Dynamic Pressure Distribution around a Fixed Confined Block Impacted by Plunging and Aerated Water Jets

Rafael Duarte
PhD Candidate, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland. Email: rafael.duarte@epfl.ch

Anton Schleiss
Full Professor, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland. Email: anton.schleiss@epfl.ch

António Pinheiro
Full Professor, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais 1049-001 Lisbon, Portugal. Email: apinheiro@civil.ist.utl.pt

ABSTRACT: The scour process created by the impingement of high-velocity water jets on fissured rock is the result of complex physical phenomena. Of great importance are the jet development during the trajectory through the atmosphere, the diffusion process inside the plunge pool, the pressure fluctuations at the water-rock interface and the propagation of pressure waves inside rock fissures. Air entrainment also plays an important role. Air can be entrained during the trajectory in the atmosphere and at the point of impact into the plunge pool. Particular characteristics of air bubbles, such as compressibility and buoyancy, will influence jet dissipation in the plunge pool. Furthermore, air bubbles are present at the water-rock interface, from where they can enter rock fissures and thus change properties of pressure waves propagation and amplification. These phenomena cannot be reproduced in Froude-scale models without important scale effects. Experiments were carried out with the objective of investigating the influence of jet aeration on pressures at the water-rock interface of a plunge pool and inside rock fissures. The experimental set-up generates prototype jet velocities up to 22.1 m/s. Air was provided at the nozzle by a pumped aeration system. For each test scenario, a similar non-aerated water jet was tested for comparison. The so formed air-water jets impinge into an 80cm deep plunge pool. Additionally, water depths varied from 50 to 80 cm for non-aerated tests. Corresponding non-dimensional ratios between pool depth and jet diameter varied from 6.9 to 11.1, resulting in core and developed jet impact on the bottom. The fractured rock media was represented by a confined cubic metallic block of 200 mm side placed on the bottom of the pool, equipped with 12 micro pressure transducers evenly distributed on the water-rock interface and through the represented fissures. The transient pressures were analyzed by means of non-dimensional pressure coefficients and the spectral contents of the pressure signals. Results confirm that mean pressures and oscillations are affected by the aeration of the jet, both on the water-rock interface as inside the fissures. Moreover, evidence is shown that part of the air content in the plunge pool is able to enter the fissures and influence resonance effects. This study gives useful insight on the influence of jet aeration on the rock scour process.

KEY WORDS: Air entrainment, air-water interactions, hydraulic jets, rock scour, dynamic pressures.

1 INTRODUCTION

The dissipation of the energy provided by jets issued from water release structures of hydraulic schemes is a major concern in hydraulic design. This dissipation might occur in a lined stilling basin designed for this purpose or directly on the rock bottom of the water course, provided that a careful evaluation allows so. In this case, rock scour will take place and its correct prediction is of great importance for the safety of the structure, so that spillway design may avoid excessive erosion and damage to the dam toe (Schleiss, 2002).

Rock scour prediction is a complex task. Many methods were created in the past, that consider from purely empirical methods to complete physically-based models (Bollaert and Schleiss 2003, 2005). The phenomenon is composed of different subsequent physical processes (Figure 1, Manso et al 2009), from jet issuance at the hydraulic structure to its trajectory through the air and diffusion in the plunge pool. The energy that was not dissipated in the plunge pool will form dynamic pressures at the water-rock interface. These will propagate inside fissures, and joint break-up might occur. Finally, if fissures are completely interconnected, block ejection can occur, as a function of the dynamic pressures around it and the resistance against the displacement.

