Journal of Hydraulic Research Vol. 45, No. 6 (2007), pp. 853–858

Discussion

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

By ERIK BOLLAERT and ANTON SCHLEISS, Journal of Hydraulic Research, IJHR, Volume 41, 2003, Number 5, pp. 451–464

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1 Introduction

We would like to express our congratulations to the authors for having carried out an interesting work that let us know better the effects of the high velocity jets on plunge pool bottom and scour of rock.

The results obtained by the authors are very interesting but established, just exclusively, for the case of circular jets. Besides, the knowledge of the falling jet process is of crucial importance for the downstream physical phenomena. So, we would like to make some observations on wide rectangular nappes or rectangular jet in the following subjects: the initial jet turbulence intensity T_u, the jet break-up length L_b, the impingement jet thickness B_j, the mean dynamic pressure coefficient C_p and the fluctuating dynamic pressure coefficient C'_p.

2 Estimation of the initial jet turbulence intensity in the nappe flow case

The experimental equation of the break-up length for circular jet, established by Ervine *et al.* (1997) is

$$\frac{L_b}{D_i F_i^2} = \frac{1.05}{C^{0.82}} \tag{1}$$

where C is the turbulence parameter

$$C = 1.14 T_u F_i^2 \tag{2}$$

T_u and F_i are the initial turbulence intensity and Froude number at the issuance.

So the jet break-up length for nappe flow case would obey the following general form:

$$\frac{L_b}{B_i F_i^2} = \frac{K}{C^{0.82}} \tag{3}$$

If the Horeni's expression for rectangular jet

$$L_b = 6q^{0.32} \tag{4}$$

is transformed into a function of the general jet break-up length, we have

$$\frac{L_b}{B_i F_i^2} = \frac{6q^{0.32}}{B_i F_i^2} \frac{(1.14 T_u F_i^2)^{0.82}}{(1.14 T_u F_i^2)^{0.82}} \tag{5}$$

We observe that the Kcoefficient is

$$K = \frac{6q^{0.32}}{B_i F_i^2}(1.14 T_u F_i^2)^{0.82} \tag{6}$$

Moreover, the jet velocity when leaves the weir spillway in arch dam (velocity at issuance) is $V_i = \sqrt{2gh_0}$, being $h_0 \approx 2h$. The energy head in function of specific flow is

$$h = \left(\frac{q}{C_d}\right)^{2/3} \tag{7}$$

If we replace in Eq. (6) and make the respective manipulations, then we obtain the Turbulence Intensity in function of specific flow

$$T_u = \frac{q^{0.43}}{IC} \tag{8}$$

where IC represents the initial conditions of flow at issuance; so that

$$IC = \frac{14.95 g^{0.50}}{K^{1.22} C_d^{0.19}} \tag{9}$$

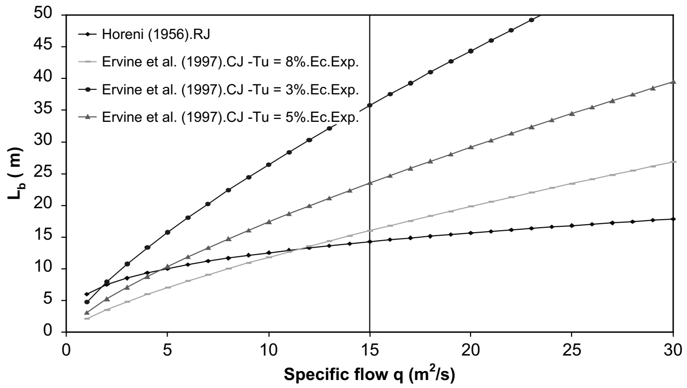

Figure 1 Jet break-up length for rectangular and circular jets.

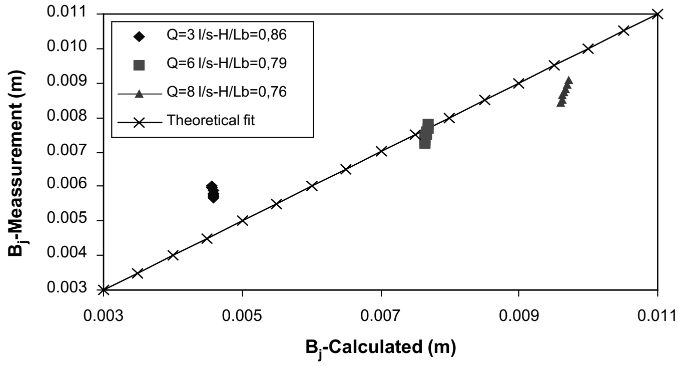

Figure 2 Comparison between measurement and calculated rectangular impingement jet thickness.

