RBRH
Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 28, e22, 2023
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.282320230013

Hydrodynamic pressures on a stepped spillway with an aerator system subjected to different air flow rates

Pressões hidrodinâmicas sobre um vertedouro em degraus com sistema aerador submetido a diferentes vazões de ar

Rute Ferla[1], Carolina Kuhn Novakoski[2], Guilherme Santanna Castiglio[1], Mauricio Dai Prá[1], Marcelo Giulian Marques[1] & Eder Daniel Teixeira[1]

[1]Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil
[2]Universidade Federal de Santa Maria, Cachoeira do Sul, RS, Brasil
E-mails: ruteferla@hotmail.com (RF), carolina.novakoski@ufsm.br (CKN), guilhermecastiglio@gmail.com (GSC), mauricio.daipra@ufrgs.br (MDP), mmarques@iph.ufrgs.br (MGM), eder.teixeira@ufrgs.br (EDT)

Received: February 03, 2023 - Revised: May 06, 2023 - Accepted: June 13, 2023

ABSTRACT

Aerator systems promote additional insertion of air into the flow and can reduce the risk of cavitation and consequent damage to hydraulic structures. This work analyzes the hydrodynamic pressures on the steps of a physical model (with a chute inclination of 53.13º) subjected to different aeration conditions. When comparing the results with different air intake coefficients in the flow, it was concluded that the incorporation of air does not change in a generalized way all the statistical parameters associated with hydrodynamic pressures on the steps. However, with the insertion of air in the flow, there was an increase in the minimum pressure values measured in the region of the jet impact and downstream. Empirical equations for predicting the distribution of pressures on the steps under induced aeration conditions were proposed, valid for structures whose ratio between the height of the deflector and the height of the steps is equal to 0.167, with an aerator system installed at the beginning of the stepped chute.

Keywords: Hydraulic structures; Cavitation; Physical modeling; Deflector.

RESUMO

Sistemas aeradores promovem a inserção adicional de ar no escoamento e podem reduzir a chance de ocorrência de cavitação e consequentes danos nas estruturas hidráulicas. Este trabalho analisa as pressões hidrodinâmicas sobre os degraus de um modelo físico (com inclinação de calha de 53,13º) submetido a diferentes condições de aeração. Comparando-se os resultados com diferentes coeficientes de entrada de ar no escoamento, concluiu-se que a incorporação de ar não altera de forma generalizada todos os parâmetros estatísticos associados às pressões hidrodinâmicas sobre os degraus. Contudo, com a inserção de ar no escoamento, observou-se aumento nos valores mínimos de pressão medidos na região do impacto do jato e logo a jusante. Propõe-se equações empíricas para previsão da distribuição das pressões nos degraus nas condições de aeração induzida, válidas para estruturas cuja razão entre a altura do defletor e a altura dos degraus é igual a 0.167, com sistema aerador instalado no início da calha em degraus.

Palavras-chave: Estruturas hidráulicas; Cavitação; Modelagem física; Defletor.

INTRODUCTION

Compared to smooth chute spillways, stepped spillways increase the energy dissipation of the flow along the chute, which reduces the dimensions and, consequently, the costs of the energy dissipation structure. However, stepped chutes are more susceptible to cavitation in the flow than smooth chutes, due to the irregularities formed by the steps and the negative pressures that occur, particularly, on the vertical faces. In hydraulic structures, the phenomenon of cavitation is usually associated with the occurrence of noise, vibrations and damage to the concrete surface (especially erosion), as highlighted by, among others, Tullis (1982) and Falvey (1990).

One of the protective measures against cavitation damage is flow aeration, which occurs through the insertion of aerator systems in hydraulic structures – a condition called "induced aeration". The insertion of air into the water increases the compressibility of the mixture, reducing the intensity of the forces resulting from the collapse of the vapor cavities (Falvey, 1990; Bollaert & Schleiss, 2003), which protects the chute against the harmful effects of cavitation, even if the phenomenon occurs. Peterka (1953), based on studies in forced conduits with concrete blocks subjected to high-speed flows, concluded that about 7% of the air in the flow (concerning the volume of water) was sufficient so that there was no erosion in the concrete. The studies by Dong & Su (2006) and Dong et al. (2007, 2008, 2010), also carried out in forced conduits, corroborated the conclusions of Peterka (1953). These authors also identified that, with the insertion of air, there was also an increase in the pressures in the flow – which would contribute to the lower risk of cavitation in the flow.

In practice, the performance of stepped spillways without aerators has been satisfactory, even during extreme flood events (Matos & Meireles, 2014; Chanson, 2015). In these cases, it is possible that the natural aeration of the flow itself has been able to protect the steps from cavitation damage, due to the low specific design flows (Frizell et al., 2013) – on the order of 15 to 20 m^2/s, on average (Amador et al., 2009; Matos et al., 2022). In Brazil, after the occurrence of a considerable flood event in 2010, there were reports of damage to the spillway of the Dona Francisca Dam, as reported by Matos et al. (2022). However, the origin of the damage cannot be proved.

There are records, especially in the last two decades, of the construction of stepped spillways with aerator systems – such as different types of pillars, in Chinese dams Dachaoshan, Shuidong and Suofengying (Koen et al., 2017); crest-splitter teeth aerator, as in the Wadi Dayqah dam (Prisk et al., 2009), and deflector-type aerators in conjunction with an air chamber, as in the Cotter dam, in Australia (Willey et al., 2010).

The slope $\alpha \approx 53^{o}$ (1.00V:0.75H) of the downstream wall is usual in dams built-in roller compacted concrete (RCC), a common technique adopted in the construction of slopes on steps. The behavior of pressures on stepped spillways has been the subject of deep investigation in recent years, and the works of Sánchez-Juny (2001), André (2004) and Amador (2005) can be highlighted. In addition to that, authors have contributed to the study of air concentration profiles in these structures in conjunction with aerators, such as Pfister et al. (2006), Terrier (2016), among others.

Arantes (2007), through a study by numerical simulation, compared the results of minimum pressure in the flow on a stepped spillway with a chute slope $\alpha \approx 53^{o}$ in the condition with an aerator (induced aeration) and without aerator (natural aeration). Arantes (2007) identified that, in the induced aeration condition, the hydrodynamic pressures were less negative (which means less vulnerable to cavitation occurrence) than in the natural aeration condition.

The conclusions of Arantes (2007) differ from those of Marques et al. (2019), who developed medium pressure studies in a physical model of a stepped spillway with $\alpha \approx 53^{o}$. Marques et al. (2019) compared the results obtained with the aerator system (formed by a deflector and air chamber) with those of the natural aeration condition. There was no significant change in the average pressure values obtained by Marques et al. (2019), considering the natural and induced aeration conditions, except for the portion of the flow influenced by the launching and impact of the jet – which only happens in the induced aeration condition. Downstream of this region, the average pressures in both conditions were similar.

Priebe (2020) developed studies of aeration induced by piers and deflectors in the flow over stepped spillway with $\alpha \approx 53^{o}$, analyzing the behavior of the longitudinal distribution of pressures (medium and extreme) on the steps, through an experimental study. The author evaluated both the pressure results and the visual aspect of the flow, under induced and natural aeration conditions. Regarding the behavior of extreme pressures (in this case, with a probability of not exceeding 0.1%, $P_{0.1\%}$) on the vertical face of the steps, the data from Priebe (2020) indicate important differences between the results of induced and natural aeration – not only in the region influenced by the launch and impact of the jet on the steps but also downstream of it. For the same region of the spillway, while in the natural aeration conditions the minimum pressure in the flow was of the order of -0.60 m, in the induced aeration condition it was of the order of -0.10 m. The data obtained by Priebe (2020) indicate that, with the incorporation of air in the flow, there was a "softening" of extreme minimum pressures, that is, an increase in pressures – which is consistent with the expected behavior, when taking into account the previous conclusions of Peterka (1953) and Dong & Su (2006).

On the other hand, Priebe et al. (2021), when analyzing experimental pressure results in a stepped spillway ($\alpha \approx 53^{o}$) with aerators composed only of piers, identified that the hydrodynamic pressures were not attenuated in the induced aeration condition when compared to the natural aeration condition.

