Scour estimation of the Paute-Cardenillo Dam

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ABSTRACT

The study analyzes the expected changes in the Paute River, located in Ecuador, as a result of the construction of the Paute-Cardenillo Dam (owned by Celec Ep-Hidropaute). The dam will integrate the National Electric System of Ecuador with a total electricity installed capacity of 600 MW which will produce 13000 GWh per year. To evaluate the stability and safety of the structure, it is necessary to ascertain the shape and dimensions of the scour generated downstream from the dam. The scour, due to the operation of the spillway and outlets, is studied with three complementary procedures: empirical formulae obtained in models and prototypes, semi-empirical methodology based on pressure fluctuations-erodibility index and computational fluid dynamics simulations.

DAM CHARACTERISTICS

The Paute-Cardenillo Dam, located in Ecuador, is a double curvature arch dam with a maximum height of 135 m to the foundations. The top level is located at an altitude of 926 meters. The reservoir has a length of 2.98 km with normal maximum water level located at 924 meters. The river bed consists of a layer of 24 m of alluvial, below which there is a layer of 10 m of weathered rock. It has a free surface weir controlled by sluices that spill a flow of Q_4=700 m^3/s (return period *TR*=4 years) and a half-height outlet with two almost symmetrical ducts. Considering the maximum normal operating level (924 m), the intermediate outlet capacity is Q_{40}=1760 m^3/s. Hence, the total flow of the weir and half-height outlet is Q_{100}= 2340 m^3/s. If the bottom outlet were considered, the discharge capacity of the dam would be Q_{10000}=5520 m^3/s.

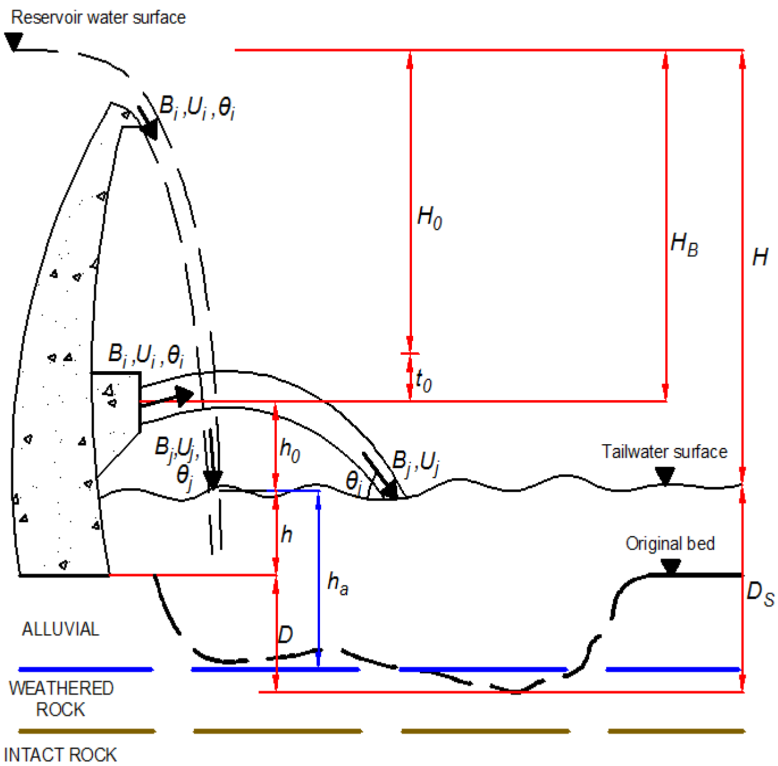
EMPIRICAL FORMULAE

In the study, 29 formulae are examined. The scour hole is estimated for flows of various return periods.