The discharge coefficient is $C_d \approx 2.1$ in hydrodynamic spillway case (Units International System). The K value for circular jet is similar to $K = 1.05$. However, the break-up length at circular jet is higher than at rectangular jet (over the double, see Fig. 1), so that K could vary possibly between 0.40 and 0.80, depending on the particular case.

3 Estimation of the Impingement jet thickness

The impingement jet thickness is

$$B_j = B_g + B_s = B_g + 2\xi \tag{10}$$

where B_g is the thickness by gravitational considerations, B_s is the thickness by lateral spread and ξ is the lateral spread distance of turbulent jet in the atmosphere.

Following Ervine *et al.* (1997)

$$\xi = kv't = k\left(\frac{v'}{V_i}\right)V_i\frac{V_j - V_i}{g} \tag{11}$$

where we define a turbulence parameter $\varphi = k(v'/V_i) = kT_u$; t is the time for the jet to fall any distance; v' is the streamwise turbulent component; V_i and V_j are the mean jet velocity at issuance and the mean jet velocity at impact in the pool respectively.

If we replace the mean velocities in Eq. (11), then

$$\xi = 2\varphi\sqrt{h_0}\left[\sqrt{H} - \sqrt{h_0}\right] \tag{12}$$

so, the impingement thickness is:

$$B_j = \frac{q}{\sqrt{2gH}} + 4\varphi\sqrt{h_0}\left[\sqrt{H} - \sqrt{h_0}\right] \tag{13}$$

where H is the water level difference between upstream and downstream of the structure.

We know that at circular jet case the transverse turbulent velocities are $u' = w'$ and $u' = 0.38v'$; so that the root-mean-square of the streamwise turbulent component is

$$\overline{v'} = \sqrt{u'^2 + v'^2 + w'^2} = 1.14\ v' \tag{14.a}$$

Then the lateral spread is

$$\xi = kT_uV_it = 1.14\ v't \tag{14.b}$$

In the case of nappe flow we have that $w' \ll u'; u' = 0.38\ v'$. Then the root-mean-square of the streamwise turbulent component is

$$\overline{v'} = \sqrt{(0.38\ v')^2 + v'^2} = 1.07\ v' \tag{15.a}$$

and the lateral spread it would be

$$\xi = kT_uV_it = 1.07\ v't \tag{15.b}$$

So the turbulent parameter for nappe flow is

$$\varphi = 1.07\ T_u \tag{16}$$

Figure 2 shows a first verification of the method that was obtained in a small model, Castillo (1989). For a general validation of the method, it would be necessary to obtain further information in models and prototypes.

4 Mean dynamic pressure coefficient C_p

The authors present an exhaustive analysis of the mean dynamic pressure coefficients, however this coefficients correspond, in general, to jet break-up length lower than $H/L_b < 0.50$. The only exception to this, corresponds to Puertas's data that cover the jet break-up lengths situated between $0.4 < H/L_b < 2.7$, if we estimate L_b with Horeni's formulation (1956). Puertas (1994) made a multivariant treatment of the most outstanding non-dimensional variables. The expression proposed is:

$$\frac{\Delta p_{max}}{H\gamma} = \frac{3.88q}{Y\sqrt{2gH}} \tag{17}$$

The expression is valid whenever an effective cushion is guaranteed

$$Y_e \succ \left[\frac{0.113}{\sqrt{2g}}Hq\right]^{2/5} \tag{18}$$

However, Puertas's formulation is the product of a global treatment of data and for this reason underestimates the C_p coefficient.

Castillo (1998) carried out a new analysis with Puertas's (1994) and Castillo's (1989) data and proposed different formulations of $C_p = f(Y/B_j,\ H/L_b)$. In Fig. 3 these results are presented, together with the results for circular and rectangular jets (aerated and no aerated cases) from another authors.

