Evaluation of the effect of rock surface irregularities on energy gradient in unlined dam spillways

Yavar Jalili Kashtiban
University of Quebec at Chicoutimi, Chicoutimi, Canada

Ali Saeidi
University of Quebec at Chicoutimi, Chicoutimi, Canada

Marie-Isabelle Farinas
University of Quebec at Chicoutimi, Chicoutimi, Canada

Javier Patarroyo
Hydro-Québec Production Unité Expertise en barrages, Montréal, Canada

ABSTRACT: Rock scouring downstream of dams has raised concerns for dam safety. To assess hydraulic erodibility, it is important to consider both geomechanical and hydraulic factors. Unlined spillways are typically created through controlled blasting, resulting in irregular rock surfaces. Previous studies have not comprehensively considered various geometrical parameters, including joint opening, joint spacing, and surface irregularities, and their impact on hydraulic parameters. This study aims to investigate the influence of surface irregularities in 25 different configurations on hydraulic parameters. The findings will contribute to improving the current equation for the hydraulic erosive parameter in future research. ANSYS-Fluent CFD simulations were performed to analyze the determined unlined spillway geometries. Results showed that increased irregularity height reduced maximum velocity and energy, but led to increased total head loss and rock mass erosion. Furthermore, the water-rock interface experienced three times higher energy loss compared to the water surface.

Keywords: Rock mass, Geomechanics, Unlined spillways, Erodibility, CFD.

1 INTRODUCTION

Unlined dam spillways and other hydraulic safety structures protect dams during high water events. The hydraulic erodibility of these structures and the hydraulic characteristics of flowing water over these constructions affect dam safety. The erosion caused by flowing water is a complex phenomenon that can occur instantly or over time. To improve the analysis of hydraulic erosive parameters, both the hydraulic and rock mass aspects of erosion must be considered. Important hydraulic erosive parameters include unit stream power dissipation, water velocity, shear stress, stress intensity, and lifting force. The existing methods of assessing and predicting hydraulic erodibility are limited, and channel bottom irregularities (rock surface geometry) are not considered in most cases. Therefore, investigating various spillway surface geometries can help determine how unlined spillways' surface irregularities affect hydraulic parameters. The primary aim of this study is to investigate the impact of rock mass surface irregularities, specifically in 25 different configurations, on hydraulic parameters. The ultimate goal is to enhance the current equation for the hydraulic erosive parameter in future research, utilizing the insights gained from this study. Table 1 summarizes the existing equations for hydraulic erosive parameters (Kashtiban et al. 2021; Pells 2016 and Saeidi et al. 2020).

Table 1. Existing hydraulic erosive indices.

Hydraulic erosive parameter		Equation
Parameter	Approach	
Stream power dissipation (Π_{UD})	(Van Schalkwyk 1994)	$\Pi_D = \rho \cdot g \cdot q \cdot S$
	(Annandale 1995)	$\Pi_D = \gamma \cdot q \cdot \Delta E$
	(Pells 2016)	$\Pi_{UD} = \rho \cdot g \cdot q \frac{dE}{dx}$
Velocity (V)	Chézy (1769)	$V = C\sqrt{R_H \cdot S}$
	(Manning et al. 1890)	$V = \frac{1}{n} {R_H}^{2/3} \cdot S^{1/2}$
Shear stress (τ_b)	(Yunus 2010)	$\bar{\tau}_b = \rho \cdot g \cdot R_H \cdot S \cos\beta$ $\bar{\tau}_b = \rho \cdot g \cdot R_H \cdot S_f \cos\beta$
Stress intensity (K_I)	CFM (Bollaert and Schleiss 2002)	$K_I = 0.8 \cdot P_{max} \cdot F \cdot \sqrt{\pi \cdot L_f}$
Lifting force (F_L)	DI (Bollaert and Schleiss 2002)	$I = \int_0^{\Delta tpulse} (F_u - F_o - G_b - F_{sh}) \cdot dt = m \cdot V_{\Delta tpulse}$
	QSI (Bollaert 2010)	$F_{QSL} = C_{uplift} \cdot L_{block} \cdot \frac{V_{X,max}^2}{2g}$

