Evaluation of the effect of rock surface irregularities on the hydraulic parameters of water in unlined dam spillways

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Yavar Jalili Kashtiban, Ali Saeidi & Marie-Isabelle Farinas
Department of Applied Sciences, University of Quebec at Chicoutimi, Chicoutimi, QC G7H 2B1, Canada

Javier Patarroyo
Hydro-Québec Production Unité Expertise en barrages, 75 Boulevard René-Lévesque Ouest, Montréal, QC H2Z 1A4, Canada

ABSTRACT
In recent years, rock scouring or erosion downstream of dams has become an increasing dam safety concern. Several theoretical, semi-theoretical, semi-analytical, and numerical methods can be used to assess rock erosion in hydraulic structures. In most existing methods, the hydraulic erosive agent is unclear, and the hydraulic hazard parameter on the spillway surface is almost too challenging to determine. To develop and propose a new approach and equation for a hydraulic erosive parameter, in this study, we started by determining the effect of different geometries of the spillway discharge channel invert (surface irregularities) on various hydraulic parameters, such as velocity and pressures.

RÉSUMÉ
Ces dernières années, l'érosion des roches en aval des évacuateurs de cru est devenue un problème important pour la sécurité de ces structures. Plusieurs méthodes théoriques, semi-théoriques, semi-analytiques et numériques peuvent être utilisées pour évaluer l'érosion des roches dans les ouvrages hydrauliques. Dans la plupart des méthodes existantes, l'agent érosif hydraulique n'est pas clair et le paramètre de danger hydraulique à la surface du déversoir est presque trop difficile à déterminer. Pour développer et proposer une nouvelle approche et une nouvelle équation pour le paramètre érosif hydraulique, dans cette étude, nous avons commencé par déterminer l'effet de différentes géométries du radier du canal de décharge du déversoir (irrégularités de surface) sur divers paramètres hydrauliques, tels que la vitesse et les pressions.

1 INTRODUCTION

The safety of hydraulic structures such as unlined dam spillways, sluice gates, stilling basins, and plunge pools is so important because their poor design can result in both human and financial harm. Concerns about dam safety can be decreased by studying on hydraulic erodibility of hydraulic structures. Therefore, studying the hydraulic characteristics of flowing water over hydraulic constructions is always important. The terms' erodibility', 'scour', and 'hydraulic erosion' are considered synonymous technical words to explain erosion that occurs when the erosive intensity of water surpasses the rock mass resistance (Rock 2015, Pells 2016). Briefly, the erosive capacity of flowing water can cause hydraulic erodibility in dam spillways if it surpasses the rock mass resistance.

Erodibility of rock mass due to flowing water is a complicated mechanism that usually occurs instantly or during the time. Brittle failure, fatigue failure, rock block removal, peeling off, and rock block abrasion are the various types of hydraulic erosion mechanisms (Figure 1).