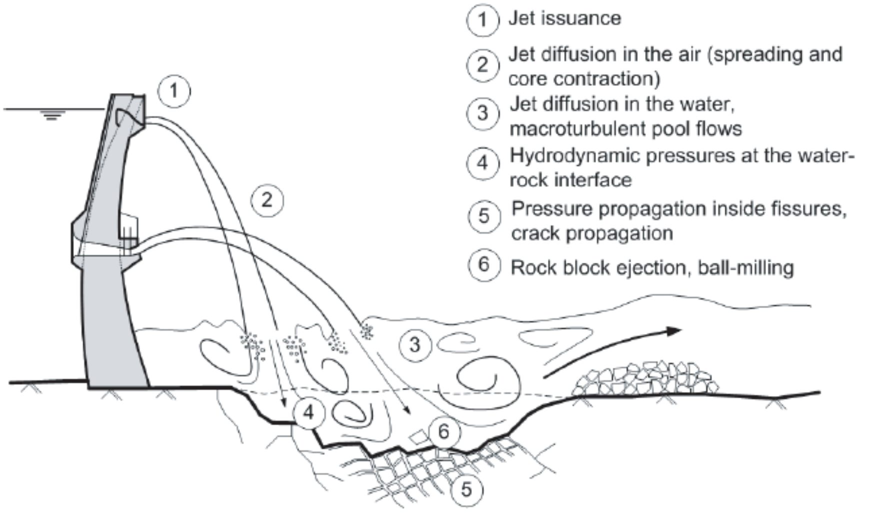

Figure 1 Physical processes involved in rock scour (Manso et al, 2009)

A thoughtful analysis of the processes shows that scour is a function of the three main media involved: water, air and rock (Bollaert and Schleiss, 2003). The objective of the experimental study addressed in this paper is to analyze the influence of jet aeration on the dynamic pressures acting on an embedded block and at the water-rock interface. This will provide important insight to a more complete evaluation of rock scour evolution. For such, a passive and an active aeration systems were developed to provide air to the water jets (Duarte et al, 2012). A companion paper (Duarte, 2013) presents results of air bubble diffusion patterns throughout the shear layer of the jet in the plunge pool.

2 EXPERIMENTAL SET UP

2.1 Facility

The experimental study was conducted at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). The set-up (Figure 2) reproduced aerated high-velocity jets of up to 22.1 m/s impinging vertically on a plunge pool. The experimental apparatus for this study included:

- A 63.4 m head pump provides the required energy for the jets. The water is provided through a 300 mm supply conduit. A honeycomb grid and an air vent at the upper part of the conduit enables a more homogeneous velocity distribution in the transversal section of the jet.
- At the downstream end of the supply conduit, a 72 mm diameter cylindrical nozzle models the jet.
- The plunge pool is reproduced by a 3 m diameter cylindrical basin. Stop logs at both sides are used to regulate the plunge pool water depth Y from 0 to 80 cm. The distance from the bottom of the pool to the nozzle is 1m.
- At the bottom, a rock block was represented by a system composed by a metallic cavity 201 mm high, 202 mm long and 202 mm wide, where a 200 mm sided metallic cube was inserted. This system composed by a highly instrumented box and a highly instrumented block simulated open 3D

joints of 1mm.

Compressed air was provided to the water jet in the nozzle by means of 6 small aluminium tubes symmetrically inserted. Flexible tubes were used to assemble the air flow for measurement of the air discharge.

Figure 2 Pictures of the experimental facility before and during tests. In the left picture the fixed confined block can be seen in the middle

2.1 Instrumentation

To perform dynamic pressure measurements, 12 pressure transducers of type KULITE HKM-375M-17-BAR-A were placed in the central section of the highly instrumented block. These sensors have a flush-mounted metal diaphragm with an absolute pressure range between 0 and 17 bars and a precision of ± 0.1% of the full scale output. The sensors have been developed to measure highly dynamic pressure phenomena, such as shock waves. Hence, they exhibit a very high resonance frequency (750 kHz).

Four transducers were evenly placed at the top of the block, between the center (stagnation point) and the side of the block. Four transducers were evenly placed in the vertical wall of the block and the last four were evenly placed at the bottom of the block, between center point and its side. By doing so, the former 4 transducers were able to measure dynamic pressures on the bottom of the plunge pool, while the remaining 8 transducers measured pressures inside the fissures (Figure 3).

