Rock Scour at Hydraulic Structures: A Practical Engineering Approach

By E.F.R. Bollaert, C.E., PhD

INTRODUCTION

Rock scour occurs when the erosive capacity of water flowing over it exceeds the ability of the rock to resist. Typical environments are overtopping dams and spillways, plunge pools and stilling basins, bridge piers and abutments, coastal protection structures, unlined rock tunnels, etc.

Assessment of rock scour needs sound comprehension of the erosion characteristics of turbulent flows leading to scour. Similarly, it is necessary to understand the failure mechanisms of rock. Fluvial erosion of rock as it appears in the vicinity of engineering structures mainly occurs following three physical-mechanical processes:

1. rock block removal (pressures in joints or shear flow),
2. rock mass fracturing (suddenly or progressively),
3. rock block abrasion (long term).

Each of these processes has its own time-scale of occurrence, ranging from instantaneous to long term. While certain short term actions have been rather well described in literature, sound assessment of medium and long term fluvial actions on fractured rock is still in its initial phases of development. Their relevance to scour depends on the characteristics of the turbulent flow and on the shape and the protrusion of the rock blocks. For small-sized rocky material, shear flow is generally predominant, just like for a granular riverbed. For large-sized irregular rock blocks, however, the shape, dimensions and protrusion of the blocks significantly impact the failure process. Dynamic water pressures build up at the water-rock interface. The assessment of the fluctuating part of these pressures inside joints between blocks is a key factor for appropriate modeling of rock scour.

MECHANISMS OF ROCK SCOUR

<u>Rock block removal</u>

Rock may fail by removal of distinct blocks. This may happen by uplift (quasi-vertical ejection), by horizontal displacement, or by a combination of both movements. Flow turbulence is thereby of utmost importance, because shear stress based concepts often cannot explain how large blocks can be removed or how turbulent flow can break up blocks into smaller pieces. Which one of the movements will be most plausible depends on the size, dimensions and protrusion of the blocks compared to the surrounding rock mass. These parameters directly define the relevance 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)

Uplift of a rock block may be estimated in a simple manner 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. During time periods for which the net force balance on the block remains positive (lift), the block will start to move. This uplift impulsion is transformed into an uplift velocity given to the block. Finally, the uplift velocity is transformed into an uplift height. The net uplift force is thereby assumed independent of the movement of the block, movement that progressively increases the volume of the joint between the block and the surrounding mass.

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. 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 high-velocity air-water jet.

Figure 1 illustrates the pressure fluctuations over and under a block at a bridge pier founded on rock. The pressures in the rock joints are thereby computed by a two-phase transient wave propagation model, based on the pressure fluctuations at the joint entrances between the blocks.

