Dynamic Response of a Rock Block in a Plunge Pool due to Asymmetrical Impact of a High-velocity Jet

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Abstract: *Flood release structures of high-head dams generate high-velocity plunging jets. These may scour the downstream rocky riverbed and even damage the dam foundation. Assessment of the scour evolution is essential to ensure the safety of the dam and appurtenant structures, as well as to guarantee the stability of its abutments.*

In the framework of a research project, near-prototype scaled experimental installation generating high-velocity jet impact in a plunge pool has been equipped with an artificial rock block.

Pressure fluctuations over and under the block as well corresponding block movements are recorded for a jet impacting at the block upper face. The jet impact is situated along one of the block side faces, resulting in asymmetrical jet impact conditions. The analysis focuses on the reponse of the block due to the water pressures acting above the block and inside the fissures surrounding for both core and developed jets.

Keywords: *rock scour, block movement, high-velocity water jets and plunge pool*

1. INTRODUCTION

A large-scale experimental facility has been built at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). This facility reproduces high-velocity plunging water jets and their turbulent pressure fluctuations that develop inside artificially generated rock joints (Bollaert, 2002). Between 1998 and 2006, the facility has been used to perform two PhD research projects. The first one studied the behaviour of a plunge pool with a flat bottom and 1- or 2-dimensional fissures for different fissure geometries (Bollaert, 2002). The second one studied different plunge pool geometries (lateral confinement) with different diameter and depths of the scour zone related to a simple 1-dimensional fissure (Manso, 2006).

One of the main finding obtained by this experimental facility is the amplification of pressure fluctuations inside rock joints. This amplification is due to the two-phase character of the air-water mixture inside the joints, which allows pressure wave reflection, amplification and even resonance. The pressure fluctuations inside the simulated rock joints are caused by the pressure excitation of the jet at the joint entrance. This excitation depends not only on the form of the plunge pool and the associated macro-turbulent flow pattern, but also on the rock joint geometry. The above mentioned rock joints were of simple shapes, i.e. 1-dimensional or simplified 2-dimensional geometries.

Real rock joints, however, have a much more complex geometry and are often interconnected (3-dimensional configuration). The basic geometrical parameters (thickness and shape of the joint, angle between the joint and the water jet, connections between the joints, etc.) influence the dynamic pressures generated by the water jet inside the joint. Assessment of the influence of these parameters on block uplift is the topic of an ongoing PhD research project. Furthermore, plunge pool aeration and joint aeration may also influence the pressures and their transient propagation inside the joints are studied in parallel.

2. EXPERIMENTAL FACILITY AND DATA AQUISITION

2.1. Experimental Facility

A 300 mm diameter water supply conduit with a cylindrical-shaped jet outlet models the free falling jet (Figure 1). Due to constructive limitations, the supply conduit has a 90° bend just upstream of the jet outlet system. The end of the water supply conduit has been equipped with a 72 mm diameter (internal) cylindrical nozzle. The inflow conditions are symmetrical.

The plunge pool is simulated by a 3 m diameter cylindrical basin in steel reinforced Plexiglas with a height of 1.4 m. The maximum distance between the nozzle outlet and the plunge pool bottom is 1.0 m. The bottom of the basin is made of a rigid steel frame, covered by a 10 mm opaque Plexiglas plate. Inside the basin, two rectangular boxes (overflow boxes) made of opaque Plexiglas adjusts the water level by a flat plate that is inserted. A restitution system consisting of four conduits of 220 mm diameter simulates the downstream conditions. These conduits are connected to the overflow boxes and conduct the water into the main reservoir of the laboratory (volume: 800 m^3). The 63 m head pump is situated in the main reservoir of the laboratory, from which the water is pumped into the supply conduit. After being transferred through the restitution conduits, the water returns to the main reservoir. A closed water circulation system is so obtained. The maximum discharge is 120 l/s, which corresponds to an average jet outlet velocity of about 30 m/s.

