Determining the most representative parameter for quantifying the rock block size used for evaluating the hydraulic erodibility of rock

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ABSTRACT
The most commonly used method for assessing the hydraulic erodibility of rock is the Annandale's method. This method is based on a correlation between the erosive force of flowing water and the capacity of rock resistance. This capacity is evaluated using the Kirsten's index which could be determined according to certain geomechanical parameters related to the rock mass, including the rock block size parameter. This parameter is evaluated in Annandale's method by combining the *RQD* index (Rock Quality Designation) with the joint sets number (J_n) to create the quotient K_b (RQD/J_n). Some researchers showed that the quotient K_b provides no meaningful quantification of rock block size. Other researchers stated that using three-dimensional block volume measurements, instead of the K_b parameter, improves the rock block size estimation. This paper presents a developed method allowing to determine the most representative parameter for quantifying rock block size in the framework of evaluating the hydraulic erodibility of rock.

RÉSUMÉ
La méthode la plus couramment utilisée pour évaluer l'érodabilité hydraulique du roc est la méthode d'Annandale. Cette méthode est basée sur une corrélation entre la force érosive de l'eau et la capacité de résistance du roc. Cette capacité est évaluée à l'aide de l'indice de Kirsten, qui pourrait être déterminé en fonction de certains paramètres géomécaniques liés au massif rocheux, tels que taille des blocs rocheux concernés par l'érosion. Ce paramètre est évalué dans la méthode d'Annandale en combinant l'indice RQD (*Rock Quality Designation*) avec le numéro correspondant au nombre de famille de joints (J_n) pour créer le quotient K_b (RQD/J_n). Certains chercheurs ont montré que le quotient K_b ne fournit pas une quantification significative de la taille des blocs rocheux. D'autres chercheurs ont mentionné que l'utilisation de mesures tridimensionnelles du volume de blocs, au lieu du paramètre K_b, améliore l'estimation de la taille des blocs rocheux. Cet article présente une méthode novatrice permettant de déterminer le paramètre le plus représentatif pour quantifier la taille des blocs rocheux dans le cadre de l'évaluation de l'érodabilité hydraulique du roc.

1 INTRODUCTION

During the Cincinnati Symposium (Kirkaldie 1988) that focused on engineering rock mass classification systems, it was proposed that the mechanical excavatability and the hydraulic erodibility[1] of earth materials could be considered as similar processes (Moore and Kirsten 1988). Van-Schalkwyk (1989), Pitsiou (1990), and Moore (1991) then demonstrated that the existing rock mass classification systems used for evaluating the mechanical excavatability of rock incorporate most of parameters that affect the hydraulic erodibility of rock. Van-Schalkwyk et al. (1994) tested several rock mass characterization indices for evaluating the hydraulic erodibility of rock, and they found that the indices generated similar results. However, Kirsten's index (Kirsten 1982, 1988) is more accurate. This index, initially developed to evaluate the excavatability of earth materials, has since been adopted for assessing the hydraulic erodibility of earth materials where the "direction of excavation" of the original index has been replaced by the "direction of flow" (Pitsiou 1990, Doog 1993, Annandale and Kirsten 1994, Van-Schalkwyk et al. 1994, Annandale 1995, 2006, Kirsten et al. 2000). In these cited works, the assessment of hydraulic erodibility is based on a correlation between the erosive force of flowing water and the capacity of the rock to resist the erosive force. The erosive force of flowing water is the hydraulic energy, expressed in kW/m^2, generated by the flowing water. This erosive force is usually called the available hydraulic stream power (P_a). For its part, the resistance capacity of rock is evaluated using the Kirsten's index (Kirsten 1982, 1988), which is determined according to certain geomechanical parameters related to the rock mass, such as the compressive strength of intact rock (M_s), the rock block size (K_b), the joint shear strength (K_d), and the relative block structure (J_s), which considers the effect of a block's shape and orientation relative to the direction of flow. Block size is an extremely important parameter for evaluating rock mass behavior (ISRM 1978, Barton 1990). The most common indicator of block size was introduced by Cecil (1970) who combined the *RQD* index (Rock Quality Designation) with the joint set number (J_n) to create the quotient K_b (RQD/J_n). This quotient was later adopted by Barton et al. (1974) into the Q-system and by Kirsten (1982) for his excavatability index. However, Palmstrom et al. (2002), discussing the

[1] « erodibility » is used here to describe significant localized erosion of rock that occurs when the rock is submitted to hydraulic erosive power.

limitations of the Q-system (Barton et al. 1974), argued that the block size factor K_b provides no meaningful quantification of block size. Grenon and Hadjigeorgiou (2003) have also concluded, from in-situ investigations in Canadian mines, that K_b is an inaccurate parameter for characterizing block size. Furthermore, Pells et al. (2017) argued that at the time of its development, the *RQD* index, used as part of K_b parameter, was developed for a specific application and this parameter is sometimes applied inconsistently in practice. On the other hand, Palmstrom (2005), and Palmstrom and Broch (2006) stated that using of three-dimensional block volume measurements (V_b), instead of the K_b parameter, would improve the quality of Q-system results. This paper presents a method for determining the most representative parameter for quantifying the rock block size used for evaluating the hydraulic erodibility of rock.

