DYNAMIC PRESSURES AROUND A CONFINED BLOCK IMPACTED BY PLUNGING AERATED HIGH-VELOCITY JETS

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Abstract

The impingement of high-velocity water jets on unlined plunge pools causes scour on the rock foundations. The scour process is the result of complex physical phenomena that happen consecutively. Turbulence and dynamic pressures play a major role, especially in the jet development during air travel, in the diffusion process in the pool, in the pressure fluctuations in the water-rock interface and in the pressure propagation inside rock fissures.

Air entrainment significantly influences the whole process. Air bubbles in the plunge pool influence energy dissipation by counter-acting the flow. The bubbles may also enter rock fissures, where they will change properties of pressure wave propagation and amplification. Air is entrained in the jet during the air trajectory and also in the plunge pool at impact. These phenomena cannot be reproduced in Froude-based reduced-scale models without important scale effects.

The present research aims at assessing the influence of air entrainment on dynamic pressure fluctuations caused by impinging high-velocity jets. Near-prototype jet velocities and pressures were reproduced experimentally. A cubic metallic block representing an element of the fissured rock was conceived to measure dynamic pressures at 12 different positions. Plunge pool water depths varied from 0 to 80 cm, while jet velocities varied from 2.5 to 22.1 m/s. Jet aeration was provided by 6 openings in the jet nozzle.

The results confirm that mean pressures and pressure fluctuations are reduced with air entrainment. The conclusions provide relevant elements for future research on the influence of air entrainment on high-velocity jets for scour assessment.

Introduction

In the design of hydraulic structures, exceeding incoming discharges are often released downstream by the creation of water jets. It might be the most suitable solution, especially in the case of high head dams or where chute spillways represent a high cost of construction. These jets impinge in the plunge pool and carry a large amount of energy, and its correct and safe dissipation is of crucial concern for hydraulic engineers.

If the quality of the foundations allows and the plunge pool is chosen to be unlined, scour of the rock will often occur. Correctly assess its development is of great importance for the safety of the structure.

Rock scour due to water jets is caused not only by the mean pressures applied on the water-rock interface, but is also influenced by its variations. Bollaert and Schleiss (2003) provided broad reviews on rock scour due to high-velocity water jets. Bollaert (2002) and Bollaert and Schleiss (2005) carried out comprehensive experimental researches with near-prototype jet velocities and proposed a physically-based method that considers fully transient pressures.

Plunge pool rock scour is a function of the three phases involved in the process: water, rock and air (Bollaert, 2002). Although developments have been made to correctly describe rock scour development, the influence of the air concentration is still a question of debate.

Jet air entrainment and air bubbles dissipation in the plunge pool were studied in works such as those of McKeogh and Ervine (1981) and Chanson et al. (2004). One of the first experimental studies to determine the effect of air content on plunge pool scour was performed by Mason (1989). Canepa and Hager (2003) investigated the scour created by an inclined jet impinging on a pool whose bottom consisted of sediments. Pinheiro and Melo (2008) studied the effect of aeration on hydrodynamic force on lined plunge pool floors.

The ongoing research project aims at a comprehensive description of the dissipation of the air entrained by high-velocity jets in the plunge pool and its influence on the dynamic pressures on the pool bottom and inside rock fissures.

This paper presents the first results of experiments with passively aerated high-velocity jets and comparison with non-aerated jets and provides useful conclusions and recommendations for further research in the field.

Theoretical aspects

Rock scour due to plunging water jets is a complex phenomenon, composed by a series of complex processes that occur consecutively. The resulting plunge pool geometry evolution is the result of physical-mechanical interactions between three phases involved in the process: Water, air and rock. Figure 1 shows a sketch of the processes that take place from jet issuance to the flow of water and the segregated rocks downstream.

