A reduced-scale physical model of a spillway to evaluate the hydraulic erodibility of a fractured rock mass

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Abstract

The hydraulic erosion of the rock mass within dam spillways must be considered when assessing the stability of dam infrastructures. As this erosion results from the interaction between water and the rock mass, commonly applied methods to evaluate this phenomenon use the notion of a threshold line, a correlation between the water's erosive force and the resistance of the rock mass against erosion. These methods are empirical or semi-empirical, and they have limitations regarding the characterization of this phenomenon. These methods are based on specific hydraulic and rock mass parameters, including a number of parameters that are irrelevant to the erosion process; thus, there is a need to upgrade the existing methods or to seek new solutions to characterize hydraulic erosion. We present a laboratory-scale physical model to determine the effects of rock mass parameters on erosion. This model is designed to determine individual and interactive effects of several hydraulic and rock mass parameters on erosion, including joint opening, block size, joint

shear strength, and the nature of potentially erodible surfaces, as well as water pressure (static and dynamic), variations of flow rate and velocity, and channel roughness.

Article highlights

- Design of a reduced physical model of a spillway
- Identification of various rock mass parameters controlling rock resistance against the erosive force of water
- Identification of the key parameters affecting the hydraulic load within spillways
- Multiple geomechanical parameters of the rock mass compared to the erosive force of water

Keywords: Erosive force, Hydraulic pressure, Laboratory tests, Physical model, Rock mass, Spillway

List of notations

B_f: Width of a flow section measured at the water surface (m)

eGSI: Geological strength index for erodibility

E_{doa}: Erosion, discontinuity orientation adjustment

F: Limit correction factor for stress intensity

F_e: Scale factor

F_O: Force on a block (kN)

F_u: Force under a block (kN)

Fr: Froude number

G_b: Submerged weight of a rock block (kN)

GSI: Geological strength index

g: Acceleration due to gravity ($m\cdot s^{-2}$)

J_a: Joint alteration number

J_n: Number of joint sets

J_o: Joint aperture (m)

J_r: Joint roughness number

J_s: Relative block structure

K_h: Kirsten's index

$K_{I,in}$: In situ resistance of a rock mass ($MPa\cdot m^{1/2}$)

L_f: Total joint length (m)

m: Mass of rock (kg)

Q: Water flow rate ($m^3\cdot s^{-1}$)

q: Discharge per unit width of the channel ($m^2\cdot s^{-1}$)

R_H: Hydraulic radius (m)

RM: Real model of the spillway (actual spillway)

RMEI: Rock mass erodibility index

RQD: Rock quality designation

RSPM: Reduced-scale physical model of the spillway

T: Tensile strength (MPa)

u: Flow velocity ($m \cdot s^{-1}$)

V_b: Block volume (m^3)

θ : Channel tilt angle (°)

ν : Kinematic viscosity ($m \cdot s^{-1}$)

ρ : Density of water ($kg \cdot m^{-3}$)

1 Introduction

The potential instability of a rock mass underlying dams or other geotechnical works is an ever-present danger to both the safety of persons and equipment. One danger is the phenomenon of erosion of the rock mass in dam spillways. Rapid erosion of the rock mass by water flowing at fluctuating hydraulic pressures can produce scour and break down the complex structure of the rock. The unexpected erosion of massive rock has seriously damaged several dam spillways and has resulted in expensive maintenance costs for several other large dams. For example, a large cavity in the spillway of the Oroville dam in California, which resulted in a massive water discharge, produced more than $2 million US in damage and required the evacuation of many people downstream of the dam. At the 113 m high Copeton embankment dam in Australia, a significant water flow in the bedrock spillway formed a 20 m deep gorge (Pells 2016).

Several methods have been proposed to predict rock mass hydraulic erosion within dam spillways, and some of these methods are currently used in the spillway design phase (Moore *et al.* 1994; Pells 2016). All methods use the notion of a "threshold line," which is obtained by determining the relationship between the erosive force of water and the rock mass resistance. In these methods (Table 1), hydraulic conditions are assessed by considering an erosive force (dissipation of the hydraulic power of the water) and the quality of the rock mass by way of a resistance index. Most of these methods are empirical or semi-empirical and are based mainly on the results of a few laboratory-scale models (Annandale 2006). Hence, important questions remain unanswered in regard to the effectiveness of these methods.

Table 1 Methods currently used to predict the hydraulic erosion of a rock mass

Multiple indices have been developed to determine rock resistance to erosion using various parameters of the intact rock and the rock mass:

- The Kirsten index (K_h) is based on the confined compressive strength of the intact rock (M_s), the shear strength of the rock joints (K_d), the size of the rock blocks (K_b), and the relative structure of the blocks (J_s), for which the latter parameter considers the effect of the shape and orientation of the blocks with respect to the flow direction of water in the channel;
- The geological strength index for erodibility (*eGSI*) is based on the geological strength index (*GSI*), a classification index of the rock mass developed by Hoek *et al.* (Hoek *et al.* 1998), and the relative structure of the blocks (E_{doa}), for which the latter parameter considers the effect of the shape and orientation of the blocks with respect to flow;
- The rock mass erodibility index ($RMEI_B$) is based on the relative importance factor (*RF*) and the likelihood (*LF*) of five geomechanical parameters (*P1* to *P5*), *P1* representing the kinematically viable mechanism for detachment of a block, *P2* being the nature of the potentially eroded surface, *P3* as the nature of the joints contained within the rock mass, *P4* as the spacing between the joints, and *P5* representing the block's shape;

- The in situ resistance indices ($K_{I,in}$) are based on the tensile strength of the rock (T in MPa), the unconfined compressive strength (UCS in MPa), and the in situ horizontal confinement stress (σ_c in MPa).

