The paper was published in the proceedings of the 11th International Conference on Scour and Erosion and was edited by Thor Ugelvig Petersen and Shinji Sassa. The conference was held in Copenhagen, Denmark from September 17th to September 21st 2023.

New Probabilistic 2D Jet Impingement Rock Scour Model

Michael F. George,[1] and George W. Annandale[2]

[1]BGC Engineering, Inc., 600 12th Street, Suite 300, Golden, CO 80401, USA; e-mail: mgeorge@bgcengineering.com, Corresponding author.
[2]George W. Annandale, Inc., 13156 W. Nadine Way, Peoria, AZ, 85383, USA; e-mail: george@georgewannandale.com

ABSTRACT

Scour of rock is a challenging problem for practitioners given the inherent variability in the scour process. An overview of a new probabilistic model to evaluate 2D spatial scour potential for jet impingement conditions based on the Erodibility Index Method (Annandale 1995, 2006) is presented. A discretized 2D geologic domain is input into the model and vertical and horizontal scour is estimated based on the spatial relationships between the erosive capacity and rock resistance. Variables within the scour model are assigned probability distributions based on available data or engineering judgement and Monte Carlo simulation is used to generate several thousands of scour profiles. Results for a spillway project in California are shown using the new scour model. Model output provided useful information for risk assessment and was used to estimate the probability of scour reaching the control section, potentially resulting in a breach, as well as determining distributions of eroded rock volumes which may be transported downstream.

INTRODUCTION

Rock scour downstream of dams and spillways associated with impinging jets is an important issue for dam safety. Jet formation can occur under a variety of conditions including chute spillways, overflow spillways, dam overtopping, gated/pressurized outlets, head-cuts, flip bucket spillways, and tunnel outlets to name a few (Figure 1).

Prediction of rock scour due to jet impingement can be challenging for practitioners given the inherent variability in the scour process. Existing tools for evaluation of scour in rock are predominantly limited to evaluating the threshold of when scour will initiate (i.e., will the rock erode or not) or estimating the depth of scour (1D). More recent work by Bollaert (2012, 2021) has examined 2D scour holes for plunging jets using the Comprehensive Scour Model (CSM). In this paper, a new probabilistic scour model to evaluate 2D spatial scour for plunging jets presented based on the Erodibility Index Method (EIM) (Annandale 1995, 2006).