Novakoski (2021) and Novakoski et al. (2021) experimentally analyzed the flow characteristics on stepped spillways ($\alpha \approx 53^{o}$) subjected to induced aeration, considering the installation of different deflector geometries on the first step of the chute. Regarding the hydrodynamic pressures on the steps, the authors concluded that there was no significant variation between the pressures observed in the flow with induced aeration and with natural aeration, either on the vertical or horizontal face of the steps – with the exception, mainly, of the zone influenced by the point of impact of the jet. This conclusion applies to both medium and extreme pressures (in this case, $P_{0.1\%}$ and $P_{99.9\%}$, the latter associated with the probability of not exceeding the pressures equal to 99.9%).

Similar conclusions were also observed by Ferla et al. (2021), when they evaluated experimental results of extreme negative pressures ($P_{0.1\%}$, $P_{1\%}$ and $P_{5\%}$) on the vertical face of the steps of a spillway (α ≈ 53º) subjected to different conditions of induced aeration, compared to natural aeration. However, the results of Ferla et al. (2021) identified a tendency to increase pressures in conditions where the incorporation of air in the flow was greater when compared to natural aeration.

It should be noted that, while Peterka (1953), Dong & Su (2006) and Dong et al. (2007, 2008, 2010) developed their studies using forced conduits, the other authors mentioned considered flows submitted to the free surface, which may be related to the differences found. Furthermore, although the spillway of all authors who evaluated free surface flow has the same slope (α ≈ 53º), the aerator systems considered have a wide range of geometries, which may also have impacted the conclusions obtained in each work.

Which means it can be inferred that there is no consensus regarding the behavior of hydrodynamic pressures in the induced aeration condition, compared to natural aeration, especially concerning the supposed increase in induced aeration pressures. This is because some of the studies already carried out are divergent, even under similar conditions, and it is not possible to identify, at the moment, whether or not air insertion is associated with increased pressures. While Marques et al. (2019), Novakoski (2021) and Priebe et al. (2021), for example, did not identify significant variations between the different conditions, Arantes (2007), Priebe (2020) and Ferla et al. (2021) verified them in some cases – which also concurs with Peterka (1953) and Dong & Su (2006), for example.

Thus, the objective of this work is, through hydraulic physical modeling, to evaluate the behavior of the longitudinal distribution of the hydrodynamic pressures acting on a stepped spillway with an aerator system. To this end, test configurations that allow the insertion of different air intake coefficients in the system (β) will be considered, in addition to the natural aeration condition, which will serve as a basis for comparisons.

MATERIALS AND METHODS

Experimental installation and test conditions

An existing experimental facility was used in the Laboratory of Hydraulic Works of IPH/UFRGS, which comprises a physical model of a spillway with a stepped chute. The model is 0.50 m wide, about 4 m long (in the longitudinal direction of the chute) and 60 steps (being possible to install instrumentation up to step No. 52). The dimensions of the vertical and horizontal faces of each step are 0.06 m and 0.045 m, respectively (resulting in a chute slope equal to 1.00V:0.75H, α = 53.13º). Upstream of the stepped chute, there is a standard profile Waterways Experiment Station (WES), developed by the U.S. Army Corps of Engineers, operated freely (without gates). There are no transition steps between the WES profile and the stepped chute. The physical model used is generic, therefore, it does not represent in itself any prototype. However, if taken into account the 1:10 geometric scale (model:prototype), the reduced structure used would correspond to prototypes with steps 0.60 m high, or else to steps 0.90 m if considered the 1:15 geometric scale. Step heights of 0.60 m and 0.90 m are very common in RCC structures.

Three distinct test conditions were considered in the installation described, illustrated in Figure 1, which are:

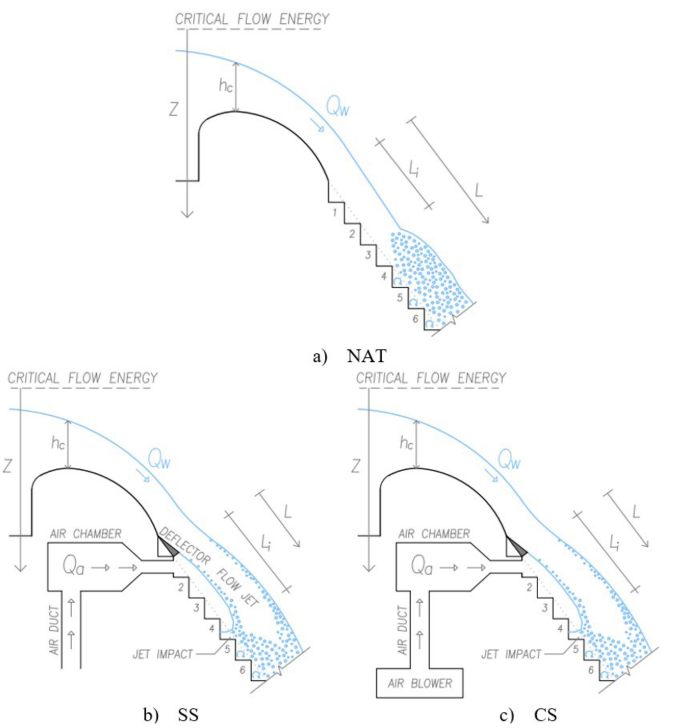


Figure 1. Schematic representation, in side view, of the test configurations (a) NAT (natural aeration), (b) SS (induced aeration without blower) and (c) CS (induced aeration with blower).

I. Natural aeration (NAT): configuration without the presence of aerating elements in the spillway. In this case, aeration begins with the full development (in depth) of the turbulent boundary layer in the flow;

II. Induced aeration without blower (SS): configuration with the presence of deflector (t = 10 mm, θ = 7.6º and width of 0.50 m, accordingly Figure 2), together with an air chamber (whose dimensions are indicated in Figure 3), installed on the first step of the chute. The deflector is supported on the horizontal face of the step, while the vertical face of the same step is removed to enable connection with the air chamber. The air is directed to the chamber via a circular pipe (air duct) with an internal diameter of 69 mm and 0.70 m in length (i.e. about 10 times the internal diameter). In this case, in addition to the upper aeration of the flow (coming from the free surface), the air is also inserted by the lower portion of the flow jet, immediately downstream of the deflector. In the SS configuration, the air entry into the chamber occurs by the natural action of the flow over the spillway, which provides the suction of air through the duct of the aerator system, without mechanical induction;

III. Blower-induced aeration (CS): configuration similar to the previous one (SS), however, the air entry into the chamber is mechanical, with the aid of a blower (Einhell BT-VC 1450S), whose rotation control is done through a frequency inverter (Weg CFW-08). It should be highlighted however, that the purpose of this configuration is to evaluate the pressure values in situations with β coefficients higher than those of the SS condition, and it is not intended to enable the installation of a mechanical air injection system in a prototype.

Tests were performed to measure hydrodynamic pressure on the steps and air intake by the aerator system (to extract the air intake coefficient β), in the specific flow range q (flow per meter of model width) equal to $0.20 \, m^2/s \leq q \leq 0.50 \, m^2/s$ (in physical model). The summary of the conditions tested is given in Table 1.

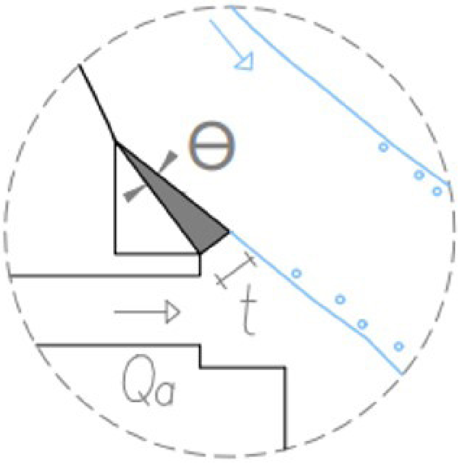


Figure 2. Details of the deflector.

