Plunge Pool Pressures Due to a Falling Rectangular Jet

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Abstract: This Technical Note presents the results of a large set of laboratory tests and tries to determine the conditions that ensure the existence of a water cushion that is not expelled by the impingement of a nappe (effective cushion). Second, values of mean dynamic pressures at the stagnation point of nonsymmetric plunge pools downstream of arch dams are assessed.

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Introduction

Free overflow spillways are frequently constructed as outlets for arch dams. These structures generate high-velocity rectangular jets, or nappes, impacting downstream. To avoid direct action of the nappe on the riverbed it is common practice to construct an auxiliary structure (downstream cofferdam), which creates a plunge pool. This pool receives the impact of the falling nappe, so when the nappe reaches the riverbed, it has lost most of its energy, i.e., its scouring capacity.

The nappe absorbs a certain amount of air during its fall, and the thickness of the compact core of the nappe becomes smaller due to gravity. A certain degree of turbulence is reached, which depends on the velocity of the water in the nappe (Ervine et al. 1997) and on outlet conditions.

The thickness of the water cushion in the plunge pool is the main point of this Technical Note. Aki, referred by Cui Guang Tao et al. (1985), provided a classification of water cushions according to their behavior when receiving the impact of a nappe. Two different situations can be pointed out. First, the cushion is not deep enough to absorb the nappe and the energy of the nappe is great enough to expel the cushion, so a hydraulic jump is developed in the stilling basin near the cofferdam [Fig. 1(b)]. Second [Fig. 1(a)], the cushion is able to avoid the formation of a jump, and a certain amount of energy is absorbed by the cushion. A separation is proposed based upon the relationship between the thicknesses of the cushion (h) and the nappe (B). The goodness of this definition of the separation line will be discussed.

Studies of the pressure field on a plunge pool floor started in the 1960s. A classic reference is the study by Cola (1966) who, based on the momentum conservation law, proposed a formula to evaluate the mean dynamic pressure at the stagnation point (the point where the nappe reaches the floor). The parameters involved and the structure of the equation were

$$\Delta P_{\max} = C\rho \frac{v^2 B}{2h} \tag{1}$$

where $\Delta P_{\max}$ = mean dynamic pressure at the stagnation point; ρ = water density; C = coefficient to be fit by experimental means; v = velocity of the water when reaching the pool; B = thickness of the nappe; and h = thickness of the cushion, which is set equal to the cofferdam height.

The coefficient C has been calculated by several writers for very heterogeneous experimental facilities and conditions very heterogeneous (Cola 1966; Hartung and Häusler 1973; Ervine et al. 1997). The values of C are in the range of 5–8 for these writers.

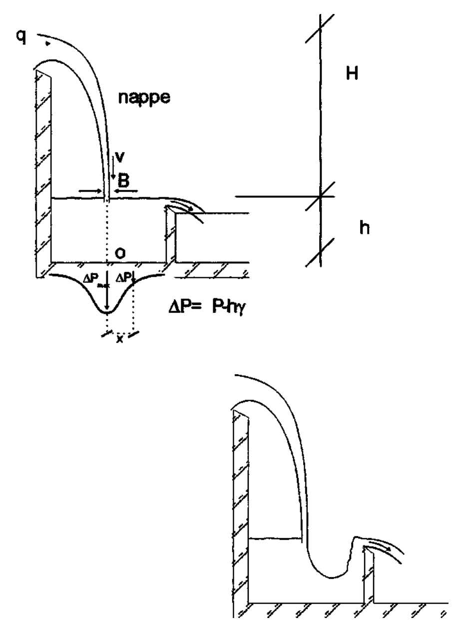

Fig. 1. (a) Effective cushion and (b) noneffective cushion

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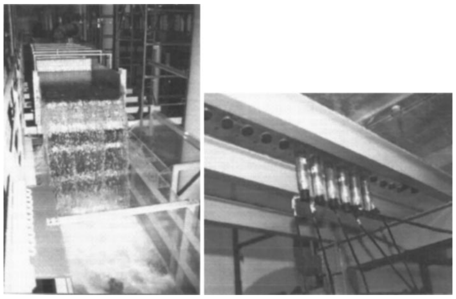

Fig. 2. Experimental facilities. Upper and lower basin. Set of sensors.

