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# EXTREME NEGATIVE PRESSURES AND CAVITATION TENDENCY ON STEEPLY SLOPING STEPPED SPILLWAYS

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**Abstract**. *Stepped spillways have become an appropriate alternative to many dams worldwide because of its ease of construction and economy. Another advantage of the use of this type of structure is the significant energy dissipation along the chute, caused by the macroroughness of the steps. However, the use of this structure may be limited due to the risks of cavitation at the steps, associated to the occurrence of significant pressure fluctuations and extreme negative pressures. With the objective of studying the risk of cavitation in steeply sloping stepped spillways, experimental tests were carried out on a stepped chute assembled at the Hydraulic Research Institute of Federal University of Rio Grande do Sul (IPH/UFRGS), in Brazil. The mean and extreme pressures associated with the non-exceedance probabilities of 0.1% were analyzed near the step edges. The analysis of the extreme negative pressures scaled to appropriate prototypes suggests that cavitation tendency may occur in the vicinity of the point of inception for unit discharges larger than about 11 to 17 m$^2$/s.*

## 1 INTRODUCTION

For centuries, dams have been used for a wide variety of purposes, such as water storage, flood protection, power generation, among others. In several dams, the spillway chutes are comprised of steps with the purpose of increasing the energy dissipation during the passage of the flow. The use of this form of energy dissipation is growing due to its great efficiency in decreasing the residual energy in comparison to the smooth chutes. The diffusion of this type of solution for higher dams and larger flow rates requires additional in depth studies, namely on the skimming flow hydraulics.

Until the 1970s, the information required for the design of this type of spillway was scarce. Since then, from the development and expansion of Roller Compacted Concrete (RCC) technology, several experimental studies were carried out on stepped spillways by researchers such as [1], [2], [3], [4], [5] and [6], among others, focusing on the pressure field along the chute. [6] verified that unit discharges below 10 m$^2$/s would not lead to cavitation risk and that above 15 m$^2$/s would. [4] concluded that the maximum unit discharges without risk of cavitation tendency in the vicinity of the onset of air entrainment (point of inception) would be around 11.3 to 15.6 m$^2$/s, and for [3],

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incipient cavitation could occur for unit discharges between 11.5 and 14.0 $m^2/s$. In these studies, pressure levels with *non-exceedance probabilities* of 0.1% were chosen to estimate cavitation tendency, based on prototype and laboratory data gathered on macroturbulent flows, as per [8].

As the use of these structures may be limited due to the risks of cavitation on the steps, associated with the occurrence of significant pressure fluctuations, the objective of this paper is, through the characterization of the loads acting in stepped spillways, to preliminarily define the limit unit discharges so that cavitation tendency is not expected to occur. It should be emphasized that the study was carried out based on detailed statistical analysis of pressure fluctuations in fairly large scale Froudian models, which are unable to simulate cavitation phenomena correctly. However, results of the critical cavitation index obtained by [9], using laboratory experiments in a specialized reduced ambient pressure chamber, were found to be of the same order of magnitude as those obtained in the vicinity of the point of inception by [3] and [4], based on extreme pressures with non-exceedance probabilities of 0.1%, as shown in [10].

In addition, the study was carried out taking into account only the hydraulic characteristics of the flow. Inadequate constructive characteristics of the spillway or operation may increase the risk of erosion or cavitation occurrence and, in this way, reduce the maximum unit discharges recommended for this type of structure.

## 2 METHODOLOGY

In order to study the tendency of cavitation, extreme pressures with 0.1% probability of non-exceedance occurring in the vertical and horizontal faces of the steps were analyzed. Minimum pressure heads equal to or lower than -10.09 m will lead to cavitation considering the water vapor pressure at 20°C.

For the determination of the extreme pressures with a 0.1% probability of non-exceedance near the step edges, the reanalysis of data acquired by [5], as per [6], was considered. The experiments data were acquired on a stepped chute assembled at Hydraulic Research Institute of Federal University of Rio Grande do Sul (IPH/UFRGS), in Brazil. The chute is 2.54 m high, with a slope of 1V:0.75H and 0.06 m high steps. Unit discharges up to 0.30 $m^2/s$ were tested. The hydrodynamic pressures were measured on both the horizontal and vertical step faces, near the respective outer edges, using pressure transducers, whose pressure head accuracy was 7.5 mm and 12.5 mm in the vertical and horizontal taps, respectively. The transducers were positioned 5 mm away from de edge on the horizontal faces of the steps and 7 mm away from the edge on the vertical faces. The frequency of data acquisition was 128 Hz and the respective duration was 15 minutes. Further information on the experimental setup and data acquisition can be found in [5] and [6].

