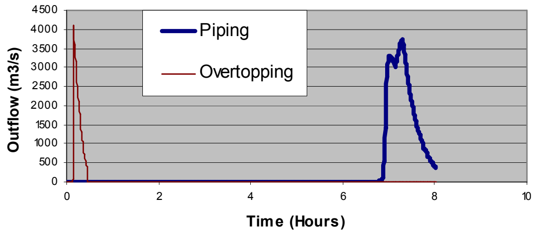

Figure 7 Piping failure vs. overtopping failure (both using BREACH)

BREACH also models composite dams by averaging values of the different properties of the two different layers (such as cohesion, friction angle, porosity, mean diameter, and specific weight). It then uses these averaged values to model failure of the composite dam as a modified homogeneous structure. This method can be considered simplistic and does not represent the real behaviour of the composite dam when it fails.

In a more recent study it was also found that the model is very sensitive to variations of the simulation time step. In this study doubling the time step completely changed the outflow hydrograph for the breached embankment dam. Modelling results should be independent of simulation time step.

4. Conclusions

4.1 Ease of use:

The original BREACH model is a command line application that reads an input file that is a fixed format file. The user might find some difficulties in creating such a file since any error in format of the data might lead to either the model crashing or producing wrong results. The model only accepts imperial units. A Graphical User Interface (GUI) for the Breach model developed by Mohamed [5] makes it easier to create the input file in the correct format through a user friendly GUI. Within the GUI, the user can also run the model, view the model output, and export its output data into different formats and data can be in imperial or metric units.

4.2 Assumptions used in constructing the model

Several assumptions have been used in the BREACH model including:

- Uniform erosion along the breach channel.
- The optimum channel hydraulic efficiency factor (B_r).
- Parallel retreat of the breach channel.
- Soil slope stability analysis.

It is clear from observation and the analysis of shear stress along the breach channel sides and bed that erosion along the breach channel is not uniform and it is also different above and below the water level within the channel. The optimum channel hydraulic efficiency factor (B_r) has been obtained under steady state conditions for rectangular channels in rivers. It is noticeable that conditions during breaching differ from these and these assumptions may not be valid for breach simulation. The assumption of parallel retreat of the breach channel is incompatible with the steady state flow conditions assumed on the downstream face of the dam as it violates the sediment continuity equation. The analysis used to determine the slope instability condition has not incorporated the water levels within the dam body and in the breach channel. The first assumption might also affect the stability analysis since lateral erosion will tend to steepen the banks (Osman et al [7]) and the breach side slope will get steeper and steeper as the water flows into the breach. This means that the side slope of the breach is not constant throughout the simulation time or between successive slope failures, which is the assumption used within this model.

4.3 The results presented cases

Each one of the cases presented in Figures 3, 4, 5 and 7 show different anomalies found in the BREACH model. These include:

- A characteristically sudden rise in flow that indicates an instantaneous failure of the dam. Instantaneous failure is not a realistic mode of failure for earth dams if they fail through overtopping.

- Breach dimensions are not well predicted even if the outflow hydrograph is predicted reasonably.
- Inconsistent simulation of breach growth between overtopping failure and breach growth after collapse of an initial piping failure even though the subsequent growth processes should be very similar, if not identical.
- Volume of the predicted flood hydrograph periodically does not match the initial reservoir stored volume.
- Model results sensitivity to simulation time step variation.

4.4 Consequence of the Uncertainties in BREACH

Given the ease of availability of the BREACH model, and the lack of alternative models, BREACH has been used widely within the UK and around the world as part of dambreak assessment studies. Results from such studies typically feed into risk management and emergency planning work. Hence any errors within the BREACH model predictions could influence a significant number of dam and flood defence owners, both in their reliable development of emergency action plans and also in management and maintenance of their assets where these operations have been based on risk (impact) assessments. The significance of any errors will be greatest felt where the main impact of potential flooding is near to the dam or flood embankment (i.e. the first 5-10km from the dam). Beyond this region, attenuation of the flood wave (which depends greatly upon local topography) will tend to reduce any error in peak flood level estimation, although large errors in flood hydrograph volume could still have a noticeable effect.

This review shows that the BREACH model should only be used with caution since there are a number of apparent inconsistencies within the code that may produce spurious modelling results. Research into breach formation is continuing at HR Wallingford, with a new breach model (HR BREACH) being developed to overcome many of the deficiencies found within the NWS BREACH model and to benefit from modern day programming and computing resources.

5. References

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NOTES

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