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INFLUENCE OF ROCK SCOUR GEOMETRY ON DYNAMIC PRESSURES DUE TO JET IMPACT

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The direct impact of falling jets on the riverbed downstream of high dams is often used for dissipation of water energy from floods. The paper highlights the influence of pool geometry on plunging jet diffusion and thus on the hydrodynamic loads transmitted to the rocky riverbed. Systematic model tests were performed with circular jets at prototype velocities impacting on flat and non-flat plunge pools. Lateral confinements of 5.5, 11 and 16.5 times the diameter of the falling jet were tested. Dynamic pressures were measured at the water-rock interface and inside a close-end rock fissure at frequencies of 1-2 kHz. Pressure coefficients and density power spectra are presented. The results show that mean dynamic pressures transmitted to the foundation are reduced by the confinement. Jet development is enhanced, notably for shallow pools. Inside rock fissures, resonance was observed for a dimensionless pool depth (Y/D=4.2), normally associated to core jet impact. Transient flow regimes responsible for scour propagation depend therefore on the degree of jet confinement by the pool geometry.

1. Introduction

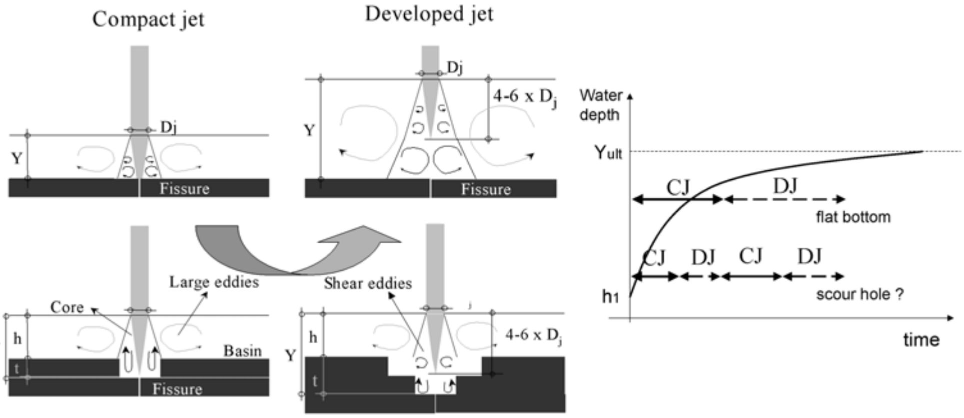
The direct impact of falling jets on the riverbed downstream of high dams is often used as a solution for the dissipation of water energy from floods. The construction of expensive concrete structures for energy dissipation can thus be avoided. However, the assessment of the scour evolution is mandatory for dam safety. It is a complex water-air-rock interaction problem. For large dams, scaled physical model tests are often performed. The results are combined with prototype observations to develop empirical formulae for ultimate scour prediction. The applicability of empirical methods is limited to the range of tested parameters and does not represent the complex interaction between a highly aerated water jet and the rock bed. Correction factors to account for jet aeration, two-phase pool flow and local rock parameters have been added. However, it is still not possible to properly estimate the evolution of scour with time and in space. Therefore, the use of empirical methods is often limited to the preliminary stages of a project. The applicability for rock scour of existing relationships for scour progression in loose sand or gravel beds is very limited. They do not consider the time needed for rock break-up by crack formation and propagation, nor the time needed for block downsizing (ball-milling). A comprehensive review and discussion about scouring downstream of dams can be found in Schleiss (2002).

Systematic research to understand better the physical processes involved in rock scour is carried out at the Laboratory of Hydraulic Constructions (LCH-EPFL) since 1998 (Bollaert, 2002, Manso et al. 2004). The purpose is to develop and enhance tools which allow the simulation of scour evolution based on a profound understanding of all physical processes from jet impact to crack propagation. Time-dependent processes like crack propagation by fatigue and block displacement are considered. At the present stage of knowledge, a physically based model for prediction of scour in rock as a function of time is already available for practice (Bollaert 2002, 2004). The model relates hydrodynamic pressures in rock joints with the resistance of these joints against cracking. For given jet characteristics at issuance and given tailwater levels downstream, the dynamic pressures transmitted to the foundation are used to estimate the loads at the fracture tips. Depending on the dynamic character of the pressure loads, the crack propagates either by brittle failure (hydraulic fracturing) or by fatigue. Once blocks are created, they are displaced by a net uplift pressure persisting during a certain time interval. Scour evolution is simulated by erosion of successive flat rock layers. This model represents a simplification of the basic physical processes such that a practicing engineer can easily handle it. Since its development, it has been applied to several dam scour problems worldwide (Bollaert 2004). Further research on jet-pool geometry interaction, pressure propagation in complex fissures, time effects and persistence of pool pressure fields is ongoing. The current paper intends to highlight the interaction between jet diffusion and the geometry of the plunge pool at given stages of scour. First, jet diffusion in flat and confined plunge pools is discussed from a theoretical point of view. Second, preliminary results of ongoing experimental work on jet impact in confined plunge pools are presented and discussed.