The data acquisition device is a National Instruments (NI) card type USB-6259 series M. The NI device is driven with laboratory developed software running in the LabVIEW© environment. For each test run, 65’536 samples were obtained at an acquisition frequency of 1kHz. For assuring repeatability of the results, 3 runs were undertaken per configuration.

The compressed air was controlled with a ball valve and the entrained air discharges were directly measured with a Wisag 2000 series flowmeter.

3 TEST PROGRAM AND ANALYSIS PROCEDURE

For all test configurations, the jet was impinging on the center of the block, which was rigidly fixed. Table 1 presents the range of the varying parameters, where Y is the plunge pool water depth, D_i is the jet diameter at issuance and V_{aw} is the velocity of the air-water jet at issuance.

Table 1 Overview of the test program

Y [m]	Y/D_i	V_{aw} [m/s]	Air supply
0.50	6.9	4.9 to 22.1	no
0.60	8.3	4.9 to 22.1	no
0.70	9.7	4.9 to 22.1	no
0.80	11.1	4.9 to 22.1	0%, 8%, 15%, 23%

The aeration of the jet is determined by the air-to-water ratio β, which is defined by:

$$\beta = \frac{Q_a}{Q_w} \tag{1}$$

where Q_a is the air discharge and Q_w is the water discharge.

Three β values were chosen for each aerated jet: 8%, 15% and 23%. In all cases a non-aerated jet was also tested. The air-water mixture velocity or total velocity V_{aw} of the four jets were the same for comparison purposes.

The jets are thus considered as having the same issuance velocity but composed of fluids of different mean apparent densities. By doing so, a homogeneous mixture of air and water inside the nozzle can be assumed. The mean apparent density of the mixture ρ_{aw} is determined by:

$$\rho_{aw} = \left(\frac{1}{1+\beta}\right)\rho_w + \left(\frac{\beta}{1+\beta}\right)\rho_a \tag{2}$$

where ρ_w is the density of water and ρ_a is the density of air. Considering that ρ_a y$10^{-3}\rho_w$, , the second part of the sum might be neglected for practical purposes, but this was not the case in this study.

The kinetic energy per unit mass E_k of the jet at impact is given by:

$$E_k = \rho_{aw} V_j^2 / 2 \tag{3}$$

where V_j is the jet velocity at impact against the plunge pool. It should be noted that an aerated jet with the same total velocity compared to a non-aerated jet has a reduction of kinetic energy corresponding to

$$1 - \frac{E_{k(aeratedjet)}}{E_{k(nonaeratedjet)}} = \frac{Q_a}{Q_a + Q_w} = \frac{\beta}{1+\beta} \tag{4}$$

The dynamic pressure data were analyzed by means of the mean pressure and RMS fluctuations. The corresponding non-dimensional coefficients C_p and C_p' were computed as described below (Ervine et al 1997):

$$C_p = \frac{(P_{mean} - P_{atm}) - \rho_w g Y}{\rho_{aw} V_j^2 / 2} \tag{5}$$

$$C_p^{'} = \frac{\sigma}{\rho_{aw} V_j^2 / 2} \tag{6}$$

where P_{mean} is the mean pressure obtained in Pascal, P_{atm} is the atmospheric pressure in Pascal, g is the gravitational acceleration and σ is the RMS value of the pressure fluctuations in Pascal.

3 RESULTS AND DISCUSSION

3.1 Time domain analysis

The comparison of jets with the same total velocity and different air-to-water ratios for aerated jets is shown in Figure 3 for a jet velocity of 22.1 m/s, which corresponds to the highest tested value. A vertical cut of the central section of the block is shown. The top of the block corresponds to the pressures applied against the water-rock interface. Pressure measurement positions in this region were called PB 1 to 4, where PB stands for pool bottom for clarity. In similar way, measurement positions on the side of the block and on its bottom were called VF 1 to 4 (vertical fissure) and HF 1 to 4 (horizontal fissure). The jet impinges towards the center of the block and produces an axisymmetric distribution of pressures around it.

