Experimental study of joint opening and block protrusion effects on rock mass erosion in unlined spillways

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ABSTRACT: Rock mass erosion in dams' spillways can cause damages to the spillway structure and result in expensive repairs. In order to study rock mass characteristics having an effect on rock mass erosion in unlined spillways, a scaled physical model of a real dam spillway was built in a laboratory of Université du Québec à Chicoutimi. This physical model also allows studying the hydraulic parameters of the flow which have an effect on rock mass erosion. Some tests were undertaken to study the effects of joint opening and block protrusion on the hydraulic parameters in the simulated rock joints. The distribution of water pressure was measured on the faces of an instrumented block. The results obtained show that the main force having an effect on the block uplift is the water force acting on the top of the block. This force is mostly affected by protrusion configuration.

Keywords: Physical model, Spillway, Rock Mass, Erosion.

1 INTRODUCTION

The excavation of a spillway in the rock mass causes irregular surfaces in the spillway channel. Unlined spillways are particularly vulnerable to erosion because the rock mass is directly exposed to the erosive power of the flow. The cost of lining an entire spillway with concrete is very high and time-consuming, which is why often only more vulnerable sections are lined. However, erosion sometimes occurred in channel sections that were initially not considered vulnerable and in a good quality rock mass.

1.1 Existing erosion evaluation methods

The most used erosion evaluation method is that of Annandale's (1995) scour threshold based on the Kirsten Index (Kirsten 1982). Using the same index, Van Schalkwyk et al. (1994) and Kirsten et al. (2000) also developed a scour threshold. However, the classification provided by these scour thresholds proved to misclass some erosion situations. Originally, the Kirsten Index was developed to evaluate rock mass excavatability, which is why it might not be appropriate to evaluate rock mass erodibility. More recently, Pells (2016) developed two erosion evaluation indices : the erodibility Geological Strength Index (eGSI) and the Rock Mass Erodibility Index (RMEI). The classification provided by these indices is proved better than that of the Kirsten Index (Pells 2016). However, some classification errors still occur in proportions between 20 and 60 % within the erosion classes (Boumaiza et al. 2021). More erosion evaluation methods exist, but they are mostly applicable to plunge pools rather than spillway channels.

1.2 Rock mass erodibility

Rock mass characteristics have various effects on its erodibility. The previous study of Boumaiza et al. (2021) revealed that, in order from the most to the least important, the following characteristics have significant effect of rock mass erodibility in unlined spillways: joint shear strength, block protrusion, block volume, joint opening, block shape and orientation and rock mass deformation modulus. None of the existing erosion evaluation methods take in consideration all of these characteristics – and their combined effect on rock mass erosion was never quantified. For this purpose, a scaled physical model of Hydro-Québec Romaine-4 dam spillway was built in a laboratory of Université du Québec à Chicoutimi. It will be used to calibrate a future numerical model allowing more variation in the rock mass and hydraulic parameters having an effect on rock mass erosion. The first step of this study is to evaluate the effect of rock mass parameters, in this case joint opening and protrusion, on rock mass erodibility.

2 PHYSICAL MODEL

The physical model (Figure 1a) was built based on Froude's number scale of 1:40 to the real spillway and allows varying rock mass characteristics having an effect on its erodibility as well as hydraulic characteristics having an effect on the erosive power of the flow. To simulate rock mass, a total of nine concrete blocks are used, of which one is connected to pressure sensors (Figure 1b). The pressure can be measured on each face of the block using elbows connected to water entries inside the block (Figure 1c). The elbows permit measuring the static and the dynamic pressure – as a pitot tube. The pressure sensors are located outside of the channel. Upstream of the blocks is a static water sensor: a carbon stick floating of the water connected to a Linear Variable Differential Transformer (LVDT) (Figure 1b).