In terms of the erosive force of water, two indices or hydraulic parameters are most often considered:

- The dissipation of energy (Π_{UD} in kW·m^{-2}) includes the density of water (ρ in kg·m^{-3}), gravity acceleration (g in m·s^{-2}), the energy loss during flow (dE/dx), and the flow rate per unit length of channel width $\left(q = Q/B_f \text{ in } \mathrm{m}^2 \cdot \mathrm{s}^{-1}\right)$, where B_f is the channel width (m), and Q is the water flow rate (m^3·s^{-1});
- The stress applied to the rock mass (K_I in MPa·m$^{1/2}$) includes the maximum instantaneous dynamic pressure in the diving pool (P_{max}), the correction factor depending on the type of the joint when it is a persistent joint (F), and the total length of the joint (L_f in m).

In some dam settings, significant spillway erosion has been observed, although the applied prediction methods had indicated that marked erosion should not occur. In most of these cases, existing methods were limited in their predictions of rock mass erosion, and it is challenging to identify the cases for which these methods work best. The existing methods do not consider all geomechanical and hydraulic conditions observed in spillways, and certain hydraulic and geomechanical parameters used by these methods are irrelevant (Boumaiza *et al.* 2019; Koulibaly *et al.* 2021). In most of these methods, the Kirsten index is used as the rock mass resistance parameter; however, this index had been developed initially for evaluating the excavability of a rock mass. It is therefore necessary to upgrade existent methods or to develop a new method for evaluating rock mass erosion. As a prerequisite step for developing a new approach, the most important geomechanical parameters in the erosion process and their relative effect on erosion must be determined. This step requires a comprehensive analysis of rock mass erosion that captures all appropriate geomechanical and hydraulic parameters. A laboratory-scale model provides a very effective means for determining the effect of several parameters that control the hydraulic erosion of a rock mass.

Numerous physical models have been developed to study this hydraulic erosion process. These physical models are designed to study the hydraulic characteristics of the flow, evaluate the phenomena of erosion in granular materials or within a rock mass, or validate the assumptions of methods used to predict erosion.

In general, these physical models can be classified into two categories: models that only study the hydraulic parameters and those that also include the study of the geomechanical parameters of the rock mass subjected to erosion. The first category of physical model focuses in particular on the study of hydraulic parameters affecting erosion, such as the slope of the channel, the flow rate, the flow velocity, and the roughness of the surface of the flow channel (Withers 1991; Manso et Schleiss 2006; Lesleighter *et al.* 2016; Gu *et al.* 2017; Kote et Nangare 2019). Some models in this first category aim to find solutions for reducing the hydraulic power downstream of spillways, whereas others simulate water flow or spillway erosion downstream under specific conditions (Sawadogo 2010; Tuna 2012; Wilkinson *et al.* 2018).

The second category of model studies the effects of some geomechanical parameters of the rock mass on hydraulic erosion. These models make it possible to evaluate the distribution of the pressure applied by the flow on instrumented blocks; the configuration of these blocks is intrinsically linked to a few geomechanical parameters, including the orientation of joints and the shape and protrusion of the blocks. The type of water flow considered in the configuration of these models is either a plunging jet or an open channel flow (Table 2).

Table 2 Summary of the physical models of spillways developed to study the effects of geomechanical parameters of a rock mass on erosion, including model type, the evaluated geomechanical parameter, and the assessment method of the parameters: quantitative if measurements are carried out or qualitative if the parameter is characterized by a simple comparison

These models assess hydraulic erosion by considering various geomechanical parameters individually in relation to hydraulic pressure. A more comprehensive approach would also evaluate possible interactions between these geomechanical parameters and their combined effects on the erosion process, as most geomechanical parameters are interrelated.

Boumaiza *et al.* (2019) proposed a hierarchy of rock mass parameters according to their influence in the erosion processes within a spillway. Thus, the relevance of these physical models (Table 2) can be further evaluated according to their applicability to study the effect of each identified geomechanical parameter involved in the erosion process (Table 3).

Table 3 Summary of the parameters evaluated by existing physical models

Some parameters have been studied more than others; the well-studied parameters include joint orientation and the protrusion of the blocks, although their interactive effect has not yet been considered. Most other parameters remain poorly investigated; for example, the shear strength of joints has not been studied extensively; however, it has been identified as having a critical role in the erosion of a rock mass (Boumaiza *et al.* 2021). Thus, these physical models only partially evaluate the hydraulic erosion process. Another major issue facing existing physical models is the representativeness of the characteristic erosion parameters. Problems encountered in multiple cases include the model shape not reflecting actual dam structures, the use of very low flow rates relative to those observed within spillways, and the non-representativeness of the rock mass. An example of the latter is using a single block instrumented with concealed joints to represent the rock mass (Montgomery 1984; Reinius 1986; Pells 2016). Other problems include using several blocks that do not allow for quantifying the geomechanical parameters (Annandale *et al.* 1998; Sawadogo 2010) or using steel blocks with slots, which are not representative of an actual rock mass (Bollaert et Schleiss 2002). A more appropriate physical model should assess the effect of individual parameters and their interaction to better characterize the hydraulic erosion process.

