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Scour of rock due to the impact of plunging high velocity jets Part I: A state-of-the-art review

Affouillement du rocher par impact de jets plongeants à haute vitesse Partie I: Un résumé de l'état des connaissances

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ABSTRACT

This paper presents the state-of-the-art on methods to estimate rock scour due to the impingement of plunging high velocity water jets. The following topics are addressed: empirical formulae, semi-empirical and analytical approaches, determination of extreme pressure fluctuations at plunge pool bottoms and, finally, the transfer of these pressure fluctuations in joints underneath concrete slabs or rock blocks. Available methods on rock scour have been thoroughly investigated on their ability to represent the main physical-mechanical processes that govern scour. This reveals lack of knowledge on turbulence and aeration effects, as well as on transient pressure flow conditions in rock joints. These aspects may significantly influence the destruction of the rock mass and should be accounted for in scour evaluation methods. Their relevance has been experimentally investigated by dynamic pressure measurements at modeled plunge pool bottoms and inside underlying one-and two-dimensional rock joints. Test results are described and discussed in Part II of this paper.

RÉSUMÉ

Le présent article résume le savoir-faire des méthodes d'évaluation de l'affouillement du rocher due à l'impact de jets d'eau à haute vitesse. Il traite notamment des formules empiriques et approches analytiques, des fluctuations de pressions extrêmes dans des fosses d'affouillement, et finalement du transfert de pressions dynamiques sous des dalles en béton ou des blocs de rocher. Une comparaison de l'état actuel des connaissances avec les processus physiques du phénomène indique un manque de savoir-faire dans les domaines de la turbulence et de l'aération, ainsi que des écoulements non-stationnaires dans les fissures du rocher. Ces aspects peuvent fortement influencer la destruction du rocher et, par conséquent, doivent être considérés dans des méthodes d'évaluation. Leur importance a été investiguée expérimentalement par des mesures de pressions dynamiques sur le fond de fosses d'affouillement et à l'intérieur de fissures du rocher. Les résultats des mesures sont décrits et discutés dans la Partie II de l'article.

Keywords: Rock scour; state-of-the-art; transient pressure waves; future research.

1 Introduction

Hydraulic structures spilling excess water from dam reservoirs have been a major engineering concern for a long time. The transfer of water to the downstream river may scour the dam foundation and the downstream riverbed. On the long term, this scour process may create structural safety problems. Hence, accurate prediction of time evolution and ultimate scour depth is required.

Ultimate scour depth is traditionally estimated by use of empirical or semi-empirical formulae that partially neglect basic physical processes involved. Especially the role of fluctuating dynamic pressures in plunge pools and their transfer inside underlying rock joints is unknown. Also, empirical expressions are often only applicable to the specific conditions for which they were developed (Whittaker and Schleiss, 1984). They neglect the influence of aeration on dynamic pressures and cannot correctly simulate the resistance of the rock against progressive break-up.

Since the 1960's, fluctuating dynamic pressures have been measured and described by their statistical characteristics. Hence, methods based on extreme positive and negative pressure pulses clarified dynamic uplift of stilling basin concrete linings and scour hole formation in jointed rock. During the 1980's and 1990's, the influence of time-averaged (Montgomery, 1984; Reinius, 1986; Otto, 1989) and instantaneous (Fiorotto and Rinaldo, 1992; Liu *et al.*, 1998; Fiorotto and Salandin, 2000) pressure differences over and under concrete slabs or rock blocks has been investigated experimentally and described theoretically.

Scouring is a highly dynamic process that is governed by the interaction of three phases (air–water–rock). This dynamic character is highlighted by the appearance of significant transient pressure wave phenomena (oscillations, resonance conditions) inside rock joints, due to the bounded geometry of the joints. Two physical processes are of major importance: (1) hydrodynamic jacking, causing a break-up of the rock mass by progressive

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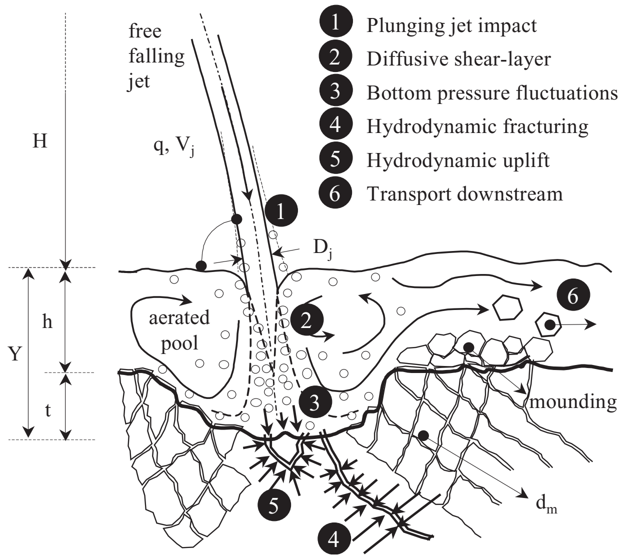

Figure 1 Main parameters and physical-mechanical processes responsible for scour formation.

growing of its joints and faults, and (2) hydrodynamic uplift, ejecting distinct rock blocks from their mass. Presently, no approach is able to describe these phenomena, due to their complex behavior. More reliable scour evaluation should account for the influence of transient pressure wave phenomena on the instantaneous pressures inside rock joints.

Scour formation can be described by a consecutive series of physical-mechanical processes (Fig. 1): (1) aerated jet impact, (2) turbulent shear-layer diffusion in plunge pool, (3) fluctuating dynamic pressures at the water–rock interface, (4) propagation of these pressures into underlying rock joints and hydraulic fracturing of the rock, (5) dynamic uplift of single rock blocks, and finally (6) downstream displacement and/or deposition (mounding) of the broken-up material.

An overview of existing scour evaluation methods distinguishes between empirical formulae (based on field or laboratory observations), combined analytical-empirical methods (combining empiricism with some physical background), methods that consider extreme values of fluctuating pressures at the plunge pool bottom, and, finally, methods based on time-averaged or instantaneous pressure differences over and under the rock blocks. At the end of the paper, a theoretical framework for a physically-based method to evaluate rock scour and its time evolution is outlined. The method is based on the transient and two-phase nature of air–water pressure wave propagation inside rock joints.

2 Existing methods to evaluate ultimate scour depth

2.1 Parametric synthesis

Table 1 provides an overview of the most common methods to evaluate scour due to high-velocity plunging jets: empirical formulae, semi-empirical expressions, plunge pool bottom pressure fluctuations and pressure difference techniques. The parameters that are used by each of these methods are subdivided into three groups, according to the relevant phases (water, rock and air). Time evolution is added as a fourth group.

2.2 Empirical expressions

Empirical formulae are a common tool for hydraulic design criteria because easy to apply. Model and prototype results are related to the main parameters of the formula in a straightforward manner, by use of some general mathematical technique (e.g. dimensional analysis). With a minimum of physical background, a global evaluation of the problem is performed and general tendencies can be outlined.

However, the complete physical background is not accounted for and special care has to be taken when applying these formulae. This was pointed out by Mason and Arumugam (1985), who analyzed a large number of existing formulae. The accuracy of the different formulae showed substantial differences whether model or prototype conditions were used as input for the parameters. Beside the difficulty to simulate geomechanic aspects or flow turbulence on laboratory scaled model tests, this points out that empirical formulae may be affected by significant scaling effects.

General scour expression

In general, scour formulae valid for plunging jet impact express the ultimate scour depth Y [m], defined as the scour depth beyond the original bed level, t [m], plus the tailwater depth, h [m], according to the specific discharge, q [m^2/s], the fall height, H [m], and the characteristic particle diameter of the downstream riverbed, d [m]. Some authors (e.g. Martins, 1973) added the tailwater depth h [m] as specific parameter in the formula. Mason and Arumugam (1985) compared the application of 25 such formulas to 26 sets of scour data from prototypes and 47 sets of scour data from model tests. Their best fit of both model and prototype conditions resulted in the following general form (see Fig. 1 for parameters):

$$Y = t + h = K \cdot \frac{H^y \cdot q^x \cdot h^w}{g^v \cdot d_m^z} \tag{1}$$

where $K = (6.42 - 3.10 \cdot H^{0.10})$, $v = 0.30$, $w = 0.15$, $x = (0.60 - H/300)$, $y = (0.15 - H/200)$ and $z = 0.10$.