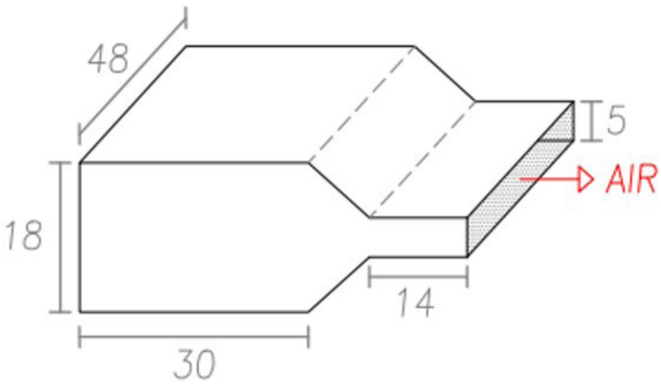


Figure 3. Approximate dimensions of the air chamber, in cm.

Table 1. Test conditions.

Aeration Condition	q (m²/s)	β (%)	Aeration start step[1]
Natural Aeration (NAT)	0.20	-	11
	0.30	-	18
	0.40	-	23
	0.50	-	28
Induced aeration without blower (SS)	0.20	3.6	6
	0.30	2.4	6
	0.40	1.4	5
	0.50	1.3	5
Blower-induced aeration (CS)	0.20	6.0	6
		8.0	7
		10.0	8
	0.30	6.0	7
		8.0	8
		10.0	8
	0.40	2.0	6
		6.0	8
		8.0	8
		10.0	8
	0.50	2.0	8
		6.0	8
		8.0	8
		10.0	7

[1]NAT condition: step where the incipient aeration in the flow is identified; SS and CS conditions: jet impact step.

In the CS configuration, pre-established values of β equal to 2%, 6%, 8% and 10% were tested, following the range of average coefficients indicated by Peterka (1953). Table 1 also contains β measured in the SS condition, whose knowledge guided the decision making of the coefficients to be explored in the CS condition: it was decided to analyze only the values higher than those measured in the SS configuration. For example, for q = 0.20 m^2/s, since β measured in the SS condition was equal to 3.6%, it was decided not to analyze the condition of β = 2% in the CS configuration at this flow rate (see Table 1).

The step associated with the beginning of aeration in the flow is also indicated in Table 1: in natural aeration condition, it was established as the incipient aeration point, while in induced aeration, the point of impact of the jet on the steps was adopted (since, from then on, it is already possible to identify the aerated flow in this condition, according to the schematic representation of Figure 1b and Figure 1c).

Coefficient β measurement

The air intake coefficient (β), defined by. Equation 1, was measured under SS and CS conditions. In the NAT condition, since there is no aerator system, there is also no β coefficient.

$$\beta = \frac{Q_a}{Q_w} \quad (1)$$

In which Qa is the airflow [m^3/s] and Qw is the water flow [m^3/s], see Figure 1.

The water flow (Q_w) was obtained directly by reading the electromagnetic flow meters (Incontrol CEV 1000, Siemens Mag 6000, Emerson 09-FM-D119), installed in the pipes that feed the physical model. The estimate of the airflow (Q_a) was made indirectly, by measuring the air intake velocity in the air duct, multiplying this value by the cross-sectional area of the circular pipe. For this, a Pitot-Prandtl probe (Dwyer 166-12, diameter 1/8”) coupled to a differential pressure transmitter (Rücken, RTBP-420-DIF) was used. The Pitot-Prandtl probe was positioned on the axis of the air duct, 0.21 m upstream of the air chamber. Before the definition of the central position of the piping – taken as a reference to the measurement of air velocity – the airflow velocity profile was surveyed inside the adduction tube. This procedure indicated a velocity profile with practically uniform behavior along the pipe diameter, which led to and substantiated the adoption of the axis of the air duct as a reference position for measurements.

The time and frequency of data acquisition in the pressure differential transmitter were equal to, respectively, 10 minutes and 100 Hz, computing in 60,000 data per test. To define the velocity, the mean of the values acquired over the 10 minutes of the test was considered.

Measurement of hydrodynamic pressures

The measurement of the hydrodynamic pressures was performed employing piezoresistive pressure transducers (Omega PX419, Sitron SP96, Hytronic TM25), installed on the vertical and horizontal faces of the steps, under NAT, SS and CS conditions. For all the test configurations considered, the pressure taps were positioned 8 mm from the outer edge of each step, on the chute axis (therefore, 0.25 m away from each of the side walls). The connection between the pressure tap on the steps and the instruments was made by flexible nylon piping (internal diameter of 1.7 mm), approximately 0.10 m to 0.15 m in length each. More details regarding the validation of the data acquisition methodology can be found in Appendix A.

In all pressure measurement tests, the time and frequency of data acquisition in the transducers were equal to, respectively, 10 minutes and 100 Hz, computing in 60,000 data per test per instrument.

Data acquired by the transducers were analyzed in the time domain. The statistical parameters obtained in the treatment of the experimental data were:

I. mean pressures (P_{med});

II. standard deviation of pressures (P_σ) and

III. pressures with non-exceedance probabilities of 0.1% and 99.9% ($P_{0.1\%}$ e $P_{99.9\%}$, respectively), also called extreme pressure indicators,

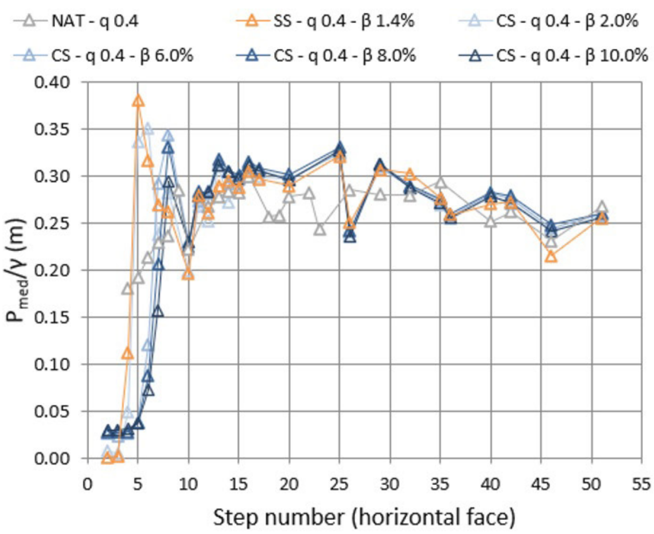
along the length of the chute, on the vertical and horizontal faces of the steps.

RESULTS AND DISCUSSIONS

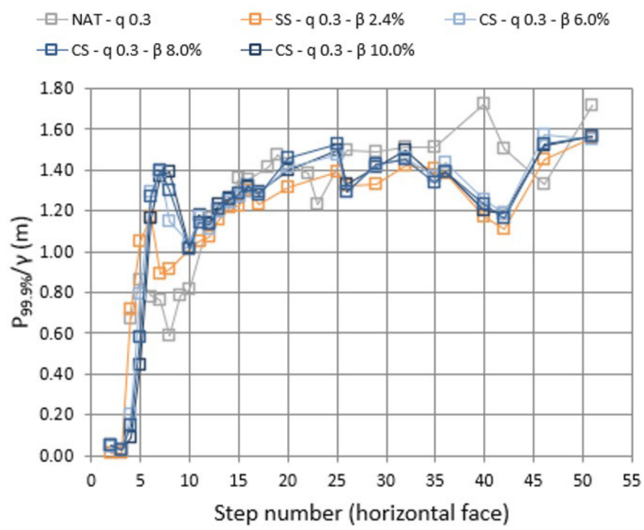
Regarding the hydrodynamic pressures on the steps, Figure 4 presents part of the results associated with the statistical parameters evaluated in this work. In this case, the results are presented in terms of measured pressure (P/γ) along the steps, under NAT, SS and CS conditions, for selected flows. All data are associated with the reduced physical model scale. The β coefficient measured under the conditions SS and CS, according to Table 1, is shown in the respective caption. In general, the behavior of said parameters is similar in the other tested flows and which are not represented in Figure 4. Further details associated with the results obtained are described in the sequence.

In general, all statistical parameters analyzed are similar in the SS and CS configurations, regardless of the air intake coefficient in the aerator system (β). On the steps positioned upstream of the jet impact, the statistical parameters of the SS and CS configurations are close to zero, as expected, given that there is no water flow in contact with the steps in this region (according to the schematic representation in Figure 1b and Figure 1c). Downstream, towards the final section of the chute, the results of the NAT, SS and CS conditions tend to have similar values in all parameters analyzed.

