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THE INFLUENCE OF GEOMECHANIC AND HYDROLOGIC UNCERTAINTIES ON SCOUR AT LARGE DAMS: CASE STUDY OF KARIBA DAM (ZAMBIA-ZIMBABWE)

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ABSTRACT

A new engineering model, the Comprehensive Scour Model (CSM), has been developed for prediction of erosion in fractured media, such as rock, concrete or clays (Bollaert, 2004; Bollaert and Schleiss, 2005). The model is physically-based and relies on break-up by progressive fracturing of existing discontinuities as well as on subsequent dynamic ejection of so formed loose elements. It is not only able to predict the ultimate state of scour, but also the time evolution of the phenomenon as a function of flood duration and discharge. In the following, the model is applied to scour formation of the plunge pool downstream of Kariba Dam (Zambia-Zimbabwe). Emphasis is given on the influence of rock mass resistance and flood duration uncertainties on scour evolution as a function of time.

Keywords: scour prediction, time evolution, geomechanic and hydrologic uncertainties

INTRODUCTION

A comprehensive model to evaluate and predict scour of fractured media has been developed (Bollaert, 2004; Bollaert and Schleiss, 2005). The model is based on a parametric description of the main physical processes that are responsible for scour. The model parameters are chosen in a way to enhance and simplify practical applications, without compromising underlying physics. The main processes responsible for scour applied to a plunge pool behind a dam are presented in Figure 1.



Figure 1. Physical-mechanical processes of scour of fractured media, such as rock in a plunge pool.

A high-velocity plunging jet diffuses through the pool and generates a turbulent shear layer. The impact of this shear-layer at the bottom results in dynamic pressure fluctuations. These may enter and progressively fracture underlying joints, until these encounter each other. Then, instantaneous net pressure differences over and under the formed blocks may eject them from the surrounding mass. The blocks may be further broken-up by re-circulation in the plunge pool (ball-milling), or transferred to the downstream river. The present scour model focuses on time-dependent fracturing of joints by water pressure fluctuations and on dynamic ejection of single blocks by net uplift pressures.

1. COMPREHENSIVE SCOUR MODEL (CSM)

The Comprehensive Scour Model (Bollaert, 2004) comprises two methods that describe failure of jointed media. The first, the *Comprehensive Fracture Mechanics* (CFM) method, determines the ultimate scour by expressing brittle or time-dependent joint propagation due to water pressures. The second, the *Dynamic Impulsion* (DI) method, describes ejection of blocks from their mass due to sudden uplift pressures. The structure of the model consists of three modules: the falling jet, the plunge pool and the fractured medium. The latter implements the aforementioned failure methods.

1.1. Falling Jet Module

This module describes how the characteristics of the jet are transformed from dam issuance to plunge pool (Fig. 1). Three main parameters characterize the jet at issuance: the velocity V_i , the diameter (or width) D_i and the initial turbulence intensity Tu, defined as the ratio of velocity fluctuations to mean velocity. The jet trajectory is based on ballistics and air drag and is not outlined further. The jet module computes the longitudinal location of impact, the total trajectory length L and the velocity and diameter at impact V_j and D_j . The turbulence intensity defines the spread of the jet δ_{out} (Ervine et al. 1997) and the degree of break-up of the jet. Typical outer spread angles are 3-4 %. The corresponding inner angles of spread are 0.5 - 1 %. Superposition of outer spread to initial jet diameter D_i results in the outer jet diameter D_{out} , used to determine the extent of the zone at the pool bottom where severe pressure damage may occur. Relevant mathematical expressions can be found in Bollaert (2004) and Bollaert and Schleiss (2005).