This dimensional formula (using SI units) is applicable for free jets issuing from flip buckets, pressure outlets and overflow works. It gives results with a standard deviation of the results of 25% for model test conditions and 30% for prototype test conditions. The applicability for the fall height H lies between 0.325 and 2.15 m for models, and 15.82 and 109 m for prototypes. It covers cohesive and non-cohesive granular models, with model mean particle sizes d_m between 0.001 and 0.028 m. For prototype rock, it considers a mean equivalent particle size d_m of 0.25 m. Mason and Arumugam also found that consideration of the jet impact angle (Mirtskhulava *et al.*, 1967; Martins, 1973; Chee and Kung, 1974; Mason, 1983) didn't improve the accuracy of the results. This is in accordance with a study performed by Fahlbusch (1994), who found that a jet impact angle of 60° to 90°, which covers most of the angles encountered in practice

Table 1 Existing methods to evaluate ultimate scour depth and summary of hydraulic, geomechanic and aeration parameters. (References from before 1984 are given in Whittaker and Schleiss, 1984, and/or Mason and Arumugam, 1985, the other references are listed at the end of the article.) Authors marked with * propose an expression based on prototype conditions or observations.

Type	Year	Author(s)	Applicability	Time	Hydraulic characteristics									Geomechanical characteristics									Aeration characteristics			
					Hydrostatic						Hydrodynamic			Gran. soil			Jointed rock mass									
				T [-]	q [m^2/s]	h [m]	H [m]	g [m/s^2]	V_j [m/s]	θ [°]	RMS [-]	$S_{xx}(f)$ [m^2]	trans [-]	d_m [mm]	w_s [m/s]	ρ_s [kg/m^3]	σ_c, σ_t [N/m^2]	RQD [%]	N_j [-]	z [-]	α [°]	ϕ_j [°]	C [-]	β [-]	Tu [%]	L_b [m]
Empirical	1932	Schoklitsch	plunging jet	–	■	–	■	–	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1937	Veronese A	horiz. & plunging jet	–	■	–	■	–	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1937	Veronese B	as A, but $d_m < 0.005$ m	–	■	–	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1939	Jaeger	plunging jet	–	■	■	■	–	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1953	Doddiah *et al.*	plunging jet	■	■	–	■	–	–	–	–	–	–	■	■	–	–	–	–	–	–	–	–	–	–	–
	1957	Hartung	plunging jet	–	■	–	■	■	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1963	Rubinstein	ski-jump, rock cubes	–	–	■	■	■	■	■	–	–	–	–	–	–	–	–	–	■	–	–	■	–	–	–
	1966	Damle *et al.**	ski-jump	–	■	–	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1967	Kotoulas	plunging jet	–	■	–	■	–	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1969	Chee and Padiyar	flip bucket	–	■	–	■	–	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1974	Chee and Kung	plunging jet	–	■	–	■	■	–	■	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1973	Martins A	plunging jet, rock cubes	–	■	■	■	–	–	■	–	–	–	–	–	–	–	–	–	■	–	–	–	–	–	–
	1975	Martins B	ski-jump	–	■	–	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1978	Taraimovich	ski-jump	–	–	–	■	–	■	■	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–
	1981	INCYTH	plunging jet	–	■	–	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1982	Machado A	plunging jet, rocky bed	–	■	–	■	■	–	–	–	–	–	■	–	–	–	–	–	–	–	–	■	–	–	–
	1982	Machado B	plunging jet, rocky bed	–	■	–	■	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–	■	–	–	–
	1985	Mason and Arumugam*	plunging jet	–	■	■	■	■	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1989	Mason	plunging jet	–	■	■	■	■	–	–	–	–	–	■	–	–	–	–	–	–	–	–	–	■	–	–
Semi-empirical	1960	Mikhalev	plunging jet	–	■	■	■	■	–	■	–	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–
	1967	Mirtskhulava *et al.**	plunging jet, rocky bed	–	■	■	■	■	■	■	–	–	–	–	■	■	■	–	–	■	–	–	■	–	–	–
	1967	Poreh and Hefez	circ. submerged imp. jet	–	■	–	■	–	■	–	–	–	–	■	–	■	–	–	–	–	–	–	–	–	–	–
	1975	Zvorykin	ski-jump	–	–	■	–	–	■	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1983	Mih and Kabir	circ. submerged imp. jet	–	–	■	–	■	■	■	–	–	–	■	–	■	–	–	–	–	–	–	–	–	–	–
	1985	Chee and Yuen	plunging jet	–	–	■	–	■	■	■	–	–	–	■	–	■	–	–	–	–	–	–	–	–	–	–
	1985	Spurr*	plunging jet	■	■	■	■	■	■	■	–	–	–	■	–	–	■	■	■	■	■	–	–	–	–	–
	1991	Bormann and Julien*	grade-control, plung. jet	–	■	–	–	■	■	■	–	–	–	■	–	■	–	–	–	–	–	–	–	–	–	–
	1993	Stein *et al.*	plunging jet	■	–	–	–	■	■	■	–	–	■	–	–	–	–	–	–	–	–	–	–	–	–	–
	1994	Fahlbusch	general	–	■	■	–	■	■	■	–	–	–	■	–	–	■	–	–	–	–	–	–	■	–	–
	1998	Annandale & al.*	general	–	■	■	■	■	■	■	–	–	–	■	–	■	■	■	■	■	■	■	–	■	–	–
	1998	Hoffmans	general	–	■	■	–	■	■	■	–	–	–	■	–	■	–	–	–	–	–	–	–	■	–	–
Plunge pool pressure fluctuations	1983	Xu Duo Ming	rectang. impinging jet	–	■	■	■	■	■	■	■	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1985	Cui Guang Tao	rectang. impinging jet	–	■	■	■	■	■	■	■	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1987	Franzetti and Tanda	circular impinging jet	–	■	■	■	■	■	–	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1991	Armengou	rectang. falling nappe	–	■	■	■	■	■	–	■	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1991	May and Willoughby	rectangular slot jet	–	■	■	■	■	■	–	■	■	–	–	–	–	–	–	–	–	–	–	–	■	■	■
	1994	Puertas and Dolz	rectang. falling nappe	–	■	■	■	■	■	–	■	■	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	1997	Ervine & al.	circular impinging jet	–	■	■	■	■	■	–	■	■	–	–	–	–	–	–	–	–	–	–	–	■	■	■
Pressure difference techniques	1963	Yuditskii	oblique imp. rect. jet	–	■	–	–	■	–	■	–	–	–	–	–	■	–	–	–	■	–	–	–	–	–	–
	1986	Reinius	parallel flow impact	–	–	■	–	■	■	–	–	–	–	–	–	■	–	–	–	–	■	–	–	–	–	–
	1989	Otto	oblique imp. rect. jet	–	–	–	–	■	■	■	–	–	–	–	–	■	–	–	–	■	–	■	–	–	–	–
	1992	Fiorotto and Rinaldo	concrete slab uplift	–	■	■	■	■	■	–	■	–	–	–	–	■	–	–	–	■	–	–	–	–	–	–
	1998	Liu & al.	rock block uplift	–	■	■	■	■	■	■	■	■	–	–	–	■	–	–	–	■	–	–	–	–	–	–
	1999	Liu & al.	vibration. slab uplift	–	■	■	■	■	■	■	■	■	–	–	–	■	–	–	–	■	–	–	–	–	–	–
	2000	Fiorotto and Salandin	anchored slab uplift	–	■	■	■	■	■	–	■	■	–	–	–	■	–	–	–	■	–	–	–	–	–	–
Transient pressure jacking/uplift	2002	Bollaert	vertical and oblique impinging jets and naps, concrete slab and rock block uplift	■	■	■	■	■	■	■	■	■	■	–	–	■	■	■	■	■	■	■	■	■	■	■

for plunging jets, has negligible influence on the ultimate scour depth.

