Multiphase Transient Flow and Pressures in Rock Joints due to High Velocity Jet Impact: an Experimental and Numerical Approach

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I. Introduction

The impact of high velocity plunging jets that issue from outlet structures of high-head dams can significantly scour the downstream bedrock. Traditionally, the equilibrium scour depth is estimated with empirical or semi-empirical formulae that partially neglect the governing physical bases. Above all, the relationship between pressures at the plunge pool bottom and their corresponding pressures inside underlying rock joints is unknown. A better understanding of this phenomenon of pressure transfer is necessary to assess the basic physical-mechanical processes of rock mass destruction. These are hydrodynamic fracturing of open- or closed-end rock joints and hydrodynamic uplift of the so formed rock blocks.

A research study has been carried out at the Laboratory of Hydraulic Constructions in Lausanne (EPFL), in collaboration with the Laboratory of Applied Hydrodynamics and Hydraulic Constructions in Liège (ULG), focusing on experimental and numerical modelling of dynamic pressures in rock joints, due to high velocity jet impact.

An experimental facility simultaneously measures pressures at a modelled pool bottom and inside artificially created one-and two-dimensional underlying rock joints. The jet outlet velocities are at near-prototype scale (up to 35 m/s), in order to obtain realistic aeration of the pool. Furthermore, a water level of up to 0.70 m in the plunge pool guarantees a correct modelling of the spectral content of the turbulent fluctuations of the jet at the bottom of the pool. The test results for closed-end one-dimensional rock joints highlight the formation of transient two-phase pressurized flow phenomena in the form of standing waves and resonance conditions [1]. The presence of air bubbles in the pressurized flow inside the rock joints is of crucial significance on the wave propagation, because it strongly influences the wave celerity and thus makes the problem non-linear [2]. The quantity of air that is available in a joint depends on the air content of the pool and on the instantaneous pressure value inside this joint. This highly non-linear process generates extreme pressures inside the rock joints that can attain values of up to several times the maximum pressure at the pool bottom.

In the following, emphasis is given on a comparison between the experimental pressure results and their corresponding numerical simulation for a 1D closed-end joint. The numerical model is based on a set of one-dimensional transient flow equations for a homogenously distributed two-phase fluid. The continuously changing air content in the joint is introduced by means of a constitutive equation that relates the pressure wave celerity with the governing pressure. The numerical implementation is based on a 2nd order finite-volume scheme.

II. Experimental facility

The experimental set-up (Fig. 1) consists of two main parts [2]: a) a 3m-diameter cylindrical basin in steel reinforced plastic, simulating the plunge pool, and b) a 1mm thin steel sheeting, modeling a rock joint. This sheeting is pre-stressed between two 100 mm thick steel plates of 1 ton each. The jet outlet has a cylindrical or convergent shape with a nozzle diameter of 57 or 72 mm. A series of 8 flush-mounted micro pressure sensors (pressure range 0-17 bar, precision +/- 0.1 % FS, 3mm-diameter) simultaneously register dynamic pressures at the plunge pool bottom and inside the rock joint, with acquisition rates of maximum 20 kHz. The

"Proceedings of the 2001 International Symposium on Environmental Hydraulics

water depth in the plunge pool can be varied from 0 to 0.7 m and allows the creation of a high-velocity diffusing shear layer that impacts the underlying joint. The turbulence intensities at the jet outlet reach 4-5%.