Figure 1 illustrates the skimming flow on the chute along with the main flow characteristics used for the normalization of the pressure head along the chute. Therein $d_c$ is the critical flow depth, L is the distance along the chute pseudo-bottom, measured from the crest of the spillway, $L_i$ is the distance from the crest of the spillway to the point of inception and $d_i$ is flow depth at the point of inception.

Figures 2 and 3 include, for the horizontal and vertical faces of the steps, respectively, normalized mean and extreme pressures with 0.1% probability of non-exceedance, where $L_i$ and $d_i$ were obtained from [12].

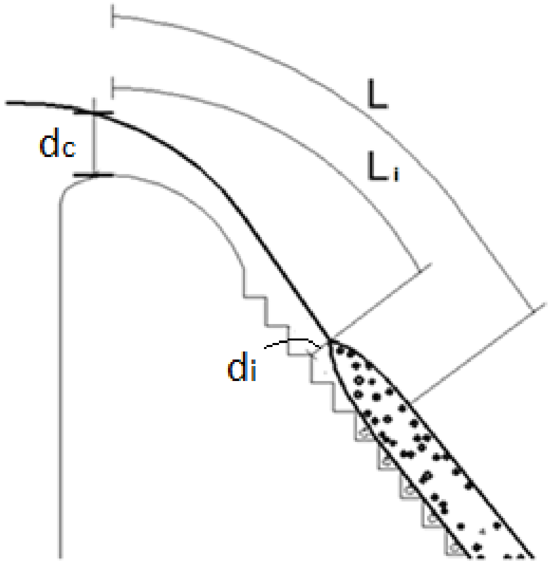


Figure 1 – Scheme of the main flow characteristics used for the normalization of the pressure head along the chute.

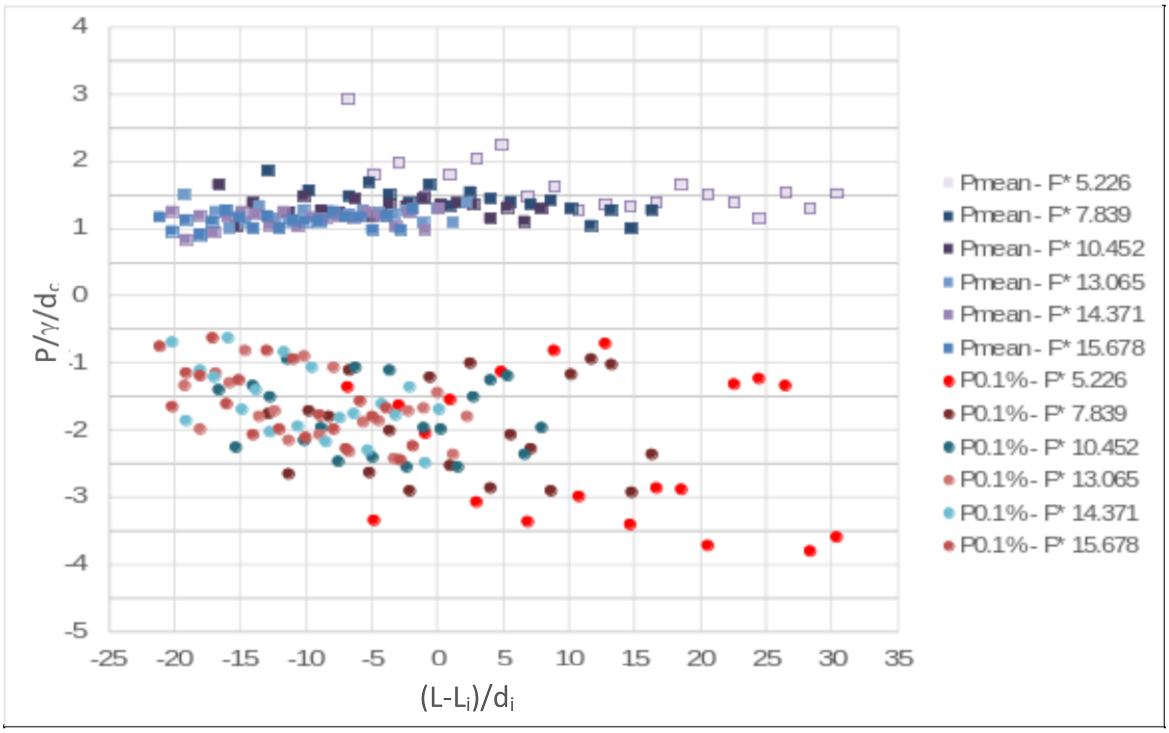


Figure 2 – Mean and extreme pressures ($P_{0,1\%}$) acting on the horizontal faces of the steps, in the vicinity of their edges.

