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Dam Breach Modeling: Combining Geotechnical and Hydraulic Engineering Concepts

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Dam Breach Modeling: Combining Geotechnical and Hydraulic Engineering Concepts

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ABSTRACT

This paper describes how geotechnical and hydraulic engineering concepts were combined to develop a computer model that can be used to simulate the rate and extent of breaching of earth embankments characterized by transverse cracks and foundations experiencing the presence of earth fissures. The rate of breaching is an important parameter for developing emergency evacuation plans once breaching occurs or is anticipated. In addition, breach rate and its maximum extent determines the outflow characteristics from the reservoir, which is required to conduct inundation modeling and mapping. Other uses of the model include evaluation of potential solutions to prevent breaching of the dams and foundations.

The model computes the erosive power of water by making use of basic principles of hydraulics and boundary layer theory, and represents the erosion characteristics of the soil by making use of results from geotechnical testing executed with the Erosion Function Apparatus (EFA) and the Vertical Jet Tester (VJT). The former is executed in the laboratory and the latter insitu. The elements of the computer model are discussed in the paper, as is its qualitative verification.

Keywords: rate of erosion, dam breach, fissure, crack, Holocene, Pleistocene, EFA, Vertical Jet Tester, VJT, modeling, re-cementation of soils.

INTRODUCTION

The Flood Control District of Maricopa County (District) operates and maintains 22 flood control dams in Maricopa and Pinal Counties, Arizona. More than half of the District's dams were constructed over 25 year ago, three of which were constructed over 50 years ago. Since the original construction of the dams, several factors relative to the physical conditions of the dams themselves, and the environment in the vicinity of the dams have changed significantly. These include urbanization downstream of the dams, development of earth fissures, and transverse desiccation cracking at frequent intervals across the embankments. The earth fissures potentially affect the integrity of the dam foundations and the transverse cracks could lead to single or multiple breaches. In light of these and other changes, the District has implemented a phased program to evaluate and rehabilitate (as needed) the dams in the District's portfolio.

MODEL DESCRIPTION

A particular feature of breaching through embankment cracks and foundation fissures is that erosion is assumed to occur in a downstream direction. What is meant by this is that the erosion does not occur in the same manner as piping failure. In piping failure earth material is removed at the downstream side as material is discharged downstream, with the pipe developing in an upstream direction. In the case of erosion of a crack or fissure, the erosion process differs. The crack or fissure already exists, characterized by two vertical planes, initially separated by a small distance. As water flows through the crack or fissure earth material is eroded from the two vertical planes and transported downstream, increasing the distance between the planes as material is removed.

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The embankment dam cross sectional shape is conventional and each of the six breach model types that were developed represents different initial embankment crack and dam foundation fissure conditions (Table 1). The models that were developed can simulate breaching due to overtopping and due to transverse vertical cracks that either extend from the top of the embankment downwards, or are located below a central embankment filter that extends partway down. The model can also simulate erosion of a small circular hole that extends across the embankment, below a partial vertical filter.

The erosion of foundation fissures can be simulated for two optional conditions. The one option is to simulate fissure erosion underneath cutoff walls at the up- and downstream ends of the embankment, intended to protect the foundation against erosion (the objective is to lengthen the flow path and thus reduce the erosive capacity of the water). The other option is to simulate erosion of a fissure below a lowered embankment. As in the former case, the intent is to lengthen the flow path by lowering the base of the embankment.

Table 1. Typical model types representing varying initial embankment crack and dam foundation fissure configurations.

Model Number	Description
Breach Model 1	Overtopping of embankment
Breach Model 2	A transverse crack across an embankment that originates at the crest of the dam and continues for some distance below the crest. The embankment does not include a center filter or barrier
Breach Model 3	A transverse small circular / square hole that is located below a filter or barrier within the embankment and traverses across it in a downstream direction.
Breach Model 4	A transverse vertical crack below a filter in the embankment that traverses across the embankment in a downstream direction.
Breach Model 5	A transverse fissure in the Pleistocene foundation of an earth embankment that traverses across the embankment footprint with cutoff walls at the up- and downstream ends of the earth embankment.
Breach Model 6	A transverse fissure in the Pleistocene foundation below an earth embankment that traverses across the embankment footprint below a lowered base of the embankment.