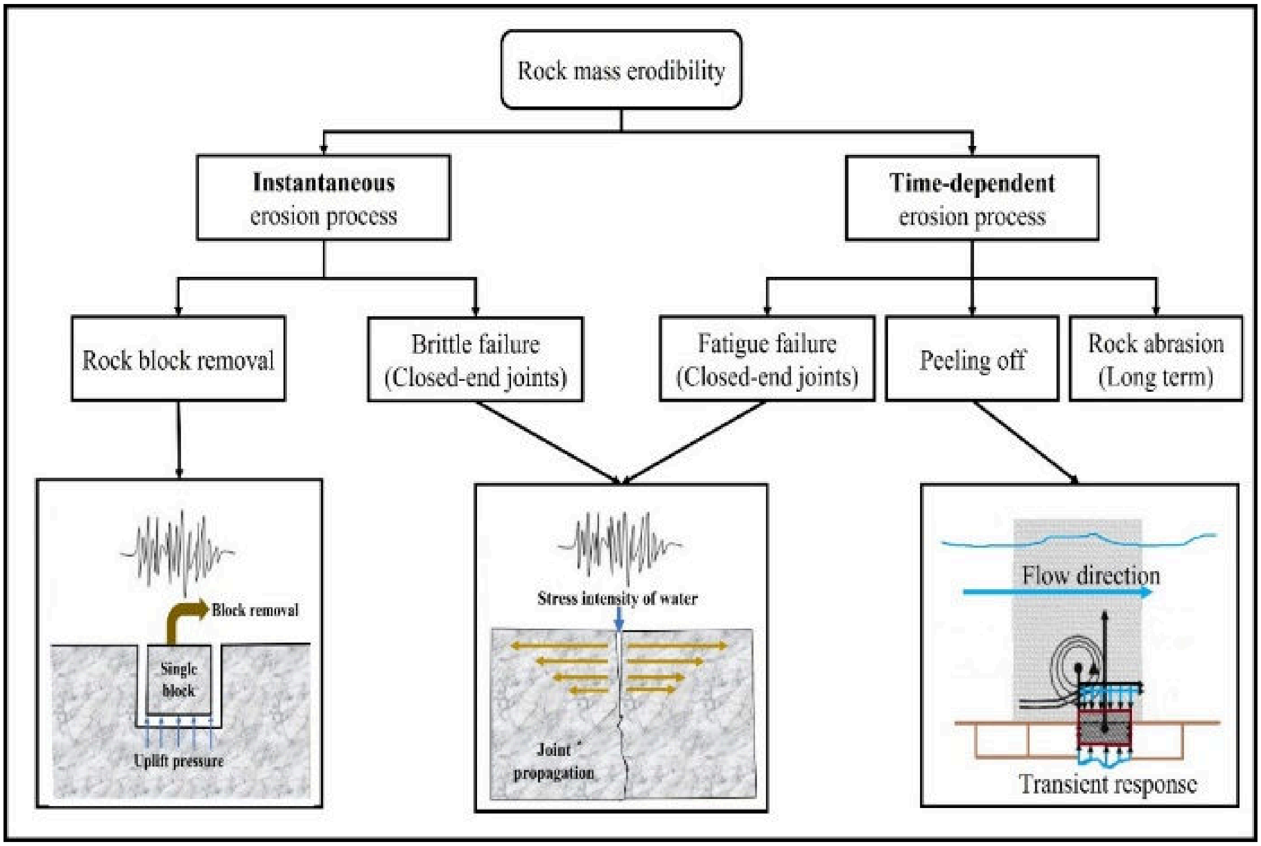

Figure 1. Rock mass erodibility mechanisms (Jalili Kashtiban, Saeidi et al. 2021)

This phenomenon should be studied in both hydraulic and rock mass aspects. Studying the effect of various geometries of hydraulic constructions on the hydraulic characteristics of flowing water could help better analyze the hydraulic erosive parameter.

Several hydraulic erosive parameters were reviewed in this paper. In many studies, to calculate the erosive parameter of water, the unit stream power dissipation of water (Π_{UD}), the velocity of the flowing water (V), the shear stress (τ_b) applied to a rock surface, the stress intensity (K_I), or the lifting force (F_L) have been used as the hazard parameter.

Because of the lack of a reliable index and the complicated nature of estimating the actual erosive parameter of water, most hydraulic erosion assessments use energy dissipation rate as the erosive capacity of water (Moore, Temple et al. 1994, Van Schalkwyk 1994, Annandale 1995, Kirsten, Moore et al. 2000, Annandale 2006). The energy dissipation index is chosen not for its ability to represent erosive forces accurately but for its simplicity. Among approaches that use energy dissipation as a hydraulic erosive agent, Pells' equation seems to be the most reliable (Pells 2016). A measure of energy dissipation may not consider all the complexities involved with erosion; for example, spillway geometry (surface profile) and flow modes are potentially influenced by a measure of erosion.

The average velocity (V) of flowing water cannot be solely a representative index of hydraulic erosive parameters because it is not unique and depends on the profile of the flow channel surface, the viscosity of the fluid, and the nature of the flow.

The average shear stress at the surface of the flow channel (τ_b) is assumed to be representative of the hazard parameter. However, it is impossible to solve all erosion problems within dam spillways by solely considering shear stress, such as hydraulic erosion caused by dynamic block removal, brittle failure, or fatigue failure.

Bollaert et *al.* (Bollaert and Schleiss 2002, Bollaert 2010) proposed a comprehensive scour model (*CSM*) with three various approaches such as comprehensive fracture mechanics (*CFM*) approach for analyzing erodibility in close-ended joints, dynamic impulsion (*DI*) approach for analyzing erosion in open-ended joints (single block), and the quasi-steady impulsion (*QSI*) approach to compute scoured depth in the plunge pool walls. In Bollaert's *CFM* method, the stress intensity (K_I) is considered as a hydraulic erosive parameter and calculated based on the maximum pressure in the pool bottom and could not calculate the pressures applied to joint tips. In Bollaert's *DI* approach, the uplift force is considered as a hydraulic erosive parameter. Bollaert proposed *DI* approach based on impulsion and Newton's second law. This methodology does not consider several geomechanical and geometrical parameters of rock masses. In the *DI* approach, the vertical fracture assumption causes the shear force (F_{sh}) to be zero. Bollaert's QSI method can calculate the scour depth in a plunge pool wall. Accordingly, the forces applied to channel bottoms are determined according to the F_{QSL} (quasi-steady lift force) on a protruding block, where the F_{QSL} is dependent on uplift pressure and flow velocity.

