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Analysis of hydraulic parameters in determining the occurrence of cavitation in the spillways of the Furnas, Luiz Carlos Barreto de Carvalho and Batalha hydroelectric power plants

Análise dos parâmetros hidráulicos na determinação da ocorrência de cavitação nos vertedouros das usinas hidrelétricas Furnas, Luiz Carlos Barreto de Carvalho e Batalha

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ABSTRACT

The hydrodynamic conditions to which hydraulic structures such as spillways and stilling basins of dams are submitted under given conditions favor the occurrence of cavitation, damaging the concrete surfaces. This damage may be intensified by the cumulative effect of the successive hydrologic events that characterize the operational regime of these structures. Thus, the purpose of the present article is to identify the propensity for damage caused by cavitation by using *SpillwayPro* software to estimate the hydraulic parameters of flow (mean velocities and cavitation indices) based on information on smooth chute spillways at the Furnas, Luiz Carlos Barreto de Carvalho and Batalha hydroelectric power plants. The results shown were compared to the critical limits of cavitation defined in the literature on photographic records of inspections performed in the field. The highest mean velocities estimated coincided with the zones where the worst potential damage of the structures was identified. Nevertheless, most of the cavitation indices obtained did not present results similar to the limits presented by different authors, and thus do not favor the indication of cavitation risks due to this parameter in the spillways examined.

Keywords: Cavitation index; Hydraulic surfaces of concrete; Operation of hydraulic structures; *SpillwayPro*.

RESUMO

As condições hidrodinâmicas as quais estão submetidas estruturas hidráulicas de barragens, como vertedouros e bacias de dissipação, em determinadas condições favorecem a ocorrência do fenômeno da cavitação produzindo danos nas superfícies de concreto, que podem ser intensificados pelo efeito acumulativo dos sucessivos eventos hidrológicos que caracterizam o regime de operação destas estruturas. Desta forma, a presente artigo visa identificar a propensão da ocorrência de danos por cavitação através da utilização do software SpillwayPro para a estimativa dos parâmetros hidráulicos do escoamento (velocidades médias e índices de cavitação) a partir de informações de vertedouros de calhas lisa das usinas hidrelétricas Furnas, Luiz Carlos Barreto de Carvalho e Batalha. Os resultados apresentados foram comparados aos limites críticos de cavitação definidos em literatura aos registros fotográficos das inspeções realizadas em campo. As maiores velocidades médias estimadas coincidiram com as zonas onde foram identificados os piores potenciais danos nas estruturas. Enquanto que, os índices de cavitação obtidos não apresentaram, em sua maioria, resultados semelhantes aos limites expostos por diferentes autores, desfavorecendo assim, o indicativo de riscos por cavitação por esse parâmetro nos vertedouros verificados.

Palavras-chave: Índice de cavitação; Superfícies hidráulicas de concreto; Operação de estruturas hidráulicas; SpillwayPro.

INTRODUCTION

In hydraulic structures such as spillways and stilling basins, responsible for the safety of dam integrity, the phenomenon of cavitation is widely studied since its hydrodynamic efforts, originating in turbulent flows and characterized by high velocity flows and high complexity, may generate cumulative and irreversible damage to the surfaces of the lining of these devices (Colgate, 1977; Falvey, 1990; Bhate et al., 2021; Schleiss et al., 2023). Cavitation is defined as the formation and later collapse of bubbles of vapor, water or different gases dissolved in the fluid, by the brusquely diminished pressure and significant increase of flow velocity (Pinto et al., 1988; Quintela & Ramos, 1980; Tullis, 1982; Bhate et al., 2021; Hampe et al., 2020; Mortensen, 2020).

Notably, concrete surfaces of smooth flume spillways and high drop bottom outlets, when the boundaries of surface with flow are well finished, accept mean velocities higher than the range of 30.0 to 35.0 m/s without presenting cavitation problems. Nevertheless, when the irregularities on the concrete surface surpass the maximum slope relations of 20:1, the acceptable mean velocities for the non-occurrence of damage by flow cavitation are significantly reduced, indicating limits of mean velocities from 12.0 to 28.0 m/s (Ball, 1976; Falvey, 1990).

Various authors specify the beginning of the cavitation process by means of minimum limits defined based on critical cavitation indices (σ_{cr}). Some examples are mentioned by Ball (1976), Arndt et al. (1979) and Falvey (1990) for smooth chute structures, while Amador et al. (2009), Pfister et al. (2006), Frizell et al. (2013) and Pfister & Boes (2014) present limits for stepped spillways. The lowest values presented in the literature were established by Ball (1959), Arndt et al. (1979), Falvey (1982) of $\sigma_{cr} \leq 0.20$ for surfaces without the presence of any irregularities. Besides defining the beginning of the occurrence of damage from cavitation, they allow delimiting regions with the possible occurrence of phenomena for spillways based on different chute slopes.

According to Ball (1976), for abraded concrete with roughnesses less than 20.0 mm deep, the limit of cavitation index will be 0.60. For the structures of *Endsills* and stilling basins, Khatsuria (2005) informs that the characteristic indices of the flow may range between 1.05 and 1.75.

Aiming to avoid hydrodynamic flow conditions that favor the phenomenon of cavitation, the discharges, velocities and maximum mean pressures of operations are verified at each stage of a project. Lee & Hoopes (1996), Wahl et al. (2019) and Wahl & Falvey (2022) elaborated a model to predict the occurrence of damage by cavitation utilizing factors that influence the phenomenon: cavitation index, velocity, air concentration, resistance of the material and time of exposure to the action of flow. Many scale model studies and damage analysis at prototype scale attribute the damage generated by the phenomenon of cavitation and/or erosion in hydraulic structures to maximum velocities and minimal extreme instantaneous pressures (Bhate et al., 2021; Matos et al., 2022; Schleiss et al., 2023). Lopardo (1996, 2013), Hampe et al. (2020), Mousavi et al. (2020a, 2020b) and Steinke Junior et al. (2021) recommends the analysis of pressures with a 0.1% probability of non-exceedance to look at tendencies to cavitation in structures submitted to macroturbulent flows at high velocities.