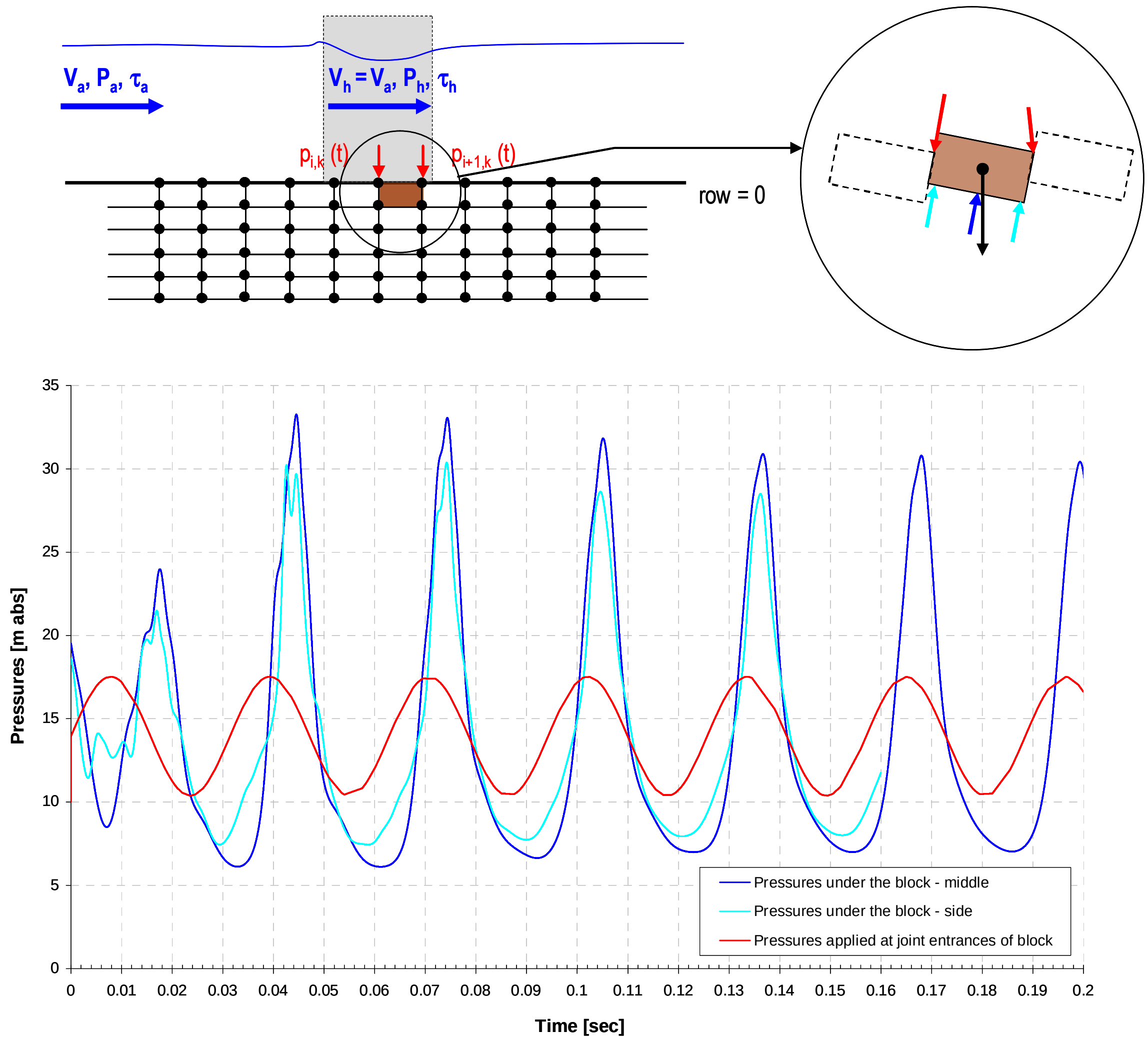

Figure 1. Pressure fluctuations over and under a rock block at a bridge pier foundation

Rock mass fracturing

Rock may also fail by sudden or progressive hydraulic fracturing, which is mathematically described by the theory of linear elastic fracture mechanics.

Brittle fracture occurs when the stress intensity (in the rock mass) at the edges of closed-end fractures is greater than the in-situ fracture toughness of the rock (Bollaert, 2002). The stresses induced by water pressures at fracture tips are governed by the geometry of the fracture and the stabilizing support of the surrounding rock. The in-situ fracture toughness of the rock depends on the mineralogical composition of the rock, the in-situ stress field and the unconfined compressive strength (UCS) or tensile strength of the rock mass. Hence, independent of the fracture patterns, soft sedimentary rocks will be more vulnerable to fracture propagation than granitic or basaltic rocks for example. Figure 2 presents the laboratory-measured fracture toughness of a range of different rocks. These values are adapted to in-situ conditions by accounting for the confining pressure σ_c. A general expression, independent of the type of rock mass, has been proposed by Bollaert (2002):

$$K_{I\,ins} = (0.008 \text{ to } 0.010) \cdot UCS + (0.054 \bullet \sigma_c) + 0.42$$