In this paper, we develop a reduced-scale physical model (RSPM) of a spillway having an inclined flow channel. The model is constructed at the pilot–plant scale. The development of this model is based on a comprehensive analysis of rock mass erosion (Boumaiza *et al.* 2019; Koulibaly *et al.* 2021). This model is relatively complete, as it allows the study of the effect of geomechanical parameters and hydraulic parameters on erosion via various installed instruments. The represented geomechanical parameters and their individual and/or interactive effects include joint opening, shear strength and orientation, rock surface irregularity or protrusion, and block size. In terms of the hydraulic aspects, analyzing the uplift pressure for removing blocks can be investigated by studying the water velocity distribution in joints as a function of water flow velocity in the channel, joint opening, and waviness.

This RSPM allows studying for the first time various hydraulic and geomechanical parameters affecting spillway erosion, assessing their relative importance in the erosion process, and examining the interactions between these parameters. The results of these experiments can be then compared with existing erosion observation cases to calibrate jointed rock mass numerical models for studying erosional phenomena at an actual scale and for developing new models to predict erosion.

2 Design methodology

According to the design models, spillways can be classified according to the energy dissipation process associated with water flow. Energy is dissipated either in a flow channel or in a plunge pool at the downstream end of the spillway structure. In the first case, different configurations can be encountered depending on channel geometry, including flow parallel to the channel bed, hydraulic jumps, and knickpoint flow caused by changes in channel angle. For the second case, the primary flow mode is a plunging jet into a dissipation pool. In most field cases, both energy dissipation modes occur directly on unlined rock masses, and the use of spillways having flow channels is the most globally widespread (Khatsuria 2004). Thus, our designed RSPM represents a flow channel spillway. To represent rock mass geomechanical parameters in the development of this RSPM, this study undertook an analysis of the erosion mechanisms in the unlined spillways—the hydraulic parameters are based on conditions observed at the Romaine IV dam in Québec, Canada. A dimensional analysis was carried out to better represent these parameters; thus, the reference hydraulic parameters of the RSPM and the parameters of the rock mass are representative and scaled to observations from an existing spillway. Instruments were installed on the RSPM to monitor the key parameters in rock erosion. These different scaling stages of the model are explained in the following sections.

2.1 Mechanism of rock mass hydraulic erosion

Hydraulic erosion can occur through three mechanisms: erosion by instantaneous brittle fracturing, continuous brittle fracturing of the rock mass, and the dynamic removal of rock blocks from the rock mass (Bollaert et Schleiss 2002; Annandale 2006; Bollaert 2010). Erosion of the rock mass by instantaneous brittle fracturing occurs when the intensity of the induced fluctuating pressure in the joints is greater than the resistance of the rock; hence, the rock mass breaks into smaller pieces, and these fragments are then easily transported by flowing water (Fig. 1).

Fig. 1 Erosion by instantaneous brittle fracture (Annandale 2006)

The second mechanism is continuous fracturing or the fatigue failure mode, which occurs where the instantaneous brittle fracture of the rock mass is not possible. Fatigue failure occurs when the stress intensity within joints does not exceed the resistance of the rock mass. The rock mass fragments, however, because of the continuous water pressure load present in the joints; thus, it is a highly time-dependent erosion mechanism (Fig. 2).

Fig. 2 Erosion by the continuous fragile fracturing of a rock mass or hydrofracturing by fatigue (Annandale 2006)

The third erosion mechanism is the removal of blocks, which depends on the water pressure within the joints of a fractured rock mass. The amplitude of fluctuating pressure changes over time within a turbulent flow, and the pressure applied within the rock joints can heighten the pressure directly below the blocks. The rock mass is then eroded by the dynamic expulsion of a block when the lifting pressure under the block exceeds the load resistance of the block in the rock mass (Fig. 3). The parameters influencing the resistance of the block are the submerged weight of the block (G_b), the pressure forces on top of the block (F_o), and the shear resistance forces along the sides of the block (F_{sh}).

Fig. 3 Erosion by block removal, named dynamic block impulses, (**a**) via the removal of blocks in a plunging stream (Bollaert et Schleiss 2002; Annandale 2006) and (**b**) via the removal of blocks in a flow parallel to the bottom of the flow channel (Annandale 1995)

Of these three erosion mechanisms, dynamic block removal is the most common erosion mechanism of fractured rock masses within spillways, confirmed by field observations around the globe (Boumaiza *et al.* 2019). This erosion mechanism is the case in particular for crystalline rock masses, which are classified as very high-strength rocks. Hence, this RSPM is designed by considering the characteristic parameters of the dynamic block removal erosion mechanism (Fig. 3).