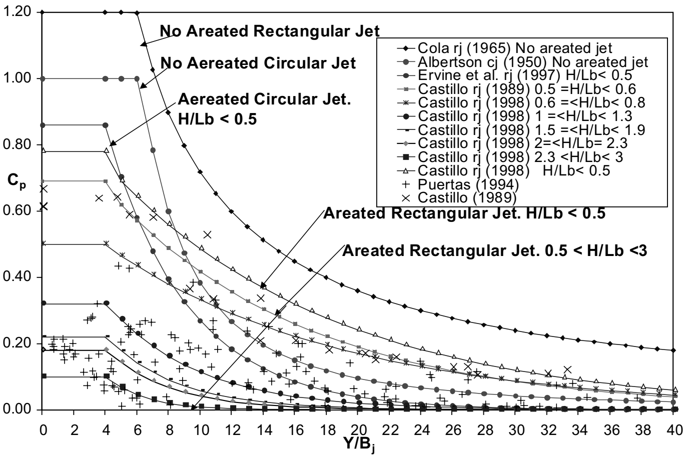

Figure 3 Mean Dynamic Pressure Coefficient. For aerated rectangular jet $C_{\mathrm{p}} = f(Y/B_{\mathrm{j}},\ H/L_{\mathrm{b}})$.

Table 1 Parameters of the exponential law of the mean dynamic pressure coefficients in function of the different jet break-up length

H/L_{b}	a	b	$C_{\mathrm{p}}\ (Y/B_{\mathrm{j}} \leq 4)$
< 0.5	0.98	0.070	0.78
0.5–0.6	0.92	0.079	0.69
0.6–0.8	0.65	0.067	0.50
1.0–1.3	0.65	0.174	0.32
1.5–1.9	0.55	0.225	0.22
2.0–2.3	0.50	0.250	0.18
2.4–3.0	0.50	0.400	0.10

The general formulation to obtain the mean dynamic pressure coefficient for aerated rectangular jet or nappe flow case, follows a exponential law:

$$C_{\mathrm{p}} = \frac{H_{\mathrm{m}} - Y}{V_{\mathrm{j}}^2/2g} = ae^{-b(Y/B_{\mathrm{j}})} \tag{19}$$

where H_{m} and Y are the mean head and depth at plunge pool; V_{j} and B_{j} are the velocity and thickness of the impingement jet. The parameters are shown in Table 1 and the minimum regression coefficient obtained for different curves fitting was 0.90.

The region of jet core impact is between 4 and 5 times the jet thickness.

5 Fluctuating dynamic pressure coefficient C'_{p}

The root-mean-square value of the pressure fluctuation depends on both the Y/B_{j} ratio and the initial turbulence intensity of the jet T_{u}.

The authors′ data have been obtained with velocities higher than 20 $\mathrm{m}^{-1}\mathrm{s}$ and for this reason, they affirm that the results are exempt of scale effects and, thus, representative for prototype jets.

Figure 4 shows the results from Bollaert (2002) for different turbulence intensity, Jia *et al.* (2001) and Castillo (1989) where two data were corrected towards the general tendency, Castillo *et al.* (1991).

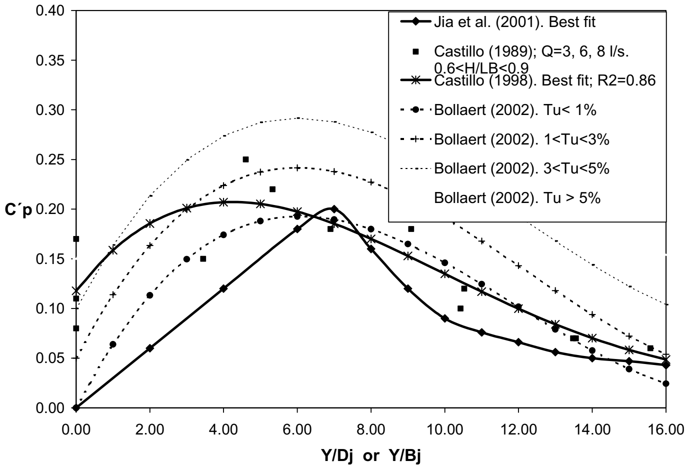

Figure 4 Fluctuating dynamic pressure coefficient. Cirular jet : Bollaert (2002) and Jia *et al.* (2001). Rectangular jet or nappe flow case: Castillo (1989) and Castillo *et al.* (1991).

