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PRESSURE CHARACTERIZATION OF UNDEVELOPED AND DEVELOPED JETS IN SHALLOW AND DEEP POOL

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ABSTRACT

This paper presents the main results obtained from the analysis and revaluation of experimental data corresponding to different instantaneous pressure registers, measured under the jets centre line at the bottom of the plunge pools. The pressure signals for undeveloped and developed jets (disintegrated jet) in shallow pool (establishment of the flow) and deep pool (established flow) are identified; the probability of occurrence of the measured pressure values is determined by means of the probability density function, which is also compared to a Gaussian distribution.

These results are discussed and compared with the case of circular jets. Then, formulae are proposed in the following subjects: jet turbulence intensity at issuance conditions, T^*_u, jet break-up length, L_b, impingement jet thickness, B_j, mean and fluctuating dynamic pressure coefficient, C_p and C'_p, and finally, extreme pressures, C^+_p and C^-_p.

Keywords: dams, spillways, plunge pool, energy dissipation, pressures characterization.

1 INTRODUCTION

The rectangular jet or nappe flow constitutes one of the types of plunge pools in arch dams. The selection of the plunge pool depth is usually a technical and economic decision between a deep pool, which needs no lining, or a shallow pool, which needs a liner. Therefore, a designer needs to know the magnitude, frequency and extent of the dynamic pressure on the pool floor as a function of the jet characteristics.

The characterization of pressures in plunge pools has been obtained using different scale models, from the early works of Moore (1943), Lencastre (1961), Cola (1965), Beltaos (1976), Xu-Do-Ming et al. (1983), Lemos (1984), Cui Guang Tao et al. (1985), Ervine and Falvey (1987), Withers (1991), Ervine et al. (1997), Bollaert (2002) and Manso et al. (2005).

In Spain, this line of research has been undertaken at the Technical University of Cataluña UPC by Castillo (1989, 1998), Armengou (1991), Castillo et al. (1991, 1999), Puertas (1994) and at the Technical University of Cartagena UPCT by Castillo (2002, 2006) and Castillo et al. (2004).

The main mechanisms of energy dissipation are the spreading of the plunging jet (aeration and atomization in the air), air entrainment by the entering jet and its diffusion in the pool and finally, the impact with the pool base (see Fig. 1). For design considerations, both issuance and impingement conditions are defined: The issuance conditions, located at the exit of the spillway structure, are defined by the mean velocity $V_i = (2gh_0)^{1/2}$, where h_0 is approximately equal to two times the energy head, h; the impingement conditions, situated at entrance to the pool, are the mean velocity, V_j, and the impingement jet thickness, $B_j = B_g + \xi$, where, B_g, is the thickness by gravity conditions and ξ, is the jet lateral spread distance by turbulence effect.

The jet break-up length, L_b, constitutes an important parameter. Beyond this distance, the jet is completely developed. It no longer contains a core, but essentially consists of blobs of water that disintegrate into finer and finer drops.

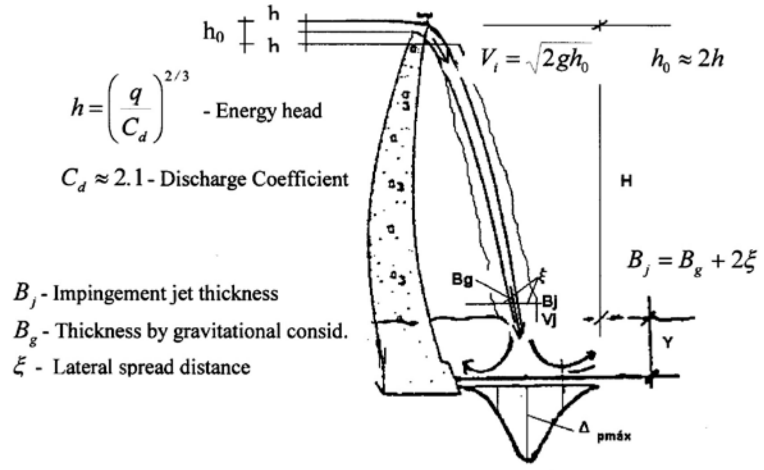


Figure 1 Plunge pool at dam toe.

Individual blobs and drops of water slow down due to air drag and eventually reach terminal velocity. The latter occurs when drag introduced by the air equals the weight of individual water globules or drops. Such interaction limits the erosive capacity of a fully developed jet (Annandale, 2006).