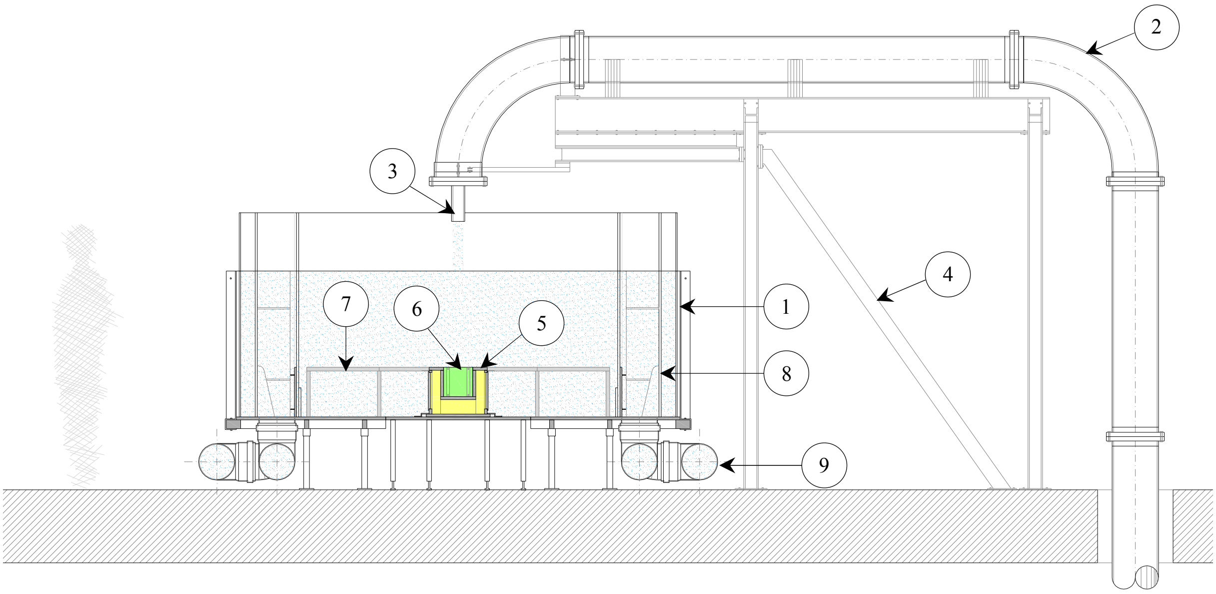

Figure 1: General view of the experimental facility (transversal section): (1) plunge pool, (2) water supply conduit, (3) outlet nozzle, (4) supporting steel structure, (5) measurement box, (6) highly instrumented block, (7) new plunge pool bottom, (8) overflow boxes and (9) water restitution system.

The measurement box represents the rock foundation. It's a structure composed of steel plates (Figure 2). The dimensions are 402 mm of length, 402 mm of width and 340 mm of height. The thickness of the steel plates is 20 mm. Inside this box, a large series of cavities allow to insert pressure and displacement transducers. All cavities are interconnected. To allow manipulation inside these cavities (i.e. modify the transducers position), all lateral walls have a 250 mm movable lid. The walls near the highly instrumented block are pre-perforated allowing to change the pressure transducers position. This allows to measure the water pressure generated by the jet inside the joint between the block and its surroundings, as well as to measure the corresponding displacement of the block. The box is impermeable to protect the electrical equipment.
In the centre of the measurement box, a large cavity allows inserting the highly instrumented block. The highly instrumented block represents a single rock block in the rock mass with one degree of freedom (vertical movements). The cavity has a length of 202 mm, a width of 202 mm and a height of 201 mm. The block has a cubical shape with a side length of 200 mm. The width of the steel plates has been optimized to have a density similar to real rock (2'400 - 2'500 kg/m^3). On the top of the block, some holes have been pre-perforated to fix the pressure transducers. Between the measurement box,

and the block, a 3-dimensional fissure of 1 mm width is so created.
In total, 95 different positions are available for pressure transducer insertion. For the acceleration transducer and for the displacements transducer, however, the positions are fixed. Inside the block, pressure and vibration transducers have been inserted to measure the pressure at the pool bottom under high-velocity jet impact and to measure the vibration of the block. On the outside walls of the block, eight vertically oriented guide plates have been constructed. These guide plates (eight contact points with the measurement box) limit the degree of freedom of the block to vertical movements only.
Finally, both the measurement box and the block have been placed inside the 3 m diameter cylindrical basin which simulates the plunge pool (Figure 2 on the left).

Figure 2: Left: Measurement box and highly instrumented block insert into the cylindrical basin which simulates the plunge pool. Right top: Highly instrumented block is being inserted into the centre cavity of the measurement box. Right bottom: Highly instrumented block is fully installed inside the measurement box.

