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Determination of the extent of scour is an important factor in the design of dams and spillways. The case study presented herein for Kariba Dam provides a practical application of the total dynamic pressure coefficient with Annandale's Erodibility Index Method (EIM) and Bollaert's Comprehensive Fracture Mechanics (CFM) and Dynamic Impulsion (DI) models. The total dynamic pressure coefficient has been developed to incorporate the effects of jet break up on the average and fluctuating dynamic pressures. The maximum scour depth predicted using the above methods shows very good agreement with the scour observed at the site to date.

I. Introduction

Determination of the extent of scour is an important factor in the design of a dam whether it be during an overtopping event or from flows discharged through the spillway. Often times a plunge pool is used as a cushion to dissipate energy from the falling jet of water.

Previous work by Bollaert [1] attempted to quantify pressures within a plunge pool when subject to an impacting jet by use of a dynamic pressure coefficient. This coefficient accounts for the average dynamic pressure associated with the impacting jet, the fluctuating dynamic pressure, as well as any amplification that may occur in rock joints due to resonance, but does not account for the degree of jet break up. Advancements regarding the effects of jet breakup on the mean and fluctuating dynamic pressures have been made by Castillo [2] and Ervine, Falvey and Withers [3], respectively. This has lead to the development of a total dynamic pressure coefficient.

The case study presented herein for Kariba Dam shows practical application of the total dynamic pressure coefficient using Annandale's Erodibility Index Method (EIM) [4,5] and Bollaert's Comprehensive Fracture Mechanics (CFM) and Dynamic Impulsion (DI) [1] in the verification of extent of plunge pool scour witnessed to date on site.

II. Project Background

Kariba Dam is double curvature concrete arch dam located on the Zambesi River between Zambia and Zimbabwe. The dam itself extends 130 m above its bedrock foundation comprised of granitic gneiss [6]. The dam spillway contains six rectangular shaped gates with openings of 8.8 m by 9.1 m [7]. Since 1959 after the dam's construction, several large flows passed through the spillway and resulted in the formation of a downstream plunge pool (Figure 1). The largest flow occurred in 1981 with a peak discharge of 9444 m^3/s, after which the scour hole reached a maximum depth of approximately 85 m below the original ground surface to an elevation of about 305 m [6].

This case study has been performed using the same initial assumptions made by Bollaert when he preformed a similar study at the dam [7]. For Bollaert's analysis a single gate was analyzed assuming an average opening of 75 %. Typical outlet velocities were approximated at 21.5 m/s, with a maximum elevation in the reservoir at 487.5 m and an average tailwater elevation of 400 m [7].

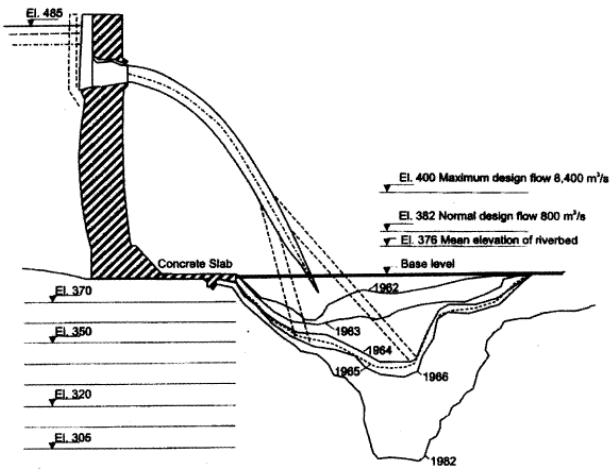


Figure 1. Scour hole formation at Kariba Dam [6]

III. Scour Processes

Three mechanisms have been identified that lead to the break-up and removal of a rock mass when subjected to the forces associated with a falling jet of water. These include [1]:

- dynamic impulsion,
- brittle fracture, and
- sub-critical (fatigue) failure.

Dynamic impulsion refers to the ejection or "plucking" of individual rock blocks from their matrix due to pressure imbalances between the top and bottom of the block caused by the impinging jet. This mechanism is only applicable when the rock mass is already completely broken into individual rock blocks or when the rock mass has been completely fractured by brittle fracture or fatigue failure [1].

Brittle fracture refers to the instantaneous break-up of a rock mass along existing close-ended fissures. A close-ended fissure refers to a discontinuity that is not persistent through the rock mass. Scour progression in this failure mode generally occurs very rapidly and in an "explosive" manner. The pressure from the falling jet applied to the rock joint can be amplified as much as 20 times due to resonance that can occur in a close-ended fissure [1].

