A PROTOTYPE-SCALED ROCK SCOUR PREDICTION MODEL

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ABSTRACT

Scour of rocky foundations in plunge pools and stilling basins results from the interaction between an aerated turbulent flow environment and a fractured solid mass. As such, the phenomenon is quite complex and difficult to assess by means of straightforward mathematical techniques. One of the main problems in developing rock scour assessment methods is that most of the physics involved cannot be described and tested on a laboratory scale.

The present paper first outlines the major physics behind scour formation of fractured rock in plunge pools and stilling basins and points out why a prototype-scaled assessment of both flow turbulence and geomechanical characteristics is important to obtain sound prediction results.

Second, a physical and prototype based rock scour prediction method is presented in more detail. The model consists of a series of modules that allow estimating the time development of rock scour in plunge pools behind high-head dams and, by combining different mechanisms of progressive rock break-up, is able to predict the 3D scour evolution with time of a rocky foundation. Both theoretical bases and practical applications are discussed.

INTRODUCTION

Rock scour can occur when the erosive capacity of water exceeds the ability of rock to resist it. Typical environments where rock scour is a concern are downstream of overtopping dams, downstream of spillways, in plunge pools, around bridge piers, in unlined rock tunnels, and in channels and at other structures constructed in rivers and marine environments.

Assessment of rock scour needs sound comprehension of the characteristics of turbulent flows leading to scour, necessary for the development of practical methods to quantify the erosive capacity. Similarly, it is necessary to investigate and understand the failure mechanisms of rock to develop practical approaches for quantifying its ability to resist the erosive capacity of water.

Fluvial erosion of rock mainly occurs following three physical processes (Bollaert, 2002):

1. rock block removal (due to pressure fluctuations in the joints or to shear flow),
2. rock mass and rock block fracturing (suddenly or progressively with time),
3. rock mass and rock block abrasion (long term agents).

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Each of these processes is discussed in more detail further on. The importance of either of these processes not only depends on the characteristics of the turbulent flow, but also on the shape and the protrusion of the rock blocks. For small-sized material, shear flow is generally predominant. For irregular rocky riverbeds, however, the shape, dimensions and protrusion of the blocks are of importance and may enhance sudden uplift of the block. Significant dynamic pressure fluctuations can build up at the water-rock interface. These pressures are particularly relevant in case of turbulent flows, such as jets or hydraulic jumps. The assessment of the fluctuating part of these pressures is a key factor for appropriate modeling of rock scour.

Nevertheless, one of the main problems in developing rock scour assessment methods is that most of the physics involved cannot be described and analyzed on a laboratory scale. The turbulent behavior and pressure fluctuations of the air-water mixture impacting the rock blocks cannot be correctly reproduced in the laboratory using scales smaller than about 1:10. Also, the propagation of these pressures inside the fractures and joints that separate the rock blocks does not allow scaling effects.

In the following, turbulent pressure fluctuation measurements performed on a near-prototype scaled laboratory facility are first discussed and compared with the corresponding values provided by several small-scale facilities. The near-prototype facility simulates the impact of an aerated jet into an artificial plunge pool. Jet impact pressures have been measured at different locations along the bottom of this pool. The influence of the prototype character of the facility on the pressure characteristics is highlighted.

Second, the so defined near-prototype pressure fluctuations are used as boundary conditions for a physics-based rock scour prediction model. The model consists of a series of modules that allow estimating the time development of scour in fractured rock. Each of the modules represents a particular mechanism of rock break-up. Practical application of these modules allows predicting the 3D scour evolution of an unlined plunge pool rocky riverbed. In the following, both physical bases and practical applications are discussed.

PHYSICS OF ROCK SCOUR

Mechanisms of rock scour

Fractured rock impacted by turbulent pressure fluctuations may react in a quite particular manner. Depending on the importance of the pre-fracturing state of the rock and of the water pressure fluctuations, scour may form by different means. The most significant ones are rock block removal, fracturing of the rock mass or of its already formed blocks, and rock mass or rock block abrasion. Each of these processes has its own time-scale of occurrence, ranging from instantaneous to long term action. While certain short term actions have been rather well described in literature, such as block displacement by bottom shear stresses, sound assessment of medium and long term actions on fractured rock is still in its initial phases of development. The physics of these actions are quite complex and thus difficult to incorporate into a scour prediction practical engineering model.

<u>Rock block removal (by uplift and/or displacement)</u>
Rock may fail by removal of its distinct blocks. Removal of rock blocks may happen by (vertically oriented) uplift (ejection from the surrounding mass and blocks), by horizontal displacement, or by a sequence or combination of both movements. These are important observations, as application of a shear stress concept cannot always explain how large blocks of rock can be removed from a rock formation or how turbulent flow can break rock blocks into smaller pieces.

Which of the block movements will be most plausible depends on the size, dimensions and protrusion of the distinct blocks compared to the surrounding rock mass. These parameters directly define the relevance and importance of the following pressure forces that may lift the block (Bollaert and Hofland, 2004):

1. static uplift forces = f (density)
2. quasi-steady uplift forces = f (block protrusion, local flow velocity)
3. turbulent uplift forces = f (turbulent pressure fluctuations)