The maximum extent of a breach and the time to breach completion are dependent on the magnitude and spatial distribution of the erosive power of water, and on the erosion characteristics of the soil. The magnitude of the erosive capacity of water (expressed as either shear stress or stream power) is a function of the potential energy of the water contained in the reservoir and on the geometric properties of a crack or fissure. The magnitude and spatial distribution of the erosive power of water flowing through cracks or fissures under pressure (Breach Models 3, 4 and 6) differs from that in Breach Models 1, 2 and 5, which are essentially open channel flow scenarios.

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The model calculates variation in the erosive capacity of the water in the cracks and fissures as a function of time due to changes in the water surface elevation within the reservoir (its potential energy) and as a function of space due to changes in the dimensional characteristics of a breach, particularly its width and width-depth ratio. The latter two properties play a role in determining flow type, i.e. whether flow is laminar, transitional or turbulent, and dictates the distribution of the erosive capacity of water along the edges of cracks and fissures. The erosive characteristics of laminar and turbulent flow differ.

The width-depth ratio of an opening determines how the erosive capacity of the flowing water within a breach is distributed. If a crack or fissure consists of, say, a very narrow rectangular section, most of the erosive capacity of the water will be applied to the long sides of the rectangle (vertical sidewalls of the crack or fissure), and very little will be applied to the narrow sides of the rectangle (the bottom and top of the crack or fissure). As a crack or fissure widens, the distribution of the erosive capacity of the flowing water along the edges of the feature change. Using research by Knight and Patel (1983) it is possible to develop equations for calculating the distribution of the erosive capacity of the water along the edges of the widening cracks and fissures.

Erosion rate is dependent on the relationship between the erosive capacity of water and the soil properties. Test procedures specifically designed to relate erosion rate of a soil to the erosive power of water can be used to characterize the soils. Typical procedures include using the Erosion Function Apparatus (EFA) (Briaud et al. 2001) or the Vertical Jet Tester (VJT) apparatus (Hanson and Simon 2001). Using test results from site-specific samples it is possible to develop breach models that represent site-specific erosion conditions.

CRACK AND FISSURE HYDRAULICS

The model simulates flow for three different cases:

Case 1
The flow in the fracture / crack is laminar and the distribution of applied stream power is shown in Figure 1. The applied stream power is calculated based on the assumption of laminar flow.

Case 2
The flow is turbulent, but the fracture / crack is still very narrow. The largest portion of the stream power is applied to the vertical sides, as illustrated in Figure 1. The applied stream power is calculated based on the assumption of turbulent flow.

Case 3
The flow is turbulent and the fracture has widened to the extent that the distribution of the erosive capacity of the water can be more appropriately expressed by relationships developed by Knight and Patel (1983). These distributions differ slightly for pressurized and free surface flow.

In what follows the procedure used to simulate breach formation is explained in terms of stream power. Applied stream power per unit area can be expressed as

$$P = \int \left(\tau \cdot \frac{dv}{dy} \right) \cdot dy \qquad (0.1)$$

where P = applied stream power, $\tau \cdot \frac{dv}{dy}$ = applied stream power per unit volume of water, $\hat{o}$ = shear stress, v = flow velocity, y = distance from boundary.

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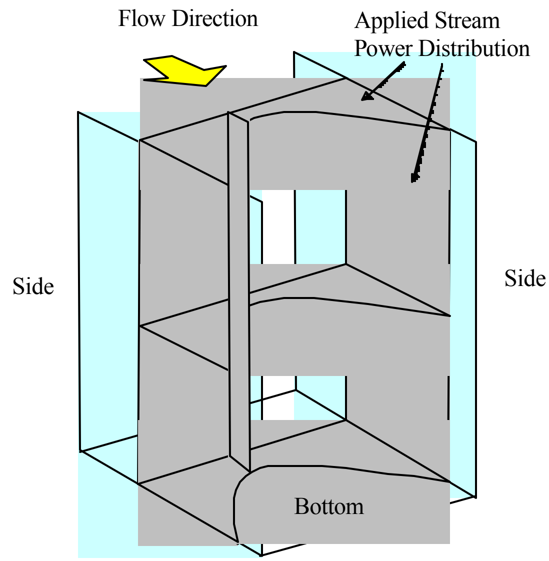

Figure 1. Distribution of Stream Power withink a narrow vertical space. The characteristic dimension is the width of the fissure, which is very small.