Fatigue failure refers to the time-dependent break-up of a rock mass along existing close-ended fissures. Failure by fatigue is generally slower, occurring over an extended period of time as is the case for Kariba Dam. Cyclic pulses generated by the impinging jet propagate fractures bit by bit until the rock mass is completely broken-up into individual rock blocks [1]. The time to propagate a fissure through a certain distance of rock may be calculated by [8]:

$$\frac{dL}{dN} = C(\Delta K)^m \qquad (1)$$

Where:

N = number of pressure cycles or "pulses" that will lead to fatigue failure,

C, m = rock properties,

ΔK = range of stress intensities within the rock joint due to the impinging jet, and

L = distance of fissure growth required for failure (m).

IV. TOTAL DYNAMIC PRESSURE COEFFICIENT

Recent research by Castillo [2] and Ervine, Falvey and Withers [3] regarding the effects of jet break up on the average dynamic pressure and fluctuating dynamic pressure, respectively, has been combined with that from Bollaert [1] to form the total dynamic pressure coefficient. This may be written as:

$$C_t = C_p + \Gamma \cdot RF \cdot C_p^{`} \qquad (2)$$

Where:

C_p = average dynamic pressure coefficient [2].

$C`_p$ = fluctuating dynamic pressure coefficient [1].

G = amplification factor for resonance that can occur in close-ended rock joints applied to $C`_p$ [1].

RF = reduction factor dependent on the degree of jet breakup applied to $C`_p$ based on research by Ervine, Falvey and Withers [3].

A. Average Dynamic Pressure Coefficient (Cp)

Recent research by Castillo [2] compares the effects of varying degrees of jet break up on the average dynamic pressure coefficient for rectangular jets. Castillo compares the average dynamic pressure coefficient to the ratio of plunge pool depth (Y) to jet impact thickness (d) for varying jet break up ratios (Figure 2). The degree of jet break up is determined by the ratio of the jet trajectory length (L) to the jet break up length (L_b). As the jet break up ratio (L/L_b) increases the average dynamic pressure coefficient decreases.

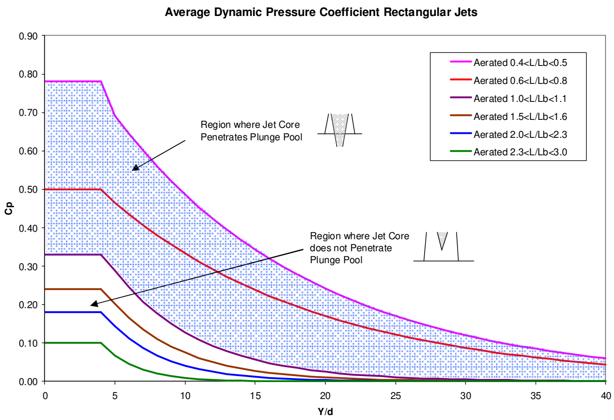


Figure 2. Calculation of C_p [2]

The length of the jet, calculated by Annandale [5], may be expressed as:

$$L = \int_0^x \sqrt{1 + \left[\tan(\theta) - \frac{2x}{K\left[4(d + \frac{v^2}{2g})\cos(\theta)^2\right]} \right]^2} \cdot dx \qquad (3)$$

Where:

x = horizontal distance to impact (m).

θ = the angle of issuance.

d = the depth/thickness of the jet at issuance (m).

v = the initial velocity of the jet at issuance (m/s)

K = a coefficient representing energy loss of the jet.

Two separate equations to calculate the jet break up length are used depending on the method being utilized to determine the erosive capacity of the jet. Case studies have shown that the equation developed by Horeni [9] for rectangular nappes yields best results when used with Annandale's method. However, an equation developed from experimental testing on round jets by Ervine, Falvey and Withers [3] provides best results when used with Bollaert's method. The two equations are provided below.

Fout! Objecten kunnen niet worden gemaakt door veldcodes te bewerken.
(4)

Where:

q = the unit discharge (m^2/s).

$$L_b(Ervine) = \frac{1}{2} \cdot d \cdot Fr^2 \cdot \frac{\frac{-1}{2} \cdot C + 1 + \frac{1}{2} \cdot (C^2 + 4 \cdot C)^{\frac{1}{2}}}{C} \qquad (5)$$

Where:

d = the depth/thickness of the jet at issuance (m).

