FLUCTUATING PRESSURES AT THE BOTTOM OF A PLUNGE POOL

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ABSTRACT
The paper describes the results of a laboratory set of experiments made to investigate the pressure fluctuation field on beneath of a plunge pool subjected to jet impingement. As an example this phenomenon takes commonly place in the case of the drop structure, where the elevation reduces with a take off and impinging portion. When the downstream bottom is nearly horizontal and made of concrete or rock, there is no significant scour, and the drop is followed by a stilling basin where the hydraulic jump takes place. The relevance of the topic is related to the structural design of the linings of the dissipation basin downstream barrages or check dams. Nevertheless the knowledge of the stresses at the basis of plunge pool dissipation basins can be useful to predict a localized erosion process. With reference to the specific case of the prototype of a dam spillway and downstream energy dissipation basin, we discuss the effect of a variable water cushion depth on the reduction of the severe pressure fluctuations that take place at the bottom of the stilling basin. The experiments are made on a 1:40 laboratory model, recording the dynamic behavior of pressure fluctuations in a set of different positions on beneath the plunge pool. The experimental results presented in dimensionless form, give a better understanding of the fluctuating pressure reduction that can be obtained increasing the cushion depth.

Keywords: plunge pool, pressure fluctuations, dissipation structures.

INTRODUCTION
The whole energy dissipation process in the passage from the reservoir upstream a dam to the tailwater, involves – from a general point of view – several aspects, each one ascribed to a different phenomena [Novak et al., 2001]: the downhill spillway surface, the free-falling jet, the impact into the pool, the hydraulic jump in the dissipation basin and the outflow into the river. A large portion of energy dissipation is related to the aeration/disintegration of plunging jet and to the phenomena that take place in the downstream dissipation basin. So that a better understanding of these dissipation processes is of primary interest not only for large dams, but also for smaller check dams and, more generally, for drop structures.
The drop structures are those where the elevation reduces with a take off and impinging portion: the approach flow plunges into a water cushion and the energy is dissipated for air resistance before the impingement, impact, wall jet deviation and hydraulic jump. The jet entrains a considerable amount of air as it enters the water cushion and forms two counter rotating macro vortices which diameter is of the same order as the pool depth. The impact structures that receive and deflect the jet dissipate the excess energy by jet diffusion [e.g. Hager, 1995]. In correspondence to the hydraulic jump, the incoming flow is converted into turbulence which is contained initially into large eddies and then is passed down the energy cascade and is finally dissipated by the smaller eddies [e.g. Rajaratnam, 1995]. Both energy

dissipation processes are associated with the origin of severe pressure fluctuations at the bottom of the stilling basin.

Ervine et al. [1997] consider the effect of a falling jet and the air entrainment on the plunge pool pressure fluctuations and the same topic was recently discussed by Melo [2002]. The literature works on dynamic pressures and the ultimate scour are discussed by Castillo [2002], while Jia et al. [2001] simulate computationally the scouring process due to a two dimensional plane impinging jet in a plunge pool. An experimental work similar to those presented in our paper is reported by Puertas and Dolz [2002]. They measure the dynamic pressure increment at the point of impact of the jet, demonstrating that an effective cushion enlarges the area of noticeable pressures as a consequence of the spreading of the jet.

The experimental analysis here proposed considers the fluctuating pressure at the base of the dissipation basin of a prototype dam and its modifications, in terms of maximum values, for different depth of the water cushion within the basin. Our goal is to reach a better understanding of the two major physical mechanisms involved in the energy dissipation process: *i*) the impact at the impingement point of a falling jet and *ii*) the turbulence phenomena under the hydraulic jump occurring downstream.