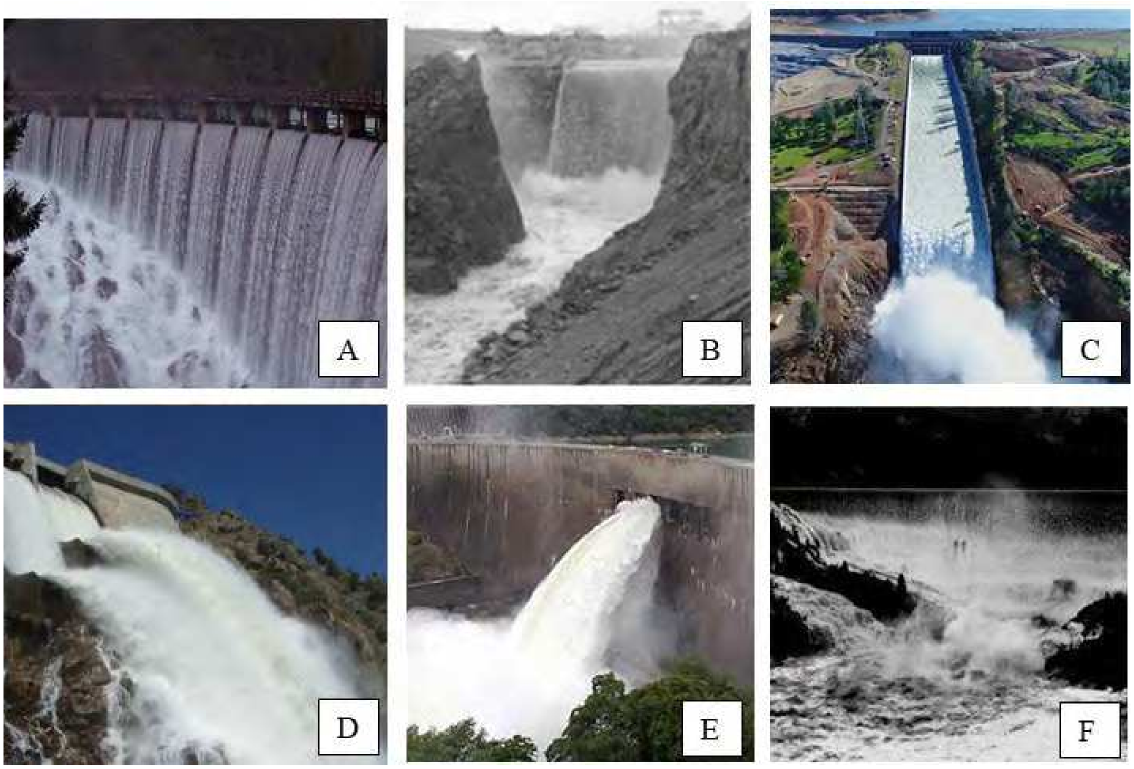

Figure 1. Jet formation due to A) overflow spillway (Lost Creek Dam), B) head-cut formation (Ricobayo Spillway), C) chute spillway (Oroville FCO Spillway), D) flip bucket spillway (Willams Fork Dam), E) gated mid-level outlet (Kariba Dam), and F) dam overtopping (Gibson Dam).

Scour occurring at the toe or abutment of a dam or at the base of a spillway can result in damage to the structure or failure of the structure completely leading to an uncontrolled release from the reservoir. For spillways, specifically, failure of the upstream rock face in a scour hole formed by jet impingement can result in headward migration of scour. Upstream migration of a head-cut can be problematic from a dam safety perspective should scour undermine the spillway control section and lead to an uncontrolled release from the reservoir (as was the concern during the recent 2017 Oroville spillways event).

2D JET SCOUR MODEL & APPLICATION

A new model to evaluate 2D spatial scour potential for spillways is presented based on the EIM (Annandale 1995, 2006). A discretized 2D geologic domain is input into the scour model and vertical and horizontal scour is estimated for a given discharge based on the spatial relationships between the erosive capacity and rock resistance. The resulting 2D scour hole geometry is also informed by the stability of the rock slopes defining the upstream and downstream scour hole walls. Modeling is performed probabilistically where variables are assigned probability distributions based on available data or engineering judgement. Probabilistic tools provide a meaningful way to quantify variability in the scouring processing (e.g., George 2015, George 2017, George & Sitar 2016). In the model, Monte Carlo simulation is used to generate several eroded spillway profiles to capture a range in spillway performance given variable uncertainty.

The EIM is a widely accepted semi-empirical index that relates material resistance to the erosive capacity of flow. When the flow erosive capacity exceeds the material resistance, scour will occur (Figure 2).