Most of the equations were obtained by dimensional and statistic analysis of data obtained in Froude scale reduced models, with few formulae based on prototypes and many obtained for the ski-jump. As discharge is produced by a free surface weir and in pressure conditions by an intermediate outlet, the general expression is modified which provides the following simplified general expression:

$$D_s = h + D = K\frac{q^x H_n^y h^w}{g^v d^z} \quad (1)$$

where D_s is the scour depth below tailwater level, h the tailwater depth, D the scour depth below the original bed, K an experimental coefficient, q the specific flow, H_n the energy net head, and d the characteristic size of bed material. The meaning of the rest variables can be seen in Figure 1.



x, y, w, v , z. Empirical exponents defined by regression or optimization.
t_0 = energy losses in the duct.
$H_n = H_0 = H_B - t_0$. Net energy head at the exit of the outlet.
$H_n = H$. Falling height from reservoir level to tailwater level (ski-jump and free surface weir).
h_0. Vertical distance between outlet exit and tailwater level.
h_a. Vertical distance between tailwater level and scour bed.
B_i, U_i, θ_i. Thickness, velocity and angle of the jet in initial conditions.
B_j, U_j, θ_j. Total thickness, velocity and angle of the jet in impingement conditions.

Figure 1 Scheme of scour in Paute-Cardenillo Dam.

Table 1 shows the coefficients corresponding to five simplified formulae with values that fall in the mean values +/- 1 standard deviation, while Table 2 shows five more general expressions with values in the same range.

Figure 2 shows the results obtained for the free surface weir. The mean value +/- 1 standard deviation is indicated. If the mean value for the design flow (700 m^3/s) were considered, the scour could reach a depth of 15 m. However, if the mean value + 1 standard deviation were taken into account, then the flow of 500 m^3/s would penetrate the weathered rock (scour about 30 m).

Table 1. Coefficients of five scour simplified formulae with values that fall in the mean value +/- 1 standard deviation.

Author	*K*	*x*	*y*	*z*	*d*
Hartung (1959)	1.400	0.64	0.360	0.32	d_{85}
Chee and Padiyar (1969)	2.126	0.67	0.180	0.063	d_m
Bisazand and Tschopp (1972)	2.760	0.50	0.250	1.00	d_{90}
Martins-A (1975)	1.500	0.60	0.100	0.00	-
Machado (1980)	1.350	0.50	0.3145	0.0645	d_{90}

Table 2. Five scour general formulae with values that fall in the mean value +/- 1 standard deviation.

AUTHOR (YEAR)	FORMULAE
Jaeger (1939)	$D_S = 0.6q^{0.5}H_n^{0.25}(h/d_m)^{0.333}$
Rubinstein (1965)	$D_S = h + 0.19\left(\frac{H_n + h}{d_{90}}\right)^{0.75}\left(\frac{q^{1.20}}{H_n^{0.47}h^{0.33}}\right)$
Mirskhulava (1967)	$D_S = \left(\frac{0.97}{\sqrt{d_{90}}} - \frac{1.35}{\sqrt{H_n}}\right)\frac{q \cdot sin\theta_T}{1 - 0.175 \cdot cot\theta_T} + 0.25h$
Mason-B (1989)	$D_S = 3.39\frac{q^{0.60}(1+\beta)^{0.30}h^{0.16}}{g^{0.30}d^{0.06}}$
Bombardelli and Gioia (2006)	$D_S = K\frac{q^{0.67}H_n^{0.67}h^{0.15}}{g^{0.33}d^{0.33}}\left(\frac{\rho}{\rho_s - \rho}\right)$

d_m. Average particle size of the bed material
d_{90}. Bed material size in which 90% is smaller in weight
θ_T. Impingement jet angle
g (9.81 m/s^2). Gravity
β. Air-water relationship
ρ. Water density
ρ_s. Density of sediment

