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Spillway and Dam Foundation Erosion: Predicting Progressive Erosion Extents

by
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Introduction

Allowing a concrete dam to overtop during extreme flood events is an alternative to spillway augmentation. Designing for dam overtopping requires an analysis of the erosion potential of the dam foundation and abutments. Current formulas for evaluating erosion have limited applicability. Existing formulas do not track erosion as a function of time, and have limited application in hard-rock or cohesive foundation materials.

PG&E, EPRI, Reclamation, Colorado State University, and HDR Engineering are collaborating on improving technology for estimating the progressive extents of dam foundation erosion due to overtopping. This paper compares erosion prediction methods, and explains the basis for the development of new technology. The primary objective of the investigation is to develop a scheme for estimating the progressive extents of erosion for cohesive and noncohesive materials as well as fractured rock masses. The investigation involves researching existing methods and data, conducting a systematic series of physical model tests, and developing a numerical model for simulating the progressive extents of erosion. A numerical model with properly formulated boundary conditions, simulating physical processes rather than parametric empirical correlation, will provide a useful tool for estimating progressive extents of dam foundation erosion.

Erosion Prediction Technology

Mason and Arumugam (2) list 31 methods of calculating scour depth, and divide these into five groups. The first group, 17 equations, relates scour depth to discharge, head drop and characteristic particle size. The second group, 2 equations, adds the impact of tailwater depth. The third group, three equations, is empirical in nature, and relates estimated scour depth to jet dimensions and characteristics. The fourth group, eight equations, developed by six Russian authors, relate scour depth to drop height, particle diameter, tailwater depth and the angle with which the falling stream enters the downstream area. The fifth group, one equation, is for equations that include a time parameter. Mason (3) also treats the impact of air entrainment on plunge pool scour. The equations and associated coefficients of Mason and Arumugam (2) and Mason (3) are state of the art.

Veronese (4) and Mason (2) developed the most prominent scour equations. Equation 1 is the Veronese equation. Reclamation includes the Veronese equation in Design of Small Dams (1).

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$$D = 1.32 H^{0.225} q^{0.54} \tag{1}$$

D = depth of scour below tailwater (in feet).
H = effective head (in feet).
q = unit discharge (in ft^3/s-ft).

The Veronese equation is unbounded, does not consider tailwater and neglects material properties. Equation 2 is the Mason equation. Note that the Mason equation is dimensionally homogeneous.

$$D = \frac{3.27 q^{0.60} H^{0.05} h^{0.15}}{g^{0.30} d^{0.10}} \tag{2}$$

h = tailwater depth
d = d_{90} of foundation material
g = acceleration of gravity

The Mason equation is also unbounded, and while it does include a material factor, d, it is unlikely that this factor adequately represents the wide variety of materials and material properties encountered in dam foundation are abutment areas. The Mason formula is the product of thorough research, a comprehensive set of data, including scale model studies and prototype case studies, and a superior dimensional analysis that results in dimensional homogeneity of the formula.

New Technology

Erodibility Index, K_n

Hydraulic erodibility is a threshold condition expressed with a graphical relationship or an equation. At the erodibility threshold the agitating agent and the capacity of the material to offer resistance to erosion are related in the following functional manner:

$$P = \mathrm{f}(K_n) \tag{3}$$

P= magnitude of the agitating agent
$\mathrm{f}(K_n)$ = functional capacity of the material to resist erosion
K_n = Erodibility Index

The capacity of earth material to resist erosion is a function of its strength. Mass strength, particle/block size, interparticle bond strength, relative shape and orientation determine the strength of earth material. The Erodibility Index, K_n, is a rigorous method representing the strength of earth material. Annandale describes the Erodibility Index (5) The index represents the ability of earth material to resist erosion by the expression

$$K_n = K_m \cdot K_b \cdot K_d \cdot K_s \tag{4}$$

K_n = Erodibility Index
K_m = Mass strength factor
K_b = Particle/Block size factor
K_d = Interparticle bond strength factor
K_s = Relative shape and orientation factor.