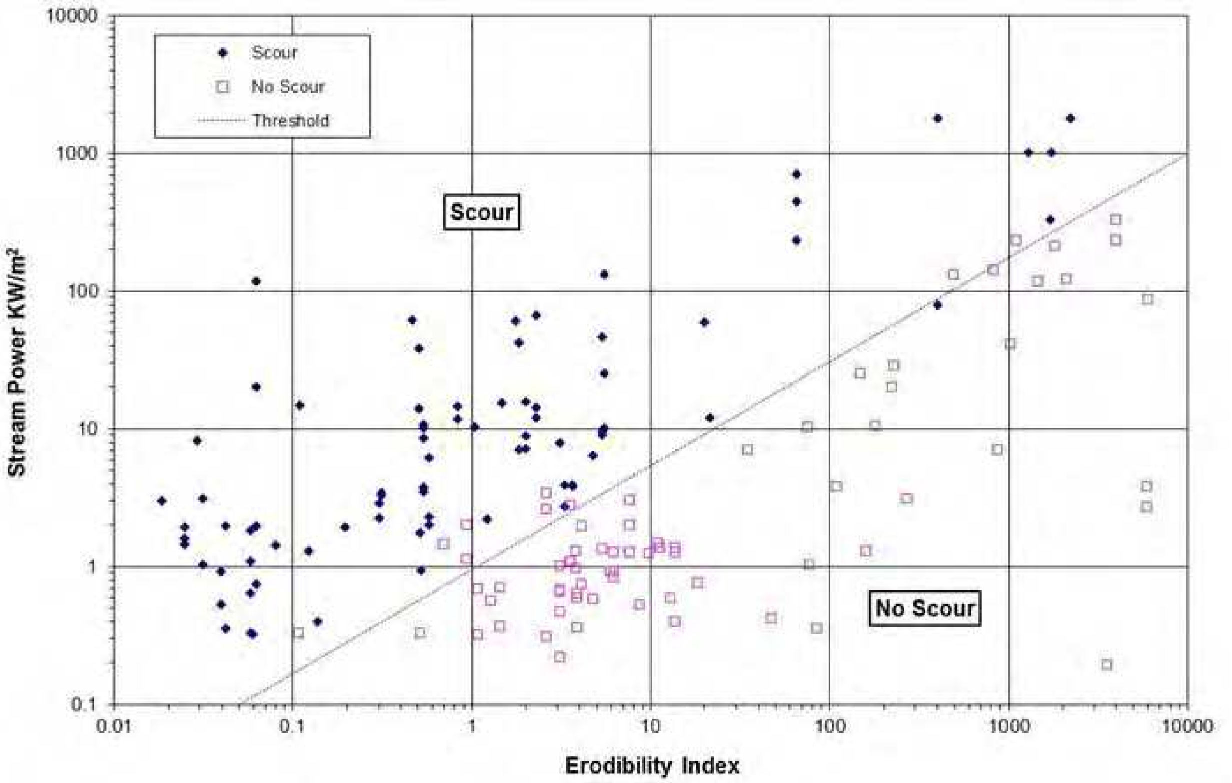

Figure 2. Erodibility Index Method threshold plot (Annandale 1995, 2006).

Erodibility Index (K) values representing the rock resistance to scour were estimated according to Annandale (1995, 2006):

$$K = M_s \cdot K_b \cdot K_d \cdot J_s$$

where M_s = mass strength number (which is a function of unconfined compressive strength (UCS) and rock density), K_b = block size number (K_b = RQD/J_n where RQD is the rock quality designation and J_n is the joint number), K_d = discontinuity shear strength number ($K_d = J_r/J_a$ where J_r is the joint roughness number and J_a is the joint alteration number), and J_s = relative joint structure number (which is a function of joint orientation relative to the flow direction and the shape of rock blocks).

Erodibility Index values can be related to resisting power (P_r) (kW/m^2) for comparison with the erosive capacity of flow using the following two equations:

$$P_r = K^{0.75}, \text{ where } K \geq 0.1$$
$$P_r = 0.48K^{0.44}, \text{ where } K < 0.1$$

A probability distribution of rock resistance (P_r) values for each engineering geologic unit within the dam foundation, plunge pool, or spillway can be assigned (Figure 3). This provides a quantitative representation of variability in scour resistance within each rock unit. A 2D geologic domain is input into the scour model which shows the spatial location of the rock units within the jet impingement region (Figure 4). The domain is discretized into a grid such that bedrock resistance can be evaluated with respect to the location of the impinging jet.

Flow erosive capacity of the impinging jet is quantified for the EIM using the unit stream power (kW/m^2) which represents the rate of energy dissipation over an area. The stream power in the jet impingement region (Figure 5) can be expressed as (Annandale 2006):

$$SP_{jet} = \frac{1}{1000} \cdot \frac{\gamma \cdot q \cdot \Delta E}{d_j} \cdot C_t$$

where γ = unit weight of water (N/m^3), q = unit discharge (m^3/s/m), ΔE = energy head at the tailwater level (m), d_j = jet thickness at impact with the rock surface (for direct impact) or plunge pool (m), and C_t (total dynamic pressure coefficient) = C_p (average dynamic pressure coefficient) + C'_p (fluctuating dynamic pressure coefficient).