2.2. Electronic Data Acquisition System

Data acquisition
The data acquisition system consists of a multifunction DAQ (Data AcQuisition) device. The DAQ device is a National Instruments (NI) card type USB-6259 series M. This device is a high-speed multifunctional data acquisition module optimized for superior accuracy at fast sampling rates. This DAQ device is characterized by 32 analog inputs SE (Single Ended) or 16 analog inputs DI (Differential) with a resolution of 16-bit and a maximal acquisition rate of 1,25 MSamples/second. The NI device is driven with author developed software running in the LabVIEW© environment.

Pressure transducers
A series of 12 KULITE HKM-350M-17-BAR-A micro pressure sensors are used for the pressure measurements. 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. A solid state piezoresistive sensing element is located immediately behind this metal diaphragm and is protected by a metal screen. Force transfer is accomplished via an intervening film of non-compressible silicone oil. This sensing sub assembly is welded to a stainless steel body. 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).

Displacement transducers
Two BAUMER AG IWRM 18I9704/S14 displacement sensors are used for displacement measurements. These sensors are of the inductive type, with an absolute measurement range between 0 and 8 mm and a precision of less than 0.005 mm (static) or less than 0.01 mm (dynamic). Due to mounting constraints of the experimental facility the measurement range is only of 5 mm.

Accelerometer transducer
A PCB PIEZOTRONICS^INC 353B14 accelerometer sensor is used for vibration measurements. The sensor is a high frequency quartz shear accelerometer with a measurement range of ±1000g (acceleration of gravity). The sensitivity of the transducer is 5 mV/g and the frequency range is between 1 and 10 kHz. Moreover, it exhibits a very high resonance frequency (> 70 kHz).

3. EXPERIMENTAL PARAMETERS

In the following the results obtained from the measurements for asymmetrical jet impact on the highly instrumented block are presented. For this configuration, the plunge pool bottom was flat and the jet impact point in the plunge pool was centred along one of the block side faces - joint vertical axis (Figure 3).

The Y/D ratio (where Y is the water level in the plunge pool and D is the nozzle diameter) is an important parameter to generate a core jet (Y/D < 4) or developed jet (Y/D > 6). The Y/D ratios between 4 and 6 (4 < Y/D < 6) generate a transition jet. Plunge pool water depths between 0.0 m and 0.7 m (with 0.1 m steps) have been tested. A core jet is generated for plunge pool water depths (Y) 0.0, 0.1, 0.2 and 0.3 m, (Y/D ratios: 0.00, 1.39, 2.78 and 4.17). A transition jet is generated for a 0.4 m water depth (Y/D ratio: 5.56). A developed jet is generated for water depths (Y) 0.5, 0.6 and 0.7 m (Y/D ratios: 6.94, 8.33 and 9.72).

The velocity of the impinging jet is another important parameter to modify the block and the joint solicitation (pressure field in the plunge pool and inside the 3-dimensional joint). Eleven different jet outlet velocities (between 2.5 m/s and 27.0 m/s or between 10 l/s to 110 l/s with 10 l/s steps) have been tested. A 72 mm nozzle has been used (D).

The 12 pressure transducers are mounted within the same vertical plane to reconstruct the pressure field around the block (Figure 3). Four transducers are installed inside the block and measure the pressure at the plunge pool bottom (N°s 309 to 312): the first on the block center (N° 309), the second at 25 mm, the third at 50 mm and the fourth at 75 mm from the block center. Four transducers are installed on one of the vertical walls of the measurement box (N°s 313 to 317): the first at 50 mm from the plunge pool bottom and the following at 50 mm interval. Four transducers are situated underneath the block (N°s 318 to 321): they have the same relative position as the four transducers that are installed inside the block (pressure at the plunge pool bottom). The displacement transducer (D1D and D2D not on the Figure 3) and the accelerometer (ACC) have a fixed position: displacement transducers under the block in measurement box and the accelerometer in the intelligent block.