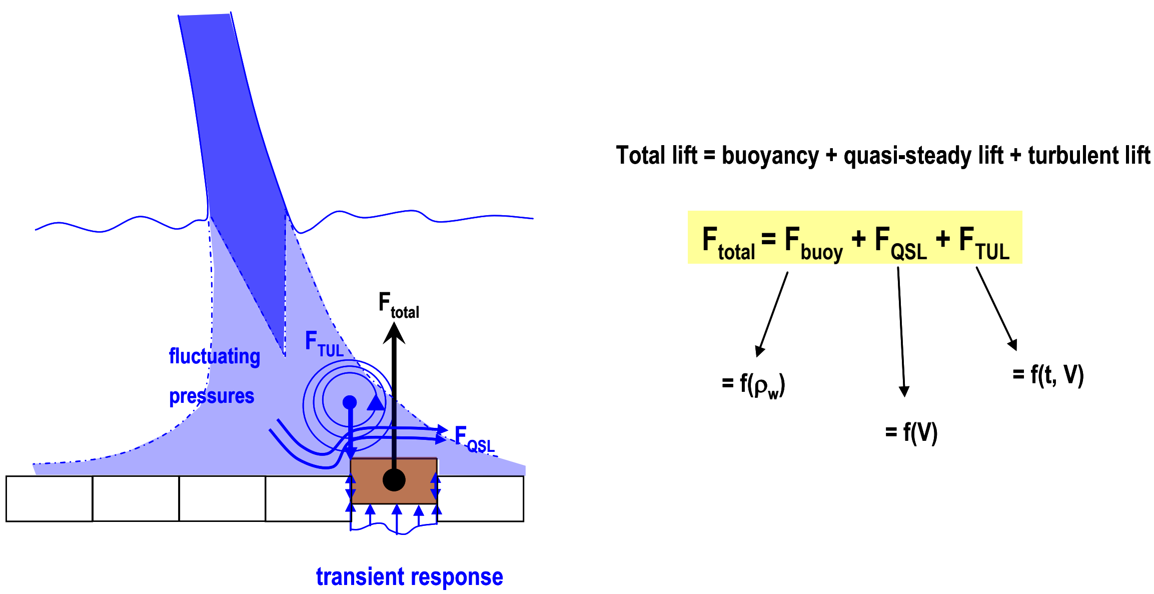

Figure 1. Rock block removal by uplift

Uplift or ejection of a rock block may be computed by defining at each time instant the uplift pressure forces on the block, together with the resistant forces defined by the mass of the block and by eventual shear and interlocking forces between the block and the surrounding mass. The force balance has to be established following the potential orientation of movement, which might be different from the vertical for oblique joint sets.

During time periods for which the net force balance on the block remains strictly positive (lift), the block will be submitted to a net uplift impulsion and will start to move. Based on Newton's second law, this net uplift impulsion is transformed into a net uplift velocity that is given to the block. Finally, the uplift velocity is transformed into an uplift displacement or height. The net uplift force is thereby assumed independent of the movement of the block, movement that increases the volume of the joint between the block and the surrounding mass.

Nevertheless, in reality, block movement and uplift forces are highly correlated. Experimental research is actually ongoing at the Swiss Federal Institute of Technology in Lausanne to solve this complex correlation (Federspiel et al., 2009). An artificial rock block has been equipped with pressure and acceleration sensors to detect the direct relation between the pressures over and under the block and its detailed movements. The block is being impacted by a near-prototype air-water jet.

For the time being, for practical applications, sound calibration of the rock block uplift module showed that a block may be considered ejected when the computed net uplift displacement (height) is superior to 20 % of the total block height (Bollaert, 2004).

<u>Rock mass/block fracturing</u>

Rock may also fail by sudden or progressive fracturing of its mass or of large size distinct blocks. Such hydraulic fracturing mainly occurs inside pre-existing fractures, but may also be initiated along a massive piece of rock. Hydraulic fracturing is mathematically described by the theory of fracture mechanics.

Sudden or brittle fracture of rock occurs when the stress intensity (of the rock mass) at the edges of closed-end fissures, resulting from the presence of fluctuating water pressures inside the fissures, is greater than the fracture toughness of the rock (Bollaert 2002, Bollaert 2004). The stresses induced by water pressures inside the fissures are governed by the absolute values of the water pressures and by the geometry of the fissure and the stabilizing support of the surrounding rock mass. The fracture toughness of the rock mass or rock block depends on the mineralogical composition of the rock, the in-situ vertical and horizontal stress fields and the unconfined compressive strength or tensile strength of the rock mass.

Brittle fracturing of rock occurs in an instantaneous manner and typically results in the rock mass breaking up into distinct blocks, or the already existing rock blocks breaking up into smaller pieces. During real-life flood situations, brittle fracturing may occur during peak pressure pulses entering the rock fissures at the bottom of the plunge pool or rocky riverbed. The time period necessary for the turbulent flow to generate such peaks during an overflow event is generally considered very small, i.e. typically a few minutes.