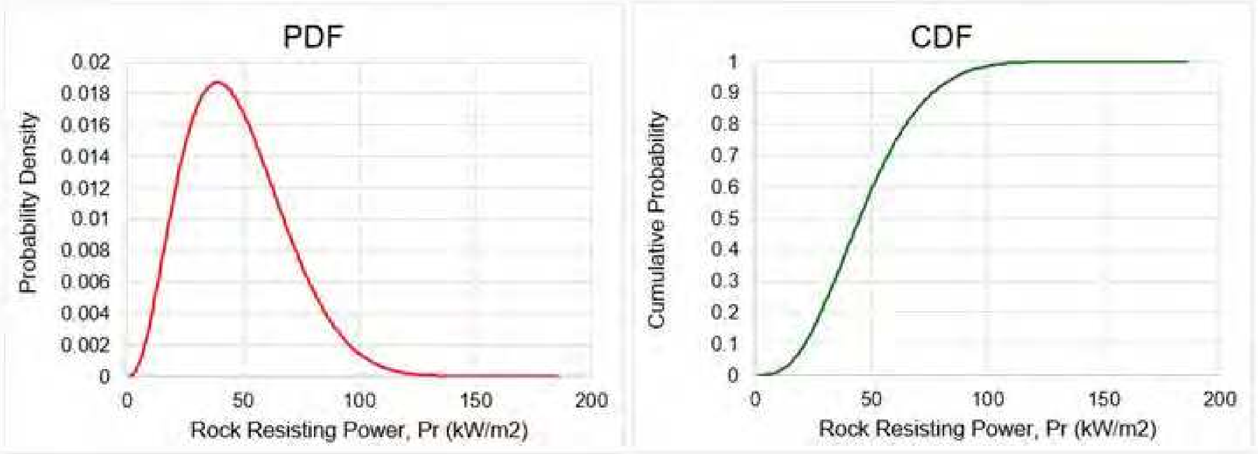

Figure 3. Example probability density distribution (PDF, left) and cumulative probability distribution (CDF, right) of rock resistance (P_r).