2.2 Identification of the relevant parameters

The forces involved in hydraulic erosion are the erosive force of the water and the resistance force of the rock mass. The resistance of the rock depends on several geomechanical parameters, including *UCS*, K_b, K_d, V_b, J_o, E_{dao}, J_s, and *NPES* (Table 1). The effect of certain parameters on rock mass erosion has been widely criticized; some parameters have no significant effect on rock mass erosion, and others do not correctly reflect the considered rock mass parameters. For example, the irrelevance of K_b is linked to the limited performance of *RQD* when characterizing a rock mass (Palmström 2001; Palmstrom 2005; Pells *et al.* 2016). *UCS* is not suitable for evaluating the resistance of the rock mass to erosion because high values for this parameter are observed at most dam sites. In reality, most *UCS* values are greater than the compressive strength of concrete-lined spillways, such as observed at the Mokolo dam, South Africa, where high erosion rates have been observed on resistant rocks, as defined according to *UCS* values.

In reality, rock mass resistance to erosive forces depends mainly on the discontinuities present in a rock mass and its related parameters, such as block size, block orientation, spacing, persistence, and roughness of the joint sets (Bieniawski 1989). Boumaiza *et al.* (2019) developed a methodology for determining the most critical parameters affecting the erosion process on the basis of the observed rock mass erosion data collected at 110 dam sites across the globe. They concluded that the most relevant parameters for erodibility are the shear strength of the joints (J_r), the joints' openings (J_o), the volume of the rock blocks (V_b), the shape and orientation of the blocks in relation to the direction of water flow (E_{doa}), and the nature of the potentially erodible surface (*NPES*). The RSPM considers all these geomechanical parameters in modeling the rock mass.

Indices commonly identified for the erosive force of water are the rate of energy dissipation (Π_{UD} in $\mathrm{kW\,m^{-2}}$), the average flow velocity ($\bar{u}$ in $\mathrm{m \cdot s^{-1}}$), and the average shear stress on the bottom surface of the flow channel ($\bar{\tau}_b$ in kPa). Koulibaly *et al.* (2021) noted the lack of agreement in regard to the representativeness of these indices. Most studies have shown that those indices that depend mainly on pressure are most relevant for representing the erosive force of water. Also, when considering the various erosion mechanisms (Figs. 1–3), hydraulic pressure appears as the leading force causing the brittle fracturing of the rock and block uplifting.

An exciting application of a reduced-scale physical model is the study of a phenomenon that is impossible to study at an actual scale; nonetheless, the reduced-scale version must ensure a good representation of the studied parameters. The parameters considered in the present case are the erosive force of the water (the pressure) and the geomechanical parameters of the rock mass (J_r, J_o, V_b, E_{doa}, and *NPES*).

2.3 Dimensional analysis for selecting the hydraulic parameters of the physical model

In fluid mechanics, laboratory-scale models are generally developed to study phenomena that are difficult or impossible to study at a larger field scale. Dimensional analysis is required to ensure the representativeness of hydraulic parameters at different scales. In such analyses, the three aspects to consider are the geometric, kinematic, and dynamic similarities (Cengel 2014). The geometric similarity, indicating that the reduced model has the same geometric shape as the actual feature under study, is assured by simple scaling. Kinematic similarity requires that the flow velocity at any point in the reduced model be proportional to the velocity at the corresponding point in the actual system. The dynamic similarity is obtained when all forces of the reduced model flow are proportional to the corresponding forces in the actual flow.

In the hydroelectric dam industry, it is common to predefine hydraulic parameters to reduce the effects of the erosive force of water. The velocity of water leaving the reservoir and flowing within the flow channel must be between 15 and 30 m·s^{-1}, depending on the nature of the rock mass. Thus, realistic reference parameters are assured by designing our RSPM according to field data collected from the Romaine IV dam spillway in eastern Québec (Hydro-Québec; Fig. 4). However, the RSPM design also permits altering other hydraulic conditions, including flow rate, velocity, and channel inclination. Moreover, the number of concrete blocks, their size, and arrangement are also varied to represent different configurations of the rock mass.

Fig. 4. Spillway (*within the dashed lines*) of the Romaine IV dam, Québec (Canada)

The similarity conditions are met by using appropriate values, including the characteristics of the actual dam system, the scale factor, and the use of dimensionless numbers to allow the transposing of the geometric dimensions and hydraulic parameters. Different scale factor (*Fe*) values can be considered for dimensional analysis, and we selected a value of 1/40 on the basis of the available laboratory space and the allocated budget. This *Fe* value ensures adequate representativeness of the RSPM. Two dimensionless numbers must also be considered: 1) the Froude number (*Fr*) to respect the similarity conditions, and 2) the Reynolds number (*Re*) to verify the invariability of the hydraulic conditions at both scales. Equation (1) is used to determine the characteristic dimensions of the RSPM as a function of the dimensions of the actual system.

$$Fr_{RM} = \frac{u_{RM}}{\sqrt{g \cdot l_{RM}}} = Fr_{RSPM} = \frac{u_{RSPM}}{\sqrt{g \cdot l_{RSPM}}}, \qquad (1)$$

where *Fr* is the Froude number at the scale of the actual dam setting (real model; *RM*) and at the scale of the RSPM, *u* is the flow velocity at both scales, and *l* represents the dimensions in meters at both scales. The dimensions obtained for the RSPM with Eq. (1) are summarized in Table 4.