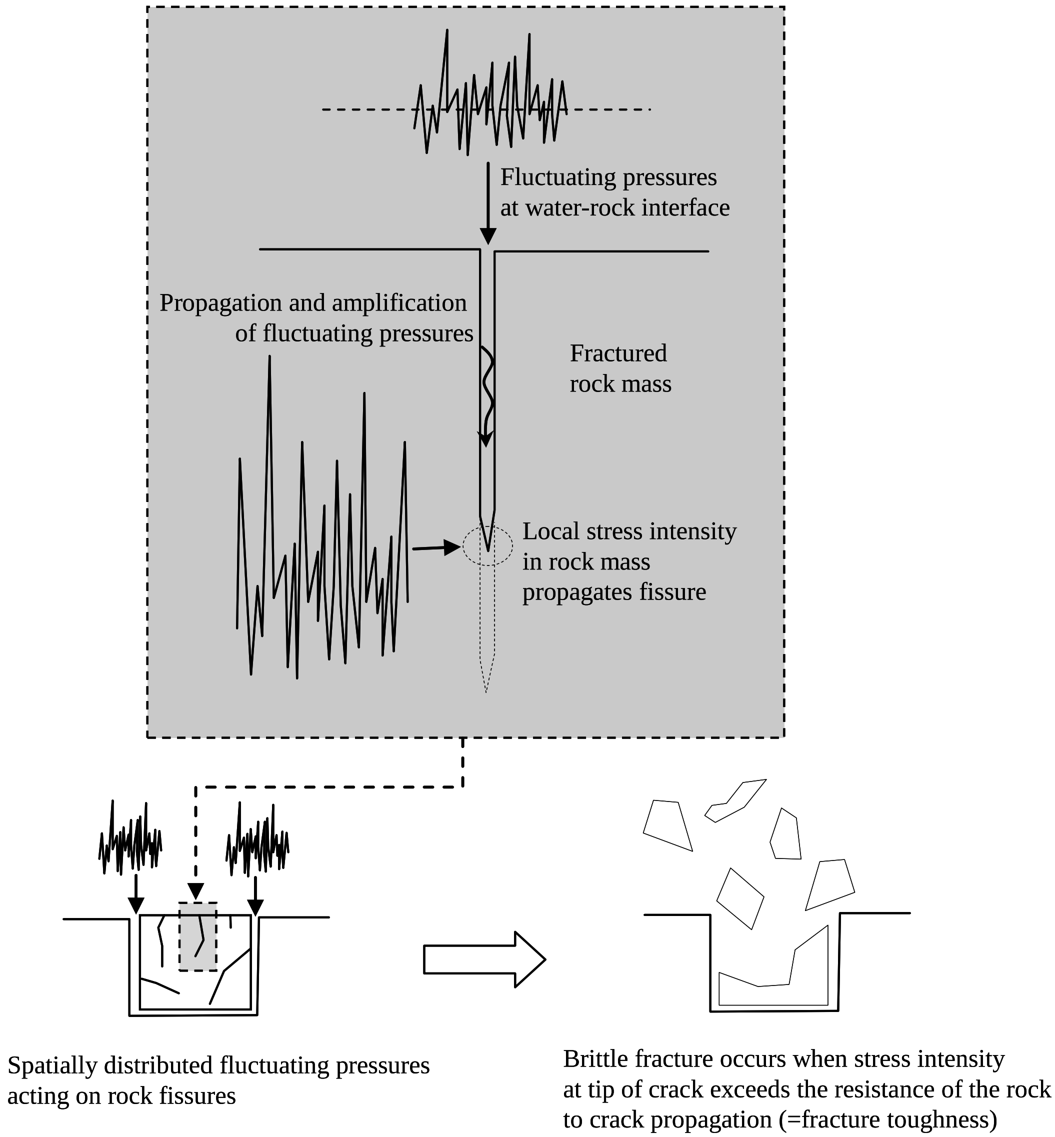

Figure 2. Rock block fracturing

Second, fatigue or subcritical fracturing of rock occurs when the stress intensities generated at the edges of closed-end fissures do not exceed the fracture toughness of the rock. The continuous presence of severe pressure fluctuations inside the fissures during a flood event may, on the medium or long term, result in break-up of the rock due to fatigue. The rock fissure typically breaks up (lengthens) progressively, depending on the number and the intensity of pressure cycles inside. This failure type is thus time-dependent and takes an end when the fissure has been completely formed, i.e. when it encounters another (existing) fissure present in the rock mass. More details can be found in Bollaert (2002, 2004) and Bollaert and Schleiss (2005). An example of subcritical failure is the well-known scour at Kariba Dam in Zambia-Zimbabwe (Bollaert, 2005).

Rock mass/block peeling off
Peeling off of rock blocks from their mass is a specific combination of both quasi-steady forces and brittle or fatigue fracturing. The phenomenon typically occurs for rock composed of multiple thin near-horizontal layers, such as occurring in sedimentary rock.

The destabilizing forces are not due to flow turbulence alone, but are principally generated by the flow deviation due to a protrusion "e" of the block along the bottom (e_{block} in Figure 3). This flow deviation generates drag and lift forces on the exposed faces of the block, which are governed by the relative importance of the protrusion of the block into the flow and by the local quasi-steady flow velocity in the immediate proximity of the block ($V_{backflow}$ in Figure 3).

These forces may develop brittle or fatigue fracturing of the joint between the block and the underlying rock mass. In many cases, the exposed block is detached or almost detached and no further fracturing is a priori needed to uplift the block from its mass. In case the fissure should need further fracturing before complete detachment of the block, brittle fracturing by the quasi-steady flow forces is the most plausible and common process. Nevertheless, in the immediate vicinity of turbulent shear flows along the bottom, turbulent pressure fluctuations and fatigue failure might also be relevant.

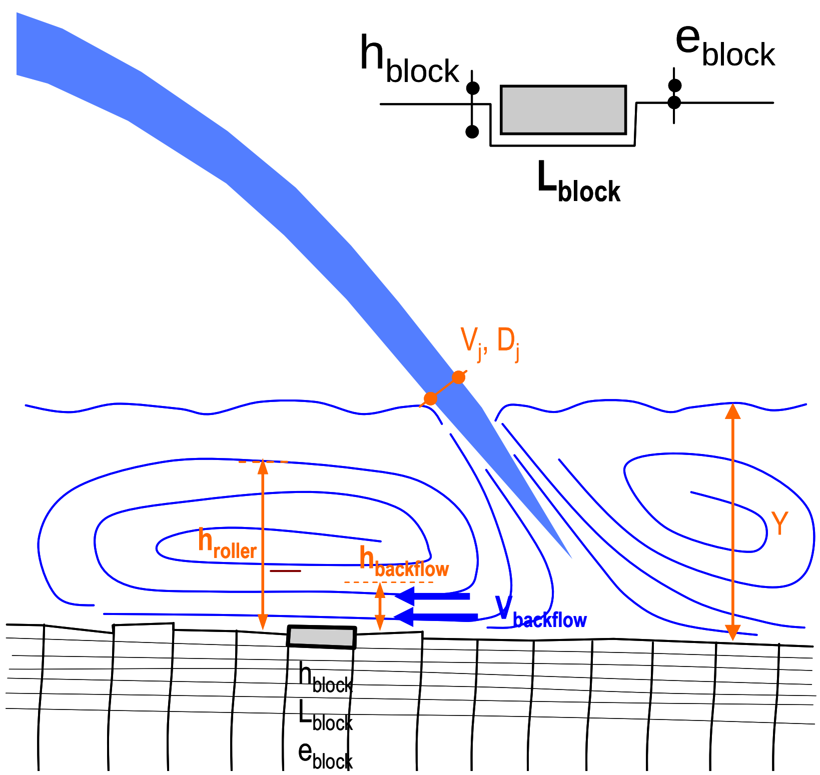

Figure 3. Peeling off of rock blocks at surface during flow event

Rock abrasion

Finally, rock may also scour by abrasion. Scour by abrasion can occur if the fluid interacting with the rock is abrasive enough relative to the resistance offered by the rock to cause it to scour in a layer-by-layer fashion. The process is enhanced by surface weathering of the exposed rock mass.