Sanagiotto (2003), Amador et al. (2009), Conterato et al. (2015), Dai Prá et al. (2016), Osmar et al. (2018), Canellas (2020), Priebe et al. (2021), Ferla et al. (2021) and Matos et al. (2022) analyzed minimum extreme pressures in stepped spillway chutes considering differents ranges of specific discharges, chutes with a slope and step widths. Kermani et al. (2013) developed a risk classification for cavitation damage in the stepped spillway of dam of *Shahid Abbaspour*, in the Iran, based on the flow velocity and the cavitation index from tests on a reduced scale model of 1V: 62.5H. Their research identified that for $V \leq 5.0$ m/s and $\sigma > 1$ there is non-occurrence of cavitation damage, for 5.0 m/s < $V \leq 16.0$ m/s and $0.45 < \sigma \leq 1.0$ there is a possibility of damage, with the occurrence of cavitation damage confirmed in $V \geq$ 16.0-18.0 m/s and $0.25 < \sigma \leq 0.45$. The occurrence of severe damage was associated with $V >$ 40.0-45.0 m/s and $\sigma \leq 0.17$.

Novakoski et al. (2017), Hampe et al. (2020), Mousavi et al. (2020a, 2020b) and Steinke Junior et al. (2021) performed similar analyses in stilling basins observing pressure fluctuations in scaled down physical models and their effects at prototype scale.

In spillways, studies carried out by Falvey (1990), in the United State Bureau of Reclamation (USBR), that evaluating the serious damage caused by the phenomenon of cavitation in the dam tunnel Glen Canyon in 1983 and his experiences in aerator projects for the Glen Canyon (V = 32.0 e 35.0 m/s), Hoover (V = 41.0 m/s), Yellowtail (V = 43.0 m/s), Flaming Gorge (V = 34.0 m/s) and Blue Mesa plants (V = 35.0 m/s), identified the speed limits, exposure time and critical cavitation indices associated with these structures and the damage represented in them. Considering the operating characteristics of the prototypes under study Falvey (1990) defined the essential design criteria for the non-occurrence of cavitation damage on the concrete surface of smooth channel spillways and in the segments corresponding to the crest of stepped spillways, widely used to this day (Bhate et al., 2021; Mortensen, 2020).

Generally, the risk connected to the occurrence of the cavitation phenomenon is estimated by means of the hydraulic characteristics of flow, and the mean velocity, cavitation index and flow pressure are the main parameters evaluated in studies of economic feasibility and durability of the concrete surfaces.

The main hydraulic parameters of velocity and cavitation indices along the hydraulic surfaces of the spillways of the hydroelectric plants (HPPs) of Furnas, Luiz Carlos Barreto de Carvalho (LCBC) and Batalha that belong to Furnas Centrais Elétricas were estimated considering the *SpillwayPro* software developed by the United States Bureau of Reclamation (USBR). The results obtained using the software were extracted based on the simulation of different ranges of flow, including the maximum discharges spilled (Qmax), defined by means of the historical series of flow rates from each HPP. Geometrical information regarding the profiles and general characteristic of each spillway evaluated was also used. In this way the behavioral trends were looked at for the behavior of the hydraulic parameters of velocity and cavitation index for different conditions of operation considered, specifically for the sites where changes or irregularities were found in the concrete of the hydraulic surfaces of each undertaking involved, detected during a field campaign for the inspection of the structures.

Due to the difficulty in accessing the overflow structures of hydroelectric plants, which differently the North American reality, are constantly activated during the period of hydrological floods in Brazil, information on the conditions of the concrete coating of these plants is extremely rare. Therefore, this research objective, based on the evidence and location of irregularities present on the surface the spillways, to identify the behavior of the hydraulic characteristics of the flow as flow increases occur up to the maximum flow rate occurring in each HPP. We chose to use the *SpillwayPro* software due to its wide practical applicability for obtaining results, in addition to being a widely used tool in sizing and understanding spillways studied by the Bureau of Reclamation.

It is worth noting that research on the phenomenon of cavitation based on physical and numerical modeling is constantly being developed by the scientific community, mainly for stepped spillways, due to their high energy dissipation and ease of construction when compared to conventional spillways. Thereby, most of the criteria for using spillways (cavitation indices, flow velocities, surface curvatures, etc…) were developed in the 1950s to 1980s, and are still considered today in studies of these structures, which justifies the difficulty of access to the most recent bibliography on the study presented here.

The information and results obtained in this article are part of the scope of the Research and Development (R & D) project titled "Study of Concrete for Hydraulic Surfaces" funded by Foz do Chapecó Energia with the participation of Furnas Centrais Elétricas, of the Laboratory of Hydraulic and of concrete of the US Bureau of Reclamation (USBR) and of the Federal University of Rio Grande do Sul (UFRGS) through the Instituto de Pesquisas Hidráulicas (IPH) - Laboratório de Obras Hidráulicas (LOH).

MATERIAL AND METHODS

The hydraulic structures utilized to perform this study were inspected by a technical team composed of professionals from Furnas Centrais Elétricas, Laboratório de Obras Hidráulicas (LOH/UFRGS) and DESEK, aiming to identify the conditions of the concrete surfaces of the spillways and energy stilling basins. The main characteristics of the hydroelectric power plants considered in this study are shown in Table 1.

The cross-sections that presented surface irregularities or alterations of the concrete were looked at during the technical visits, thus providing information to delimit regions of interest of this study. It should be highlighted that the alterations found do not present a danger to the integrity or functioning of the safety devices of these plants.

The alterations on the concrete surfaces, in general, are classified as localized erosions, spallings, exposure of large aggregates, discontinuities close to the concrete joints and /or dilation and fissures (Figure 1).

Table 1. General characteristics of the plants and hydraulic structures considered in this study.

