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Methodology to evaluate cascade dams breaks for analysis and safety design

Metodologia para avaliação de rupturas hipotéticas de barragens em cascata para análise e segurança de projeto

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ABSTRACT

Among the main issues that may arise when evaluating studies of cascade dam ruptures, perhaps the most important, is to determine if the downstream dam can start into a cascade rupture, considering the hypothesis of the preliminary rupture of the upstream dam. This paper proposes a methodology to determine if a pair or a group of dams can fail in a cascade, suggesting a safe distance between them to avoid this effect. Additionally, this paper proposes a reunion with other researchers' methodologies in a step-by-step sequence, identifying when a cascade dam break is likely and should be included in the hypothetical dam break studies.

Keywords: Cascade dam break methodology; Breach equation; Breach formation time; Numerical model.

RESUMO

Dentre as principais questões que podem surgir quando da avaliação de estudos de ruptura de barragens em cascata, uma das mais importantes é determinar se uma barragem a jusante poderá entrar em ruptura por efeito de cascata, considerada a hipótese da ruptura preliminar da barragem a montante. Este artigo propõe uma metodologia para avaliar esta necessidade em um par ou conjunto de barragens em cascata. Além disso, este artigo propõe agrupar metodologias de outros pesquisadores em uma sequência para resultar em uma avaliação mais realista nos estudos de ruptura hipotética, como também para propor uma distância segura de novos projetos em relação a uma barragem existente de forma a minimizar a possibilidade de uma ruptura em cascata.

Palavras-chave: Ruptura de barragens em cascata; Equação de brecha; Tempo de formação de brecha: Modelos reduzidos.

INTRODUCTION

According to the Colorado Dam Safety Branch (Colorado, 2010), the definition of overtopping breaching failure is that this mechanism typically begins by cutting and removing soil from the downstream slope toe and advancing to the dam's crest.

After cutting down the crest and with sufficient erosion, a first initial section takes form in the dam' massif. The dam may fail in this weak section, or the erosion descent may continue through the mass until the breach reaches the base of the embankment. When the breach reaches the natural soil, which has lower erodibility, and of great longitudinal extension, the process is reduced or even interrupted, depending on the erodibility of the present soil and the observed velocities.

Once the breach reaches the reservoir, erosion occurs on the downstream slope and the lateral sides of breaches, with high-speed development, until the breach reaches its final size and shape. The continuity of the subsequent flows will attack the slope of the breach and promote its widening laterally until the dam's shoulders (natural terrain) have been reached or the volume of the dam has been exhausted. According to MacDonald & Langridge-Monopolis (1984), the intermediate berms also contribute to this process, which can cause changes in the flow regime along the downstream slope. However, slope ruptures also occur along this process due to geotechnical destabilization due to the increase of the mean face angle and soil saturation (Saliba, 2009).

The description above of dam break applies to a single dam, where the flow passing through the top of the dam and in the breach had a low energy grade line, being this one related to the single reservoir volume, and the flow velocities are low, compared to the cascade dams' volumes and energy grade lines. Nevertheless, in a cascade dam break, the flow passing through the breach is preponderantly turbulent. The flow velocities are high once a dam break has already occurred upstream, as Campos (2020) demonstrated.

In the early days of breach formation equations, studies were based on the simple equation for just one dam, as developed by Wahl (1998, 2004) or by Froehlich (2008, 2016), and those same works still present some reviews, due to the complexity of resuming the dam break in one equation over time. For the cascade dam break equation phenomenon description, it surely should be an even more complex and defying task.

The cascade failure mode assumes that one or more upstream dams have a break, which would lead to the arrival of a flood wave to the reservoir of the downstream dam. The formation conditions of this breach account for a residual energy portion of the upstream dam failure. So, by hypothesis, this flood wave is not wholly weakened in this downstream reservoir, thus leading to a failure process like the one with the fastest formation time.

The focus of this research is precisely this type of failure mode, considering the overlaps of the hydrographs of ruptures in a cascade of dams.

The main difference between a single overtopping to a cascade overtopping is the initial conditions of breach formation. While in the single dam break, the flow conditions above the crest of the dam refer mainly to a fluvial regime, in the case of the cascade overtopping, these conditions change by the arrival of the upstream dam rupture wave, increasing flow energy quickly, leading to earlier potential supercritical and more erosive conditions. The higher velocities flow associated more elevated the potential to destroy the downstream dam.

