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STEPPED SPILLWAY WITH PRE-AERATION: MEAN PRESSURES AND JET'S REACH

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RESUMO – Vertedouros em degraus contribuem para a segurança das barragens durante cheias e para a dissipação da energia de montante ao longo da calha. Dadas as vantagens na utilização de vertedouros em degraus, pesquisas vêm sendo desenvolvidas de modo a aumentar as vazões específicas e evitar danos causados pelo fenômeno da cavitação, através da inserção de elementos aeradores. O objetivo deste trabalho é avaliar o alcance do jato e as pressões médias em um vertedouro em degraus com a inserção de defletor e sistema de aeração localizados no primeiro degrau. Utilizou-se um modelo físico reduzido de um vertedouro em degraus com 1,15 m de largura e 20 degraus com 9 cm de altura cada. Observou-se que o alcance do jato ocorreu nas proximidades dos degraus 6, 7 e 13, respectivamente, para defletores cuja altura é de 15, 18 e 36 mm. Pela análise das pressões médias foi possível concluir que a inserção de elementos aeradores causa um pico de pressão na região de impacto do jato e uma perturbação nas pressões a jusante.

ABSTRACT – Stepped spillways contribute to the safety of dams during the flow of excess water and allow for the dissipation of a significant amount of the upstream energy along the stepped chute. Considering the advantages of stepped spillways, some studies are being conducted in order to increase the specific yields endured by these structures in order to avoid cavitation damages through the insertion of aeration elements. The goal of this paper is to assess the jet reach and the mean pressures in a stepped chute with the insertion of a deflector with an air entrance system located on the first step. A physical model with 1.15 m wide and 20 steps with a height of 9 cm was utilized in this research. The jet range observed occurred near the steps 6, 7 and 13, respectively, for deflectors with 15, 18 and 36 mm high. Through the mean pressures analysis it was possible to ascertain that the insertion of the aeration elements cause a peak in the mean pressures at the jet's impact region and a pressure disturbance downstream of this point.

Palavras-Chave – Elementos aeradores, defletor, escoamento aerado

INTRODUCTION

Spillways are hydraulic structures that contribute to the safety of dams and other associated structures since they allow for the flow that surpasses the capacity of the reservoir to be reconducted to its original watercourse. Particularly, stepped spillways are characterized by providing additional

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energy dissipation, imparted by the contact between the flow and the steps, which act as significant roughness elements in the chute, imposing resistance to flow.

In spite of the advantages provided by the dissipation of part of the flow energy along the chute, the use of stepped spillways is limited to specific yields of approximately 15 m³/s/m (Gomes, 2006; Osmar, 2016) due to the possibility of occurrence of cavitation on the steps and consequent wear on the structure. Amador et al. (2009) indicate the criterion of maximum velocity of 15 m/s in order to avoid the occurrence of extreme negative pressures that may cause cavitation. As observed by Dai Prá (2004), the concern with the consequences of cavitation in stepped spillways is increasing due to higher tendency for structures to be designed and subjected to higher specific yields.

Peterka (1953) provided quantitative information regarding the possibility of reducing cavitation erosion in concrete structures through flow aeration. The author concluded that air concentrations of about 6 to 8% (i.e. air volume in relation to water volume) was sufficient to protect the concrete surface from erosion due to cavitation.

Therefore, it can be indicated that an alternative that allows for the increase of the specific yield capacity in stepped spillways, minimizing the chances of cavitation occurring, is the insertion of aeration elements along the chute. Such elements are responsible for promoting induced aeration, additional and prior to the aeration that naturally occurs in flows along stepped spillways, and have been studied by authors such as Mojtaba (2015), Terrier (2016), Novakoski et al. (2018), among others.

In smooth chute spillways one of the main aerators used is the deflector, an element that provides deflection of the flow and creates a region with favorable conditions to air entrance. While it is common practice in smooth chute spillways, the alternative of inserting deflectors into stepped spillways is recent. The behavior of the flow in stepped spillways when aerators are inserted is different in comparison to the naturally aerated flow occurring in structures without such elements: the insertion of deflectors, for example, causes the appearance of a jet in the flow and, consequently, changes the magnitude of the pressures in this region.