Once the jet hits the pool surface, the air is swept along by the entering jet, the diffusion begins and the solid part of the jet is completely disintegrated in a depth of approximately four times the impingement thickness, B_j (established flow). The disintegration conditions of circular jets have been thoroughly studied mainly by Ervine and Falvey (1987) and Ervine et al. (1997), who produced different formulae. Nevertheless, the case of rectangular jet or nappe flow has not been studied in any grade of depth.

2 GENERAL ANALYSIS OF PRESSURES REGISTERS

For circular jets, there are exhaustive pressure registers and analysis, obtained from a model with velocities greater than 20 m/s and turbulence intensity until 5 % (see Ervine et al. 1997, Bollaert, 2002). However, these coefficients generally correspond to the jet break-up length relation $H/L_b \leq 0.50$.

For the nappe flow or rectangular jet case, the following ranges have been obtained:

Castillo´s (1989) data cover a range of $0.50 \leq H/L_b \leq 0.90$. The data correspond to different falling heights H between 1.60 m to 1.76 m, seven water cushion heights Y (0–0.04–0.08–0.12–0.16-0.20–0.25 m) and three specific flows q (0.0125–0.0250–0.050 m^2/s).

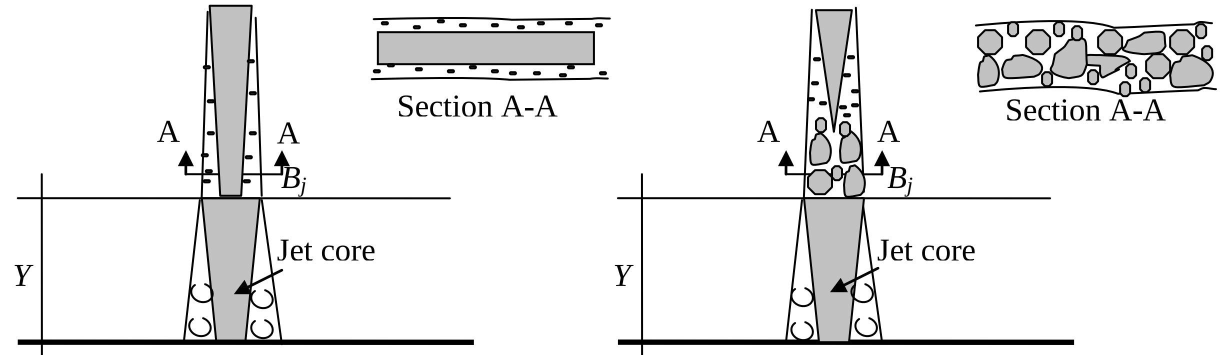
Puertas´ (1994) data cover a range of $0.50 \leq H/L_b \leq 2.70$. Four falling heights with H (1.85-2.88-4.43-5.45 m), ten water cushions heights Y (0.08–0.16–0.24–0.32–0.40–0.48–0.56-0.80 m) and a range of the specific flows q (0.026 to 0.150 m^2/s).

Castillo´s and Puertas´s instantaneous pressures were registered at the bottom of the pool by means of piezoresistive pressure transducers. Around 200 registers were obtained, 2400 points each, with a data acquisition rate of 20 points per second.

Figure 2 depicts the four types of jet that were registered and that will be described and discussed in the following paragraphs.