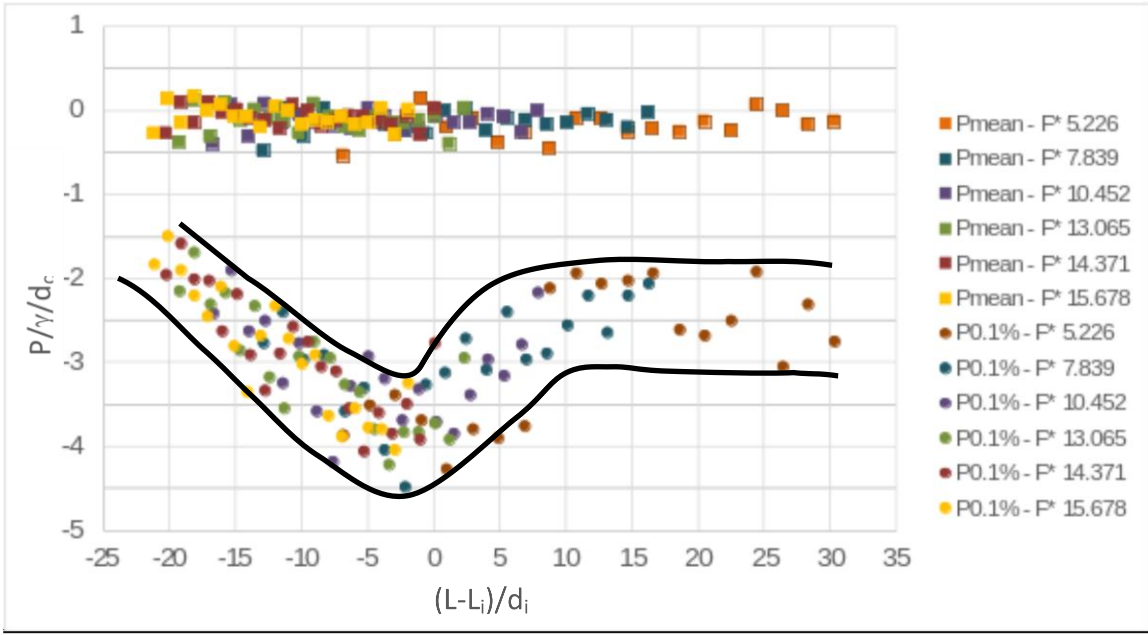


Figure 3 – Mean and extreme pressures ($P_{0,1\%}$) acting on the vertical faces of the steps, in the vicinity of their edges.

Figures 2 and 3 show that the most critical extreme pressures, that is, that have higher negative values, occur in the vertical faces of the steps. However, significant negative pressures may also take place on the horizontal step faces, in the vicinity of the step edge. Following the analysis, only the most critical situation was studied. As can be observed in Figure 3, the extreme pressure data form a range of points delimited by an upper curve and a lower curve, qualitatively drawn on the figure. A region of extreme low pressures is observed approximately for -5 < $\frac{L-L_i}{d_i}$ < 0. For $\frac{L-L_i}{d_i}$ ~ - 2, the normalized extreme pressure $\frac{\frac{P_{0.1\%}}{\gamma}}{d_c}$ ranges between -3.2 and -4.5. These values were used in order to estimate the critical unit discharge to avoid the tendency of cavitation. A simplistic methodology is presented below:

- Considering that the onset of cavitation occurs for $\frac{P_{0.1\%}}{\gamma}$ = -10.09 m, the critical flow depths ($d_c$) were calculated for the lower and upper limits of the extreme pressure peak observed in Figure 3, respectively as:

$$\frac{\frac{P_{0.1\%}}{\gamma}}{d_c} = -4.5 \quad (1)$$

$$\frac{\frac{P_{0.1\%}}{\gamma}}{d_c} = -3.2 \quad (2)$$

- The range of critical unit discharges for the tendency of cavitation were calculated from

$$q = \sqrt{d_c^3 \times g} \quad (3)$$

where q is the unit discharge and g is the acceleration of gravity.