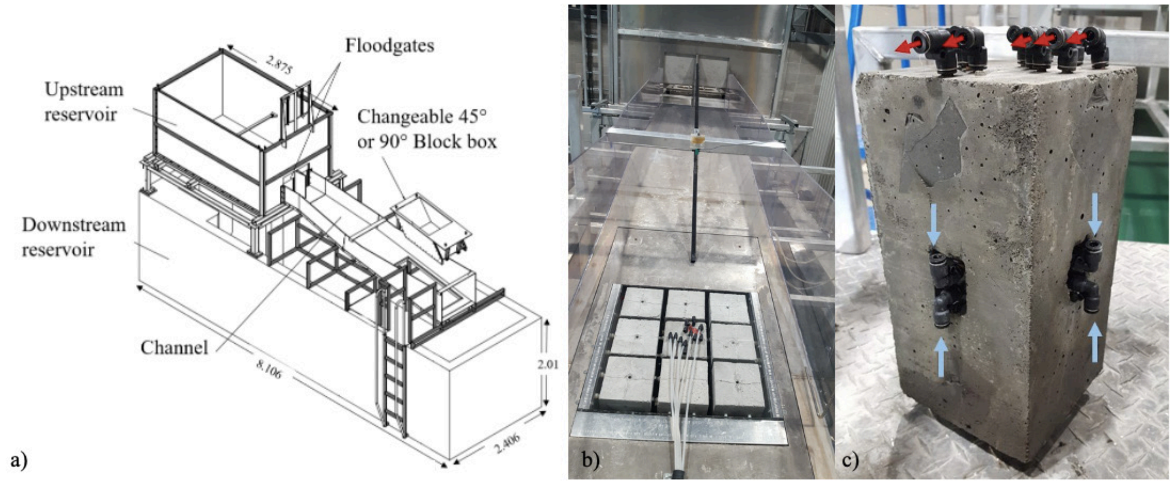


Figure 1. a) Physical model (Koulibaly et al. 2022); b) Channel with the static pressure sensor, the nine blocks and the instrumented block in the centre; and c) instrumented block with the water entries (blue arrows) and the water exits (red arrows).

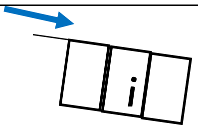
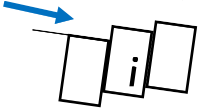
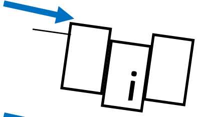
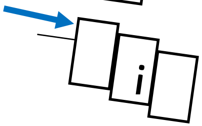
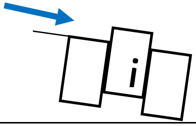
2.1 Parameters variation

For this study, flow velocity was varied equally for each test using different pump frequencies. Four flow velocities were tested: 3.3 m/s, 4.0 m/s, 4.7 m/s and 4.9 m/s. These flow velocities relate to the pump frequency and water height in the upstream basin. The following flow rates are obtained for each flow velocity, respectively: 180 L/s, 240 L/s, 315 L/s and 340 L/s. The floodgates apertures remained constant at 25 cm throughout the tests. The purpose of the first tests using the physical model were to determine the relative effect of joint opening and block protrusion on the pressure distribution around the instrumented block.

2.1.1 Protrusion variation

The effect of protrusion on the pressure distribution around the block was measured for different blocks configurations and protrusion heights. The blocks' configurations were always varied in a two-dimensional way i.e., all the blocks of each row had the same height. Table 1 illustrates all the configurations and the protrusion heights tested.

Table 1. Blocks configurations and protrusion heights tested.

Configuration # and setup		Protrusion of upstream row (mm)	Protrusion of the centre row (mm)	Protrusion of downstream row (mm)
0		0	0	0
3		0	6[a] 13 20[a]	12[a] 26 40[a]
4		13 20 30	0	13 20 30
6		12[a] 26 40[a]	6[a] 13 20[a]	0
8		0	13 20 30	0

[a]These protrusion heights were only tested with a 3 mm joint opening.

Protrusion heights were varied using different bolt lengths. When the protrusion height is zero, an opening of 7 mm remains under the blocks.

2.1.2 Joint opening variation

The lateral aperture between the blocks is defined as the joint opening. Joint openings were set using three to four spacing bolts on the blocks' lateral faces. Because of the elbows' widths placed on the water entries, the minimum aperture permitted using these elbows is 10 mm. Three joint openings were tested: 38 mm, 20 mm and 10 mm. An additional joint opening of 3 mm was also tested, but only top and bottom pressures were measured. More protrusion heights were tested for the 3 mm joint opening (Table 1).

3 RESULTS AND DISCUSSION

The raw pressure measurements include the static pressure, the dynamic pressure and the position pressure. The static pressure is the water height above the water entry. It can be calculated adding the known position of the water entry below the block top and the water height above the channel using the static water sensor. The dynamic pressure depends on the flow velocity in the opposite direction of the elbow, given with equation 1. P_{dyn} is the dynamic pressure, v is the flow velocity and g is the gravitational acceleration.

$$P_{dyn} = {}^{v^2}/_{2g} \tag{1}$$

The position pressure is the height difference between the block's water entries and the pressure sensors position outside of the channel. It is a constant that must be subtracted from the raw results in order to have only the static and dynamic pressures. Static pressure remained constant during all tests and only slightly varied when varying the flow velocity. Using the raw measurements, the position pressure and the static pressure, it was then possible to isolate dynamic pressure and to obtain the flow velocity on each face of the block.