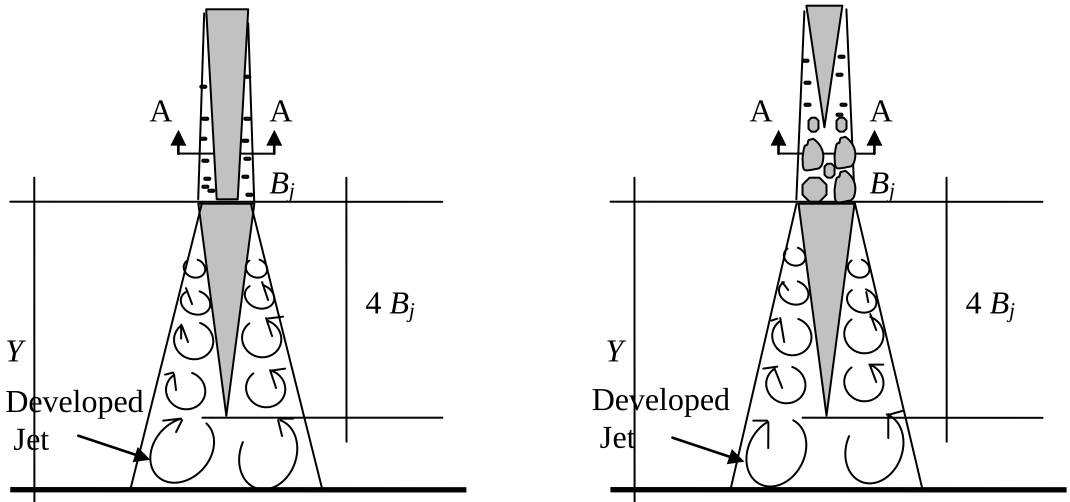
In figure 3 are shown the typical pressure registers corresponding to undeveloped jets (H/L_b<1, left figures), developed jets (H/L_b>1, right figures) and also to shallow pool (Y/B_j<4, establishment of the flow) and deep pool (Y/B_j>4, established flow).

In the case of undeveloped jets, a constant pressure pattern occurs in general, with similar pressure peaks above and under the mean pressure. These peaks substantially decrease, when the water cushion (established flow case) increases. Low-frequency core turbulence is clearly visible in shallow water cushion (flow establishment case) and where pressure drops are produced near the atmospheric pressure level.



(a) Undeveloped jet: $H/L_b < 1$
Establishment of the flow: $Y/B_j < 4$ (Shallow pool)

(b) Developed jet: $H/L_b > 1$ (Disintegrated jet)
Establishment of the flow: $Y/B_j < 4$ (Shallow pool)



(c) Undeveloped jet $H/L_b < 1$
Established flow: $Y/B_j > 4$ (Deep pool)

(d) Developed jet: $H/L_b > 1$ (Disintegrated jet)
Established flow: $Y/B_j > 4$ (Deep pool)

Figure 2 Diagram of the four different types of jets.

For developed jet cases, more fluctuating pressures are registered due to the presence of a turbulent shear-layer impacting on the pool bottom. This effect increases with fall height and water cushion. The global effect is an increase of energy dissipation and a substantial reduction of the pressure at the bottom.

The Probability Density Function PDF defines the probability of occurrence of pressure values as a function of their deviation from the mean pressure.

In Figure 4, some pressure registers in non-dimensional form (difference of each pressure from the mean value as a function of the standard deviation) are represented and compared with the Gaussian curve, valid for normally distributed values.

Undeveloped jet ($H/L_b = 0.6$) and shallow pool cases ($Y/B_j < 4$) are characterized by presenting the PDF very similar to the Gaussian curve. When they correspond to lower fall height (impingement jets with lower velocities), skewed pressure distributions are generated with the increase of fall heights (higher velocities). The results tend to concord with those obtained from circular jets.

In the shallow pool case ($Y/B_j<4$, establishment of the flow), a slightly positive skewed PDF is generated for undeveloped jets, is changing to the centre for developed jets ($H/L_b<2$) and tends to negative skewed for developed jets ($H/L_b >2$). This corresponds to a quite constant pressure pattern (jet core), alternated with occasional lower pressures caused by low-frequency turbulences.

Deep pool (Y/B_j>4, established flow) generates a negatively skewed PDF with the appearance of a significant amount of low pressures when increasing the fall height and the water cushion.