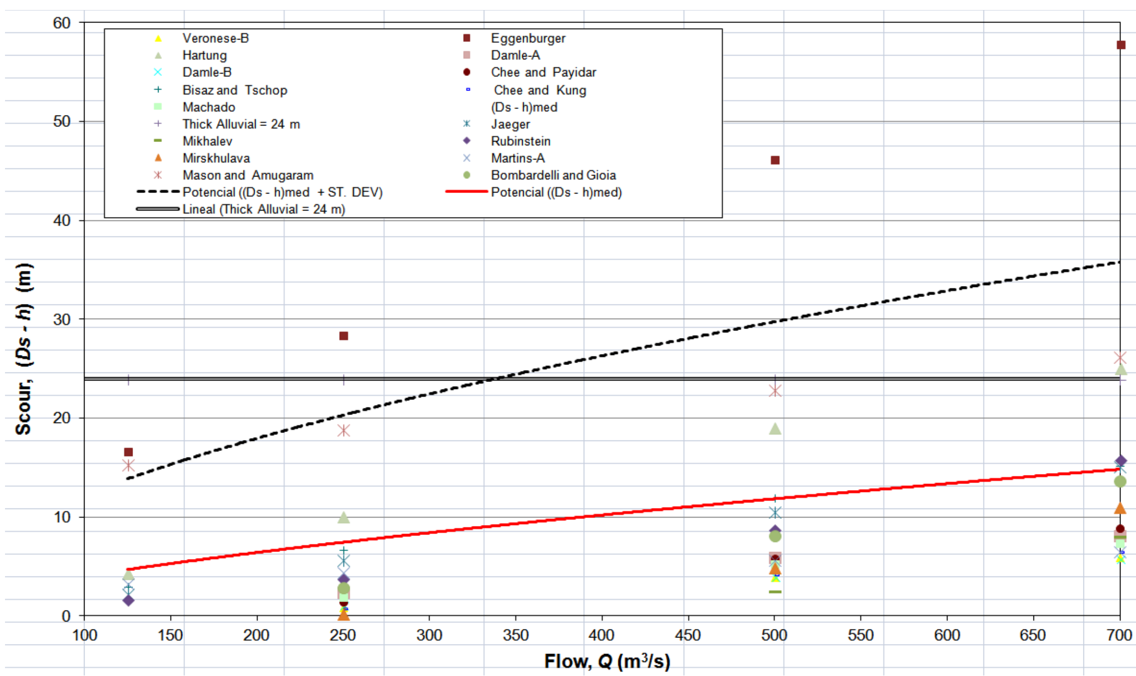


Figure 2. Scour of alluvial and weathered rock for the free surface weir.

SEMI-EMPIRICAL METHODOLOGY

The erodibility index is based on an erosive threshold that relates the magnitude of relative erosion capacity of water and the relative capacity of a material (natural or artificial) to resisting scour. There is a correlation between the stream power or magnitude of the erosive capacity of water (P) and a mathematical function [$f(K)$] that represents the relative capacity of the material to resisting erosion. On the erosion threshold, this may be expressed by the relationship $P = f(K)$. If $P > f(K)$, with the erosion threshold being exceeded and the material eroded.

Scour in turbulent flow is not a shear process. It is caused by turbulent, fluctuating pressures (Annandale, 2006). Quantification of pressure fluctuations of incident jets in stilling basins has been studied mainly by Ervine and Falvey (1987), Ervine et al. (1997), Castillo (1989, 2002, 2006, 2007), Castillo et al. (1991, 2007), Puertas (1994), Bollaert (2002), Bollaert and Schleiss (2003), Melo et al. (2006), and Felderspiel (2011).

The dynamic pressures of jets are a function of the turbulence intensity at the discharge conditions, length of the jet flight, diameter (circular jet) or thickness (rectangular jet) in impingement jet conditions and water cushion depth.

Annadale (1995, 2006) summarized and established a relationship between the stream power and the erodibility index for a wide variety of materials and flow conditions. The stream power per unit of area available of an impingement jet is:

$$P_{jet} = \frac{\gamma Q H}{A} \tag{2}$$

where γ is the specific weight of water, Q the flow, H the drop height or the upstream energy head, and A the jet area on the impact surface. The erodibility index is defined as:

$$K = M_s \cdot K_b . K_d \cdot J_s \tag{3}$$

where M_s is the number of resistance of the mass, K_b the number of the block size, K_d the number of resistance to shear strength on the discontinuity contour, and J_s the number of structure relative of the grain. Table 3 shows the formulae of the parameters.

Table 3. Erodibility index parameters (Adapted from Annandale, 2006).

