Prototype Validation of Erodibility Index for Scour in Fractured Rock Media

by
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ABSTRACT

This paper summarizes an experiment simulating the erosion of a simulated rock mass by an impinging jet. Light weight concrete blocks, placed in two layers and dipped 45 degrees in the downstream direction, simulate a fractured rock mass. A jet impinging at an angle of less than fifteen degrees from the vertical simulates flow overtopping a dam. The experimental hypothesis states that a geomechanical index defines an incipient motion threshold for rock and other earth materials by relating the erosive power of water to the relative ability of earth materials to resist erosion. This experiment confirms the hypothesis.

Introduction

In 1992 Pacific Gas & Electric Co., the Electric Power Research Institute, Reclamation, Colorado State University, and Dr. George Annandale formed the Dam Foundation Erosion Study Team. That study team developed an hypothesis for estimating the progressive extents of dam foundation erosion due to overtopping. The objective was a new approach to estimate the extents of erosion coupling hydraulics and a geomechanical index system. Since that time the study team has worked towards the experiment described in this paper, and two companion papers [1] [2], as confirmation of the geomechanical index hypothesis.

The experiments by the Dam Foundation Erosion Study Team are aimed at improving technology for predicting and analyzing scour in the foundation areas of dams, below spillways, and in plunge pools. This paper summarizes an experiment simulating the erosion of a simulated rock mass by a impinging jet. Light weight concrete blocks, placed in two layers and dipped 45 degrees in the downstream direction, simulate a fractured rock mass. A geomechanical index describes the relative ability of the simulated rock mass to resist erosion. The rate of energy dissipation describes the relative erosive power of the water jet.

Dam Foundation Erosion Hypothesis

Earlier researchers compiled and correlated data pertaining to plunge pool erosion. Spurr and Mason concluded that further research into the rate of plunge pool development and the impact of varying rock types on erosion was necessary. Spurr [3] in a discussion of a paper by Mason [4] summarizes the problems with current foundation erosion prediction schemes:

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> *"Thus the discusser contends that time must be considered together with the unique hydraulic and geological processes existing at each site, the amount of surplus energy contained by a given jet at impact over and above the threshold resistance of the bedrock to scour, the shape of the sides of the scour hole, and the size of the downstream bar in order to determine the plunge pool's maturity before any meaningful comparison can be made. This is specifically true when predicting scour in any plunge pool which does not respond as though its bed material were essentially non-cohesive."*

Mason [5] in response to Spurr writes,

> *"The quantification of plunge pool scour rates, in conjunction with varying rock types is an area where much useful research remains to be done."*

The Dam Foundation Erosion study hypothesises that erodibility is a threshold condition that can be expressed in functional terms. At the erodibility threshold the agitating agent and the capacity of the material to offer resistance to erosion are equal.

$$P = f\left(K_h\right) \tag{1}$$

P = the magnitude of the agitating agent
f(K_h) *= the functional capacity of the material to resist erosion*

The agitating agent in this case is the erosive power of water discharging incident to or over the material. The capacity of the material to resist erosion can be described by means of an index that accounts for the relative contribution of the important elements determining the strength of the material. If $P > \mathrm{f}(K_h)$ the erodibility threshold has been exceeded and the material will erode. Conversely, if $P < \mathrm{f}(K_h)$ the erodibility threshold is not exceeded, and erosion will not occur. Annandale specified the functional relationship between P and K_h [6] using data obtained from US Department of Agriculture Soil Conservation Service records of emergency spillway scour and erosion.

Experiment Facility

A companion paper [2] describes the experimental facility and procedures. Briefly, the facility simulates overtopping and erosion in the foundation areas of a dam or spillway. The facility includes a basin, 10 m (30.5 ft) wide by 16.75 m (55 ft) long and 4.5 m (15 ft) deep, and an 8.7 cm (3.4375 in) by 3.05 m (10 ft) wide nozzle discharging up to 3.4 m^3/s (120 ft^3/s) at an angle of fifteen degrees from vertical. Figure 1 shows the facility including diffuser and nozzle, jet, layers of blocks, and the overall configuration of the experiment.