Summary

As a summary, Figure 4 presents the sequence of failure processes of an exposed rock mass. The exposed rock may first of all be weakened by weathering before flow impact.

Next, during flood situations, distinct rock blocks available at the exposed water-rock interface may be ejected and/or displaced towards downstream, where they may form a mound. They may also be submitted to brittle or instantaneous fracturing into smaller pieces, followed by displacement.

When applying ejection or fracturing processes to near-horizontal small layers of rock, and combining them with quasi-steady flow forces, peeling off of flat blocks at the surface of the rock mass is generated.

If the blocks cannot be ejected, displaced towards downstream, instantaneously fractured or peeled off from the surface layer, they still may scour by progressive fracturing into smaller pieces or being "tumbled" inside the pool by turbulent eddies, until they get smaller or finally break into pieces that may be ejected and displaced towards downstream. This process is called fatigue fracturing.

Furthermore, both brittle and fatigue fracturing enhance break-up of the rock mass into distinct rock blocks. As such, their action constitutes the onset of rock block uplift or ejection as described before.

Knowledge of how scour will occur is important for development of economical design solutions. For example, if a rock scour analysis concludes that scour will occur by brittle fracture and dynamic impulsion only, it is necessary to develop mitigation measures to protect against scour. If, in another case, an analysis indicates that scour will occur by sub-critical failure (fatigue) only, it might not be necessary to design mitigation measures.

This might be the case if it is found that the rock will only scour after (for example) 30 days of continuous submission to fluctuating pressures. If the design flood would only submit the rock to (for example) 10 hours of fluctuating pressures, the rock is much less likely to experience damage during such a flood and protection against scour may not be warranted.