Material	Formulae	Parameters
Rock	$M_s = 0.78 C_r UCS^{1.05}$ $when$ $UCS \leq 10\,MPa$ $M_s = C_r UCS$ $when$ $UCS > 10\,MPa$ $C_r = \frac{g\rho_r}{\gamma_r}$	C_r. Relative density ratio. ρ_r. Rock density. g (9.81 m/s^2). Gravity. γ_r ($27 \cdot 10^3$ N/m^3). Specific weight of the intact rock.
Non-cohesive granular	The relative magnitude is obtained from the *SPT* results. When this value exceeds 80, the non-cohesive granular material is considered equivalent to rock.	
Rock	$K_b = \frac{RQD}{J_n}$	*RQD* values are between 5 and 100, J_n between 1 and 5, and K_b between 1 and 100.
Non-cohesive granular	$K_b = 1000 D^3$	*D*. Diameter of the average block.
Rock	$K_d = \frac{J_r}{J_a}$	
Non-cohesive granular	$K_d = tan\phi$	Φ. Angle of residual or internal friction of the granular material.

The threshold of rock strength to the stream power, expressed in kW/m^2, is calculated and based on the erodibility index K.

$$P_{rock} = 0.48 K^{0.44} \quad if \quad K \leq 0.1$$
$$P_{rock} = K^{0.75} \quad if \quad K > 0.1 \tag{4}$$

The dynamic pressure in the bottom of the stilling basin is based on two components: the mean dynamic pressure (C_p) and the fluctuating dynamic pressure ($C_p´$). These dynamic pressure coefficients are used as estimators of the stream power reduction coefficients, by an effect of the jet disintegration in the air and their diffusion in the stilling basin (Annandale, 2006). Hence, the dynamic pressures are also a function of the fall height to disintegration height ratio (H/L_b) and water cushion to impingement jet thickness (Y/B_j). Thus, the total dynamic pressure is expressed as:

$$P_{total} = C_p\left({}^{Y}\!/_{B_j}\right)P_{jet} + F\,C_p{}'\left({}^{Y}\!/_{B_j}\right)P_{jet} \tag{5}$$

where $C_p(Y/B_j)$ is the mean dynamic pressure coefficient, $C_p'(Y/B_j)$ the fluctuating dynamic pressure coefficient, P_{jet} the stream power per unit of area, and F the reduction factor of the fluctuating dynamic pressure coefficient. In the rectangular jet case (nappe flow), Castillo and Carrillo (2012, 2013) adjusted the formulae by using new laboratory data (see Figures 3, 4 and 5).

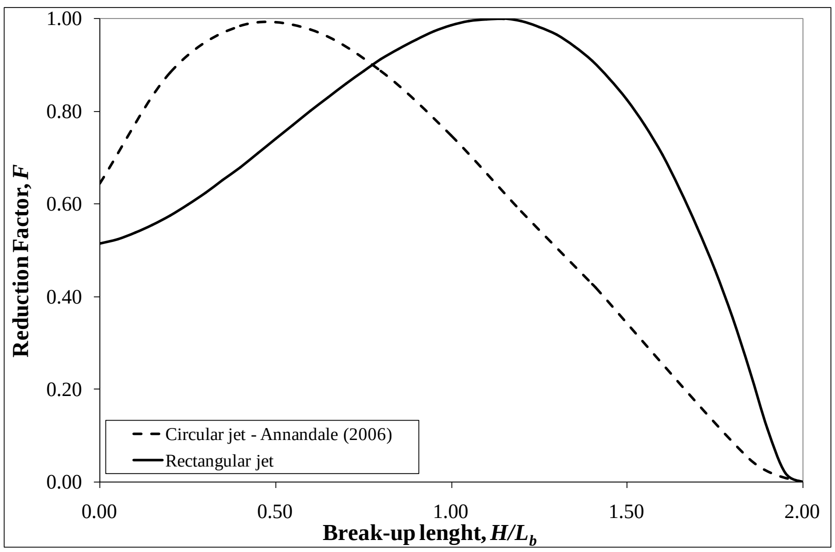


Figure 3. Reduction factor *F* of fluctuating dynamic pressure coefficient.

Table 4 shows the values of the different variables considered and their respective calculus in the semi-empirical methodology.