1.2. Plunge Pool Module

This module describes the hydraulic and geometric characteristics of the jet when traversing the plunge pool water depth. This defines the water pressures at the rocky bottom of the pool. The water depth Y is essential. For near-vertically impacting jets, it is defined as the difference between the water level and the bottom at the point of impact. The water depth increases with discharge and scour formation. Initially, Y equals the tailwater depth t (Figure 1). During scour formation, Y has to be increased with the depth of the formed scour h. The water depth Y and jet diameter at impact D_j determine the ratio of water depth to jet diameter at impact Y/D_j . This ratio is directly related to jet diffusion and related pressure fluctuations.

Dynamic pressures acting at the bottom can be generated by core jets, for small water depths Y, or by developed jets, appearing for Y/D_j higher than 4 to 6 (for aerated plunging jets). The most relevant pressure characteristics are the mean dynamic pressure coefficient C_{pa} and the root-mean-square (rms) coefficient of the fluctuating dynamic pressures C'_{pa} , both measured directly under the centerline of the jet. These coefficients correspond to the ratio of pressure head (in [m]) to incoming kinetic energy of the jet ($V^2/2g$) and can be found for example in Bollaert (2004):

$$C_{pa} = 38.4 \cdot \left(1 - \alpha_i\right) \cdot \left(\frac{D_j}{Y}\right)^2 \text{ for } Y/D_j > 4-6$$
[1]

$$C_{pa} = 0.85$$
 for Y/D_j < 4-6 [2]

$$\alpha_i = \frac{\beta}{1+\beta}$$
[3]

Eqs. [1]-[3] are based on Ervine et al. (1997). The air concentration at jet impact α_i is defined as a function of the volumetric air-to-water ratio β . Plausible prototype values for β are 1-2. For a given α_i , mean and fluctuating dynamic pressures are defined as a function of Y, D_i and Tu.

The rms coefficients depend on the initial turbulence intensity Tu of the jet at issuance. Typical prototype values for Tu are around 4-5 %. Table 1 presents the rms surface pressure coefficients that are used as input to Eq. [4]. As a function of the intensity of the turbulence of the jet, a turbulence offset (a_4) between 0.00 and 0.15 has to be chosen:

$$C'_{pa} = a_1 \cdot \left(\frac{Y}{D_j}\right)^3 + a_2 \cdot \left(\frac{Y}{D_j}\right)^2 + a_3 \cdot \left(\frac{Y}{D_j}\right) + a_4$$
[4]

It is assumed that the root-mean-square values of the pressure fluctuations at the water-rock interface, expressed by the C'_{pa} coefficient, depend on the Y/D_j ratio and on Tu. The measured data have been approximated by a polynomial regression. The shape of this regression was obtained through curve fitting of the bandwidth of upper data as given by Ervine et al. (1997), while its exact position is based on the present near-prototype scaled experiments. Each case in Table 1 corresponds to a degree of (low-frequency) jet stability. Tu is considered to be fully representative for low-frequency instabilities of the jet. The curves are valid up to a Y/D_j ratio of 18-20. For higher ratios, the C'_{pa} value that corresponds to a ratio of 18-20 are proposed. Compact jets are smooth-like during their fall, without any possible source of low-frequency instability. Highly turbulent jets have a Tu value higher than 5 %. In between, two other curves have been defined. They are applicable to lowly or moderately turbulent jets.

Tu at jet issuance from the dam (Bonacit, 2004).							
Tu [%]	\mathbf{a}_1	a ₂	a ₃	a_4	Type of jet		
< 1	0.000220	-0.0079	0.0716	0.000	compact		
1-3	0.000215	-0.0079	0.0716	0.050	lowly turbulent		
3-5	0.000215	-0.0079	0.0716	0.100	moderately turbulent		
> 5	0.000215	-0.0079	0.0716	0.150	highly turbulent		

Table 1. Polynomial coefficients of Eq. [4] as a function of initial turbulence intensity Tu at jet issuance from the dam (Bollaert, 2004).