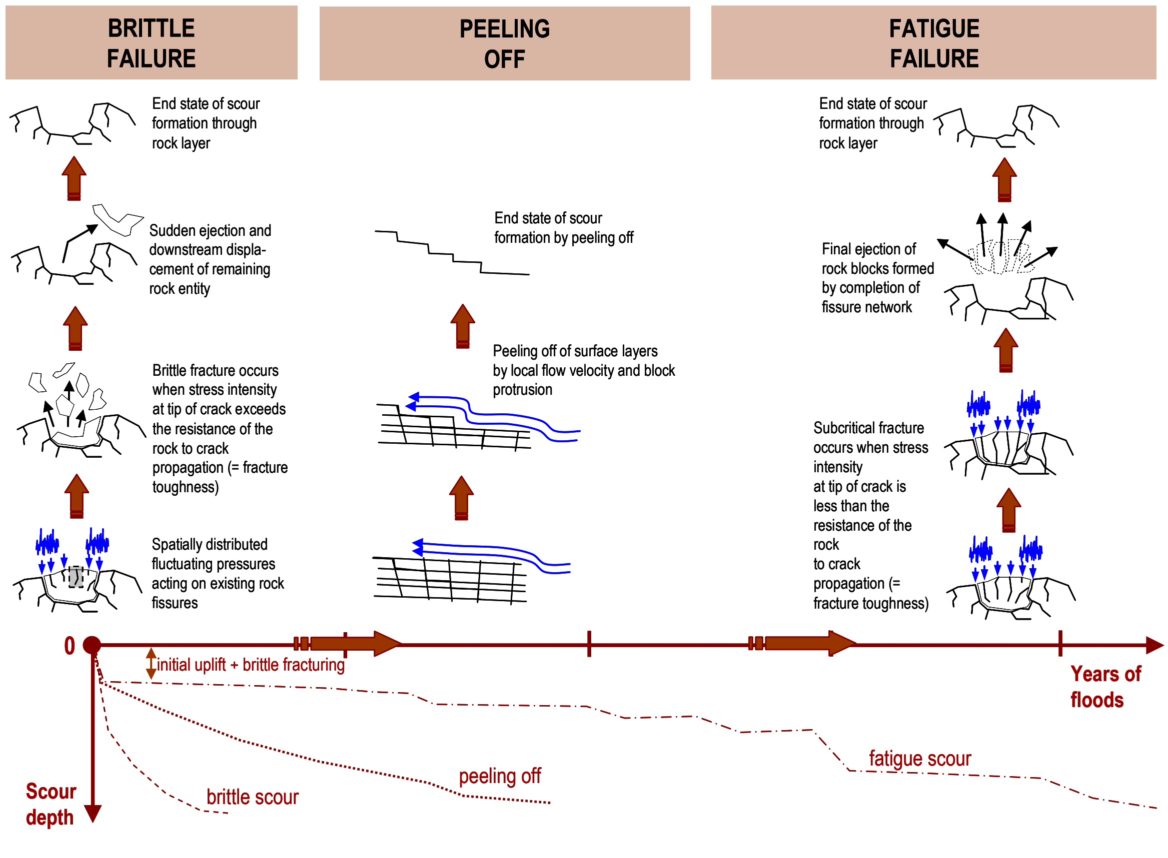

Figure 4. Sequence of failure phenomena of rock

SCALING EFFECTS OF ROCK SCOUR

General

The three phases that govern scour of rock are the impingement of a jet into a plunge pool (liquid phase), the aeration of the jet and the plunge pool (gaseous phase), and finally the rock mass itself (solid phase). Each phase obeys to different laws of similitude. The liquid phase is generally based on Froude similarity, focusing on a correct modelling of the ratio of inertial over gravity forces. The diameter of a plunging jet at impact, for example, is highly influenced by gravitational acceleration, which results in a contraction of the jet. Air entrainment, however, also depends on the Reynolds and the Weber numbers. The aeration characteristics of a free falling jet are dictated by the influences of two opposite forces: the surface tension tends to keep the jet together and is characterized by the Weber number, while the initial turbulence intensity of the jet tries to disperse the jet and is described by the Reynolds number. Finally, break-up and resistance of the solid phase is based on gravity and on fracture mechanics. The latter approach generates rock mass stresses that directly depend on the dimensions and geometry of the fissures and on the in-situ stress field of the rock mass. Hence, no scale model installation is capable to simultaneously satisfy all the similitude criteria. Therefore, priority should be given to an experimental installation that has prototype properties. Such a facility has been developed at the Swiss Federal Institute of Technology in Lausanne (Bollaert, 2002 & 2004) and is illustrated in Figure 5.

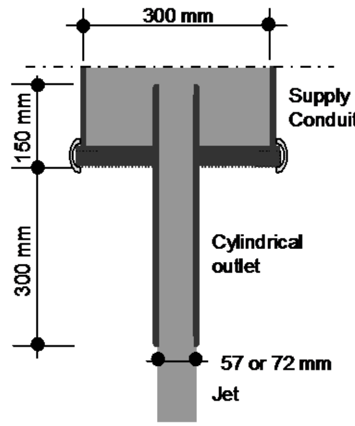

Figure 5. Photo of the facility showing the upstream water supply conduit, the cylindrical jet outlet and the plunge pool basin. Sketch of the cylindrical jet outlet system.

Jet impact velocities are at near-prototype values. This ensures a correct reproduction of the two predominant physical phenomena in the pool: 1) the aeration of the pool due to jet impact, and 2) the turbulent pressure fluctuations generated at the pool bottom. The turbulence at the plunge pool bottom depends, strictly speaking, on the turbulence at impact of the jet and on the geometry of the jet and the pool. The geometrical characteristics are not at prototype scale on the present facility. However, by using near-prototype jet velocities and prototype ratios of pool depth to jet diameter, prototype turbulence could be generated.

Dynamic pressure fluctuations

The dynamic pressures measured at the pool bottom under the jet centreline are presented in Figure 6. The mean pressure values are in good agreement with literature data obtained by small-scale facilities. However, the RMS (root-mean-square) values and the extreme positive and negative values of the pressures are significantly higher on prototype compared to the available small-scale literature data. The increase in RMS pressure fluctuations is on the order of 0.05 to 0.10. The increase in positive extreme pressures is around 0.20 – 0.30. These increased values are merely due to the higher frequency part of the spectral content of an impacting jet, which cannot be generated on a small-scale model. The higher range of frequencies is well simulated on the facility. With scale models the energy in the higher frequencies is dampened by viscosity. Thus, the higher frequency components are generally poorly represented in the spectral density of the pressure fluctuations at the bottom. This means that extreme values are not represented well in scale models, whereas they will be in this facility.

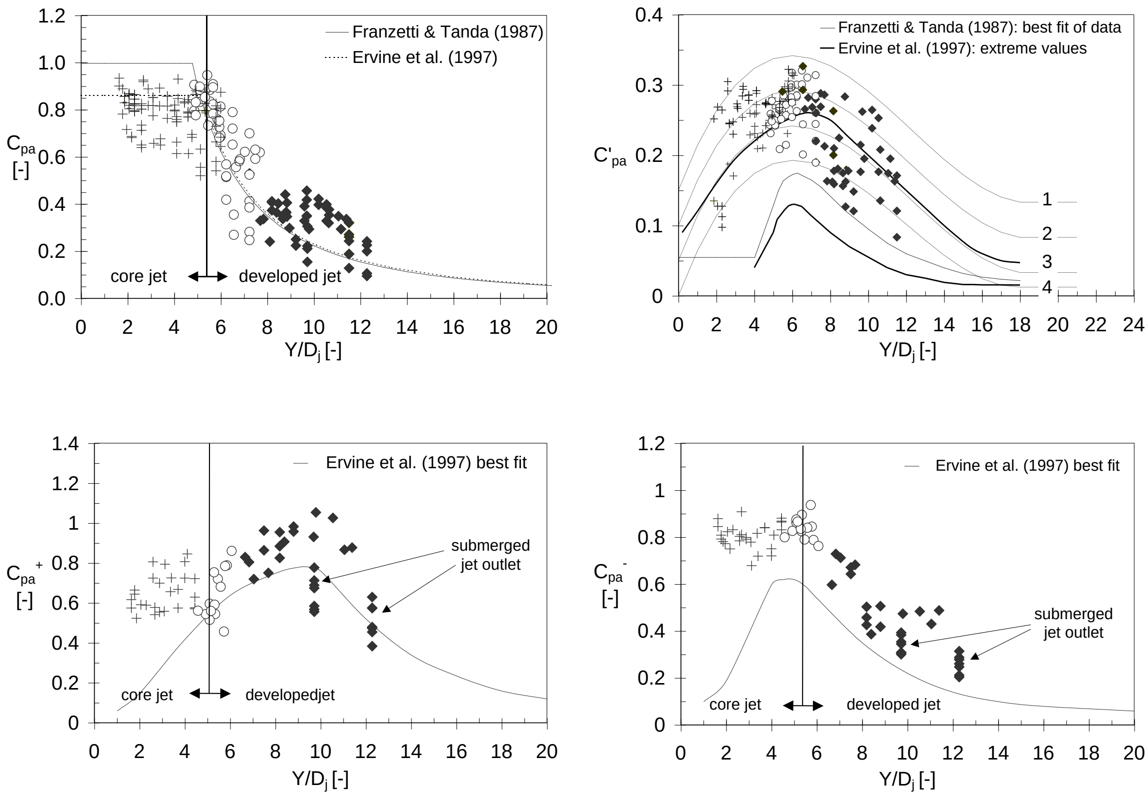

Figure 6. a) Non-dimensional mean dynamic pressure coefficient Cp; b) Non-dimensional fluctuating dynamic pressure coefficient C'p; c) Non-dimensional positive extreme dynamic pressure value Cpa+; d) Non-dimensional negative extreme dynamic pressure value Cpa-.