Rock mass scale effects

The difficulty of laboratory tests consists in simulating the rocky foundation by a material that adequately represents the dynamic behavior of jointed rock (Whittaker and Schleiss, 1984). For this reason, most scour tests assume that the rock mass is already broken up and make use of crushed granular material to represent the scaled broken-up rock. However, such test conditions favor the formation of a downstream material bar (mounding), which generally results in an underestimation of the total scour depth (Yuditskii, 1971; Ramos, 1982). During such tests, the so-called "dynamic scour limit" is obtained, whereas progressive removal of the bar, like it occurs in reality by crushing of the material, results in the more realistic "ultimate static scour limit".

Nevertheless, reasonable results can be obtained in terms of the ultimate scour depth (Mirtshkulava *et al.*, 1967; Martins, 1973), but the extension of the scour hole is often overestimated. This is because the slopes of the scour hole cannot be correctly generated under laboratory conditions. In order to bypass this problem, slightly cohesive material is generally used as binder material, such as cement, clay, paraffin (Brighetti, 1975; Johnson, 1977; Gerodetti, 1982; Quintela and Da Cruz, 1982). These cohesive model tests are mostly performed after dam construction, because prototype data are needed for appropriate calibration.

Furthermore, not all grain sizes are appropriate for model tests (Veronese, 1937; Breusers, 1963; Mirtshkulava *et al.*, 1967; Machado, 1982). For example, the ultimate scour depth in model tests is not influenced anymore by grain size when it is smaller than 2 to 5 mm. Also, formulae that use a d_{90} as characteristic grain size are generally less accurate than formulae based on a mean grain size diameter d_m (Mason and Arumugam, 1985).

Aeration scale effects

Aeration of jets during fall and upon impact in a pool mainly depends on the initial jet turbulence intensity (Tu), causing spread of the jet, and on the gravitational contraction of the jet. Aeration is Froude, Reynolds and Weber number dependent and cannot be accurately reproduced by Froude based models.

A simplified way to consider aeration is by introducing a reduction factor C [-] in the empirical scour formulae (Rubinstein, 1963; Johnson, 1967; Martins, 1973; Machado, 1982). A more sophisticated approach makes use of the volumetric air-to-water ratio β [-] ($= Q_a/Q_w$) at jet impact. Mason (1989) developed an expression similar to Eq. (1), but replaced H by β in order to account for aeration:

$$Y = 3.39 \cdot \frac{(1+\beta)^{0.30} \cdot q^{0.60} \cdot h^{0.16}}{g^{0.30} \cdot d_m^{0.06}} \tag{2}$$

The relation between β and H has been developed by Ervine (1976) for vertical rectangular jets, with B_j and V_j denoting the jet thickness and velocity at impact, H the jet fall height and V_{air} the minimum jet velocity required to entrain air (~1 m/s):

$$\beta = 0.13 \cdot \left(1 - \frac{V_{air}}{V_j}\right) \cdot \left(\frac{H}{B_j}\right)^{0.446} \tag{3}$$

Equation (2) was found very accurate to represent model scour data and gives a reasonable upper bound of the ultimate scour depth when applied to prototype conditions. Mason limited the application to $\beta < 2$ and stated that air entrainment on prototypes may not be significantly different from that encountered on reasonably sized laboratory models, assuming that there may be a physical limit of β of around 2–3. This value is rather easily obtained in large-scale model tests, provided that the jet velocities are sufficiently high (>15–20 m/s).

Correct modeling of aeration and assessment of its influence on rock scour still remains a challenge, due to scale effects and the random and chaotic character of air entrainment. Unfortunately, aeration significantly influences several basic processes responsible for scour hole formation: jet aeration during its fall, plunge pool aeration upon jet impact and rock mass break-up by transient air–water pressure waves inside the joints.

Time scale effects

Macroscopic time scale effects are generated by duration and frequency of occurrence of flow discharges from the dam. Scour formation is generally expressed as a semi-logarithmic (Rouse, 1940; Breusers, 1967; Blaisdell and Anderson, 1981; Rajaratnam, 1981), hyperbolic (Blaisdell and Anderson, 1981) or more complex asymptotic (Stein *et al*., 1993; based on excess shear stress) function of discharge time. Prototype observations generally indicate a high scour rate at the beginning of the phenomenon, almost reaching the ultimate depth (95%). Further scour formation needs significant time. For practical purposes, time is of less significance when assuming that the ultimate scour depth is completely generated during the peak discharge of the incoming hydrograph and that the rock mass is already broken up. The latter statement, however, completely excludes the time-consuming process of progressive break-up of the rock from the analysis.

Concluding remarks

Although significant scale effects may exist, empirical formulae are useful to get a first-hand estimation of the ultimate scour depth and to identify scour tendencies. The challenge, however, is to use the most appropriate formula. The great number of formulae makes it possible to establish a confidence interval of scour depths. As such, empirical formulae are mainly useful during preliminary design stages.

2.3 Semi-empirical expressions

Expressions based on analytical developments, but calibrated by the use of available experimental data, are classified as "semi-empirical" relationships. Analytical background applies "initiation of motion" theories, uses conservation equations or directly considers geomechanical characteristics. Many of these expressions are based on the theory of a two-dimensional jet impinging on a flat boundary.

Two-dimensional (2D) jet diffusion theory

Diffusion of a 2D jet in a plunge pool has initially been described assuming a hydrostatic pressure distribution and an infinitesimal plunge pool thickness. The concept of a jet of uniform velocity field penetrating into a stagnant fluid is based on the progressive growing of the thickness of the boundary shear layer by exchange of momentum. This shear layer is characterized by two effects: an increase of the total cross section of the jet and a corresponding decrease of the non-viscous wedge-like core between the boundary layers, indicated in Fig. 2. Hydrostatic pressure assumption leads to a constant core velocity. The core length depends on the inner angle of diffusion α_{in}, about 4–5° for submerged jets (= jet outlet is under water level) and around 8° for highly turbulent impinging jets (McKeogh, 1978, cited in Ervine and Falvey, 1987). An overview of studies investigating the core length is presented at Table 2, were the core extension is determined as K_c times the jet diameter D_j or the jet width B_j. The scatter of the obtained K_c values is probably caused by different jet outlet test conditions.

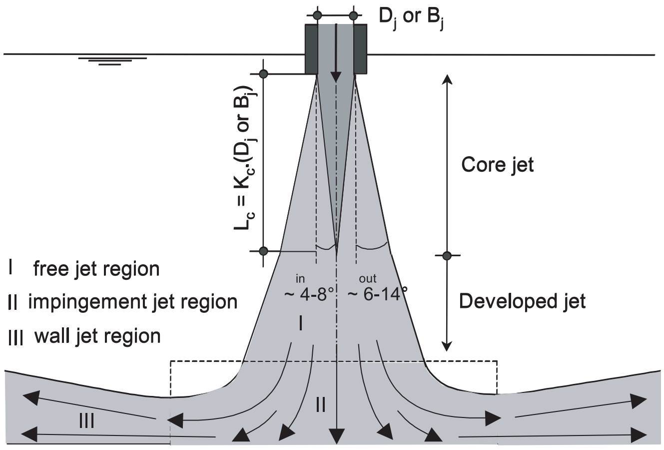

Figure 2 2D jet diffusion showing the jet core length (jet development region) and the developed jet region, the inner and outer angles of diffusion (McKeogh, 1978, cited in Ervine and Falvey, 1987), and the main regions of jet impingement (Beltaos and Rajaratnam, 1973).

However, this fundamental 2D jet diffusion concept doesn't account for the existence of flow boundaries, which largely modify the hydrostatic pressure distribution. Several researchers investigated the influence of the flow boundary on the jet's pressure and velocity fields. The most complete study of plane and circular, oblique and vertical jet impingement on a flat and smooth surface has been done by Beltaos and Rajaratnam (1973, 1974) and Beltaos (1976). They proposed three distinct flow regions: the free jet, the impingement jet and the wall jet region (Fig. 2). The most severe hydrodynamic action of the flow occurs in the impingement region, near the solid boundary. There, the hydrostatic pressure of the free jet region is progressively transformed into highly fluctuating stagnation pressures and an important wall shear stress (due to lateral jet deflection). Hence, the impingement region is directly related to scour formation, because the pressure fluctuations that are generated enter underlying rock joints and progressively break up the rock mass.