1.3. Fractured Rock Module

Pressures at the bottom are used for determination of pressures inside joints. The parameters are: 1) maximum dynamic pressure C_{p}^{max} , 2) amplitude of pressure cycles Δp_c , 3) frequency of pressure cycles f_c and 4) maximum dynamic impulsion C_{I}^{max} . The 1st parameter is relevant to brittle propagation of joints (DI method). The 2nd and 3rd parameters express time-dependent propagation of joints (CFM method). The 4th parameter defines uplift of blocks.

 C_{pa}^{max} is obtained through multiplication of C_{pa}^{\prime} with an amplification factor Γ^{+} , and by superposition with C_{pa} . Γ^{+} expresses the ratio of peak value inside the joint to rms value of pressures at the bottom and is defined as follows:

$$\begin{split} \Gamma^{+} &= \nu - 8 + 2 \cdot Y/D_{j} & \text{for } Y/D_{j} < 8 \\ \Gamma^{+} &= \nu + 8 & \text{for } 8 \le Y/D_{j} \le 10 & [5] \\ \Gamma^{+} &= \nu + 28 - 2 \cdot Y/D_{j} & \text{for } 10 < Y/D_{j} \end{split}$$

in which v is close to 0 for joints with several side branches or joints that are not tightly healed, and up to maximum 12 for tightly healed joints. The former joints were found to produce less significant pressure peaks, due to pressure diffusion and air dampening effects.

The maximum pressure is written as:

$$P_{max}[Pa] = \gamma \cdot C_p^{max} \cdot \frac{V_j^2}{2g} = \gamma \cdot \left(C_{pa} + \Gamma^+ \cdot C_{pa}'\right) \cdot \frac{V_j^2}{2g}$$
[6]

The frequency of the pressure cycles f_c follows the assumption of a perfect resonator system and depends on the air concentration in the joint α_i and on the length of the joint L_f . For practice, a first hand estimation for f_c is 50 to 200 Hz, considering a mean wave celerity of 200 to 400 m/s and joint lengths of 0.5 to 1 m.

Second, the resistance of the fractured medium has to be determined. The cyclic character of the pressures makes it possible to describe joint propagation by fatigue stresses occurring at the tip of the joint. This can be done by Linear Elastic Fracture Mechanics (LEFM). A simplified methodology is proposed (Bollaert, 2004). It is called the Comprehensive Fracture Mechanics (CFM) method and is applicable to any partially jointed medium. Pure tensile pressure loading inside joints is described by the stress intensity factor K_I , which represents the amplitude of stresses generated by water pressures at the tip of the joint. The corresponding resistance of the medium against joint propagation is expressed by its fracture toughness K_{Ic} .

Joint propagation distinguishes between brittle and time-dependent propagation. The former happens for a stress intensity higher than the fracture toughness of the material. The latter is occurring for a stress intensity inferior to the material's resistance. Joints may then propagate by fatigue, which depends on the frequency and amplitude of the load cycles. The stresses in the medium are characterized by K_I :

$$K_{I} = P_{max} \cdot F \cdot \sqrt{\pi \cdot L_{f}}$$
^[7]

in which K_I is in MPa \sqrt{m} and P_{max} in MPa.



Figure 2. a) Main configurations for partially jointed media; b) Boundary correction factor F.

The boundary correction factor F depends on the type of crack and on its persistency, i.e. its degree of cracking a/B or b/W. Figure 2 presents two basic configurations for partially jointed media. The choice

of the most relevant geometry depends on the type and the degree of jointing. A summary of F values is also presented in Fig. 2. For practice, values of 0.5 or higher are considered to correspond to completely broken-up media, i.e. the DI method becomes more applicable than the CFM method. For values of 0.1 or less, a tensile strength approach is more plausible than a Fracture Mechanics approach.