There are several limitations to the existing methods, and they can only be used in specific situations and conditions. Additionally, for assessing rock mass erodibility, a unique parameter is lacking to measure the erosive agent of water. For example, the unit stream power dissipation of water (Π_{UD}), which is based on the internal flow conditions, can be determined by various equations. Stress intensity (K_I) was initially developed for metallurgical cases and used only to determine the possibility of crack propagation in intact rocks but not in rock masses especially for the prediction of joint propagation in rock masses. This parameter was developed for the case of plunge pool erosion and its application in the case of unlined spillway structures is questionable.

On the other hand, based on previous studies, we found that geometrical parameters of rock mass effect on hydraulic parameters of unlined spillways have not been considered comprehensively, and it seems crucial to evaluate the effect of various unlined spillways geometry (water-rock interface or channel bottom profiles) on hydraulic parameters. Table 1 summarizes the existing hydraulic erosive parameters.

In the present study, by considering various geometries and conditions, we tried to examine the effect of unlined spillways' surface irregularities on hydraulic parameters such as pressures and flow velocity. After determining the geometries used in the unlined spillways using the developed equations for this regard, various simulations have been performed using computational fluid dynamics (*CFD*) by ANSYS-Fluent. According to blasting patterns in dam spillways, some surface irregularities are considered, and we propose a methodology to assess and analyze the effect of irregularities on hydraulic erosive parameters. Figure 2 shows the schematic of the unlined dam spillway and considered geometrical parameters.