The agitating agent in the case of the hydraulic erodibility of earth material is the erosive power, P, of water discharging incident to or over the material. The rate of energy dissipation, is a measure of the erosive power of discharging water. The greater the rate of energy dissipation, the greater the magnitude of pressure fluctuations, and the greater the erosive impact. The following relationship is an expression for the Rate of Energy Dissipation.

$$Rate\,of\,Energy\,Dissipation = \gamma q \Delta E \tag{4a.}$$

γ= Unit weight of water
v= Velocity

$$\Delta E = \frac{v^2}{2g} \tag{4b.}$$

If $P > \mathrm{f}(K_n)$ the erodibility threshold has been exceeded and the material will erode. Conversely, if $P < \mathrm{f}(K_n)$ the erodibility threshold is not exceeded, and erosion will not occur. Figure 1 shows the threshold relationship in graphical form. The data that forms the threshold relationship in Figure 1 comes from an analysis of 150 field observations, including 137 made by the SCS (NRCS) and ARS at emergency spillways in Kansas, Arkansas. The Study Team developed an algorithm, utilizing this threshold relationship, that will estimate the erosion of diverse types of earth materials. The following section presents the algorithm, explaining the procedures for estimating the progressive extents of erosion.

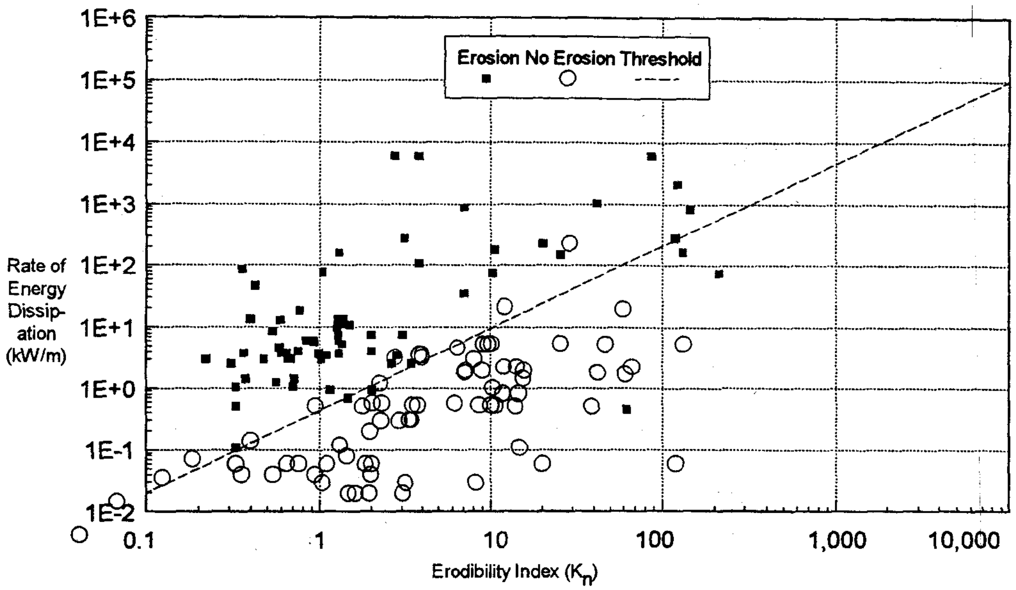

Figure 1. Graphical depiction of erosion threshold.

Erosion Prediction Algorithm

1. Express geomechanical properties as an erodibility index. Determine the erodibility index through field and laboratory investigations and create index database.
2. Fit a three-dimensional (3-D) grid to known geology and topography. A 3-D grid creates a computational grid that is cubical in nature.
3. Assign a radial vector to each face of each cube, where the vector magnitude and direction represent the erodibility index on that face for all directions of flow.
4. Create an accounting system for fluid and material continuity and global timer.
5. Correlate hydraulic agitation and erosion (Figure 1).
6. Correlate displacement and hydraulic agitation. In most formulae, displacement is a function of particle size and hydraulic agitation. Many procedures that correlate displacement and hydraulic agitation already exist.
7. Start the global timer
8. Input boundary conditions, that is, ODF (Outflow Design Flood) and tailwater (HEC 2).
9. Predict the flow patterns in developing scour hole.
10. Determine hydraulic agitation based upon flow patterns.
11. Predict dislodgement based upon threshold relationship.
12. Predict displacement. Dislodgement and displacement multiplied by the time step gives the volume of material removed per time step.
13. Use the resulting topography as feedback to hydraulic agitation and erodibility. The updated flow field is input into reevaluating the erodibility of the newly exposed faces.
14. Increment the global timer and return to step 9.