Fr = the Froude number at issuance.

$C = 1.07 \cdot T_u \cdot Fr^2$, where T_u is the turbulence intensity.

B. Fluctuating Dynamic Pressure Coefficient (C`p)

The fluctuating dynamic pressure coefficient relates the variation in pressure fluctuations with respect to the average dynamic pressure. $C`_p$ is calculated from the following graph (Figure 3) based on research conducted by Bollaert [1].

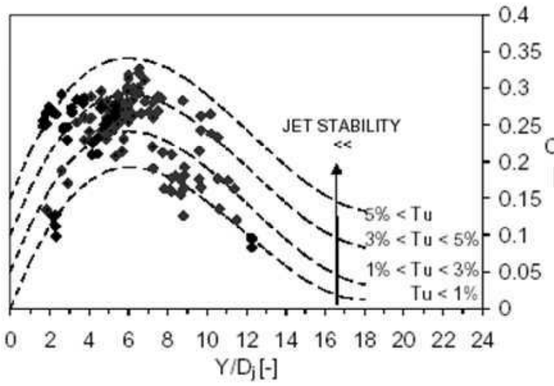


Figure 3. Determination of $C`_p$ [1]

As indicated, peak pressure fluctuations occur for plunge pool to jet thickness ratios (Y/D_j) of approximately six. For clarification, D_j in Figure 3 refers to the inner core thickness of the jet at impact. This is opposed to Castillo's research which uses the outer thickness of the jet at impact (this accounts for jet spread due to aeration).

Two scaling factors are also applied to the fluctuating dynamic pressure coefficient to account for amplification in close-ended rock joints as well as for varying degrees of jet break up.

Amplification in close-ended ended can occur due to resonance, thus causing significant pressure spikes at the tip of the fissure. These pressure spikes may be quantified by applying an amplification factor, Γ, developed by Bollaert (Figure 4) [1].

As indicated, peak amplification of nearly 8 to 20 times the original signal occurs for Y/D_j ratios of approximately 8 to 10.

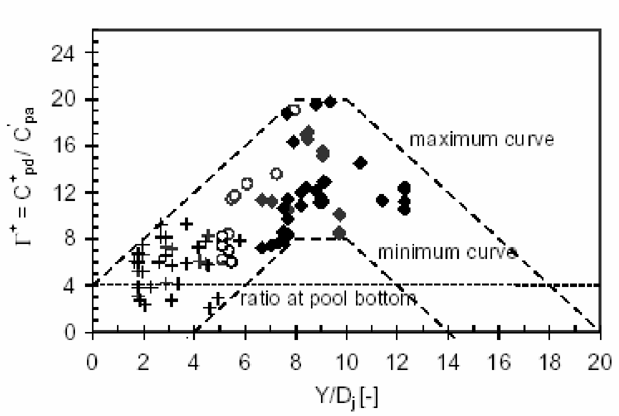


Figure 4. Determination of Γ [1]

Additionally, the erosive capacity of the jet needs to account for the response of the fluctuating pressures to the degree of jet break up. Similar to the average dynamic pressure, the fluctuating dynamic pressure decreases with increasing degrees of jet break up, ultimately resulting in diminished erosive capacity. Figure 5 shows a relationship developed by Ervine, Falvey and Withers [3] between the fluctuating dynamic pressure coefficient and the jet length to jet break up length ratio (L/L_b).

Based on this relationship, a reduction factor (RF) was determined and applied to Bollaert's fluctuating dynamic pressure coefficient ($C`_p$) depending on the degree of jet break up [5].

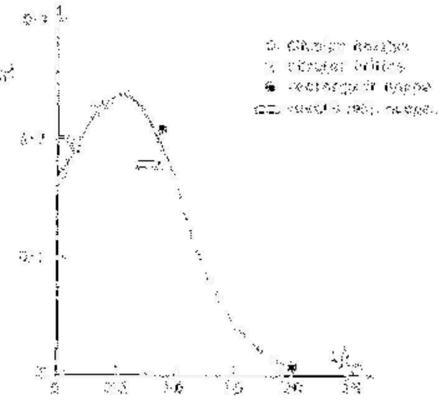


Figure 5. Relation of $C`_p$ to break up length ratio (L/L_b) [3]

V. Scour Prediction Methods

Two methods are used to predict the amount of scour likely to occur for a given discharge. These are Annandale's EIM [4,5] and Bollaert's CFM and DI models [1]. In general, the EIM is used to determine a total scour depth, while the CFM and DI model are used to give insight to the type of failure (i.e., brittle fracture, fatigue, or dynamic impulsion) occurring over that total depth, in addition to providing a total scour depth. For Kariba Dam, the scour depths predicted by the EIM as well as the CFM (namely fatigue failure) are of most importance.