This paper is of experimental nature and uses physical modeling with the objective of evaluating the magnitude of the mean pressures that occur in the chute of a stepped spillway, as well as to analyze the behavior of the flow when subjected to aeration elements, in the form of a deflector and an opening for air entrance.

EXPERIMENTAL SETUP

The mean pressure data and the analysis of the length of flow jet reach were obtained through physical modeling. The reduced scale physical model used is built in the Laboratório de Hidráulica

Experimental (LAHE), owned by Furnas Centrais Elétricas S. A., and consists of a stepped spillway with a Creager ogee built in concrete. The chute of the spillway has a slope of 1V: 0.75H, width of 1.15 m and 20 steps whose vertical faces measure 9 cm each, as indicated in Figure 1, where the letter V indicates the pressure taps on the vertical faces of the step, the letter H indicates the pressure taps on the horizontal faces and the numbers indicate the positions of the steps in the direction of the flow.

The supply circuit of the model consists of two motor-pump sets, of 40 and 50 HP, which conduct the water to an upper reservoir. The water is conducted by gravity pull through 250 mm diameter cast iron pipes to a tank with flow straightening structures and then to the spillway approaching channel.

Aeration is induced in the flow through a deflector between the ogee and the first step, followed by a slot in the vertical face of the subsequent step. This slot allows for air to enter through the lower portion of the flow, in accordance with Figure 2. Upstream of the opening there is a pipe of 100 mm internal diameter where the air is adhered as indicated in Figure 1. No additional equipment was used to induce air entrance into the flow, other than the deflector and the slot in the subsequent vertical face.

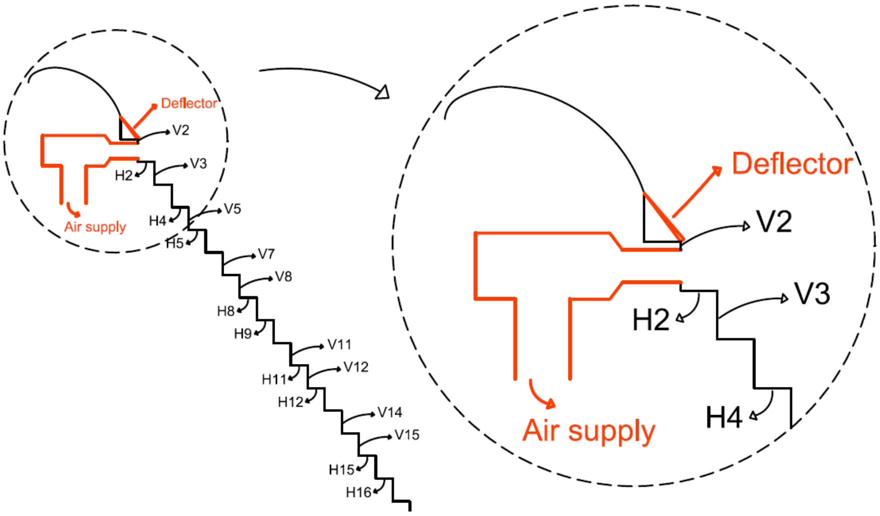

Figure 1 – Model, deflector and air supply system.

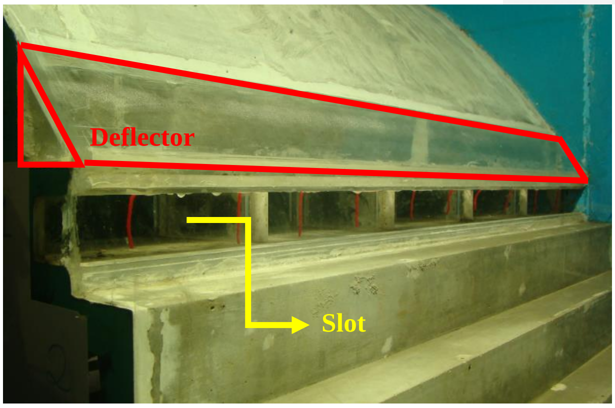

Figure 2 – Deflector and slot for air entrance.