2 METHODOLOGY

The methodology of a study outlines the steps that were taken to achieve the research objectives. In this case, the objective was to determine the effects of spillway surface irregularities on the hydraulic performance of unlined spillways. We have presented the steps of our methodology in subsections in a flowchart (Figure 1). Initially, we analyzed available data from Pells (2016) to identify and select the most effective geometric parameters of spillways and irregularities. The chosen parameters, along with observed controlled-blasting patterns and available data, were used to develop a specific model geometry. Using ANSYS-Fluent software, we then simulated water flow over this rock geometry and extracted the results using CFD-Post

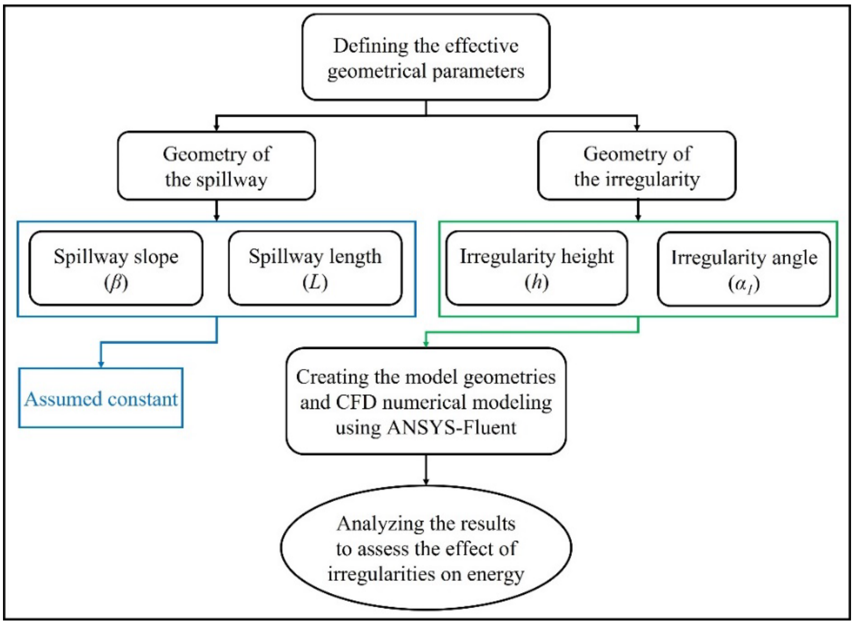

Figure 1. Methodology flowchart.

2.1 Identification and selection of effective geometric parameters

The first step involved analyzing available data from Pells (2016), which involved more than 100 case studies from dams in Australia, Africa, and the United States. The spillway geometric parameters that were considered in this study included spillway length, spillway slope, and the geometric parameters of the irregularities, which included the length, height, and angle of the irregularities. These parameters were selected based on sensitivity analysis and their effectiveness in determining the hydraulic performance of unlined spillways and blasting using data from Pells (2016).

Blasting is a common method of breaking and removing rock mass in mining, tunneling, and dam construction operations (Kashtiban et al. 2022 a). The researchers observed that the drilling and blasting produced irregularities along a spillway's surface profile. Burden and spacing were important factors to consider when designing blasting patterns for unlined dam spillways. Burden denotes the distance between a blasting-hole row to the excavation face or between blasting-hole rows, while spacing refers to the distance between blasting holes along the same row (Lopez et al. 1995).

2.2 Determining the model geometry

The selected parameters were combined with observed controlled-blasting patterns to create a specific model geometry. Selection of geometries for unlined surface profiles: The researchers considered the spillway geometric characteristics of spillway length and spillway slope, as well as the length, height, and angle of each irregularity (Kashtiban et al. 2022 b). The selected irregularity (Figure 2) angle was between 12° and 40°, and the irregularity height varied between 10 and 30 cm. Irregularity length was proportional to the height and angles and was generally between 1 and 2 m. In this step of the study, we compare the results of the simulations only for the irregularity angle of 12°.