## 3 RESULTS AND DISCUSSION

Table 1 shows the results obtained for the critical flow depths and maximum unit discharges calculated for the situation where tendency of cavitation would occur, based on the analysis of extreme pressures with a 0.1% probability of non-exceedance. The results may be applied on steeply sloping stepped spillways (1V:0.75H), for step heights of about 0.6 to 0.9 m (i.e., scaling to 10:1 to 15:1 prototypes), and for sufficiently high chutes so that inception of air entrainment occurs down the slope, regardless of the flow rate. The maximum unit discharges are displayed in Figure 4, in comparison to the zones where cavitation may take place according to previous studies by various authors.

| $\frac{P_{critical}}{\gamma}$ (m) | $\frac{\frac{P_{0,1\%}}{\gamma}}{d_c}$ | $d_c$ (m) | q ($m^2$/s) |
|---|---|---|---|
| -10.09 | -4.5 | 2.25 | 10.60 |
| -10.09 | -3.2 | 3.11 | 17.20 |

Table 1: Results obtained for tendency of cavitation ($\frac{P_{0,1}}{\gamma} \leq -10.09\ m$).

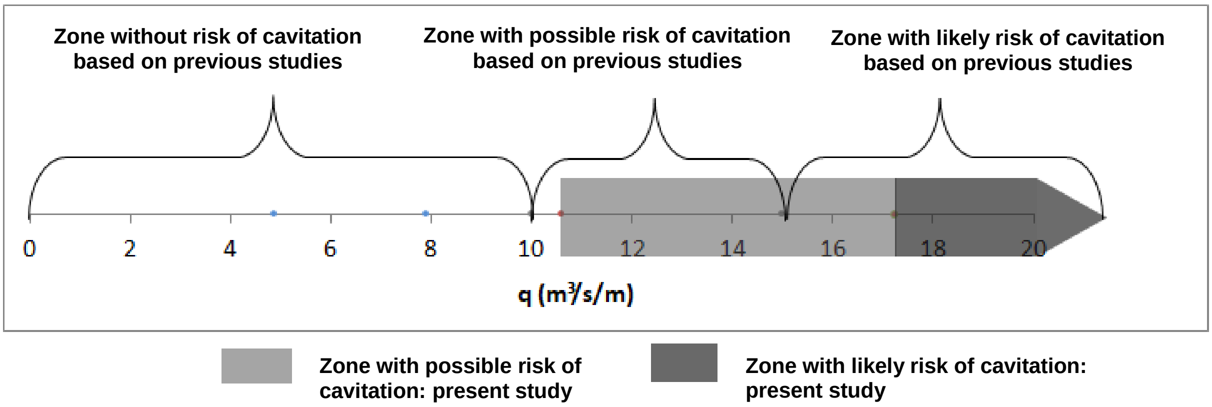


Figure 4 - Limit flow rates regarding the tendency of cavitation on steeply sloping stepped spillways, based on critical extreme pressure data with a very low probability of non-exceedance, in the vicinity of the point of inception: comparison with other studies.

As can be observed in Table 1 and Figure 4, up to unit discharges of approximately 11 $m^2$/s, such type of stepped spillways are most likely not subject to cavitation. In the range of unit discharges between about 11 $m^2$/s and 17 $m^2$/s, cavitation may possibly occur. The tendency of cavitation seems more consolidated for unit discharges greater than about 17 $m^2$/s.

The present results are in line with those of [3] and [4], which suggested maximum unit discharges ranging between 11.5 to 14 $m^2$/s and 11.3 to 15.6 $m^2$/s, respectively. Considerably higher limits were obtained by [11], between 20 and 30 $m^2$/s, based on a simplistic comparison of the cavitation index with the estimated critical cavitation index for skimming flows, for step heights between 0.30 and 1.20 m. A similar study presented in [14], based on a larger set of data for estimating the location and equivalent clear water depth at the point of inception ([12]), lead to a limit unit discharge of 18 $m^2$/s for a step height of 0.60 m, hence more conservative than those of [11], but less restrictive than those obtained in the present study.

## 4 CONCLUSIONS

The objective of this paper was to identify the range of maximum unit discharges for which cavitation may occur on steeply sloping stepped spillways (1V:0.75H), for prototype step heights of about 0.6 to 0.9 m, and for sufficiently high chutes so that inception of air entrainment occurs down the slope, regardless of the flow rate. Herein the tendency of cavitation was based on the analysis of extreme pressures with a 0.1% probability of non-exceedance.

It was possible to conclude, preliminarily, that:

- in the vertical faces of the steps, the lowest extreme normalized pressures are of the order of - 4.5, in the vicinity of the point of inception;
- in the horizontal faces of the steps, the lowest extreme normalized pressures are of the order of -3.5 to - 4.0, in the vicinity of the point of inception and further downstream;
- for unit discharges ranging from 11 to 17 $m^2$/s, cavitation may occur.

In continuation of this study, extreme pressures obtained by other researchers will be analyzed along with new data acquired on three physical models of stepped spillways.

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