2. Jet Diffusion in Flat and Laterally Confined Plunge Pools

Knowledge on dynamic pressure loads propagating inside rock joints is based on measurements performed for plunge pools with flat bottoms (Bollaert, 2002). The impinging jet freely spreads laterally. Jet diffusion in the water depends mainly on jet related characteristics and on travel distance. According to Ervine *et al.* (1997), the jet core disappears by shear at a depth of about 4 to 6 times the smallest jet dimension (diameter D or thickness b) at impact with the water cushion. Core (compact) jets generate high mean pressures at impact with a horizontal flat surface that can lead to crack formation and propagation by hydraulic fracturing (brittle failure). Once the core disappears, the jet becomes “developed” and mean pressures at impact decrease (Figure 1a, top). The remaining pressure fluctuations persist for high pool depths. Bollaert (2002) showed that pressure fluctuations have sufficient energy to further scour the rock. Pressure fluctuations can open up cracks by fatigue but also by brittle failure. The latter results from the pressure acting inside the joint system. Pressure peaks inside can exceed the maximum pressure at the water-rock interface if the frequency of the pressure loads stimulates the cracks to resonance.

Bollaert (2002, 2004) assumes that scour is mainly driven by mean pressures for core jets and by a combination of mean and fluctuating pressures for developed jets, for flat pool bottoms. However, the scour process in real-life plunge pool geometries is likely to follow a sequence of alternating vertical and lateral erosion steps of high complexity. The hydrodynamic pattern of pool flows and jet pressures is modified accordingly. The relation between the geometry of the pool and the diffusion of the jet is not straightforward. Once a first erosion hole is created, the return currents induced by wall jet reflection on the boundaries may well disturb the falling jet. For shallow pools, the disturbance to the falling jet may be such to destroy the remaining jet core, not by shear diffusion but by collision of currents. The impact pressure pattern is thus changed to that of a developed jet (Figure 1a bottom). Regarding scour evolution with time, the up to now assumed sequence of compact jet scour followed by developed jet scour might not entirely match with prototype reality. According to the empirical reasoning presented in Fig. 1a, scour may probably be better represented by a succession of alternating periods of compact and developed jet scour predominance (Figure 1b). In the following, experimental work with flat and non-flat pools brings new insight into this topic.



a) b)

Figure 1: a) Schematic representation of core (CJ) and developed jets (DJ) for flat bottom plunge pools (top) and expected contribution of a lateral confinement (bottom); b) Scour rate as a function of the predominant jet type, h_1 is the initial tailwater level and Y_{ult} is the pool depth corresponding to ultimate scour.

3. EXPERIMENTAL WORK

3.1 *Introduction*

Systematic experimental tests were performed to assess the variation of the dynamic loads transmitted to the rock riverbed in case of a non-flat pool bottom comparing with the case of a flat plunge pool. First a lateral confinement of the jet was studied. The corresponding results are presented hereafter.

3.2 *Experimental set-up and tests performed*

The experimental set-up is schematically shown in Figure 2 and is described in detail in Bollaert (2002). The jet outlet is cylindrical, having a nozzle diameter of 0.072 m. The installation produces mean jet velocities of maximum 32 m/s. The water depth in the plunge pool can be varied from 0 to 0.9 m, the nozzle being at 0.70 m of height. This allows creating a high-velocity diffusing turbulent shear layer that impacts at the entrance of the underlying rock joint (completely filled with water at the beginning of the tests). The turbulence intensities at the jet outlet are between 3 and 8 % (Bollaert 2002, Manso *et al.* 2004). At issuance, the observed jets are compact due to their small fall heights (max. 0.50 m) and small degree of break-up (max. 0.35).