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Modeling

Colorado State University and the Study Team are conducting experiments in a 1:3 scale model and a prototype scale model at their Hydraulic Laboratories. The 1:3 model provides an economy of scale, accurately modeling hydraulics, with scale effects distorting material properties and aeration effects. Accurate simulation of air-water and water-material interaction without scale effects requires a prototype scale model. The 1:3 model is in place at the Hydraulics Laboratory, Colorado State University Engineering Research Center. The prototype model requires moderate modification of the existing overtopping facility at Colorado State University. Figure 2, 3 and 4 show the 1:3 scale and prototype models.

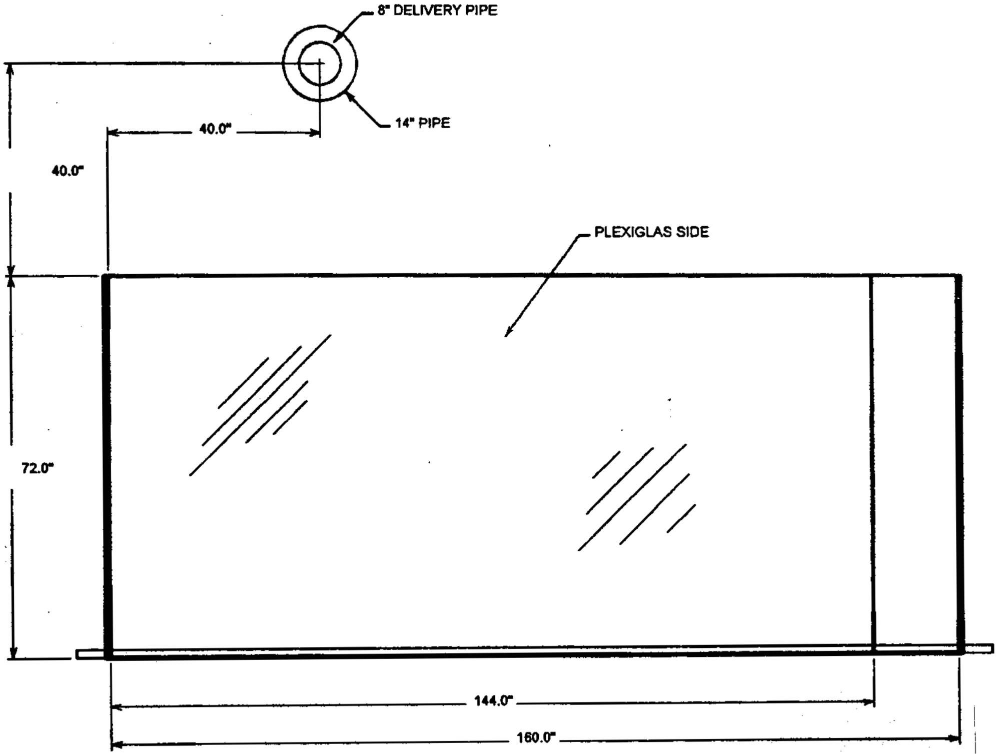

Figure 2. Side elevation of basin with orifice.

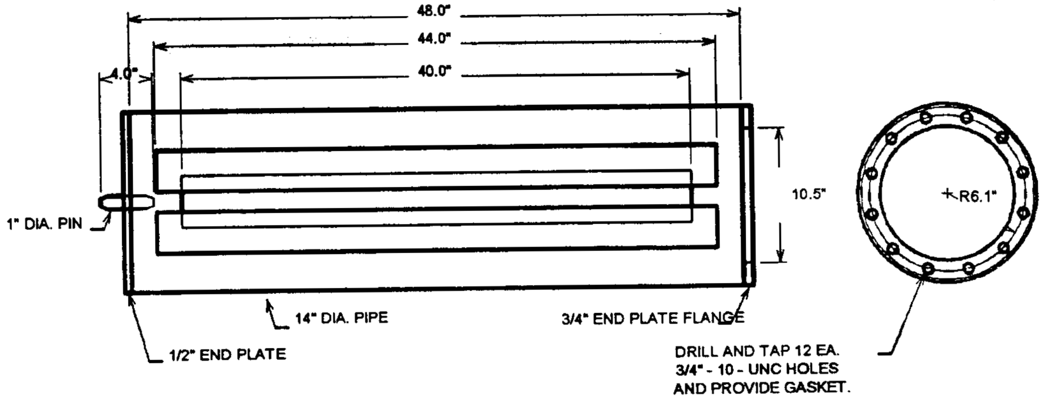

Figure 3. Orifice discharge pipe.