Nevertheless to infer from the analysis of the dynamic pressure measurements a quantitative criterion for the design of the stilling basin is of extreme importance. In fact, severe pressure fluctuations linked to the dissipative phenomena may be responsible for the failure of high head dissipation structure and of smaller check dams structures. So that our experiments are oriented to the design of the lining of dissipation basins, by evaluating – conventionally – the appropriate thickness of the protection concrete slabs. It follows a criterion, combining laboratory observation with a theoretical analysis, progressively developed on the base of measurements and statistical evaluation of turbulent pressure fluctuation at the bottom of the hydraulic jump. The criterion is based on the time instantaneous pressure differences, assuming that the pulsating pressure at the bottom of the stilling basing propagates with negligible delay through the joint seal of the slabs, allowing extreme pressure differences from the upper to the lower surface of the slabs. This way, the total force related to the pressure acting on both sides of the slab may exceed the weight of the slab and the anchor resistance. As an example, Fiorotto and Rinaldo [1992] developed a design criterion based on the uplift due to the severe pressure fluctuations associated to the dissipative phenomena in the hydraulic jump. This criterion provides an equivalent thickness s of the slab as a function of the maximum uplift force F'_{max}.

Being $h'^{+} = \max(p - p_{med})$ and $h'^{-} = \min(p - p_{med})$, the respectively the maximum and the minimum measured pressure fluctuation around the mean pressure p_{med}, and γ and γ_c the specific weight of water and concrete respectively, the equivalent thickness according with the design criterion proposed by Fiorotto and Rinaldo is:

$$s = \Omega\left(\frac{l_x}{y}, \frac{l_x}{I_x}, \frac{l_y}{I_y}\right)\frac{h'^{+} - h'^{-}}{\gamma_c - \gamma} = \frac{F'_{max}}{(\gamma_c - \gamma)l_x l_y}. \tag{1}$$

In eqn. (1) y is the depth of the incident flow, while l_x, l_y are the slab dimensions and I_x, I_y the fluctuating pressure correlation lengths, in the longitudinal and transversal direction respectively. The dimensionless coefficient Ω, related to the instantaneous spatial distribution of the fluctuating pressures, may be determined by direct measurement in hydraulic models of the maximum uplift or by using the expression provided by Bellin and Fiorotto [1995] in case of normal distributed force and pressure. If the slab is anchored, the

dynamic behavior of the whole system (the slab and the anchor) can be evaluated as in Fiorotto and Salandin [2000].

Nevertheless in this context the presence of a plunging jet in a water cushion was never considered and, more general in literature, a generic design criterion for the optimum cushion depth to reduce the dissipation basin floor stresses, still lack.

DESCRIPTION OF THE PHYSICAL MODEL
AND OF THE MONITORING APPARATUS

The experimental setup was developed on the physical model of spillway and stilling basin of the Sa Stria dam, under constraction on the Monti Nieddu river in southern Sardinia (Italy). The original 1:40 model was realized ensuring the Froude similarity to verify the performance of the dam outlet works and of the dissipation basin. In the prototype the spillway crest, divided in 4 stretch each 11.5 m long by the presence of 3 piers, is at 141.20 m a.s.l. and it ensures the evacuation of the design flood (570 m^3/s) with 144.52 m a.s.l. of the upstream reservoir level. The chute ends with a horizontal ski jump at 98.00 m a.s.l. and the dissipation basin is limited about 200 m downstream by a barrage with a spillway 70.00 m long and crest at 79.00 m a.s.l.: this barrage realizes a cushion depth large enough to localize the dissipative phenomena for all expected discharges.