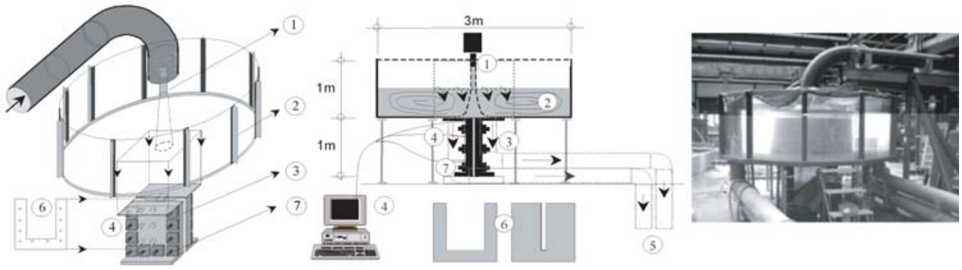


Figure 2. Perspective view and side view of the experimental facility: 1) cylindrical jet outlet, 2) reinforced plastic cylindrical basin, 3) pre-stressed two-plate steel structure, 4) Pressure sensors, 5) restitution system, 6) thin steel sheeting pre-stressed between steel structure (defining the form of artificial 1D-2D joints), 7) pre-stressed steel bars. Photo taken during operation with high pool level and a metallic cylinder for a lateral confinement of Dc/D=16.7 and t/D=8.3.

Three different lateral confinement conditions (D_c) are simulated which correspond to 5.5, 11 and 16.5 times the diameter of the jet at issuance (D). The confinement is created by 20 cm high cylinders, used separately, fixed to the pool bottom. They simulate a first step of scour depth t, corresponding to a relative ratio of t/D=2.7. The bottom of the pool on the leeside of the cylinder was not raised since that volume of water hardly contributes to pool dynamics. The height (depth) of scour and the distance of the confinement to the jet axis were selected to be of the same order of magnitude as the jet diameter and typical rock block dimensions. From the large number of tests performed, the characteristics of some selected are presented in Table 1.

Pressure measurements were done using piezoresistive micro-transducers type ®KULITE XTL-190-17BAR-A (pressure range 0-17 bar, 3 mm diameter diaphragm). The 300 mm diameter upstream conduit supplies a maximum of 120 l/s by means of a 63 m high head pump. The pressure signal was sampled at 1 to 2 kHz, for a maximum of 65536 point for each run. Control runs at 10 and 20 kHz were performed regularly to verify recording of extreme pressure values. The acquisition system comprises a multiple entry acquisition card for A/D conversion, a hardware lowpass filter and a PCI ARCNET for data storage on a PC. The system was developed jointly with the Laboratory of Hydraulic Machinery. The acquisition software allows visualization of the signal and provides primary statistics. Pressure fluctuations were measured at the bottom of the scour hole (point a, Fig. 3) and at two locations along the underlying closed-end fissure (points c and d, Fig. 3).

Table 1 – List of selected tests for flat bottom pools (FB) and lateral confinements of D_c/C=5.5 (FC), 11 (SC) and 16.5 (TC). Other parameters are the discharge Q, the velocity at issuance Vi, the length of travel in air L, the maximum plunge pool depth Y and the Reynolds number Re.

Tests	#	Q [l/s]	Vi [m/s]	L [m]	Y [m]	Re [-]
FBY_Q30	8	30	7.4	max 0.50 m	0.075, 0.20, 0.30, 0.40, 0.50, 0.60, 0.67, submerged	4.61E+05
FBY_Q40	8	40	9.8	max 0.50 m		6.15E+05
FBY_Q50	8	50	12.3	max 0.50 m		7.69E+05
FBY_Q60	8	60	14.7	max 0.50 m		9.23E+05
FBY_Q70	8	70	17.2	max 0.50 m		1.08E+06
FBY_Q80	8	80	19.6	max 0.50 m		1.23E+06
FBY_Q90	8	90	22.1	max 0.50 m		1.38E+06
FBY_Q100	8	100	24.6	max 0.50 m		1.54E+06
FBY_Q110	8	110	27.0	max 0.50 m		1.69E+06
FBY_Q120	8	120	29.5	max 0.50 m		1.85E+06
FCY030Q110	1	110	27.0	0.40	0.30	1.69E+06
FCY030Q120	1	120	29.5	0.40	0.30	1.85E+06
FCY067Q110	1	110	27.0	0.40	0.67	1.69E+06
SCY030Q110	1	110	27.0	0.40	0.30	1.69E+06
SCY067Q110	1	110	27.0	0.40	0.67	1.69E+06
TCY030Q110	1	110	27.0	0.40	0.30	1.69E+06
TCY030Q110	1	110	27.0	0.40	0.67	1.69E+06