Although in the aerated rectangular jet or nappe flow case, the velocities in the model only 5.7 $\mathrm{m\,s}^{-1}$ and $0.6 < L_{\mathrm{b}}/H < 0.9$ were reached; the maximum coefficient $C'_{\mathrm{p}} \approx 0.21$ is in good accordance with the best-fit of Jia *et al.* (2001) and would correspond to $Y/B_{\mathrm{j}} \approx 5$ and to a turbulence intensity between 1% and 3%. These values are in accordance with these structures type. The best fit obtained by Castillo (1998) was:

$$C'_{\mathrm{p}} = a(Y/B_{\mathrm{j}})^4 + b(Y/B_{\mathrm{j}})^3 + c(Y/B_{\mathrm{j}})^2 + d(Y/B_{\mathrm{j}}) + e \tag{20}$$

where $a = -6.6 \times 10^{-6}$, $b = 0.0004$; $c = -0.008$, $d = 0.0483$ and $e = 0.1179$. The regression coefficient $R^2 = 0.86$.

Notation

B_{g} = Jet thickness by gravitational consideration
B_{j} = Minimum thickness of rectangular jet or nappe flow at entry point
B_{s} = Jet thickness by lateral spread
H = Falling height
H_{m} = Mean head in plunge pool
IC = Initial conditions at issuance
K = Proportional coefficient for break-up length of rectangular jet or nappe flow
k = *Proportional coefficient for lateral spread distance of turbulent jet*
L_{b} = Jet break-up length
q = Discharge per unit width of rectangular jet
T_{u} = Turbulence intensity
u', w' = Transverse turbulent velocities
v' = Streamwise turbulent component
$\overline{v'}$ = Root-mean-square of streamwise turbulent component
V_{i} = Mean velocity at issuance
V_{j} = Mean impingement jet velocity
Y = Cushion height
Y_{e} = Effective cushion

Δp = Mean dynamic pressure
γ = Water especific weight
ρ = Water density
φ = Turbulence parameter
ξ = Lateral spread distance

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The Discusser congratulates the Authors of the paper for their interesting work and is grateful for being quoted.

He only would like to clarify that his expression:

$Y = t + h = 2, 98.$ Cv. $q^{0,5} H^{0,25}$ (notation of the Authors) is not "empirical" although for its formulation many model results and prototype repots on the ultimate scour depth caused by the impact of plunging jets were considered.

Whilst other formulas stem from statistical methods that compare the results of calculus with measured data, the Discusser reached his expression applying theoretical knowledge about the null value of dynamic pressure under the jet's centerline and the limits of its fluctuations for a certain depth of water.

His formula gives the physical limit of the scour depth taking account the hydraulic action or hydrodynamic jacking and uplift ejection but not considering the values of rock resistance. This expression envelops all known cases.

His original paper was presented in the "XII Seminario nacional de grandes barragens. Río de Janeiro—1980", before Mason's paper which he afterwards discussed in the ASCE Journal.

The Discusser agrees with the Authors that the process of destruction of rock mass is very complex and requires much research in order to obtain accurate mathematical models. However, until a fully coupled 3-phase model (Fig. 7) is developed, for an engineering project (and not only for preliminary design stages) the Discusser's formula represents an useful tool to determine the maximum theoretical hydraulic scour depth caused by a ski jump on rock or soil. Designers should bear in mind, however, that such depth might not actually be reached.

Reply by the Authors

The authors would first of all like to thank the discussers L.G. Castillo, J. Puertas and J. Dolz for their interesting study on wide rectangular nappes or jets. The estimation of the initial jet turbulence intensity in the nappe flow case is based on a direct combination of the equations of Ervine *et al.* (1997) for circular jets and Horeni (1956) for falling nappes. However, the exact turbulence intensity of the jets used by Horeni during his experiments is not known. Hence, the K value for rectangular jets can only very roughly be estimated and further research and experimental tests seem necessary to better assess the process of break-up of falling nappes and rectangular jets in general.