The distribution of applied stream power is a function of the width-depth ratio of a fracture. When the fracture is very narrow, the stream power is mainly applied to the vertical sides. Figure 1 shows that the applied stream power is greater at the sides than what it is in the middle of the flow section. This makes sense, because the velocity gradient (*dv/dy*) is greatest close to the boundary. The variation in velocity and shear stress in the vertical direction in a very narrow vertical crack is small because the critical dimension is in the horizontal direction. Therefore representation of the variation of stream power in the vertical direction is assumed to be negligible.

The stream power applied to the bottom of the opening increases when erosion increases the fissure width and the distribution of stream power is similar to that shown in Figure 2 for pressure flow and to that shonw in Figure 3 for free surface flow.

As a breach widens, the proportion of the total stream power applied to the bed increases and that applied to the vertical decreases. This change in the distribution of applied stream power is most probably the principal factor limiting the maximum width of a breach. When the applied stream power on the sides decreases to a value below the threshold stream power continued widening of the breach ceases. This phenomenon explains the observation that dam breaches oten reaches a maximum width, and then ceases to widen further.

BREACH SIMULATION CONCEPT

The simulation of breach formation requires relating the rate of erosion of a soil to the erosive capacity of flowing water. A relationship between rate of erosion and applied stream power, schematically shown in Figure 4, can be developed by making use of the Erosion Function Apparatus (EFA) or the Vertical Jet Tester (VJT) (see section dealing with geotechnical data).

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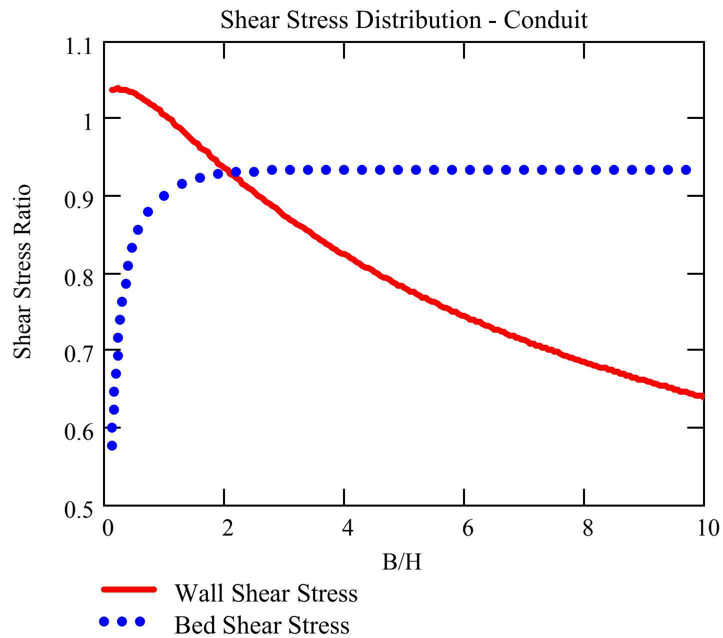

Figure 2. Distribution of shear stress under pressure flow conditions as a function of the width/depth ratio (B/H).