The jet range was obtained through the visualization of the flow and the magnitude of the mean pressure heads was obtained by 18 piezometers, with pressure taps installed in proximity to junction of the vertical and horizontal faces of the steps. The discharges tested were 115, 144, 173, 230, 316, 380 and 409 l/s, which correspond to the specific yields (discharge per spillway width) of 0.100, 0.125, 0.150, 0.200, 0.275, 0.330 and 0.355 m³/s/m, respectively. Furthermore, for each discharge tested, three deflectors of different dimensions were tested, of 15, 18 and 36 mm of height, as indicated in Figure 3.

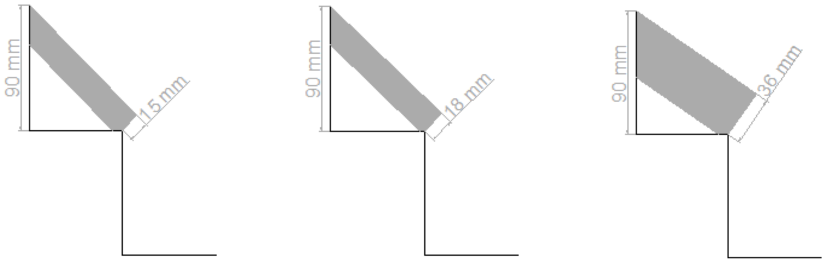

Figure 3 – Lateral view: 15, 18 and 36 mm deflectors.

EXPERIMENTAL RESULTS AND ANALYSIS

The jet impact point analysis was carried out visually, coincide with the execution of the tests, and the results are displayed in Table 1. For each deflector analyzed in particular, the jet impact point was similar for all the range of discharges tested. In the case of the deflectors of 15 and 18 mm high, the impact region was very similar, possibly because the heights were also similar. Conversely, the jet impact point for the 36 mm deflector occurred between steps 13 to 16, near the end of the spillway chute, and therefore, the steps were not used for flow energy dissipation along the spillway chute since the deflector didn´t allow for it.

Table 1 – Jet impact steps.

Discharge	15 mm deflector	18 mm deflector	36 mm deflector
115 l/s to 409 l/s	6 - 8	7 - 9	13 - 16

The mean pressures, in terms of water column height, on the vertical and horizontal faces of the step along the spillway, for the different deflectors and discharges tested, can be observed from Figure 4 to Figure 9, where the horizontal axis represents the step number and the vertical axis represents the mean pressure head in the respective step, in the vertical and horizontal faces. The pressure head resulting from the insertion of the aeration elements (deflector and air entrance system) are shown in continuous lines, while those resulting from natural aeration (without the insertion of aeration elements) are shown in dashed lines.

In the horizontal face of the steps, for all the deflectors analyzed, the pressure head were close to zero upstream of the jet impact region, distinctly from what was observed in the case of natural aeration. This occurs because the steps upstream of the jet are not in contact with water and are subjected to pressures close to atmospheric pressure due to the existence of the opening in the step that allows for air entrance.

In accordance with Figure 4, Figure 6 and Figure 8, it can be indicated that the jet impact region contributes to pressures head of greater magnitude along the chute, which was already expected since the incidence of the flow provides greater overpressure in the spillway chute. The magnitudes of the pressure head in the tests with insertion of aeration elements in the jet impact region were higher than the maximum pressure head obtained with natural aeration. Furthermore, it can be noted that, even if the impact point is similar in the 15 and 18 mm deflectors, the magnitude of the pressures was considerably different: an increase of 25% to 30% occurred in the maximum pressures head observed in the jet impact region of the 18 mm deflector in comparison to that of the 15 mm deflector, as shown in Figure 4 and Figure 6. This demonstrates that small variations in deflector size, despite not significantly altering the jet incidence region, alter the magnitude of the pressures at the site of flow impact.

Still regarding the behavior observed on the horizontal faces of the step, it was noted that downstream of the jet impact region, in the case of the 15 and 18 mm deflectors, there was oscillation in the magnitude of the pressures head, and such values were, in general, similar to the magnitude of the values obtained with natural aeration. In the case of the 36 mm deflector, it is not possible to indicate the flow behavior downstream of the jet impact region, since this occurred near the end of the spillway chute.