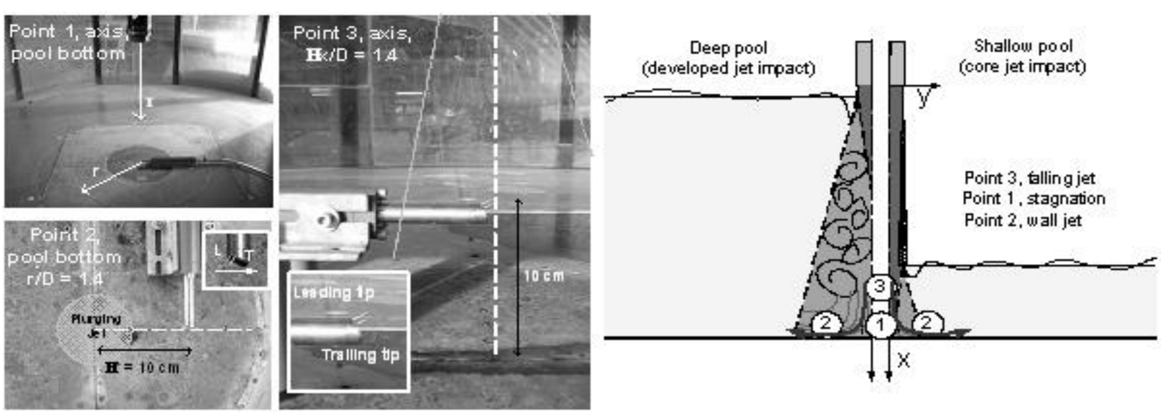

Figure 7. Positioning of optical probe and measurement points of void fraction.

Air content
The facility has been used to measure air concentrations at different locations throughout the pool (Manso et al., 2006), by means of a double fiber-optical probe. Three measurement points (MP) were selected (Figure 7): 1) impingement zone of the jet (MP1), 2) transition to wall jet region (MP2) and 3) just above the impinging jet region (MP3), 10 cm above the pool floor for different pool depths and run times.

The results are presented as a function of jet issuance velocity in Figure 8 for different Y/D ratios, in which Y stands for the pool depth and D for the jet diameter. At the jet's stagnation point (MP1, Figure 8a), measured void fractions were between 2 and 8 %, regardless of the jet velocity. Radially away from stagnation, void fractions reached values up to 40 % (MP2, Figure 8b). In other terms, at low jet velocities ($V < 10$ m/s), void fractions at the jet's stagnation point are quite similar to the ones measured radially outwards, while at high jet velocities, ($V > 20$ m/s), void fractions at the jet's stagnation point are 5-6 times less than the ones measured radially outwards.

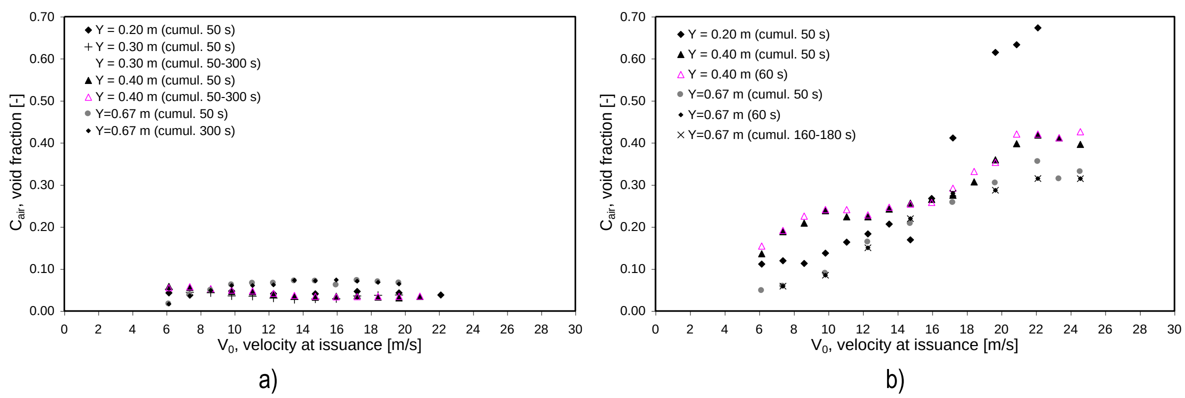

Figure 8. Void fractions measured for different pool depths: a) MP1; b) MP2 & MP3

Hence, the void fraction seems to be related to the pressure built-up when approaching the jet's stagnation point and to the sudden pressure decrease following radial jet deflection after pool floor impact. By applying the ideal gas law, the volume reduction ΔV of a given quantity (mass) of air is inversely proportional to the rise in absolute pressure Δp. The amount of air does not change, only the size of the bubbles changes due to a variation of absolute water pressure.

Following this law, prototype jet velocities are necessary to determine the exact air content near the pool bottom. The air content at the pool floor has a direct influence on the air content inside the joints beneath the rock blocks and thus also on block uplift and fracturing.