 K_{Ic} is assumed depending on the mineralogy of the medium and the tensile strength T or the unconfined compressive strength UCS. Furthermore, corrections are made to account for the effects of the loading rate and the in-situ stress field. The in-situ fracture toughness $K_{I,ins}$ is based on a linear regression of available literature data as follows:

$$K_{\text{I ins,UCS}} = (0.008 \text{ to } 0.010) \cdot \text{UCS} + (0.054 \cdot \sigma_c) + 0.42$$
 [8]

in which σ_c represents the confinement horizontal in-situ stress and T, UCS and σ_c are in MPa. Brittle joint propagation happens for $K_I > K_{I,ins}$. If this is not the case, joint propagation needs a certain time to happen. This is expressed by:

$$\frac{dL_{f}}{dN} = C_{r} \cdot \left(\Delta K_{I} / K_{Ic}\right)^{m_{r}}$$
[9]

in which N is the number of pressure cycles. C_r and m_r are material parameters that are determined by fatigue tests and ΔK_I is the difference of maximum and minimum stress intensity factors at the joint tip. To implement time-dependent joint propagation into a comprehensive engineering model, m_r and C_r have to be known. They represent the vulnerability of the medium to fatigue and may be derived from available literature data. These values express qualitative differences in sensitivity and no absolute values. Hence, any application should be based on appropriate calibration. A first-hand calibration for granite (Cahora-Bassa Dam; Bollaert and Schleiss, 2005) resulted in $C_r = 1E-7$ for $m_r = 10$.

The fourth dynamic loading parameter is the maximum dynamic impulsion C_{I}^{max} in an open-end rock joint (underneath a single block), obtained by Newton's 2^{nd} law:

$$I = \int_{0}^{\Delta t \text{pulse}} (F_u - F_o - G_b - F_{\text{sh}}) \cdot dt = m \cdot V_{\Delta t \text{pulse}}$$
[10]

in which F_u and F_o are the forces under and over the block, G_b is the immerged weight of the block and F_{sh} represents the shear and interlocking forces. The maximum net impulsion I_{max} is defined as the product of a net force and a time period. The force is firstly transformed into a pressure. This pressure is then divided by the incoming kinetic energy $V^2/2g$. This results in a net uplift pressure coefficient C_{up} . The time period is non-dimensionalized by the travel period characteristic for pressure waves inside joints, i.e. $T = 2 \cdot Lf/c$. This results in a time coefficient T_{up} . Hence, C_I is defined by the product $C_{up} \cdot T_{up} = V^2 \cdot L/g \cdot c$ [m·s]. The maximum net impulsion I_{max} is obtained by multiplication of C_I by $V^2 \cdot L/g \cdot c$. Based on near-prototype scaled model tests, the C_{up} value was measured close to 0.35.

Failure of a block is expressed by the displacement it undergoes due to the net impulsion C_I . This is obtained by transformation of velocity into uplift displacement h_{up} . The net uplift displacement necessary to eject a block is difficult to define. The necessary displacement is a model parameter that needs to be calibrated. A first-hand calibration on Cahora-Bassa Dam (Bollaert and Schleiss, 2005) resulted in a critical net uplift displacement of 0.20.

2. CASE STUDY: KARIBA DAM SCOUR (ZAMBIA-ZIMBABWE)

2.1. Introduction

Kariba Dam is a 128 m high concrete arch dam on the Zambezi River, situated on the border between Zambia and Zimbabwe. The CSM model has been applied to the scour formation downstream of the dam. Since 1962, spillway discharges from Kariba Dam have eroded an important scour hole into the gneiss rock, which extended already in 1982 about 80 m below the initial river bed (see Fig. 3) (Mason and Arumugam, 1985).



Figure 3. Kariba Dam scour hole development as a function of time.

Use of estimated annual flood periods and in-situ measured scour formation allowed calibrating the CSM model to predict future scour formation as a function of time. Especially the time-related parameters of the CSM model have been adapted to the long-duration observed prototype scour (20 years of scour follow-up between 1962 and 1981). Comparison has been made with calibration based on Cahora-Bassa Dam scour.