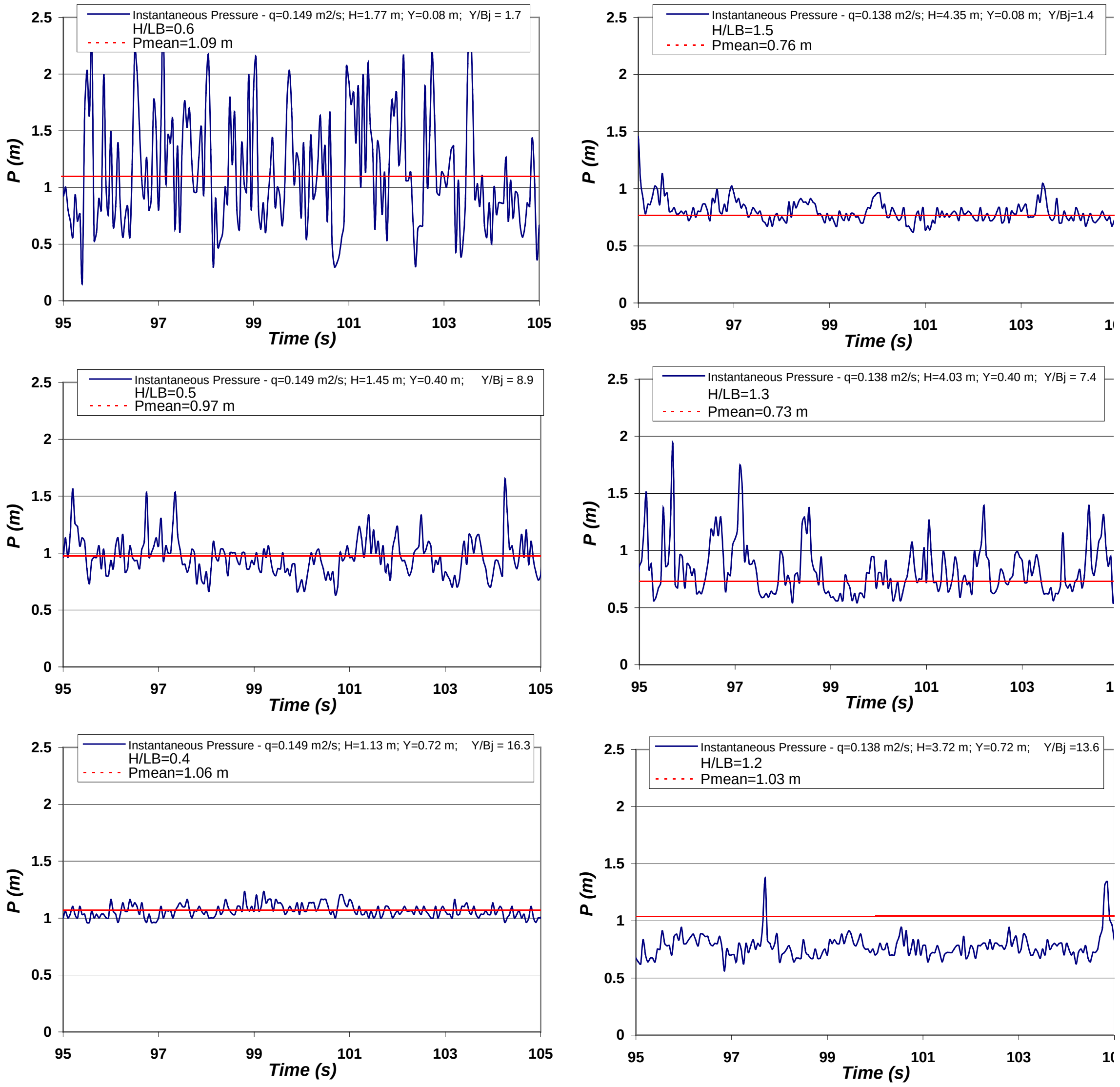


Figure 3 Pressure signal measured under the jet centreline at the plunge pool bottom. Left figures: Undeveloped jets (H/L_b<1). Right figures: Developed jets (H/L_b >1). Shallow pool (Y/B_j< 4, establishment of the flow). Deep pool (Y/B_j > 4, established flow).