2 METHODOLOGY

The proposed method for determining the most representative parameter for quantifying the rock block size used for evaluating the hydraulic erodibility is summarized in Figure 1. Each methodological step is described in the following subsections.

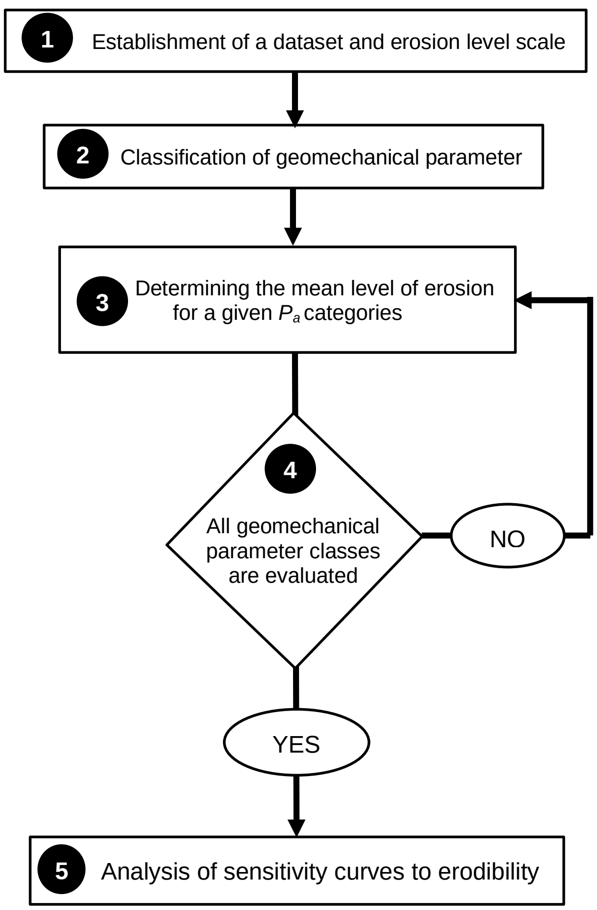

Figure 1. Algorithm for determining the most representative parameter for quantifying the block size

2.1 Step 1 - Dataset and erosion-level scale

Step 1 consists of collecting the data. The field data collected from more than 100 case studies, conducted by Pells (2016) on unlined rocky spillways of selected dams in Australia and South Africa, were selected because they provide complete data for the selected rock block size parameters (K_b and V_b), the P_a, and the observed condition of erosion. The erosion-level scale used in this study, as part of Step 1, is based on the description defined by Pells (2016) as described in Table 1.

Table 1. Erosion condition description (Pells 2016).

Max. depth (m)	General extent (m^3/100 m^2)	Descriptor	Erosion level
<0.3	<10	Negligible	1
0.3–1	1–30	Minor	2
1–2	30–100	Moderate	3
2–7	100–350	Large	4
>7	>350	Extensive	5

2.2 Step 2 - Classification of geomechanical parameter

The K_b and V_b parameters are classified in Step 2. The objective this step is to verify the level of erosion (Table 1) when a given rock mass is submitted to various P_a. The classification of the parameters relies on existing classifications from the literature or our proposed statistical classifications. In the following subsections, we describe the classifications of K_b and V_b.

2.2.1 Classification of K_b

The K_b parameter is corresponding to quotient *RQD*/J_n. As *RQD* can vary from 5%–100% and J_n values vary from 1–5 (Kirsten 1982, 1988), consequently, the K_b values range from 1–100. However, there is no existing classification system for K_b. The K_b classification framework proposed in this study is based on the statistical distribution of K_b that was established through evaluating the case studies of Pells (2016). The most representative normal distribution of K_b data is obtained based on the interval values presented in Figure 2. Accordingly, five classes of K_b are defined (Table 2).