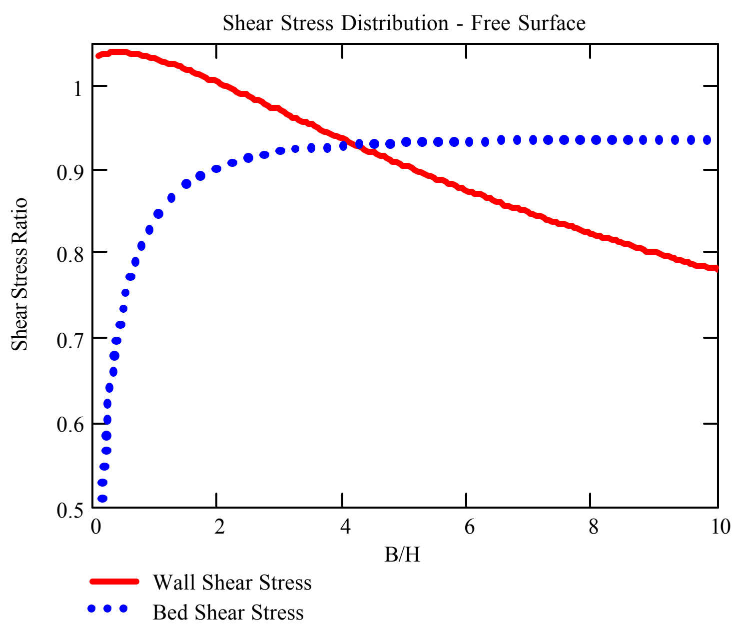

Figure 3. Distribution of shear stress under free surface flow conditions as a function of the width/depth ratio (B/H).

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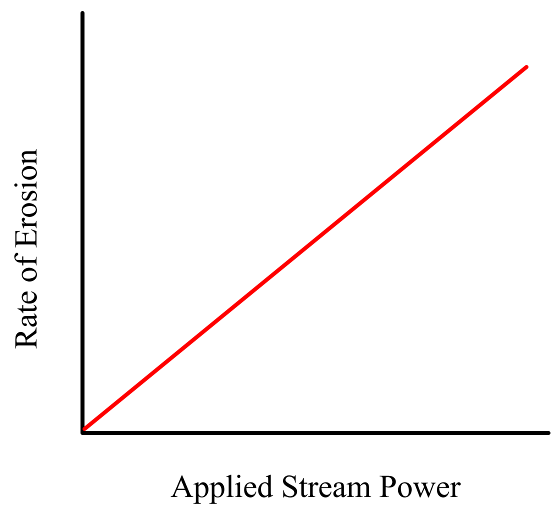

Figure 4. Schematic presentation of rate of erosion as a function of stream power.

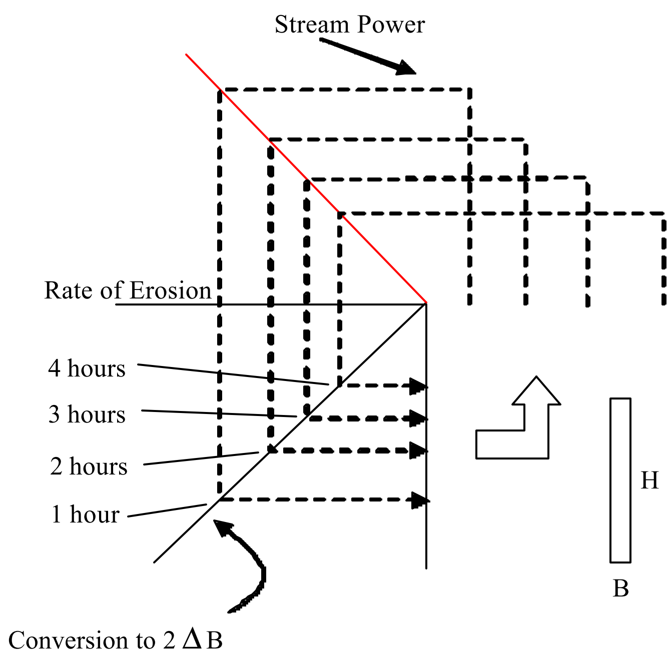

Figure 5. Breach calculation procedure, illustrating tendency to reduced rate of widening of breach.

The concept used to calculate the widening of the breach is illustrated in Figure 5. The elements of the calculation procedure consists of estimating the total stream power (or shear stress) and its distribution on the vertical and horizontal sides (the top right segment in Figure 5 – similar to Figure 1 or Figure 2), estimating the rate of scour (the top left segment of Figure 5– Similar to Figure 4 turned on its side) and once the change in width of the section is known (bottom left segment in Figure 5), re-calculate the aspect ratio and re-enter the top right segment again. If one uses a one hour time-step, then the scour is equal to the scour rate during that time step. The scour on each vertical side (wall of the fissure or crack) is equal, and one needs to convert the estimated scour to $2 \cdot \Delta B$ before calculating the revised width/depth ratio for calculations during the next time step. The procedure is repeated until erosion ceases. Figure 5 illustrates how the rate of lateral erosion decreases as the section widens.