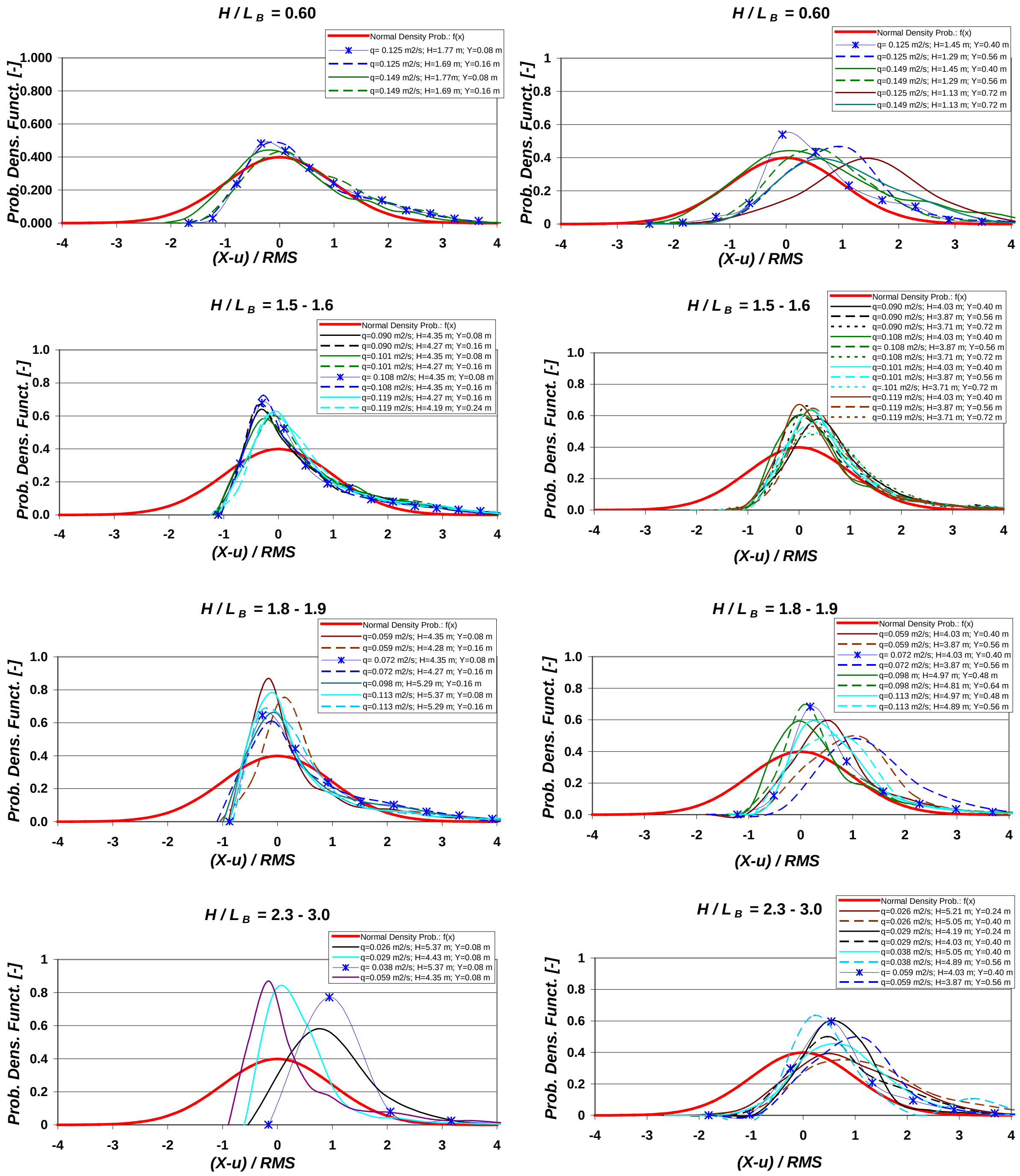


Figure 4 Probability Density Function compared to a Gaussian Distribution. Left figures: Shallow pool (Y/B_j<4, flow establishment). Undeveloped and developed jets. Right figures: Deep pool (Y/B_j>4, established flow). Undeveloped and developed jets.

3 ESTIMATION OF THE TURBULENCE INTENSITY AT ISSUANCE CONDITIONS AND JET BREAK-UP LENGTH IN NAPPE FLOW CASE

Experimental data on break-up lengths (for example Horeni, 1956) are related to horizontally issuing jets. Gravity is supposed not to affect considerably the jet break-up length, an assumption which has been supported by the evidence found in a small-scale jet model. However, some theoretical and experimental data reveal the effect of gravity on vertical jets, since it was found that the break-up length of a contracting jet is longer than a horizontally issuing jet (Takahashi and Kimura, 1972; Withers, 1991). For flows smaller than 0.25 m^2/s (laboratory tests values), the Horeni´s formula ($L_b \sim 6q^{0.32}$) seems to be correct.