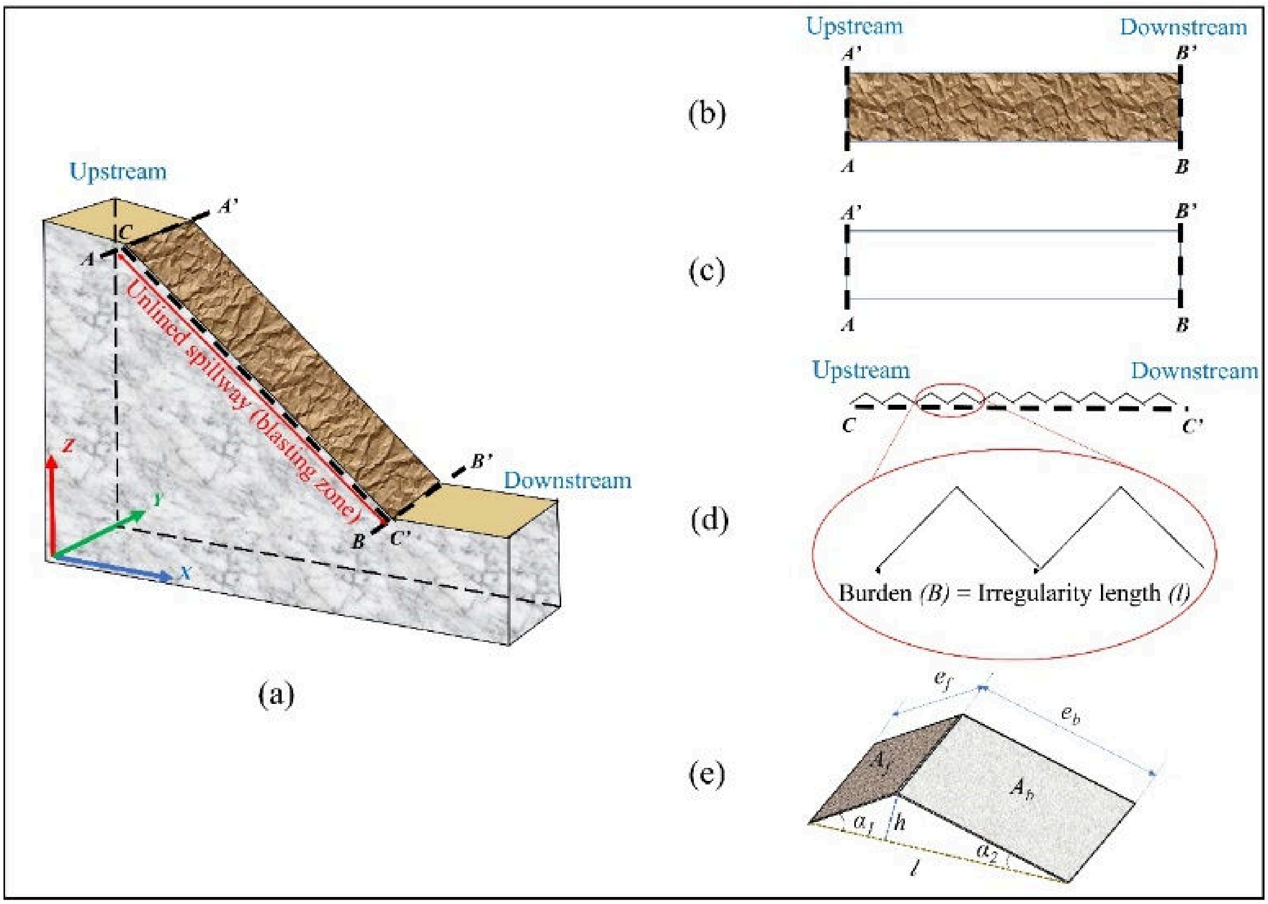

Figure 2. (a) Schematic of unlined dam spillway; (b) Channelview from above; (c) Controlled blasting pattern of the channel; (d) Channel surface profile after blasting; (e) Considered geometrical parameters

Table 1. Existing hydraulic erosive parameters

Hydraulic erosive parameter	
Parameter	**Approach**
Stream power dissipation (Π_{UD})	(Van Schalkwyk 1994) (Annandale 1995) (Pells 2016)
Velocity (V)	Chézy (1769) (Weisbach 1845, Darcy 1857) (Manning, Griffith et al. 1890)
Shear stress (τ_b)	(Yunus 2010) *MPM* (Khodashenas and Paquier 1999) (Prasad and Russell 2000) (Yang and Lim 2005) (Guo and Julien 2005) (Seckin, Seckin et al. 2006) (Severy and Felder 2017)
Stress intensity (K_I)	*CFM* *(Bollaert and Schleiss 2002)*
Lifting force (F_L)	*DI* *(Bollaert and Schleiss 2002)* *QSI* *(Bollaert 2010)*