A certain turbulence level is achieved in the nappes, which could be calculated as a function of the fall height and the discharge, as the water level in the upper resrervoir was absolutely stable. However, no direct measurements of turbulence have been done. Also the aeration degree of the nappes has not been directly measured. Ervine et al. (1997) provides information to calculate turbulence effects on falling nappes. Most of the papers on this topic dealt with symmetric pools (upstream and downstream of the jet). If one considers the free overflow over an arch dam, the pool often is not symmetric.

Franzetti (1980) did experimental work with a model of an arch dam, which had a fall height of 1.6 m. The nappe was not very thick, so some of the results may be affected by the surface tension, which compacts the nappe. The "C" values obtained by Franzetti are in the range of only 2.15–5.74. Franzetti's experiments are quite similar to those presented here.

Some other papers deal with turbulence and aeration effects in falling jets, as the one by Canepa and Hager (2003). These effects are not considered in this Technical Note.

This study has tried to analyze, for nonsymmetric pools:

- The conditions that ensure the existence of a cushion that is not expelled by the impingement of the nappe (effective cushion); and
- The mean dynamic pressure at the stagnation point when considering a nonbroken nappe impinging on an effective cushion.

Experimental Methodology

Experimental Facilities

The experimental equipment used in this research was

- A structure based on two orthoedric basins, where the upper one spills the water to the lower one, in which the cushion is formed and pressures are measured (Fig. 2). The spillway (1.2 m wide) is straight, in order to work under two-dimensional conditions. The vertical distance between the basins may be varied in order to work with different fall heights ($h+H$) from a value of 2 up to 5.5 m. The thickness of the cushion and the discharge may also be varied: $0 \leqslant h \leqslant 0.8$ m, $0.02\ \mathrm{m^2/s} \leqslant q \leqslant 0.2\ \mathrm{m^2/s}$.
- A set of piezoresistive sensors (from 4 up to 6) (Fig. 2), which measure at a frequency of 40 Hz for 1 min (2,400 measurements per test).

Tests to ensure two-dimensional character were carried out, as well as tests to ensure the effect of the length of the cushion, which, according to Armengou (1991), happens to be null if the cushion has a minimum length. This length has been set at 3.2 m. The impact angle between the nappe and the slab is nearly 90°, so no effect of the angle has been taken into account.

Dimensional Analysis

In order to apply the results of this research to structures including a falling nappe, we used nondimensional parameters. The parameters involved [Fig. 1(a)] (taking into account pressure, gravity, and inertia forces) are

$\Delta p/\gamma H$ (Dynamic pressure recorded on a point of the pool floor versus fall height. $\Delta p = p - \gamma h$);

h/H (cushion thickness versus fall height); and

$q/\sqrt{2gH^3} = B/H$ (Nappe thickness versus fall height; Froude number. It can be considered as an ideal nappe thickness when neglecting turbulence and aeration effects.)

Ten large arch dams in Spain have been analyzed, covering fall heights from 37 up to 135 m, in order to obtain their mean H and q values. The mean fall height is about 89 m, and the mean unit discharge is about 10.9 $\mathrm{m^2/s}$ (6.5 up to 23.53). The mean value of B is 0.26 m (0.18 up to 0.46), and the mean value of B/H is 0.0034 (B/H about $1.6e-3$–$8.6e-3$). As cushion heights are usually not under 4 m, and concrete-lined pools are usually not deeper than 8–12 m, expected values for h/H are in the range 0.04–0.13, and the values for B/h are about 0.025–0.085. This range has been widely covered in the experimental work.

Results

The behavior of the cushion when a nappe is impinging depends on its thickness. As has been mentioned above for nonsymmetrical plunge pools without any influences from recirculation patterns, a separation line can be established between pools whose shape remain unaltered and pools in which a hydraulic jump is developed [Figs. 1(a and b)]. The frontier proposed by Aki, which can be found in Cui Guang Tao et al. (1986), depends on the relationship B/h, where h = thickness of the cushion and B = thickness of the nappe as it enters the cushion.