2.2. Scour Parameters and their uncertainties

After dam construction in 1959, a large scour hole quickly formed in the downstream fractured rock. Typical spillway discharges and average tailwater levels are available, and the average time duration of floods has been estimated at about 3 months. Furthermore, after each major flood period between 1962 and 1981, a detailed bathymetric survey of the scour hole has been carried out. Results of these surveys can be found in Mason and Arumugam (1985).

The spillway consists of 6 rectangular gate openings of roughly 8.8 m by 9.1 m, for a total discharge of about 9'500 m³/s. The gate lips are situated at 456.5 m a.s.l. The minimum and maximum reservoir operating levels are 475.5 and 487.5 m a.s.l. The downstream tailwater level is situated between 390 and 410 m a.s.l., depending on the number of gates functioning. An average value of 400 m a.s.l. has been assumed for the computations. The net head difference results in typical jet outlet velocities of 21.5 m/s. Scour formation in the rock mass reached a level of 306 m a.s.l. in 1981, i.e. about 80 m down the initial bedrock level. The rock mass is sound gneiss with a degree of fracturing that is not known precisely. Without further noticeable information on rock mass quality, the computations have been performed for a set of conservative, average and beneficial parametric assumptions. This points out the influence of this uncertainty on the computed scour formation.

The spillway discharges are generally performed for varying gates, gate openings and operations, as a function of already formed scour. This results in complex and varying hydraulics. In the following, a 2D simplified approach is considered, assuming only one jet and a (considered reasonable) average gate opening of 75 %. The time durations of the floods also vary from year to year. Nevertheless, it is considered that the flood season generally takes several months in this region. Hence, an average duration of 3 months or 90 days per year is assumed for the scour computations.

Table 2 summarizes the parametric assumptions made for the rock mass properties. The main scour influencing parameters are the UCS strength, the initial degree of fracturing Pe and the form of the joint.

Property	Symbol	CONSERV	AVERAGE	BENEF	Unity
Unconfined Compressive Strength	UCS	100	125	150	MPa
Density rock	γr	2600	2700	2800	kg/m ³
Typical maximum joint length	L	1	1	1	m
Vertical persistence of joint	Р	0.12	0.25	0.55	-
Form of rock joint	-	single-edge	elliptical	circular	-
Tightness of joints	-	tight	tight	tight	-
Total number of joint sets	Nj	3+	3	2+	-
Typical rock block length	I _b	1	1	1	m
Typical rock block width	b _b	1	1	1	m
Typical rock block height	Zb	0.5	0.75	1	m
Joint wave celerity	С	150	125	100	m/s

Table 2. Rock mass properties under different parametric assumptions

2.3. Calibration of Fatigue Scour Parameters

Based on the parametric assumptions detailed above, the scour computations have been calibrated to match the in-situ measured scour. The used calibration parameters are the fatigue coefficients C_r and m_r described in Eq. [9]. These define the time-dependency of the scour formation and express the resistance of the medium against joint propagation by fatigue. These fatigue coefficients have first of all been calibrated for different assumptions on the rock mass strength (UCS) and the initial degree of cracking (Pe) (Table 2), as well as on the offset a_4 defining the pressure amplifications inside the joints (Table 1, Eq. [4]).

Figure 4 presents appropriate combinations of calibrated C_r - m_r values for different UCS strengths and for an initial degree of cracking of 0.25 (average value) and an offset for RMS surface pressure fluctuations of 0.05 (low to moderate value). The other parametric assumptions correspond to average values as defined at Table 1. In-situ scour formation is based on Mason and Arumugam (1985). In-situ flood durations are based on an average rainfall duration of 3 months per year. Knowledge of the real yearly flood periods would enhance precision of the computations.