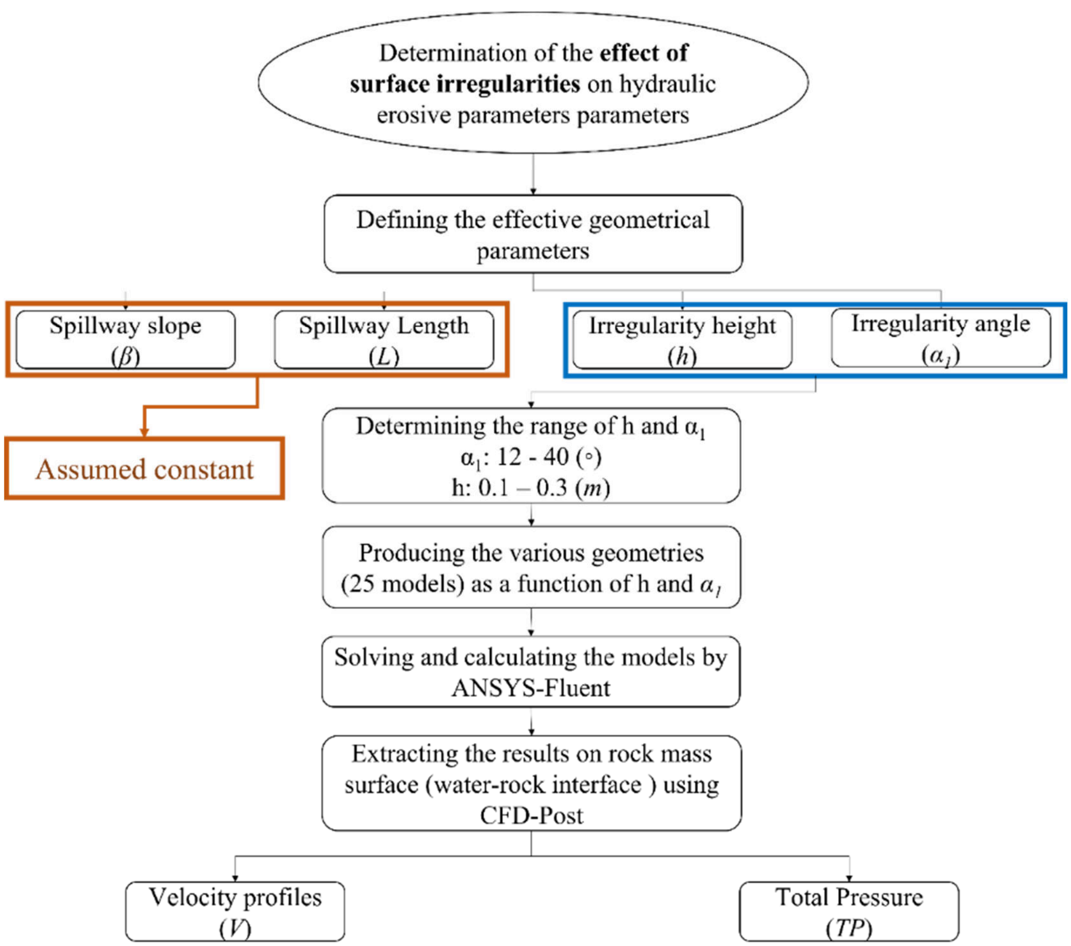

Figure 3. Methodology flowchart

2 METHODOLOGY

As previously stated, the objective of this research is to see how spillway surface irregularities affect hydraulic erosive parameters.

The methodology flowchart carried out in this study is shown in Figure 3, which is discussed further below. The parameters impacting hydraulic erosion must first be studied and selected for this purpose. The following are the most important geometrical parameters that affect hydraulic erodibility:

1- Geometrical characteristics of rock masses
2- Geometrical parameters of spillways

The spillway geometrical parameters comprise spillway length, spillway slope, length of each irregularity, the height of irregularities, and angle of irregularities [see Figure 2(e)]. Controlled blasting methods are usually used to create the surface of the unlined spillways. After performing the drilling and blasting technique to create unlined spillways on the rock mass, blasting produces some irregularities in the spillways surface profile.

Flow velocity, flow rate, and flow turbulence are all effective hydraulic erosive characteristics in hydraulic erodibility.

It's worth noting that all of the useful characteristics were chosen based on research and case studies.

2.1 Determination of geometry

Spillway geometrical characteristics in this study include spillway length, spillway slope, length of each irregularity, the height of irregularities, and angle of irregularities, as previously described.

We attempted to consider the effects of different parameters separately due to the high number of variables. The height and angle of irregularities have been studied as variable parameters in this section of the research.

The angle of the irregularities (α_1) is between 12 and 40 degrees in most situations, and the height of the irregularities (h) is between 10 and 30 cm, according to the various case studies (see Figure 2).

The length of each irregularity is proportional to its height and angle, and according to the spillways surface profile after controlled blasting, this length is generally between 1 and 2 m. A length of 1.5 m is considered for all models in this study.

The geometrical characteristics of the spillway (slope and length of the spillway) are also essential, and future studies into the effects of these parameters are suggested. In this study, based on various case studies, the spillway slope and length are assumed as 5 degrees and 50 m, respectively (the average values were chosen). The spillway geometry considered in the simulations is shown in Figure 4. There are a total of 25 geometries studied for spillway surface irregularities, as shown in Figure 5.

