Prototype Validation of Erodibility Index for Scour in Granular Media

by
R.J. Wittler[1], G.W. Annandale[2], J.F. Ruff[3], S.R. Abt[4]

ABSTRACT

This paper summarizes twelve experiments simulating the erosion of a granular material by an impinging jet. A locally available road-base granular material simulates alluvial material found near a prototype dam. A jet impinging at angles of fifteen, twenty-five, and thirty-five degrees from the vertical simulates flow overtopping a dam. The balance of the power available to erode the material and the relative ability of the material to resist erosion determines the elevation of the scour. The calculated scour elevations agree with the experimental observations. This series of experiments demonstrates the capability of the Erodibility Index for estimating scour below hydraulic structures.

Experiment Facility

A companion paper [1] describes the experimental facility and procedures. 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 angles ranging from zero to forty-five degrees from vertical. Figure 1 shows the facility, nozzle, jet, granular material, and the overall configuration of the experiment.

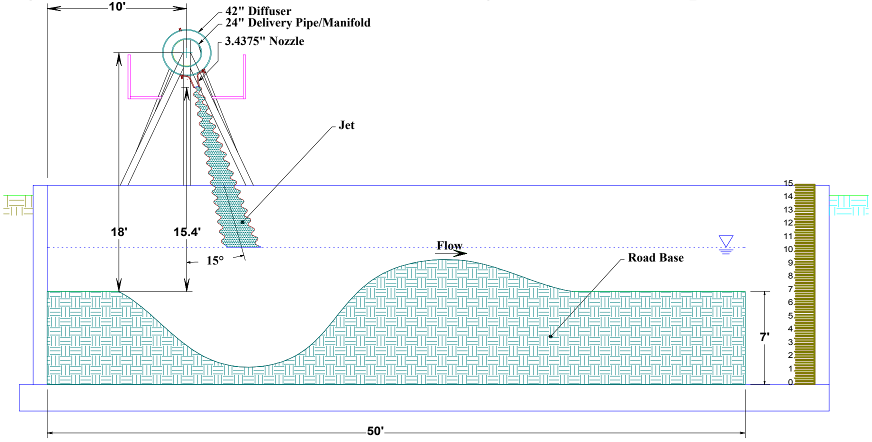

Figure 1. Profile of experimental facility at Colorado State University.

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[1] Hydraulic Engineer, US Bureau of Reclamation, D-8560, Denver, CO 80225

[2] Technical Director, Water Resources, Golder Assoc., 200 Union Blvd., Lakewood, CO 80228.

[3] Professor of Civil Engineering, Colorado State University, Ft. Collins, CO 80523

[4] Interim Associate Dean for Research, College of Engineering, Colo. St. Univ., Ft Collins, Colorado.

Experimental Parameters

This series of experiments varied the angle of issuance and the tailwater and material elevations. Tailwater elevation less material elevation is the hydraulic cushion. The cushion varied between 0.30 and 1.82 meters, in three steps. The jet issued at three angles of 15, 25, and 35 degrees. The combination of four cushions and three angles results in a matrix of twelve experiments. Table 1 lists the experimental parameters and related variables. The elevation datum of the experimental facility is the floor of the basin. Equation 1 gives the angle of jet impact, α, as a function of the nozzle velocity, v_0, the angle of issuance, ϕ , and the distance between the nozzle and tailwater, Δz. Other parameters include the discharge, Q, the velocity at impact, v_i, the air concentration of the jet at impact, A_i, the nozzle elevation, the water surface elevation, and the D_{50} (m) of the road-base material.

Table 1. Experimental parameters.