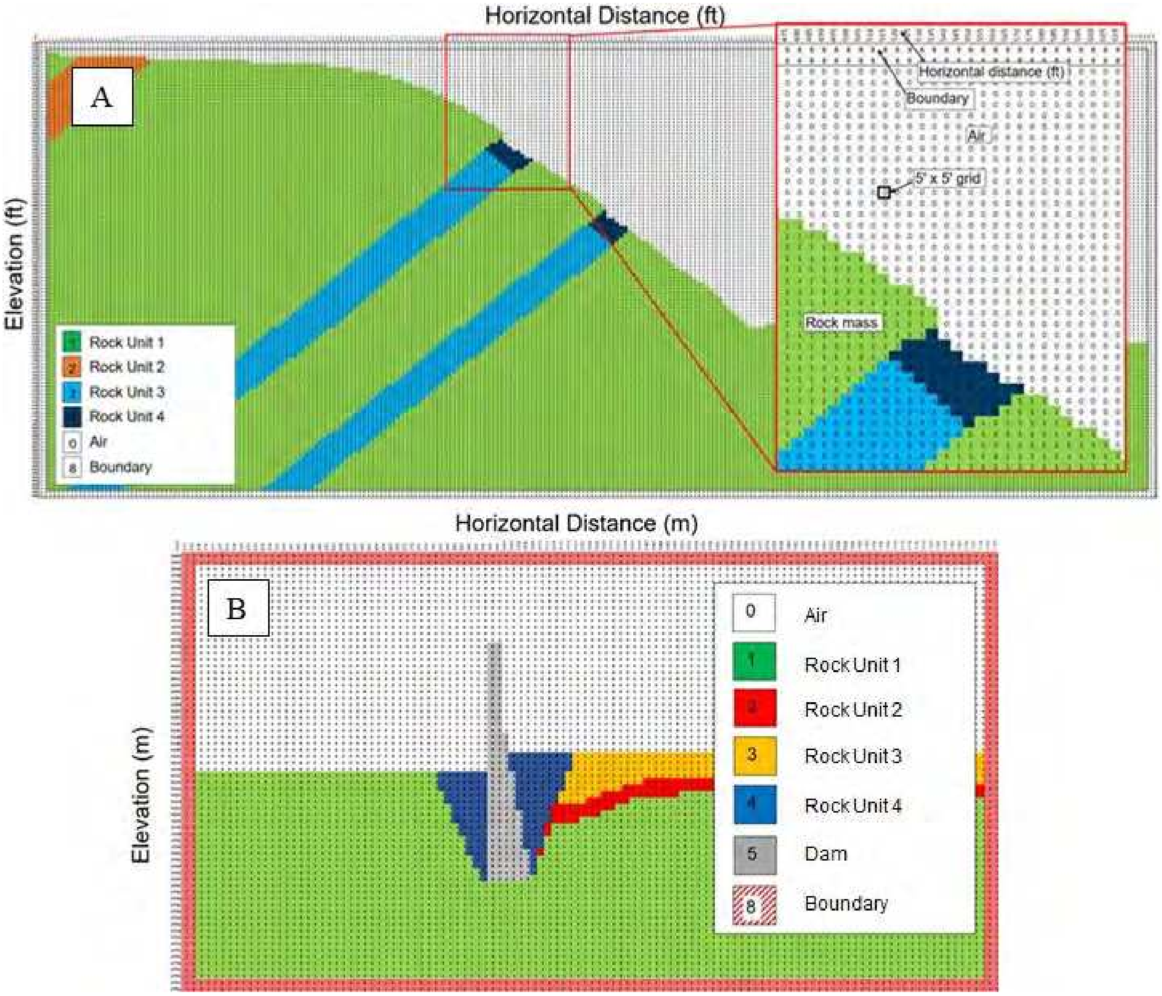

Figure 4. Example 2D discretized geologic domains of A) an unlined spillway channel for head-cut migration analysis, and B) arch dam for overtopping scour analysis.

The dimensionless average and fluctuating dynamic pressure coefficients (C_p and C'_p) account for the degree of break-up as the jet falls through the air (expressed as the ratio of the jet-length (L) to jet break-up length (L_b)) as well as the change in erosive capacity of the jet as a function of plunge pool depth (Annandale 2006, Castillo et al. 2015, Castillo & Carrillo, 2016). Initial jet parameters at the issuance point on the upstream side of a head-cut include unit discharge (q), flow velocity (u_i), flow depth (d_i) and turbulence intensity (T_u). These parameters can be estimated using standard hydraulic models (e.g., Flow3D, SpillwayPro or HEC-RAS). Parameters of the impinging jet may also be assigned probability distributions to account for variability within the parameter values.

Immediately adjacent to the jet impingement region is the wall-jet region, where flow from the jet is deflected parallel to the rock bed surface in the upstream and downstream directions (Figure 5). The flow spit between the upstream and downstream is a function of the impact angle (θ_j). The stream power of the wall jets are scaled based on the stream power of the jet along the centerline. Scour from the impinging jet will occur vertically and laterally until the erosive capacity is less than the rock resistance.