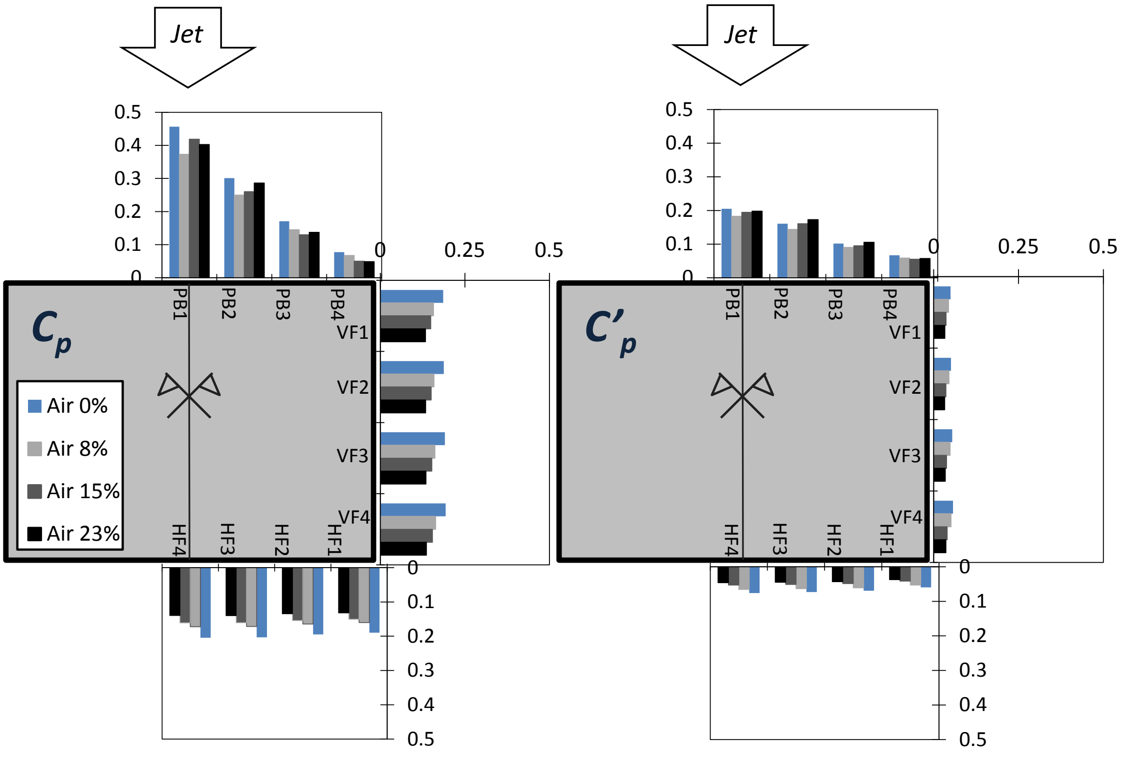

Figure 3 Scaled bar plots of the pressure coefficients around the block for a total jet velocity V_{aw} = 22.1 m/s as a function of jet aeration.

Mean pressures are maximum at the stagnation point, where velocity is zero and the transformation from kinetic energy is maximum. At the bottom of the pool, mean pressures as a function of the radial distance from jet centerline form a bell-shaped distribution, which is similar to observations by Ervine et al (1997), Bollaert and Schleiss (2005) and Federspiel (2011). Also pressure fluctuations are maximum at stagnation and seem to decrease exponentially. The reduction of the pressures with the distance from centerline is a consequence of the lateral deflection that creates a wall jet parallel to the bottom. It is interesting to note that the pressures at the bottom close to the fissure at PB4 are lower than the pressures inside the fissures. Results of both mean pressures and variations inside the fissures show almost constant values.