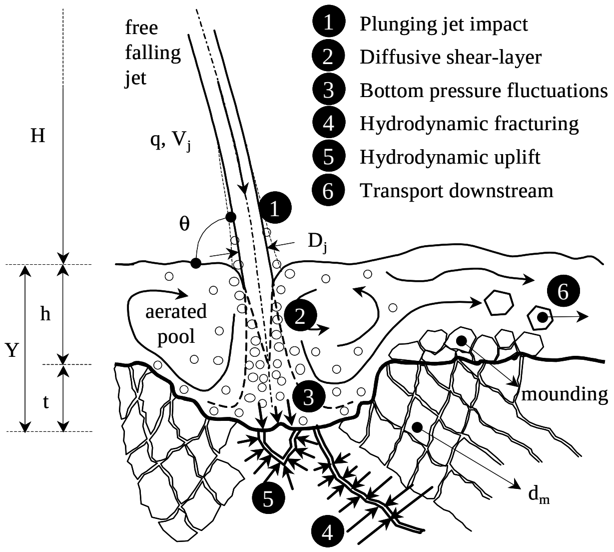

Figure 1: Main parameters and physical-mechanical processes (Bollaert, 2002)

The parameters at jet issuance and the physical processes during the jet trajectory in the air determine the plunging conditions of the jet in the plunge pool. The main parameters at the point of impact are the jet diameter *Dj*, jet velocity *Vj*, and the angle of impact *θ*. In addition to the void fraction of the jet, a large amount of air enters the plunge pool at the moment of impact.

Jet diffusion takes place in the plunge pool. It is a function of the pool depth *Y*. More precisely, the jet is said to be completely developed if the ratio $Y/D_j > 6$, or the core of the jet persists if $Y/D_j > 4$, a transition zone exists between these values.

Pool geometry might induce currents and laterally confine the jets (Manso, 2006; Manso et al. 2009) which contributes or opposes erosion and should also be considered. Also air bubbles entrained in the moment of impact tend to rise back to the surface, in opposition to the flow of the water and contributing to energy dissipation.

Diffusion in the plunge pool dissipates a part of the energy of the jet. The exceeding energy is responsible for the dynamic pressures that are applied over the pool bottom. Of great importance are the geomechanic characteristics of the rock foundations, the joint network patterns and fissures' dimensions. Pressures applied on the bottom of the plunge pool propagate through the rock fissures. Bollaert (2002) showed that pressure wave oscillation and superposition in fissures may lead to pressure amplification. The influence of air inside rock fissures is still question of debate.

Eventually, fissures will propagate until they are completely open. This means that they form a rock block, which can be ejected as a result of the integration of the pressures on its top and through the fissures and the resistance against the displacement. Both for the propagation of fissures and for block ejection, Bollaert's (2002) work showed the importance of considering pressure fluctuations instead of only mean pressures.

Influence of air entrainment

Air bubbles penetrate the plunge pool, whether due to air entrainment during the trajectory through the atmosphere, whether due to air entrainment at the point of impact with the pool. Buoyancy determines that air bubbles have the tendency to flow to lower pressure zones. In other words, air bubbles tend to rise back to surface. At the plunge pool, this property counter-acts the main flow, contributing to energy dissipation.

Air bubbles are trapped in the turbulent eddies at the entrance of the pool and are dragged towards the bottom. Eventually, a state of equilibrium establishes and the air bubbles are deflected radially and then rise back to surface. Thus, a large amount of air bubbles is often verified near the surface, which is not the case throughout the whole pool depth.

In prototype conditions of jet velocity and pressures, it is likely that if air bubbles are transported to the water-rock interface, although bubble sizes will be considerably small due to air compressibility.