3.1 Flow velocity on top of the block

To measure the effect of the configurations, protrusion heights and joint openings (JO), the flow velocity on top of the block (V_A) is compared with the flow velocity in the channel (V_{Ch}) (Figure 2). If the ratio is one, the effect of these parameters is negligible, since in the case of no protrusion the velocity on top of the block is the same as in the channel.

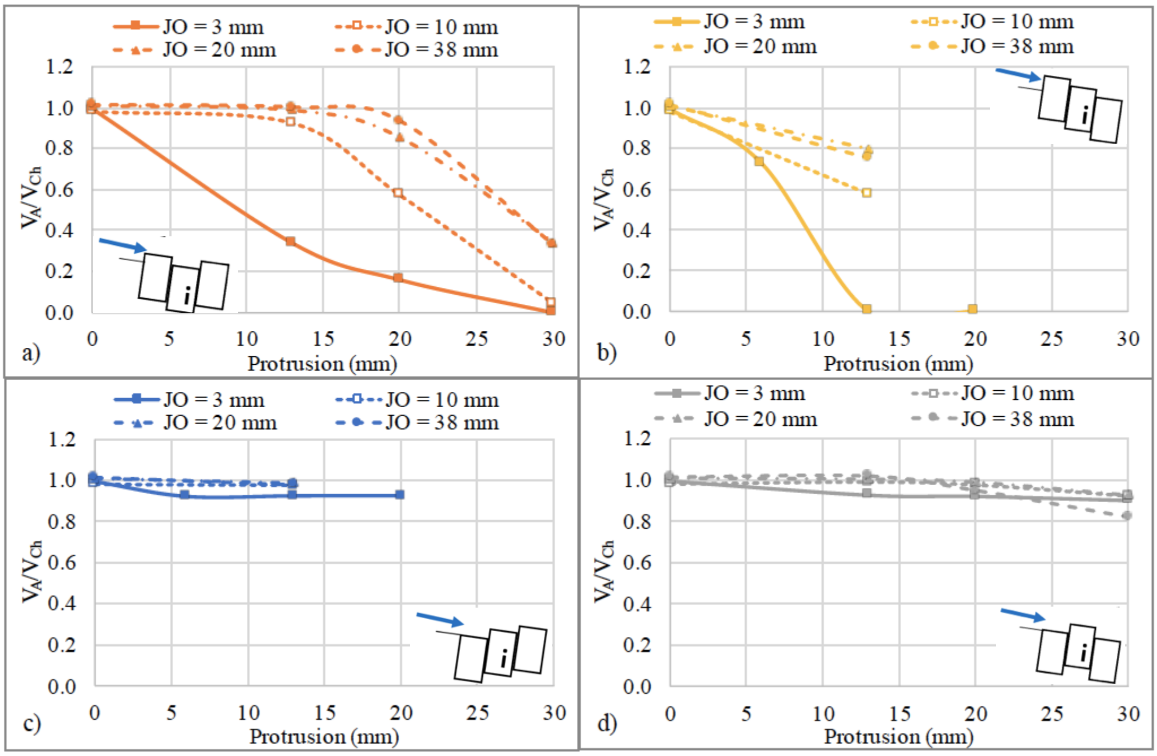


Figure 2. Variation of V_A/V_{Ch} a) protrusion configuration 4; b) configuration 6; c) configuration 3; and d) configuration 8.

Flow velocity on top of the block is mostly affected by protrusion configurations 4 and 6 (Figures 2a and 1b). For these configurations, a decrease in the joint opening and an increase in the protrusion height also affect the V_A/V_{Ch} ratio. The more the ratio decreases, the less there is pressure on top of the block. Since the pressure on top of the block acts as a stabilizing force, a decrease in V_A/V_{Ch} implies blocks that are more susceptible to be uplifted.