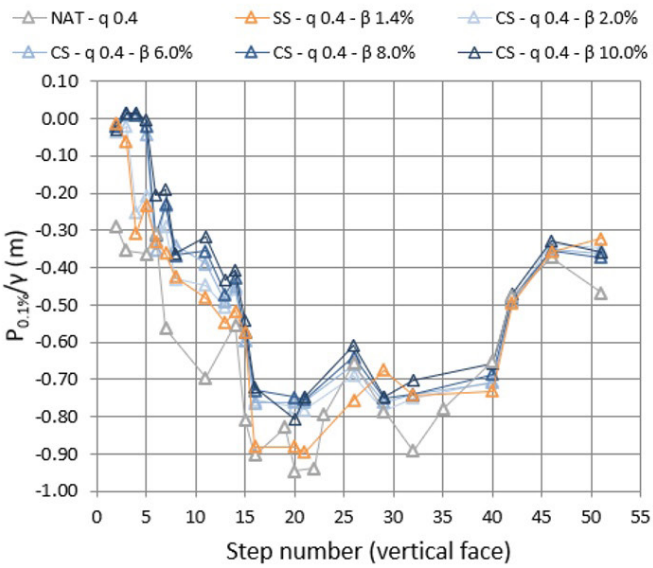
The main differences between the NAT condition and the SS and CS conditions occur in the regions influenced by the impact of the jet on the chute, represented by peaks especially in the P_{med} parameter on the horizontal face of the step (Figure 4a). Such peaks occur only in the SS and CS conditions, since, in the NAT condition, there is no impact of the jet on the steps. Taking into account only the induced aeration conditions (SS and CS), there is a tendency for, with the increase of the β coefficient, the impact of the jet on the steps to occur on steps further downstream (Figure 4a).



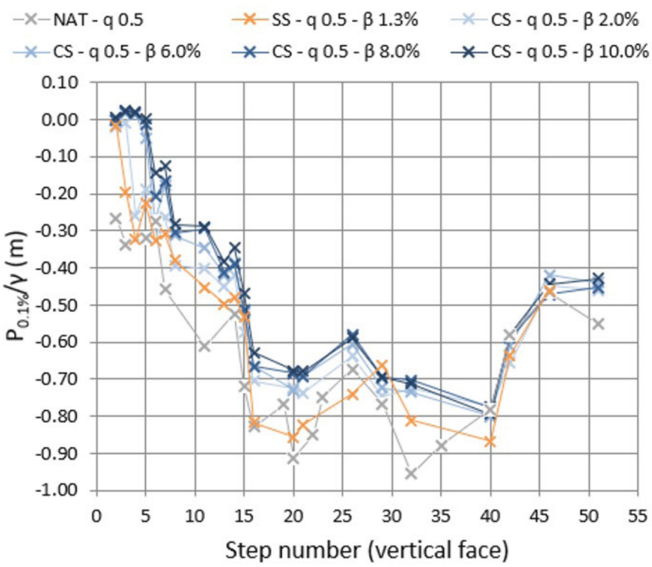
a) P_{med}, horizontal face (q = 0.40 m²/s)



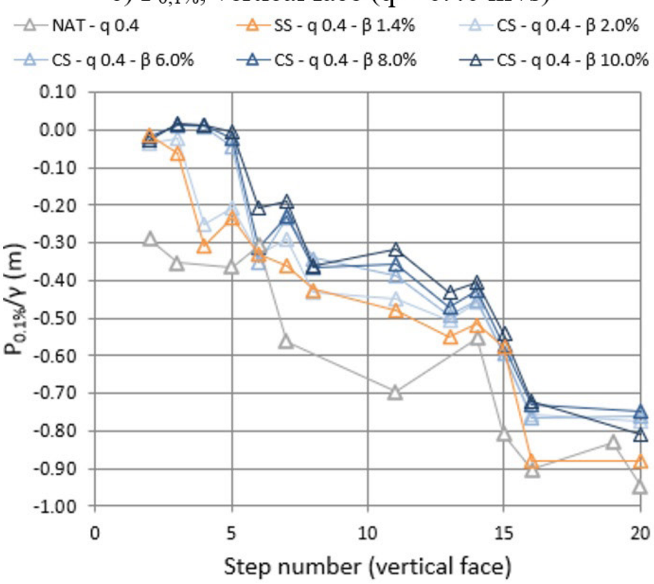
b) $P_{99.9\%}$, horizontal face (q = 0.30 m²/s)



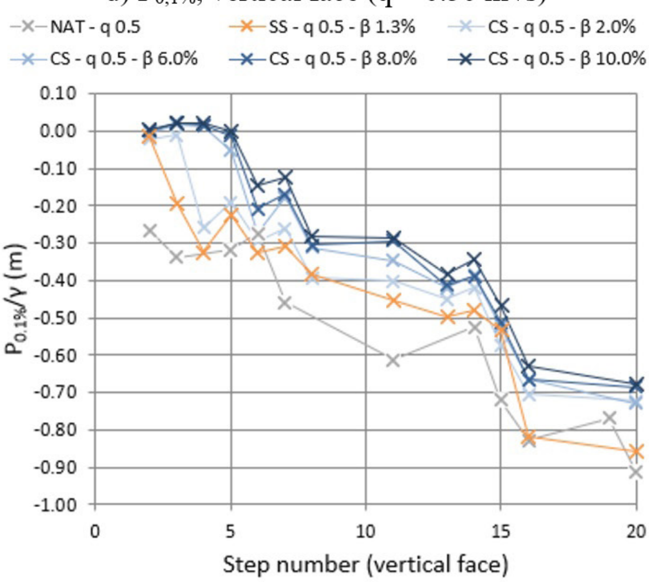
c) $P_{0,1\%}$, vertical face (q = 0.40 m²/s)



d) $P_{0,1\%}$, vertical face (q = 0.50 m²/s)



e) $P_{0,1\%}$, vertical face (q = 0.40 m²/s), in details



f) $P_{0,1\%}$, vertical face (q = 0.50 m²/s), in details

Figure 4. Statistical parameters (selected) of the pressures along the stepped chute.

This behavior is not a rule in all cases evaluated, being more evident when analyzing P_{med}, mainly on the horizontal face of the steps. In the vicinity of the air chamber (mainly in the first 4 steps of the chute), P_{med} is slightly different between the induced aeration conditions, probably due to the air insertion pressure (by the blower), which varied depending on the required β coefficient. In any case, the pressure is close to atmospheric pressure (always less than 0.04 m, in terms of piezometric column, in this region).

Regarding the statistical parameter associated with maximum pressures ($P_{99,9\%}$), a peaking trend is also identified in the results in the vicinity of the region of the impact of the jet on the steps, especially on the horizontal face (Figure 4b).

The main distinction identified between the results under NAT, SS and CS conditions was in the measurement of the statistical parameter $P_{0.1\%,}$ especially in the region influenced by the impact of the jet on the chute and just downstream of it. These results are represented in Figure 4c and Figure 4d, for the specific flows q equal to 0.40 m^2/s and 0.50 m^2/s, respectively. Figure 4e and Figure 4f present the same results, but with a limited representation up to step number 20, showing the differences in the pressures measured in the NAT, SS and CS conditions on the steps around the impact of the jet. In this region, the higher β, the higher is also $P_{0.1\%}$ (that is, the less negative is $P_{0.1\%}$), so the results associated with the NAT condition are more extreme (more negative) than those of the induced aeration conditions, in general. Such behavior is consistent with what was measured by Priebe (2020) and Ferla et al. (2021).

It should be noted that, since the parameter $P_{0,1\%}$ is associated with the lowest pressure values measured in the tests, this data is related to the susceptibility to the occurrence of cavitation on the steps. Although the minimum measured values of $P_{0,1\%}$ are similar under NAT, SS and CS conditions – on the order of -0.80 m to -0.90 m (in terms of piezometric column), according to Figure 4c and Figure 4d – the increase of $P_{0.1\%}$ (which was observed with the increase of the β coefficient) in the impact of the jet and just downstream (see Figure 4e and Figure 4f) may be associated with the reduction of the risk of cavitation in the flow and, consequently, of the damages associated with the phenomenon (mainly, of erosion in the concrete) in this region of the chute.