Dimensions of Block

The nominal dimensions of each fluted lightweight concrete block is 3x8x16 inches. Figure 2 details the commercially available concrete blocks. The flutes are roughly one-half inch wide by one inch deep transverse grooves in the face of the block, as Figure 2 illustrates.

$$\textit{Length, } L = 15.5\,in\,; \qquad J_x = 0.394\,m$$
$$\textit{Width, } W = 7.63\,in\,; \qquad J_y = 0.194\,m$$
$$\textit{Thickness, } T = 2.5\,in\,; \qquad J_z = 0.064\,m$$

Erodibility Index (K_h)

The Erodibility Index, K_h, is the product of the Mass Strength Number, M_s, the Block Size Number, K_b, the Shear Strength Number, K_d, and Relative Ground Structure Number, J_s [6].

$$K_h = M_s K_b K_d J_s \tag{1}$$

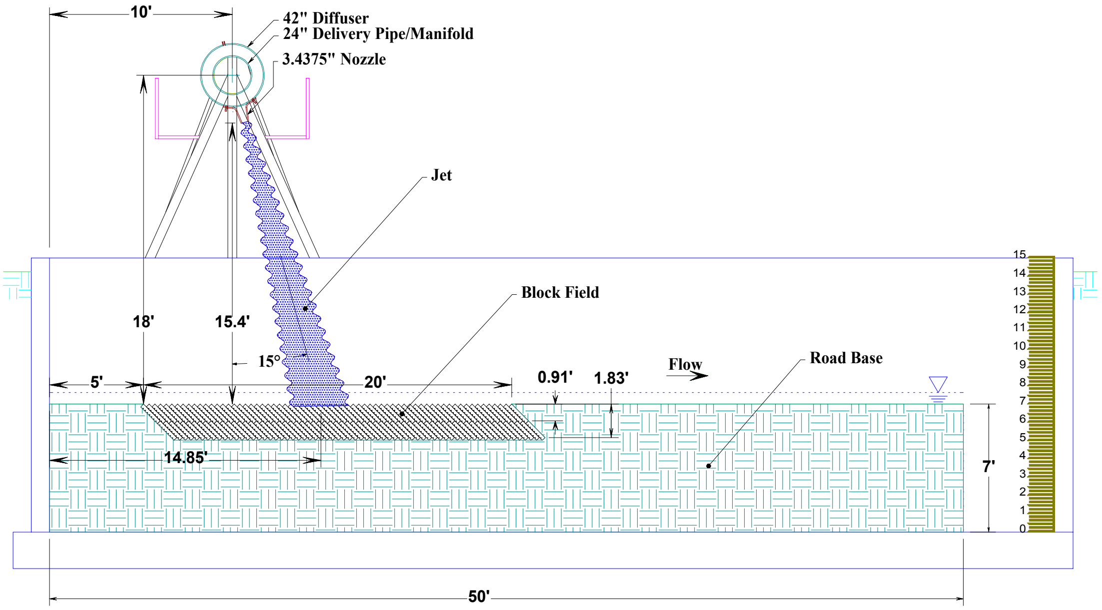

Figure 1. Profile of prototype facility. (flow is left to right)

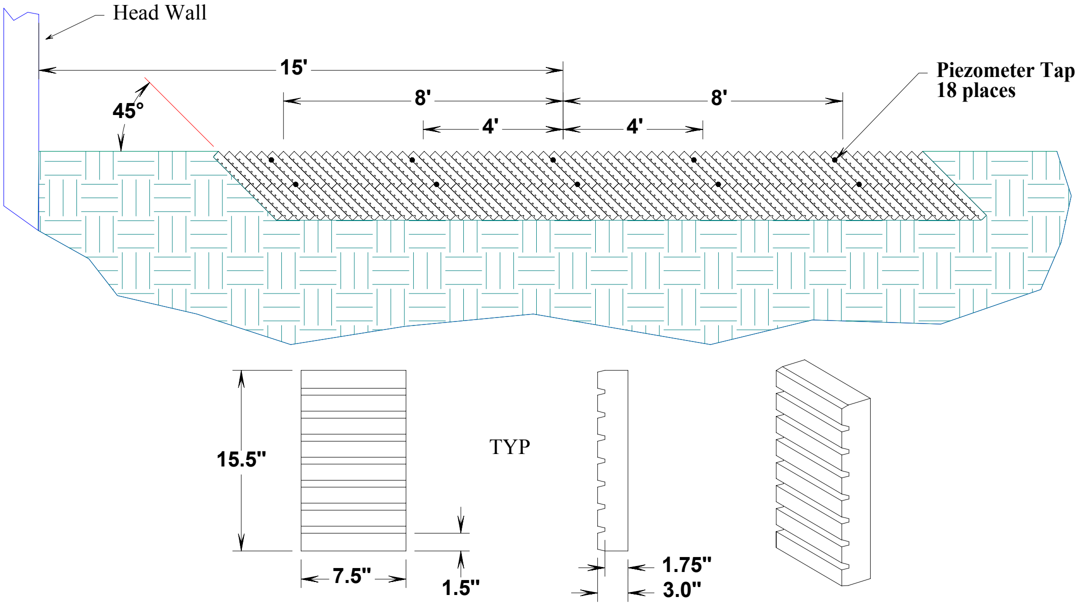

Figure 2. Concrete block details including locations of piezometer taps.