Moreover, Bohrer *et al*. (1998) predicted the velocity decay of a free falling turbulent rectangular jet in plunge pools, in order to determine its erosive potential. This has been done for compact and broken-up jets. Compact jets are thereby defined as jets with an intact core region upon impact in the pool. Broken-up jets have no inner core region anymore upon impact, due to turbulent fluctuations at the outer boundaries that progress towards the inside of the jet and that break up the core (Ervine and Falvey, 1987). Furthermore, the study accounted for jet velocity and jet density (or air concentration) at impact. Stream power, defined as the rate of energy dissipation of the jet in the plunge pool, is determined as a function of velocity decay and can be compared with the rock's resistance to erosion. The latter can be expressed by a general index (Annandale's Erodibility Index method; Annandale, 1995).

Table 2 Coefficient K_c of jet core length L_c according to different studies on (circular and rectangular) impinging or submerged jets.

Author	Year	K_c	Jet type	Analysis
Albertson *et al.*	1948	5.2	rectang	2D jet diff. + experim
Albertson *et al.*	1948	6.2	circular	2D jet diff. + experim
Homma	1953	4.8	circular	experimentally
Cola	1965	7.18	rect/subm	cons.eq. + experim.
Poreh and Hefez	1967	9	circular	2D jet diffusion theory
Hartung and Häusler	1973	5	circ/imp	angle of diff. estimate
Hartung and Häusler	1973	5	rect/imp	angle of diff. estimate
Beltaos and Rajaratnam	1973	8.26	rectang	jet momentum flux
Beltaos and Rajaratnam	1974	5.8–7.4	circular	jet momentum flux
Franzetti and Tanda	1987	4.7	circ/imp.	2D jet diff. + experim
Franzetti and Tanda	1987	6.03	circ/subm.	2D jet diff. + experim
Chee and Yuen	1985	3.3	circ/imp	dim. analys. of mom.
Cui Guang Tao	1985	6.35	rect/imp	experimentally
Ervine and Falvey	1987	4	circ/imp	experimentally + mom.
Ervine and Falvey	1987	6.2	circ/subm	experimentally
Armengou	1991	3.19	rect/imp	experimentally
Bormann and Julien	1991	3.24	rect/imp	jet diffusion coeff. C_d
Ervine *et al.*	1997	4–5	circ/imp	experimentally

This method is outlined more in detail in the paragraph dealing with geomechanical methods.

Initiation of motion concept

The concept of initiation of motion of riverbed material has been largely applied to cohesionless granular material. In a basic theoretical work, Simons and Stevens (1971) performed a complete 3D analysis of the possible hydrodynamic forces and moments on a solid particle. In general, most expressions are based on Shields' critical shear stress (Poreh and Hefez, 1967; Stein *et al.*, 1993). Other studies consider the main forces acting on a solid particle moved away by jet flow (Mih and Kabir, 1983; Chee and Yuen, 1985; Bormann and Julien, 1991), or also the stream power of the jet (Annandale, 1995). The scour depth formula established by Bormann and Julien (1991), based on jet diffusion and particle stability on scour hole slopes, is of particular interest because applicable to a wide range of outlet structures and calibrated on large-scale experiments. For plunging jets, this formula is comparable to Eq. (1):

$$\mathrm{t} = \mathrm{K} \cdot \mathrm{q}^{0.6} \cdot \frac{\mathrm{V_j}}{\mathrm{g}^{0.8} \cdot \mathrm{d}_{90}^{0.4}} \cdot \sin\theta \tag{4}$$

with

$$\mathrm{K} = 3.24 \cdot \left[\gamma \cdot \frac{\sin\phi}{(\sin(\phi+\theta) \cdot 2 \cdot (\gamma_s - \gamma))}\right]^{0.8} \tag{5}$$

A specific weight ratio γ_s/γ of 2.7 and a submerged angle of repose ϕ of the granular material of 25° are assumed. The angle of repose ϕ depends thereby on the ratio of the critical shear stress required to move upslope the granular material to the critical shear stress valid for flat bed conditions. Hoffmans and Verheij (1997) tested Eq. (4) with a large data set and found acceptable accuracy and wide-range applicability.

Conservation equations

Approaches based on the continuity, momentum or energy conservation equations express the main physical processes in a global but exact manner. Fahlbusch (1994) and Hoffmans (1998) calculated the equilibrium scour depth by application of Newton's second law of motion on a mass of fluid particles. They provide accurate and widely applicable scour predictions. Fahlbusch (1994) used 104 model or prototype measurements to verify the accuracy of his expression:

$$\mathrm{Y} = \mathrm{c_{2v}} \cdot \sqrt{\frac{\mathrm{q} \cdot \mathrm{V_j} \cdot \sin\theta}{\mathrm{g}}} \tag{6}$$

A potential scour estimation error of 40% was observed. The parameter c_{2v} has an upper limit of 3.92 and an average value of 2.79, almost identical to the value of 2.83 found by Veronese (1937). Hoffmans (1998) slightly modified Eq. (6) by relating c_{2v} to the particle diameter d_{90}. For grain diameters beyond 12.5 mm, $c_{2v} = 2.9$. For smaller diameters, $c_{2v} = 20/(d_{90*})^{1/3}$, where $d_{90*} = d_{90}(\Delta \cdot g/\nu^2)$ with $\Delta = (\gamma_s/\gamma - 1) = 1.65$ and $\nu = 10^{-6}\,m^2/s$. Based on a large data set, 80% of the experimental (laboratory) results fell within 0.5 to 2 times the values as theoretically predicted by Eq. (6).

Geomechanical characteristics

The first attempts to describe the erosion resistance of rock primarily focused on fracture frequency (RQD) and degree of weathering (Otto, 1989). However, the stage of rock mass break-up can only be assessed by incorporating the strength of the rock matrix. One of the first detailed descriptions of plunge pool geology has been proposed by Spurr (1985). He developed a procedure that determines the mean hydraulic energy that exceeds the rock mass erosion resistance. The procedure also accounts for spill durations. The rock mass erosion resistance is thereby expressed by the uniaxial compressive strength σ_c of the intact rock, together with the RMR (Rock Mass Rating) after Bieniawski (1984). This forms the basis for a classification of the plunge pool geology into three groups of different erosion resistance. An empirical formula for equilibrium scour depth is first of all calibrated at a reference plunge pool. Application of this calibrated formula to the study site is then performed by means of an index, depending on spill duration and the specific erosion resistance group of the plunge pool geology. Spurr (1985) carried out a prototype validation of his approach, however, this was limited to only one case study.

More recently, as already mentioned, a cooperative Dam Foundation Erosion (DFE) study has been conducted by the Colorado State University and the US Bureau of Reclamation (Lewis *et al.* 1996; Annandale *et al.*, 1998; Bohrer *et al.*, 1998) in order to relate stream power of the plunging jet, defined by velocity decay, to an erodibility index that expresses the rock's erosion resistance (Annandale, 1995).

The rock erosion resistance is related to an index that accounts for several geological parameters (such as uniaxial compressive strength σ_c, Rock Quality Designate RQD, material density ρ_s, block size and shape, joint set angle α_j, joint roughness, etc). These properties can be measured in the field at reasonable cost and are quantifiable through tables (Annandale, 1995). Furthermore, the influence of the plunge pool air concentration on jet velocity decay is taken into account for both compact (with core) and broken-up (= fully aerated, no core anymore) jets.

A graphical relationship between this erodibility index and the jet power has been established for a data set of 150 field observations and available literature data on sediment motion. This allowed defining an erosion threshold relationship for any given set of hydraulic conditions and for any type of foundation material (granular soils, rock, etc.). Recently, experiments on prototype scale, simulating the erosion of a fractured blocky-shaped rock mass, confirmed the theoretically derived erosion threshold (Annandale *et al.*, 1998).