Experiment	ϕ	α	Q	v_o	v_i	A_i	*Noz. El.*	*WS El.*	Δz	D_{50}
1	15°	11.9°	2.74	10.82	5.75	64.7%	6.84	3.35	3.49	1.00E-02
2	15°	12.1°	2.74	10.82	5.80	63.1%	6.84	3.66	3.18	1.00E-02
3	15°	11.7°	2.74	10.82	5.72	66.0%	6.84	3.08	3.76	1.00E-02
4	15°	12.3°	2.74	10.82	5.86	61.5%	6.84	3.93	2.91	1.00E-02
5	25°	20.2°	2.74	10.82	5.85	61.7%	6.89	3.94	2.95	1.00E-02
6	25°	19.5°	2.74	10.82	5.75	65.0%	6.89	3.34	3.55	1.00E-02
7	25°	18.8°	2.74	10.82	5.65	68.3%	6.89	2.56	4.33	1.00E-02
8	25°	19.1°	2.74	10.82	5.69	67.0%	6.89	2.90	3.99	1.00E-02
9	35°	26.9°	2.74	10.82	5.74	65.3%	6.96	3.35	3.61	1.00E-02
10	35°	27.9°	2.74	10.82	5.84	61.9%	6.96	3.97	2.98	1.00E-02
11	35°	26.5°	2.74	10.82	5.70	66.7%	6.96	3.03	3.93	1.00E-02
12	35°	25.8°	2.74	10.82	5.65	68.4%	6.96	2.59	4.37	1.00E-02

$$\alpha = \arctan\left[\frac{v_0 \sin\phi}{\sqrt{\left(v_0 \cos\phi\right)^2 + 2g\Delta z}}\right] \tag{1}$$

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 [3].

$$K_h = M_s K_b K_d J_s \tag{2}$$

Mass Strength Number (M_s)

From Table 1 of Annandale [3] the Mass Strength Number, M_s, for granular soil between loose and medium density is equal to 0.07.

Block Size Number (K_b)

The particle Block Size Number, K_b, for cohesionless granular materials can be determined directly by Kirsten [4].

$$K_b = 1000 D_{50}^3 \tag{3}$$

A median grain size, D_{50}, of 10 mm yields a block size number equal to 1.00E-03.

Shear Strength Number (K_d)

For granular materials, the Shear Strength Number, K_d, crudely approximates tan(φ), where φ is the equivalent residual (minimum) friction angle [5]. This angle for the experimental material is roughly 40°, yielding a shear strength number equal to 0.84.

Relative Ground Structure Number (J_s)

The Relative Ground Structure Number, J_s, is equal to 1.0 for granular materials.

Erodibility Index Calculation

The product of the four numbers yields an erodibility index roughly equal to 5.87E-05.

$$K_h = (0.07)(1.00E-03)(0.84)(1.0) \cong 5.87E-05 \tag{4}$$

Required Power

From Annandale [3], the power (kW/m^2) required, p_R, to erode material is a function of K_h.

$$p_R = \frac{480}{1000} K_h^{0.44} \tag{5}$$

Available Power

The power (kW/m^2) available to erode material is a function of the jet hydraulics. From Bohrer [6] the velocity along the centerline of a jet in a plunge pool is a function of the velocity at impact, the angle of impact, the air concentration of the jet at impact, given by the ratio of air and water densities, and gravitational acceleration. Equation 6 describes this functional relationship, followed by the limits of application. Equation 7 yields the distance along the centerline.

$$-\ln\left(\frac{v}{V_i}\right) = -0.5812\ln\left[\left(\frac{\rho_i}{\rho_w}\right)\left(\frac{V_i^2}{gL}\right)\right] + 2.107 \tag{6}$$

$$-0.29 < \ln\left[\left(\frac{\rho_i}{\rho_w}\right)\left(\frac{V_i^2}{gL}\right)\right] < 2.6.$$

$$L = \frac{z_1 - z_2}{\cos\alpha} \tag{7}$$

Rate of Energy Dissipation

The rate of energy dissipation, or available power, is a discretized function of the total head at various elevations along the centerline of the submerged jet. Equation 8 shows a discrete calculation for the change in head between points j and j+1. As the velocity decays, with decreasing elevation, or increasing displacement along the jet centerline, the total head decreases. Equation 9 yields the corresponding available power.

$$\Delta E_j = \frac{v_j^2}{2g} - \frac{v_{j+1}^2}{2g} + \frac{P_j}{\gamma} - \frac{P_{j+1}}{\gamma} + z_j - z_{j+1} \tag{8}$$

$$p_{Aj} = \frac{\gamma v_j \Delta E_j}{1000} \tag{9}$$

Figure 2 plots both the required power, p_R, and the available power, p_A, for experiment 1.

