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# An Enhanced Physically Based Scour Model for Considering Jet Air Entrainment

Rafael Duarte [a,*], António Pinheiro [b], Anton J. Schleiss [a]

[a] Laboratory of Hydraulic Constructions (LCH), École polytechnique fédérale de Lausanne (EPFL), Lausanne CH-1015, Switzerland
[b] Civil Engineering Research and Innovation for Sustainability (CERIS), Instituto Superior Técnico, Universidade de Lisboa, Lisbon 1049-001, Portugal

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ABSTRACT

Based on systematic experiments on the influence of air entrainment on rock block stability in plunge pools impacted by high-velocity jets, this study presents adaptations of a physically based scour model. The modifications regarding jet aeration are implemented in the Comprehensive Scour Model (CSM), allowing it to reproduce the physical-mechanical processes involved in scour formation concerning the three phases; namely, water, rock, and air. The enhanced method considers the reduction of momentum of an aerated jet as well as the decrease of energy dissipation in the jet diffusive shear layer, both resulting from the entrainment of air bubbles. Block ejection from the rock mass depends on a combination of the aerated time-averaged pressure coefficient and the modified maximum dynamic impulsion coefficient, which was found to be a constant value of 0.2 for high-velocity jets in deep pools. The modified model is applied to the case of the observed scour hole at the Kariba Dam, with good agreement.



## 1. Introduction

Many empirical engineering methods are available to estimate scour formation downstream of plunging jets. Nevertheless, such empirical formulations are site-specific and not applicable to a wider range of cases [1]. As a matter of fact, the scouring process at plunge pool floors is a result of the interactions of the three phases involved: water, rock, and air. Moreover, the highly turbulent nature of the flow and the resulting pressure fluctuations on the water-rock interface and inside rock fissures make appropriate scaling impossible in hydraulic modeling. Therefore, the applicability of Froude-based reduced-scale models is extremely limited.

The Comprehensive Scour Model (CSM) was first proposed by Bollaert and Schleiss [2,3]. It has the advantage of considering the physical phenomena involved in the scour of the rock impacted by plunging water jets. The model was developed as a result of experiments with plunging jets of near-prototype velocities impacting on closed-end and open-end fissures at the pool bottom. As such, the model reproduces the characteristics of the pressure signals of prototype jets, thus minimizing scale effects. Furthermore, Manso et al. [4,5] proposed adaptations to the CSM that took into account the influence of the pool bottom geometry and the resulting induced flow patterns.

The present study proposes adaptations to the CSM in order to consider the effect of jet air entrainment as obtained by a systematic experimental campaign. The experimental setup and test program are presented in detail by Duarte [6].

The large facility was built at the Laboratory of Hydraulic Constructions of the École polytechnique fédérale de Lausanne. The vertical jets were issued from a $d_j$ = 72 mm diameter outlet nozzle, where compressed air was added to the water flow. Near-prototype air-water jet velocities up to 22.1 m·s$^{-1}$ were reproduced. The jets impinged into a 3 m diameter cylindrical basin. Plunging and submerged jets were tested. The pool depths, $Y$, were 30 cm, 50 cm, and 80 cm deep, resulting in relative pool depths $Y/d_j$ of 4.2, 6.9, and 11.1, respectively.

On the bottom of the pool, a metallic system to represent fully

* Corresponding author.
*E-mail address:* rafael.duarte@alumni.epfl.ch

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open 3D fissures of the rock mass was implemented. It comprises a box in which a 200 mm side cubic block was inserted, with a 1 mm thick fissure between the block and the box. Dynamic pressures were measured with a frequency of 1 kHz at 12 positions uniformly distributed along one half of the block. The pressure transducers were of the type Kulite HKM-375M-17-BAR-A.

The recent research assessed the influence of the air bubbles on the jet dissipation along the plunge pool, the resulting dynamic pressures acting on the water-rock interface and inside underlying fissures on pools with a flat bottom [7] and with a confined bottom [8], as well as the ejection of blocks from the rock mass [9]. This paper ties the former work together and proposes a sound and straightforward method for the engineering practice.

## 2. Proposed adaptations of the Comprehensive Scour Model (CSM) for considering jet aeration

The CSM was developed based on a theoretical and experimental study of rock scour created by plunging high-velocity jets. The scour process is the result of complex subsequent physical phenomena and can be divided into three parts—the falling jet, the plunge pool, and the rock mass—each corresponding to a module of the CSM, as shown in Fig. 1.

In the following, the different modules of the CSM are presented. The developments refer to the proposed adaptations of the model, unless it is specifically stated otherwise.

### 2.1. Falling jet module

The falling jet module reproduces the jet characteristics during the jet's trajectory through the air. Ballistics theory governs the trajectory of the jet core. The jet develops an aerated outer layer as internal turbulence creates increasing disturbances on the jet's surface. The jet, issued with velocity $V_j$, diameter (or thickness in the case of plane jets) $d_j$, and turbulence intensity $T_u$, is subjected to acceleration of gravity $g$ during the fall length $L$, impacting the pool at the plunge section with velocity $V_i$ and diameter $d_i$. Providing enhancements to the representation of the falling jet considering aeration was not in the scope of this research project. The original references may be consulted for detailed information [2,3].