The study of Castillo (1998) summarizes relevant data concerning the mean dynamic pressure coefficients of rectangular jets with different degrees of break-up. The authors would like to comment these results with laboratory data they obtained for plunging circular jets with and without low-frequency (<1 Hz) undulations of the jets upon impact in the pool. These low-frequency jet instabilities were introduced by the presence of a 90° bend in the upstream supply conduit, which introduced secondary currents and low-frequency turbulent fluctuations into the jets at issuance. As such, it constitutes an artifact of the test installation of the authors (Bollaert, 2002). Nevertheless, it is believed that these phenomena may be relevant for prototype jet conditions. This is outlined later.

Figure 1 presents the mean dynamic pressure coefficients obtained by the authors as a function of pool depth to jet diameter ratio Y/D_j, for low jet velocities, i.e. less than $15\,\mathrm{m\,s^{-1}}$, and for high jet velocities, i.e. higher than $15\,\mathrm{m\,s^{-1}}$. It can be noticed that the mean dynamic pressures at low jet velocities substantially differ from the assumptions developed by Ervine *et al.* (1997).

This is confirmed in Fig. 2, where the mean dynamic pressure coefficients are illustrated as a function of jet outlet velocity. For jet velocities lower than $15\,\mathrm{m\,s^{-1}}$, the pressure coefficients

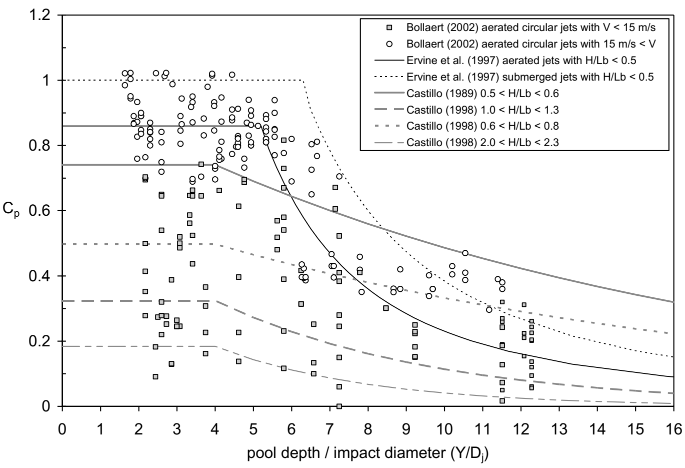


Figure 1 Mean dynamic pressure coefficients for high-velocity plunging circular jets and for different Y/D_j ratios (Bollaert, 2002).