This relationship does not take into account that both the height of the falling nappe and the discharge contribute to the power provided to the cushion. The parameter B cannot explain this phenomenon, as B is a relationship between q and $H^{1/2}$

$$B = \frac{q}{\sqrt{2gH}} \tag{2}$$

The parameters involved in the creation of a hydraulic jump are, on the one hand, H and q: the higher they are, the more energy the nappe will have; and on the other hand, the thickness of the cushion. Thus the parameter that could explain the separation must have the following structure:

$$\frac{h^{\alpha}}{q^{\beta}H^{\gamma}} \tag{3}$$

The forces involved in the ejection of the water cushion caused by the nappe seem to be analogous to that involved in the formation of a hydraulic jump in a channel [Fig. 1(b)]. When considering the momentum equation, and assuming F_1 and F_2 to be the forces generated by the pressures in a supercritical regime and in a subcritical regime, respectively,

$$F_1 - F_2 = \rho Q(v_2 - v_1) \tag{4}$$

If we accept $F_2 \gg F_1$ and $v_1 \gg v_2$, we have

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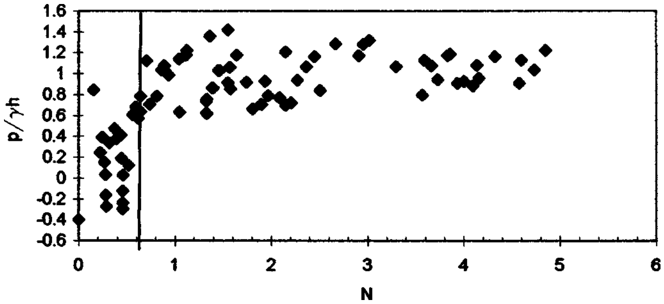


Fig. 3. Relationship between N and the quotient between the mean pressure recorded and the expected hydrostatic pressure, at points downstream of the stagnation line

$$F_2 \cong \rho Q v_1 \tag{5}$$

If the pressure distribution is considered as hydrostatic the following relations holds:

$$\rho g h^2/2 = \rho q v_1 \tag{6}$$

If the water velocity along the floor is considered linearly proportional to the velocity of the water in the nappe, then the following relationship holds:

$$g h^2/2 = A q \sqrt{2gH} \tag{7}$$

Or, in terms of nondimensional numbers

$$N = \frac{\left(\frac{h}{H}\right)^2}{\frac{B}{H}} = \frac{h^2}{q}\sqrt{\frac{2g}{H}} = 4A \tag{8}$$

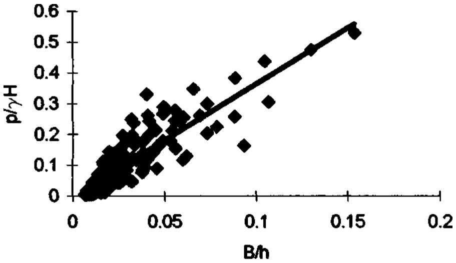
The N parameter gives a relationship between forces trying to eject and forces trying to maintain the cushion. It satisfies all the expected conditions of the parameters q, h, and H, and the sign of their exponents. Nevertheless, N does not consider turbulence and aeration effects. When these effects may be neglected, N is considered to be an accurate parameter to explain whether or not an effective cushion exists in asymmetrical plunge pools where recirculation patterns are considered of no influence to the impinging nappe.

Pressure measurements have been done at some locations clearly downstream of the stagnation line, where dynamic effects are negligible, in order to validate this fomulation. The mean pressure registered in a point downstream of the nappe must be about γh if a water cushion exists. If there is no effective cushion, the pressure registered will be quite lower than γh.

As can be seen in Fig. 3, there is a relationship between the values of N and the values of $p/\gamma h$. The areas with and without an effective cushion are separated by the line $N=0.6$. If N has a value of over 0.6, the cushion is considered effective.