PROTOTYPE-SCALED ROCK SCOUR MODEL

The Comprehensive Scour Model

The Comprehensive Scour Model (CSM) has been developed by Bollaert (2002, 2004). The model is entirely physics-based and uses the aforementioned rock scour failure modes to develop the following scour prediction modules:

1. *Dynamic Impulsion (DI) module*: expresses the net uplift displacement and impulsion on single rock blocks as a function of rock block density, dimensions, shape, and of time evolution of net instantaneous uplift forces on the block.
2. *Comprehensive Fracture Mechanics (CFM) module*: expresses brittle or subcritical fissure growth with time as a function of water pressure fluctuations at the boundary, geometry of the fissure, and type and geomechanical characteristics of the rock mass.
3. *Quasi-Steady Impulsion (QSI) module*: expresses the peeling off of thin layers of exposed rock as a function of layer thickness, protrusion, block dimensions and shape, and of local flow velocities near the pool bottom.

Modules 1 and 3 are not time dependent, even if some time is necessary in reality for these processes to occur. Module 2, however, is time dependent and accounts for the time that is needed to let a fissure propagate until a distinct block is being created. This is performed on a layer by layer (block by block) basis in the module.

The near-prototype pressure fluctuations recorded on the experimental facility are used as boundary conditions for each of the modules. After break-up and uplift of a layer of rock blocks, the plunge pool turbulent flow conditions are re-computed and the boundary conditions are automatically updated for the following layer. A detailed description of the CSM model can be found in Bollaert (2002, 2004) or Bollaert and Schleiss (2005).

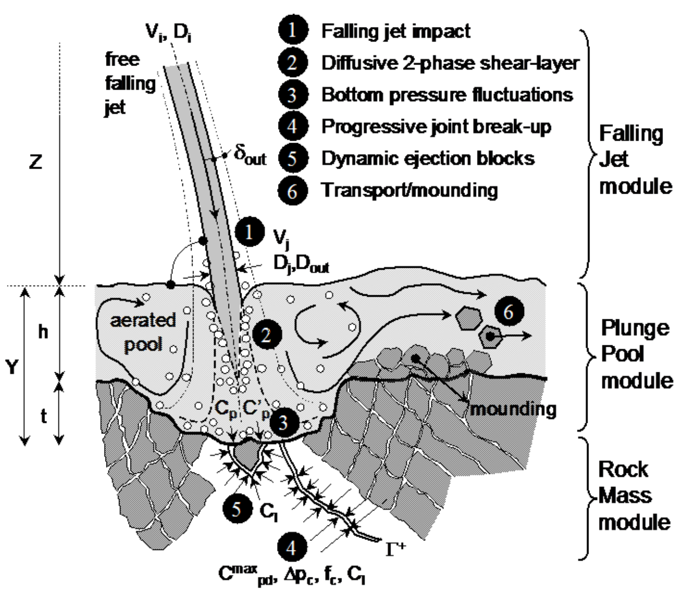

Figure 9. Sketch of physical-mechanical processes generating scour.

Application to Folsom Dam

The DI and CFM modules of the CSM model have been applied to the lined stilling basin of Folsom Dam. Folsom Dam is a concrete gravity dam with a height of about 100 m situated near Sacramento, California, United States. Due to a significant increase of the PMF estimates of the catchment area, compared to the estimates made during dam construction, the outlet works of the dam were initially proposed to be increased. This would have resulted in a significant increase of turbulent pressure fluctuations impacting the concrete lining of the downstream stilling basin.

Hence, at first, a concrete lining stability study has been performed, pointing out the need for significant additional steel anchors to keep the slabs in place. Following this, a rock scour study has been performed of the fractured rock mass underneath the concrete lining, to check for scour formation and extent under extreme conditions and following potential lining failure. In the following, examples are provided of the kind of results that were provided by both modules for the PMF event at Folsom Dam (Bollaert et al. 2006).

Figure 10 presents a plan and perspective view of the final 3D shape of the scour hole through the rocky foundation of the stilling basin. Figure 11 illustrates the time evolution of this scour formation along a longitudinal section through the stilling basin.