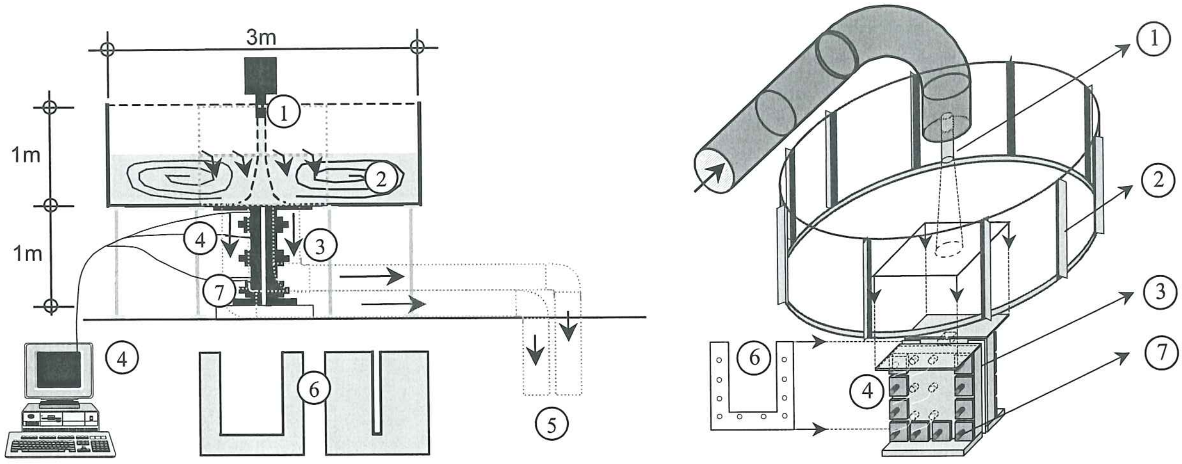
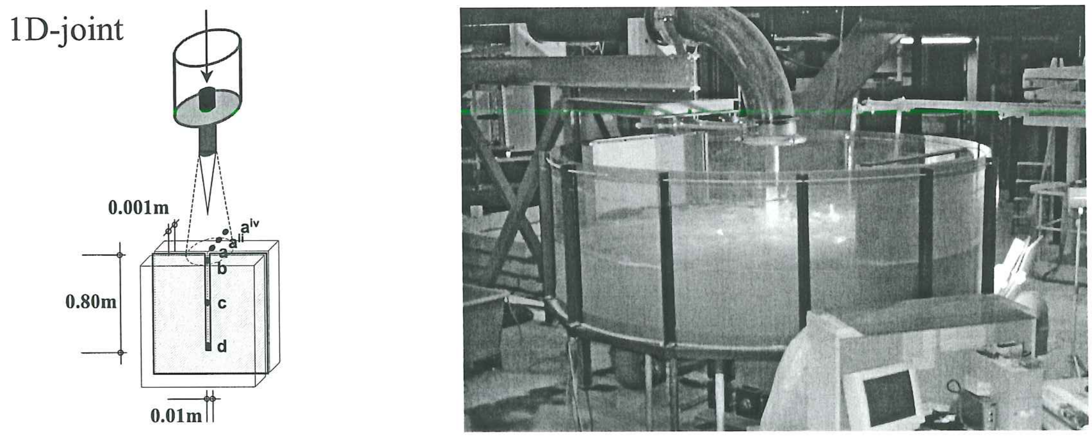


Fig.1 Side view and perspective view of the experimental facility: 1) cylindrical jet outlet, 2) reinforced plastic cylindrical basin, 3) pre-stressed two-plate steel structure, 4) PC-DAQ and pressure sensors, 5) restitution system, 6) thin steel sheeting pre-stressed between steel structure (defining the form of artificial one-and two-dimensional rock joints), 7) pre-stressed steel bars.

The artificially created rock joints are cut in a thin steel sheeting. This system creates any joint geometry with a constant thickness. In this paper, the experimental results of a one-dimensional joint (0.80m long - 0.01m wide - 0.001m thick), as indicated in Fig. 2a, are compared with the numerical modeling. The location of the pressure sensor at the pool bottom, directly under the jet's centerline, is indicated with "a". The pressure sensors "b", "c" and "d" are located at the entrance, the middle and the end of the joint. The sensor "a" is used as input signal for the numerical computations. The comparison between measured and computed pressure signals is performed for sensor "d", located at the end of the joint.



(a) (b)

Fig. 2 a) Artificial 1D closed-end rock joint with location of pressure sensors at the pool bottom ("a") and inside the joint ("b", "c", "d"); b) Photo of installation while running at a jet velocity of 10 m/s.

III. Numerical model

The numerical modeling of the pressurized flow inside the 1D rock joint makes use of the transient flow equations for a homogenous two-phase fluid. This means that the two-component air-water mixture inside the joint is simulated as a pseudofluid with average properties and, thus, only one set of conservation equations. No slip velocity or heat transfer between the two phases is considered, and the energy equation is omitted. For such a flow mixture, the density is hardly modified by the gas phase and, at relatively small gas contents (up to several %), it may be approximated by the density of the liquid.