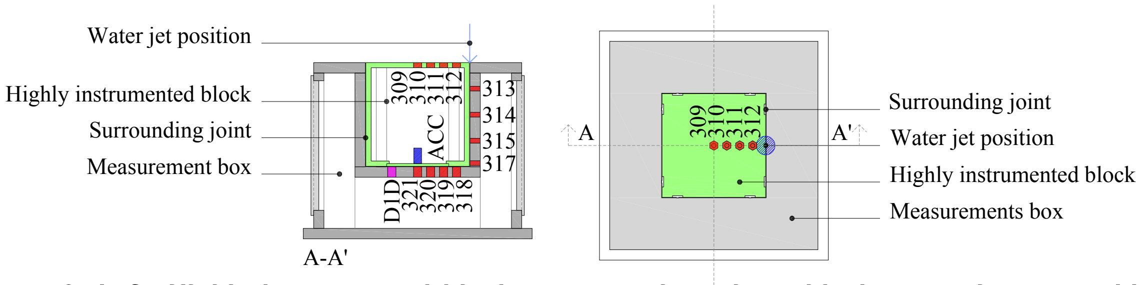

Figure 3: Left: Highly instrumented block transversal section with the transducers position. Right: Jet impact and transducers position on the top of the block (at the plunge pool bottom).

For each water level and jet outlet velocity, three test runs have been performed. The data acquisition frequency was 1 kHz and the recording time was about 65.5 seconds, providing 2^{16} = 65'536 samples for each transducer. For each test run, about 983'040 samples are so being recorded (15 transducers: 12 pressure transducers, two displacement transducers and one acceleration transducer).

4. EXPERIMENTAL RESULTS

Pressure coefficients around the free block

The equations to compute the different dynamic pressure coefficients have been discussed in Federspiel et al. (2009). In the following, the main pressure coefficients (mean pressure C_p, turbulent pressure fluctuation C_p', positive extreme pressure fluctuation $C_p{+}$ and negative extreme pressure fluctuation $C_p{-}$) are commented. The pressure coefficients are illustrated in Figure 4 for all pressure transducers (see Figure 3) and for the highest jet outlet velocity (27.0 m/s or 110 l/s).