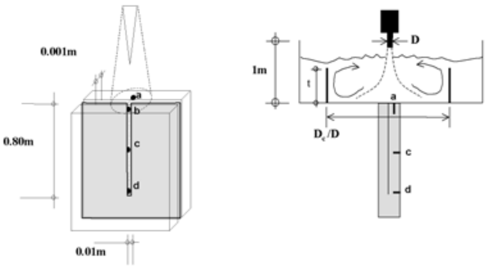


Figure 3. Schematic representations of the positions of the three pressure transducers: a) pool bottom, 25 mm from the jet axis, c) inside fissure, 0.40 m below pool bottom, d) inside fissure, 0.795 cm from the surface

3.3 *Mean dynamic pressures*

The mean loads transmitted to the rock can be defined as the ratio between the measured mean pressures at the rock interface to the incoming jet kinetic energy (Eq. 1).

$$C_{pa} = \frac{\frac{p_{mean}}{\gamma}}{\frac{V^2}{2g}} \tag{1}$$

A detailed discussion of the effect of the tailwater level on mean pressures can be found in Bollaert et al. (2004). Values of Cp_a for flat and non-flat pools are presented in Figure 4. Preliminary results seem to indicate that the three lateral confinements reduce mean pressures at impact for V=27 m/s and for tailwater levels theoretically corresponding to core jet impact (Y/D=4.2) and developed jet impact (Y/D=9.3). For Y/D=4.2 (Y=0.30 m) the value of Cp_a reduces from around 0.8 (flat pool) to 0.56 (D_c/D=

5.5). The difference in energy at impact has probably been either converted into fluctuations or dissipated by jet collision within the confinement. For Y/D=9.3, the differences are less pronounced however.

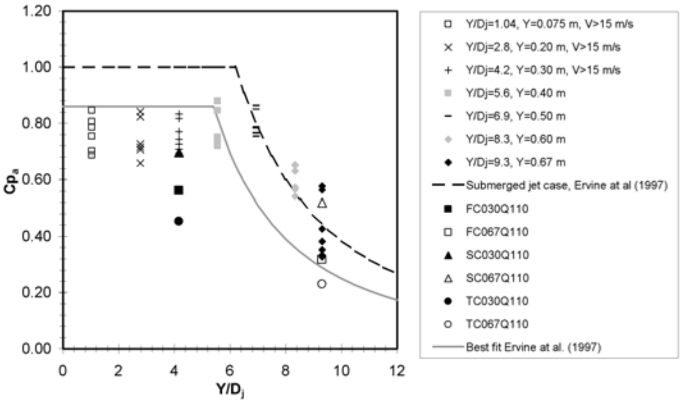


Figure 4. Dimensionless mean pressures for flat and plunge pools with D_c/D_j=5.5 (FC), with D_c/D_j=11 (SC) and with D_c/D_j=16.5 (TC), Comparison with published data by Ervine et al. (1997).

3.4 *Pressure fluctuations*

Pressure fluctuations are analysed by means of spectral analysis. Spectra of turbulent fluctuations present three main features from low to high frequencies (Chassaing 2000): (1) the production zone, related to the mean characteristics of the energy source (the jet), (2) the energy redistribution zone from large eddies at low frequencies to progressively smaller vortexes (cascade of energy) and (3) the dissipation or viscous zone, where the energy of the small turbulent structures (high frequencies) is dissipated by viscosity. Density power spectra were computed using the Welch periodogram method for Fast Fourier Transforms, with 50 % overlapping, a Hamming window and 64 blocks. For a maximum jet velocity of 29.5 m/s, two geometries (flat plunge pool $D_c/D_j=\infty$ and D_c/D_j=5.5) and two tailwater conditions are compared in Figure 5. For low tailwater level (Y/D_j=4.2, Figure 5a), a typical compact jet spectrum (-1 slope for log-log scales) is obtained for a flat pool. Once the lateral confinement is in place (first scour step), the spectrum is modified. There is more energy in the range of 15 to 180 Hz and the slope changes abruptly at about 80-90 Hz. The total energy of the fluctuations (variance) is similar in both cases but redistributed with frequency. For a high tailwater level (Y/D_j=9.3, Figure 5b), both spectra correspond to develop jets. However, the lateral confinement contributes to a considerable reduction of variance (energy) of the pressure fluctuations. Furthermore, the transition to the dissipation range of the spectrum is occurring at lower frequencies.