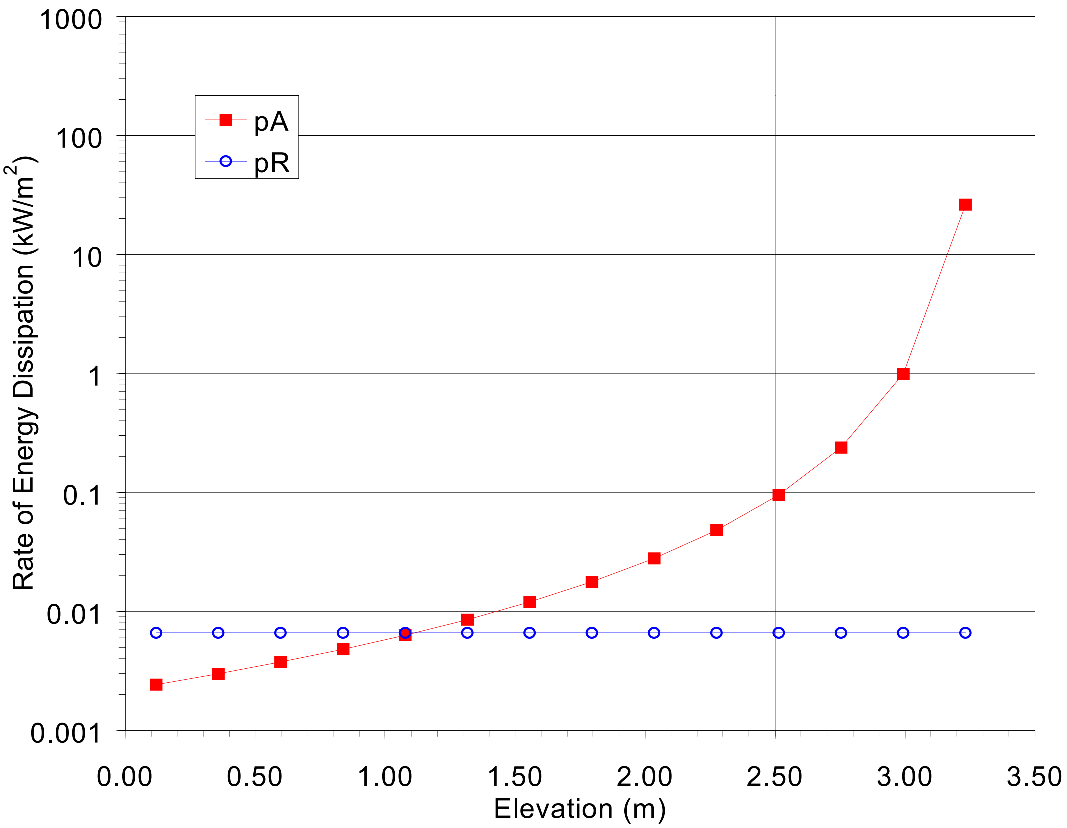

Figure 2. Power available and power required. Intersection indicates maximum scour.

Figure 3 is a similar plot for experiment 7. The intersection of the two power curves indicates the deepest elevation of scour. The required power curve plots horizontally because the road-base material is homogeneous. Thus K_h, the erodibility index, is constant throughout the material, both laterally and vertically. As predicted, the available power decreases with increasing depth, or decreasing elevation. The procedure accounts for angle of impingement and calculates the rate of energy dissipation along the centerline of the submerged jet. Air concentration influences the initial conditions. A hydrostatic pressure distribution is presumed in the head calculations. Research by Juergenson [7] indicates that a hydrostatic distribution is a safe assumption except in the zone very near the surface. Nevertheless, the empirical relationship by Bohrer (Equation 6) accounts for any non-hydrostatic effects near the surface.