Table 4. Semi-empirical methodology. Input and calculated values.

Angle of rock friction, *SPT* (º)	38	Number of join system (calculated), J_n	1.83
Specific weight (KN/m^3)	27.64	Discontinuity spacing, J_x, J_y, J_z (m)	0.5
Unconfined compress. resistant, *UCS* (Mpa)	50	Average block diameter (calculated), (m)	0.5
Relative density coefficient, *Cr*	1.024	Roughness degree, J_r	2
RQD (calculated)	82.66	Alteration degree, J_a	1

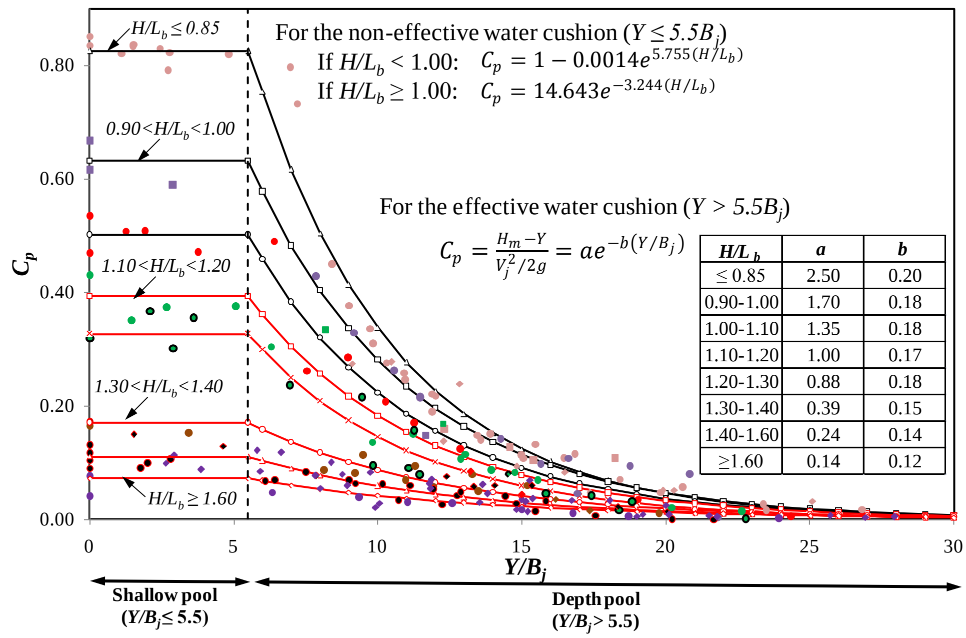


Figure 4. Mean dynamic pressure coefficient, C_p, for the nappe flow case.