2.4 *Plunge pool bottom pressures*

Dynamic pressures at the water–rock interface may result from core jet impact, occurring for small plunge pool depths Y, or from macroturbulent shear layer impact, occurring for pool depths Y greater than 4 to 6 times the jet diameter D_j (based on 2D jet diffusion theory). The following parameters are relevant: mean dynamic pressure, root-mean-square (RMS) value of dynamic pressure fluctuations, extreme positive and negative dynamic pressures, and power spectral content of the dynamic pressure fluctuations. These parameters characterize dynamic pressure loading on rock blocks or concrete linings by applying a maximum pressure underneath a rock block or concrete slab and a minimum pressure on the surface. In this way, a maximum net uplift pressure or force is determined. Ultimate scour depth is reached when this net uplift force is not capable anymore to eject the rock block or the concrete slab. Resistance to uplift is generated by the submerged weight of the slabs or blocks and by eventual shear and interlocking forces along the joints. For concrete slabs, anchor stresses may be added to this resistance.

Mean dynamic pressure under the jet's centreline

The mean dynamic pressure is expressed in a dimensionless manner by means of the C_p coefficient. This coefficient is defined as the mean dynamic pressure value H_m (in [m]) at the rock surface divided by the incoming kinetic energy head of the jet $V_j^2/2g$ (in [m]). Figure 3 gives an overview of 11 independent studies that express the C_p coefficient as a function of the ratio of pool depth to jet diameter Y/D_j.

A different behaviour can be observed between circular and rectangular jets, as well as between plunging and submerged jets. The jet core, according to 2D jet diffusion theory, extends up to 4–6 times the jet diameter D_j for plunging jets and up to 6–8 times D_j for submerged jets. Moreover, due to spreading and aeration of the plunging jet, which cause energy losses, plunging jets attain C_p values of maximum 0.8–0.9. It is interesting to observe that circular jets have a stronger decrease of C_p with Y/D_j than rectangular jets. The reason for this stronger decrease may lie in the definition of the impingement width B_j and/or in the fact that jet diffusion occurs radially (in every direction) for circular jets instead of laterally (unidirectional) in case of rectangular jets. The first aspect may be circumvented by use of an equivalent jet diameter.

Root-mean-square (RMS) value of the dynamic pressure fluctuations

The C_p' coefficient is defined as the ratio of the RMS-value of the pressure fluctuations H' (in [m]) over the incoming kinetic energy

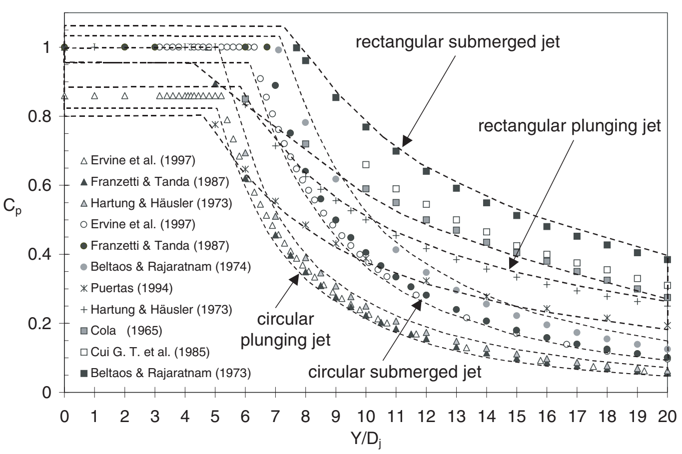

Figure 3 Mean dynamic pressure coefficient C_p as a function of Y/D_j. Summary of different studies conducted on circular plunging (triangular symbols), circular submerged (circular symbols), rectangular plunging (+ symbol) and rectangular submerged (block symbols) jets.

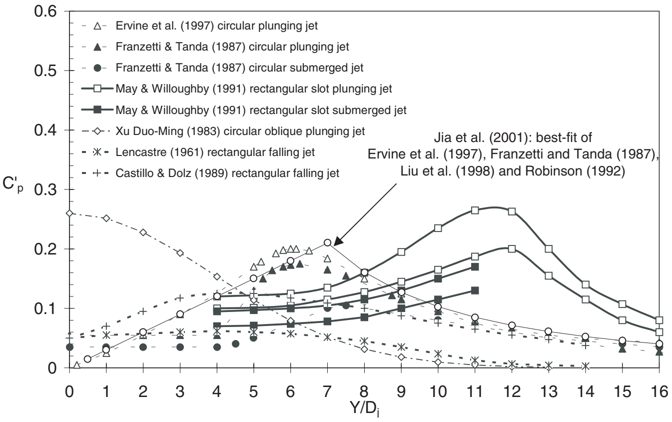

Figure 4 Root-mean-square pressure coefficient C_p' as a function of Y/D_j. Summary of different studies conducted on circular plunging (Δ symbol), circular submerged (● symbol), rectangular plunging (+ symbol), rectangular slot plunging (□ symbol), rectangular slot submerged (■ symbol) and finally oblique circular plunging (◇ symbol) jets.

of the jet $V_j^2/2g$ (in [m]). Figure 4 presents this coefficient as a function of the Y/D_j ratio based on different independent investigations. In general, RMS values are strongly influenced by the initial jet turbulence intensity Tu and by the degree of break-up of the jet, which is defined as the jet fall length over the jet break-up length L/L_b. Both parameters highly influence the macroturbulence in the plunge pool. Most studies show at first an increase of turbulence for Y/D_j ratios less than 4. Then, a maximum C_p' coefficient is generally obtained for pool depths that are 4–12 times the jet diameter at impact. Finally, an almost linear decrease of the C_p' coefficient can be observed for higher Y/D_j ratios. The phenomenon of increase and subsequent decrease, already noticed by Doddiah *et al.* (1953), is in accordance with turbulence theory: a minimum depth is required to develop large, energy containing eddies; however, with further increase of depth, energy diffusing effects become predominant. An exception are the data for oblique ($\theta \sim 40$–$50°$) impinging circular jets (Xu Duo Ming and Yu Chang Zhao, 1983).

Also, the maximum value for rectangular jets generally occurs at Y/D_j values that are higher than the ones for circular jets. This, again, is probably due to the definition of the jet width B_j. The curve presented by Jia *et al.* (2001) constitutes a best-fit of available literature data on circular and free-falling jets. Furthermore, some studies (Franzetti and Tanda, 1987; May and Willoughby, 1991) investigated the radial distribution of RMS-values outside the jet's centreline. Severe pressure fluctuations may persist far away from the impact point, even when mean dynamic pressures become close to zero. This is important when estimating the maximum scour hole extension at the pool bottom.

Extreme dynamic pressure values

Ervine *et al.* (1997) studied circular plunging jets and obtained extreme positive pressure values at the pool bottom of up to 4 times the RMS value and extreme negative pressure values of up to 3 times the RMS value. This in accordance with the positive skewness that is generally found in high-velocity macroturbulent shear flow. The maximum positive pressures occurred at a Y/D_j

ratio of 10, while the maximum negative pressures were observed at Y/D_j ratios of only 5. This is because maximum negative deviations from the mean pressure can only be obtained at rather high mean dynamic pressures, i.e. for low Y/D_j ratios.

Franzetti and Tanda (1987) investigated both circular plunging and circular submerged jets. They found that the ratio of extreme pressure value to RMS value increases with increasing Y/D_j and obtained values of up to 8 for $Y/D_j = 25$–30. This is in accordance with the findings of May and Willoughby (1991), who studied rectangular slot jets. They found that extreme values do not necessarily appear at the point of jet impact. This aspect may be important when considering net uplift pressures at locations away from the jet impact zone. May and Willoughby also found higher positive than negative extremes, appearing at about the same Y/D_j ratios as Ervine *et al.* (1997), as well as extremes that are higher for plunging than for submerged jets.

Extreme pressures are often obtained for relatively short measuring periods. Their application to prototype conditions might be questionable at first sight. For example, Toso and Bowers (1988) performed pressure measurements underneath hydraulic jumps and found extreme values during 24-hours test runs that were twice as large as the ones obtained during 10-minutes test runs. This phenomenon is in accordance with intermittency of turbulent fluctuations. However, extreme pressures only occur during high-frequency pulses and their corresponding spatial persistency is generally very small. As such, their total energy content is moderate, and these pulses can often be considered as insignificant for design purposes of large concrete slabs (>5–10 m) of plunge pool bottom linings. For small rock blocks (<1 m), on the contrary, they might be of influence. The relevance of these pulses clearly depends on the ratio of the spatial persistency (or integral scale) to the characteristic length of the concrete slab or the rock block.