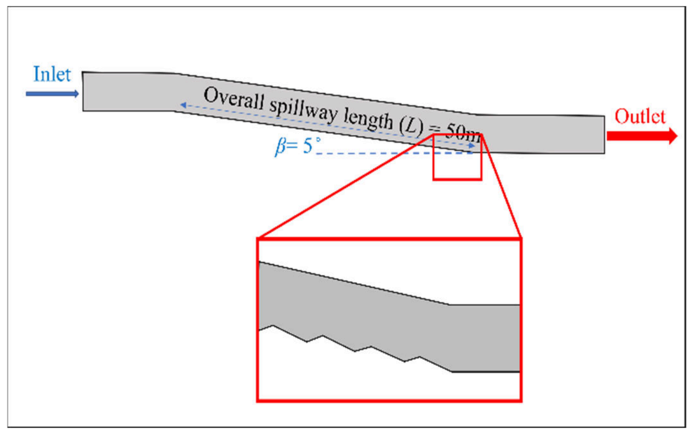

Figure 4. Considered unlined spillway geometry

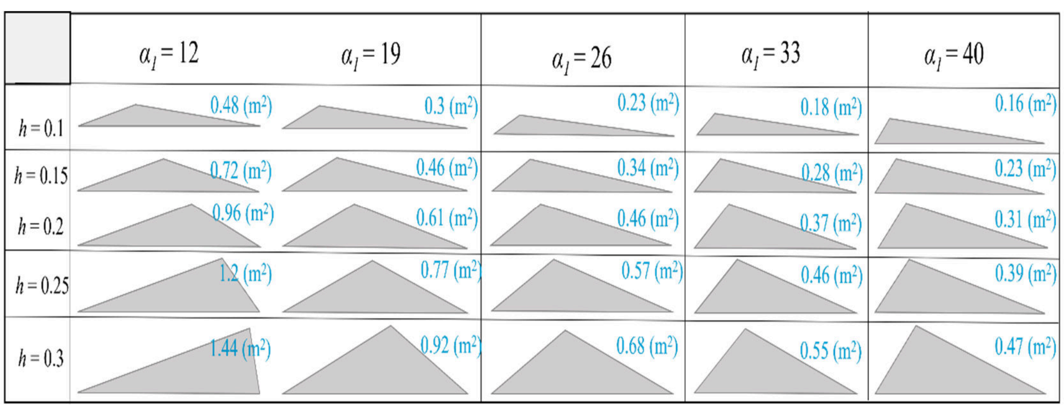

Figure 5. Various configurations of the spillway surface irregularities

2.2 Hydraulic numerical modeling

To simplify the computation of wall parameters on irregular surfaces, ANSYS FLUENT Version 2020 R2 was utilized. ANSYS FLUENT converts a generic scalar transport equation to an algebraic equation that can be solved numerically using a control-volume-based approach. The

open-channel sub-model in ANSYS FLUENT, which is partially based on the Volume of Fluid (VOF) multiphase model, was employed in this work (Manual 2009). (Hirt and Nichols 1981) employed a specific advection methodology to get a common definition of the free surface in the original VOF method, whereas ANSYS FLUENT solves the combined air-water flow system of equations (Bombardelli, Hirt et al. 2001). Additional complex turbulence models in ANSYS FLUENT are best suited to assessing hydraulic characteristics at the water-rock interface. The k-ϵ turbulence model with enhanced wall treatment conditions was used to capture the results at the water-rock interface. The enhanced wall treatment is a method of near-wall modeling that combines a two-layer model with improved wall functionalities. Solutions to the Navier-Stokes equations were derived using a stable, implicit technique in the current simulations. Pressure-velocity coupling was treated for stability using the widely used COUPLED method. To enhance momentum, the second-order upwind was used. A two-dimensional open-channel spillway was the subject of the simulations and solved in steady-state.

Table 2 shows the model input data for fluid flow modeling. There were roughly 78,000 triangular meshes in the computational domain. For a better analysis of the fluid treatment at the rock surface, ten inflation layers with a growth rate of 1.2 were considered at the channel bottom. A 3 m/s velocity-inlet boundary condition was applied. At the outflow zone, a pressure-outlet boundary condition was specified. At the water-rock interface, a no-slip boundary condition was considered. Figure 6 shows the considered model in ANSYS-Fluent and meshing.

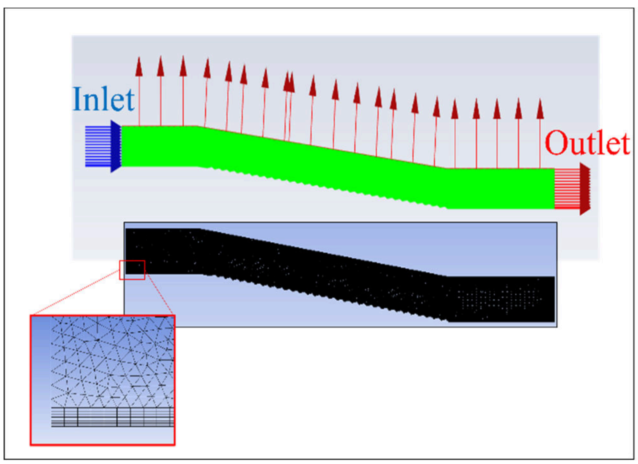

Figure 6. Numerical modeling and meshing

Table 2. Input **p**arameters **u**sed in the CFD modeling

Parameters	Value	Description
Initial flow depth	2 m	-
Initial flow velocity	3 m/s	-
Inlet boundary condition	-	Velocity inlet
Outlet boundary condition	-	Pressure outlet
Channel bottom boundary condition	-	No-slip
Unlined spillway length	50 m	-
No. of irregularities	32	-
Irregularity height (h)	10, 15, 20, 25, 30 cm	
Irregularity angle (α_1)	12, 19, 26, 33, 40 °	
Channel slope	5 °	-

3 RESULTS

The various simulation models were presented in the previous sections. For validating our results, we performed a grid independence study. Table 3 shows the results of the grid independence analysis. This analysis was performed at the last irregularity, and we checked the results for maximum velocity and water depth. From the results of grid convergence analysis, we found the optimum meshing size as 10 cm. The simulation results were extracted using CFD-Post for further analysis after the models (25 different configurations depending on various h and alpha) were solved by ANSYS-Fluent software.
Figure 7 illustrates a simulation result for h = 10cm and α_1 =19. The total pressure fluctuations (sum of dynamic and static pressure) on the water-rock interface in the section with irregularities are depicted in this figure (see studied section in figure 8-f).