However, the compressibility and the pressure wave celerity of the mixture strongly depend on the volume of free air in the liquid. Therefore, when neglecting any exchange between the phases in the conservation equations, a constitutive relationship between the wave celerity and the pressure has to be added to account for this volume. According to Wylie & Streeter (1978), this simplified approach is valid for air contents of at least up to 2 %. Martin & Padmanabhan (1979) numerically verified the homogeneous flow assumption for air contents of up to 30 %, and found correct wave celerities. Therefore, in the here presented approach, the homogeneous flow model has been applied. This hypothesis is justifiable when considering that the pressure characteristics were similar in the middle and at the end of the joint. Moreover, no further assumption can be made on the distribution of the free air inside.

The mass and momentum equations of the pseudofluid are expressed as follows:

$$\frac{\partial p}{\partial t} + \frac{c^2}{g} \cdot \frac{\partial V}{\partial x} = 0 \tag{1}$$

$$\eta \cdot \frac{\partial V}{\partial t} + \frac{\partial}{\partial x}\left(\beta V^2\right) + g \cdot \frac{\partial p}{\partial x} + \lambda \cdot V = 0 \tag{2}$$

in which p is the pressure head (m), V the mean velocity (m/s), and c the wave celerity (m/s). The terms λ, η and β account for steady, unsteady and uneven velocity distribution friction losses. They can also incorporate other possible energy losses, such as friction due to heat or momentum exchange between the phases. As such, they cannot be compared with the Darcy-Weisbach friction term that is usually applied for one-phase steady-state flow. Their values are often quite different, due to the particular damping effect generated by the two-phase transient character of the flow [4,6]. As a result of the narrow joint geometry, the encountered Reynolds numbers are very low and thus laminar flow may be assumed.

The form of the constitutive equation that relates the wave celerity with the instantaneous pressure is defined by physical and chemical laws that describe the volume and the quantity of free air in a liquid as a function of pressure. This background will not be outlined herein. Based on this physical and chemical evidence, as well as on the c-p relationships as derived from the experiments, it is assumed that, as a first approximation, a quadratic relationship is appropriate between celerity and pressure:

$$c(t) = k_1 + k_2 \cdot p(t) + k_3 \cdot p^2(t) \tag{3}$$

in which k_1, k_2 and k_3 are numerical parameters to be optimized. The numerical scheme that is used to solve a weak formulation of this set of three equations is a 2nd order finite-volume scheme. As the experimental pressure measurements revealed the appearance of violent transient and highly non-linear wave phenomena, it is obvious that a shock-capturing scheme, introducing a fit amount of numerical dissipation without excessive smearing of the peak pressures, is preferable. The numerical code defines an unsteady pressure signal as weak upstream condition and imposes a zero flow velocity downstream (at the end of the joint). Furthermore, it makes use of an adaptive time stepping.

The adjustment of the numerical parameters is based on the following criteria: mean pressure, RMS-value, maximum and minimum pressure and finally the histogram and the power spectral density of the computed pressure values are compared with the measured ones. For the histogram and the power spectral density, a least-square criterion has been applied. This optimization process has been performed for pool depths from 0.20 m to 0.67 m, for jet outlet velocities V_j from 10 to 30 m/s, and for test periods of 10 sec. each.

IV. Comparison of experimental and numerical approach

A comparison has been made between the experimentally measured pressure signals and the corresponding computed values. The measured pressure signal at the entrance of the rock joint (sensor "a" in Fig. 2a) has been used as pressure input for the numerical computations. Although these pressures were not exactly measured at the joint entrance itself, but at a distance of somewhat 2 cm aside (due to constructive limitations of the model), it is assumed that they are representative for the pressures that were simultaneously measured inside the joint (sensors "c" and "d" in Fig. 2a).