Mason (1989) performed model tests and derived one of the first empirical formula for scour estimation considering air entrainment:

$$\mathrm{Y} = 3.39\,\frac{(1+\beta)^{0.3} q^{0.6} h^{0.16}}{g^{0.3} d^{0.06}} \tag{1}$$

where the depth of scour below the tailwater level Y (Figure 1) is dependent on the tailwater depth *h*, the specific discharge *q*, the gravitational acceleration *g*, the characteristic sediment size *d* and the ratio β between air discharge Q_a and water discharge Q_w.

$$\beta = \frac{Q_a}{Q_w} \tag{2}$$

Melo (2002) showed that mean impact pressures are reduced with increasing air content in the pool. Canepa and Hager (2003) propose that scour on a granular pool bottom is dependent on a densimetric Froude number F_β that takes into consideration the three phases, air, water and sediment

$$F_\beta = \mathrm{V}\frac{(1+\beta)^{0.25}}{(g'd_{90})^{1/2}} \quad (3)$$

Where V is the water velocity and g' is the reduced gravitational acceleration, function of the densities of the fluid ρ and of the sediment ρ_s:

$$g' = \frac{\rho_s - \rho}{\rho} g \quad (4)$$

These authors analyzed the influence of the initial air content of the jet on the evolution and final extent of scour and confirmed a reduction of the erosion.

Experimental apparatus

Bollaert (Bollaert 2002; Bollaert and Schleiss 2005) implemented a large experimental facility in the Laboratory of Hydraulic Constructions of the Ecole Polytechnique Fédérale de Lausanne, capable of reproducing near-prototype high-velocity jets impinging on a plunge pool. The comprehensive research to correctly describe the mechanisms of rock scour was then followed by Manso (2006) and Federspiel (2011).

Currently, the experimental set-up (Figure 2) consists of:

- A 3 m diameter cylindrical basin in steel reinforced Lucite that simulates the plunge pool. The height of the basin is 1 m. The water level in the pool is adjusted by the insertion of flat plates in the outlet device.
- The pool bottom simulates open 3D joints and is represented by two metallic components: a "measurement box", that contains a cavity where a highly instrumented block, or "intelligent block" is inserted (Federspiel et al, 2009). This cavity has a length of 202 mm, a width of 202 mm and a height of 201 mm. The "intelligent block" has a cubic shape of 200 mm side. Between the "measurement box" and the "intelligent block", a 3-dimensional fissure of 1 mm width is so created.
- A 63 m head pump that provides the required energy for the jet through a 300 mm diameter water supply conduit.
- A cylindrical jet outlet system (nozzle) at its end, that models the jet. The jet outlet diameter is 72 mm.

Passive aeration of the jets is obtained by the insertion of 6 aluminium tubes from where the outside air is dragged by the high-velocity jets flow inside the nozzle (Figure 3).

Instrumentation

The measurement equipment for the tests consisted of:

- For measurement of the quantity of air entrained in the jet through the aluminium tubes, a hot-wire anemometer type Testoterm Testo 491 was used to assess approaching air velocities in a tube of 12.5 cm diameter. This device has a precision of ± 0.05 m/s
- For each test run, 12 pressure transducers simultaneously record the pressures around the block. The transducers are KULITE HKM-350M-17-BAR-A micro pressure sensors. 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).
- 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.

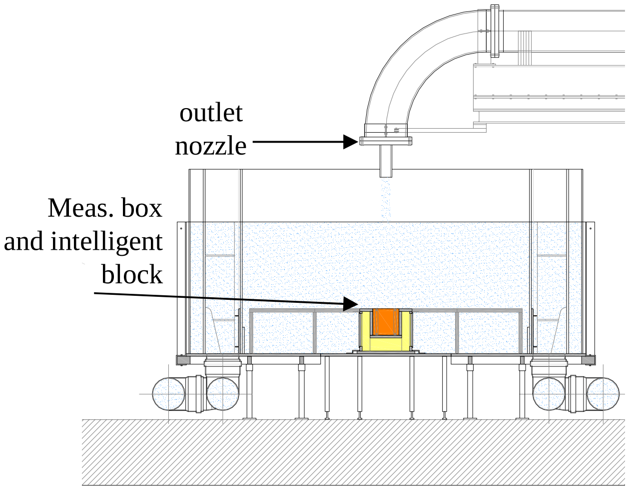

Figure 2: Side view of the experimental facility (Federspiel et al. 2009)