Power spectral content of dynamic pressure fluctuations

The power spectral content $S_{xx}(f)$, defined as the decomposition of the variance (σ^2) of the pressure fluctuations as a function of frequency, determines the frequency content of the pressure fluctuations. Figure 5 represents $S_{xx}(f)$ in both dimensional and dimensionless manner for circular and rectangular jets, according to different studies. A log–log representation has been used. Most of the studies show major spectral energy at low frequencies, i.e. 0–20 Hz. The energy is mostly contained by eddies at the scale of the plunge pool water depth. Very little information is available for higher frequencies, because high frequencies are difficult to generate on scaled model tests. However, as pointed out in Part II of this paper, higher frequencies may contain sufficient spectral energy to stimulate rock or slab joints to oscillating and even resonating transient pressures. These transient pressures, although of short-lived character, may be amplified inside joints and become much higher than the pressures at the water–rock interface. As such, it is believed that they are directly responsible for scour formation by progressive break-up of the rock joints.

Higher frequencies have been studied in the field of turbulent flow impinging on flat surfaces (Bearman, 1972; Huot *et al.*, 1986; Ballio *et al.*, 1994). Core jet impact (for $Y/D_j < 4$–6) generates a spectral content that decays in a linear manner at

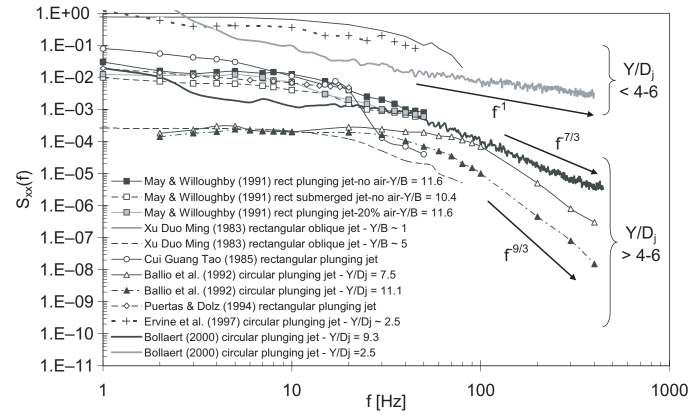

Figure 5 Power spectral content $S_{xx}(f)$ of dynamic pressure fluctuations as a function of frequency. Summary of different studies showing the difference at high frequencies between spectra of core jets ($Y/D_j < 4$–6) and spectra of developed jets ($Y/D_j > 4$–6).

log–log scale, even for very high frequencies. The rate of energy decay follows f^{-1} (f = frequency; Bollaert and Schleiss, 2001a). Developed jet impact (for $Y/D_j > 4$–6) shows two distinct regions of spectral decay: one in the low and intermediate frequency range (up to 50–100 Hz), with a non-negligible amount of spectral energy, and one at high frequencies (>50–100 Hz), with a rate of energy decay of $f^{-7/3}$ towards the viscous dissipation range (Kolmogoroff, 1941). The exact frequency at which these two regions are separated depends on the flow conditions and on the Y/D_j ratio (or jet development) (Ballio *et al.*, 1992).

In conclusion, simultaneous application of extreme positive and negative pool bottom pressures over and under rock blocks or concrete slabs may result in a net pressure difference of up to 7 times the RMS value of the pressure fluctuations, or up to 1.5–1.75 times the incoming kinetic energy of the impacting jet $V_j^2/2g$. Considering that the combination of a minimum pressure all over the slab or block surface with a maximum pressure all underneath is quasi impossible, this provides a conservative design criterion. However, it doesn't consider violent transient phenomena that might occur inside the joints and that might amplify the net uplift pressures.

2.5 *Time-averaged and instantaneous pressure differences*

Theoretically, the maximum possible net uplift pressure that may be obtained on a rock block equals one time the incoming kinetic energy head of the jet $V_j^2/2g$ (in [m] of uplift pressure). This corresponds to a complete conversion of the jet's kinetic energy into dynamic pressure underneath the block, combined with the absence of dynamic pressures all over the block's surface. In practice, the situation is more complicated. Dynamic pressures are always present over the rock's surface and rock block protrusion into the turbulent flow field may generate additional uplift pressures due to suction effects.

Yuditskii (1963) and Gunko *et al.* (1965) where the first stating that time-averaged pressure differences may be responsible for rock block uplift. They presented these pressures in dimensionless graphs as a function of the length of the block and the depth of the pool. They also pointed out the importance of instantaneous dynamic pressures that may enter the joints and disintegrate the rock. Reinius (1986), based on a study by Montgomery (1984), investigated the time-averaged dynamic pressures on a rock block subjected to water flowing parallel to its surface and for protruding rock surfaces. The obtained time-averaged net uplift pressures were maximum 67% of the incoming kinetic energy $V_j^2/2g$ and were found sufficient to cause uplift of the blocks. Hartung and Häusler (1973) highlighted in an experimental way the destructive effects of dynamic pressures entering rock joints and building up huge forces inside. Otto (1989) pointed out the progressive expansion of rock joints by the dynamic action of the jet. He quantified time-averaged uplift pressures on a rock block for oblique impinging jets. Depending on the relative protrusion of the block and the exact point of jet impact, important surface suction effects occurred, leading to net uplift pressures of almost the total incoming kinetic energy $V_j^2/2g$.

All these studies illustrate the significance of time-averaged dynamic pressures in joints, but don't explain the exact mechanism of rock destruction (Vischer and Hager, 1995). To assess the dynamic character of the uplift forces on a block, laboratory studies have been focusing on the conveyance of instantaneous surface pressures to the underside of rock blocks or concrete slabs. These investigations (Fiorotto and Rinaldo, 1992a,b; Bellin and Fiorotto, 1995; Liu *et al.*, 1998; Fiorotto and Salandin, 2000) used force and pressure transducers, installed on artificial blocks or concrete slabs, to determine maximum instantaneous pressure differences.

As shown in Fig. 6, these instantaneous pressure differences are obtained by accounting for an instantaneous and spatially distributed pressure field $p_{over}(x, t)$ over the block, and by applying everywhere underneath the block the average value of the instantaneous surface pressures that appear at both joint entrances ($p_{under}(t)$). Viscous damping of the pressures inside the joints is neglected and pressure propagation inside the joint may be

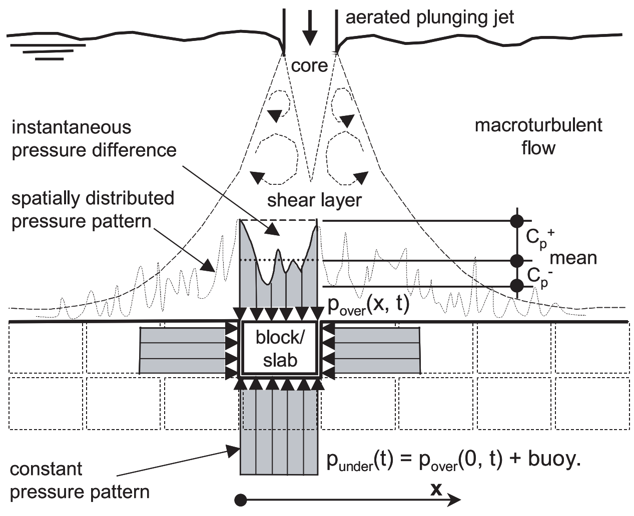

Figure 6 Instantaneous pressure differences on a single rock block subjected to the shear layer of an impinging jet (Bellin and Fiorotto, 1995).

considered as infinitely fast compared to the propagation of surface pressures (in the plunge pool). This means that any initial transient oscillations inside the joint, due to an incoming pressure pulse, are considered to be damped out during the first and very rapidly oscillating cycles of the transient. Thus, during the much longer time of application of the surface pressures at the joints, a constant pressure field is assumed to install underneath the block. This assumption is only plausible when assuming pressure wave celerities in the order of 10^3 m/s and surface macro-turbulent velocities of 10^0–10^1 m/s, i.e. one to two orders of magnitude smaller. This difference in persistence time between over- and underpressures allows to dampen out any transient oscillations that might initially exist inside the joint and forms the basis to neglect any transient influences.