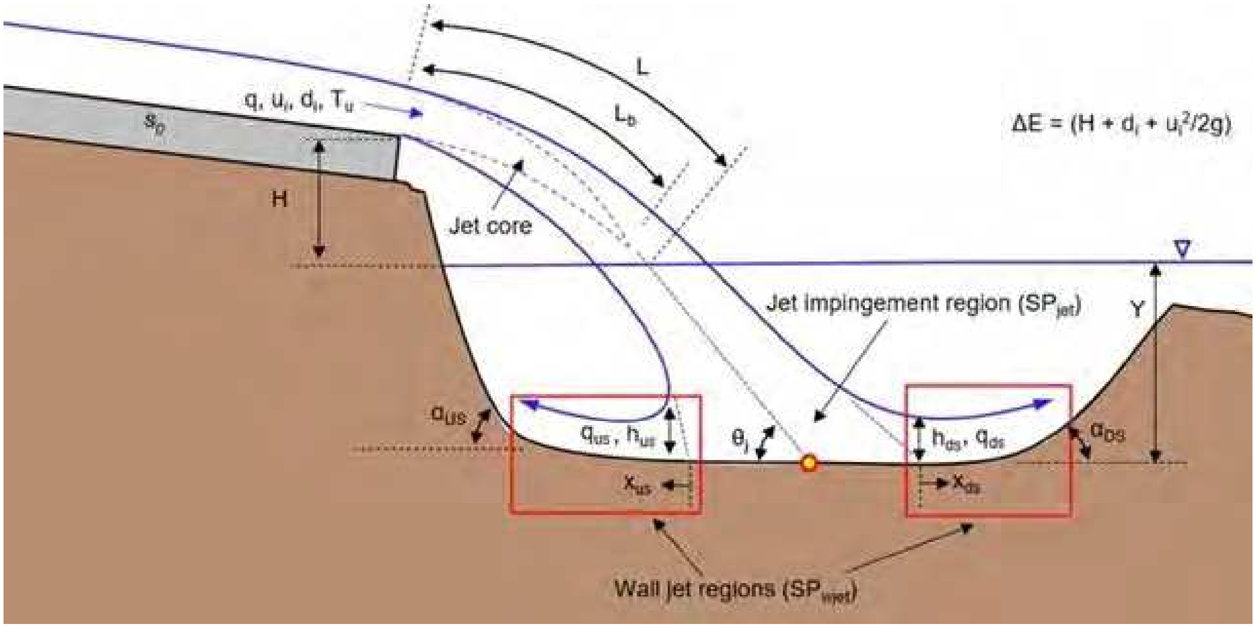

Figure 5. Schematic for 2D jet impingement scour model.

An initial 2D scour hole geometry is defined by the calculated vertical and lateral extents of scour. The upstream and downstream scour hole slopes are refined to determine an updated 2D scour hole geometry based on specified slope angles (α_{us} and α_{ds}, respectively – Figure 5). This eliminates the potential for unstable rock slopes in the scour hole that would most likely fail due to undermining. These angles can be based off stable rock slope angles determined from kinematic slope stability analysis or from measured slope angles (of an existing scour hole in the spillway or similarly oriented rock slopes nearby).

For spillway scenarios, head-cut advance occurs by two dominant mechanisms. The first is by scour of the upstream scour hole face due to the erosive power of the impinging jet in the upstream direction. The second is by deepening of the scour hole and daylighting of rock discontinuities leading to kinematic failure of rock wedges in the upstream scour. This is shown in Figure 6 (A and B). In either case, the issuance point of the jet is undermined and the head-cut will migrate upstream. Both of these conditions are considered in the 2D scour model. If the calculated 2D scour hole geometry extends upstream of the initial jet issuance point, the rock mass is susceptible to head-cut migration. In this case, another iteration in the scour model is performed and another 2D scour hole geometry is calculated. Iterations will continue until the scour hole does not progress upstream of the jet issuance location or the scour hole reaches a specific location (e.g., the spillway control section).