The geometry was simulated using the Design modeler tool of the ANSYS-Fluent software, which is a powerful computational fluid dynamics (CFD) tool that allows for the simulation of water flow over rock surfaces.

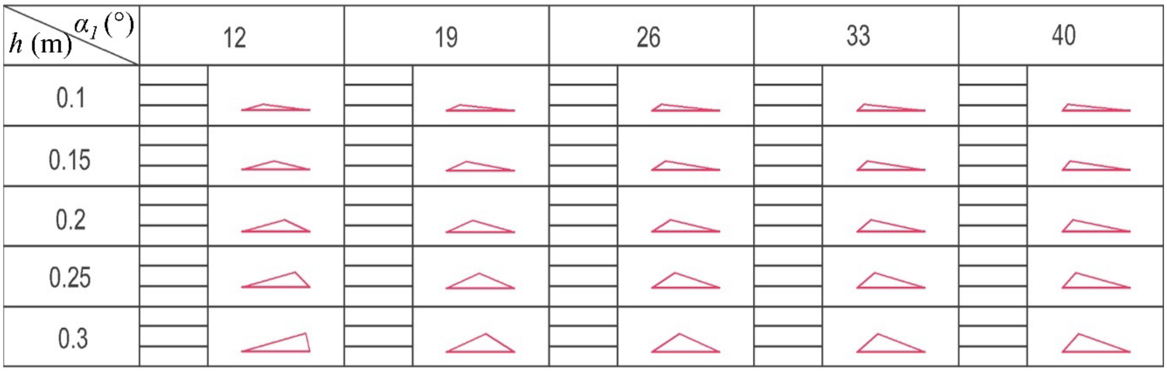

Figure 2. Configurations of the various modeled spillway surface irregularities.

2.3 Numerical modeling

To simplify the computation of wall parameters on irregular surfaces, ANSYS-Fluent Version 2020 R2 was used. ANSYS-Fluent converts scalar transport equations into algebraic equations that can be run numerically on the basis of a controlled volume approach. The open-channel submodel in ANSYS-Fluent, which is partially based on the volume of fluid (VOF) multiphase model, was used in the analysis. The k-ϵ turbulence model with enhanced wall treatment conditions captured results at the water-rock interface. Solutions to the Naiver-Stokes equations were derived using an averaged Reynold in the simulations. Pressure-velocity coupling was treated for stability using the widely used

COUPLED algorithm. The results were extracted using CFD-Post, which is a post-processing tool that allows for the visualization and analysis of CFD data (Ansys Inc. 2009).

Overall, the methodology involved a combination of data analysis and numerical modeling to determine the effects of spillway surface irregularities on the hydraulic performance of unlined spillways. The systematic approach ensured that the research objectives were met, and the results were reliable and accurate.

3 RESULTS

To verify the accuracy of our findings, we investigated grid independence. The outcomes of this evaluation are presented in Table 2, and the examination was carried out on the final irregularity, where we evaluated the maximum velocity and water depth. Our grid convergence study led us to determine that the ideal mesh size for our purposes was 10 cm.

Table 2. Grid independence study at the last irregularity.

Boundary conditions	**Structural schemes**				
Maximum size of grid cell (cm)	20	15	10	5	1
Water depth (cm)	82.1	73.3	68.9	67.9	68.1
Maximum total pressure (kPa)	52.63	60.16	63.18	63.6	63.52

The energy is determined by the pressure head, velocity head, and elevation. This article describes the computation of energy at two distinct positions: 1) at the water surface and 2) at the channel bottom. The relevant equations [equations (1) and (2)] were used to determine the energy at each position (Figure 3).