Resonance conditions were attained for Y/D_j=4.2 and V=27 m/s with the narrowest pool confinement D_c/D_j=5.5. Up to present, such resonance had only been attained for large plunge pool depths (Y/D_j>6) in flat pools (Bollaert 2002). For the tested closed-end 0.80 m long fissure the 1st mode of vibration is attained at about 30-40 Hz. In agreement with the conclusions of Fig 5, the concentration of energy at intermediate frequencies (range of 10-100 Hz) created by the D_c/D_j=5.5 confinement has generated pressures peaks six times higher than the mean pressure at the entrance. By enhancing jet development, the D_c/D_j=5.5 lateral confinement modifies the dynamic pattern of the loading at the water-rock interface for shallower pools. In comparison, pool geometries of D_c/D_j=11 and 16.5 generate pressure peaks at the end of the fissure that are only 2.2 and 2.8 times higher than the mean pressure at the entrance.

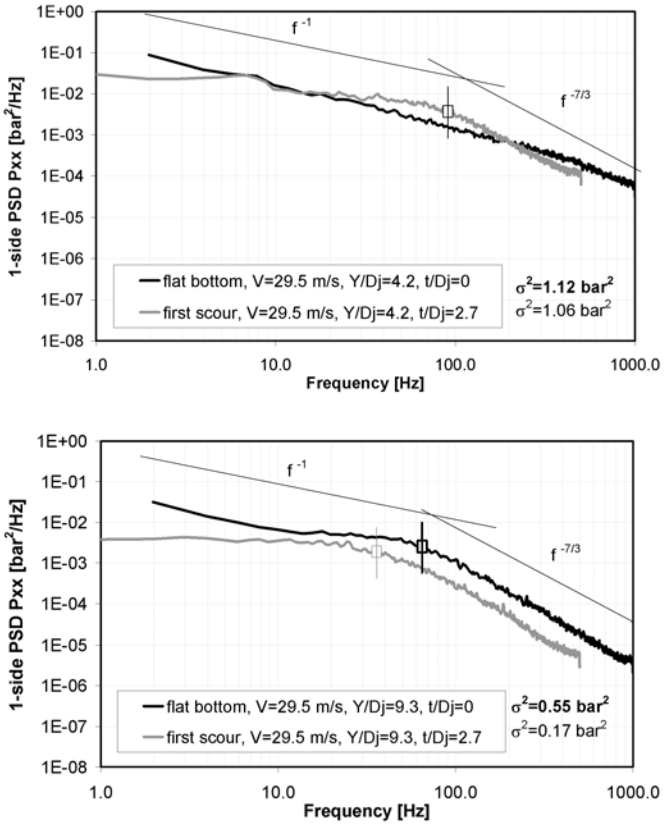


Figure 5. Density power spectra from pressure measurements, for a jet diameter D_j = 72 mm and scour depths of t/D_j =0 and t/D_j =2.7 for a "shallow" pool, Y/D=4.2 (top) and for a "deep" pool, Y/D=9.3 (bottom).

4. Conclusions and Outlook

Experimental tests have been performed to compare jet impact conditions in flat and non-flat plunge pools. Preliminary results seem to indicate that mean dynamic loads transmitted to the rocky riverbed are reduced when jet diffusion is disturbed by the lateral pool boundaries in comparison to flat wide pools. For shallow pools, jet development is enhanced and resulting fluctuating pressures have more energy at frequencies able of stimulate fissures to resonance. Transient flow regimes relevant in scour propagation depend therefore on the degree of jet confinement regarding pool dimensions. Knowledge on the interaction between pool geometry and jet diffusion is expected to improve scour predictions and design of protection works.

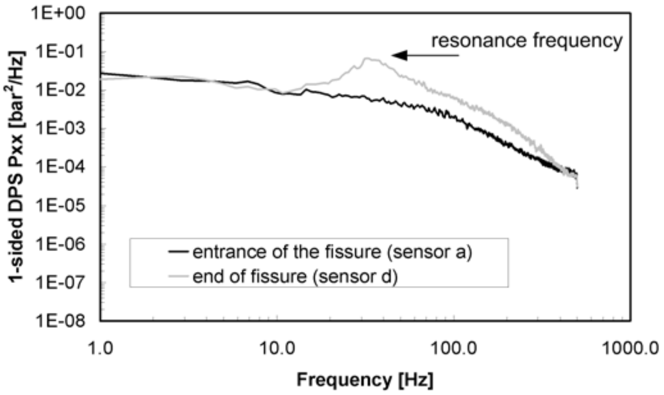


Figure 6. Density power spectra from pressure measurements, for a jet diameter D_j = 72 mm, Y/D_j=4.2, V=27 m/s, t/D_j =2.7 at the entrance of the fissure (point a), b) at the end of the fissure.

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