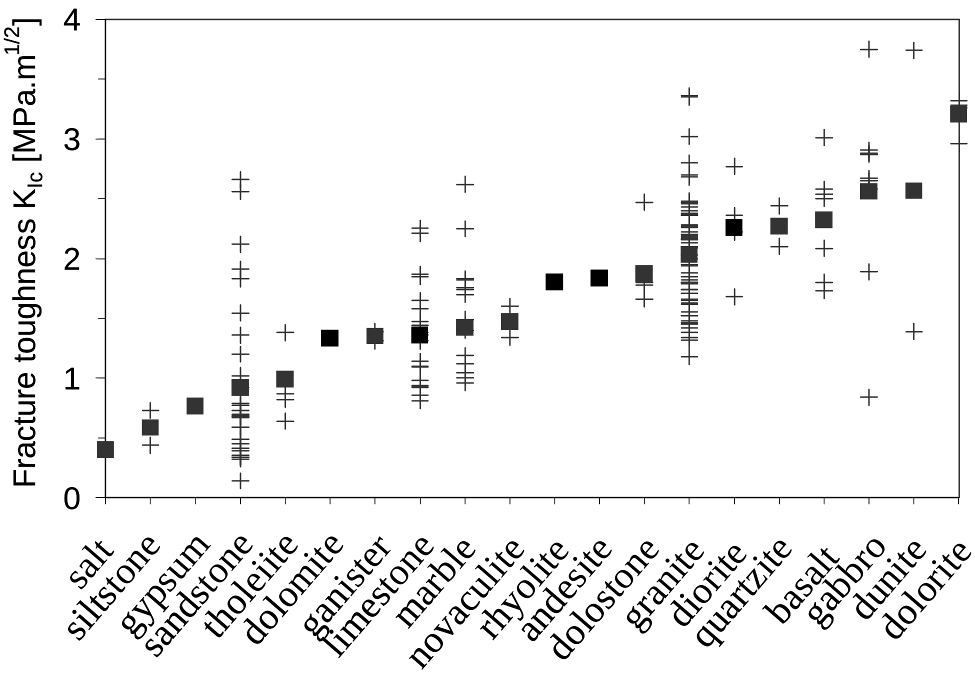

Figure 2. Fracture toughness K_{Ic} of different types of rock (Bollaert, 2002)

Brittle fracturing breaks up the rock mass into distinct blocks, or the already existing blocks into smaller pieces. During real-life floods, brittle fracturing may occur during peak pressure pulses entering the rock fractures at the bottom of the plunge pool or rocky riverbed.

Second, progressive fracturing of rock occurs when the stress intensities do not exceed the fracture toughness. Prototype-scaled laboratory tests have shown the presence of severe air-water transient pressure waves inside rock joints (Bollaert, 2002; Bollaert & Schleiss, 2005). These will, on the medium or long term, propagate an existing fracture by fatigue, depending on the number and the intensity of pressure pulses inside. This failure type is thus time-dependent and takes an end when fracture formation is completed. An example of scour by progressive fracturing is shown at Figure 3 following the PMF event at a high-head US dam (Bollaert, 2006).