HPP	State	Opening date	n° of Gates	Width of Gate (m)	Inspecion Date
Furnas	Minas Gerais	1965	7	11.5	29/09 to 05/10/2019
Luiz Carlos Barreto de Carvalho	São Paulo	1969	6	11.5	
Batalha	Minas Gerais	2013	2	8.7	22 to 24/10/19

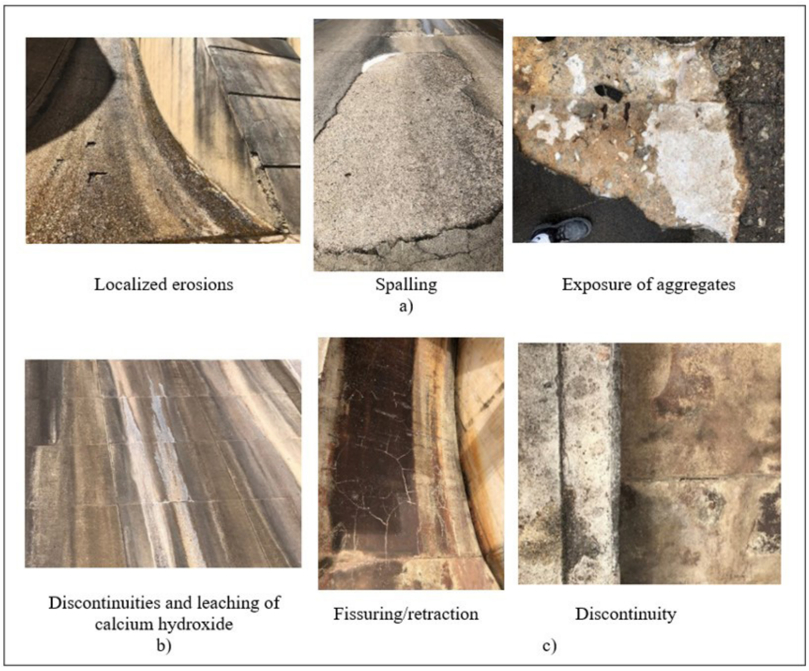

Figure 1. Alterations found on the concrete surfaces of the spillways of HPP of Furnas (a); Luiz Carlos Barreto de Carvalho (b), and; Batalha (c).

The hydraulic parameters (cavitation indices and velocities flow) evaluated in this research were obtained from the discretization of equal flow intervals based on the maximum flow rate (Qmáx.), defined through the historical series of each hydraulic structure considered. The maximum flow rate used were 3800.0 m^3/s, 4132.0 m^3/s and 302.0 m^3/s for the Furnas, LCBC and Batalha plants. The choice of simulated flow rates was carried out in order to extract the evolution of the behavior of the verified hydraulic parameters and thus establish ranges of possible occurrence of the cavitation phenomenon.

The flows, for the hydrological conditions considered, were characterized using *SpillwayPro* software. This software was developed by engineers Tony L. Wahl, K. Warren Frizell and Henry T. Falvey of the Hydraulic Laboratory of the U.S. Bureau of Reclamation (USBR), Denver – United States of America (USA). It is a free license software, originally programmed in *FORTRAN* and *Visual Basic* language, adapted for use on an electronic spreadsheet. *SpillwayPro* is utilized as a tool to characterize the flow of interest through a one-dimensional flow enabling the determination of various hydraulic parameters such as velocity, pressure, height of water surface, cavitation index and others. The simulations were performed based on the description of the longitudinal profiles of the hydraulic structures of the HPPs (Figure 2), obtained from the projects supplied directly by the companies responsible and from the bibliography existence, especially of the Comitê Brasileiro de Barragens (2002, 2010).The discharges utilized in this study are shown in Table 2.