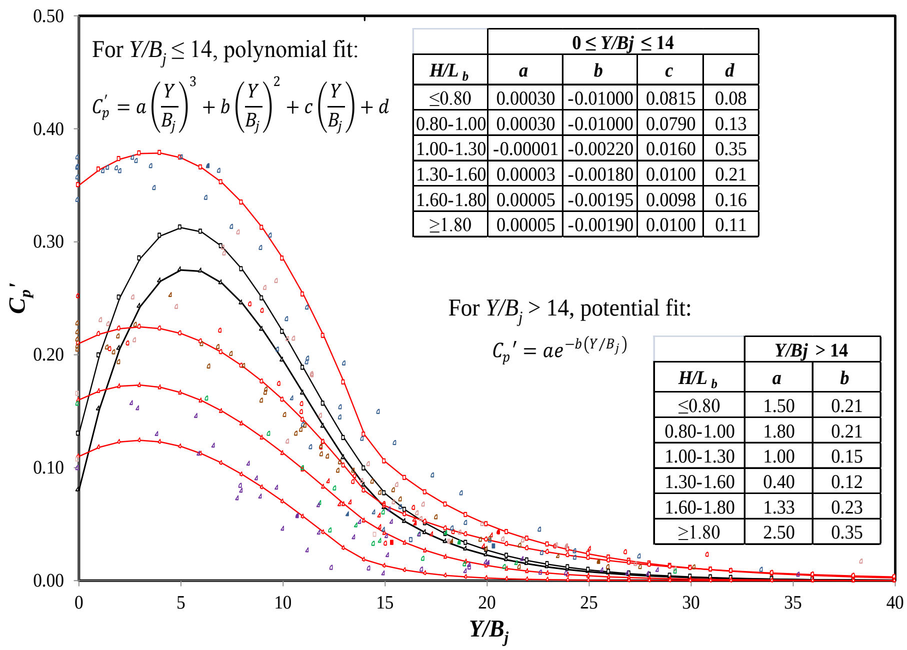


Figure 5. Fluctuant dynamic pressure coefficient, C_p', for the nappe flow case.

Table 5 shows the results obtained in the three types of material existent in the place of the dam. In Figure 6 the stream power of the free surface weir jet is indicated, together with the power threshold of alluvial, weathered and intact rock.

Table 5. Stream power of free surface jets for different flows as a function of the erodibility: alluvial, weathered rock and intact rock indexes (water cushion depth 24 m).

	Alluvial	Weathered rock	Intact rock
M_s	0.19	0.41	51.19
K_b	11.39	125	49.18
K_d	0.78	0.78	2
J_s	1	1	0.6
Erodibility index, K	1.69	40.04	3020.77
Stream power, P_{rock} (kw/m^2)	1.48	15.92	407.46

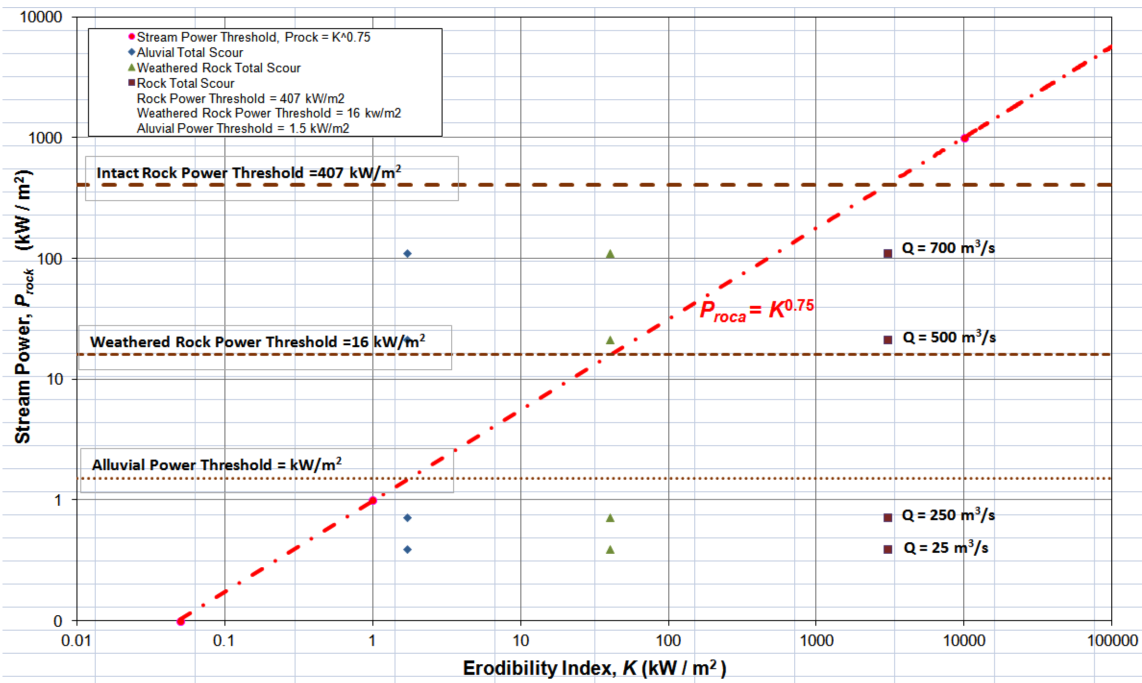


Figure 6. Free surface weir. Stream power of the jet for different flows as a function of the erodibility: alluvial, weathered rock and intact rock indexes (water cushion depth 24 m).