Figure 4 shows the results of all twelve experiments. In comparison, the calculated scour elevations are very close to the observed scour elevations. In a companion paper [2] Annandale et al. confirm the hypothesis that the erodibility index is a valid means for expressing the relative ability of earth material to resist erosion. They also confirm that the rate of energy dissipation, or stream power, quantifies the relative ability of flowing water to erode earth materials. The analysis in this paper demonstrates the applicability of the erodibility concept to granular materials in a variety of hydraulic conditions. This new procedure for estimating the depth of scour in a plunge pool accounts for angle of impact, aeration of the jet, hydraulic cushion, and material properties. Empiricism is limited to the relationship between the erodibility index and rate of energy dissipation, and velocity decay in a plunge pool. Otherwise, the procedure directly calculates the scour in a plunge pool.

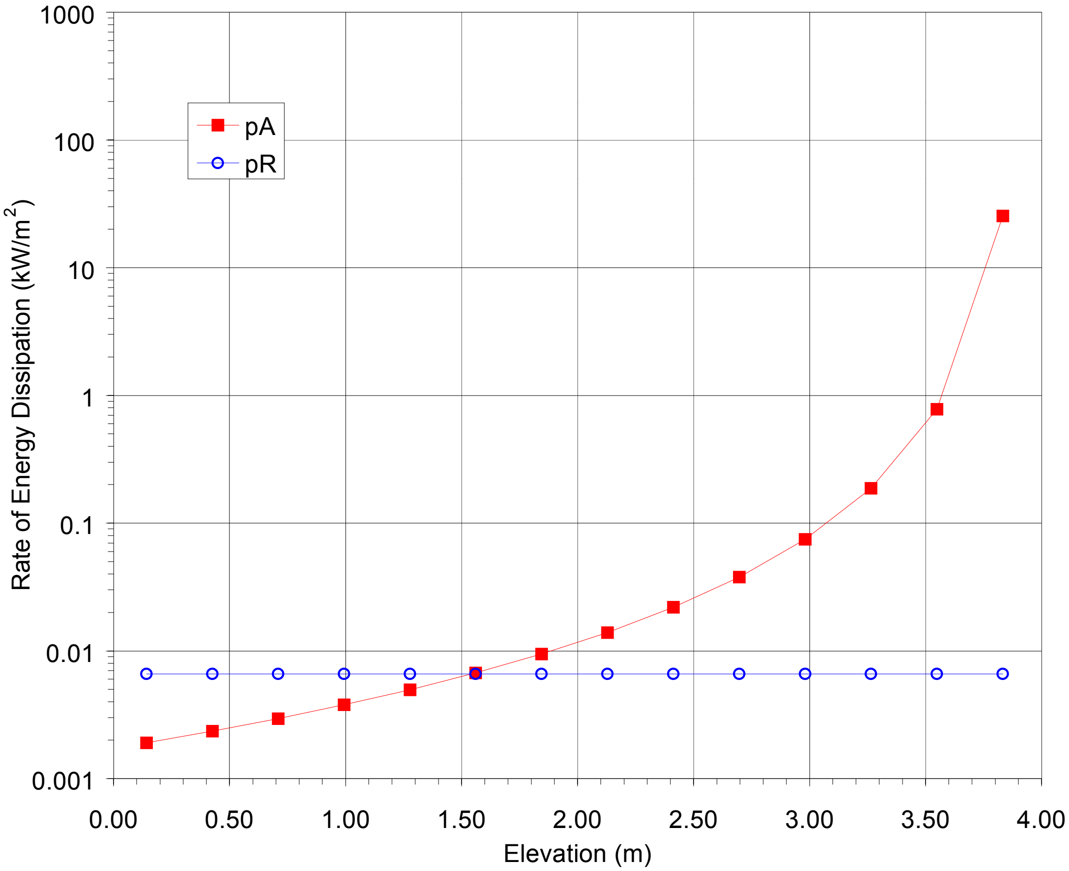

Figure 3. Power available and power required. Experiment 7.