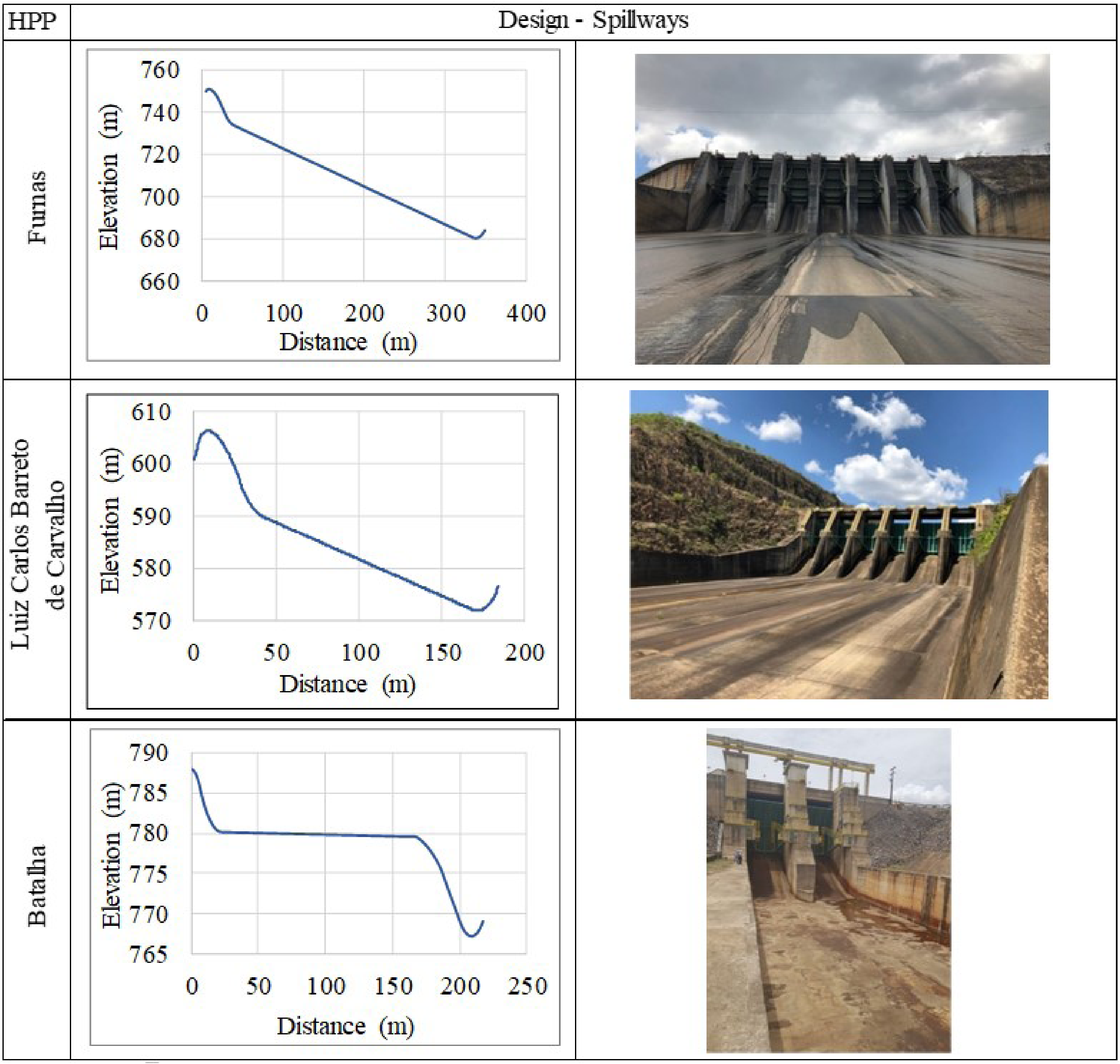

Figure 2. Longitudinal profiles and images of the hydraulic structures of the plants inspected.

The risk of cavitation was looked at in the results obtained by the simulation using *SpillwayPro* for the cavitation indices and flow velocities. The software estimates the cavitation index (σ), responsible for relating the acting forces generated by the differential high pressures and the local velocity load of the fluid, using Equation 1, widely disseminated by the bibliography (Colgate, 1977; Arndt, 1981; Falvey, 1990).

$$\sigma = \frac{P + P_a - P_v}{\rho_a \overline{V}^2 / 2} \quad (1)$$

The local pressure (P), ignoring the input of air into the flow, was estimated by Equation 2.

$$P = P_a + \rho_a h\left(g\cos\theta' \pm \frac{\overline{V}^2}{r}\right) \quad (2)$$

In this way, Equation 3 expresses the final formulation considered by the software in estimating the cavitation index for the surfaces considered.

$$\sigma = \frac{\frac{P_a}{\gamma_a} - \frac{P_v}{\gamma_a} + h\cos\theta' + \frac{h}{g}\frac{V^2}{r}}{\frac{V^2}{2g}} \quad (3)$$

where: σ the cavitation index (adm); P_a the local atmospheric pressure (kgf/m^2); γ_a the specific weight of water (kgf/m^3); P_v vapor pressure of water (kgf/m^2); V mean velocity of flow (m/s); ρ_a specific mass of water (kg/m^3); θ' angle of the bottom of the canal with a horizontal plane; h water depth in the direction perpendicular to the direction of flow (m); g acceleration of gravity (m/s^2); r curvature radius on the vertical plane of the bottom of the canal (m).

Besides the estimate performed using *SpillwayPro* for the cavitation indices based on Equation 3, it was decided, for comparative purposes, to determine the index σc by utilizing the friction factor "f" as described in Equations 4 and 5 (Arndt & Ippen, 1968; Falvey, 1990; Frizell et al., 2013; Kermani et al., 2013; Matos et al., 2022).

$$c = 4f \quad (4)$$

$$\frac{1}{\sqrt{f}} = 3.25 + 0.39\log_{10}\left(\frac{y}{k}\right) \quad (5)$$

where: c is the estimated critical cavitation index (adm); f the friction factor of the surface; y is the height of flow perpendicular to the bottom (m), and; k the roughness defined for the concrete surface of the spillway analyzed (m).

It is known that index c, estimated from the friction factor proposed for roughnesses uniformly distributed in turbulent boundary layers was widely used in the studies of Arndt (1981), Falvey (1990), Frizell et al. (2013) and Matos et al. (2022). Frizell et al. (2013) and Matos et al. (2022) used Equation 4 to estimate the occurrence and location of greatest activity of the cavitation phenomenon in spillways with steep slope steps (1V:0.75H).

However, in this study, the estimation of index c by Equation 4 will be considered an additional parameter applied to smooth chute spillways, so as to obtain new boundaries besides those already consolidated in the bibliography by Ball (1976) and Falvey (1990).

The methodology utilized to obtain the data was based on utilizing the electronic spreadsheet of the *SpillwayPro* software which uses the hydraulic characteristics of the structures as input parameters to perform the simulations based on the convergence of successive approaches. *SpillwayPro* is divided into the "*Input Geometry*" tabs (data input) and the "*Output Hydraulic*" and "*Cavitation*" output tabs, and the latter are responsible for presenting the estimated flow characteristic based on the input discharges found.

The results obtained were compared to the limits defined in the literature considering: *i) the critical cavitation indices* of de 0.20, according to Ball (1976), Falvey (1982, 1990) and Bhate et al. (2021), and 0.30 defined by Falvey (1990) without the presence of irregularities on the concrete surface of smooth spillways; *ii) the incipiente cavitation rates* of 0.60, presented Ball (1976), Arndt et al. (1979) and Falvey (1982, 1990) for concrete surfaces with roughness less than 20 mm, and of 1.80 stipulated by Falvey (1990) for

Table 2. Discharges used to characterize the spillway flow of the hydroelectric plants of Furnas, Luiz Carlos Barreto de Carvalho and Batalha.

HPP	Furnas		LCBC		Batalha	
	Q (m^3/s)	q (m^3/s.m)	Q (m^3/s)	Q (m^3/s.m)	Q (m^3/s)	Q (m^3/s.m)
Discharge considered	500.0	6.2	500.0	7.2	50.0	2.8
	1000.0	12.4	1000.0	14.4	100.0	5.7
	1500.0	18.6	1500.0	21.7	150.0	8.6
	2000.0	24.8	2000.0	28.9	200.0	11.4
	2500.0	31.0	2500.0	36.2	250.0	14.3
	3000.0	37.2	3000.0	43.4	302.0*	17.3**
	3500.0	43.4	3500.0	50.7	350.0	20.1
	3800.0*	47.2**	4000.0	57.9	400.0	22.9
	4500.0	55.9	4132.0*	59.8**	450.0	25.8
	5000.0	62.1	5000.0	72.4	500.0	28.7
	5500.0	68.3	5500.0	79.7	550.0	31.6
	6000.0	74.5	6000.0	86.9	600.0	34.4
	-	-	6500.0	94.2	650.0	37.3
	-	-	7000.0	101.4	-	-

*maximum flow rate; **maximum specific flow rate in the spillways.

well-finished concrete surfaces; *iii) the minimum speed limits* of 12.0 m/s, assigned by Ball (1976) and Falvey (1990) for spillways without irregularities greater than the slope of 20:1, and of 15.0 m/s, minimum limit defined Ball (1959) to determine the onset of mild cavitation damage on surfaces without any irregularities, and; *iv) the maximum speed limits* of 25.0 m/s, determined by Ball (1959) for the occurrence of serious cavitation damage in spillways, and the 30.0 m/s described by Falvey (1990) and Bhate et al. (2021) to determine the fully developed cavitation process.