Mass Strength Number (M_s)

The Mass Strength Number, M_s, is equal to the product of the Unconfined Compressive Strength, UCS, of the material and the coefficient of relative density. The coefficient of relativity density is the ratio of the material's unit weight to the unit weight of good quality rock, γ_s, roughly 27 kN/m^3. The UCS and unit weight, γ_b, of the concrete blocks was reported by the manufacturer, the Clalite Concrete Products company of Denver, Colorado.

$$UCS = 21\,\mathrm{MPa}\left(3046\,psi\right)$$

$$\gamma_b = 15.73\,\mathrm{kN/m^3}\left(100\,\mathrm{Lb/ft^3}\right)$$

$$M_s = \frac{\gamma_b}{\gamma_s} 21 = \frac{15.73}{27.00} 21 \approx 12 \tag{2}$$

Block Size Number (K_b)

The Block Size Number, K_b, is a function of the Rock Quality Designation (RQD) and the Joint Set Number, J_n, described by Annandale [6].

$$K_b = RQD/J_n \tag{3}$$

The RQD is a function of the orthogonal dimensions of the particle, J_x, J_y, and J_z.

$$RQD = \left[105 - 10 \middle/ \left(J_x J_y J_z \right)^{0.33} \right] = 47 \tag{4}$$

The joint set number, J_n, for three joint sets, per Annandale [6] (Table 6), is 2.73.

$$K_b = RQD/J_n = 17 \tag{5}$$

Shear Strength Number (K_d)

The Shear Strength Number, K_d, is the ratio of the joint roughness number, J_r, and the joint alteration number, J_a.

$$K_d = J_r / J_a \tag{6}$$

For rough, irregular planar surfaces the joint roughness number, J_r, per Annandale [6] (Table 8) is 1.5. From Table 9 of Annandale [6], the value of J_a for a joint separation of approximately 5 mm is 2.0.

$$K_d = J_r / J_a = 1.5/2.0 = 0.75 \tag{7}$$

The interparticle friction angle corresponds to the arctan value of K_d, arctan(0.75) = 36.9°.

Relative Ground Structure Number (J_s)

From Annandale [6] (Table 7) the value of J_s for a 45 degree dip angle in the direction of flow, and a relative shape of 15.5/2.5 = 6 (i.e., a ratio of 1:6), is 0.44.

Erodibility Index Calculation

The product of the four numbers is an estimate of the erodibility index roughly equal to 69.

$$K_h = (12)(17)(0.75)(0.44) \cong 69 \tag{8}$$

Rate of Energy Dissipation

Turbulence dissipates kinetic energy as heat. Increases in turbulence intensity concurrently result in increased rates of energy dissipation. Therefore estimates of the rate of energy dissipation, *P*, represent the relative magnitude of fluctuating pressure, and thus the erosive power of the water. The total rate of energy dissipation is equal to the product of the unit weight of water, γ, the discharge, Q, and the change in energy, ΔE.

$$P = \gamma Q \Delta E \tag{9}$$

The rate of energy dissipation per unit area, *p*, is equal to the rate of energy dissipation divided by the horizontal projection of the area of the jet at impact, A_i.

$$p = \frac{\gamma Q \Delta E}{A_i} \tag{10}$$

In this application, the change of energy, ΔE, is equal to the total available energy between the nozzle and the tail water surface. This supposes that 100% of the total available energy is dissipated in the erosion process.

Rate of Energy Dissipation Calculations

Table 1 contains the calculations describing the hydraulic and energy dissipation parameters. The total head, *H*, is the sum of the nozzle elevation and the velocity head minus the tailwater elevation. The calculations assume that one-hundred percent of the total available head is converted into kinetic energy and dissipates between the nozzle and the water surface just downstream of the scour hole. For the purpose of this experiment, a jet width at impact value of 3.0 ft, corresponding to $p = 22.6$ kW/m^2, is indicated.

Table 1. Hydraulic and Rate of Energy Dissipation calculations.