In our experiments we substitute the barrage with a series of removable stoplogs each of 4 cm of height (see Figure 1 and 2), to gain the possibility of realize different depth of water cushion in the dissipation basin. In the area affected by the jet impingement 21 openings were provided at the bottom to evaluate the dynamic pressure behavior. The tap diameter was set of 2 mm, according with previous studies of Fiorotto and Rinaldo [1992], which show that further increasing in the tap diameter reduces the magnitude of measured fluctuating pressure.
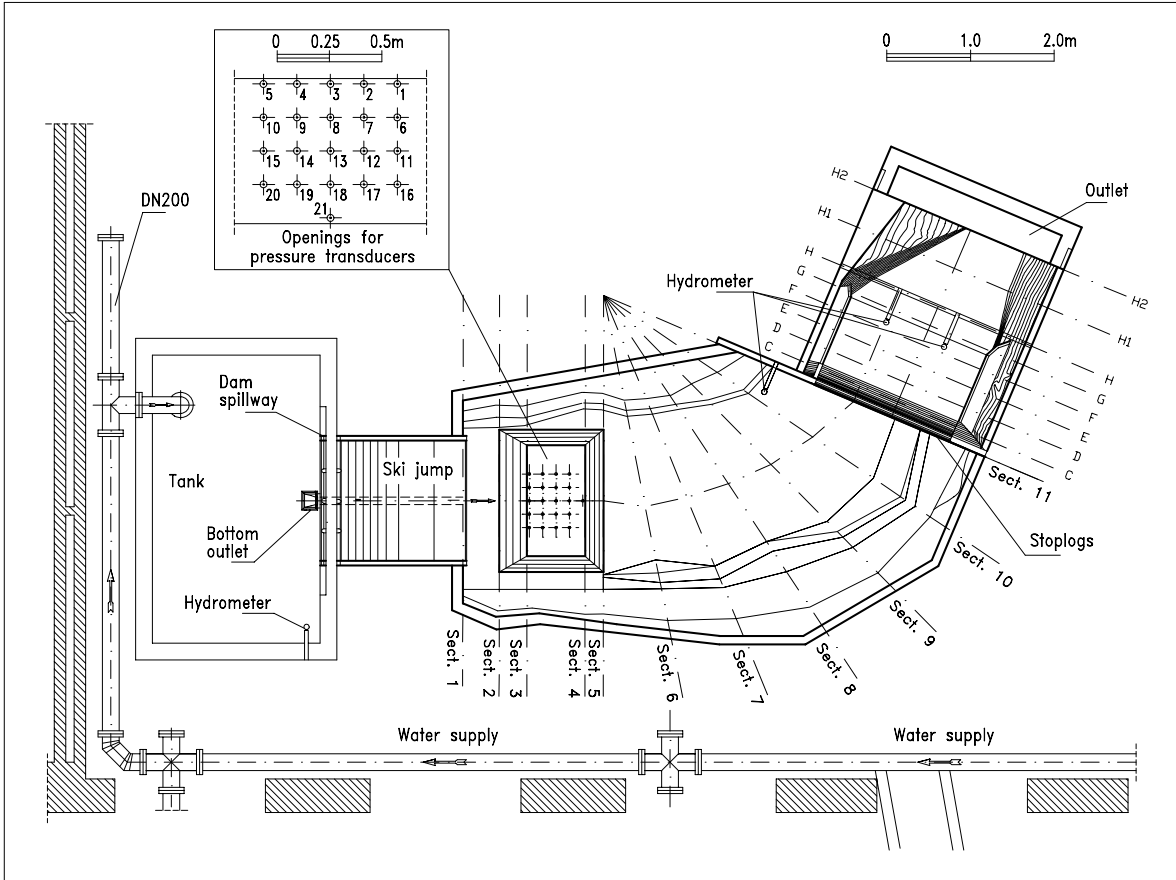

Figure 1. Experimental setup. General planimetric view of the Sa Stria dam model.

Figure 2. Experimental setup. Sa Stria dam model stilling basin, longitudinal profile.

The fluctuating pressure was measured by means of 5 AEP LAB TP14 pressure transducers, calibrated in the range of 0-1 bar and characterized by an accuracy of 0.05% in the entire range. The pressure transducers were connected to the taps by a rigid tube of 4 mm diameter and the connections were equipped with a bleed valve to allow the removal of any air entrapped during operation. The computer was linked to the transducers by a 16-channel analog-digital board (Data Translation 2801 A) and sampling was accomplished by a Global Lab program.

Since several preliminary tests indicate that the impinging jet affects uniformly the area monitored by pressure taps and no relevant differences in the dynamic pressure behavior are manifest in the transversal direction, the pressure fluctuations recordings were limited to the longitudinal axis of the stilling basin corresponding to the taps number 3, 8, 13, 18 and 21 (see Figures 1 and 2). Moreover, since the spectra analyses demonstrated that the dominant frequencies of pressure fluctuations were less than 50-60 Hz, a sampling rate of 200 Hz was adopted according to the Nyquist theorem.