The points of interest were defined according to the location of the cross-sections, where by visual inspection performed in the field, signs were found of irregularities or potential damage to the concrete surfaces of the spillway at the Furnas, Luiz Carlos Barreto de Carvalho and Batalha plants. The characteristic geometrical section adopted in simulations with *SpillwayPro* was rectangular, and the height and width dimensions were adopted according to the spans of the spillways analyzed. The roughness employed in the simulations was n = 0.002m, for the Furnas and Batalha plants and n=0.001m for Luiz Carlos Barreto de Carvalho HPP, defined based on the perceptions of height of the irregularities seen in the field in the spillways examined.

In brief, the results of the simulations performed using the *SpillwayPro* software were then compared to the estimates of the critical indices c, Equation 4, and the limits of velocity and cavitation indices defined in the literature for the case studies of the Furnas, Luiz Carlos Barreto de Carvalho and Batalha spillways.

RESULTS AND DISCUSSIONS

The maximum mean velocities and the cavitation indices of flow were obtained considering the particularities of the geometry of profiles of the hydraulic structures being studied and the discharge ranges corresponding to each plant shown in Table 2. The points of interest were defined so as to coincide with the presence of irregularities on the concrete surfaces observed in the field. Figures 3, 4 and 5 present the behavior of the hydraulic parameters obtained using *SpillwayPro* software for the smooth chute spillways at Furnas, Luiz Carlos Barreto de Carvalho and Batalha, respectively. The results extracted were then compared to the limits defined by the literature aiming to identify possible justifications for the formation of zones with potential damage to the concrete surfaces.

When the cavitation indices and maximum mean velocities estimated for different ranges of discharges were analyzed it was possible to define an overview of the hydraulic conditions to be expected for the flow in the hydraulic structures involved. The discharges considered in this study were defined in such a way as to contemplate, besides the maximum flow rates (Qmax.), discharges higher and lower than this one, thus enabling the verification of the evolution of the parameters that indicate the occurrence of the cavitation phenomenon along the structure.

Figure 3a shows, except for point P1 and P7, that the cavitation indices present similar behavior among themselves, when the different control points are compared for a same discharge. As the flow velocity increased, significant reductions were observed in the cavitation index values. For flows greater than Q=3000 m^3/s, beginning at point P4, the indices obtained were lower than the critical boundary established by Falvey (1990), of σ=0.30, for the non-occurrence of cavitation on well-finished concrete surfaces. When the critical cavitation index obtained by relation $c = 4f$ (Arndt & Ippen, 1968; Falvey, 1990; Frizell et al., 2013; Kermani et al., 2013; Matos et al., 2022) is evaluated, the results found, independently of the cross-section verified were all higher than the limit of σ_c=0.20 defined based on the characteristics of Furnas HPP.

For the Furnas HPP spillway, where zones of spalling, exposure of aggregates and localized erosions were evidenced (Figure 1), the maximum values of mean velocities defined by Qmax, resulted in values that ranged from 21.6 m/s to 29.0 m/s over the length of the cross-sections where superficial anomalies were identified. Notably, except for the first and last point (P1 and P7), the mean velocities that, according to Ball (1959) would favor the onset of damage by cavitation, were identified for discharges above Q=2500.0 m^3/s (Figure 3b), or 31.0 m^3/s.m, below the maximum flow rate, and that defined as a boundary when the cavitation indices presented in Figure 3a were evaluated.

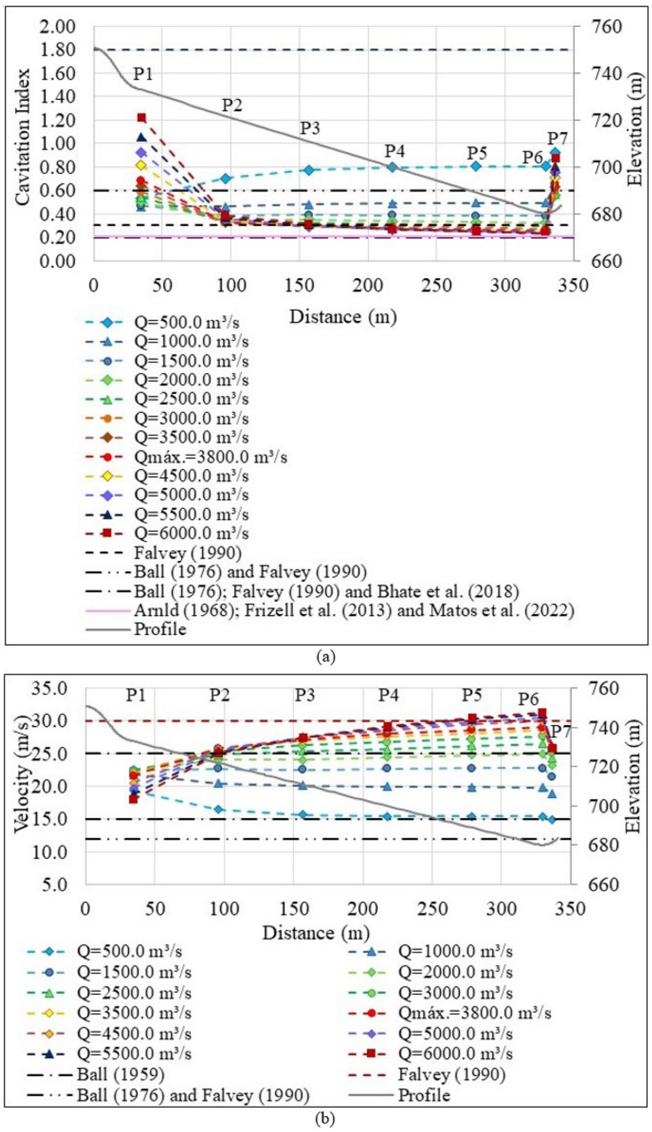

Figure 3. Hydraulic parameters of maximum mean velocity (a), and; cavitation index (b), estimated for different discharges for Furnas HPP.