GEOTECHNICAL DATA

The rate of erosion of earth materials were determined by making use of the Erosion Function Apparatus (EFA) (Briaud et. al, 2001) and the Vertical Jet Tester (Hansen 2001). The EFA subjects undisturbed soil samples to flowing water that is discharged over it at varying velocities. As the velocity and the shear stress in the apparatus changes the earth material is eroded from the exposed soil surface at varying rates. When the soil is removed the sample is pushed upwards into the apparatus to maintain contact between the flowing water and the sample. The rate at which the sample is moved upwards to maintain contact with the flowing water is recorded, as is the flow velocity in the apparatus. Once the test is complete, the shear stress acting on the sample is estimated by assuming that the Moody diagram applies to the apparatus. The relationship between shear stress, flow velocity and rate of erosion is then composed.

The Vertical Jet Tester apparatus is used to conduct in-situ tests on site. A jet is projected into the soil, which causes erosion. The rate of erosion is measured, and the information analyzed in a specified way to calculate the critical shear stress ($\hat{o}_c$) and the erosion rate coefficient (k_d) used in the equation below. The procedures to calculate the values of τ_c and k_d are not discussed here due to space limitations. The erosion rate of the soil is expressed as,

$$\varepsilon_{rate} = k_d \cdot (\tau - \tau_c) \text{ where } \varepsilon_{rate} = \text{erosion rate.} \tag{0.2}$$

Comparing the test results of the VJT and EFA tests typically results in the EFA providing much greater rates of erosion than the VJT (Figure 6). The reason for this might be found in the way shear stress is calculated when using the EFA testing procedure. The assumption that the Moody Diagram is applicable to calculate the shear stress over the sample in the EFA apparatus could possibly underestimate the magnitude of the shear stress over the sample, providing an overestimation of the rate of erosion for a particular value of shear stress.

VERIFICATION

The verification of breach formation in the embankment materials were conducted for erosion tests conducted on samples taken at a dam in Arizona for minimum and maximum representative erosion rates. The selection of these two sets of erosion rate test results was made by plotting all the EFA results on one graph (Figure 7). The erosion rate represented by sample RB-1H (3' to 5") is considered un-characteristically high, and was ignored for purposes of verifying the program. The red and blue dashed lines on the graph were fitted to the assumed maximum and minimum erosion rates for embankment material.

The simulation results using the maximum and minimum erosion rates are presented in Table 2. In general, the results indicate less erosion when the erosion rate is low, and vice versa. This is not immediately obvious for Breach Model 1, but the trend is reflected in the longer time required to breach to its maximum dimension. Comparison with published Width to Depth (W/H) ratios (Table 3) of known breach dimensions of failed earth embankment dams confirms that the simulated breaches are comparable with published results, as are the times to breaching.

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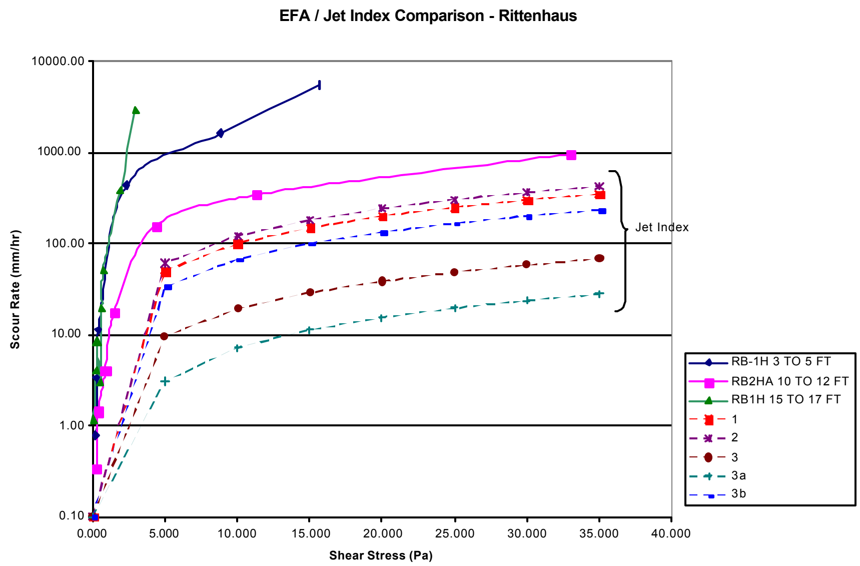

Figure 6. Comparison between rate of erosion test results obtained from teh EFA and the VJT Testing Procedures.