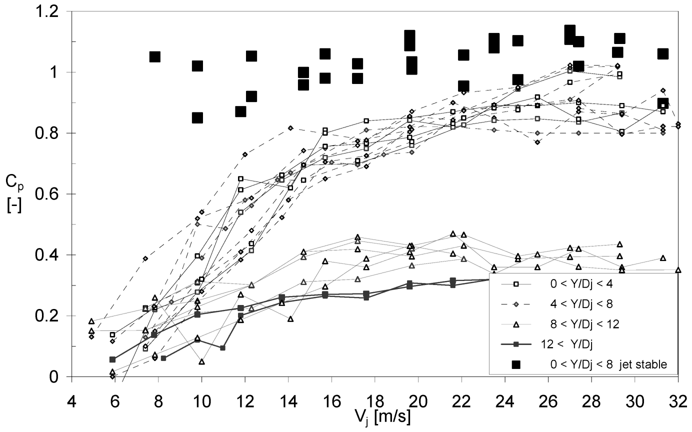


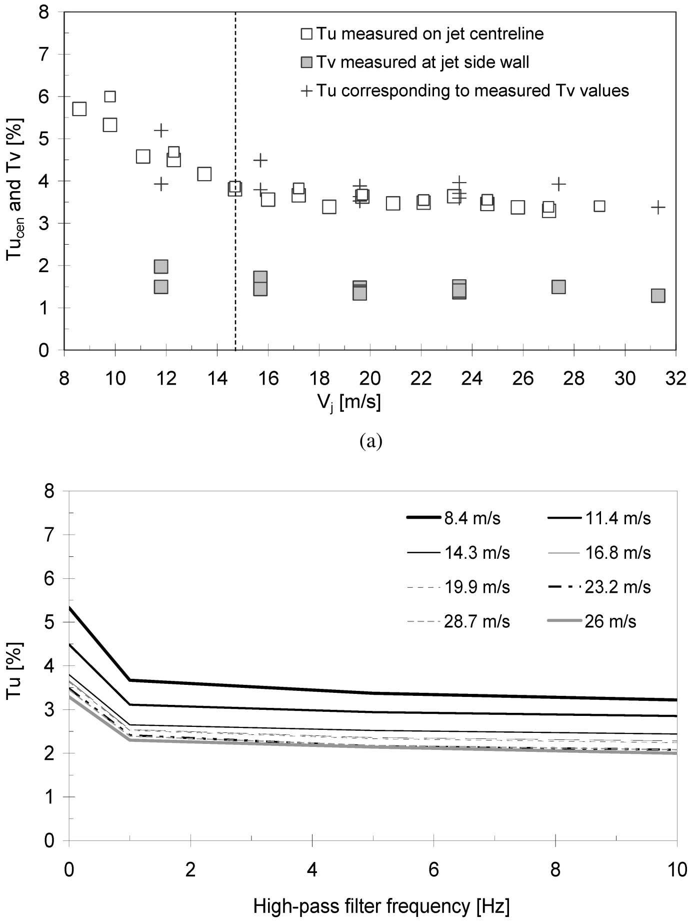
Figure 2 Mean dynamic pressure coefficients as a function of jet velocity for plunging circular jets with and without low-frequency undulations and for different Y/D_j ratios (Bollaert, 2002).

significantly depend on the jet velocity. Comparison of these data for compact jets ($L/L_b < 0.5$) with the discussers' data for broken up jets shows that good agreement is obtained for jet velocities less than $15\,\mathrm{m\,s^{-1}}$, despite the completely different jet issuance conditions.

To assess this at first hand contradictory observation, a detailed analysis of the jet conditions upon impact is necessary. Especially the influence of low-frequency undulations of falling jets seems to be a key element. To verify this influence, the time periods during which a significant widening (instability) of the authors' jet upon impact was observed have been omitted from the statistical analysis. This provides mean dynamic pressure coefficients that are quasi constant with jet velocity, as illustrated in Fig. 2 (black squares).

Hence, the authors would like to point out that jet stability in general and low-frequency undulations in particular influence the process of break-up of a jet and thus also the mean and fluctuating dynamic pressure coefficients upon impact. Low-frequency phenomena may or may not be present on prototype jets. As such, appropriate assessment of the break-up of prototype aerated plunging jets should account for the whole spectral range of turbulent fluctuations, i.e. not only the intermediate and high-frequency turbulent fluctuations induced by the boundary layer at issuance of the jet but also the low-frequency (<1 Hz) jet fluctuations that may be generated by the detailed geometry of the spillway outlet, wind effects, approach flow conditions, etc. In the same manner, jet break-up may also depend on the absolute value of the jet velocity at issuance. All these phenomena can hardly be represented on small-scale test facilities, which would mean that small-scale laboratory tests suffer from significant scaling effects.

Furthermore, the discussers state that their fluctuating pressure coefficients C'_p are in good agreement with the best-fit of data published by Jia *et al.* (2001). This could reasonably be expected because both studies are primarily based on small-scale laboratory tests using low jet velocities. The C'_p curves as proposed by the authors, on the contrary, are valid at near-prototype jet velocities and assume that the turbulence intensity of the jets at issuance also incorporates eventual low-frequency instabilities. Hence, in order to fully assess the influence of the turbulence intensity on the degree of break-up of a jet, distinction should be made between low-frequency instabilities (<1 Hz) and higher frequency turbulent fluctuations generated by the boundary layer at issuance.



(a)

(b)

Figure 3 (a) Longitudinal turbulence intensity of plunging circular jets as a function of mean jet velocity at issuance;(b) Longitudinal turbulence intensity of plunging circular jets as a function of high-pass filter frequency for different jet outlet velocities.