Aerated jets generated lower mean pressures and fluctuations. This statement was confirmed by the observations in all the measurement positions of the block, except close to the stagnation point where the results are less clear. According to Ervine and Falvey (1987), the reduction of the mean pressure values is due to the presence of air bubbles in the shear layer limiting the jet diffusion zone, and should correspond to the reduction of the kinetic energy of the jet due to air entrainment. Nevertheless, their statement corresponds to total air entrainment, which is composed by jet air entrainment and air entrainment at impact on the plunge pool water surface. In this study, it was not possible to account with air entrainment at the plunging point.

The pool depth is an important parameter to determine if the incoming jet impacts the bottom completely developed or with a remaining solid core. At the point of impact with the bottom, core jets produce mean pressures that are independent from the pool depth. Ervine et al (1997) obtained, for core jets, mean C_p values of 0.86. Core jet impact remained until a pool depth of $4D_i$. Other experimental studies indicate that core jet impact is observed for pool depths varying between 4 D_i and 6 D_i.(Bollaert and Schleiss, 2003; Federspiel, 2011).

Coefficients C_p and C'_p were plotted as a function of the normalized pool depth Y/D_i for 4 positions of the block: stagnation, PB4, vertical fissure and horizontal fissure (Figure 4). Mean values of the 4 transmitters were considered inside each fissure because of its almost constant behavior. For this analysis, non-aerated jets were considered.

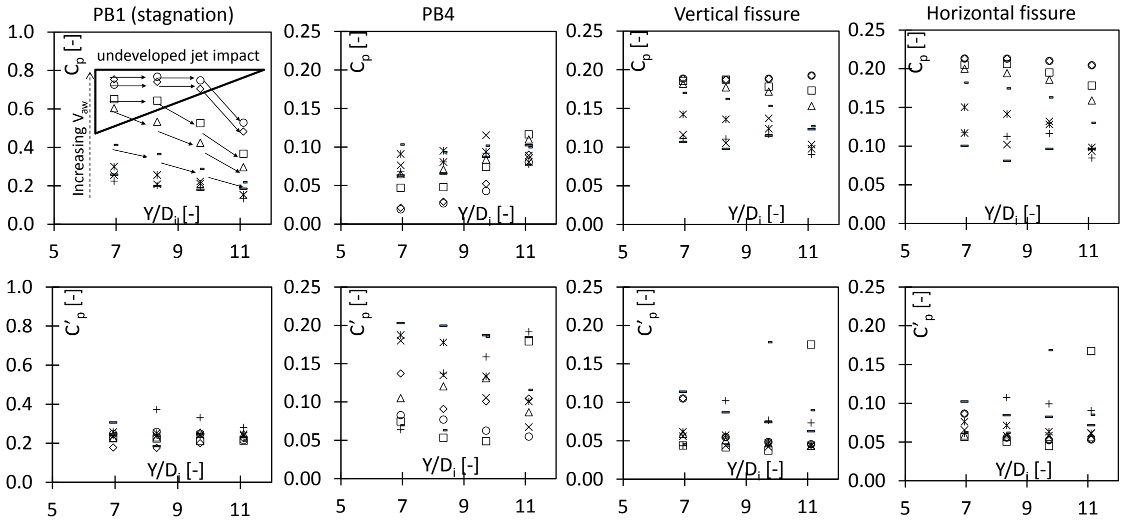

Figure 4 Mean pressure coefficient C_p (above) and RMS pressure coefficient C'_p (below) as a function of normalized depth Y/D_i in different positions of the block. (—): jet velocity = 2.5 m/s; (x): jet velocity = 4.9 m/s; (+): jet velocity = 7.4 m/s; (*): jet velocity = 9.8 m/s; (-): jet velocity = 12.3 m/s; (Δ): jet velocity = 14.7 m/s; (□): jet velocity = 17.2 m/s; (◊): jet velocity = 19.6 m/s; (○): jet velocity = 22.1 m/s.