Table 4 Summary of the dimensional parameters of the studied spillway system and the RSPM

The Reynolds number then serves to determine the flow conditions in the RSPM via Eq. (2). These conditions are then compared with the flow conditions of the RM.

$$Re_{RM} = \frac{u \cdot L}{\nu} = \frac{20 \times 3.66}{1.002 \times 10^{-6}} = 73.05 \times 10^{6} > 2000 \Rightarrow \text{turbulent flow},$$

$$Re_{RSPM} = \frac{u \cdot L}{\nu} = \frac{3.162 \times 0.092}{1.002 \times 10^{-6}} = 2.90 \times 10^{5} > 2000 \Rightarrow \text{turbulent flow}, \qquad (2)$$

where *u* is the flow velocity upstream of the spillway, *v* is the kinematic viscosity of water at 20 °C (1002 × 10^{-6} m^2·s^{-1}) (Cengel 2014), and *L* is the characteristic length corresponding to the hydraulic radius of the channel. Calculations performed with R_e produce the same flow conditions at both scales; hence, the dimensional analysis is correct. From this dimensional analysis, the hydraulic conditions are respected, i.e., the velocity and the flow rate in the channel. The total water pressure is thus represented through these parameters (velocity and flow rate), i.e., the static and dynamic pressure depend on the water height and the flow velocity in the channel, respectively. Thus, by having a flow rate, velocity, and turbulence level proportional to both scales, inversely proportional pressure is obtained, and, according to dimensional analysis, the unit pressure at the actual scale is equivalent to 40 times that of the RSPM.

2.4 Design of the rock mass test section

Rock mass erosion generally begins at a specific location in a spillway, determined by the characteristics of the rock mass and the produced flow patterns (Kirsten *et al.* 2000). For inclined channel spillways, erosion often begins in the downstream area where there may be a sudden change in the flow regime. An example is the erosion observed at the Copeton dam, Australia (Fig. 5). Therefore, the rock mass test section in the RSPM is situated in the downstream area; however, this location can be changed if necessary.

Fig. 5 Location of areas subject to erosion on an inclined spillway; (**a**) downstream erosion at the Copeton dam, Australia (Pells 2016) and (**b**) the area sensitive to erosion along an inclined flow channel (Kirsten 2000)

The test section of the RSPM is designed using the data in Table 4. This test section (reduced spillway) is integrated within a water recirculation system (Fig. 6)—using a pump and two water reservoirs—to maintain stable and continuous test conditions.

Fig. 6 The designed RSPM of the Romaine IV dam spillway; (**a**) 3D and (**b**) sectional views of the model (8.1 m long, 2.4 m wide, and 4.2 m high)

The closed-circuit physical model (Fig. 6) consists of four parts. The downstream reservoir made of reinforced concrete also serves as the foundation for the model. This reservoir also contains a centrifugal pump that provides water at a controlled rate to the upstream aluminum reservoir connected to the test section. The volume of water contained in the downstream reservoir is 24,000 L. The selected pump yields a maximum flow rate of 400 $L \cdot s^{-1}$, and a double-value opening system installed on the upstream reservoir controls the flow rate and the velocity of water entering the test section. This setup also allows assessing the effect of asymmetric flow on the rock mass (Fig. 7).

Fig. 7 View of the double-value system in the RSPM model

The RSPM is also equipped with a velocity sensor to measure the water velocity in the channel, see Table 5 for the specifications of the various measuring instruments.

The representativeness of the rock mass in the test section is one of the most critical factors of the RSPM. The casing located in the downstream part of the test section is designed to receive specifically designed concrete blocks equipped to monitor and investigate the behavior of a rock mass against water flow (note the jointed rock mass area in Fig. 6). This casing can contain various amounts of concrete blocks, depending on the desired block size. Moreover, the casing itself may be built at various dimensions and arrangements, allowing the model to vary in its rock mass geometries and permitting the analysis of a number of geomechanical parameters. This aspect is detailed further in the following sections.

2.5 Monitoring and instrument design

To investigate the response of some rock mass parameters to the erosive hydraulic forces, we instrumented a few concrete blocks with eight pressure sensors that record the water pressure applied to each face of the block (Fig. 8; Table 5). On each face, two holes are drilled for the water inlet (Fig. 8, *red arrows*), connected to the pressure sensors through their water outlet points on the top side of the block (Fig. 8a, *green arrows*). The holes in the block contain ¼″ diameter copper tubing to limit pressure loss (Fig. 9). An accelerometer placed on the top side of each instrumented block measures the geomechanical parameters controlling the relative displacement of the block under the effect of water pressure.

Fig. 8 (**a**) An example of an instrumented concrete block for measuring the water pressure on the block faces; (**b**) bolts in non-instrumented blocks used for the joint test; and (**c**) an example of a block used to test joint roughness

Fig. 9 (**a**) A series of ¼″ diameter copper pipes that vary in shape depending on the pressure measurement points; (**b**) wooden mold with copper pipes installed on each face of the block, the mold being for blocks having a smooth surface; (**c**) wooden mold with 3D printing of a rough profile, the mold being for blocks having a rough surface; and (**d**) the pouring of a concrete block

Table 5 Model and characteristics of the RSPM measuring instruments

2.6 Test design for studying the effect of geomechanical parameters

This RSPM allows evaluating the interaction between the water forces and rock mass parameters. The representativeness of the model requires that the set of concrete blocks be characterized by several geomechanical parameters, including K_d, J_o, V_b, E_{doa}, and *NPES*.