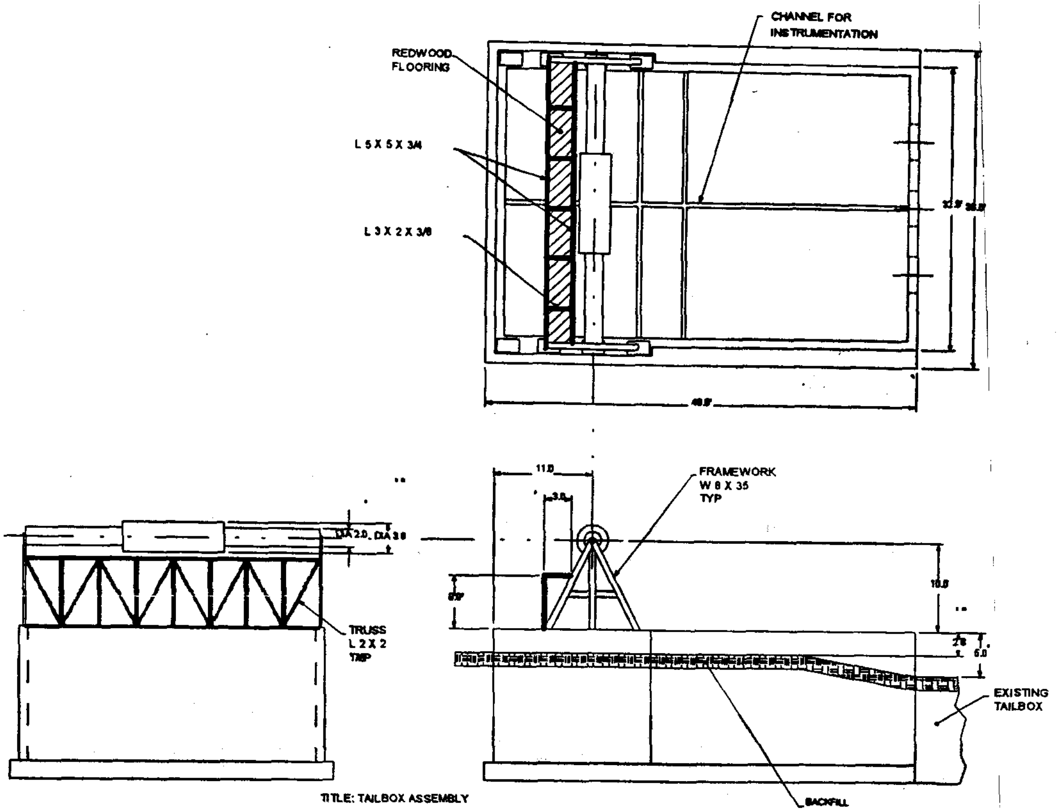

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Figure 4. Plans for the prototype scale facility.

Conclusions

Dam owners may realize considerable cost savings when designing for large outflow design floods by permitting the overtopping of dams, rather than augmenting spillway capacity. Determining the feasibility of an overtopping option requires tools for analyzing the structural stability of the dam foundation and abutment areas, accounting for erosion that will occur during overtopping. The goal of this cooperative study by PG&E, Reclamation, Colorado State University, the Electric Power Research Institute, and HDR Engineering, Inc., is to provide Dam Safety officials with such a tool. Scale and prototype modeling will help to ensure a reliable, accurate numerical scheme for estimating the progressive extents of erosion in the foundation areas of overtopped dams.

Key Words

Dam Foundation Erosion, Dam Safety, Overtopping, Spillway Erosion, Erodibility

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