The pressure fluctuations were recorded for the $Q=39.5$ and the $Q=56.3$ l/s discharge values increasing the height of the cushion depth by change the number of stoplogs at the end of dissipation basin. The duration of every experiment was 60 minutes: this duration was chosen balancing the computer disk space with the requirement of a recording time large enough to define the statistics of the measured signal.

RESULTS AND DISCUSSION

As previously stated, in our experiments we considered two different values of the water discharge, $Q = 39.5$ l/s and $Q = 56.3$ l/s, while the fluctuating pressures are measured along the longitudinal axis of the stilling basin corresponding to the cells numbered as 3, 8, 13, 18 and 21 in Figure 1.

In the following we will refer with $p_{med,i}$ the time average of pressure measured at cell i and with $var(p_i)$ its variance.

In order to evaluate the spatial distribution of the fluctuating pressure on the base of the time continuous pressure measurements along the axes of the stilling basin, the following parameters have been estimated.

1) The maximum, minimum and mean pressure relative to the five location of the cells and to different water cushion depths. The mean downstream pressure value h_v is estimated on measurements taken at cell number 21. In fact, we assume that $h_v = p_{med,21}$. The water level measured on the spillway crest of the model is $h = 8.31$ cm and $h = 6.71$ cm corresponding to the two water discharge $Q = 56.3$ l/s and $Q = 39.5$ l/s. With respect to the symbols indicated in Figure 2, $H^* = \Delta z + h - h_v$.

2) The maximum positive and negative dimensionless pressure fluctuation are defined as $C_p^+ = h'^+ / H^*$ and $C_p^- = h'^- / H^*$. The absolute values of C_p^+ and C_p^- are plotted as a function of the cells position x_i within the stilling basin in Figure 3 for $Q = 56.3$ l/s and in Figure 4 for $Q = 39.5$ l/s. The depth of the corresponding water cushion is resumed by the dimensionless parameter h_v / H^*.

3) The dimensionless variance of pressure fluctuation $\mathrm{var}(p_i)/H^*$. In Figure 5 this quantity is plotted as a function of x_i for $Q = 56.3$ l/s (left) and for $Q = 39.5$ l/s (right).

4) The spatial correlation structure of the pressure fluctuation relative to cell number 3 for different water cushion depths, evaluated as $\langle p_3 p_j - p_{med,3} \, p_{med,j} \rangle / \sqrt{\mathrm{var}(p_3) \cdot \mathrm{var}(p_j)}$, with $j = 3, 8, 13, 18$ and 21. For sake of simplicity we indicated with the symbol $<z>$, the time average of the quantity z over all the recording time. In Figure 6 are plotted as a function of the horizontal distance from the beginning of the stilling basin the correlation structures relative to the larger discharge $Q = 56.3$ l/s (on the left) and those relative to the smaller discharge $Q = 39.5$ l/s (on the right).
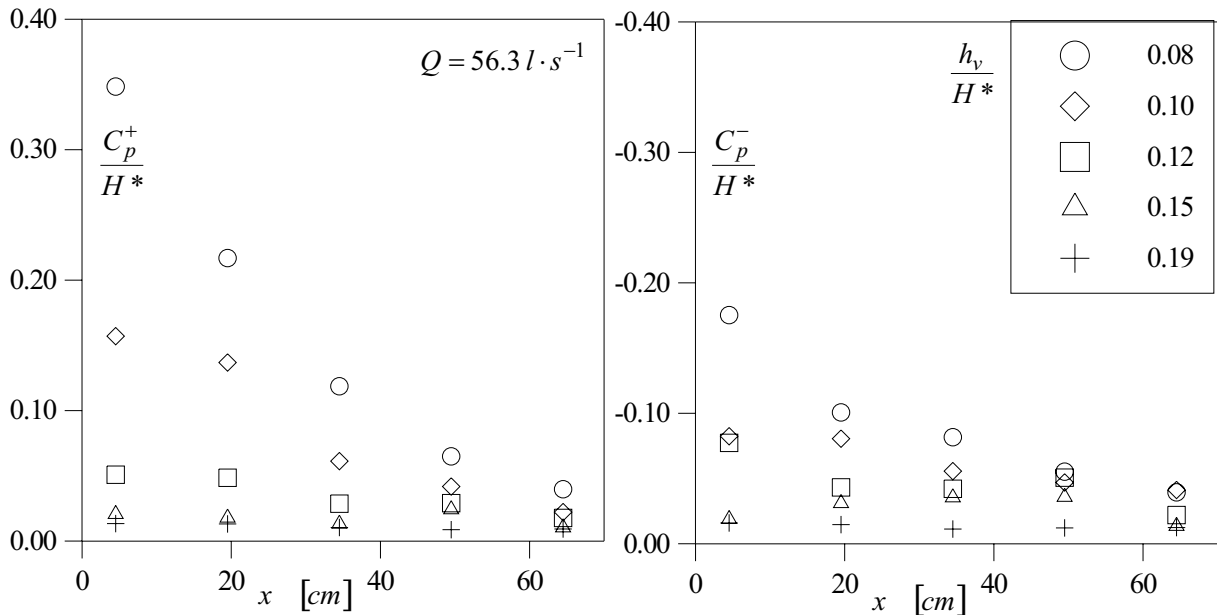