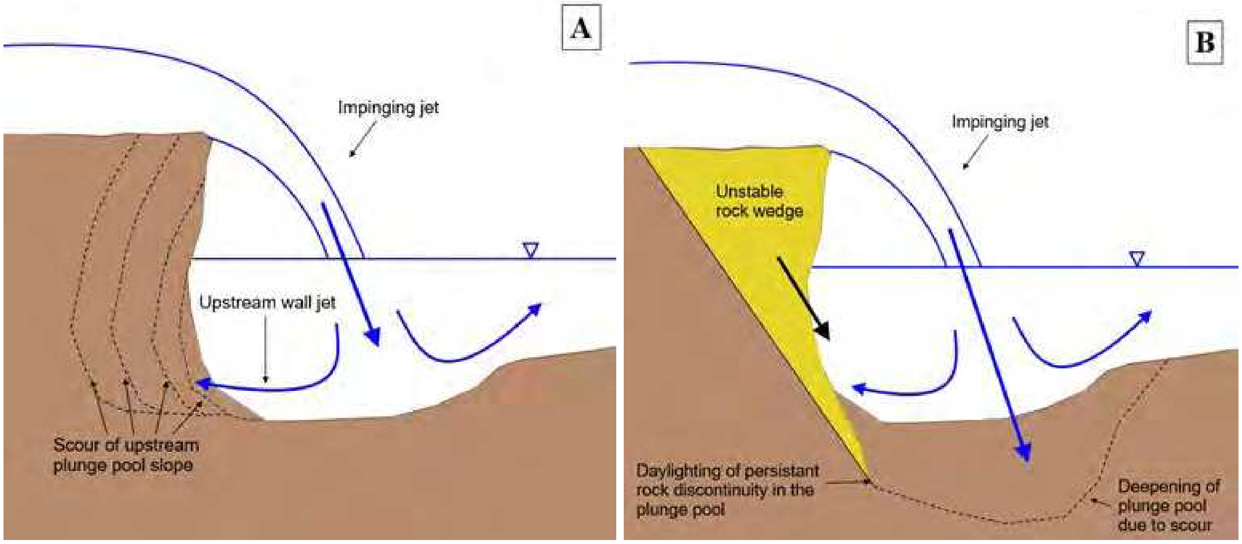

Figure 6. Spillway head-cut migration due to A) scour of the upstream scour hole face, or B) kinematic failure of rock wedges in the upstream scour hole face.

Currently, the 2D scour model is developed to evaluate the ultimate scour geometry for a constant discharge condition. This geometry does not consider the time-rate of scour nor scour progression over the course of a flood hydrograph. Rather, the discharge is assumed to remain constant for an indefinite period of time. This is commonly done in rock scour analysis given difficulties assessing time-rate of scour parameters for rock materials. Future developments will include the time-rate of scour.

Analysis with the 2D scour model is performed probabilistically using Monte Carlo simulation to capture a range in scour potential given variability in the model parameters. For each individual Monte Carlo run (which may include several iterations as described above), each variable is sampled according to their respective probability distribution and a 2D scour profile is generated. The total number of Monte Carlo runs is specified by the user. Figure 7 shows several hundred eroded spillway geometries for an unlined spillway site as an example of the output from the 2D scour model.

The resulting model output was useful to provide information on 1) the probability for a head-cut to reach the spillway control section (and result in a breach), 2) the probability for depth of scour (which may be useful in the design of a cutoff wall), and 3) a probability distribution of eroded spillway material which may be transported downstream. Given the current scour model does not consider the time-rate of scour, the scour results may be conservative, particularly in scenarios where significant head-cut migration upstream is predicted. The results still, however, provide useful information for risk assessment that can be used to inform scour potential and decisions on the need for scour mitigation measures. Risk is defined by a probability of an event and the associated consequence(s). The scour probabilities and 2D scour hole geometries estimated with the 2D model are helpful in informing and assigning event tree nodal probabilities pertaining to the likelihood of scour to occur and result in damage to a structure and/or result in breach of a reservoir.