A. *Rock Resistance*

The resisting power of the rock material is calculated for Annandale's method by assigning an empirical geo-mechanical index to the rock mass known as the Erodibility Index [5]. This is defined as:

$$EI = M_s \cdot K_b \cdot K_d \cdot J_s \quad (6)$$

Where:

M_s = mass strength number,

K_b = particle/block size number,

K_d = discontinuity or inter-particle bond shear strength number, and

J_s = relative ground structure number.

The resisting power of the rock material (kW/m^2) is then calculated from the equation below [5]:

$$P_{rock} = EI^{0.75} \quad (7)$$

When the erosive power of the jet is greater than the resisting power of the rock, scour shall occur. When the resisting power of rock is greater than that of the jet, scour will not occur.

B. *Jet Erosive Capacity*

Two methods are used to determine the erosive capacity of the impinging jet. The first method, by Annandale, describes erosive capacity in terms of unit stream power (W/m^2), while the second method, by Bollaert, relates erosive capacity in terms of pressure (Pa). The total dynamic pressure coefficient has been applied to both methods to account for variations in the average and fluctuating dynamic pressures due to jet break up.

The stream power of the impinging jet (W/m^2) for the EIM may be expressed as [5]:

$$SP_{jet} = \frac{\gamma \cdot Q \cdot H}{A} \cdot C_{t\_avg} \quad (8)$$

Where:

g = unit weight of water (N/m^3),

Q = discharge over the top of the dam (m^3/s),

H = head associated with the falling jet (m),

A = impact area of the jet (m^2), and

C_{t_avg} = average total dynamic pressure coefficient [5], which can be defined as: $C_{t\_avg} = C_{t\_1} + C_{t\_max}$, where C_{t_1} = total dynamic pressure coefficient not accounting for amplification in fissures (i.e., Γ = 1) and C_{t_max} = total dynamic pressure coefficient accounting for amplification with Γ defined by Figure 4.

For use with Bollaert's CFM and DI models, three separate pressure calculations are required. The first is the calculation of the pressure at the rock/water interface (i.e., the joint opening). This is the pressure used to calculate the amount of dynamic impulsion, which assumes fissures are open-ended and hence there is no amplification that may occur. This may be expressed as:

$$P = \gamma \cdot C_{t\_1} \cdot \phi \cdot \frac{v_j^2}{2g} \quad (9)$$

Where:

g = unit weight of water (N/m^3),

C_{t_1} = total dynamic pressure coefficient (not accounting for amplification, i.e., Γ = 1),

ϕ = energy coefficient (usually assumed = 1),

v_j = impact velocity of the jet (m/s), and

g = acceleration of gravity (m/s^2).

The second is the calculation of the maximum pressure that can be found in a close-ended fissure. This is similar to Equation 9 except that the total dynamic pressure coefficient has been adjusted to account for amplification that may occur due to resonance.

$$P_{\max\_fracture} = \gamma \cdot C_{t\_\max} \cdot \phi \cdot \frac{v_j^2}{2g} \quad (10)$$

Finally, the average pressure within a close-ended fissure may be calculated by making use of the previous two equations. This is defined as [1]:

$$P_{avg\_fracture} = 0.36 \cdot P + 0.64 \cdot P_{\max\_fracture} \quad (11)$$

The average pressure within close-ended fissure is used when calculating the amount of brittle fracture as well as fatigue failure time with Bollaert's CFM model.

VI. Scour At Kariba Dam

Scour calculations for Kariba Dam were performed for the peak discharge observed during the 1981 event and "average" rock mass parameters assumed by Bollaert [7]. These values are summarized in Table 1 below. Additional rock mass assumptions for the EIM are also included in Table 1 based on engineering judgment.