At stagnation, an undeveloped jet impact pattern can be seen. The limit between core jet and developed jet impact seems to be a function of Y/D_i and also of the impact velocity V_{aw}, instead of a constant value of Y/D_i. This indicates that jets of different kinetic energies entering the pool dissipate also differently.

Mean pressures at PB4 are consistently lower than the pressures inside the fissures. The formation of a wall jet inverts the results at this position, so that high-velocity jets generate lower C_p values. On the other hand, pressure oscillations at PB4 are higher than those in the fissures. Finally, inside the fissures, the pool depth had little influence on the dynamic pressure data, where jet velocity seems to be the most important parameter.

3.2 Frequency domain analysis

Power Spectral Densities of the pressure signals were computed using a Welch periodogram, by means of a routine developed on Matlab© environment. Computations were run with a 50 % overlapping, a Hamming window and a maximum of 3 x 65'536 samples (196'608 samples) acquired at 1 kHz and cut into 64 blocks. The procedure transforms pressure data in the time domain into the data representation in the frequency domain. The eigenfrequency of the three-dimensional fissure was measured experimentally by Federspiel (2011) and is 7 Hz.

Figure 5 (left) shows the results for the jet of maximum tested velocity (V_{aw} = 22.1 m/s) and selected positions around the block for the maximum tested aeration (β = 23%). Plunge pool depth was 0.80 m, corresponding to a ratio Y/D_j of 11. A typical developed jet behavior can be seen with a first rather constant region of the spectral contents up to around 20 Hz, followed by a roughly -5/3 linear decrease in the logarithmic scale. The transducers on the top of the block can be easily distinguished with higher spectral energies. The remaining 4 transducers inside the fissures are packed together in a narrower band, which shows a frequency filtering of pressures that enter the joints.

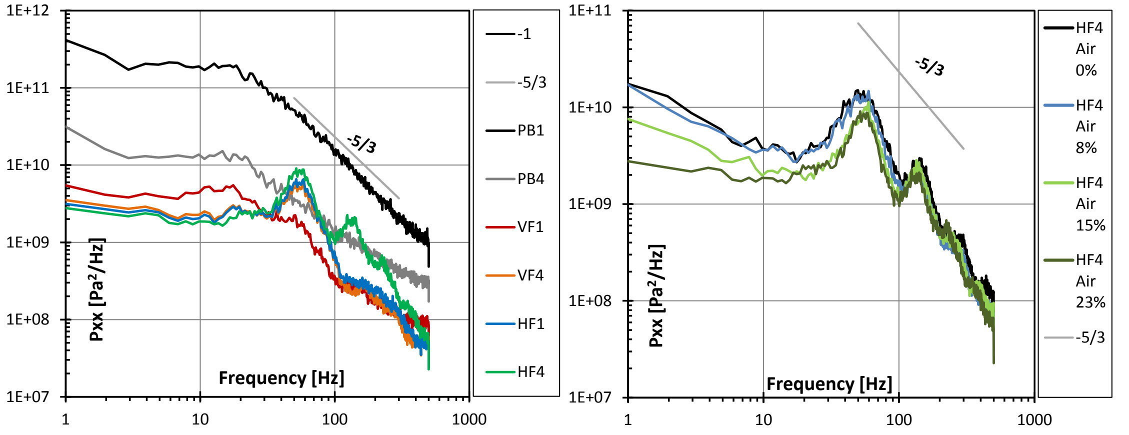

Figure 5 PSD plots using Welch periodogram. Jet velocity V_{aw} = 22.1m/s. Left: All positions for jet aeration β = 23%. Right: All aeration tests for HF4. Measurement points according to Fig. 3.

Lines from transducers belonging to the vertical fissure are colored in red and orange, while those from the horizontal fissure are colored in blue and green. Local peaks appear at harmonic frequencies, the first one is the most important at around 58 Hz. This local peak is more pronounced the closer the transducer is to the center of the horizontal fissure, being HF4 the most concerned. This feature is likely to be due to resonance effects inside the joints and the symmetry of the test configuration. The PSDs at the position HF4 for all aeration values were plotted in Figure 5 (right). It can be seen that the spectral contents are very similar but show a slight diminution with aeration. This is in accordance with the reduction of C_p’ shown in Figure 3 at HF4. Nevertheless, local peaks and slope changes are verified in a similar way for the 4 jets.