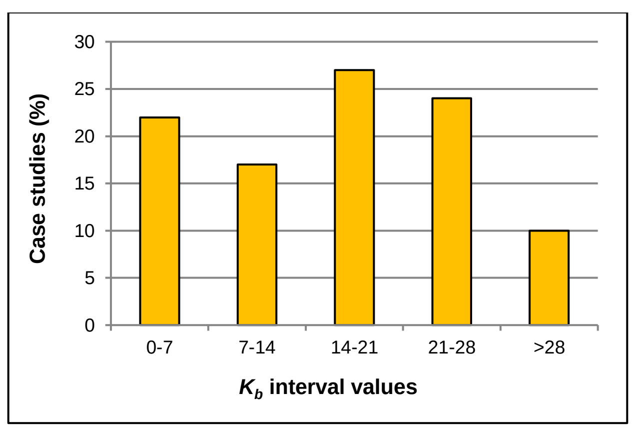

Figure 1. The statistical distribution of K_b values from the case studies of (Pells 2016).

Table 2. Proposed K_b classification.

Class	K_b
1	0–7
2	7–14
3	14–21
4	21–28
5	>28

2.2.2 Classification of V_b

The rock block volume classification of Palmstrom (1996, 1995), presented in Table 3, is adopted for this study. Furthermore, we apply three methods presented in Palmstrom (2005) for calculating the rock block volume.

Table 3. Classification of rock volume (Palmstrom 1995).

V_b (m^3)	Description
0.0002 – 0.01	Small
0.01 0.02	Moderate
0.2 – 10	Large
>10	Very large

Method 1

When the average joint spacing is used rather than the abundance of joint sets, the following expression is used to determine V_b (m^3):

$$V_b = Sa^3 \quad [1]$$

where *Sa* is the average joint spacing equal to $(S_1+S_2+S_3+S_n)/n$, where S_1, S_2, $S_3 \ldots S_n$ is the average spacing for each of the joint sets.

Method 2

When three joint sets occur, the following expression may be used to determine V_b (m^3):

$$V_b = \frac{S_1 \cdot S_2 \cdot S_3}{\sin \gamma 1 \cdot \sin \gamma 2 \cdot \sin \gamma 3} \quad [2]$$

where S_1, S_2, S_3 represent the spacing of the three joint sets, and $\gamma 1, \gamma 2, \gamma 3$ represent the angles between the joint sets.

Method 3

The block volume may be determined according to the following expression:

$$V_b = \beta \cdot Jv^{-3} \quad [3]$$

where β is the block shape factor obtained through the following equation:

$$\beta = 20 + (7a_3/a_1) \quad [4]$$

where a_3 and a_1 are the shortest and longest dimensions of a block, respectively. *Jv* is defined as the number of joints intersecting a volume of 1 m^3, as determined using $Jv = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_n$ (λ_1 is the joint frequency of joint set 1).

2.3 Step 3 - Determining the mean level of erosion for given P_a categories

In Step 3, the objective is to verify erosion levels when the same rock mass class (rock mass classes are defined in Tables 2 and 3) is subjected to various P_a. As there are several case studies within the same geomechanical class, we determine in Step 3 the mean level of erosion for a given P_a category. However, there is no existing classification of P_a. Accordingly, we performed a statistical distribution of data from the case studies (Figure 3), and we define six P_a categories (Table 4).

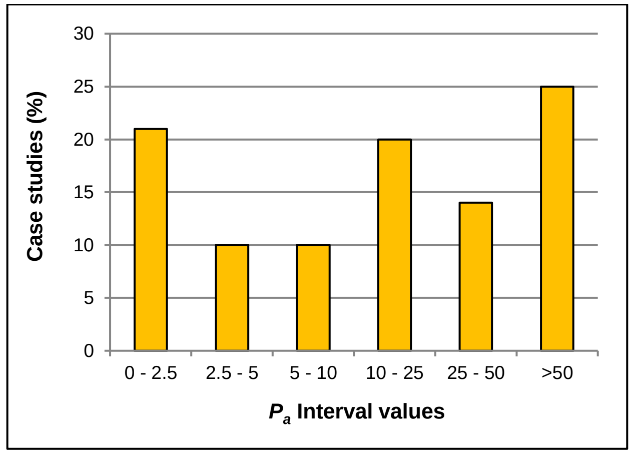

Figure 3. Statistical distribution of P_a values from the case studies of Pells (2016).

Table 4. Defined P_a categories.