Figure 3: Photos of the nozzle with aluminium tubes installed for air entrainment. In the left, flexible tubes for measurement of entrained air

Test program

The water level in the plunge pool varied from zero to 0.80 m, thus producing core jets and developed jets. Jet velocities ranged from 2.46 to 21.10 m/s. These configurations were repeated without the passive aeration system for values of Y from 0.50 to 0.80 m. The jet impingement position was in the center of the block. The block was kept unable to move.
The results of pressure measurements were analyzed by the use of the following non-dimensional parameters:

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

$$C_p' = \frac{\sigma}{V_j^2/2g} \qquad (6)$$

$$C_p^+ = \frac{P_{max} - P_{mean}}{V_j^2/2g} \qquad (7)$$

$$C_p^- = \frac{P_{mean} - P_{min}}{V_j^2/2g} \qquad (8)$$

where P_{atm} is the atmospheric pressure, and P_{mean} is the mean value, P_{max} is the maximum value, P_{min} is the minimum value, and σ is the RMS value of the pressure fluctuations.

Table 1: Summary of the test configurations

Y [m]	Y/D_j	Jet develop.	V_j [m/s]	Air supply
0.00	0.00	core jet	2.46 to 21.10	yes
0.10	1.39	core jet	2.46 to 21.10	yes
0.50	6.94	developed jet	2.46 to 21.10	yes and no
0.60	8.33	developed jet	2.46 to 21.10	yes and no
0.70	9.72	developed jet	2.46 to 21.10	yes and no
0.80	11.11	developed jet	2.46 to 21.10	yes and no

Experimental Results and Discussion

The passive aeration system provided important air discharge to the jet. It was an almost linear function of the water jet discharge. Figure 4 presents the obtained linear trend of air discharge, as well as the corresponding air-water ratio b, as a function of the water jet discharge.

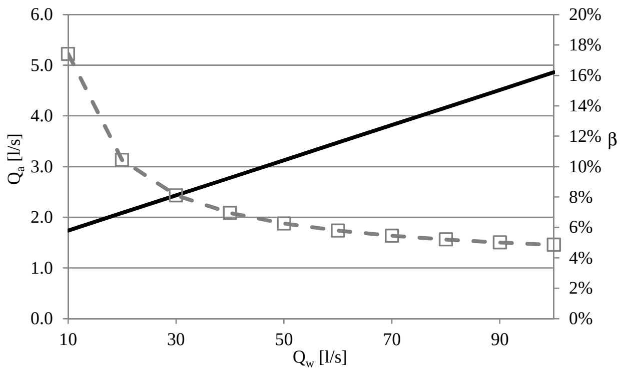

Figure 4: Passively entrained air discharge (black line) and air-water ratio (dashed grey line) as a function of the water jet discharge

Air bubbles were very small near the bottom around the jet, in the center of the pool, where they were similar to a mist or fog. The wall jet flow and buoyancy effects then made air bubbles to flow radially towards the external walls of the pool, and then to the water surface. It was clear the change in size of the bubbles while they migrate to lower pressure zones.
Figure 5 shows scaled plots of *Cp* and C_p' measured around the intelligent block, where red bars show tests without air and blue bars show tests with air. The typical behavior of these parameters is seen: On the pool bottom, (top of the block) both are maximum at stagnation, and decrease with radial distance from the jet axis. Then, in the fissures, both develop a quasi-constant behavior, at a value that is higher than the hydrostatic pressure. Values of C_p were higher for tests without air entrainment, in particular at stagnation and inside the fissures. Values of C_p' were higher for tests without air entrainment inside the fissures.