By comparing the simulation results with width / depth ratios (W/H) published by various authors as shown in Table 3, it can be concluded that the simulated values are generally on the low side, but within range for most data.

Fell et al. (2003) present a method to approximate the time for progression of internal erosion and piping, and development of a breach leading to failure of embankment dams. The method accounts for the nature of the soils in the dam when estimating the time to breach. Using this approach, and assuming the lower bound of erosion rate, application of the Fell et al (2003) approach yields a breach time of 12 to 48 hours. For the higher erosion rate, the Fell et al (2003) approach yields a breach time ranging between 3 to 12 hours. The comparison between estimated breach times using Fell (2003) and the developed program is favorable, except for Breach Model 2. The reason for this is that Fell (2003) does not consider breaching initiated by a vertical crack in an embankment, which is the initiating imperfection for Breach Model 2.

Comparing these values with those simulated, it is concluded that the simulated times to breach falls mostly within the estimates for the lower bound erosion rate using Fell et. al (2003). The times to breach, assuming a higher erosion rate, are slower than those calculated using Fell et. al (2003).

CONCLUSION

The paper summarizes the concepts used to develop a computer model to simulate dam breaching by overtopping, vertical embankment cracks, small circular holes through an embankment and foundation fissures. The model has been favorably verified for embankment breaching by comparing simulation results with published dimensions of dam breaches and Fell et al. (2003)'s method for calculating time to breach. The computer program is intended for use in preparing mitigation designs for embankment dams with desiccation cracks and foundation fissures.

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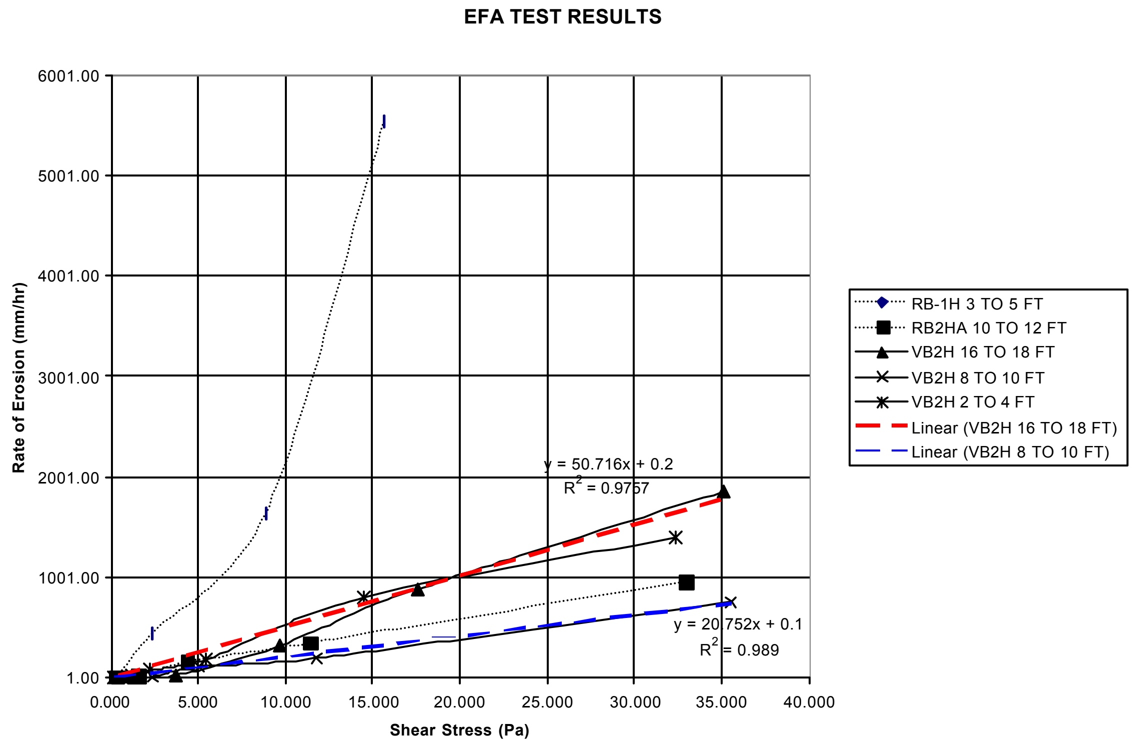

Figure 7. EFA Test Results plotted on a natural scale.