Design for evaluating the effect of joint shear strength on erosion

In a rock mass classification, the shear strength (K_d or F_{sh}) of the joints is commonly related to the ratio between joint roughness (J_r) and the degree of alteration of the joint face (J_a) (Kirsten *et al.* 2000). During erosion, however, the alteration zones or the filling materials of joints are leached and eroded in an initial phase (Fig. 10). Consequently, the critical parameter characterizing the shear strength of joints subjected to erosion is joint opening (J_o) and J_r. Joint surface irregularities are considered via the joint roughness coefficient (JRC). We produced various JRC profiles (smooth to very rough) using 3D printing (Figs. 8c and 9c). In our RSPM, the configuration of the casing and the concrete blocks permits evaluating the effect of the joint opening on rock mass erosion. A more thorough explanation of this aspect is presented in the section discussing the *NPES* parameter.

Fig. 10 Altered joint behavior of a rock mass under the effect of water pressure

Design for evaluating the effect of block orientation on erosion

Block orientation is a critical parameter affecting hydraulic erosion. It is easier for water to displace blocks when the dip of the blocks is in the same direction as the flow, and blocks are more resistant to flow when their dip is opposite to that of the direction of flow (Kirsten *et al.* 2000). Two parameters are known to characterize the effect of block orientation: J_s and E_{doa}. However, J_s is qualified by some authors as not being representative of erosion (Pells *et al.* 2016; Boumaiza *et al.* 2019); thus, E_{doa} served to define three dip values for block orientation, including 90°, −45°, and 45° to the direction of water flow (Fig. 11). Block arrangements with other dip values may be used, depending on the study objective.

Fig. 11 Arrangement of the blocks with respect to the direction of water flow (DWF); the dimensions are in cm

Design for evaluating the effect of block volume (V_b) and weight (G_b)

Block volume is a key parameter when evaluating rock mass erosion, as it is intrinsically linked to weight, which greatly influences the pressure required to uplift the blocks. In our RSPM, we designed two sets of blocks of different volumes and densities to study the effect of block volume and weight on lifting pressure. We produced blocks of 12,000 cm^3 (20 cm × 230 cm × 20 cm) and 6750 cm^3 (15 cm × 230 cm × 15 cm), having densities of 1275, 1290, 1785, 1820, and 2240 $kg{\cdot}m^{-3}$. These block sizes were chosen on the basis of rock mass data collected from more than 100 dam spillways (Pells 2016). By using grains of material with different densities, we obtain blocks of varying mass to better represent the actual variations of intact rock. The use of blocks of variable volume and density allows for determining the density at which blocks may be susceptible to displacement under the effect of a known uplift pressure. We installed accelerometers and high-definition cameras above and on one side of the test section to visualize the relative movement of the blocks.

Design for studying the nature of potentially erodible surfaces (*NPES*)

The degree of flow turbulence depends highly on the nature of the flow channel, including channel shape and channel floor roughness (protrusion and *Jo*). The flow channels of spillways are often highly irregular because of the presence of protrusions and open joints. These irregularities increase flow turbulence, creating high differential pressure values within joints. A channel having high protrusions is more susceptible to erosion by block removal. Conversely, smooth surface flow channels are less susceptible to erosion, as the likelihood of a high-pressure buildup around the rock block is relatively low (Pells 2016). Figure 12 presents some examples of rock blocks with protrusions used in our flow channel; the protrusions that we used are those most commonly evaluated by the *NPES* parameter (Montgomery 1984; Reinius 1986; Pells 2016). Joint opening (J_o) is assured by spacers seated on the concrete blocks (Fig. 8c). These spacers can be adjusted according to the desired opening (Fig. 13). Given the different nature of the concrete block surfaces, it is difficult to have $J_o < 1$ mm. Therefore, joint opening tests are limited to a 0.5 mm precision.

Fig. 12 Examples of the arrangement of concrete blocks to produce different protrusion combinations (dimensions in cm)

Fig. 13 Configurations for visualizing the variation of the joint opening (J_o); (**a**) a low J_o of approximately 1 mm and (**b**) a J_o of approximately 2.5 cm.

3 Validation of the reduced-scale physical model

Depending on the erosion mechanism under study, the pressure associated with the water flow should be sensitive to variations in flow rate, channel geometry, and various geomechanical parameters. For the RSPM to be representative, we should observe the effect of varying geomechanical parameters on pressure, including:

- The pressure associated with water flow should increase at a higher flow rate;
- The uplift pressure should increase as the spacing between the blocks increases;
- The uplift pressure should be greater when the inclination of the blocks is in the same direction as the direction of flow;
- The relative displacement of the blocks should follow uplift pressure, although this will also depend on joint opening, block volume, and block face roughness;
- The pressure associated with the flow should increase as a direct function of flow turbulence, which is mainly dependent on the slope of the test section and the nature of the potentially erodible surface, i.e., the irregularity of the area of the test section.

We tested these assumed effects by undertaking flow tests and varying some of the parameters to validate the representativeness of the RSPM. In the following subsections, the measured pressure corresponds to total pressure, which is equal to the sum of the dynamic and static pressures. Figure 14 shows the general configuration of the rock mass in the casing, in which P_A corresponds to the average pressure measured on the top side of the block, P_B is the average pressure measured on the under side of the block, P_C is the average pressure measured on the upstream side of the block, $P_{C\text{-up}}$ and $P_{C\text{-down}}$ represent the pressures measured in the upper and lower part of the upstream side of the block, respectively, and J_o represents the spacing around the block, called the joint opening.