3.2 *Flow velocity under the block*

To measure the effect of the configurations, protrusion heights and joint openings, the flow velocity on the bottom of the block (V_B) is compared with the flow velocity in the channel (Figure 3). The main component of the total pressure under the block is static pressure. This may be caused by the prismatic geometry of the block (lateral faces higher than the base width). Therefore, the ratio V_B/V_{Ch} for the case of no protrusion stays between 0.2 and 0.3 depending on the joint opening.

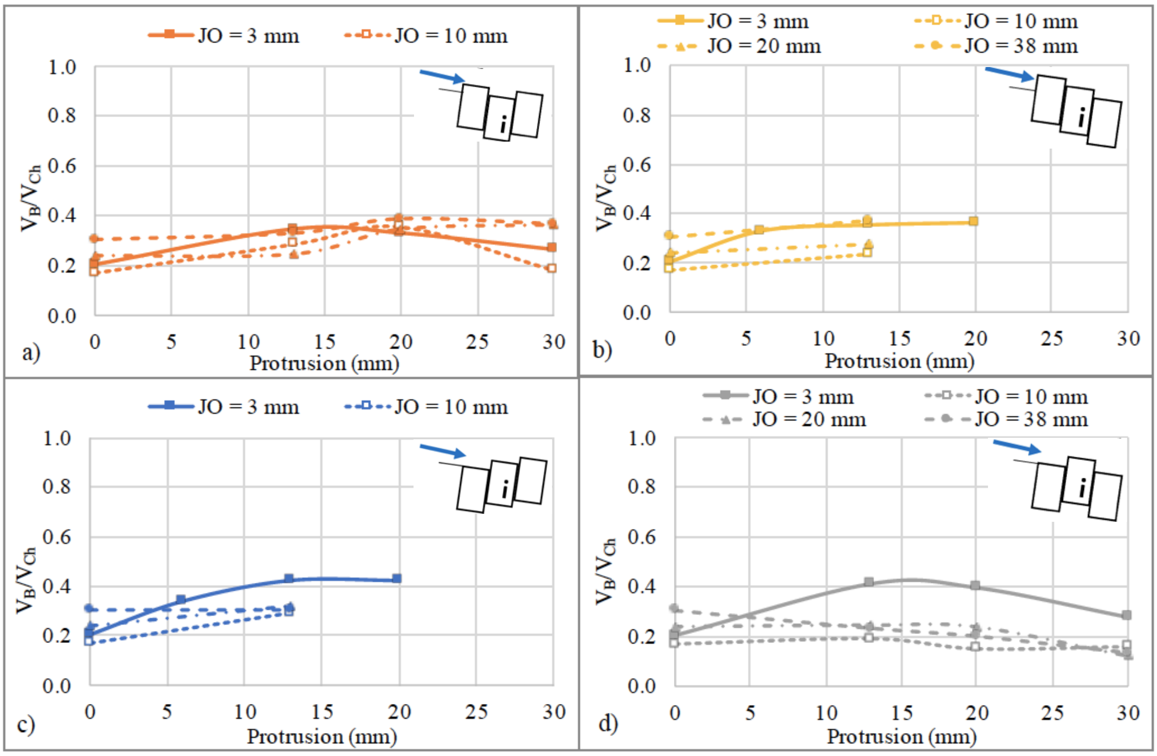


Figure 3. Variation of V_B/V_{Ch} a) protrusion configuration 4; b) configuration 6; c) configuration 3; and d) configuration 8.

Since the pressure on the bottom face of the block acts as a mobilizing force, an increase in V_B/V_{Ch} implies blocks that are more susceptible to be uplifted. No significant variation is observed in Figure 3, but the results may be different if a different block geometry is used.

4 CONCLUSION

Rock mass characteristics' affecting its erodibility in dams' spillways need to be more studied to develop a reliable erosion evaluation method. The physical model of an existing dam spillway built in a Université du Québec laboratory allows varying all rock mass characteristics known to have an effect of rock mass erodibility in spillways. It can also be used to study the hydraulic characteristics of the flow having an effect on its erosive power.

The first tests on the physical model were undertaken to study the effect of joint opening and block protrusion on the pressure distribution around an instrumented block. It was found that the dynamic pressure on top of the block vary greatly depending on the blocks' configurations used. A smaller joint opening combined with a higher protrusion height increased block's configuration effect. Pressure under the block was mainly composed of static pressure and did not vary significantly throughout the tests, but that may be caused by the blocks' prismatic geometry. Future tests on the physical model will evaluate the effect of other relevant rock mass parameters, as joint orientation, block shape, block volume and joint shear strength.

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