It is worth mentioning that all the results presented in the graphs refer to values measured in the physical model. Taking into account the risk of cavitation, the minimum pressures in the prototype should not exceed the order of -10 m (i.e. approximately the vaporization pressure of water in terms of relative pressure). That is, in the physical model in question, pressures close to -1 m could be associated with the occurrence of cavitation in the prototype (in this case, considering the 1:10 geometric scale). Regardless of the condition (with or without aeration), zones where the flow pressures are close to the vapor pressure would be subject to cavitation. In such cases, bottom aeration must be sufficient to protect the chute from cavitation damage, even if the phenomenon occurs.

Comparing the measured data with the conclusions of authors who developed similar studies, it can be highlighted that the results obtained concur with Marques et al. (2019), Novakoski et al. (2021) and Novakoski (2021). This is because both the authors mentioned and the data from this study indicated that there was no significant difference between the results of average pressure, in the conditions of natural and induced aeration – except for the region in the vicinity of the impact of the jet.

However, the results obtained in this study indicated that there was a difference (although localized) between the natural and induced aeration conditions in the statistical parameter $P_{0,1\%}$, on the vertical face of the steps – that is, there was a relation between the air intake coefficient β and the hydrodynamic pressures of the flow over the chute. Thus, the conclusions are different from those indicated by Novakoski (2021) and Priebe et al. (2021). Although all authors have evaluated spillways on similar stepped chutes (with $\alpha \approx 53^o$), the aerator systems considered are distinct. This may have impacted the β coefficient of each study, the behavior of the measured pressures and, consequently, the conclusions of the authors. The authors mentioned did not evaluate a wide range of air intake coefficients. Thus, it can be assumed that there is a minimum amount of air required for the identification of more significant differences between the pressure results in the natural and induced aeration conditions. The amount of air entered is directly related to the aerator system adopted and the flow conditions.

In any case, it is important to emphasize that, although distinctions have been identified between the data measured in the conditions of natural and induced aeration, such differences were relatively localized, not being the rule. In fact, there was an increase in $P_{0.1\%}$, on the vertical face of the step, with an increase in the β coefficient, in the impact region of the jet and nearby, downstream. However, in the other statistical parameters evaluated (P_{med}, P_{σ}, $P_{99.9\%}$, and including $P_{0.1\%}$ on the horizontal face), this difference is subtle or non-existent.

It is also worth mentioning that the average pressure results obtained differ from the expected behavior, considering the conclusions pointed out by Peterka (1953) and Dong & Su (2006). This is because, while these authors pointed out an increase in mean pressures in the flow with aeration, in the case of this study there was no relevant distinction – except for the region close to the impact of the jet on the chute. It is possible that the different conclusions obtained are related to the experimental installation adopted – since Peterka (1953) and Dong & Su (2006) considered tests on forced conduits.

The data collected under SS and CS conditions were evaluated jointly, considering all the specific flows tested, aiming at the establishment of analytical expressions that allow the estimation of hydrodynamic pressures on the steps in the induced aeration condition. The analysis of the results of all statistical parameters indicated that the behavior of the distribution of pressures along the steps is well represented by the ratio $(P_x/\gamma)/Z$ (ordinate axis), along with the adimensional position given by $(L-L_i)/h_c$ (abscissa axis), in which Z is the parameter associated with the flow energy, L is the longitudinal length along the chute, L_i is the length associated with the beginning of aeration in the flow and h_c is the critical flow depth (see Figure 1).

The curve resulting from the application of the indicated relations follows a rational function, according to Equation 2, for all statistical parameters evaluated on the vertical face of the steps (P_{med}, P_{σ}, $P_{99.9\%}$, and $P_{0.1\%}$), as well as for $P_{0.1\%}$ on the horizontal face. The rational model was also used by Matos et al. (2022) in a study similar to this – in the case, applied to experimental data on flow pressures on stepped chutes, in the condition of natural aeration. In the other parameters of the horizontal face of the steps (P_{med}, P_{σ} and $P_{99.9\%}$), the model that best represented the behavior of the data was the one translated by Equation 3. The choice of the regression model took into account the joint analysis of the results in terms of coefficient of determination, simplicity of the equation and number of constants.

$$\frac{P_x/\gamma}{Z} = \frac{a+bx}{1+cx+dx^2} \quad where \quad x = \frac{L-L_i}{h_c} \quad for \quad 0 \le x \le 20 \tag{2}$$

$$\frac{P_x/\gamma}{Z} = \frac{a}{1+\left(\frac{x}{b}\right)^c} \quad where \quad x = \frac{L-L_i}{h_c} \quad for \quad 0 \le x \le 20 \tag{3}$$

In which P_x is the statistical parameter associated with the pressure P_{med}, P_{σ}, $P_{0,1\%}$ or $P_{99,9\%}$ [Pa], γ is the specific weight of water [N/m³], Z is the parameter associated with the flow energy [m], L is the longitudinal length along the chute [m], L_i is the length associated with the beginning of aeration in the flow [m] and h_c is the critical flow depth [m], see Figure 1.

The resulting adjusted curves are represented in Figure 5, while Table 2 presents the adjustment coefficients of Equation 2 and Equation 3, for all statistical parameters evaluated here. In Figure 5 are also represented the curves associated with the 95% confidence interval.

The proposed adjustments resulted in a coefficient of determination (R^2) of the order of 0.60 a 0.87 (see Table 2). In most cases evaluated, R^2 is greater than 0.80, which suggests a good correlation between the data and the expression. Equation 2 and Equation 3 have validity in the range 0 ≤ (L-Li)/hc ≤ 20, since this is the range in which the data of this work are framed, as can be seen in Figure 5. In addition, the proposed equations are valid for an aerator system composed of a deflector (t/step height = 0.167, θ = 7.6º) installed at the beginning of the stepped chute with α ≈ 53º.

It is noteworthy that, in the establishment of the adjustment coefficients of the proposed equations, only the data associated with the induced aeration conditions (that is, SS and CS) were considered. As suggested by Figure 5, there is greater dispersion between the measured data and the fit curves in the vicinity of the jet impact (that is, in the vicinity of position $(L\text{-}L_i)/h_c = 0$), generally speaking, whereas, from position $(L\text{-}L_i)/h_c \approx 10$, the dispersion is of little significance, since these are regions further downstream in the chute and less influenced by the impact of the jet on the steps.

As suggested by Figure 4, there are regions in which differences were observed in the data obtained under SS and CS conditions, especially for parameter $P_{0,1\%}$ (Figure 4c and Figure 4d), however, such distinctions are not considered in the proposed adjustment (Equation 2). Thus, it is noteworthy that the pressure prediction model established here is conceptual, and should be adopted as a direction and preliminary estimate of pressure values under aeration conditions induced in the flow.

In this work, the data of the natural aeration condition are inserted in the range of Froude number (Fr) equal to 5.71 ≤ Fr ≤ 6.33 (referring to the incipient aeration point, according to Table 1), Reynolds number (Re) equal to $2x10^5 \le Re \le 5x10^5$ and Weber number (We) equal to 128 We ≤ 186 (referring to the incipient aeration point). In the induced aeration condition (SS and CS), there are 3.05 ≤ Fr ≤ 3.95 (calculated immediately upstream of the deflector), $2x10^5 \le Re \le 5x10^5$ (equal to the natural aeration condition) and 93 ≤ We ≤ 156 (immediately upstream of the deflector). Based on studies in a reduced step spillway model, Boes & Hager (2003) suggest that scale effects will be minimized if the minimum limits of $Re \approx 10^5$ and We ≈ 100 are respected. Therefore, according to these authors, the possible scale effects associated with the tests carried out in this study do not have a significant impact on the results obtained.