In order to estimate the turbulence intensity at issuance conditions, T^*_u, and the jet break-up length in the rectangular jet or nappe flow case, L_b, we have used as a starting point, the experimental equation of the break-up length for circular jet established by Ervine et al. (1997) and the Horeni´s expression for rectangular jet (see Castillo, 2006 and Castillo et al., 2004). Then,

$$T_u^* = \frac{q^{0.43}}{IC} \tag{1}$$

Where q is the specific flow and IC represents the initial conditions of flow at issuance; so that

$$IC = \frac{14.95 g^{0.50}}{K^{1.22} C_d^{0.19}} \tag{2}$$

The discharge coefficient is $C_d \approx 2.1$ in hydrodynamic spillway case (Units International System) and $K \approx 0.85$. The jet break-up length would be:

$$\frac{L_b}{B_i F_i^2} = \frac{0.85}{(1.07 T_u F_i^2)^{0.82}} \tag{3}$$

where B_i and F_i are the jet thickness and Froude number at issuance conditions, and T_u is the Initial Turbulence Intensity when the flow passes on spillway crest (critical flow conditions) ($0 \le T_u \le 3$ %). Therefore, for equal specific flows, the circular jet is much more compact than the rectangular jet (see Castillo, 2006).

4 ESTIMATION OF THE IMPINGEMENT JET THICKNESS

The impingement jet thickness is defined as

$$B_j = B_g + B_s = B_g + 2\xi \tag{4}$$

where B_g is the thickness for 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).

$$\xi = kv'\!t = k\left(\frac{v'}{V_i}\right)V_i \frac{V_j - V_i}{g} \tag{5}$$

but we define a new turbulence parameter $\varphi = k(v'/V_i) = kT_u^*$; where k is the proportional coefficient for lateral spread distance, 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 impingement conditions, respectively. If we replace the mean velocities in (5), then

$$\xi = 2\varphi\sqrt{h_0}\left[\sqrt{H} - \sqrt{h_0}\right] \tag{6}$$

H is the water level difference between upstream and downstream of the structure and h_0 is equal two times the energy head at the spillway, $h_0 \approx 2h$ (see Fig. 1) and $\varphi = 1.07T^*_u$, (see Castillo et al., 2004 and Castillo, 2006). Thus, the impingement thickness for rectangular jet or nappe flow case is:

$$B_j = \frac{q}{\sqrt{2gH}} + 4\varphi\sqrt{h_0}\left[\sqrt{H} - \sqrt{h_0}\right] \tag{7}$$

5 MEAN AND FLUCTUATING DYNAMIC PRESSURE COEFFICIENTS

Castillo (1998, 2004, 2006) carried out a new analysis with Puertas´s and Castillo´s data and proposed formulations of $C_p=f$ (Y/B_j, H/L_b). In Figure 5, the obtained results are presented together with other authors' results (circular and rectangular jets).

We can see that for the case of $H/L_b \leq 0.5$ a single curve is obtained, whereas for $H/L_b > 0.5$ a family of curves is obtained in function of this parameter.

We can also see from this figure the disintegration of the solid part of the jet occurs at a depth of approximately four times the impingement jet thickness ($Y<4B_j$, establishment of the flow). In this range, the following relations for mean dynamic pressure, C_p, and energy dissipation DE_{air}, in function of H/L_b parameter are valid (see Castillo, 2006):

$$C_p = 0.36(H/L_b)^{-1.04} \tag{8a}$$

$$DE_{air} = 1 - 0.36(H/L_b)^{-1.04} \tag{8b}$$

For $H/L_b > 0.5$, the general formulation to obtain the mean dynamic pressure coefficient for aerated rectangular jet or nappe flow, follows an exponential law:

$$C_p = \frac{H_m - Y}{V_j^2/2g} = ae^{-b(Y/B_j)} \tag{9}$$

where H_m and Y are the head mean 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, being R^2=0.81 the minimum regression coefficient obtained for different curves fitting.