Q	=	40	ft^3/s	1.133	m^3/s
Nozzle Elev.	=	22.44	ft	6.840	m
Velocity Head	=	3.74	ft	1.139	m
Tailwater Elevation	=	7.63	ft	2.326	m
Total H	=	18.55	ft	5.653	m
Jet Width	=	10.0	ft	3.048	m
Jet Thickness	=	3.0	ft	0.914	m
Density of Fluid	=	9.82	kN/m^3		
$p_{3.0}$	=	22.6	kW/m^2		

Hydraulic Cushion

Depth gages upstream and downstream of the jet impact zone report a depth of roughly 0.192 m (0.63 ft) or elevation 7.63 feet at 1.133 m^3/s total discharge. The tailwater depth, or hydraulic cushion, *h*, directly influences the scour potential of the jet and the rate of energy dissipation calculations. The cushion effect is minor in this experiment because the jet possesses momentum that displaces the tailwater and impacts directly upon the blocks.

Jet Thickness at Impact

Estimates by experiment observers of jet thickness at point of impact range from 2.5 ft (0.76 m) to 3.5 ft (1.07 m). The contraction coefficient for this vena contracta is roughly 0.95.

Field and Experimental Data Comparison

Figure 3 shows the experimental data in relation to the original field data and the threshold relationship proposed by Annandale [6]. The proximity of the experimental data to the threshold confirms the hypothesis that the Erodibility Index is applicable for overtopping conditions in earth materials.

Conclusions

The discharge in the prototype facility, and its associated rate of energy dissipation, was significantly larger than previous modeling attempts. Similarly, the material simulating the rock formation was substantially similar to a fractured rock mass. The Study Team successfully estimated the Erodibility Index factors for the simulated fractured rock mass. The experimental data point showing the erosive power of the jet and the relative ability of the simulated rock to resist scour is in proximity to the erodibility threshold defined by Annandale [6].

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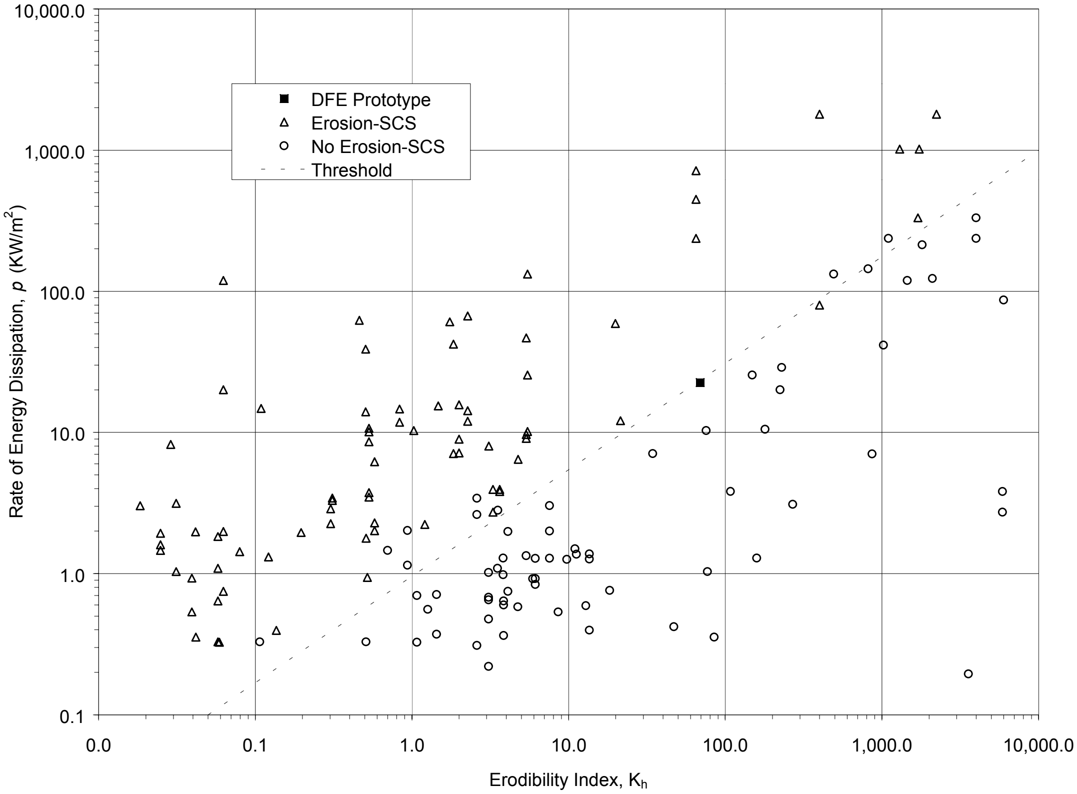

Figure 3. Comparison of experimental findings to field data and erosion threshold proposed by Annandale [6].

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