On the vertical faces, pressures head were close to zero upstream of the jet impact region, as observed in the horizontal faces, as shown in Figure 5, Figure 7 and Figure 9. In the jet impact region, in the case of the 15 mm deflector, the mean pressure is slightly higher, in comparison to that resulting from natural aeration, unlike the peak observed in the case of the 18 mm deflector, which assumes mean pressure values considerably higher than those obtained with natural aeration.

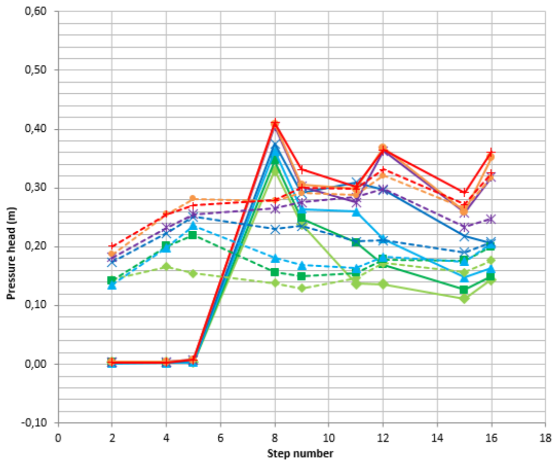

Figure 4 – 15 mm deflector – mean pressure head on the horizontal face versus spillway step number.

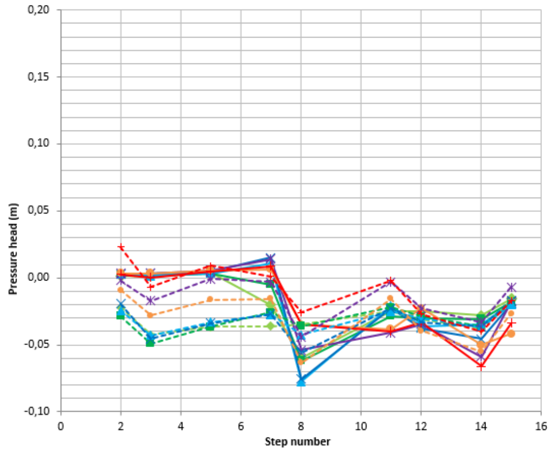

Figure 5 – 15 mm deflector - mean pressure head on the vertical face versus spillway step number.

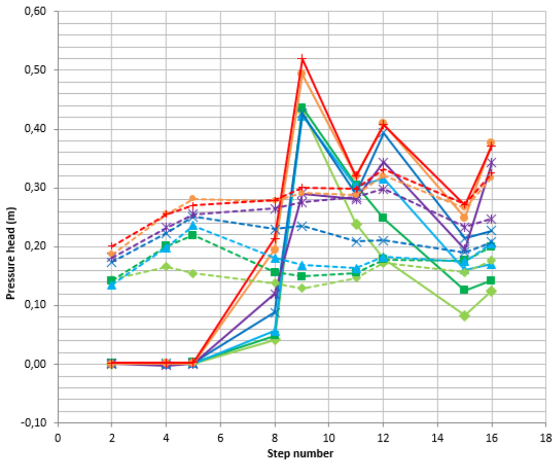

Figure 6 – 18 mm deflector - mean pressure head on the horizontal face versus spillway step number.

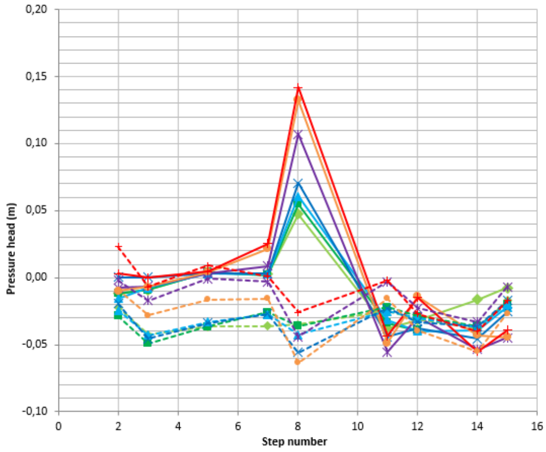

Figure 7 – 18 mm deflector - mean pressure head on the vertical face versus spillway step number.