When the results of the cavitation indices and mean velocities for points P1 and P7 were evaluated, close to the beginning of the chute and at the beginning of the launching shell of the Furnas HPP spillway, behavioral discrepancies were found, compared to the results of the other points along the structure. These divergences can be justified by the presence of significant vertical curvatures of the overflow profile in relation to the flow current lines, where these, due to the effect of the inertial forces responsible for favoring accelerations that are tangential and perpendicular to the current lines of the concave and convex surfaces, may then generate local interferences in the flow dynamics. Although the *SpillwayPro* identifies a significant alteration in the geometry in these sections (P1 and P7), the software does not attribute the increased hydrostatic pressure expected mainly at point P7. Therefore, the cavitation indices and the mean velocities estimated do not correspond to the values expected in these positions (Figure 3).

The cavitation indices estimated for Luiz Carlos Barreto de Carvalho HPP (Figure 4a) express similar behavior to each other when compared to the different discharges simulated. None of the results obtained for this parameter were inferior to the minimum limits described by Falvey (1990) of 0.30 or Ball (1976), Falvey (1982, 1990) and Bhate et al. (2021) of 0.20. In brief, the highest indices recorded were defined by the discharges of 500 m^3/s and 1000 m^3/s, corresponding to the specific discharges of 7.2 and 14.4 $m^3/s.m$, respectively.

Figure 4b shows that, for the sections defined between points P2 to P5, the maximum flow rate (Qmax.=4132.0 m^3/s) resulted in maximum mean velocities higher than the maximum limit defined by Ball (1959) of 25.0 m/s. Even though the estimate of these velocities was lower than that established by Falvey (1990) and Bhate et al. (2021), that is, $V \geq 30.0$ m/s, as a boundary value, the fact that they coincide with the discontinuity zones of the concrete surface is a reason to be alert to monitoring these areas, since the effects produced by cavitation on the surfaces are cumulative over time.

The geometrical similarity between the Furnas (Figure 3a and 3b) and Luiz Carlos Barreto de Carvalho (Figure 4a and 4b) plants produced similar behaviors as a response of the hydraulic parameters.

Another relevant aspect is that for both spillways, the interval and order of magnitude of the simulated discharges were similar between the overflow structures, so that the cavitation indices and estimated mean velocities express the same tendency to evolution of the cavitation indexes and the velocities.

The highest cavitation indices for the Batalha plant (Figure 5a) were obtained compared to the results analyzed for the other HPPs, consequently from the lowest mean velocity ranges (Figure 5b) estimated. For the discharges higher than 200 m^3/s, the cavitation indices do not surpass the minimum limits of 0.30 by Falvey (1990) and Bhate et al. (2021).

Figure 5b shows that the mean maximum velocities obtained for Qmax.=302.0 m^3/s ranged from 15.6 to 17.7 m/s, between the first and last section of interest, presenting values close to the minimum limits determined by Ball (1976) and Falvey (1990) and Ball (1959), of 12.0 and 15.0 m/s, respectively. Only for discharge above 250 m^3/s were the estimated average velocities higher than 12.0 m/s and lower than 20.0 m/s.

Again, it can be seen that in the sections defined by points P6 and P7 for Batalha HPP, the presence of significant alterations in the slope of the structure geometry leads to identifying the segments in which flow behavior changes occur.

Just as at the other plants, Batalha presented sudden changes of results at the points where zones with a greater intensity of potential damage on the concrete surfaces were detected. Nevertheless, the cavitation indices and the estimated maximum mean velocities do not allow actually stating that cavitation occurred at Luiz Carlos Barreto de Carvalho and Batalha, since they did not reach the critical values defined by the literature.

Considering the results presented in Figures 3, 4 and 5 the lowest values of cavitation indices were selected for each of the points of interest at the three smooth chute spillways (Furnas, LCBC and Batalha), as presented in Table 3 and inFigure 6 together with the respective flow characteristics.