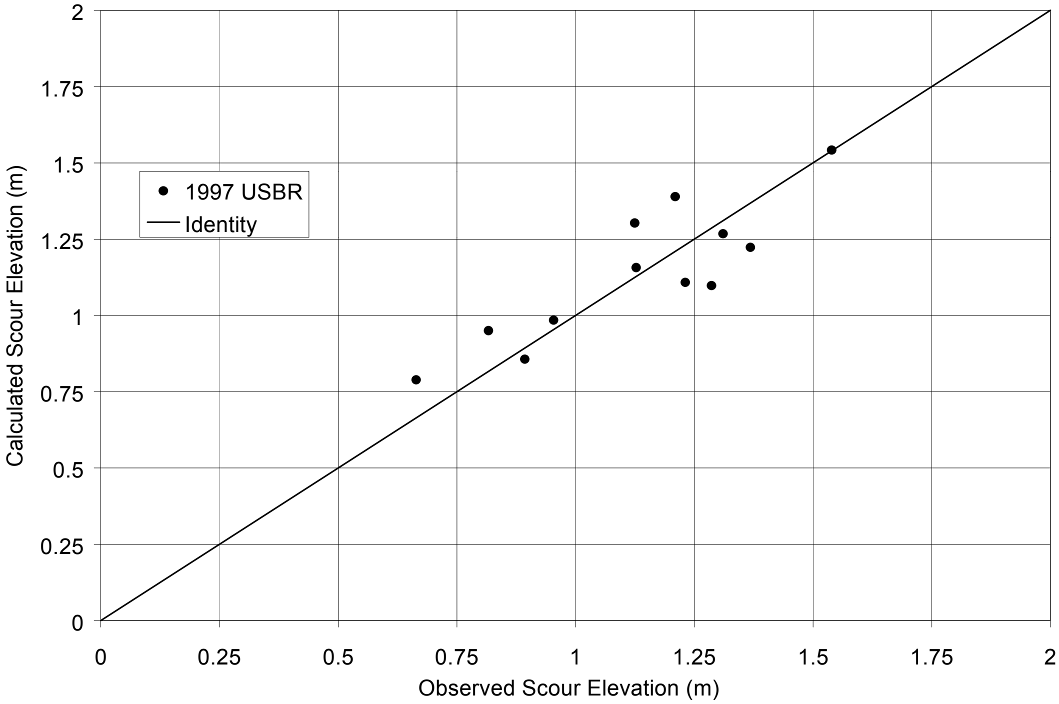

Figure 4. Comparison of calculated and observed scour elevations.

Conclusions

This paper summarizes twelve experiments simulating an overtopping jet plunging into a forming plunge pool. The eroding material is a locally available road-base. The Erodibility Index of the material and the corresponding power required to erode the material is a function of the geotechnical properties of the material. The power available to erode the material is a function of the velocity and air concentration at impact, and the rate of velocity decay of the submerged jet. Results show that the procedure predicts the observed elevation of equilibrium scour adequately.

References

[1] Kuroiwa, J., Ruff, J.F., Wittler, R.J., Annandale, G.W., "*Prototype Scour Experiment in Fractured Rock Media.*" Proceedings of 1998 International Water Resources Engineering Conference and Mini-Symposia, ASCE, Memphis, TN, August, 1998.

[2] Annandale, G.W., Wittler, R.J., Ruff, J.F., Kuroiwa, J., "*Prototype Validation of Erodibility Index for Scour in Fractured Rock Media.*" Proceedings of 1998 International Water Resources Engineering Conference and Mini-Symposia, ASCE, Memphis, TN, August, 1998.

[3] Annandale, G.W., "*Erodibility.*" Journal of Hydraulic Research, Vol. 33, No. 4, pp. 471-494. 1995.

[4] Kirsten, H.A.D., 1992. Personal Communication [3]

[5] Barton, N., Lien, R., Lunde, J., "*Engineering Classification of Rock Masses for the Design of Tunnel Support*." Rock Mechanics, Vol. 6, No. 4, pp. 189-236. 1974.

[6] Bohrer, J.G., Abt, S.R., Plunge Pool Velocity Prediction of Rectangular, Free Falling Jets. US Bureau of Reclamation, Dam Foundation Erosion Study, Phase II report. R.J. Wittler Study Team Leader. November, 1996.

[7] Juergenson, J.P., Abt, S.R., Flow Pattern and Circulation Velocity Prediction in Plunge Pools Formed by Overtopping Steep Dams. US Bureau of Reclamation, Dam Foundation Erosion Study, Phase IV report. R.J. Wittler Study Team Leader. May, 1998.

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Published Reference

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