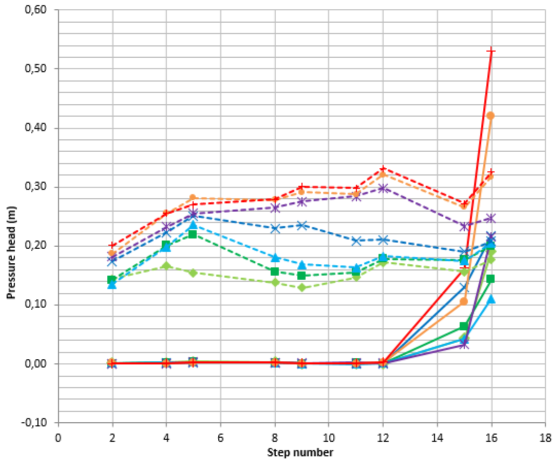

Figure 8 – 36 mm deflector - mean pressure head on the horizontal face versus spillway step number.

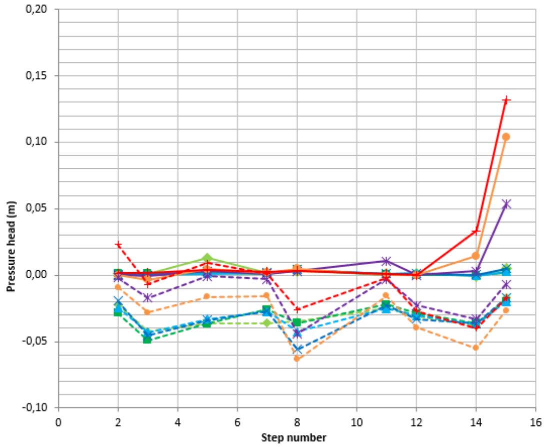

Figure 9 – 36 mm deflector - mean pressure head on the vertical face versus spillway step number.

Deflector, 115 l/s
Deflector, 144 l/s
Deflector, 173 l/s
Deflector, 230 l/s
Deflector, 316 l/s
Deflector, 380 l/s
Deflector, 409 l/s

Natural, 115 l/s
Natural, 144 l/s
Natural, 173 l/s
Natural, 230 l/s
Natural, 316 l/s
Natural, 380 l/s
Natural, 409 l/s

For the deflectors of 15 and 18 mm, downstream of the jet impact region, oscillations in the values of the pressures occur, with values similar to those observed in the case of natural aeration. Furthermore, considering the same deflectors indicated, it can be ascertained that the minimum value of the mean pressures head obtained is smaller or very close to the value attained with natural aeration.

It is not possible to analyze the behavior of the pressures on the vertical face for the 36 mm deflector, since the jet impact occurred on the last instrumented steps of the model, near the end of the spillway chute.

CONCLUSIONS

The goal of this paper was to assess the jet reach and the mean pressures in a stepped chute with the insertion of a deflector and an air supply system located on the first step. Through the mean pressures analysis it was possible to perceive that, on the horizontal faces of the steps, upstream the jet's impact site, the mean pressures were close to zero, lower than the same measurements on a stepped chute with natural aeration (without aeration elements). Near the jet's impact site a peak of pressures occurred, exceeding the same values acquired with natural aeration. Downstream from this point, there was an oscillation with higher and lower values in comparison to natural aeration. For the vertical faces of the steps, it was possible to note that, such as was observed on the horizontal faces, upstream of the jet's impact, the pressures are near zero, higher than the same pressures obtained with natural aeration. In addition, near the jet's impact, a peak was observed, albeit lower than the peak which occurred on the horizontal faces of the steps. Downstream of the jet's impact, pressures oscillate near the values acquired with natural aeration.

The conclusions were that the insertion of the aeration elements causes a peak of mean pressures at the jet's impact region as well as a pressure disturbance downstream of this point. For the deflector with 36 mm high, the jet's impact occurred on the final half of the chute, so it is believed that the stepped spillway cannot perform its function of energy dissipation appropriately. Thus, studies of new deflector geometry are recommended.

Additionally, it is indicated that, while the maximum and minimum mean pressures resulting from the analysis with insertion of aeration elements are more extreme, both positively and negatively, than those resulting from natural aeration, the pressures with low probabilities of non-exceedance must be analyzed (0.1% probability, for example), with and without the insertion of aerators, in order to allow for additional conclusions to be drawn in regards to pressure loads acting on the structure.

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