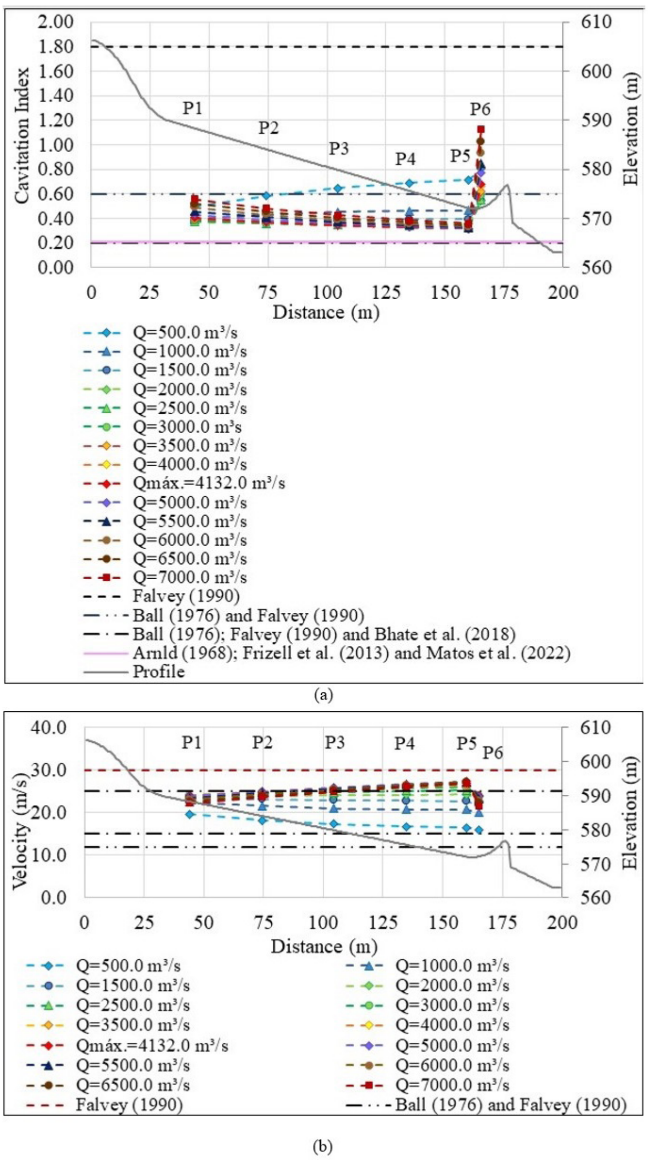

Figure 4. Hydraulic parameteres of maximum mean velocity (a), e; cavitation index (b), estimated for different discharges for Luiz Carlos Barreto de Carvalho HPP.

Table 3 shows that, differently from what was expected analytically by Equation 3, the lower cavitation indices (σ) mostly do not coincide with the higher discharges found. For the Furnas and Luiz Carlos Barreto de Carvalho plants, only points P3 and P5, respectively, presented the lowest cavitation indices connected to the maximum flow rates of 3800.0 and 4132.0 m^3/s. In brief, it was observed that the addition to the height of the water flow (h_o) became one of the dominant parameters for the reduction of the values of σ obtained, since the estimated mean velocities were close to the maximum velocities presented in the literature. Differently from what was advocated in the literature (Ball, 1959, 1976; Falvey, 1990; Bhate et al., 2021), where the velocity boundaries are considered one of the main project criteria to estimate the occurrence of the cavitation phenomenon, the height of the water cover (and consequently, the mean pressure) in studying the smooth chute spillways of Furnas, LCBC and Batalha, achieved greater relevance and, therefore, greater variation, than the estimated mean velocities.

As to the critical indices (σ_c) estimated according to Equation 4, values can be seen that are very close to each other and to the minimum boundary attributed by Ball (1976), Falvey (1990) and Bhate et al. (2021) to well finished surfaces ($\sigma_c = 0.20$). The critical indices ranged from 0.20 to 0.23 for the structures looked at, and the highest $\sigma_c \cong 0.23$ identified was the Furnas plant, where greater roughnesses were adopted in the simulations, compatible with those identified in the field, especially located in the zones with greater surface irregularities.

Compared to the surface irregularities found along the chutes of the three spillways (Furnas, LCBC and Batalha), the estimates of the lower cavitation indices and their respective velocities were found mainly for the Furnas plant, coinciding with the more marked localized erosion zones, spallings and exposure of aggregates. On the other hand, for Batalha HPP no velocities higher than 20.1 m/s were estimated and, consequently σ lower than 0.42, coinciding with the irregularities identified as lower intensity, especially when compared to the other plants inspected (Figure 6).

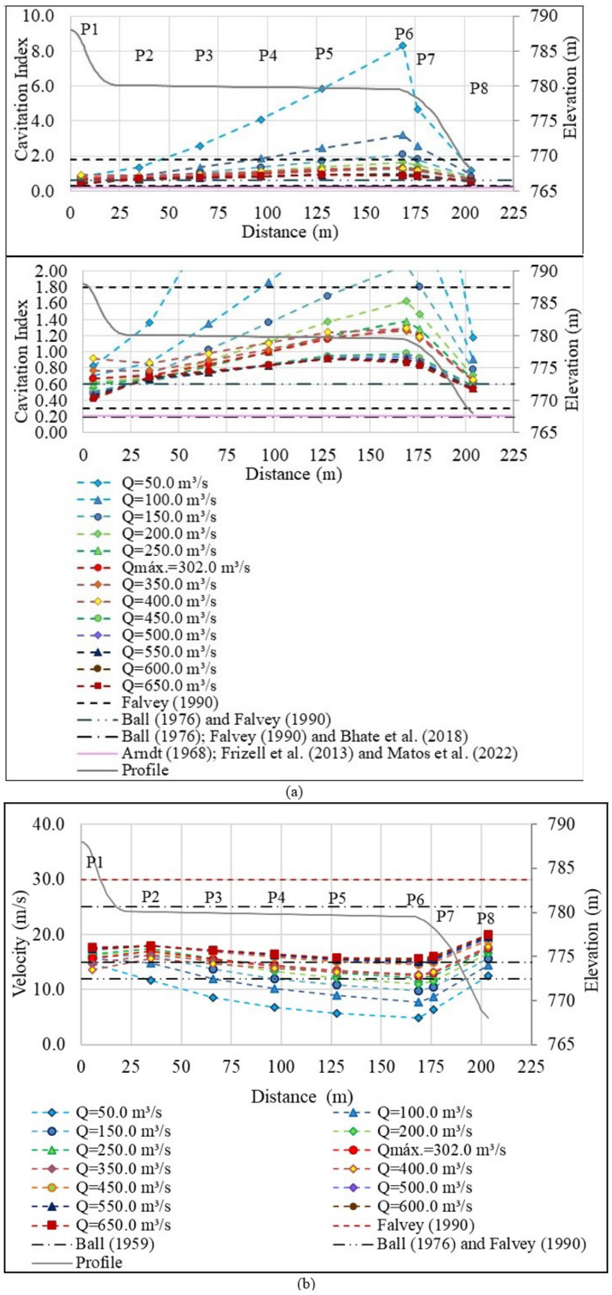

Figure 5. Hydraulic parameters of maximum mean velocity (a), and; cavitation index (b) estimated for different discharges of Batalha HPP.