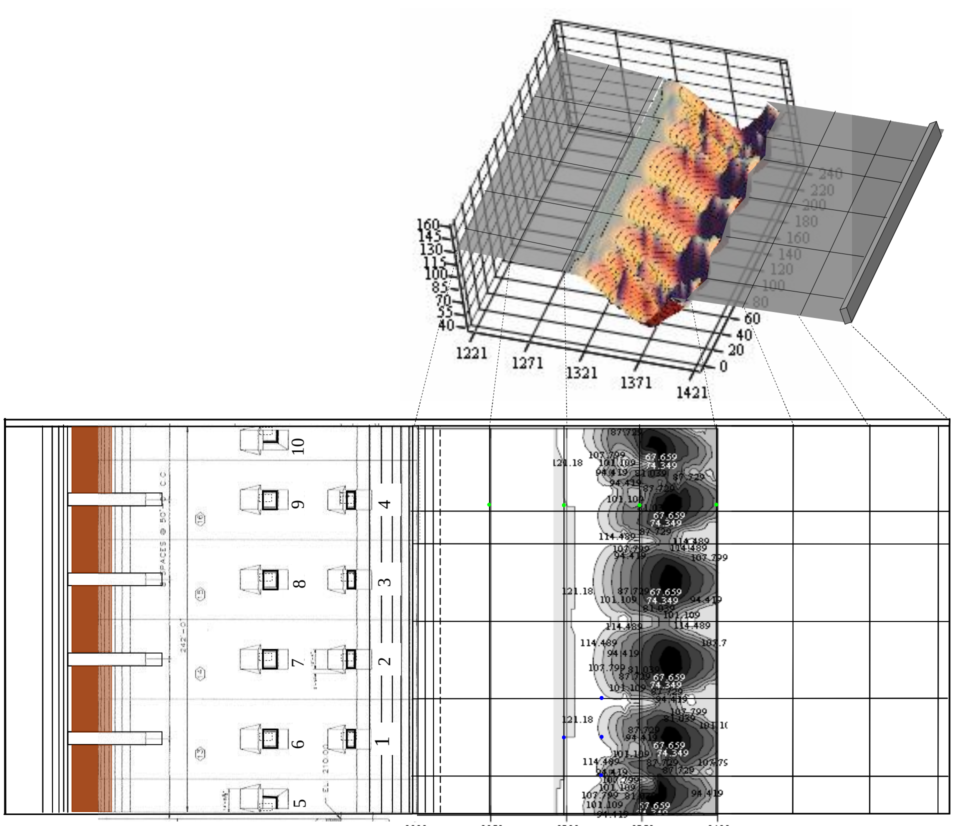

Figure 10. Plan view and perspective view of scour contours in stilling basin due to upper tiers functioning.

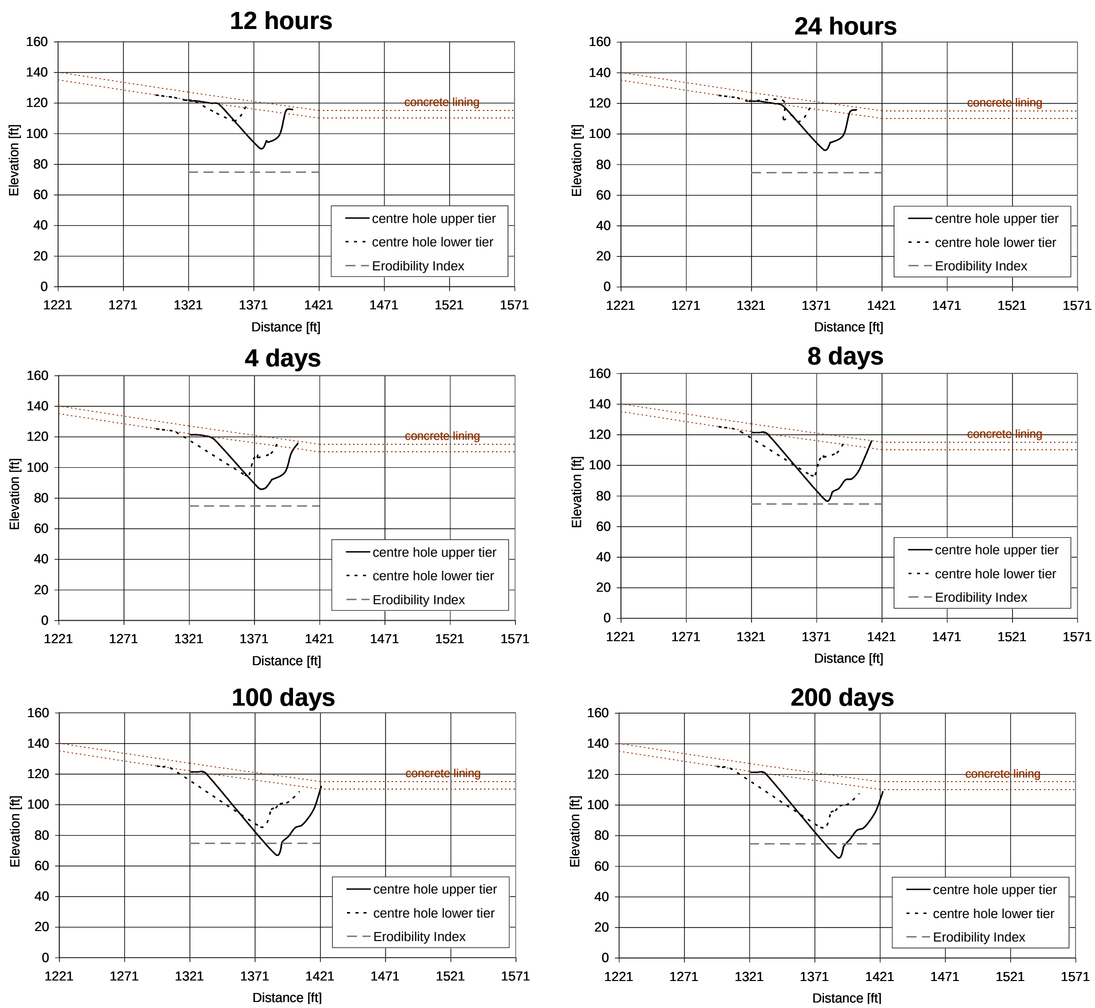

Figure 11. Scour formation in stilling basin due to upper or lower tiers functioning during PMF event and as a function of discharge duration.

One can easily detect the areas of impact of the jets issuing from the outlet works in Figure 10. Also, it can be seen in Figure 11 that the model predicts 20-30 ft of scour formation within the first 12-24 h of a PMF flood, while subsequent scour deepening would need far more time to occur. Finally, no scour forms near the toe of the dam.

CONCLUSIONS

The present paper outlines the main mechanisms of scour of fractured rock in plunge pools and riverbeds impacted by high-velocity turbulent flows. These mechanisms of break-up are significantly different from the traditional shear-stress based erosion principles applied in hydraulics. They involve a complex interaction between the gas, liquid and solid phases and cannot be appropriately scaled in a laboratory model. As such, sound assessment of their behaviour needs prototype scaled approaches.

Based on a vast series of experimental tests at near-prototype scale and complementary numerical modelling of turbulent pressure fluctuations generated at the water-rock interface, a comprehensive scour model has been developed incorporating the main mechanisms of scour of fractured rock in a physics based manner. Application of the scour model provides rock scour formation with time of flooding and the ultimate scour extent for each of the break-up mechanisms described in the present paper. When calibrated based on past flood events and related scour formation, the model is particularly suited to predict future scour evolution as a function of future flood events.

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