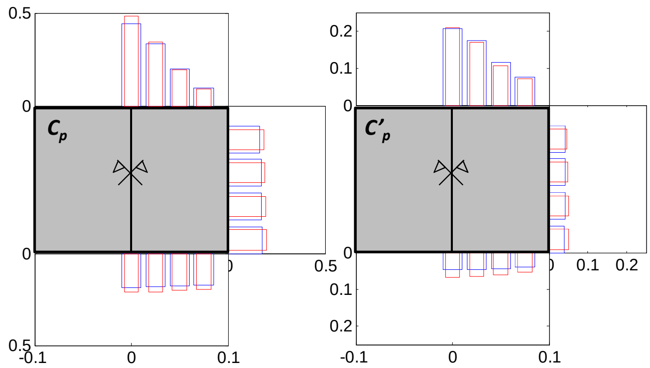

Figure 5: Scaled plots of *Cp* and C_p' around block. *Y/D*$_j$=11.11; V_j = 19.65m/s. Red: without air. Blue: with air.

It is interesting to notice that the fourth transducer in the pool bottom measured values of C_p consistently lower than those seen in both fissures. This is certainly due to a release in pressure after the creation of a wall jet.

The general behavior as a function of V_j can be seen in Figure 6, that shows results of aerated tests for Y/D_j = 6.94. Curves for V_j = 2.46 m/s and V_j = 21.14 m/s are highlighted in black, while the intermediate values are in grey.

At stagnation, C_p values are maximum and increase with V_j. The behavior tends to reverse with radial distance from the jet axis and the higher velocities show lower C_p values close to the joint entry. C_p values inside the joints are almost constant and increase with V_j.

The opposite situation can be seen for the three other parameters: values of C_p', C_p^+ *and* C_p^- vary inversely with V_j. Inside the joints, C_p' decreases apparently in an asymptotic manner with V_j. A similar pattern is seen for C_p^+ *and* C_p^- .

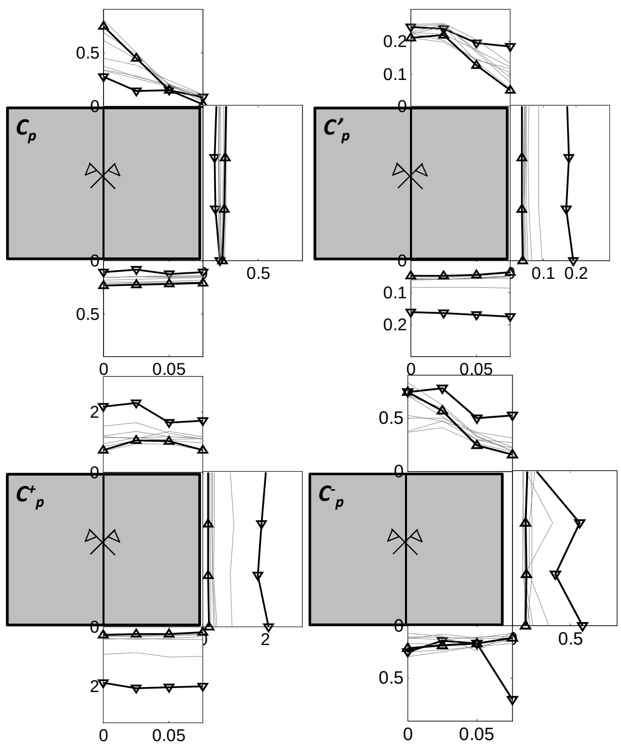

Figure 6: Scaled plots of Cp, C_p', C_p^+ *and* C_p^- for all V_j around block. Downward triangle: V_j = 2.46 m/s. Upward triangle: V_j = 21.14 m/s. Intermediate values in grey. Aerated test, Y/D_j = 6.94.

Spectral content

Power Spectral Densities - PSD were obtained by means of a FFT algorithm using WELCH periodogram computed in 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 Spectral Density Pxx can be understood as the relative energy of each frequency range and so highlights the dominant frequencies. Obtained PSDs for tests with and without passively entrained air are shown in Figure 7.