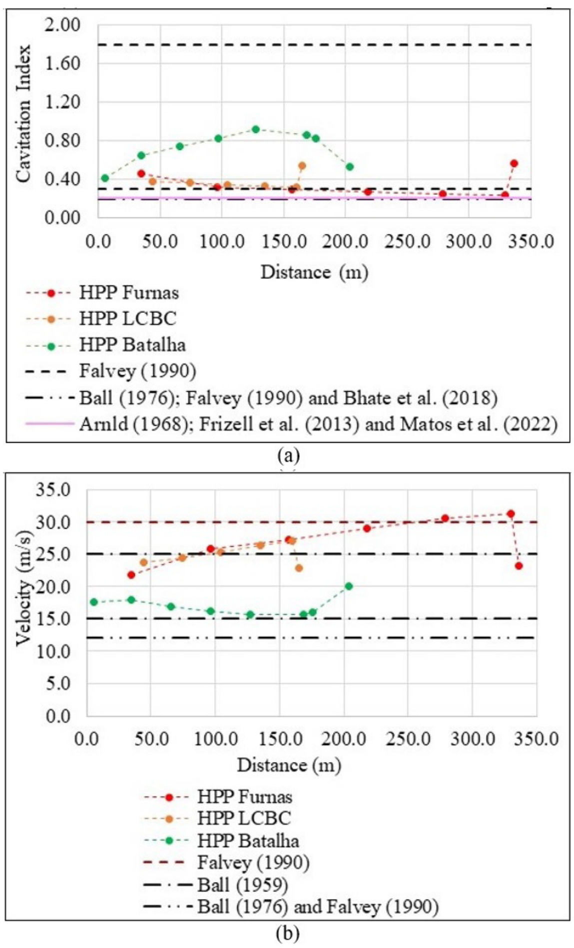

Figure 6. Analysis of the behavior of the lowest cavitation indices (a) and their corresponding mean velocities (b) for the Furnas, Luiz Carlos Barreto de Carvalho and Batalha HPP.

Table 3. Hydraulic parameters defined based on the lowest cavitation indices (σ) presented by the SpillwayPro software for the Furnas, Luiz Carlos Barreto de Carvalho (LCBC) and Batalha plants.

HPP	Point	σ	Q (m/s)	q (m³/s/m)	Vel. (m/s)	ho (m)	Max Vel. (m/s)	σc
Furnas	P1	0.46	1000.0	12.4	21.7	0.57	22.5	0.22
	P2	0.32	3500.0	43.4	25.8	1.68	25.8	0.20
	P3	0.29	3800.0*	47.2	27.1	1.74	27.4	0.20
	P4	0.26	5000.0	62.1	28.9	2.15	29.1	0.20
	P5	0.24	6000.0	74.5	30.4	2.44	30.4	0.20
	P6	0.23	6000.0	74.5	31.3	2.38	31.3	0.20
	P7	0.56	2000.0	24.8	23.1	1.07	26.0	0.21
LCBC	P1	0.37	2000.0	28.9	23.7	1.22	24.0	0.21
	P2	0.35	2500.0	36.2	24.4	1.48	24.9	0.21
	P3	0.34	3000.0	43.4	25.2	1.72	25.9	0.20
	P4	0.32	4000.0	57.9	26.4	2.19	26.7	0.20
	P5	0.31	4132.0*	59.8	26.9	2.22	27.3	0.20
	P6	0.54	2000.0	28.9	22.9	1.26	24.0	0.21
Batalha	P1	0.41	650.0	37.3	17.6	2.12	17.6	0.20
	P2	0.65	450.0	25.8	17.9	1.44	18.0	0.21
	P3	0.74	450.0	25.8	16.9	1.53	17.2	0.20
	P4	0.82	550.0	31.6	16.2	1.94	16.4	0.20
	P5	0.91	600.0	34.4	15.6	2.20	15.8	0.20
	P6	0.86	650.0	37.3	15.6	2.39	15.6	0.20
	P7	0.82	650.0	37.3	16.0	2.34	16.0	0.20
	P8	0.53	650.0	37.3	20.0	1.86	20.0	0.20

*maximum flow rates extracted from the historical series of discharges recorded at each HPP.

The lowest cavitation indices presented for Luiz Carlos Barreto de Carvalho HPP were similar to the results obtained for the Furnas HPP, but when compared to the irregular ones present in both structures, it can be seen that the potential damage zones of LCBC are less intense than those presented on the surface of the Furnas spillway.

CONCLUSIONS

Based on the geometrical characteristics of the spillway profiles and the maximum flow rates (Qmax.), it was possible to identify the behavior of the hydraulic parameters of mean velocity and cavitation index for the spillways of the Furnas, Luiz Carlos Barreto de Carvalho and Batalha hydroelectric power plants by using the *SpillwayPro* software.

The mean velocity results obtained for the three spillways analyzed showed that the water cover heights were more relevant and therefore presented greater variations than the mean velocities proper, especially for the Luiz Carlos Barreto and Batalha plants. Likewise, the lower cavitation indices estimated did not correspond to the highest mean velocities estimated, but rather to the greater increases in depth of flow (h_o). Both considerations were attributed partly to the existence of changes of concavity in the hydraulic surfaces.

The higher mean velocities estimated and closest to the maximum boundaries defined by Ball (1959, 1976) and Falvey (1990), were recorded for the Furnas spillway, coinciding with the plant where the largest areas with surface irregularities were seen. When the cavitation indices extracted for all control sections along each structure were compared to the boundaries defined according to Ball (1976), Falvey (1990) and Bhate et al. (2021), no propensities to the occurrence of cavitation phenomena at their spillways were evidenced.

Analyzing the lower cavitation indices and their respective mean velocities (Table 3), it could be seen that, on the contrary of what was analytically expected, the lowest σ mostly do not coincide with the highest maximum flow rates (Qmáx.). This information is an important indicative element of the need for studies that aim to investigate a broad range of discharges to which the structure may be submitted, based on the historical series of discharges at each enterprise, since the hydraulic parameters characteristic of the cavitation phenomenon may not be attached to the maximum flow rates. Obviously, since it is a phenomenon with cumulative effects, the concrete surfaces of the hydraulic structures must be regularly checked by field inspections so as to identify the local conditions of possible pathological manifestation that may arise during the operation of these structures.

It should be emphasized that the irregularities in the concrete of the surfaces recorded along the spillways of the plants inspected (exposure of aggregates, localized erosions and spallings) do not compromise any aspect of the functionality and operation of the safety devices of these dams, and they are only surface alterations common to concrete when exposed to the bad weather events in the environment.

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