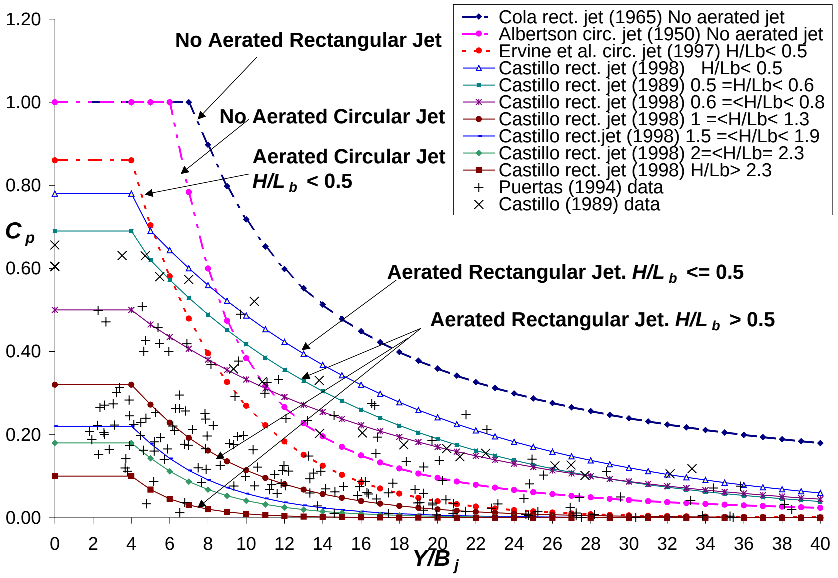


Figure 5. Mean dynamic pressure coefficient.

H/L_b	a	b	C_p (Y/B_j <= 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
> 2.3	0.50	0.400	0.10

Table 1 Parameters of the mean dynamic pressure coefficient formulation, C_p.

The root mean square pressure fluctuation is defined like $C'_p = H'/(V^2_j/2g)$, where H' is the root mean square value of the pressure head fluctuation. Figure 6 shows the results for different turbulence intensity, T_u (Bollaert, 2002 to circular jet case) and different parameter, H/L_b (Castillo, 2006 to rectangular jet case). Bollaert´s (2002) and Bollaert and Schleiss (2003) data (circular jet case) were obtained with velocities higher than 20 m/s, and that is the reason why they affirm the results are exempt from scale effects and therefore, representative for prototype jets.

Although in the aerated rectangular jet or nappe flow case, the velocities in the tests were reached only up to 10 m/s, the maximum coefficient is $C'_p \approx 0.31$ ($H/L_b < 1.4$). This is in good accordance with the best fit of Bollaert (2002) for 3 %<T_u<5 %, but C'_p corresponding to a value of $Y/B_j \approx 5$. These values agree with such types of structure. We can observe that there is not a clear grouping with regard to the ratio of fall height per jet break-up length, H/L_b. The data can only be grouped in three principal zones, so $H/L_b \leq 1.4$, $1.4 < H/L_b \leq 2$ and $H/L_b > 2$. The expressions to quantify the fluctuating dynamic pressure coefficient as a function of the parameters Y/B_j and H/L_b are found in Castillo (2006).

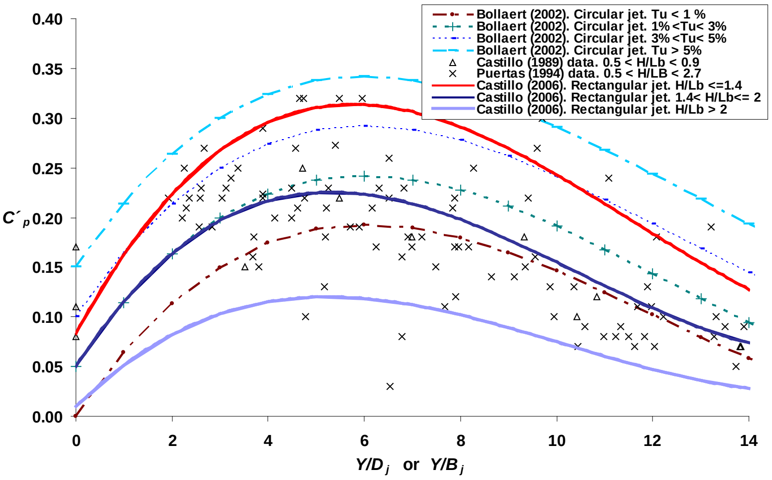


Figure 6 Fluctuating dynamic pressure coefficients, C'_p.

6 EXTREME DYNAMIC PRESSURE COEFFICIENTS

Figures 7 and 8 shows the extreme positive $C^+_p=(P_{max}-H_m)/(V^2_j/2g)$ and negative $C^-_p=(H_m-P_{min})/(V^2_j/2g)$ pressure values.