Figure 3. Case of water discharge $Q = 56.3$ l/s. Spatial distribution of the maximum (left) and minimum (right) dimensionless pressure fluctuation for different water cushion depth. In the legend is indicated the correspondence between symbols and mean dimensionless cushion depth.

Figure 3 and Figure 4 demonstrate the existence of a limit water cushion depth, above which no relevant further reduction of the extreme pressure fluctuation is detectable. In the cases

examined, such limit depth seems to be around $h_v/H^* = 0.12 \div 0.13$. When the water cushion is close to the this limit value and $Q = 56.3$ l/s (squared symbols in Figure 3) the extreme pressure fluctuation caused by the jet impingement and by the hydraulic jump are about the same order of magnitude. For shallower water cushions the major pressure fluctuations are due to the jet impingement.
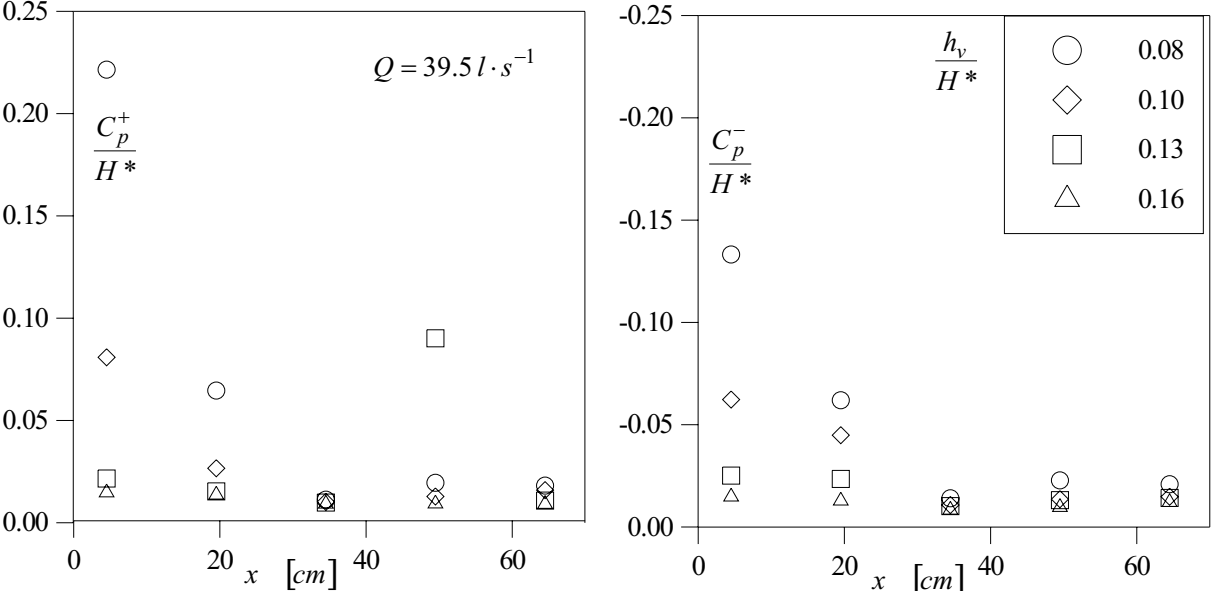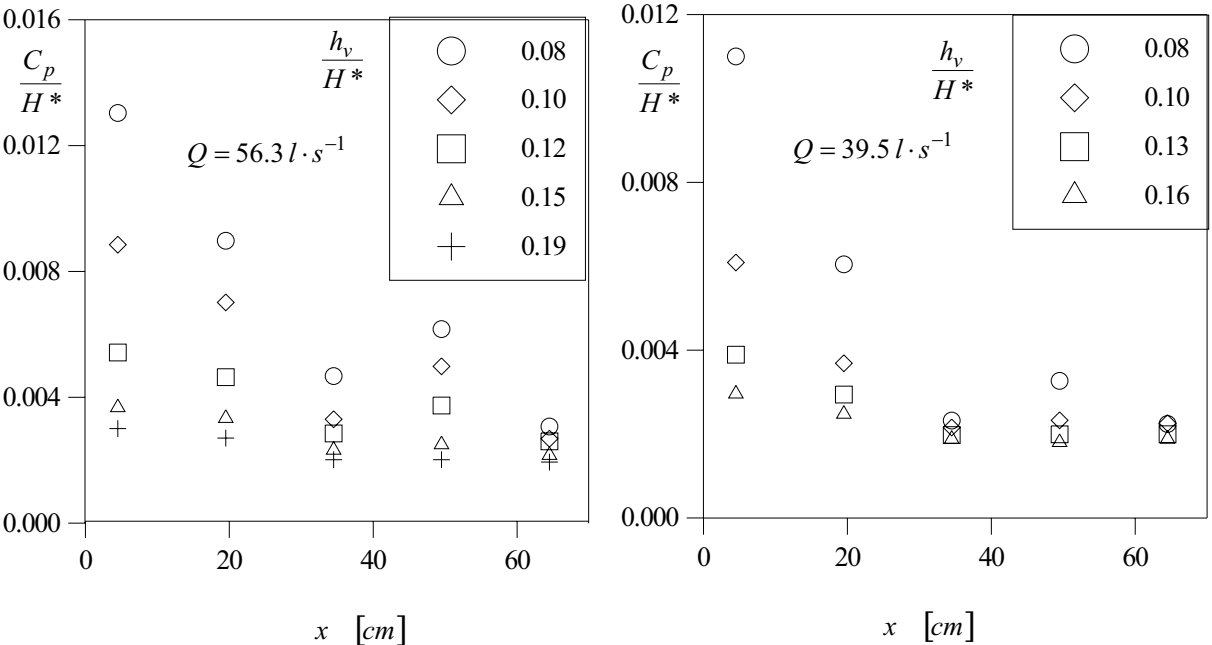

Figure 4. Case of water discharge $Q = 39.5$ l/s. Spatial distribution of the maximum (left) and minimum(right) dimensionless pressure fluctuation for different water cushion depth. In the legend is indicated the correspondence between symbols and mean dimensionless cushion depth.

Figure 5. Spatial distribution of the variance of the dimensionless pressure fluctuation for different water cushion depth. Case of water discharge $Q = 56.3$ l/s (left) and $Q = 39.5$ l/s (right).

In Figure 4, it is manifest that the maximum positive pressure fluctuation for a ratio $h_v/H* = 0.13$ and $Q = 39.5$ l/s was measured in the tap number 18 while the general behavior indicates that the maximum pressure fluctuations were measured at tap 3, in the position where the jet plunges in the pool. Because of the extreme pressure fluctuations have a small probability of occurrence, this fact can be related to the duration of experiments limited to 60 minutes, so that a longer acquisition time may gives a more robust statistics on the extreme pressure fluctuations. Nevertheless this fact not affects the general spatial behavior of the fluctuating pressures confirmed also by the analysis of the variances reported in Figure 5.