Category	P_a (kW/m^2)
1	0 – 2.5
2	2.5 – 5
3	5 – 10
4	10 – 25
5	25 – 50
6	>50

The mean level of erosion for a given P_a category is calculated using Eq. (5) (Saeidi et al. 2009, 2012), where, in this study, μ_D represents the mean erosion level for a given hydraulic steam power category, and P_i is the probability of erosion level D_i, where *i* is ranking of the erosion level classes from 1 to 5 (Table 1). P_i is calculated according to Eq. 6, where n_i is number of case studies of erosion level D_i, and n_t is the total number of case studies, both considered for each P_a category. An example of how the mean erosion level was calculated is presented in Table 5.

$$\mu_D = \sum_{i=1}^{5} P_i \cdot D_i \quad [5]$$

$$P_i = \frac{n_i}{n_t} \quad [6]$$

Table 5. Example of calculating μ_D

Erosion class	D_i	n_i
Negligible	1	3
Minor	2	3
Moderate	3	1
Large	4	1
Extensive	5	0
	n_t	8
	μ_D	2

2.4 Step 4 - Evaluating all parameter classes

After calculating the mean level of erosion for a P_a category (e.g. for Category 1 of Table 4; P_a = 0–2.5 kW/m^2), the identical process for calculations is then run for all P_a categories listed in Table 4. Each series of calculations for the P_a categories is run for only a single geomechanical parameter class (e.g. Class 1 of the K_b classification in Table 2) at a time. Accordingly, a best-fit curve representing the calculated mean level of erosion versus the average of all considered P_a categories are then plotted for this single class of geomechanical parameter. Step 4 aims to runs the identical process of calculations for each class of a single geomechanical parameter (e.g. the calculating process for classes 1 to 5 of K_b classification as indicated in Table 2).

2.5 Step 5 - Analysis of sensitivity curves to erodibility

A best-fit curve representing the calculated mean level of erosion versus the average of all considered P_a categories can be plotted based on all the classes of a single geomechanical parameter. We consider these best-fit curves to be the sensitivity curves to erodibility that can be used in our subsequent analyses. In technical terms, sensitivity curves to erodibility produce a synthetic value of the potential level of erosion at a given value to P_a for a specific geomechanical parameter class. The main objective of Step 5 is to analyze the obtained sensitivity curves. For a geomechanical parameter, the obtained sensitivity curves to erodibility showing a logical sequence can be considered as curves associated with a most representative parameter for quantifying the rock block size used for evaluating the hydraulic erodibility of rock. Otherwise, it can be concluded that the parameter cannot be considered as a representative parameter.

3 RESULTS AND DISCUSSION

Sensitivity curves to erodibility according to rock block size (K_b and V_b) are shown in Figure 4. Rock block volume V_b was calculated using the three described methods (Section 2.2.2).