Table 3. Grid independence study at the last irregularity

Meshing size / Measured Parameter	15 cm	10 cm	5 cm
Maximum Velocity (m/s)	10.31	10.64	10.68
Water depth (cm)	73.3	68.9	68.1

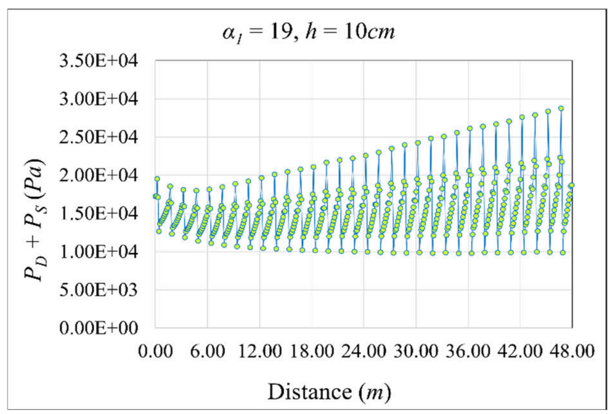

Figure 7. Total pressure (dynamic and static) profile on the water-rock interface for the configuration of α_1=19 and h= 10 cm

As there are so many results for total pressure fluctuations in the rock surface for different simulated models, not all of them are shown in this paper; instead, Figure 8 shows the upper boundary line of these fluctuations. The upper boundary results of total pressure-spillway length fluctuations for 25 various setups in different categories are shown in Figure 8.
Figure 8 (a) shows various results for different irregularity heights (h) at alpha = 12, Figure 8 (b) shows results at alpha = 19, Figure 8 (c) shows results at alpha = 26, Figure 8 (d) shows results at alpha = 33, and Figure 8 (e) results at alpha = 40.

Figure 9 illustrates the velocity profiles as a function of flow depth for various irregularity heights at the last irregularity.

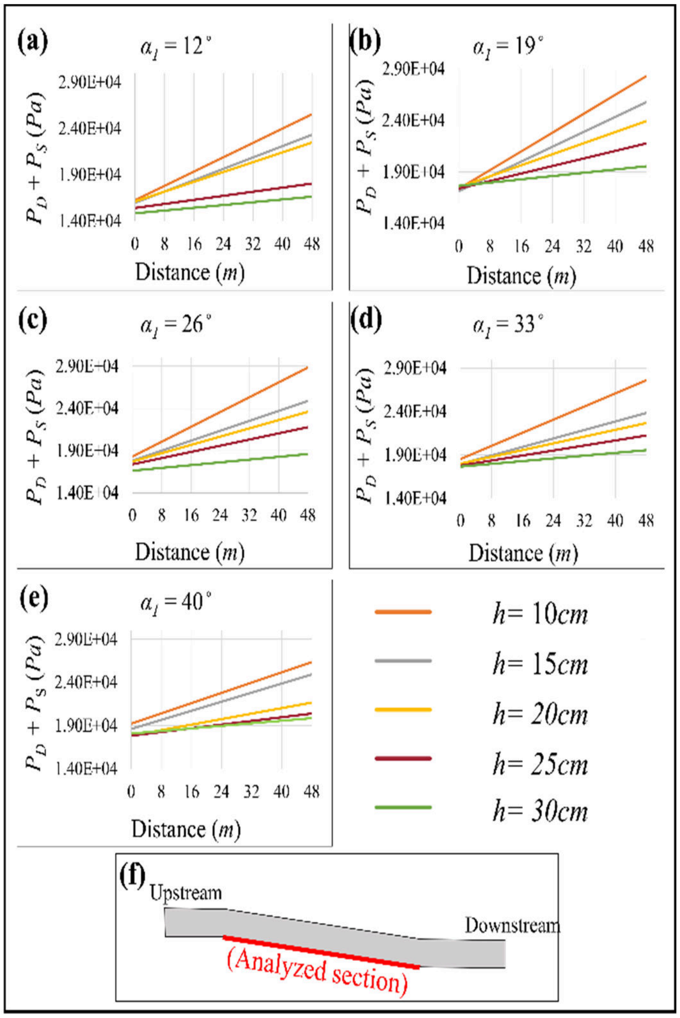

Figure 8. Total pressure profiles on water-rock interface as a function of spillway length for various irregularity heights; (a) α_1= 12°; (b) α_1= 19°; (c) α_1= 26°; (d) α_1= 33°; (e) α_1= 40°; (f) analyzed section (red line)