The results presented were obtained in a physical model, however, they are also valid in the prototype scale, safeguarding the maximum geometric limit of 1:15, according to Pinto et al. (1982) and Boes & Hager (2003). In this case, Equation 2 and Equation 3 can be used in the spillway design stage, aiming at estimating the mean pressure (P_{med}), maximum pressure (associated with a 99.9% probability of occurrence, $P_{99.9\%}$), minimum pressure ($P_{0.1\%}$) and pressure fluctuations (P_{σ}) to which the prototype would be subjected.

Table 2. Coefficients of Equation 2 and Equation 3.

		a	b	c	d	R^2
Horizontal face (Figure 5a, c, e, g)	P_{med}	$2.48x10^{-1}$	3.66	$7.80x10^{-1}$	-	0.86
	P_{σ}	$2.45x10^{-1}$	4.37	$6.40x10^{-1}$	-	0.84
	$P_{0.1\%}$	$-3.41x10^{-1}$	$-4.85x10^{-1}$	2.55	$1.17x10^{-1}$	0.60
	$P_{99.9\%}$	1.12	8.45	$7.45x10^{-1}$	-	0.87
Vertical face (Figure 5b, d, f, h)	P_{med}	$4.14x10^{-2}$	$-1.48x10^{-2}$	$-6.89x10^{-2}$	$3.31x10^{-1}$	0.68
	P_{σ}	$7.93x10^{-2}$	$-6.31x10^{-4}$	$-4.75x10^{-2}$	$1.49x10^{-2}$	0.86
	$P_{0.1\%}$	$-2.71x10^{-1}$	$-1.95x10^{-3}$	$-1.48x10^{-1}$	$2.33x10^{-2}$	0.80
	$P_{99.9\%}$	$2.89x10^{-1}$	$-7.43x10^{-3}$	$4.98x10^{-2}$	$4.92x10^{-3}$	0.86

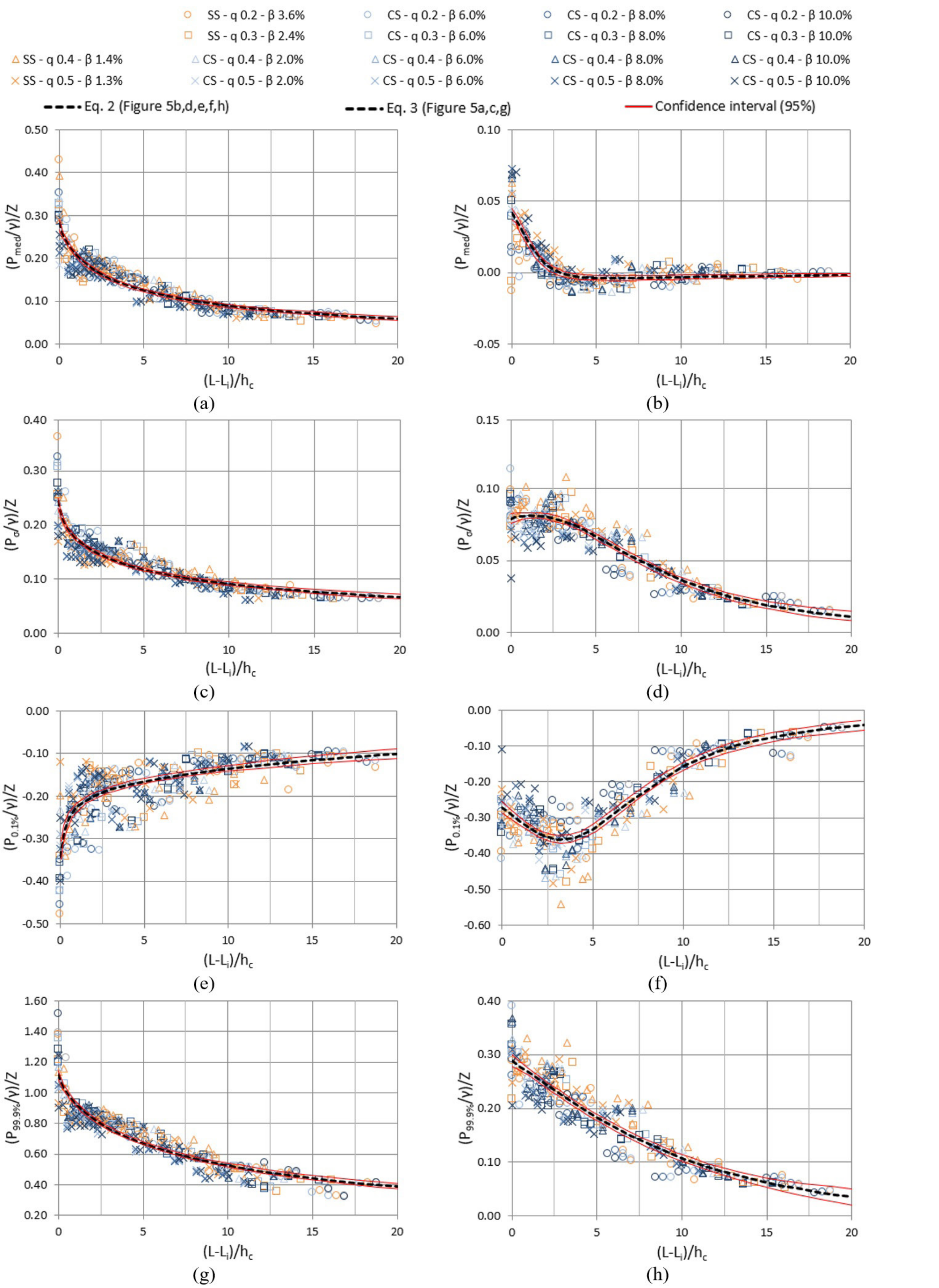


Figure 5. Statistical parameters of pressures on the horizontal (a, c, e, g) and vertical (b, d, f, h), faces, dimensionless by the relations $(P_x/\gamma)/Z$ and $(L\text{-}L_i)/h_c$.

CONCLUSIONS

The objective of this study was to evaluate the behavior of the longitudinal distribution of the hydrodynamic pressures acting on a stepped spillway with an aerator system, using tests in a physical model. Different flow conditions, submitted to natural (NAT) and induced aeration (SS and CS) were evaluated, in the range of specific flow rates between 0.20 m^2/s and 0.50 m^2/s, in a stepped chute with inclination $\alpha \approx 53°$. In induced aeration, air intake coefficients β of the order of 1% to 10% were considered. The hydrodynamic pressures of the flow over the chute were evaluated in terms of the statistical parameters P_{med}, P_{σ}, $P_{0.1\%}$ and $P_{99.9\%}$, on the vertical and horizontal faces of the steps.

As main conclusions obtained, it is highlighted:

i. The main differences between the pressure results of the NAT, SS and CS configurations occur in the regions of the impact of the jet on the steps and just downstream of it, following what was observed by Marques et al. (2019), Novakoski et al. (2021) and Novakoski (2021);

ii. In the downstream most portions of the chute, the pressure results for all configurations analyzed tend to similar values;

iii. In general, the higher the coefficient β, the further downstream the point of impact of the jet occurs in the chute. This behavior is most evident when analyzing P_{med} on the horizontal face of the steps;

iv. In most cases, right after the impact of the jet on the steps, the higher the β coefficient, the higher the value of $P_{0.1\%}$ on the vertical face. That is, it can be considered that $P_{0.1\%}$ softening occurred on the vertical face of the steps, with an increase in β. This result concurs with that observed by Priebe (2020) and Ferla et al. (2021), being evident only on the vertical faces of the steps, however, it goes against what was indicated by Novakoski et al. (2021) and Priebe et al. (2021). This suggests that there should be a minimum amount of air required to identify more significant differences between the pressure results under natural and induced aeration conditions;

v. The average pressure results obtained differ from the expected behavior, considering the conclusions pointed out by Peterka (1953) and Dong and Su (2006). In this case, it is possible that the different conclusions obtained are related to the experimental installation adopted;

vi. A model was proposed to estimate the hydrodynamic flow pressures, on the vertical and horizontal faces of the steps of an inclined chute ($\alpha \approx 53°$), in the induced aeration condition (Equation 2), valid in the range $0 \leq (L\text{-}L_i)/h_c \leq 20$ and $3.05 \leq Fr \leq 3.95$, considering an aerator system composed of the deflector (t/step height = 0.167, $\theta = 7.6°$) installed at the beginning of the stepped chute, resulting in a coefficient of determination of the order of 0.60 to 0.87.