The variance of the pressure fluctuations is an index of the stress on the bottom of the stilling basin. Once more, Figure 5 shows how the major part of the stress is caused by the jet impingement whereas the stress caused by the hydraulic jump is less than half of the one caused by the jet.

The area under the evaluated correlation points is a measure of the longitudinal correlation length I_x of the pressure fluctuations. As the water cushion depth increases, the diffusion of the impinging jet prevails on phenomena related to the jet deflection. So that the fluctuations of pressure with statistically comparable behavior interest a more extended area, leading to a larger correlation length. This fact can be recognized from the Figures 6 for both the discharges here considered.
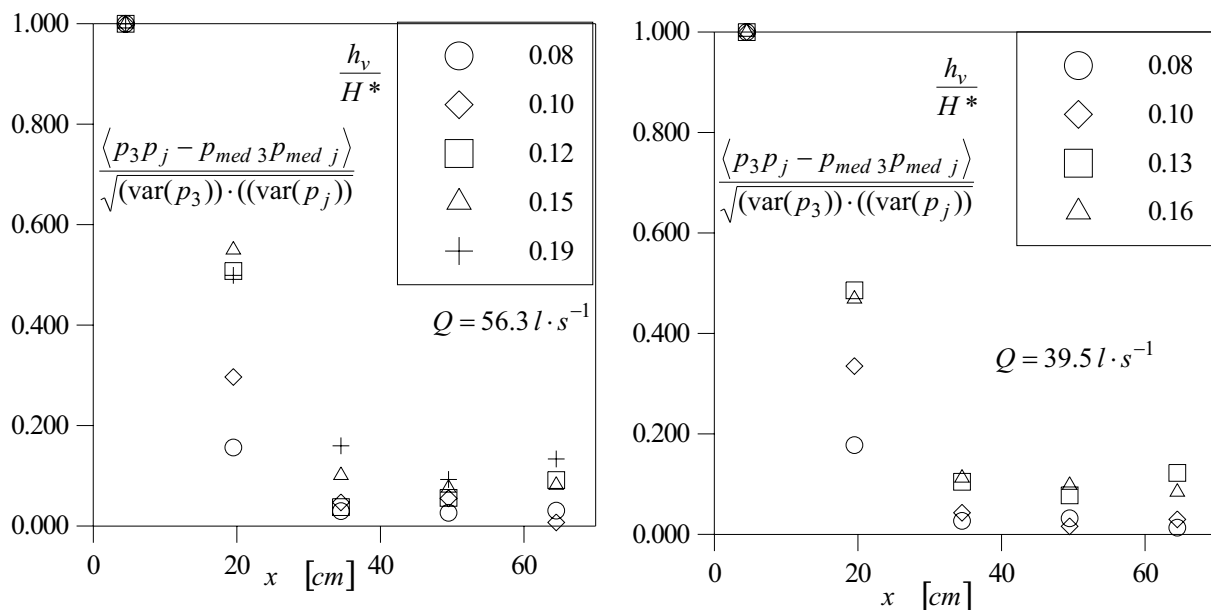

Figure 6. Longitudinal correlation structure of the pressure fluctuation referred to the first cell, for different water cushion depth. Case of water discharge $Q = 56.3$ l/s (left) and $Q = 39.5$ l/s (right).

CONCLUSIONS

From a design point of view the results obtained demonstrate that the depth of the water cushion influences the thickness of the dissipation basin linings through the reduction of the pressure fluctuation as the water cushion depth increases up to a certain limit value. As well, the water depth is connected to the planimetric critical dimension of the slabs – if this kind of lining is adopted – through its influence on the correlation structure and thus on the integral scale.

Further research would be necessary in order to define guidelines for engineering design that quantify in the more general case the optimum cushion depth and the relative attenuation on the dissipation processes that take place within the plunge pool stilling basin.

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