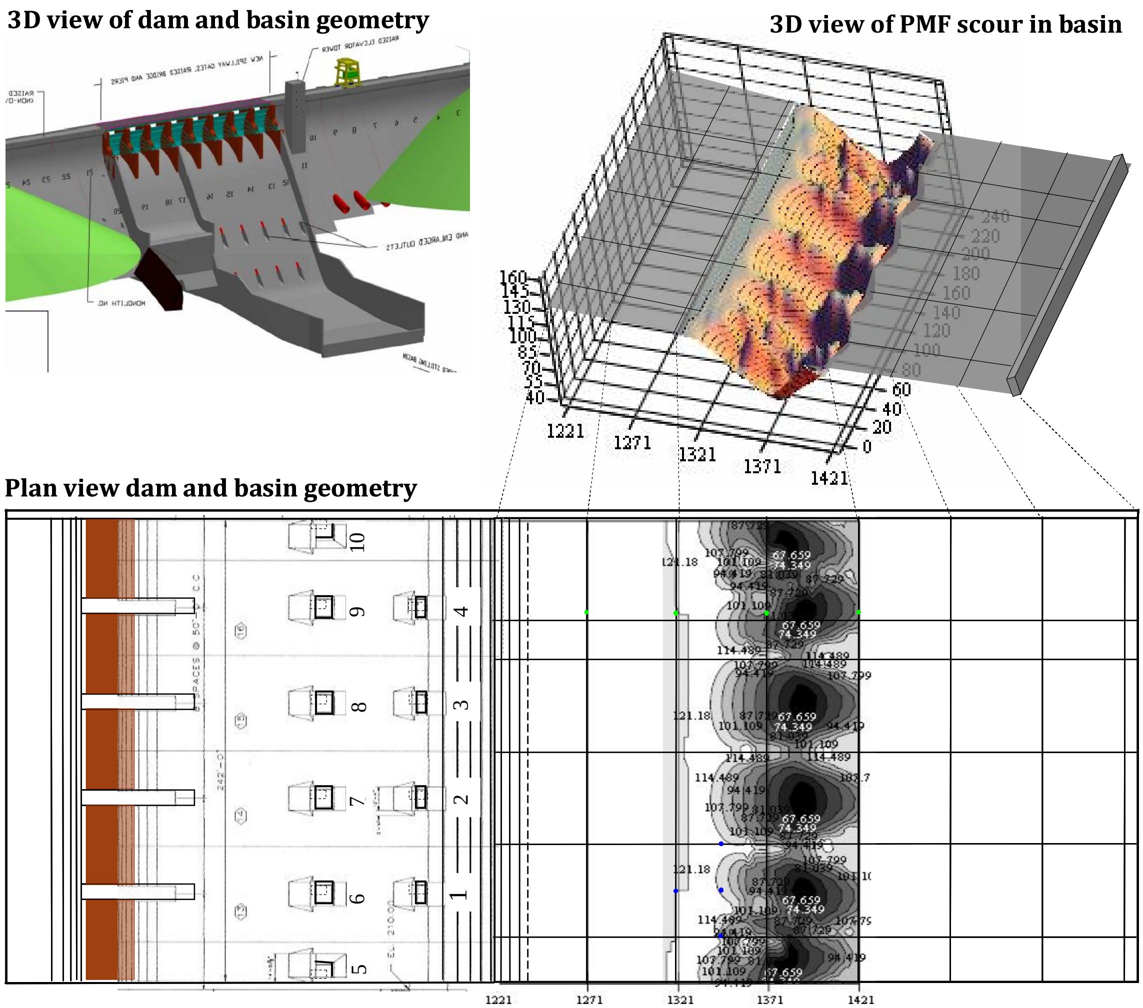

Figure 3. PMF scour formation downstream of US dam by progressive fracturing

<u>Rock block peeling off</u>

Peeling off of blocks is a specific combination of both quasi-steady forces and brittle or fatigue fracturing. The phenomenon typically occurs in case of thin near-horizontal rock layers. The destabilizing forces are not due to flow turbulence alone, but are principally generated by a local flow deviation due to a protrusion of the block along the bottom. 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 and by the local quasi-steady flow velocity in its immediate proximity.

The corresponding pressures may develop brittle or fatigue fracturing of the joint between the block and the underlying rock. In case the exposed block is detached or almost detached, no further fracturing is needed to uplift the block by pressure fluctuations entering laterally into the joint.

Rock mass/block 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 and, because of its lengthy time scale, often neglected compared to the other failure mechanisms.

Summary of failure mechanisms

Figure 4 summarizes the most pertinent failure mechanisms of fractured rock in the vicinity of hydraulic structures, distinguishing between instantaneous and time-dependent processes.