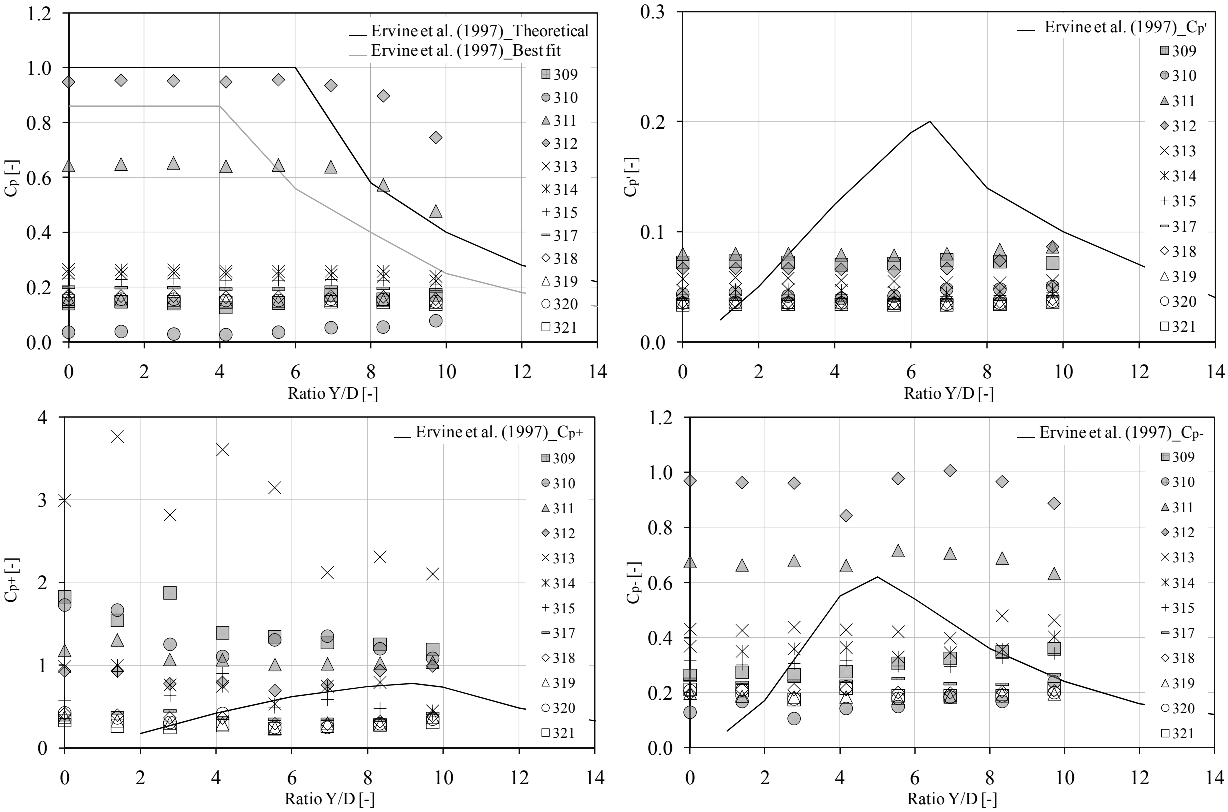

Figure 4: Top left: C_p mean pressure coefficient. Top right: C_p' turbulent pressure fluctuation coefficient. Bottom left: $C_p{+}$ positive extreme pressure fluctuation coefficient. Bottom right: $C_p{-}$ negative extreme pressure fluctuation coefficient.

The *mean pressure coefficient (C_p)* recorded with sensor N° 312, i.e. located directly under the jet axis, is in reasonable agreement with the theoretical curves developed by Ervine et al. (1997) and with previous pressure records made by Bollaert (2002) and Manso (2006). The mean pressure coefficients recorded further away from the jet axis and inside the joint (around the block) are lower than the corresponding coefficients located directly under the jet axis, which could reasonably be expected. The Ervine's curves were developed for transducer situate at the plunge pool bottom and spaced in a radial pattern from the jet axis center. The mean pressure coefficient for transducers situated inside the joint and under the block fluctuates between 0.05 and 0.40 but is very concentrated between 0.15 and 0.35.

The *turbulent pressure coefficients (C_p')* recorded all around the block differ from the theoretical curve developed by Ervine et al. (1997). The higher discharges (> 80 l/s) generated lower coefficient values but the lower discharges (< 30 l/s) generate higher coefficient values. The transducer N° 312 has to follow the Ervine's curve for all discharges but further away from the jet axis and inside the joint lower could be expected. The turbulent pressure coefficient for transducers situate at the plunge pool bottom fluctuates between 0.03 and 0.34. For low Y/D ratios (Y/D < 2), however, the recorded values are slightly higher than the theoretical curves. This curve has a minimal Y/D ratio of 1. The pressure fluctuation coefficient for transducers situated inside the joint and under the block fluctuates between 0.03 and 0.25.

The *positive extreme fluctuation coefficients (C_{p+})* for core jets (i.e. Y/D ratios lower than 4) are much higher than the theoretical curve developed by Ervine et al. (1997) for the transducers positioned along the plunge pool bottom. This curve starts with a Y/D ratio equal to 2. The transducer next to the jet axis (N° 312) provides values close to the unity and follows more or less this curve. The other transducers (N°s 309 to 311) have much higher values compared to the Ervine's curve. For developed jets (i.e. Y/D ratios higher than 4), the measured values are still higher than this curve, although the discrepancies diminish compared to core jets. The positive extreme fluctuation coefficient for the transducers situated inside the joint and under the block (N°s 313 to 321) fluctuates between 0.15 and 4.0. The first transducer at the entrance of the joint (N° 313) shows extremely high values. These might be generated by a slight form of cavitation occurring at the entrance of the rock joint, as it was previously already reported by Bollaert (2002) for 1D rock joints.

The *negative extreme fluctuation coefficients (C_{p-})* for Y/D ratios lower than 2 (a part of core jets) are higher than the theoretical curve developed by Ervine et al. (1997). This curve starts with a Y/D ratio equal to 1. The transducers situate at the plunge pool bottom near the jet axis (N°s 312 and 311) are always higher related to the curve. For Y/D ratios higher than 2 (core, transition and developed jets), the measured values are in good agreement with the Ervine's curve developed. The negative extreme fluctuation coefficient for the transducers situated inside the joint and under the block (N°s 313 to 321) fluctuates between 0.03 and 2.5.

Displacements and accelerations measurements of the free block

Displacement and acceleration measurements were performed at the same time than the pressure measurements. The results for these measurements are illustrated in Figure 5.