Fig. 14 Schema of the setup for evaluating the effect of geomechanical parameters on the applied pressure measured on the block

3.1 The effects of inflow rate on water pressure

To evaluate the effect of the flow rate on the water pressure, we applied various inflow rates (0.233, 0.566, and 0.666 $m^3 \cdot s^{-1}$). We used a concrete block having a 25 mm protrusion with a 25 mm spacing between blocks (*Jo*) (Fig. 14). We observed, as expected, that pressure on the upstream side of the block, i.e., the side facing flow circulation, was greater as the flow rate increased (Fig. 15).

Fig. 15 Effect of flow rate (water inflow) on the applied pressure measured on the upstream face of the rock mass

3.2 The effect of joint openings (J_o) under the block and protrusions (*NPES*) on water pressure

To evaluate the effect of J_o and *NPES* on the water pressure applied to the top and underside of the rock blocks, we produced from Fig. 14 a setup using a rock mass characterized by a 25 mm gap between the blocks and 15, 25, and 53 mm of spacing under the test block, a spacing that is inversely related to the height of the protrusion (Fig. 14). Our test results matched the hypothesized outcome, as we observed a greater uplift pressure as J_o under the block and *NPES* increased (Fig. 16). A channel flow surface characterized by high protrusions (high irregularity) heightens the turbulence of the water flow and the related pressure (Fig. 16b). The increased uplift pressure is expected to depend on the spacing below the rock block (Fig. 16a) because the infiltration of water below the block is linked directly to this opening.

Fig. 16 Effect of (**a**) J_o under the block on uplift pressure, measured on the underside of the block, and (**b**) a protrusion (*NPES*) on the pressure applied to the top of the block

3.3 The effect of J_o on pressure

During testing, we gradually changed J_o around the block (Fig. 14) to visualize its effect on uplift pressure P_B and the pressure applied to the upstream side of the block ($P_{C\text{-up}}$ and $P_{C\text{-down}}$).

Fig. 17 The effect of J_o around the block on the applied pressure

We expected the applied pressure within the joint to increase with larger joint openings. Both resulting curves ($P_{C\text{-up}}$ and $P_{C\text{-down}}$) illustrate that the pressure applied to the upstream side was greater with increased J_o (Fig. 17). We also note that the uplift pressure of the block increased with J_o around the block and that pressure on top of the block was lower than the underside pressure. This difference is expected because total pressure in the turbulent flow equals the sum of the static and dynamic pressures related to the water flow. Depending on the water height differential between points P_B, $P_{C\text{-down}}$, and $P_{C\text{-up}}$, the static pressure at point P_B must be greater than at $P_{C\text{-down}}$, and $P_{C\text{-down}}$ must be greater than $P_{C\text{-up}}$. The contribution of the static pressure in our measurements was relatively high (Fig. 17), which was useful for validating the representativeness of the total pressure measured using our RSPM.

4 Discussion, recommendations, and research perspectives

Predicting the hydraulic erosion of the rock mass in dam spillways represents a real challenge because the parameters characterizing this phenomenon are not well quantified. The rock mass resistance index and the erosive force of the water, used to evaluate hydraulic erosion, are based on specific parameters, and some of them are irrelevant to erosion (Pells *et al.* 2016; Boumaiza *et al.* 2019; Koulibaly *et al.* 2021). Our RSPM can resolve this issue by evaluating the interactions between the erosive force of water and the geomechanical parameters characterizing the rock mass. The most important parameters deemed as relevant to explain hydraulic erosion are considered by the RSPM. These parameters include flow rate, flow velocity, flow turbulence, pressure, the slope of the flow channel, and the rock mass geomechanical parameters (K_d, J_o, V_b, E_{doa}, and *NPES*). Our tests validated the representativeness of this RSPM for evaluating interactions between the rock mass's geomechanical parameters and the water's erosive force, and our obtained results correspond well to the expected results. This RSPM can thus be used to successfully identify and quantify the relevant hydraulic and geomechanical parameters and evaluate the interaction between these parameters to improve the characterization of hydraulic erosion in spillway channels.

This RSPM is currently being used in multiple characterization studies of hydraulic erosion. Ongoing studies are characterizing and quantifying the previously identified geomechanical and hydraulic parameters. Examples of current research focused on the characterization of hydraulic erosion through the use of this RSPM include:

- Development of criteria for determining water velocity in joints as a function of joint opening, surface protrusion, and the velocity of water in an open channel, a known problem in jointed rock masses;
- Determination of the relative effect of geomechanical parameters on erosion;
- Evaluation of the interactive effect of joint opening and rock surface erosion on the vulnerability of a rock mass to erosion;
- Evaluation of the individual and interactive effects of J_o and V_b on erosion;
- Use of other forms of blocks;
- Modification of numerical modeling using the RSPM model for representing rock mass phenomena at a large scale.

Nonetheless, the RSPM model also has some limitations in its applicability. First, the erosion of intact rock, and therefore brittle fracturing, is neglected in this model. Moreover, because of the lack of dimensional analysis in rock mechanics, unlike in hydraulic engineering, the selected rock mass scale model relying on 100 actual field cases occurs at scales of 1/20 and 1/40. Finally, the RSPM does not allow a J_o smaller than 1 mm in its current form.