The presence of a cushion makes a great difference in terms of energy dissipation. If there is a cushion, energy is lost not only during the fall, but also in the cushion itself before reaching the floor. Eddies are formed and their movement dissipates some of the energy. If the cushion is not effective, and a hydraulic jump is formed, little energy is lost in the cushion before impacting the floor, and the dynamic pressures on the floor are expected to be higher for the same height and discharge.

As mentioned before, the mean dynamic pressure at the stagnation point, Cola (1966), can be written as



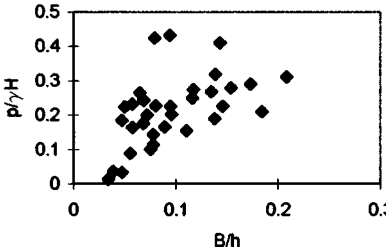


Fig. 4. Relationship between $\Delta p_{\max}/\gamma H$ and B/h for data with (a) and without (b) an effective cushion. Poor agreement to a linear trend of the right-hand data may be observed.

$$\Delta P_{\max} = C\rho \frac{v^2 B}{2h} \tag{9}$$

This expression includes the term h, i.e., the thickness of the cushion. If the cushion is not effective, h is not a relevant term and the expression by Cola would be inappropriate. To verify this statement, a test has been carried out. Cola's formula can be expressed as

$$\frac{\Delta p_{\max}}{\gamma H} = C\frac{B}{h} \tag{10}$$

The expression

$$\frac{\Delta p_{\max}}{\gamma H} = A + C\frac{\frac{B}{H}}{\frac{h}{H}} \tag{11}$$

has been tested with a Student "t" test with a 90% confidence level for the hypothesis $A=0$ for both the data from effective cushion experiments ($N>0.6$) and the data from noneffective experiments ($N\leqslant 0.6$). The plot of these data is as follows (Fig. 4).

The statistics of the fits, whose interest is to confirm if a linear trend without intercept can be considered as a fitting curve, are shown in Table 1.

The values from effective cushion tests are properly adjusted by a linear regression without intercept (Cola's theory) ($C=3.8$). The fits with all the data or with the data from noneffective cushions do not show this behavior if the above figures are considered (the confidence interval for the intercept does not include the zero value).

Table 1. Confidence Intevals for Linear Trends Between $\Delta p_{\max}/\gamma H$ and B/h

Factor	R^2	Confidence interval A	
Total	0.55	0.023	0.058
Without effective cushion	0.3	0.011	0.15
With effective cushion	0.75	−0.02	0.006

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Thus, two behaviors may be observed, one for each set of data. The data from effective cushions seem to fit quite well to Cola's expression, while the data from noneffective cushions do not have a good adjustment. This may be explained by the fact that h has no influence in the second case and so the expression by Cola is not suitable for this set of data.

Conclusions

The main conclusions of this research on vertically falling nappes are

- A frontier can be established between effective water cushions and noneffective water cushions, based on the so-called N parameter: for $N<0.6$ a hydraulic jump developes, for $N>0.6$ nappe diffuses through the cushion.
- The expression by Cola for mean dynamic pressures at the stagnation point is only useful for effective water cushions. The value obtained for the constant (C) is about 3.8.

The present research did not account for nappe turbulence and aeration and eventual plunge pool recirculation currents. All of these phenomena might have a significant influence on the stability of the nappe upon impact and thus the efficiency of the water cushion. To account for these effects in prototype falling nappes further research must be done.

Notation

The following symbols are used in this technical note:
(All parameters have been evaluated using SI unit system)

A = Generic parameter;
B = thickness of the nappe;
C = Cola's linear trend coefficient;
D = jet diameter;
F = generic force;
g = acceleration due to gravity;
H = fall height;
h = thickness of cushion;
p = pressure;
Q = discharge;
q = unit discharge;
R^2 = determination coefficient;
r = distance to the jet center (for circular jets);
v = water velocity;
γ = specific gravity of water;
Δp = dynamic pressure; and
ρ = water density.

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