In order to analyze the hydrodynamic pressures associated with different air intake coefficients in the flow, a mechanical device for forced air injection was used. However, this methodology should be understood only as an experimental artifice and does not intend to enable the installation of a similar system in a prototype. Coefficient β is related to the water flow, the flow capacity in the air duct and the geometry of the aerator/deflector. Thus, given a design flow and an air gallery geometry, one can opt for changes in the aerator/deflector geometry to increase the air intake coefficient in a prototype, using, for this purpose, the expressions established by Pfister & Hager (2010) or Terrier (2016), for example.

In addition to that, it is noteworthy that the main objective of aeration in spillways is to protect the structure against the harmful effects of cavitation, even if the phenomenon occurs. Although aeration has altered part of the hydrodynamic pressure parameters evaluated here, and this may be related to the reduction of the risk of cavitation (due to the mitigation of pressures), the objective of the insertion of aerators is not the mitigation of pressures.

ACKNOWLEDGEMENTS

The authors are grateful to the National Council for Scientific and Technological Development (CNPq, Brazil), the Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil), the Institute of Hydraulic Research (IPH/UFRGS, Brazil) and FURNAS Centrais Elétricas (Brazil) for providing the conditions and the financial support for the experimental works.

REFERENCES

Amador, A. (2005). *Comportamiento hidráulico de los aliviaderos escalonados en presas de Hormigón compactado* [PhD thesis]. Departamento de Ingeniería Hidráulica, Marítima y Ambiental, Universitat Politècnica de Catalunya, Barcelona.

Amador, A., Sánchez-Juny, M., & Dolz, J. (2009). Developing flow region and pressure fluctuations on steeply sloping stepped spillways. *Journal of Hydraulic Engineering*, *135*(12), 1092-1100. http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0000118.

André, S. (2004). *High velocity aerated flows on stepped chutes with macro-roughness elements.* (Communication, 20). Laboratoire de Constructions Hydrauliques, Ecole Polytechnique Fédérale de Lausanne, Lausanne.

Arantes, E. J. (2007). *Caracterização do escoamento sobre vertedouros em degraus via CFD* [PhD thesis]. Programa de Pós-graduação em Engenharia (Hidráulica e Saneamento), Universidade de São Paulo, São Carlos.

Boes, R., & Hager, W. H. (2003). Two-phase flow characteristics of stepped spillways. *Journal of Hydraulic Engineering*, *129*(9), 661-670. http://dx.doi.org/10.1061/(ASCE)0733-9429(2003)129:9(661).

Bollaert, E., & Schleiss, A. (2003). Scour of rock due to the impact of plunging high velocity jets Part I: a state-of-the-art review. *Journal of Hydraulic Research*, *41*(5), 451-464. http://dx.doi.org/10.1080/00221680309499991.

Chanson, H. (2015). Discussion of "Cavitation Potential of Flow on Stepped Spillways" by K. Warren Frizell, Floriana M. Renna, and Jorge Matos. *Journal of Hydraulic Engineering*, *141*(5), 07014025-1-07014025-2. http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0000808.

Dong, Z., & Su, P. (2006). Cavitation control by aeration and its compressible characteristics. *Journal of Hydrodynamics*, *18*(4), 499-504. http://dx.doi.org/10.1016/S1001-6058(06)60126-1.

Dong, Z., Chen, L., & Ju, W. (2007). Cavitation characteristics of high velocity flow with and without aeration on the order of 50 m/s. *Journal of Hydrodynamics*, *19*(4), 429-433.http://dx.doi.org/10.1016/S1001-6058(07)60136-X.

Dong, Z., Liu, Z., Wu, Y., & Zhang, D. (2008). An experimental investigation of pressure and cavitation characteristics of high velocity flow over a cylindrical protrusion in the presence and absence of aeration. *Journal of Hydrodynamics*, *20*(1), 60-66. http://dx.doi.org/10.1016/S1001-6058(08)60028-1.

Dong, Z., Wu, Y., & Zhang, D. (2010). Cavitation characteristics of offset-into-flow and effect of aeration. *Journal of Hydraulic Research*, *48*(1), 74-80. http://dx.doi.org/10.1080/00221680903566083.

Falvey, H. T. (1990). *Cavitation in chutes and spillways* (Engineering Monograph, No. 42 USBR). Denver: RNW.

Ferla, R., Novakoski, C. K., Priebe, P. S., Dai Prá, M., Marques, M. G., & Teixeira, E. D. (2021). Stepped spillways with aerators: hydrodynamic pressures and air entrainment. *Revista Brasileira de Recursos Hídricos*, *26*, e04. https://doi.org/10.1590/2318-0331.262120200110.

Frizell, K. W., Renna, F. M., & Matos, J. (2013). Cavitation potential of flow on stepped spillways. *Journal of Hydraulic Engineering*, *139*(6), http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0000715.

Koen, J., Bosman, D. E., & Basson, G. R. (2017). Large unit discharge stepped spillway designs with crest piers and flares. In *SANCOLD 2017* (pp. 1-10). Johannesburg, South Africa.

Marques, M. G., Ferla, R., Novakoski, C. K., Prá, M. D., Teixeira, E. D., Endres, L. A. M., Prestes, A. C., Moraes, P. J., Rigo, A. F., & Canellas, A. V. B. (2019). Stepped spillway flow: pre-aeration with deflector. In *Proceedings of the 38th IAHR World Congress*. Panamá: IAHR.

Matos, J., & Meireles, I. (2014). Hydraulics of stepped weirs and dam spillways: engineering challenges, labyrinths of research. In *Proceedings of the 5th International Symposium on Hydraulic Structures – Hydraulic Structures and Society: Engineering Challenges and Extremes*. Brisbane: The University of Queensland. http://dx.doi.org/10.14264/uql.2014.11.

Matos, J., Novakoski, C. K., Ferla, R., Marques, M. G., Dai Prá, M., Canellas, A. V. B., & Teixeira, E. D. (2022). Extreme pressures and risk of cavitation in steeply sloping stepped spillways of large dams. *Water (Basel)*, *14*(3), 306. http://dx.doi.org/10.3390/w14030306.

Novakoski, C. K. (2021). *Análise da macroturbulência do escoamento sobre vertedouro em degraus com aeração induzida por defletor e câmara de ar* [PhD thesis]. Programa Pós-graduação em Recursos Hídricos e Saneamento Ambiental, Universidade Federal do Rio Grande do Sul, Porto Alegre.

Novakoski, C. K., Ferla, R., Priebe, P. S., Abreu, A. S., Marques, M. G., Dai Prá, M., Canellas, A. V. B., & Teixeira, E. D. (2021). Induced aeration flow over stepped spillways: mean pressures, air entrainment and flow behavior. *Revista Brasileira de Recursos Hídricos*, *26*, e34. https://doi.org/10.1590/2318-0331.262120210098.

Peterka, A. J. (1953). *The effect of entrained air on cavitation pitting*. Minneapolis: International Association for Hydraulic Research and Hydraulics Division.

Pfister, M., & Hager, W. H. (2010). Chute aerators II: hydraulic design. *Journal of Hydraulic Engineering*, *136*(6), 360-367. http://dx.doi.org/10.1061/(ASCE)HY.1943-7900.0000201.

Pfister, M., Hager, W. H., & Minor, H. (2006). Bottom aeration of stepped spillways. *Journal of Hydraulic Engineering*, *132*(8), 850-853. http://dx.doi.org/10.1061/(ASCE)0733-9429(2006)132:8(850).

Pinto, N. L., Neidert, S. H., & Ota, J. J. (1982). Aeration at high velocity flows I/II. *International Water Power & Dam Construction*, *34*(2), 34-44.

Priebe, P. S. (2020). *Influência da aeração induzida por pilares no escoamento sobre vertedouros em degraus* [PhD thesis]. Programa Pós-graduação em Recursos Hídricos e Saneamento Ambiental, Universidade Federal do Rio Grande do Sul, Porto Alegre.