Considering a water cushion depth of 24 m, the flow rate of 500 m^3/s would have the power to erode weathered rock, although the design flow of 700 m^3/s would not have enough power to erode the intact rock. These results confirm that the maximum scour of the free surface weir could be near to 34 m.

NUMERICAL SIMULATION

As a complement of the empirical and semi-empirical methodologies, three-dimensional mathematical model simulations were carried out. These programs allow a more detailed characterization than one-dimensional and two-dimensional numerical models and, thus, a detailed study of local effects of the sediments transport. The numerical simulation of the hydraulic behavior and scour by the action of the free surface weir, intermediate and bottom outlets were also analyzed.

The computational fluid dynamics (CFD) program FLOW-3D was used. This program solves the Navier-Stokes equations discretized by finite differences. It incorporates various turbulence models, a sediment transport model and an empirical model bed erosion (Guo, 2002; Mastbergen and Von den Berg, 2003; Brethour and Burnham, 2011), together with a method for calculating the free surface of the fluid without solving the air component (Hirt and Nichols, 1981). Pressures obtained in the stagnation point and their associated mean dynamic pressure coefficients were compared with the parametric methodology proposed by Castillo (2006, 2007).

In order to simulate the proper functioning of the free surface weir, several simulations were carried out by means of sensibility analysis: air entrainment models, turbulence models, grid size and type of solver, among others (Figure 6).

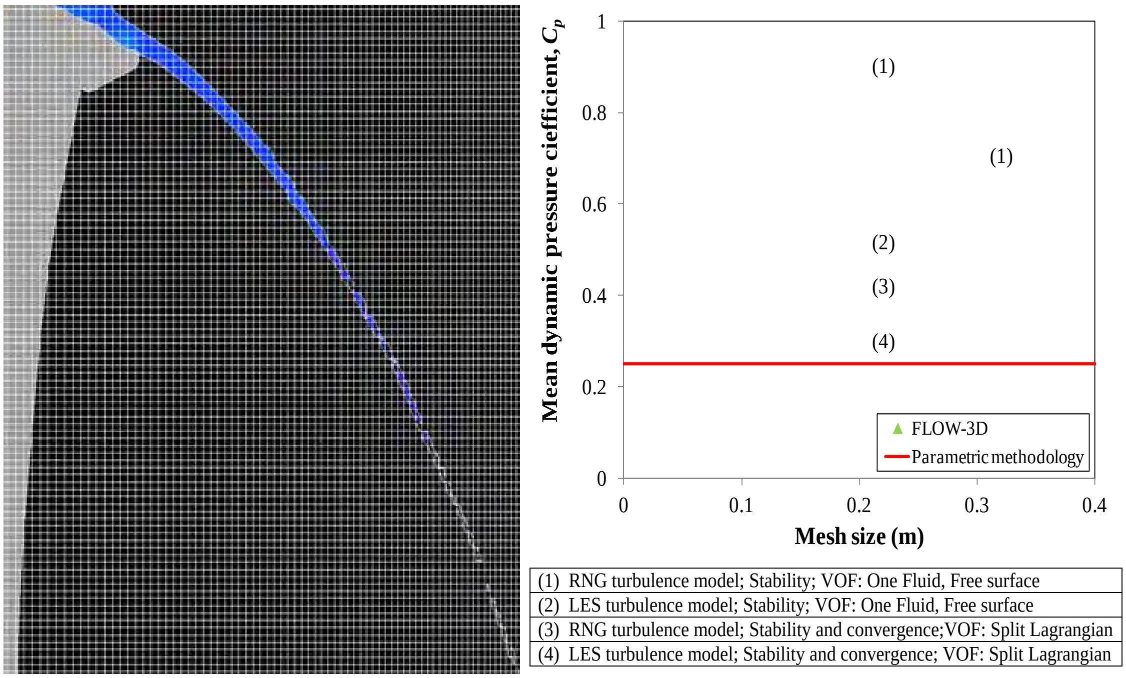


Figure 6. Mesh and sensibility analysis of FLOW-3D.

