Rock behavior in plunge pools of high-head dams

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ABSTRACT: The behavior of unlined rocky foundations in plunge pools and stilling basins of high-head dams is governed by an interaction between aerated high-velocity turbulent flow and a fractured rock mass. During dam crest overflows or spillway functioning, the rock mass located immediately downstream is generally subjected to scour. In some cases, the so formed scour hole may even endanger the stability of the dam and its appurtenant structures. Prediction of the behavior and time evolution of fractured rock in plunge pools is complex and, today, remains very difficult to assess by means of straightforward mathematical techniques. Major problems in developing rock scour assessment methods are the geo-mechanical behavior of the in-situ rock mass and the fact that the physics involved cannot be described and tested on a laboratory scale. The present paper first outlines the major physics and the behavior of scour formation of fractured rock in plunge pools and stilling basins. Second, a physical based and prototype scaled rock scour prediction method is presented. The model has been developed based on prototype-scaled measurements of turbulent pressure fluctuations at water-rock interfaces and inside single rock joints, both of which have been reproduced in an experimental facility. The facility allows generating turbulent air-water flows of up to 35 m/s and is capable to record the corresponding water pressures and hydraulic jacking effects generated by the turbulent flow inside the underlying rock joint. 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, such as for example fracture mechanics, is able to predict the scour evolution with time of a rocky foundation.

1 PHYSICS OF ROCK SCOUR

1.1 *Introduction*

Rock scour occurs when the erosive capacity of water exceeds the ability of the 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 block fracturing (suddenly or progressively with time),
3. rock mass and block abrasion (long term agents).

The first two processes are discussed in more detail further on. The relevance 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.

As such, use of a near-prototype scaled experimental facility at the Laboratory of Hydraulic Constructions of the EPFL has allowed recording pressure fluctuations generated by near-prototype high-velocity jets 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.

1.2 *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 for example 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.

1.3 *Rock block removal (by uplift and/or displacement)*

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) = F_{QSL}
3. turbulent uplift forces = f(turbulent pressure fluctuations) = F_{TUL}

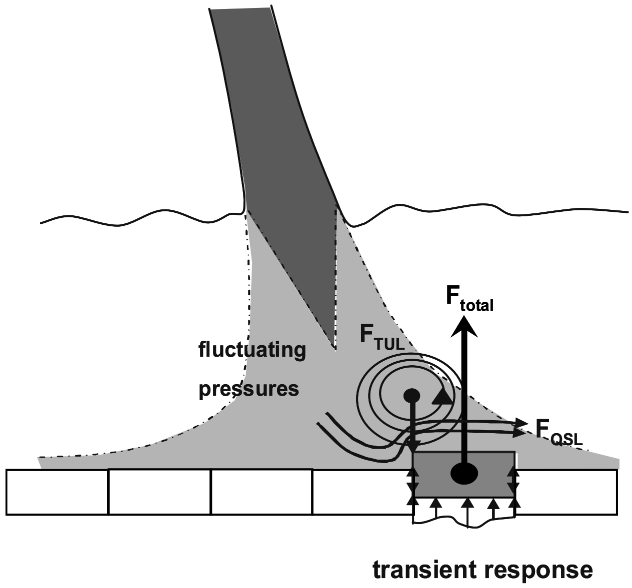

Figure 1. Rock block removal by uplift

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 Ecole Polytechnique Fédérale de Lausanne (EPFL)to solve this complex correlation. 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 (Federspiel et al. 2009).

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).

1.4 *Rock mass/block fracturing*

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.

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).

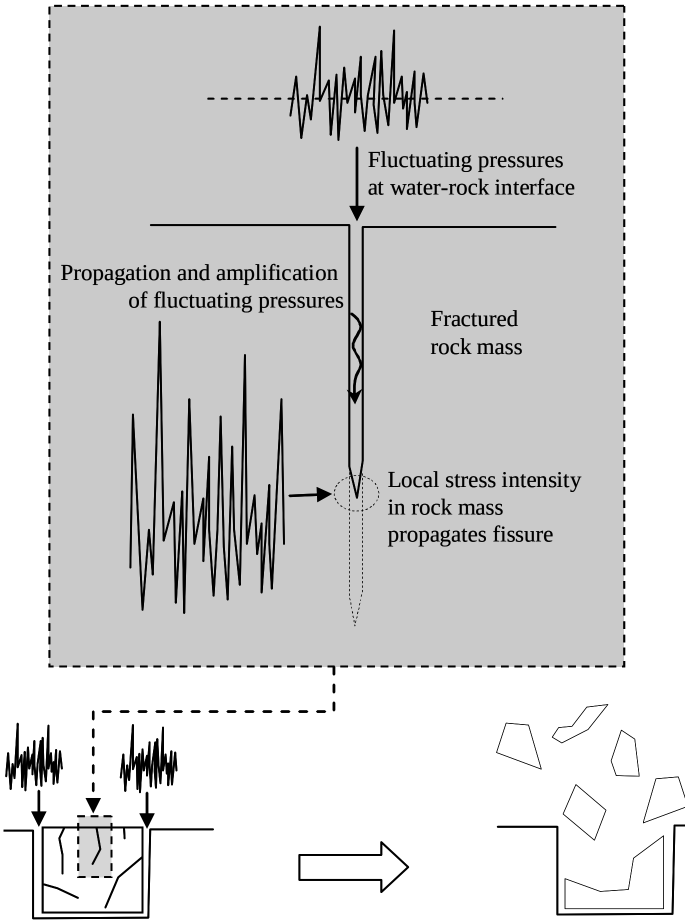

Figure 2. Rock block fracturing

2 SCOUR PREDICTION MODEL

2.1 *Prototype-scaled experimental facility*

An experimental installation simultaneously measures dynamic water pressures at plunge pool bottoms and inside underlying, artificially created rock joints. The main elements of the installation are a plunging high-velocity jet, a plunge pool and a single rock joint (Bollaert 2002).