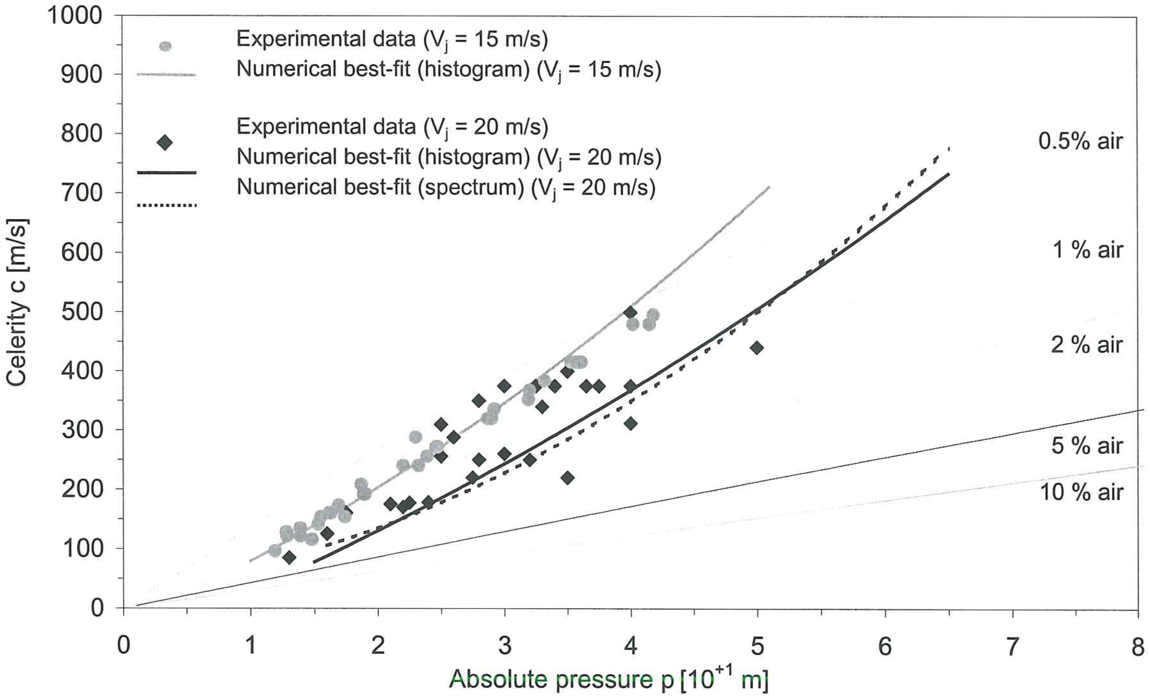


Fig. 3 Curves of constant air content (air volumes are at atmospheric pressure) and celerity-pressure relationships inside a 1D closed-end rock joint: comparison between experimentally derived data (● and ◆- signs) and a numerical optimization. For a jet velocity of $V_j = 20$ m/s, the numerical best-fit is obtained based on both the histogram and the power spectral density of the pressure values.

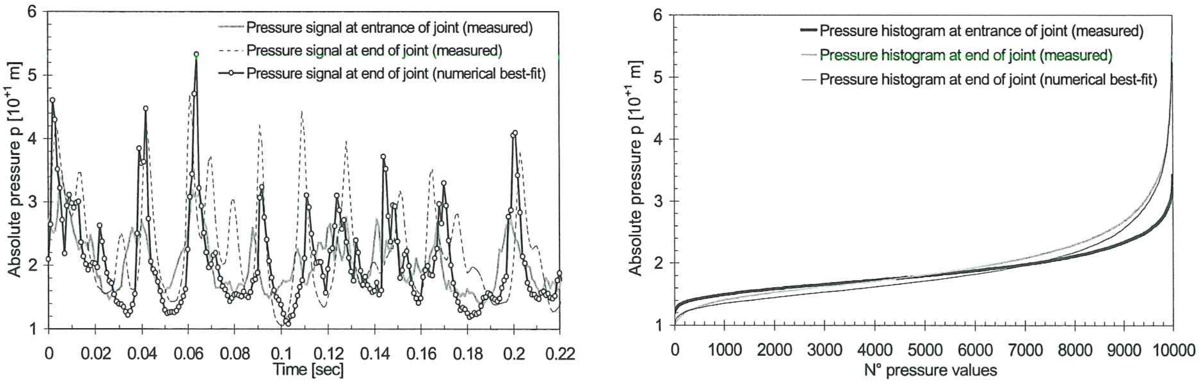
The constitutive equation that relates the wave celerity c to the instantaneous pressure p in the joint is thus the key element for a comparison between experimental and numerical modeling. Fig. 3 first of all presents a set of c-p curves in which each curve corresponds to a constant quantity of free air. Therefore, the indicated air volumes are valid at atmospheric pressure conditions only. These curves are purely indicative, and their comparison with measured and/or computed relationships determines if the quantity of free air in the joint remains constant throughout the pressure range.