Fiorotto and Rinaldo (1992a,b) modelled hydraulic jump impact on concrete slabs of different geometries and bottom roughness. These scaled model tests confirmed the assumptions of neglecting damping. They incorporated a dimensionless reduction factor Ω that accounts for the net uplift forces. This factor accounts for the instantaneous spatial structure of the surface pressure field (Fig. 6) and, thus, depends on the form and the dimensions of the block or the slab. They derived a design criterion for dynamic uplift of concrete slabs of stilling basins due to hydraulic jump pressure fluctuations:

$$s = \Omega \cdot (C_p^+ + C_p^-) \cdot \frac{V_j^2}{2g} \cdot \frac{\gamma}{\gamma_s - \gamma} \tag{7}$$

The equivalent slab thickness, s (in [m]), is expressed as a function of Ω and of positive and negative pressure extremes at the surface of the slab. Bellin and Fiorotto (1995) measured and validated values for Ω (between 0.10 and 0.25), as a function of the shape of the slabs and of the incoming Froude number F of the hydraulic jump. The Froude number F is thereby defined as the ratio of the inflow velocity of the hydraulic jump, V_i, to the square root of the product of gravity times the incoming flow depth, $\sqrt{g \cdot h_i}$. Their results were based on simultaneous pressure and force measurements on simulated concrete slabs. For practical design purposes, C_p^+ and C_p^- are safely assumed equal to 1 in Eq. (7), corresponding to a maximum net uplift pressure equal to half of the incoming kinetic energy $V_j^2/2g$. Fiorotto and Salandin (2000) extended this criterion to the design of anchored slabs by accounting for the persistence time of pressure peaks underneath the slabs. The governing equation assumes a constant underpressure during the persistence time and expresses the dynamic equilibrium of the slab as a forced and undamped mass vibration. This criterion, however, does not account for transient pressure waves that might amplify the pressures inside the joints.

Liu *et al.* (1998) performed an experimental and numerical study of the same phenomenon, but for jets impacting in plunge pools. They focused on fluctuating net uplift forces on simulated rock blocks, which resulted in a design criterion for rock block uplift. Maximum measured net uplift pressures fluctuated between 2.2 and 4.2 times the RMS value of the surface pressure fluctuations (σ_s), for frequencies between 0 and 12 Hz. Considering that extreme pool bottom pressures generally represent 3 to 4 times the RMS values (Ervine *et al.*, 1997, see §2.4), this results in a net uplift pressure equal to 0.55 to 1.05 times the incoming kinetic energy. The upper bound of net uplift pressures was thereby systematically obtained for very small plunge pool water depths, for which the jet directly impacts one of the joints of the simulated rock block. Developed jet impact generated uplift pressures close to the lower bound of 0.55. The scale of the rock blocks, on the order of 10^{-1} m, and the low pressure acquisition rates (<200 Hz) did not allow generation and measurement of short-lived transient effects inside the joints.

Jia *et al.* (2001) presented a numerical model that calculates the uplift forces on granular loose-bed material due to plane impinging jets. The mechanism of uplift was empirically introduced and calibrated based on Hoffmans' modification of Eq. (6). The obtained relationship between the surface pressure fluctuations and the net fluctuating uplift is in agreement with the findings of Liu *et al.* (1998). They pointed out the need for further research in order to improve the understanding of the exact physical mechanism of uplift.

The assumption of infinitely high pressure wave celerities, which results in no transient wave effects inside the joints, is only acceptable if the impacting jet contains no frequencies that might be able to stimulate the underlying joints to oscillations and/or resonance pressure waves. Assuming that the resonance frequency f_{res} of an open end joint underneath a slab or a block is defined as $c/2 \cdot L$ (open end resonator system, c is the wave celerity and L is the joint length), and assuming jet impact frequencies less than 10 Hz, classical wave celerities of about 1000 m/s would be able to stimulate the joints to oscillating and resonance conditions if the joint length L were on the order of 10^2 m (Fiorotto and Rinaldo, 1992b). Such joint lengths are out of the realm of practical engineering.

For this reason, existing scour evaluation methods deal with net uplift forces in a sort of steady-state differential manner, whereby the underpressures are assumed constant and determined by the surface pressures entering the joints. By neglecting any possible pressures over the surface of the blocks or the slabs, this results in maximum net uplift forces that are equal to the kinetic energy head of the incoming jet.

3 Theoretical framework for a multiphase transient scour evaluation method

Two statements contradict the above assumption. First, free air that is present in the water may largely decrease the pressure wave celerity and the theoretical resonance frequency of a joint. A very slight change in free air content drastically changes the gas–liquid compressibility and, thus, the corresponding wave celerity. Assuming that an aerated water jet generates air entrainment in rock joints, it seems plausible to account for a reduced wave celerity of the air–water mixture inside the joints. For a free air concentration of 1% and a pressure wave celerity of 200 m/s, resonance effects might be generated inside the joints for joint lengths L of only O (10^1) m, i.e. a realistic value. Second, it has been emphasized that prototype-scaled turbulent shear flows may contain non-negligible spectral energy at high frequencies (>10 Hz), especially in the case of high-velocity jet impact (Fig. 5).

Therefore, for prototype jet or hydraulic jump impact in plunge pools, it is believed that transient wave effects inside joints might significantly influence net uplift forces on slabs or rock blocks and that they constitute a potential key to a physically more appropriate modelling of rock scour or dynamic slab uplift. Such a transient approach seems hazardous due to the complex nature of jointed rock and due to the unknown characteristics of pressure waves travelling inside the joints. It is obvious that the analysis of the problem requires a fully transient computation, able to reproduce violent transient two-phase phenomena. Their relevance for design purposes is developed in Part II of the paper.

Direct application of fully transient theory on pressure waves inside rock joints is not available in literature. Kirschke (1974) numerically studied the propagation of water hammer waves in one-dimensional fine discontinuities of rigid, elastic or plastic rock media, but only for steady pressures at the joint entry. Furthermore, very little is known on the influence of air on dynamic pressures in joints, which is a further key element for any fully transient analysis inside the rock matrix. Transient flow theory, on the contrary, is well developed in the fields of pressure surges in pipelines and acoustics. Numerical techniques are available that account for phenomena such as resonance and damping, aeration and cavitation, etc.

To fill up this lack of knowledge, model tests on different rock joint geometries have been carried out at the Laboratory of Hydraulic Constructions of the Swiss Federal Institute of Technology in Lausanne (LCH-EPFL). The purpose of the tests was to verify whether highly transient pressure wave phenomena are of influence on the process of progressive break-up of rock joints by hydrodynamic jacking and on the process of dynamic uplift of rock blocks (or concrete slabs) by net uplift pressures. The experiments focused on pressure fluctuations inside simulated rock joints under the impact of aerated high velocity jets. The velocity of the jets is at prototype scale (up to 35 m/s), in order to obtain realistic aeration rates and turbulence spectra. Both two- and one-dimensional rock joints have been simulated, with open (= single rock block) or closed (= fractured rock mass) end boundaries. Pressures have been measured simultaneously at the pool bottom and inside the joints, at a data acquisition rate of up to 20 kHz, in order to detect any transient phenomena.

The experimental results reveal considerable jet energy in intermediate and high frequency ranges (up to 50–100 Hz) and significant pressure amplification inside 1D joints, even for very short joint lengths (less than 1 m). Very low wave celerities have been observed (<50–100 m/s), due to significant aeration inside the joints. Peak pressures in the joints amplified up to 5–6 times the corresponding maximum pressure at the pool bottom (Bollaert and Schleiss, 2001a; Bollaert, 2002). Test results are discussed in detail in Part II of this paper.