The jet is modeled by means of a cylindrical outlet. The plunge pool is simulated by a 3 m diameter reinforced Lucite basin. The rock joint is modeled by two 100 mm thick steel plates with a surface of 1 m2. Between these two plates, a 1 mm thin stainless steel strip has been sandwiched by means of 10 pre-stressed steel bars (36 mm diameter). The shape of the joint is then defined by cutting this shape out of the steel strip before insertion. Micro-pressure sensors have been integrated in the plunge pool bottom and inside the steel plates. These sensors are flush-mounted and allow measuring the water pressures at an acquisition rate of maximum 20 kHz. Emphasis is given on the near-prototype character of the facility, by using centerline jet velocities of up to 30 m/s and by using prototype-scaled planar rock joints. The jet diameter is 57 mm or 72 mm and the plunge pool water depth can be set between 0 and 1 m. The latter range represents small-scale values but should not be considered as geometrically scaled real values.

The plunge pool water depth aims at diffusing the impacting jet, such that prototype aeration and turbulence conditions are generated in the turbulent shear layer at the water-rock interface. These conditions are mainly governed by the velocity and the initial turbulence intensity of the impacting jet. The former is at prototype scale. The latter has been measured and was found to be representative for prototype falling jets (values of 3 to 6 %).

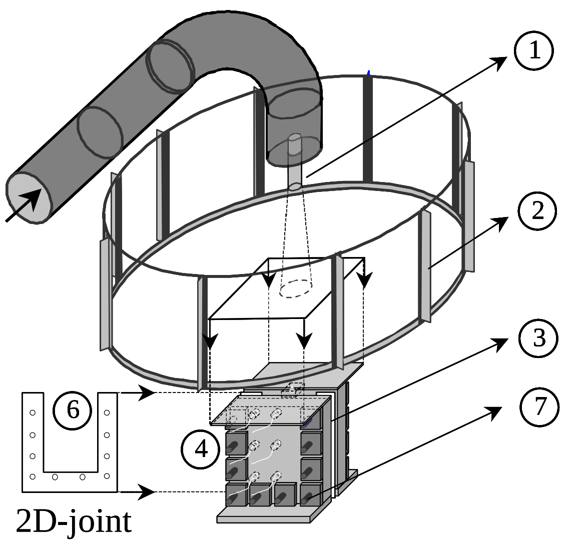

Figure 3. Perspective view of the facility: 1) cylindrical jet, 2) reinforced plastic basin, 3) pre-stressed steel structure, 4) PC-DAQ and sensors, 5) restitution system, 6) steel sheeting pre-stressed between steel structure, 7) pre-stressed steel bars (Bollaert, 2002).

2.2 *The Comprehensive Scour Model*

The Comprehensive Scour Model (CSM) has been developed by Bollaert (2002, 2004) and Bollaert & Schleiss (2005). 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*: 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*: 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.

Module 1 is 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).

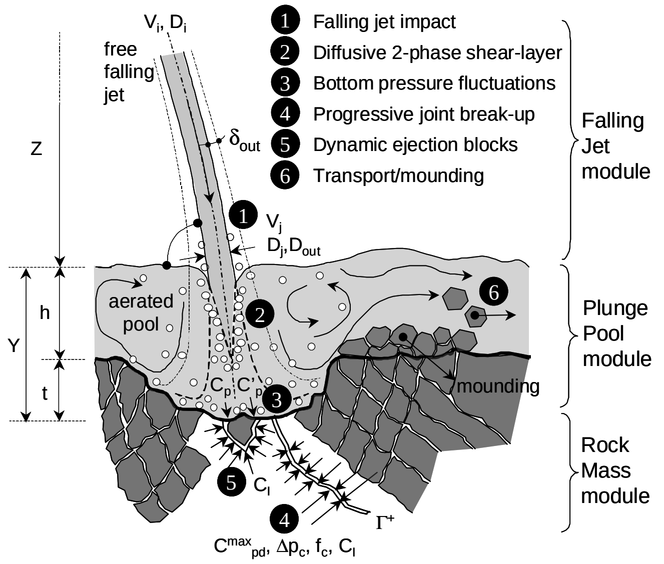

Figure 4. Sketch of physical-mechanical processes generating rock scour

3 CONCLUSIONS

Based on a sound analysis of the physics pertinent to rock scour behind high-head dams, near-prototype scaled experimental pressure measurements of falling high-velocity jets have allowed developing a physics based rock scour prediction method available to practicing engineers.

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