This has been done by the authors for their near-prototype jets (Bollaert, 2002). As presented in Fig. 3(a), the longitudinal

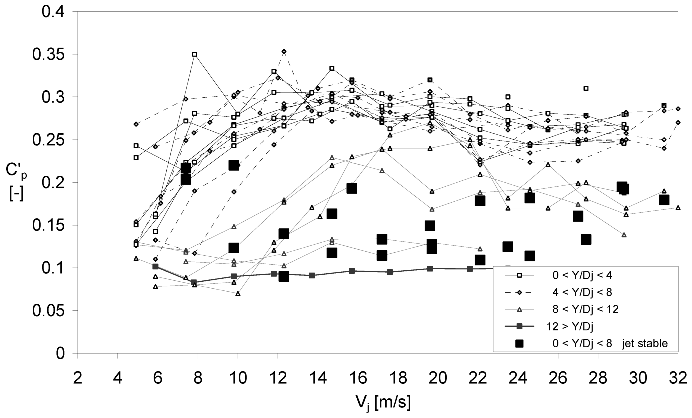


Figure 4 Fluctuating dynamic pressure coefficients as a function of jet velocity for plunging circular jets with and without low-frequency instabilities and for different Y/D_j ratios (Bollaert, 2002).

turbulence intensity Tu for circular plunging jets was typically between 3.5 and 6%, depending on jet velocity. When assuming that the transversal turbulence intensity Tv is about 40% of Tu (based on Ervine and Falvey, 1987), the measurements of Tv are found in good agreement with the Tu measurements on the authors' installation.

Filtering of the instabilities with frequencies less than 1 Hz from the raw pressure signals recorded at jet issuance decreases the remaining turbulence intensity to values between 2 and 3.5%. Figure 3(b) illustrates that further filtering of higher frequencies (> 1 Hz) does not significantly change the turbulence intensities of the jet.

Thus, as previously found for the mean dynamic pressure coefficients, low-frequency instabilities may also significantly influence the longitudinal turbulence intensity of the jet. This influence has finally been verified for the fluctuating dynamic pressure coefficients C'_p at the point of impact of the jet on the plunge pool bottom.

Figure 4 presents the C'_p coefficients measured by the authors as a function of jet velocity at issuance for different pool depth to jet diameter ratios Y/D_j. The results are compared with the hypothetical C'_p coefficients of the authors' when filtering the low-frequency instabilities (< 1 Hz), which are called "stable jets" in Fig. 4 (black squares). A substantial decrease of the fluctuating pressure coefficients is observed over the whole range of jet outlet velocities.

It is obvious that low-frequency undulations of falling jets may have a significant impact on the characteristics of the jets upon impact in the pool. The challenge is to assess the relevance of these phenomena for real-life falling jets. At prototype jet velocities, part of the fluctuating energy of the jet is transferred towards higher frequencies (Bollaert and Schleiss, 2003) and the relative importance of the low-frequency instabilities probably will be different than from model studies. Nevertheless, it is believed that low-frequency instabilities are plausible and even highly probable for real-life jets, because one or more effects that may generate these instabilities are present on prototype jets.

As a conclusion, it may be stated that the characteristics of a jet plunging into a pool (turbulence intensity, mean and fluctuating pressures, air content, etc.) are strongly influenced by phenomena such as jet stability and low-frequency fluctuations, spillway geometry and approach flow conditions, wind effects, etc. (Bollaert, 2002). These phenomena cannot be fully assessed under laboratory conditions, although the authors have made some progress by using near-prototype jet velocities in their experiments, but are believed to be as relevant as the geometry of the jet during its fall.

Especially for rectangular falling jets as presented by the discussers, it is believed that jet stability and low-frequency fluctuations may be of importance given the relatively small thickness of the nappes. It is not clear to which extent the data of the discussers are affected, or what would be their pressure coefficients and break-up lengths when transferred to prototype falling nappe conditions. Hence, precaution should be taken when applying small-scale laboratory data to prototype conditions.

Based on the work initiated by Bollaert (2002) and Bollaert and Schleiss (2003), further research is actually being performed at the Laboratory of Hydraulic Constructions of the EPFL on the influence of the longitudinal turbulence intensity at jet issuance on mean and fluctuating dynamic pressures upon impact (Bollaert *et al.,* 2004) and on the influence of a lateral confinement of the jet due to the plunge pool geometry (Manso *et al.,* 2004).

Second, the authors also want to express their gratitude to L. Machado for the precisions concerning the basics of the scour expression he developed. The authors agree that, despite the ongoing developments and research in the field of physically based models, empirical and semi-empirical expressions remain useful tools for a first-hand assessment of scour formation during all stages of the project.

Nevertheless, the authors strongly recommend combining the use of such expressions with more physically based methods to obtain the best possible assessment and overview of potential scour formation as a function of time. A physically based scour evaluation method has recently been developed by Bollaert (2004).

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