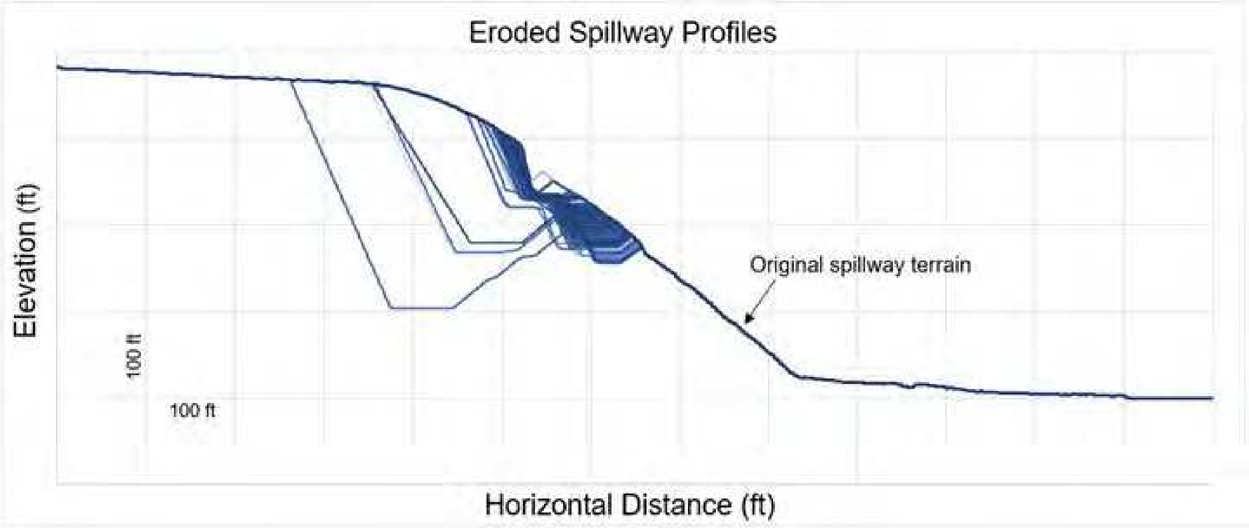

Figure 7. Eroded 2D spillway profiles for an unlined spillway from Monte Carlo analysis.

CONCLUSIONS

An overview of a new probabilistic rock scour model is presented to estimate 2D eroded geometries for jet impingement conditions (e.g., spillway chutes, dam overtopping) based on the EIM (Annandale 1995, 2006). The 2D eroded geometry provides greater insight for owners, regulators and practitioners into the potential impacts to structures and surrounding infrastructure due to scour compared to other methods that only estimate whether a material will erode or how deep scour will occur (e.g., 1D scour).

The probabilistic approach allows a more meaningful way to incorporate variability in the scouring process and quantify the impacts associated with parameter uncertainty on scour estimates. Scour probabilities estimated with the model also provide useful information to inform risk assessments for use in risk-informed decision making (RIDM) and risk-informed design (RID).

The current 2D scour model evaluates the ultimate scour hole geometry, which is the maximum scour hole that can develop given an indefinite duration at a constant discharge. Future planned developments will include the ability to simulate the time-rate of scour.

REFERENCES

Annandale, G.W. (1995). Erodibility. Journal of Hydraulic Research, 33(4): 471-494.

Annandale, G.W. (2006). *Scour technology: mechanics and engineering practice*, New York, McGraw-Hill.

Bollaert, E.F.R. (2012). Wall jet rock scour in plunge pools: a quasi-3D prediction model. *Hydropower & Dams,* 19(4): 1-9.

Bollaert, E.F.R. (2021). The rocsc@r cloud: An innovative digital platform to compute and record rock scour. *Hydropower & Dams,* 28(5).

Castillo, L.G., Carrillo, J.M., and Blazquez, A. (2015). Plunge pool dynamic pressures: a temporal analysis in the nappe flow case. Journal of Hydraulic Research, 53(1): 101-118.

Castillo, L.G. and Carrillo, J.M. (2016). Pressure and velocity distributions in plunge pools, 2nd Int. Seminar on Dam Protection Against Overtopping, Fort Collins, Colorado, USA.

George, M.F. (2015). 3D block erodibility: Dynamics of rock-water interaction in rock scour. Ph.D. Dissertation. UC-Berkeley.

George, M.F. (2017). Reliability-based rock erodibility for dam foundations, spillways and tunnels. Proc. 85th Int. Commission on Large Dams, July, Prague Czech Republic.

George, M.F. and Sitar, N. (2016). System reliability approach for rock scour. Int. Journal of Rock Mech. and Mining Sci., 85: 102-111.