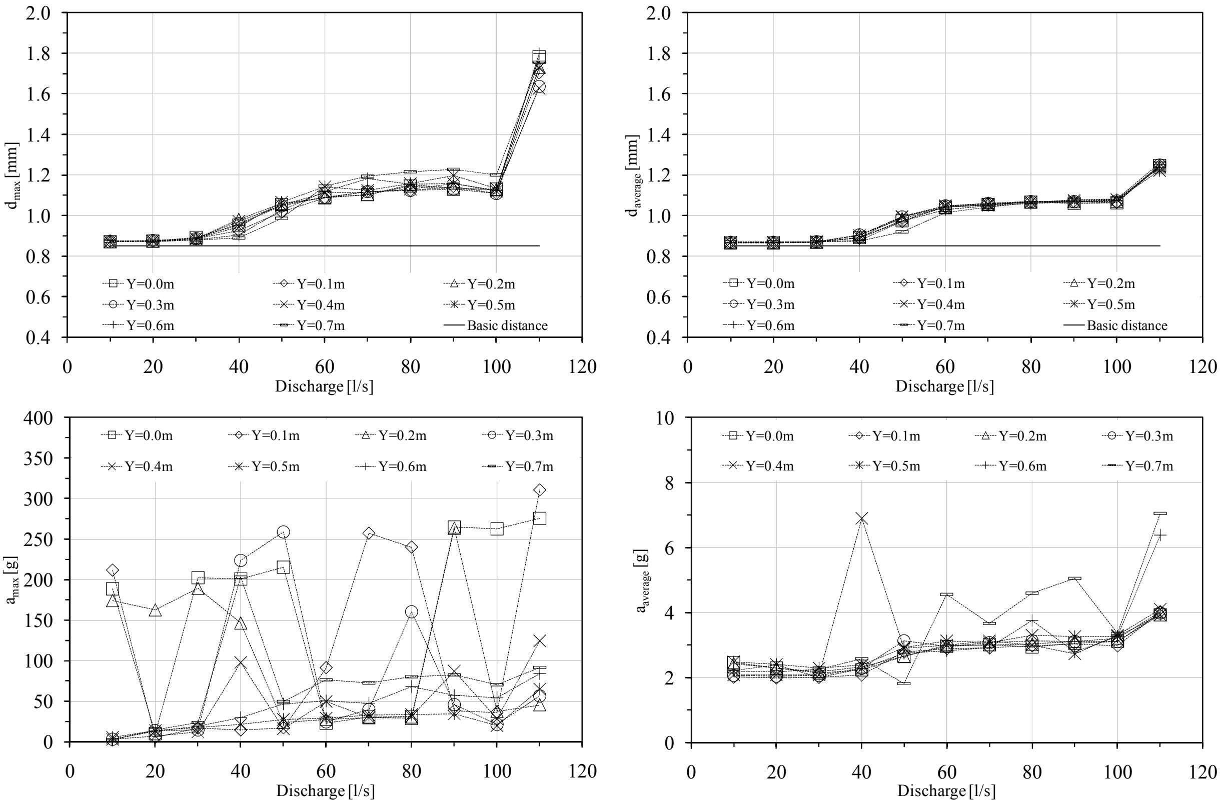

Figure 5: Top left: Maximum vertical displacement. Top right: Average vertical displacement Bottom left: Maximum acceleration. Bottom right: Average acceleration.

The block starts to move vertically (the only degree of freedom of the block) for discharges situated around 30-40 l/s (7.4-9.8 m/s). The displacement increases with the jet velocity to reach a maximum value at the maximum jet velocity (27 m/s). The displacement behaviour is similar for all plunge pool water levels (core, transition and developed jets). The maximum displacement is situated between 1.6 and 1.8 mm. The acceleration measurements show that the largest recorded values are related to a water level less than 0.3 m (core jets). For transition and developed jets the fluctuations of the acceleration values are very small. The average values are quite similar for all water levels.