4 Conclusion and future research

Knowledge on the interaction between dynamic pressure fluctuations at a plunge pool bottom and fully transient pressure wave propagation in rock joints is actually lacking. Hence,

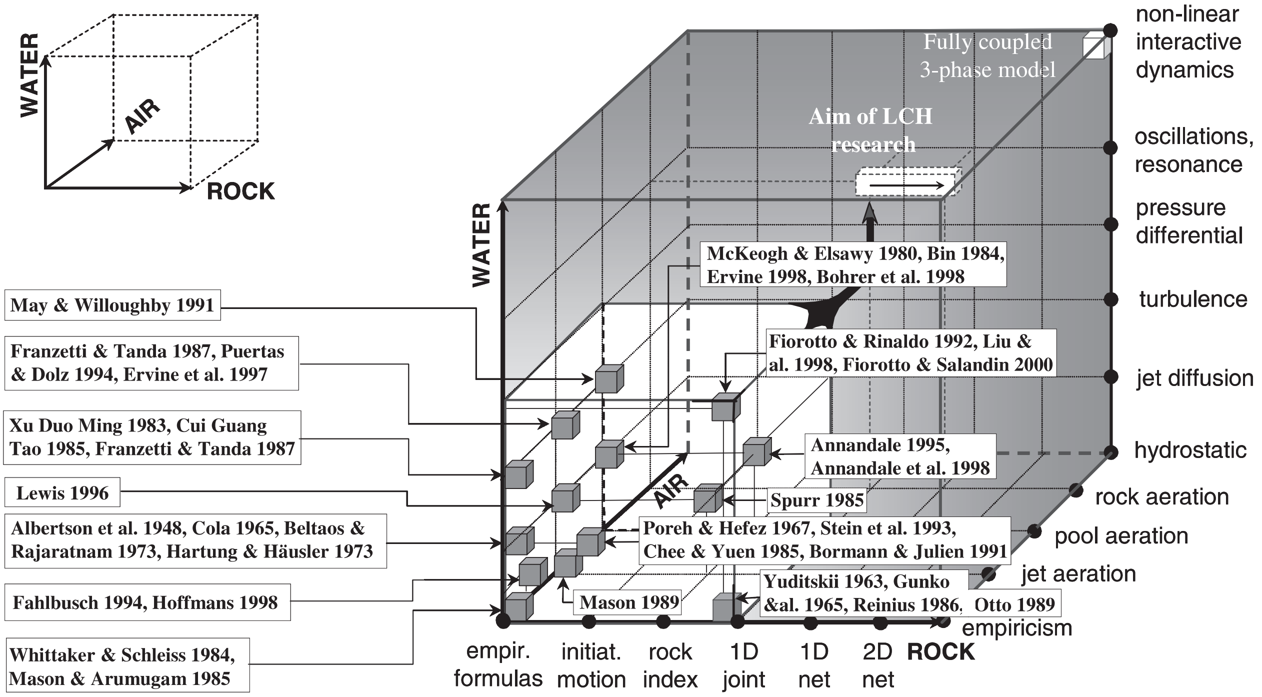

Figure 7 A three-phase cubic representation of the actual state-of-the-art on ultimate scour depth evaluation methods (Bollaert and Schleiss, 2001b; Bollaert, 2002).

air–water transient pressures in joints have to be investigated at high frequencies (in the order of 10^3 Hz). This will guarantee the detection of possible oscillatory and/or resonance flow effects. The corresponding physical-mechanical processes of hydrodynamic jacking and dynamic uplift, causing scour of rock, have to be investigated in detail. This will allow a physically more appropriate assessment of the phenomenon.

Rock scour due to the impact of high velocity jets is a three-phase transient phenomenon governed by the interaction of air, water and rock. The state-of-the-art on rock scour evaluation methods can be illustrated by a three-dimensional cubic graph, shown in Fig. 7 (Bollaert and Schleiss, 2001b; Bollaert, 2002). The main axes represent rock, water and air characteristics. The small gray cubes comprise existing evaluation methods, which get progressively more sophisticated along the axis.

Beside the numerous works in the field of jet and pool aeration, the most complete methods considering the three phases are Spurr's (1985) method and Annandale's (1995) method, both corresponding to erodibility index methods. Fiorotto and Rinaldo (1992a,b) and Fiorotto and Salandin (2000) made significant contributions in the water–rock interaction field for horizontal jet impact, but without accounting for aeration or transient wave effects.

The white cube in Fig. 7 clearly shows the two main groups of research studies on the front and the left side of the main cubic volume: rock–water and air–water studies. The aim of the present research is to extend existing scour knowledge by combining geomechanical, aeration and fully hydrodynamic aspects. Experimental and numerical modeling will aim to bring the state-of-the-art closer to the final objective, i.e. a 3-phase fully interactive transient model, taking into account all relevant physical processes. Experimental results of transient pressures in simulated rock joints are described and analyzed in Part II of this paper.

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Notations

c = pressure wave celerity [m/s]
d_m = mean grain size/block size [m]
d_{90} = grain size diameter for which 90% of the mixture is smaller than d_{90} [m]
f = frequency [Hz]
g = gravitational acceleration [m²/s]
h = scour depth below initial bed level [m]
h_i = mean inflow depth of hydraulic jump [m]
p_{over} = pressure over a rock block or concrete slab [m]
p_{under} = pressure underneath a rock block or concrete slab [m]
q = discharge per unit width [m²/s]
t = tailwater depth [m]
trans = oscillatory and resonance phenomena [-]
z = rock block size [m]
B_j = jet thickness at impact [m]
C = air reduction coefficient [-]
C_p = mean dynamic pressure coefficient $= (H_m)/(V_j^2/2g)$ [-]
C'_p = fluctuating dynamic pressure coefficient $= (H')/(V_j^2/2g)$ [-]
C_p^+ = extreme positive dynamic pressure coefficient $= (H_{max} - H_m)/(V_j^2/2g)$ [-]

$C_p^- =$ extreme negative dynamic pressure coefficient $= (H_m - H_{min})/(V_j^2/2g)$ [-]
$D_j =$ jet diameter at impact [m]
$F =$ incoming Froude number of hydraulic jump [-]
$S_{xx}(f) =$ power spectral content of pressure fluctuations [m^2]
$H =$ jet fall height [m]
$H' =$ RMS value of dynamic pressure fluctuations [m]
$H_m =$ mean dynamic pressure head [m]
$H_{max} =$ maximum dynamic pressure head [m]
$H_{min} =$ minimum dynamic pressure head [m]
$K =$ parameter for empirical scour formulae (Eqs. (1) and (4)) [-]
$K_c =$ parameter to express the jet core length L_c [-]
$L =$ jet fall length or rock joint length [m]
$L_b =$ jet break-up length [m]
$L_c =$ jet core length [m]
$N_j =$ number of joint sets [-]
$Q_a =$ air discharge [m^3/s]
$Q_w =$ water discharge [m^3/s]
RMS = Root-mean-square value of pressure fluctuations [m]
RQD = Rock Quality Designation [%]
Tu = initial jet turbulence intensity [%]
$V_{air} =$ minimum air entrainment velocity [m/s]
$V_i =$ mean inflow velocity of hydraulic jump [m/s]
$V_j =$ mean jet velocity at impact [m/s]
$Y = t + h$, total plunge pool depth [m]
$\alpha_j =$ dip angle of joint set j [°]
$\beta =$ volumetric air-to-water ratio $= Q_a/Q_w$ [-]
$\phi =$ angle of repose of bed material [°]
$\phi_j =$ residual friction angle of joint set j [°]
$\omega =$ mean particle fall velocity [m/s]
$\gamma =$ water specific weight [N/m^3]
$\gamma_s =$ particle/rock specific weight [N/m^3]
$\theta =$ impact angle of the jet with the horizontal [°]
$\sigma_c =$ uniaxial compressive strength [N/m^2]
$\sigma_s =$ RMS of surface pressure fluctuations [m]
$\sigma_t =$ uniaxial tensile strength [N/m^2]
$\sigma_u =$ RMS value of underpressure fluctuations [m]
$\Delta = (\rho_s - \rho)/\rho = \gamma_s/\gamma - 1 =$ relative density [-]

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