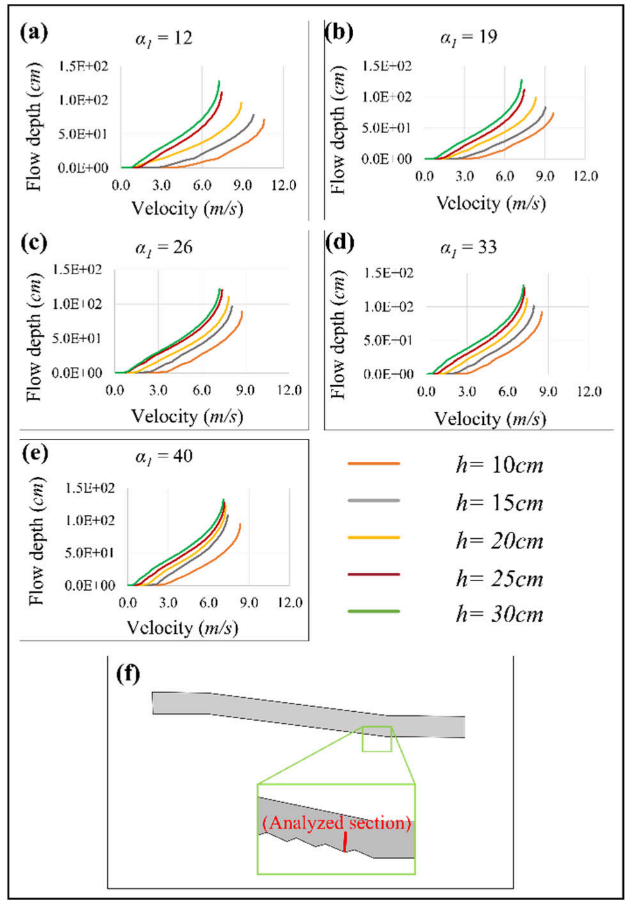

Figure 9. Velocity profiles as a function of flow depth for various irregularity heights (flow depth= 0 m refers to the channel bottom); (a) α_1= 12°; (b) α_1= 19°; (c) α_1= 26°; (d) α_1= 33°; (e) α_1= 40°; (f) analyzed section (red line)

4 DISCUSSION AND SUMMARY

In the present study, by considering various geometries and conditions, we tried to examine the effect of unlined spillways surface irregularities on hydraulic parameters such as pressures, shear stress, and flow velocity. After determining the geometries used in the unlined spillways using the developed equations for this regard, various simulations have been performed using computational fluid dynamics (*CFD*) by ANSYS-Fluent. These irregularities affected hydraulic parameters, as shown by the results.

Based on the results, it may be concluded that erosion susceptibility is more likely downstream and at the spillway's toe than in other locations. Because the amplitude of total pressure fluctuations increases with distance from the upstream, the applied pressure to remove the rock block is greater than the resistance pressure, as shown in Figure 7. Because the upper bound of this graph represents the pressures applied to surfaces that are in the flow's opposite direction, while the lower-bound displays the pressures applied to surfaces in the flow's direction. On the other hand, the applied pressures downstream are greater than upstream, as shown by the graphs in Figure 8.

In Figure 8, the total pressure value (dynamic pressure and static pressure) decreases as the height of the irregularity (*h*) increases in a constant α_1. Irregular surfaces, according to Pells and Annadale's research, are more vulnerable to hydraulic erodibility than smooth surfaces. As a result, we conclude that the total pressure could not be a representative hydraulic erosive parameter.

Figure 9, which illustrates the flow velocity-flow depth at the end of the spillway, shows that for constant α_1, increasing irregularity height (*h*) decreases flow velocity while increasing flow depth. The contrary is also true, by increasing alpha, the flow velocity drops at a constant h. Flow velocity alone, like total pressure, cannot be used solely as a hydraulic erosive parameter of rock mass erodibility in dam spillways since the results are contrary to previous studies by Annadale and Pells.

5 CONCLUSION

Based on the results, we can conclude that:

- By increasing the α_1, the maximum velocity decreases.
- In a constant α_1, by increasing the irregularity height (*h*), the maximum velocity (V_{max}) decreases.
- In a constant α_1, by increasing the irregularity height (*h*), the water depths increase, and maximum velocity (V_{max}) occurs at upper depth depths.
- In a constant α_1, by increasing the irregularity height (*h*), the total pressure (P_T) decreases.
- According to the results, it can be concluded that the total pressure and flow velocity, solely are not appropriate erosive parameters for hydraulic erodibility, and it is preferable to focus on applied forces and energy in future research.

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