Power Spectral Density (PSD): comparison between free and fixed block

Pressure fluctuations may also be analyzed by means of a power spectral analysis. Power spectral densities (P_{xx}) are computed using the Welch periodogram method for the Fast Fourier Transforms (FFT) 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. P_{xx} is expressed as a function of frequency *f* and represents the decomposition of the pressure fluctuations with frequency. This allows visualizing the relative importance of each frequency compared to the total spectral content. That has been done in Figure 6 for a core jet (Y = 0.20 m and Y/D = 2.78), in Figure 7 for a transition jet (Y = 0.40 m and Y/D = 5.56) and in Figure 8 for a developed jet (Y = 0.60 m and Y/D = 8.33) where on the left the highly instrumented block is free to move along the vertical axis and on the right the block is fixed for the same jet outlet velocity (V = 24.6 m/s or Q = 100 l/s).

The graphs in Figure 6, Figure 7 and Figure 8 represent a comparison between all pressure transducers and the displacement transducer located directly under the block (D1D) and representative for the movements of the block.

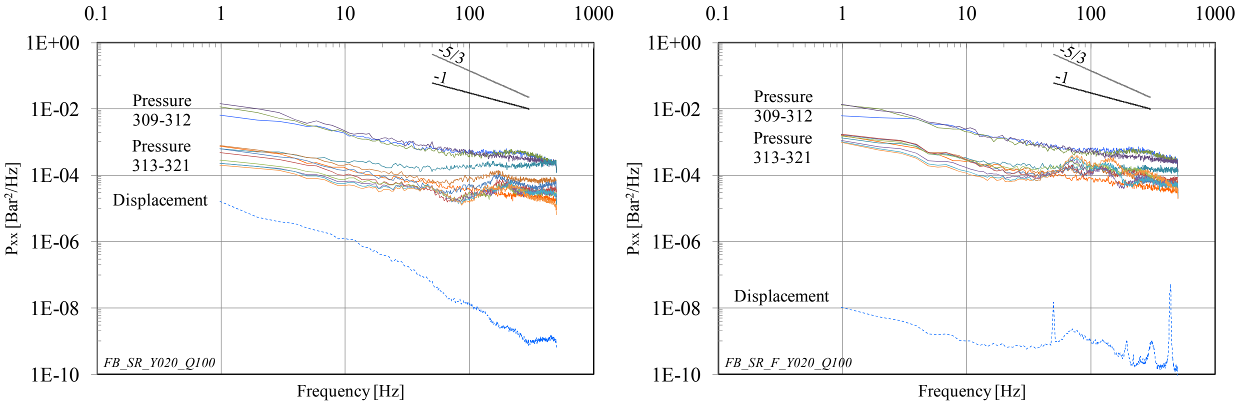

Figure 6: PSD for Core jet: Y = 0.2 m and V = 24.6 m/s. Left: Free block. Right: Fixed block.

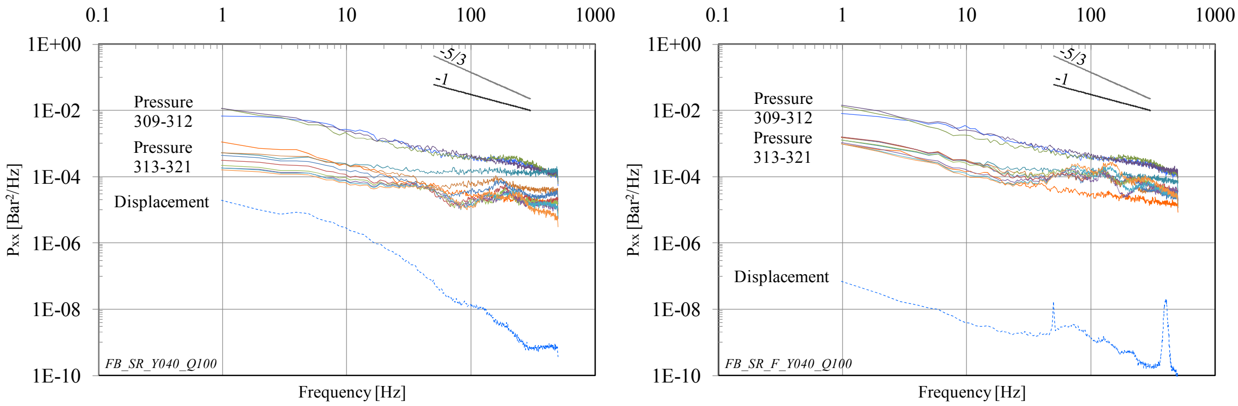

Figure 7: PSD for transition jet: Y = 0.4 m and V = 24.6 m/s. Left: Free block. Right: Fixed block.