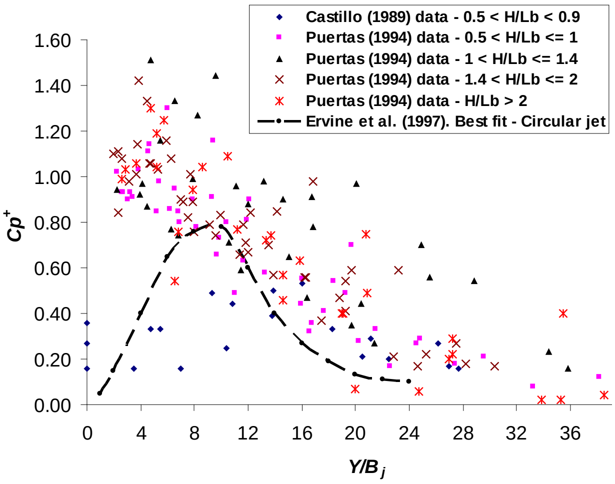


Figure 7 Positive extreme press. coeffic.C^+_p.

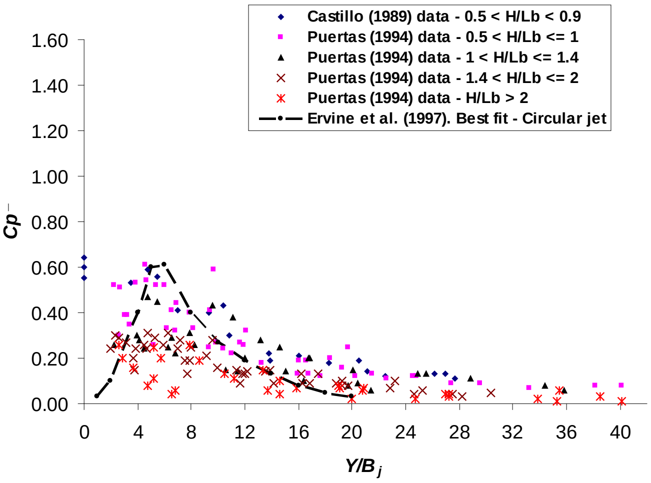


Figure 8 Negative extreme press. coeffic. C^-_p.

The obtained values have not permitted to establish any type of grouping. For positive extremes, the measured values are much higher than the data found in the literature available (Ervine et al., 1997 and Bollaert et al., 2003). The most important deviations are produced in the developed jet case, range $1<H/L_b<2$ and established flow $4<Y/B_j<12$. The maximum value could be at C^+_p ~1.3 for a relation $Y/B_j=8$.

However, the negative extreme values are better agree with the previously published data related to the circular jet case, obtaining the maximum value C^-_p ~0.6 for a relation $Y/B_j=6$.

7 CONCLUSIONS

From the practical design methodology for plunge pools with impingement jets of rectangular type or nappe flow here presented, the following conclusions have been drawn:

The estimation of the jet thickness at impingement conditions is a very important factor for the determination of the pressure and jet footprint.

The only cases where the PDF are similar to the normal distribution correspond to undeveloped jet ($H/L_b<0.6$) (impingement jets with lower velocities) and shallow pool ($Y/B_j<4$).

The establishment of the flow zone in no aerated jets is greater than in aerated jets cases: $Y/D_j\approx 6.2$ (circular jet) and $Y/B_j\approx 7.8$ (rectangular jet). However, in both circular and rectangular aerated jets, the flow zone is $Y/B_j \approx 4$.

In aerated jets, when $Y/B_j<4$, the mean dynamic head is $C_p=0.86$ (circular jet) and $C_p=0.78$ (rectangular jet). The air energy dissipation in a rectangular jet is greater than a comparable circular jet (aerated or no aerated jet).

Fluctuating dynamic pressure coefficients C'_p can be grouped in three principal zones, so $H/L_b\leq 1.4$, $1.4<H/L_b\leq 2$ and $H/L_b>2$. The maximum coefficient $C'_p\approx 0.31$ is produced for $H/L_b<1.4$ and $Y/B_j \approx 5$.

The values obtained for extreme dynamic pressure coefficients have not permitted to establish any type of grouping. The C^+_p coefficients in rectangular jets are much higher than in the circular jets case. These values could be at C^+_p~1.3 ($Y/B_j=8$).

Negative extreme values in rectangular jets are in better agreement with the circular .jets case, obtaining a maximum value C^-_p~0.6 ($Y/B_j=6$).

A limitation of the described work is that both the disintegration length and turbulence intensity have been assumed and adapted from the results of other authors.

In order to improve the methodology, further measurements are required from models and prototypes, specially concerning turbulence and aeration. At the Hydraulic Laboratory of the Technical University of Cartagena UPCT, a substructure is being constructed to do tests with some falling heights and flow ranges.

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