Table 2. Simulation Results using assumed minimum and maximum erosion rates from Figure 12.

Scenario	Minimum Erosion Rate VB2H 8' to 10'			Maximum Erosion Rate VB2H 16' to 18'			
	Final Size	W/H	Time (h)	Final Size	W/H	Time (h)	
Breach_Model 1	104.1' W x 20' H	5.21	10h	100.9' W x 20' H	5.05	5h	Depth of
Breach_Model 2	14.6'W x 14'H	1.04	40h*	44'W x 20'H	2.2	65h	Depth of
Breach_Model 3	8.5'W x 8.5'H	1.00	22h	24.5' W x 20' H	1.2	16h	1"x1" squ
Breach_Model 4	35'W x 20'H	1.75	18h	48'W x 20'H	2.4	14h	10' slot, 1

Note: The test results for RB-1H 3' to 5' has such high erosion rates that it is not considered reasonable.
* The time for this breach is less than that for the higher erosion rate because the water surface plunges below the bottom of the fissure prior to all the water flowing from the reservoir.

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Table 3. Published Width / Depth Ratios of observed dam breach dimensions.

REFERENCE	RATIO	COMMENT
Johnson & Illes (1976)	0.5H < W < 3H	The simulated B/H ratios for simulated embankment breaching all lies within the range indicated.
Singh & Snorrason (1982, 1984)	2H < W < 5H	The ratios for the maximum erosion rate used in the simulations generally falls within the range.
FERC (1987)	2H < W < 4H	The ratios for the maximum erosion rate used in the simulations generally falls within the range.
Reclamation (1988)	Breach Width = 3H	The simulated breach widths are generally smaller than the ratio proposed by the Bureau of Reclamation.

REFERENCES

Briaud, J.L., Ting, F.C.K., Chen, H.C., Cao, Y., Han, S.W. and Kwak, K.W. 2001. "Erosion Function Apparatus for Scour Rate Predictions", Journal of Geotechnical and Geoenvironmental Engineering, Vol. 127, No. 2.

Knight, D.W. & Patel, H.S. 1983. "Boundary Shear in Smooth Rectangular Ducts" Journal of Hydraulic Engineering, Vol. 111, No. 1, January 1985, ASCE.

Fell, R.; Wan, C.F.; Cyganiewicz, J.; and Foster, M. 2003. "Time for Development of Internal Erosion and Piping in Embankment Dams" Journal of Geotechnical and Geoenvironmental Engineering, Vol. 129, No. 4, April 1, 2003.

Hanson, G.J. 2001. "Field and Laboratory Jet Testing Method for Determining Cohesive Material Erodibility". Proceedings of the Seventh Federal Interagency Sedimentation Conference, Reno, Nevada. March 2001.

Hanson, G.J. and Simon, A. 2001. Erodibility of cohesive streambeds in the loess area of the midwestern USA, Hydrological Processes, 15, pp 23-38.

Johnson, F.A. and Illes, P. 1976. "A Classification of Dam Failures" International Water Power and Dam Construction, December 1976, p. 43-45.

Singh, K.P. and Snorrason, A. 1982. "Sensitivity of Outflow Peaks and Flood Stages to Selection of Dam Breach Parameters and Simulation Models, SWS Contract Report 288, Illinois Department of Energy and Natural Resources, State Water Survey Division, Surface Water Section at the University of Illinois, 179p.

Singh, K.P. and Snorrason, A. 1984. "Sensitivity of Outflow Peaks and Flood Stages to the Selection of Dam Breach Parameters and Simulation Models", Journal of Hydrology, Vol 68, P. 295-310.

Federal Energy Regulatory Commission (FERC) 1987. Engineering Guidelines for the Evaluation of Hydropower Projects, FERC 0119-1, Office of Hydropower Licensing, July 1987, 9p.

U.S. Bureau of Reclamation, 1988. "Downstream Hazard Classification Guidelines", ACER Technical Memorandum No. 11, Assistant Commissioner-Engineering and Research, Denver, Colorado, December 1988, p. 57.