5 Conclusion

We designed and produced an innovative RSPM for studying the rock mass erosion processes in dam spillways. This RSPM includes the most important hydraulic and geomechanical parameters that interact during hydraulic erosion events. We found water pressure to be the most important hydraulic parameter requiring evaluation against the relevant geomechanical parameters of a rock mass, including J_o, E_{doa}, V_b, *NPES*, and K_d. We equipped the test section of the RSPM with a set of concrete blocks having pressure measurement points on each block face. By changing the arrangement of these concrete blocks, we could represent different geomechanical parameters and evaluate water pressure in relation to the various rock mass configurations. Thus, this RSPM will allow, in the near future, a more complete evaluation of the hydraulic erosion of a rock mass within spillway outflow channels. Well-identified and quantified geomechanical and hydraulic parameters will improve existing methods for evaluating hydraulic erosion and favor implementing new methods to better predict rock mass erosion in large-scale hydroelectric dam spillways.

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References

Annandale G. 1995. Erodibility. Journal Of Hydraulic Research, 33 : 471-494.

Annandale G, Wittler R, Ruff J et Lewis T. 1998. Prototype validation of erodibility index for scour in fractured rock media. Water Resources Engineering'98 : 1096-1101.

Annandale GW. 2006. Current Technology to Predict Scour of Rock. Golden Rocks 2006, The 41st US Symposium on Rock Mechanics (USRMS), 2006/1/1/, Golden, Colorado.

Bieniawski ZT. 1989. Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering. John Wiley & Sons.

Bollaert E. The comprehensive scour model: Theory and feedback from practice. Dans : 5th International Conference on Scour and Erosion, San Francisco, 2010.

Bollaert E et Schleiss A. 2002. Transient water pressures in joints and formation of rock scour due to high-velocity jet impact. EPFL-LCH.

Boumaiza L, Saeidi A et Quirion M. 2019. A method to determine relevant geomechanical parameters for evaluating the hydraulic erodibility of rock. Journal of Rock Mechanics and Geotechnical Engineering.

Boumaiza L, Saeidi A et Quirion M. 2021. A method to determine the relative importance of geological parameters that control the hydraulic erodibility of rock. Quarterly Journal of Engineering Geology and Hydrogeology, 54.

Cengel Y. 2014. Heat and mass transfer: fundamentals and applications. McGraw-Hill Higher Education.

Gu S, Liqun R, Xing W, Hongwei X, Yuefei H, Jiahua W et Songdong S. 2017. SPHysics Simulation of Experimental Spillway Hydraulics. Water, 9. doi : 10.3390/w9120973.

Hoek E, Marinos P et Benissi M. 1998. Applicability of the Geological Strength Index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation. Bulletin of Engineering Geology and the Environment, 57 : 151-160.

Khatsuria RM. 2004. Hydraulics of spillways and energy dissipators. CRC Press.

Kirsten HA, Moore JS, Kirsten LH et Temple DM. 2000. Erodibility criterion for auxiliary spillways of dams. International journal of sediment research, 15 : 93-107.

Kote AS et Nangare PB. 2019. Hydraulic Model Investigation on Stepped Spillway's Plain and Slotted Roller Bucket. Engineering, Technology & Applied Science Research, 9.

Koulibaly AS, Saeidi A, Rouleau A et Quirion M. 2021. Identification of Hydraulic Parameters Influencing the Hydraulic Erodibility of Spillway Flow Channels. Water, 13 : 2950.

Lesleighter EJ, Bollaert EFR, McPherson BL et Scriven DC. 2016. Spillway Rock Scour Analysis - Composite of Physical & Numerical Modelling, Paradise Dam, Australia. 6th IAHR International Symposium on Hydraulic Structures, 27-30 june, Portland.

Manso PFdA et Schleiss A. 2006. The influence of pool geometry and induced flow patterns in rock scour by high-velocity plunging jets. EPFL (Lausanne).

Montgomery RA. 1984. Investigations into rock erosion by high velocity water flows. Royal Institute of Technology, Stockholm.

Moore JS, Temple DM et Kirsten HAD. 1994. Headcut advance threshold in earth spillways. Bulletin of the Association of Engineering Geologists.

Palmstrom A. 2005. Measurements of and correlations between block size and rock quality designation (RQD). Tunnelling and Underground Space Technology, 20 : 362-377.

Palmström A. 2001. Measurement and characterization of rock mass jointing. In-situ characterization of rocks : 49-97.

Pells S. 2016. Erosion of rock in spillways. School of Civil and Environmental Engineering, University of New SouthWales.

Pells SE, Pells PJ, Peirson WL, Douglas K et Fell R. 2016. Erosion of rock in spillways.

Reinius E. 1986. Rock erosion. International Water Power and Dam Construction, 38 : 43-48.

Sawadogo O. 2010. Scour of Unlined Dam Spillways. Stellenbosch University, Stellenbosch University, 166 p.

Tuna MC. 2012. Effect of offtake channel base angle of stepped spillway on scour hole. Iranian Journal of Science and Technology Transactions of Civil Engineering, 36 : 239-251.

Wilkinson C, Harbor DJ, Helgans E et Kuehner JP. 2018. Plucking phenomena in nonuniform flow. Geosphere, 14.

Withers WJ. 1991. Pressure fluctuations in the plunge pool of an impinging jet spillway. University of Glasgow, Glasgow, 357 p.