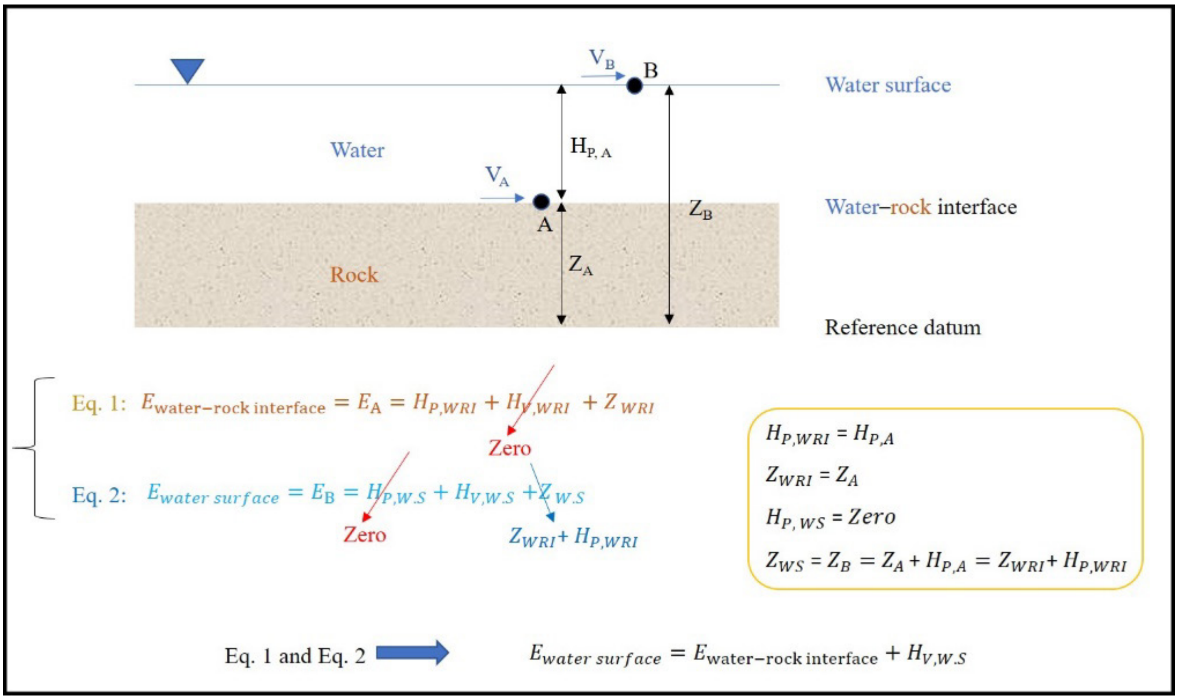

Figure 3. Calculation of energy at the water–rock interface and water surface.

$$E_{\text{water-rock interface}} = H_{P,WRI} + H_{V,WRI} + Z_{WRI} \quad (1)$$

$$E_{water\,surface} = H_{P,W.S} + H_{V,W.S} + Z_{W.S} \; , \tag{2}$$

where $E_{water\text{–}rock\ interface}$ represents the energy at the channel bottom, $H_{P,WRI}$ and $H_{V,WRI}$ are the pressure head and velocity head, respectively, at the channel bottom. Z_{WRI} is the elevation of the channel bottom, $E_{Water\,surface}$ is the energy at the water surface, $H_{P,WS}$ and $H_{V,WS}$ represent, respectively, the pressure head and velocity head at the water surface, Z_{WS} is the elevation of the water surface from the datum, and $Z_{water\,surface} = Z_{rock} + H_{P,WRI}$. These parameters are mesured in meters.

To determine the energy at the surface of the rock mass, we calculated the velocity head and pressure head, with the former being at a minimum and the latter at a maximum. In contrast, at the water surface, the velocity head was at a maximum, while the pressure head was zero. The difference between the energy at the water surface and the energy at the water-rock interface was the dynamic pressure or velocity head.

Using this information, we calculated the energy of the water at the water-rock interface and water surface across the entire analyzed area, and illustrated the energy gradients and differences in energy along the profile (Figure 4). We found that energy decreased upstream to downstream and being lost along the profile. We also observed that when the angle was held constant, more energy was lost as the height increased, and less energy was lost when the height decreased.