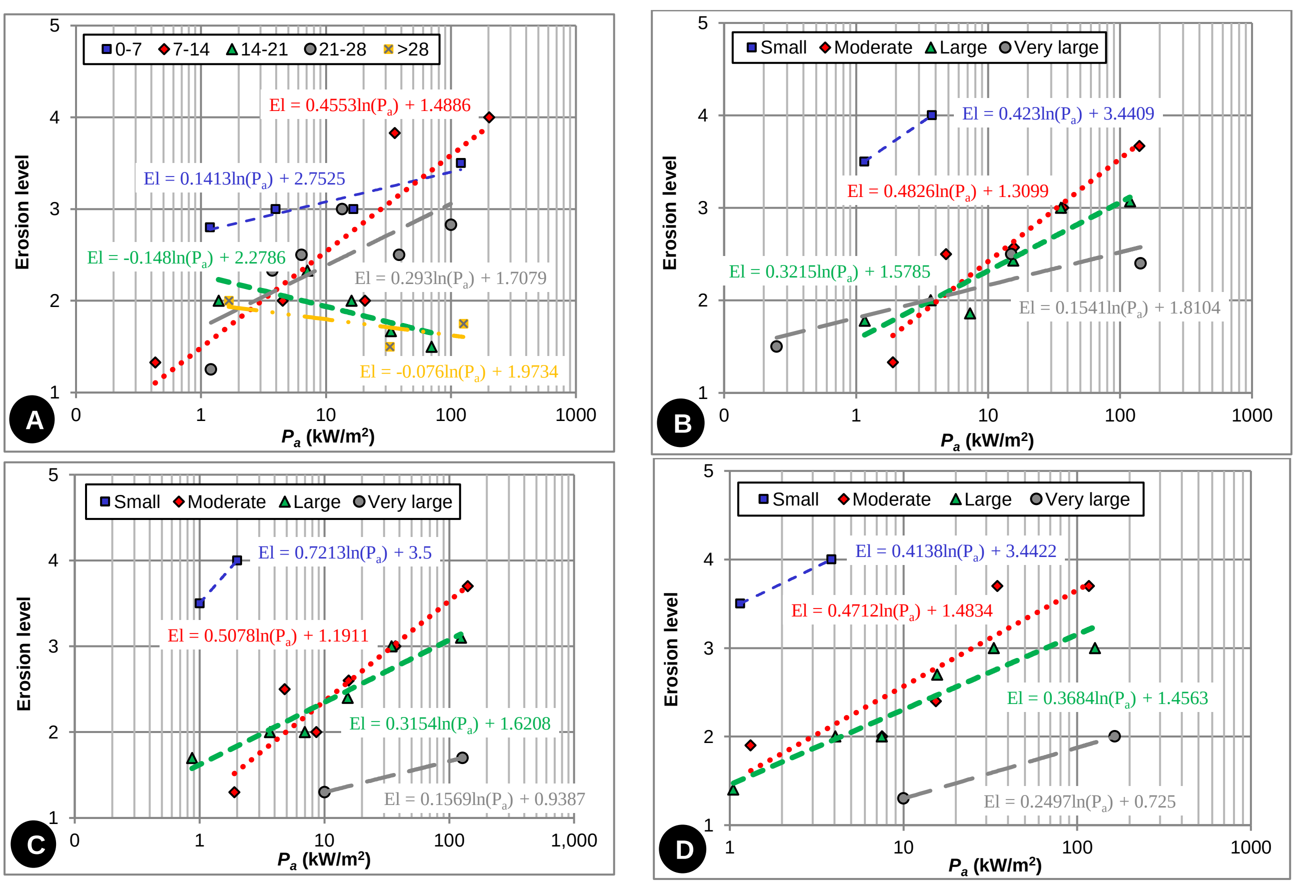

Figure 4. Sensitivity curves to erodibility based on rock block size: A) K_b classification; B) V_b calculated according to Method 1; C) V_b calculated according to Method 2; D) V_b calculated according to Method 3.

Sensitivity curves to erodibility based on K_b show that a rock mass characterized by a K_b of Class 1 (K_b = 0–7) is, as expected, the most sensitive to erodibility (Fig. 4A). However, this curve is intersected by the curve representing Class 2 (K_b = 7–14) when P_a = 60 kW/m^2. Accordingly, Class 2 becomes subsequently more sensitive than Class 1 as P_a increases. On the other hand, the sensitivity curves to erodibility for classes 3 and 5 decrease as P_a increases. This is not logical as an increased P_a should beget an increase in the amount of erosion. Also, the sensitivity curve to erodibility representing Class 2 (K_b = 7–14) is more sensitive than the Class 4 sensitivity curve to erodibility (K_b = 21–18). However, this pattern is only observed when P_a is >4 kW/m^2. Below this threshold, Class 4 is more sensitive to erodibility than Class 2, rendering this behavior invalid. Given these patterns, K_b cannot be selected as a representative parameter for quantifying the rock block size used for evaluating the hydraulic erodibility of rock.

Sensitivity curves to erodibility based on V_b, when V_b is calculated according to Method 1, show that for moderate, large, and very large classes, very large volumes (>10 m^2) are the least sensitive to erodibility, and sensitivity is subsequently more important as V_b decreases (Figure 4B). However, this is only noted when P_a is >6 kW/m^2. Method 1 thus provides a good evaluation for a large range of P_a values; however, at values <6 kW/m^2, Method 1 produces invalid results. Similar patterns are observed when V_b is calculated via Method 2 (Figure 4C) and Method 3 (Figure 4D). Methods 2 and 3 provide a good evaluation, although only when P_a values are >10 kW/m^2 and >1 kW/m^2, respectively.

Overall, use of the three-dimensional block volume measurement, rather than the K_b parameter, provides a better characterization of the rock block size. Palmstrom (2005) argues that their method (Palmstrom 1995, 1996), based on volumetric joint count (Method 3), provides the best characterization of the block volume. We also select this method as it provides a good evaluation for much of the range for P_a compared to methods 1 and 2.

4 CONCLUSION

Our method for determining the most representative parameter for quantifying the rock block size used for evaluating the hydraulic erodibility is derived from case studies of erosion in unlined rocky spillways of selected dams in Australia and South Africa. The K_b parameter, defined to represent rock block size in the context of hydraulic erodibility, can be improved by replacing it with the V_b parameter. Kirsten's index includes the K_b parameter that our study deemed to be non-representative parameter for quantifying the rock block size used for evaluating the hydraulic erodibility. Furthermore, it can be considered that the use of the three-dimensional block volume measurement (V_b), rather than the K_b parameter, could improve the characterization of rock block size. The V_b parameter could be adopted in a new hydraulic erodibility index that could be used to provide a more accurate assessment of the hydraulic erodibility of rock.

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