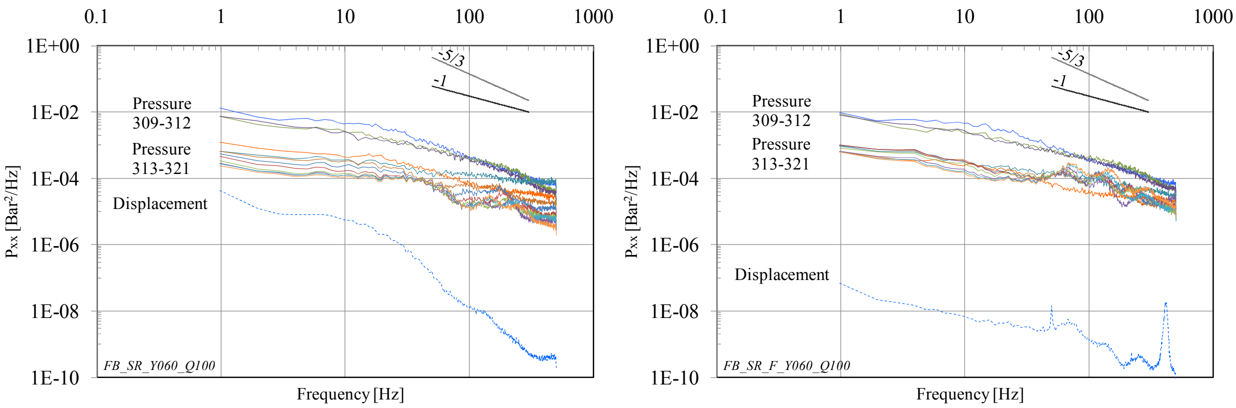

Figure 8: PSD for developed jet: Y = 0.6 m and V = 24.6 m/s. Left: Free block. Right: Fixed block.

For both core and developed jets, the low frequency part of the spectral content (f < 10 Hz) looks quite similar between pressure fluctuations and block displacements for the block free to move vertically. For higher frequencies, however, the spectral energy of the movements of the block (D1D) quickly decreases, while the corresponding spectral content of the pressure fluctuations at the plunge pool bottom (N° 309 to 312) only follows a -1 slope of decrease. For the configuration with the fixed block, the energy dissipation is almost constant and follows a -1 slope of decrease for all transducers.

Two different main peaks are detected in the PSD signal for the pressure transducer situate inside the joint (all around the block) for the configuration with the free block: the first between 20 and 100 Hz and the second between 100 and 300 Hz but it's compose by two sub peaks, the first between 100 and 200 Hz and the second between 200 and 300 Hz with a similar energy content. Both main peaks appear for all jets impact (core, transition and developed jet).
For the configuration with the fixed block, both main peaks appear but the first one moved near the second one (between 50 and 100 Hz). The second main peak is always composed by two sub peaks (the first one between 100 and 200 Hz and the second one between 200 and 400 Hz).
The physics that are responsible for these peaks are still under investigation and not fully clear yet. At first sight, the peaks might be related to fundamental resonance frequencies of the pressure waves travelling through the joint around the block or to eigenfrequencies of the block itself due to is inertia. A test was performed to evaluate the eigenfrequency of the block in dry and wet conditions (the block is impacted by hammer blows). The PSD analyses show a frequency range between 5 and 9 Hz with a 7 Hz peak. None of the peaks appear in the PSD of the surface pressure signal as such they are not present at the plunge pool bottom.

5. CONCLUSION AND OUTLOOK

The test runs show some difference between the calculated pressure coefficients and the literature. This difference could reasonably be expected due to the transducers position (our transducers are situate further away from the jet axis and inside the joints).
The displacements and the accelerations measurements show a change in the block solicitation between 30 and 60 l/s. For lower and higher discharges the displacements and the accelerations are roughly constant but in this discharges range an increase its observable.
The PSD analysis shows a similar behaviour for the case with the free block free and for the case with fixed block. Two zones of increased power spectral density have been detected, which are not related to the eigenfrequencies but could be related the travelling pressure waves inside the joint.
Subsequent analysis will be performed for different configurations (jet impact position on the block) with the aim to determine a direct relationship between the net dynamic uplift pressures on the rock block and its vertical displacements and/or vibrations.

6. ACKNOWLEDGMENTS

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