The experimental results are used to perform pressure pulse propagation speed measurements between the pressure sensors in the middle (position "c" in Fig. 2a) and at the end (position "d" in Fig. 2a) of the joint. Wave celerities can so be defined for different levels of the pressure that propagates through the joint. The celerities that are obtained for a pool depth of 0.67 m and for jet outlet velocities V_j of 15 m/s and 20 m/s are presented in Fig. 3 (● and ♦-signs). They increase quite linearly with increasing pressure. This increase, however, is significantly different from the one corresponding to the curves of constant air content. Therefore, it might be assumed that some air is released and/or re-entrained as a function of the pressure conditions in the joint.

Furthermore, the experimental data exhibit more scatter for a jet velocity of 20 m/s than for a jet velocity of 15 m/s. This probably happens because, beside the changes in air content inside the joint, the air content in the plunge pool itself also continuously fluctuates. The wave celerities are determined at different times during the total test run period and, therefore, do not always correspond to the same air content in the plunge pool. These changes in plunge pool air content generally increase with increasing jet velocity and have a significant impact on the air concentration and thus the wave celerity inside the joint.

Different quadratic c-p relationships have been tested in the numerical model. Based on the aforementioned adjustment criteria, the friction factors and the parameters k_1, k_2 and k_3 have been optimized. Fig. 3 presents the numerical best-fit of c-p relationships (continuous lines) and compares them with the experimentally derived data points. It can be seen that, in the range of the measured pressure values, a good agreement is obtained. For a jet velocity of 15 m/s, only the numerical best-fit based on an adjustment of the histogram of the pressure values is presented. For a jet velocity of 20 m/s, both the numerical best-fit based on the histogram and the numerical best-fit based on the power spectral density are shown. Although some slight differences can be noticed, they exhibit the same slope.

Furthermore, for the jet velocity of 20 m/s, a comparison of the recorded pressure values has been represented in Fig. 4. This has been done in two different ways: Fig. 4a shows an experimental and numerical pressure record in the time domain, while Fig. 4b compares the measured and computed histograms. It can be seen that satisfactory agreement is obtained in the time domain. Generally, both the peak pressures and the periods of low near-atmospheric pressures are well simulated.



a)

b)

Fig. 4 Comparison between experimentally measured and numerically simulated pressures inside a one-dimensional closed-end rock joint: a) pressure record in the time domain, b) pressure histogram.

Due to the aforementioned continuously changing air content in the plunge pool, the exact instantaneous amount of air inside the joint cannot be represented by only one c-p relationship. In fact, while the general form of the c-p curves doesn't change (defined by basic physical laws), its parameters may slightly differ around some mean value. This is difficult to account for in the numerical computations and, therefore, the used c-p relationship has to be considered as a mean approach. Moreover, a constant distribution of the air content throughout the joint length is assumed.

However, the mean c-p relationship is representative for the whole test run period and produces a correct simulation of the measured extreme pressure peaks and spikes, as well as of the histogram of pressure values. This is important because these extreme values are most relevant when applying rock mass failure criteria based on tensile stresses [3].

A comparison of the measured and computed histograms shows that very good agreement is obtained towards the upper and lower ends, i.e. for pressure peaks and spikes respectively. Agreement over the whole range of pressures was difficult to accomplish. This might be due to unsteady and multiphase friction losses that are dependent on the pressure conditions. For example, during peak pressures or rapid pressure changes, the most appropriate friction value might be substantially different from the one that is valid during pressure spikes. This is not taken into account by the numerical model.

It may be concluded that, with regard to the application of rock mass failure criteria based on extreme tensile stresses, the here adopted numerical approach generates appropriate pressure conditions inside the tested rock joints.

V. Conclusions

Dynamic pressure fluctuations inside closed-end one-dimensional rock joints, due to high velocity plunging jet impact, have been measured experimentally and computed numerically. A comparison between these two approaches has been performed by use of the transient two-phase flow equations and a constitutive relationship between the wave celerity and the instantaneous pressure values of the two-phase flow mixture inside the joint. The numerical optimization of this constitutive relationship is mainly based on histograms and power spectral densities of the measured pressures, and results in a good agreement between experimental and numerical modeling. An automatic adjustment of the involved parameters, based on a genetic algorithm, is actually under investigation.

The here presented numerical approach will be incorporated into a new, physically-based evaluation method for the ultimate scour depth of rock masses under high velocity jet impact. With regard to future engineering design purposes, a pre-and postprocessing environment is under development.

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