### 2.2. Plunge pool module

The plunge pool module represents the diffusion of the jet throughout the pool depth. This process dissipates a fraction of the energy of the jet. The jet entrains large quantities of air into the water pool at the plunge section, which strongly influences the diffusion properties. The jet aeration, or air-to-water ratio, is defined as $\beta = Q_a/Q_w$, where $Q_a$ and $Q_w$ are the air and water discharges, respectively. To compute $\beta$, the expression proposed by Ervine et al. [10] is considered:

$$\beta = K_1\left(1-\frac{V_e}{V_i}\right)\sqrt{\frac{L}{d_i}} \tag{1}$$

where, $K_1$ is a parameter that varies between 0.2 for smooth turbulent jets and 0.4 for very rough jets; $V_e$ is the onset velocity of the jet at the plunge section above which air entrainment begins, normally taken as ~1 m·s$^{-1}$.

The mean density of the air-water jet inside the pool $\rho_{aw}$ is given by

$$\rho_{aw} = \frac{1}{1+\beta}\rho_w + \frac{\beta}{1+\beta}\rho_a \tag{2}$$

where, $\rho_a$ and $\rho_w$ are the air and water densities, respectively. The input of energy to the process is determined by the kinetic energy per unit volume of the air-water jet at the plunge section:

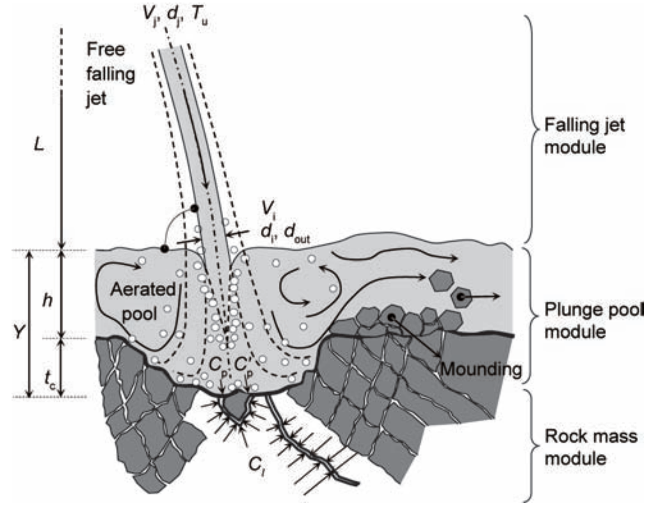


**Fig. 1.** Physical processes responsible for scour formation and definition of the main parameters. Adapted from Ref. [2].

$$E_k = \frac{1}{2}\rho_{aw}V_i^2 \tag{3}$$

After plunging into the pool with aeration $\beta$, mean density $\rho_{aw}$, and kinetic energy $E_k$, the dissipation process of the jet begins. The inner core of the jet is progressively disintegrated from its contour toward the centerline, where the flow remains approximately at the same velocity as at the plunge section. The jet core vanishes according to the following expressions [7]:

$$\begin{cases} \dfrac{y_c}{d_i} = 7.74\times10^{-6}\dfrac{V_i d_i}{\nu} & \text{if } 7.74\times10^{-6}\dfrac{V_i d_i}{\nu} \le A' \\ \dfrac{y_c}{d_i} = A' & \text{if } 7.74\times10^{-6}\dfrac{V_i d_i}{\nu} > A' \end{cases} \tag{4}$$

where, $y_c$ is the core development length; $\nu$ is the kinematic viscosity of the fluid; the parameter $A'$ is 3.5 for submerged jets and 7.8 for plunging jets; the term $V_i d_i/\nu$ corresponds to the Reynolds number of the jet at the plunge section. Once the jet core is disintegrated, the jet velocity decay follows a linear function of the pool depth for both submerged and plunging jets.

The remaining kinetic energy of the jet is converted into dynamic pressures acting on the plunge pool bottom. The time-averaged pressures $p_{mean}$ are maximal at the intersection of the jet centerline with the water-rock interface, which is commonly referred to as stagnation. The time-averaged pressure coefficient is defined as $C_p = (p_{mean} - \rho_w gY)/E_k$. For the non-aerated jets at stagnation, $C_p$ is reproduced by the following relationship [7]:

$$C_p = \psi\left(0.926 - 0.0779\frac{Y-y_c}{d_i}\right)^2 \quad \text{if } Y > y_c \tag{5}$$

$$\psi = \frac{1}{1+\exp\left[-5.37\times10^{-6}\left(\dfrac{V_i d_i}{\nu} - 6.63\times10^5\right)\right]} \tag{6}$$

If $Y < y_c$, the core of the jet impacts directly on the rock bottom and $C_p = 0.86$. The parameter $\psi$ reflects the loss of energy that takes place at the impingement region formed at the vicinity of the intersection of the jet centerline with the pool bottom (for a complete description of the impingement of axisymmetric developing jets, refer to the work of Beltaos and Rajaratnam [11]). Duarte et al. [7] showed that $\psi$ is a logistic function of the jet velocity that asymptotically reaches the value 1 for high jet velocities.