We can observe that the results are anomalous when RNG k-ε turbulence model and the one fluid free surface method are used. So, if the mesh size is reduced from 0.30 m to 0.20 m, C_p changes from 0.71 to 0.90. However, when the RNG k-ε model is used with the split Lagrangian free surface method, then the results are more similar to the expected value. The most accurate results were obtained by using a mesh size of 0.2 m, and large eddy simulation (LES) turbulence model. In the solver options, the stability and convergence method was selected and the free surface solved with the split Lagrangian method.

Table 6 compares the mean pressure and the mean dynamic pressure coefficient obtained by the non-effective water cushion case. Results were similar to the parametric methodology. It may be observed that the mean dynamic pressure and C_p coefficient obtained with FLOW-3D are somewhat greater than parametric methodology values, which is due to the air entrainment model not resolving the two-phase flow in an appropriate way.

Table 6. Comparison of pressures and C_p, considering a water cushion depth of 2 m.

	Parametric methodology	FLOW-3D
Drop height (m)	102.0	102.0
Mean dynamic pressure (m)	30.56	33.44
Mean dynamic pressure coefficient, C_p	0.28	0.31

As far as scour is concerned, free surface weir jets tended to impact on a small area. The upstream face of the scour bowl occurred approximately 29 m downstream from the dam. The plant scour was near 24 m long and 53 m wide (Figure 8). Erosion generated a scour depth of 22 m, which was a little greater than that calculated with the mean value of the empirical formulae and similar to that obtained with semi-empirical methodology.

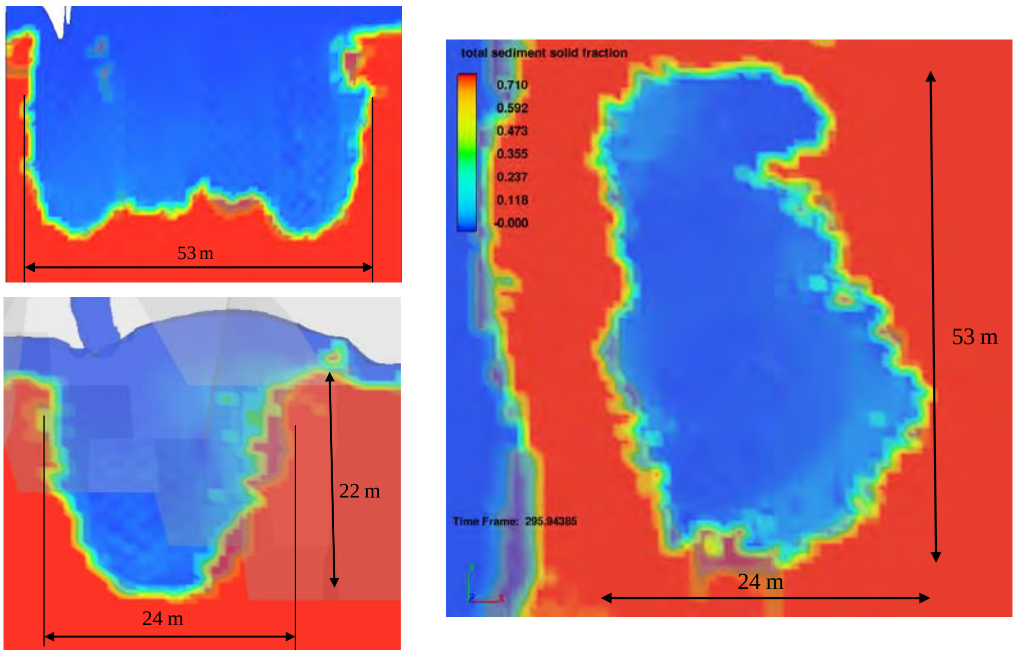


Figure 8. Front, lateral, and top view of the scour due to the free surface weir.

CONCLUSION

In this paper, similar results have been obtained by solving the problem from three different perspectives: empirical formulations, erosion potential semi-empirical formulation and CFD simulations. The results demonstrate the suitability of crossing methodologies to solve complex phenomena. Thus, numerical simulations were used to complement the classical formulations, allowing a better understanding of the physical phenomena in order to obtain an adequate solution.

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