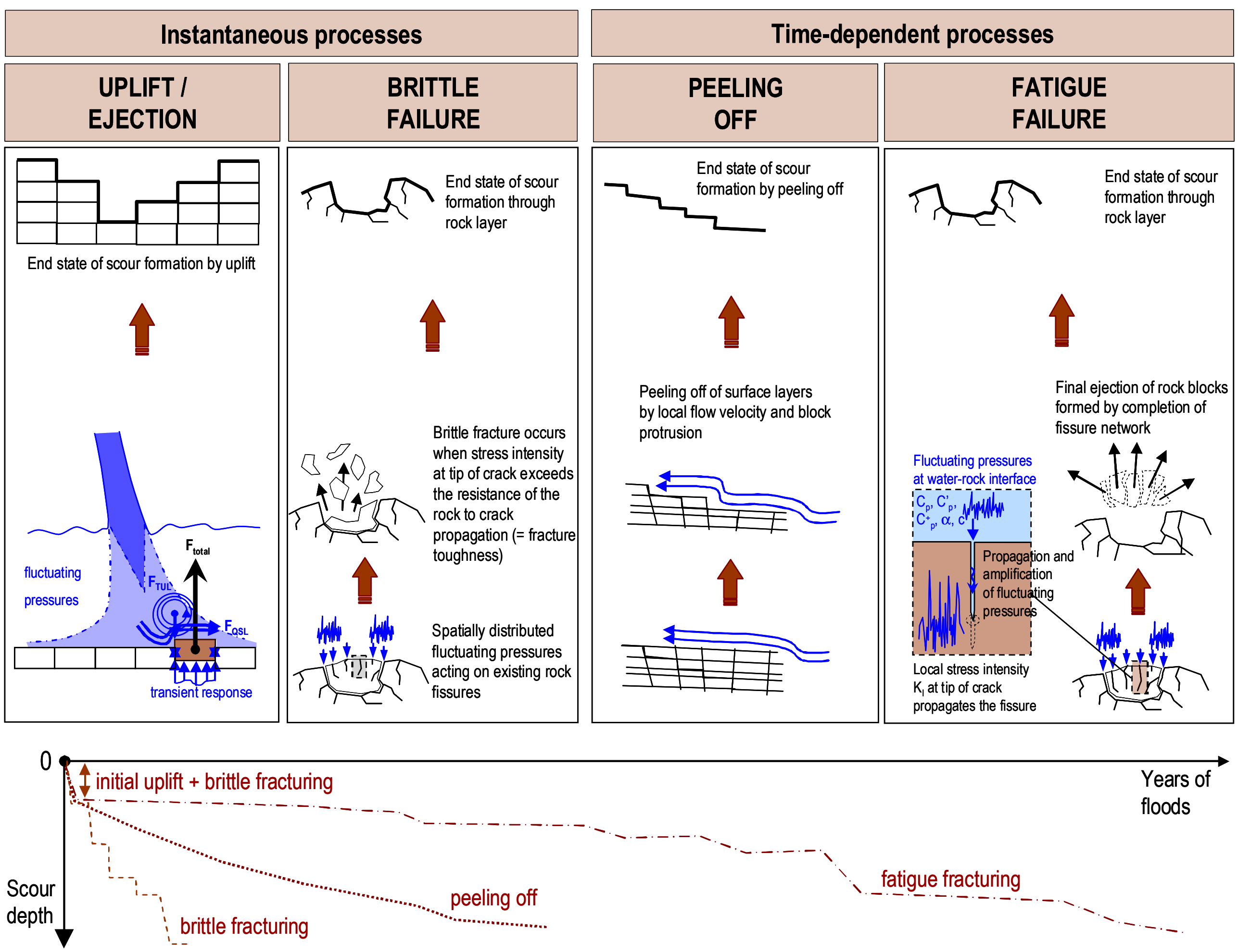

Figure 4. Principle failure mechanisms of fractured rock at hydraulic structures

ROCK SCOUR PREDICTION MODEL

The Comprehensive Scour Model (CSM) has been developed by Bollaert (2002, 2004), based on a vast series of prototype-scaled turbulent pressure measurements in artificially created rock joints. The model is physics-based and uses the aforementioned failure modes to develop the following scour prediction modules:

1. *Dynamic Impulsion (DI) module*: net uplift and impulsion on single rock blocks as a function of density, dimensions, shape and time evolution of instantaneous forces on the block.
2. *Comprehensive Fracture Mechanics (CFM) module*: brittle or progressive fracture propagation as a function of pressure fluctuations, fracture geometry, and geomechanical characteristics of rock.
3. *Quasi-Steady Impulsion (QSI) module*: peeling off of blocks along thin layers as a function of layer thickness, protrusion, block dimensions and shape, and of local flow velocities near the interface.

Module 1 is not time dependent, even if some time is necessary in reality for these processes to occur. Module 2 is time dependent. Module 3 is either instantaneous or time-dependent. The scour computations are performed on a layer by layer (block by block) basis in each module. Turbulent pressure fluctuations are thereby used as boundary conditions. After break-up and uplift of a layer of blocks, turbulent pressures are automatically adapted and updated for the next layer.

The model is in principle applicable to any kind of fractured rock and flow environment, provided that flow turbulence can be readily defined at the interface. Current developments and applications exist for plunge pools, chutes, stilling basins and bridge pier foundations.

CONCLUSIONS

The principle failure mechanisms of fractured rock impacted by turbulent flows are outlined. These are significantly different from the traditional shear-stress based erosion principles applied in hydraulics. 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. The model computes rock scour with time of flooding and determines the ultimate scour depth for each of the failure mechanisms and for any kind of fractured rock. 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, for any kind of turbulent flow environment.

Biography

Erik F.R. Bollaert, PhD, is Civil Engineer and President of AquaVision Engineering, an engineering company based in Lausanne, Switzerland, and specializing in scour and erosion of rocks and soils in fluvial environments. He can be reached at: admin@aquavision-eng.ch.