4 CONCLUSIONS

Circular high-velocity jets were reproduced, impinging vertically into a pool. At the bottom of the plunge pool, a highly instrumented metallic cube was inserted into a cavity represented a rock block surrounded by a 3D open joint. Dynamic pressures were obtained at 12 positions around the block, being 4 at the water-rock interface and 8 inside the fissures. The jets were aerated using a compressed air system. Jets with the same total velocity and different mean apparent densities were compared.

Results show that jet aeration effectively reduces mean pressures and fluctuations. This statement was confirmed for all the positions on the block, except for stagnation. Results of tests with different pool depth show that the limit between core jet and developed jet impact seems to be a function of jet velocity and the normalized pool depth, instead of a constant value of Y/D_i which indicates that jets impinging with different kinetic energies dissipate also differently in the plunge pool. Local peaks identified in the spectral densities of the pressure signals show that open 3D joints are subject to pressure wave resonance effects and amplification.

This paper presents current results of a broader research on rock scour analysis that has the objective of understanding the effect of air entrained by water jets on dynamic pressures around an embedded block. In that context, air concentration, bubble count and local velocities in different points of the plunge pool were also assessed and are part of a companion paper by Duarte (2013).

ACKNOWLEDGEMENT

This research project is funded by the Fundação para a Ciência e a Tecnologia (FCT, Portugal, Grant No. SFPH/BD/51074/2010).

References

Bollaert E.F.R.; Schleiss A.J., 2003. Scour of rock due to the impact of plunging high velocity jets Part I: A state-of-the-art review, Journal of Hydraulic Research, Vol.41, N° 5, pp. 451-464, 2003.

Bollaert E.F.R.; Schleiss A.J., 2005. Physically based model for evaluation of rock scour due to high-velocity jet impact, Journal of Hydraulic Engineering, 131(3), 153-165.

Duarte, R., Bollaert, E., Schleiss, A., Pinheiro, A., 2012. Dynamic Pressures around a Confined Block Impacted by Plunging Aerated High-Velocity Jets, Proceedings of the 2nd European IAHR Congress, 27-29 juin 2012, Munich, Germany

Duarte, R., (2013). Air Concentrations in Plunge Pools Due to Aerated Plunging High-Velocity Jets and Dynamic Pressures in Underlying Fissures, Proceedings of the 35th IAHR World Congress, 8-13 Sept. 2013, Chengdu, China

Ervine, D.A.; Falvey, H.T., 1987. Behavior of Turbulent Water Jets in the Atmosphere and in Plunge Pools, Proceedings of the Institution of Civil Engineers, Part 2, pp. 295-314.

Ervine, D.A.; Falvey, H.T.; Withers, W., 1997. Pressure Fluctuations on Plunge Pool Floors, Journal of Hydraulic Research, Vol. 35, N° 2, pp. 257-279.

Federspiel, M.P.E.A., 2011. Response of an embedded block impacted by high-velocity jets. Communication 47, Laboratory of Hydraulic Constructions, Ed. A. Schleiss, LCH-EPFL, Lausanne, ISSN 1661-1179.

Manso, P.; Bollaert E.F.R.; Schleiss A.J., 2009. Influence of Plunge Pool Geometry on High-Velocity Jet Impact Pressures and Pressure Propagation inside Fissured Rock Media, Journal of Hydraulic Engineering, Vol. 135, No. 10, October 1, 2009.

Schleiss, A.J., 2002. Scour evaluation in space and time - the challenge of dam designers, Proceedings of the International Workshop on Rock Scour due to High-Velocity Jets, Lausanne Switzerland, 25-28 September 2002, Swets & Zeitlinger