Priebe, P. S., Ferla, R., Novakoski, C. K., Abreu, A. S., Teixeira, E. D., Dai Prá, M., & Marques, M. G. (2021). Influence of aeration induced by piers on the starting position of the flow aeration and extreme pressures in stepped spillways. *Revista Brasileira de Recursos Hídricos*, 26, e13. https://doi.org/10.1590/2318-0331.262120200113.

Prisk, M., Richards, M., & Hieatt, M. (2009). Delivering Wadi Dayqah, Oman's tallest dam. *Proceedings of the Institution of Civil Engineers. Civil Engineering*, *162*(6), 42-50. https://doi.org/10.1680/cien.2009.162.6.42.

Sánchez-Juny, M. (2001). *Comportamiento hidráulico de los aliviaderos escalonados en presas de hormigón compactado: análisis del campo de presiones* [PhD thesis]. Departamento de Ingeniería Hidráulica, Marítima y Ambiental, Universitat Politècnica de Catalunya, Barcelona.

Sánchez-Juny, M., & Dolz, J. (2005). Experimental study of transition and skimming flows on stepped spillways in RCC dams: qualitative analysis and pressure measurements. *Journal of Hydraulic Research*, *43*(5), 540-548. http://dx.doi.org/10.1080/00221680509500152.

Sánchez-Juny, M., Bladé, E., & Dolz, J. (2007). Pressures on a stepped spillway. *Journal of Hydraulic Research*, *45*(4), 505-511. http://dx.doi.org/10.1080/00221686.2007.9521785.

Sánchez-Juny, M., Bladé, E., & Dolz, J. (2008). Analysis of pressures on a stepped spillway. *Journal of Hydraulic Research*, *46*(3), 410-414. https://dx.doi.org/10.3826/jhr.2008.3152.

Terrier, S. (2016). *Hydraulic performance of stepped spillway aerators and related downstream flow features.* (Communication, Vol. 63). Lausanne: Laboratoire de Constructions Hydrauliques, Ecole Polytechnique Fédérale de Lausanne.

Tullis, J. P. (1982). *Cavitation in hydraulic systems.* São Paulo: USP Escola Politécnica.

Willey, J., Lesleighter, E., Ewing, T., & Dymke, J. (2010). *Refinement of the hydraulic design of a complex stepped spillway through numerical and physical modelling*. Retrieved in 2023, June 13, from https://www.researchgate.net/publication/290597062_Numerical_and_physical_modelling_for_a_complex_stepped_spillway

Authors contributions

Rute Ferla: Literature review, physical model tests, methodology elaboration, data analysis and writing of the manuscript.

Carolina Kuhn Novakoski: Physical model tests, data analysis and paper review.

Guilherme Santanna Castiglio: Conception of the physical model, physical model tests and paper review.

Mauricio Dai Prá: Physical model tests, data analysis and paper review.

Marcelo Giulian Marques: Conception of the physical model, methodology elaboration, data analysis and paper review.

Eder Daniel Teixeira: Methodology elaboration, data analysis and paper review.

Editor in-Chief: Adilson Pinheiro
Associated Editor: Michael Mannich

APPENDIX A. COMPARISON WITH DATA FROM OTHER AUTHORS.

The pressure data used in this work were obtained with the aid of piezoresistive pressure transducers, such as the instruments used by Sánchez-Juny & Dolz (2005), Sánchez-Juny et al. (2007, 2008), Amador et al. (2009), among others. In this work, the Omega PX419 (-0.7 m to 0.7 m; -3.5 m to 3.5 m; errors of 0.08% of the full scale) and Sitron SP96 (-1.5 m to 3.0 m; -0.7 m to 2.75 m; errors of 0.5% of the full scale) transducers were mainly used, strategically positioned along the channel (in accordance with the flow zone and the measurement range of each instrument).

Natural aeration data obtained in the same model and under the same conditions as those of this study were used by Matos et al. (2022). When comparing the measured data with those presented by Sánchez-Juny & Dolz (2005) and Sánchez-Juny et al. (2008), in a chute with α = 51º, Matos et al. (2022) identified compatible behaviors and results between the works.

Additionally, P_{med} data of the natural aeration condition obtained in the physical model of this work were compared to those of André (2004), who used silicon over silicon piezoresistive micro-sensors in the collection of hydrodynamic pressures on stepped spillways. In this case, the data acquired by André (2004) in the position closest to the outer edge of the steps are considered. It should be noted, however, that André (2004) considered a chute slope α = 30º, while, in the present work, it is considered a structure with α ≈ 53º. Therefore, this is a comparison that should be analyzed with caution.

The results of this comparison are presented in Figure A1. There is a total similarity in the results of P_{med} on the vertical face of the steps (Figure A1b) between both works. In the case of the horizontal face of the steps (Figure A1a), P_{med} data obtained in the physical model of the present work resemble the maximum results indicated by André (2004). It is possible that the justification for such differences is precisely the distinct slope of the chute, which, in turn, is related to the behavior of the flow inside the cavity formed by the steps and, consequently, to the incidence of the jet on each of the horizontal faces, along the chute. It is precisely the jet incidence on the steps that impacts the pressures on the horizontal faces, which may be the justification for the differences found between the data.

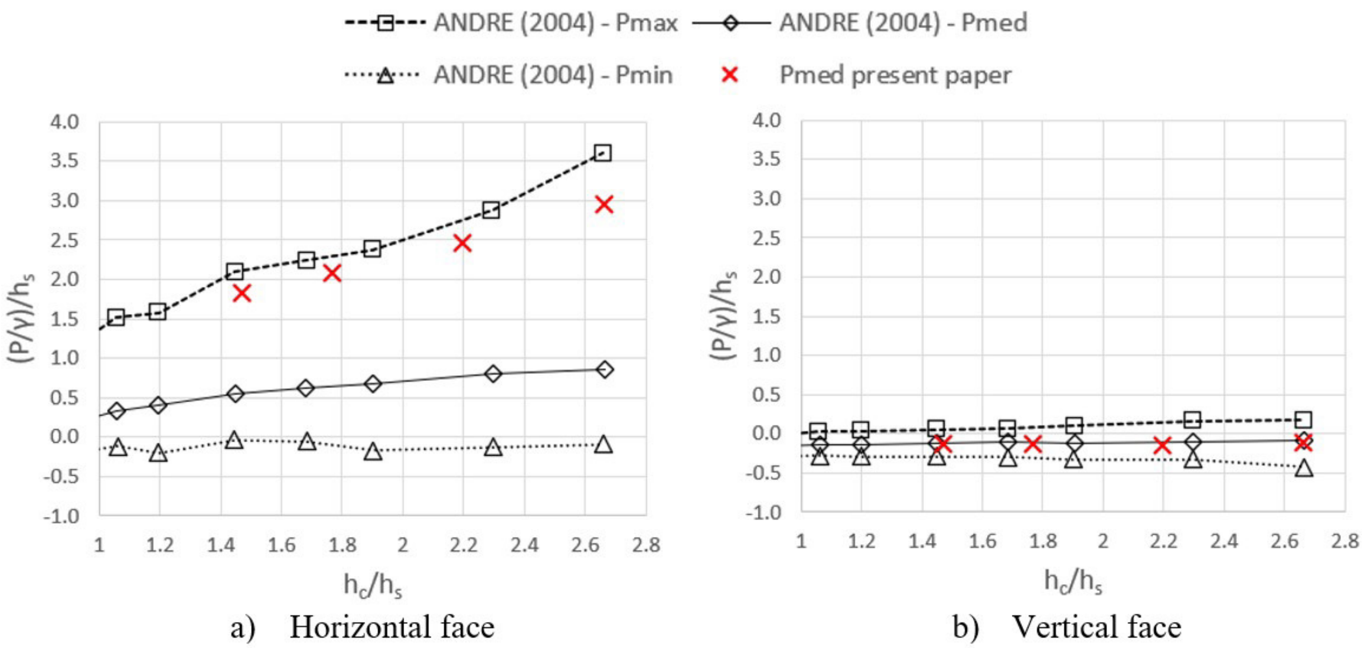


Figure A1. Comparison between a part of the data acquired in this work (natural aeration condition) and those of André (2004), where h_s is the height of the steps.