At the water surface, the energy was related to the elevation and velocity head, which were at their maximum, while the pressure head was at its minimum. We found that the energy increased along the profile relative to the energy at the water-rock interface, with this increase being around 0.3 times upstream and 2.5-3.5 times downstream relative to the energy at the water-rock interface.

Differences in the energy at the water surface (Figure 4a) and water-rock interface (Figure 4b) were related to the flow velocity and dynamic pressure. We observed that energy loss at the water-rock interface was greater than at the water surface because, in the former position, the velocity difference was not zero in the latter position, and the velocity-distance graphs sloped upward. In contrast, the velocity differential between upstream and downstream was close to zero, and the slope of the energy-distance relationship was zero. The sum of the elevation head and pressure head was the same for both positions. A greater velocity increased the amount of energy and decreased energy loss.

Figure 4(a) and Figure 4(b) show the results for the energy on the water surface and water-rock interface, respectively. The analyzed section of the energy is shown in Figure 4(c). The results of the Figure 4 are for the configuration of α_1= 12˚and various irregularity heights.

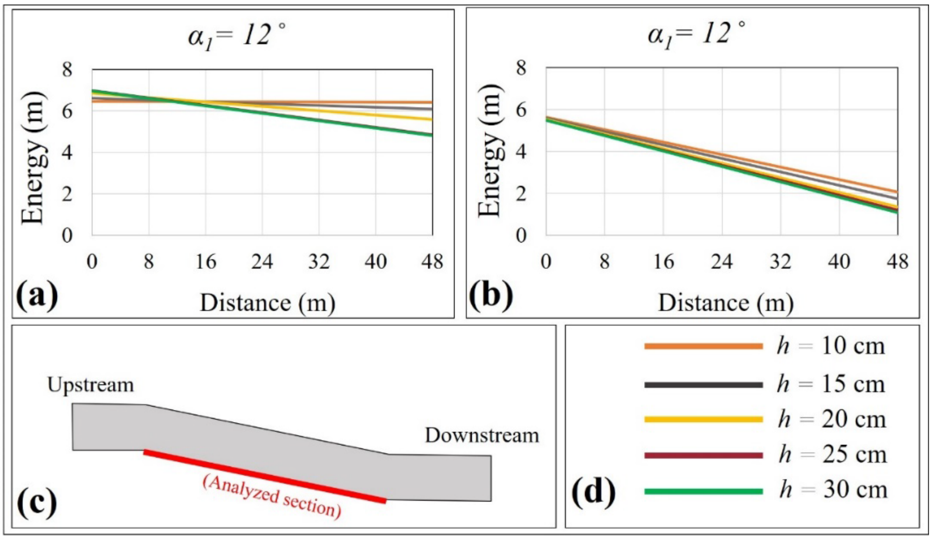

Figure 4. (a) The profile of the energy on the water surface for α_1= 12˚and various irregularity heights; (b) The profile of the energy on the water-rock interface for α_1= 12˚and various irregularity heights; (c) the analyzed section of the channel profile (red line).

4 CONCLUSIONS

In summary, the article focuses on investigating the effects of spillway surface irregularities on the hydraulic performance of unlined spillways.

The methodology involved a systematic approach that combined data analysis and numerical modeling to determine the effects of unlined spillway's surface geometry on hydraulic parameters such as velocity and energy. The study identified effective geometric parameters and determined the model geometry using ANSYS-Fluent software.

The results of the study showed that the energy at the water surface was 25 percent greater than that at the channel bottom due to the higher velocity head at the water surface. The energy decreased upstream to downstream. The energy at the water surface increased along the profile relative to the energy at the water-rock interface. Energy loss at the water-rock interface was greater than at the water surface (three times greater), due to the slope of the energy-distance graphs. Overall, the study provides valuable insights into the complex phenomenon of hydraulic erosion and how spillway surface irregularities can affect dam safety.

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