TABLE I. Rock Mass Parameters

Parameter	Value
Unconfined Compressive Strength (UCS)	125 MPa
Joint Persistency	25%
Maximum Joint Length	1 m
Joint Tightness	Tight
Joint Alteration/Filling*	None
Joint Roughness*	Rough & Undulating/Planar
Number of Joint Sets	3
Rock Quality Designation (RQD)*	80
Fatigue Coefficient, m	10
Fatigue Coefficient, C	1.3x10^{-6}
	*Value assumed for EIM

Given the rock parameters above, a rock resistance of approximately 600 kW/m^2 was calculated for the EIM. Figures 6 and 7 show the maximum scour depths predicted for fatigue failure and the EIM.

Figure 6. Scour by fatigue failure using CFM model.

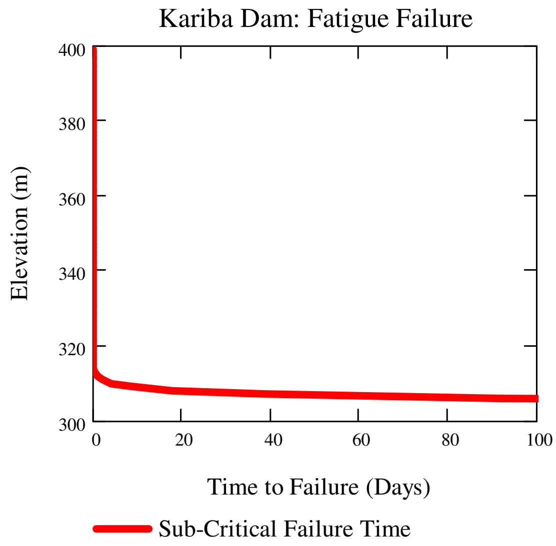
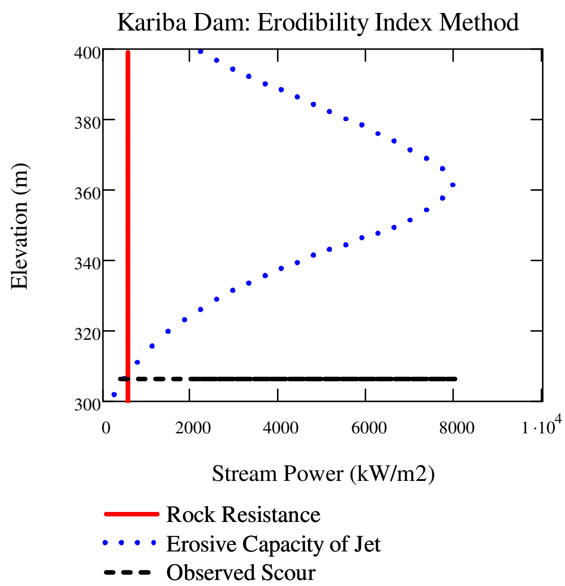


Figure 7. Scour prediction with the EIM



In Figure 6, the scour extent is shown as a function of time. Note that at about an elevation of 310 m (i.e., a plunge pool depth of nearly 90 m), the time it takes to fail the rock mass by fatigue begins to increase exponentially. It is just below this elevation that it is believed that scour progression would cease.

Figure 7 relates the scour extent by the use of a threshold value. At an elevation approximately a few meters above the observed scour elevation (305 m), the erosive capacity of the jet (measured by stream power) becomes less than the resisting capacity of the rock mass, suggesting no further scour.

As indicated, both methods produce nearly spot-on results in predicting the ultimate scour depth. This gives good promise to the use of the total dynamic pressure coefficient with the EIM, CFM and DI models.

VII. Conclusions

The application of the total dynamic pressure coefficient to Annandale's EIM and Bollaert's CFM and DI models appears to produce accurate representations of the maximum scour depth witnessed at Kariba Dam. The total dynamic pressure coefficient incorporates the effects of jet break up on the average and fluctuating dynamic pressures likely to result in a plunge pool from an impinging jet based on research by Castillo and Ervine, Falvey and Withers.

Incorporating the effects of jet break up is key when determining the extent of scour likely to occur for a given discharge as for increased degrees of break up, less scour is to be expected. This is an important factor when designing a plunge pool or plunge pool protection in the sense that huge costs could be alleviated if the extent of scour predicted is less than what would have been calculated not accounting for jet break up.

VIII. References

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Key Words

Scour, plunge pool, Erodibility Index Method, jet break up, dynamic pressures, prediction, case study, Kariba Dam, Comprehensive Fracture Mechanics, Dynamic Impulsion.