A semi-logarithmic scale has been used, resulting in linear relationships between C_r and m_r . For relatively low rock mass strengths (UCS strengths of about 25 MPa), the C_r value becomes independent from the m_r value, because brittle (or instantaneous) joint break-up is occurring and time effects become negligible. For higher rock mass strengths (UCS strengths of 50 to 100 MPa), the C_r values are mostly between 1E-7 and 1E-8. For the highest considered UCS strengths (125 to 175 MPa), the C_r values and the C_r -m_r semi-logarithmic slope decrease with increasing UCS strength.

Comparison has also been made with the calibration made for the scour formation at Cahora-Bassa Dam, which resulted in a C_r value of 1E-7 and a m_r value of 10 (Bollaert and Schleiss, 2005).

Based on the results in Figure 4, it can be concluded that, without sound knowledge on the UCS strength of the in-situ rock, errors of several orders of magnitude might be made regarding the fatigue law that describes time-dependent rock joint break-up and thus scour formation.



Figure 4. C_r -m_r relationships as calibrated for different UCS strengths and Pe = 0.25, RMS offset = 0.05.

Furthermore, other possible calibrations of the fatigue parameters C_r and m_r have been performed for different initial degrees of cracking Pe and for different RMS offsets. Figure 5 presents the results for initial degrees of cracking between 0.20 and 0.30 and for RMS offsets between 0.00 and 0.15.

The former range of values represents plausible average cracking values. Lower values would mean that the rock mass has almost no cracking, while values higher than 0.30 indicate significant cracking. For significant degrees of cracking, the DI method becomes a more reliable estimate than the CFM method because time evolution is not an issue anymore.

For an equal offset of 0.05, increasing the Pe value from 0.20 to 0.30 results in a decrease of the C_r value of half to one order of magnitude. Modifying the RMS offset from 0.00 to 0.15, for a Pe = 0.25, modifies the C_r value by one to two orders of magnitude.



Figure 5. C_r-m_r relationships as calibrated for different Pe and RMS offset values.



Figure 6. Scour formation as a function of time for different UCS strengths.

Generally speaking, for a given UCS strength, the influences of the Pe and RMS offset values are of less importance than a sound knowledge of the UCS strength itself. Nevertheless, they may still have a non-negligible influence on the computed scour formation.

For chosen values of $C_r = 7E-8$ and $m_r = 9$, the scour formation as a function of time is presented in Figure 6 for a wide range of UCS strengths. Significant differences in scour formation are observed, underlying the need for sound UCS knowledge. Especially at lower UCS strengths, scour formation becomes very sensitive to the absolute UCS value.

2.4. Computed versus in-situ estimated days of discharge

Finally, a comparison has been made between the computed and in-situ estimated accumulated days of discharge (Figure 7). For UCS strength assumptions of 75 and 125 MPa and for an initial degree of break-up of Pe = 0.25, appropriate calibration of the C_r and m_r fatigue parameters resulted in a number of days of discharge per year that is in good agreement with the in-situ estimated values.

For a low UCS strength assumption of only 25 MPa, brittle (or instantaneous) rock mass failure is observed during the first years of operation, followed by a high number of days of discharge in the last few years. This curve is clearly not realistic, showing that this combination of parameters is not suited.

It is obvious that, for a different assumption on the number of days of discharge, different scour results would be obtained. Knowledge on flood durations is thus of importance in the calibration of numerical models for scour prediction as a function of time.



Figure 7. Comparison of computed and in-situ estimated number of days of discharge, corresponding to the in-situ measured scour formation.

3. CONCLUSION

As a conclusion, it may be stated that appropriate calibration of a numerical model for scour prediction as a function of time needs the assessment of a significant number of hydraulic, hydrologic, geometric and geomechanic parameters. Especially the time duration and average discharge values of floods, the intrinsic rock mass strength and the initial degree of fracturing of the rock mass have to be known in a sufficiently precise manner to obtain values that can be used for practical applications.

When these values are available or can be reasonable estimated based on in-situ observations or based on values from similar dam sites, the numerical model can be used to predict further scour formation as a function of time and/or to evaluate the ultimate scour depth on the long term.

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