In the PSD graphs it is possible to notice that the four transducers in the top of the block possess higher spectral energy. The corresponding lines are easily recognizable, and follow roughly a 5/3 slope decrease, especially for frequencies higher than 10 Hz. The transducers inside the joints have closer spectral densities, and are almost indistinguishable in the graphs. They tend to follow a -1 slope decrease. They present a local peak on 100 Hz < f < 200 Hz, more precisely around 145 Hz, and the closest to the symmetry axis on the bottom of the block the more pronounced the peak. Federspiel (2011) found a similar pattern, for which a physical explanation is under investigation.

The PSD plots for tests with and without passive air entrainment show very similar results, with aerated tests showing slightly higher values.

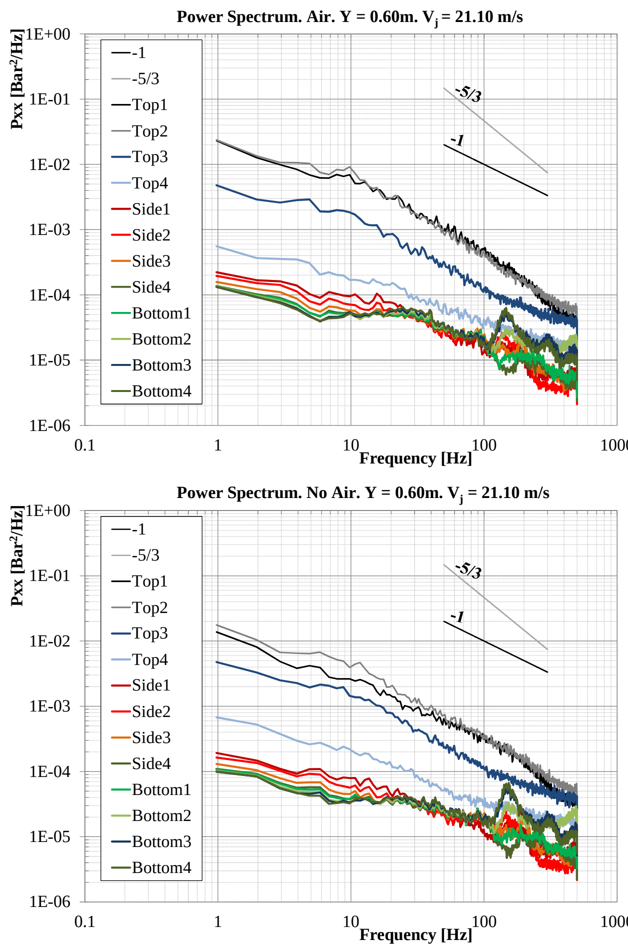

Figure 7: PSD plots for developed jets, with entrained air (top) and without entrained air (bottom).

Conclusions and recommendations

Experiments have been performed to assess dynamic pressures around a block positioned on the bottom of a plunge pool submitted to vertical high-velocity impinging water jets with and without passive air entrainment. The air entrainment system used consisted of the introduction of 6 aluminium tubes in the jet nozzle to allow outside air to be dragged by the high-velocity water flow inside the nozzle. This system was efficient to entrain an air discharge to the jet which was a linear function of the water discharge. The jet impingement position was in the center of the block, which was kept unable to move.

Results show that, regarding jet velocities under near-prototype conditions, the passively aerated jets generated lower mean pressures and pressure oscillations on the top and inside the fissures around a block. The obtained spectral contents were very similar, with aerated tests showing slightly higher values.

Impinging jets represent a more realistic situation in the field of hydraulic engineering and dam design. Nevertheless, it is not possible to assess the total air discharge entrained in the plunge pool with the aeration system that was used. Although air entrained in the jet during the travel between the nozzle and the water surface in the pool can be neglected in this case, there is an important amount of air entrained in the plunge pool at impact that remains unknown.

This paper presents the first findings of a broader research that aims at assessing the influence of jet aeration in a comprehensive and physically-based manner. Future developments will consider the measurement of void fraction, air bubble rate and chord length in different positions in the plunge pool, as well as the use of submerged jets for a better knowledge of the total entrained air.

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