A Brazilian case of a cascade dam break (Saliba, 2009) occurred on January 19, 1977, when the Euclides da Cunha dam overtopped near the right shoulder of the dam, about 30 cm above the dam crest. This overtopping occurred due to a 260.0 mm rainfall in the preceding 24 h, and the spillway gates could not be opened. The Euclides da Cunha dam is in the Pardo River, about 6.0 km downstream of São José do Rio Pardo, SP. According to Carvalho (2007), the overtopping began at 20:30 on January 19, 1977, but the actual rupture occurred only at 03:30 on January 20, 1977, with a maximum depth of about 1.20 m (Powledge et al., 1989). Figure 1 shows an aerial scene after the rupture of the Euclides da Cunha dam.

The flood resulting from the rupture took about half an hour to reach the Armando Sales de Oliveira dam, located 6.0 km downstream, whose rupture occurred at 04:00 on January 20, 1977, also with a maximum depth of about 1.20 m (Powledge et al., 1989). Figure 2 shows the breach opened by the overtopping, which had very steep lateral slopes.

Figure 1. Rupture by overtopping of the Euclides da Cunha dam (Saliba, 2009).

Figure 2. Rupture of dam Armando Sales de Oliveira after the cascade overtopping on 01/21/1977 (Saliba, 2009).

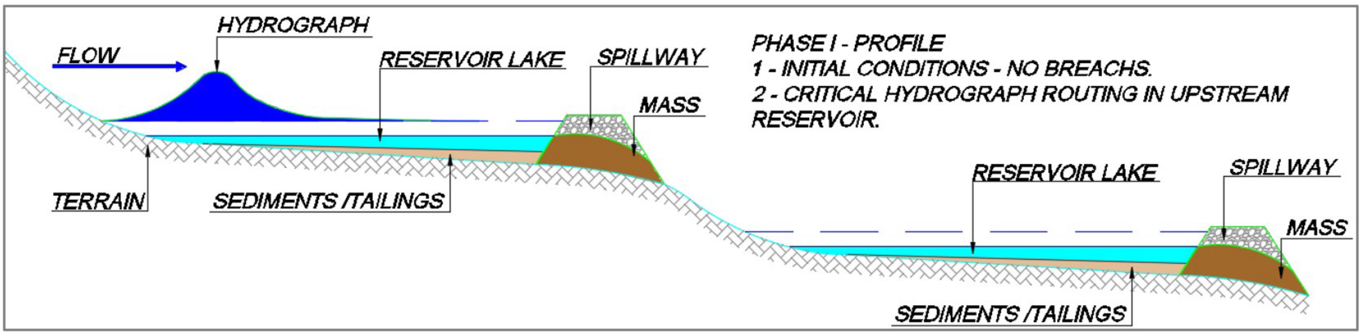

Figure 3. Preview of cascade dam break process – Phase I.

In this last example, the distance between the dams did not attenuate enough the hydrograph peaks to avoid the downstream dam rupture, indeed, conserving the energy. The data of rain contribution between the dams are no longer available to verify the exact conditions of failure.

A paper presented by Pereira et al. (2003) discusses the results of studies of the development and implementation of mathematical model support decisions for simulation and analysis of flood waves propagation caused by the rupture of dams in cascade in the hydroelectric generation cascade of the Paranapanema River.

According to Pereira et al. (2003), that model considered the simulation of a complete one-dimensional hydrodynamic flow model in cascaded rivers and reservoirs, subject or not to the control of a hydraulic structure. The results from Pereira et al. (2003) highlighted three possible cascade dam break scenarios. In the worst case, the rupture of the Xavantes dam would lead to the rupture of another six dams downstream caused by a cascade dam break wave.

However, Pereira et al. (2003) do not mention the equation used to describe the breach evolution due to cascade dam break, its formation time, or even whether the conditions of breach formed by cascade dam break are used to represent the phenomenon adequately. In the Pereira et al. (2003) paper the reservoir routing was handled with a mass balance equation, the transport equation is based on the unidimensional fixed bottom Saint-Venant equation, which combines the principles of mass conservation and momentum, and to model the flow through the breach the broad crest equation is adapted to the critical depth.

Alhasan et al. (2015) developed an equation to preview the breach development, although that is justified as an approximation from a three-dimensional problem to a one-dimensional and not focused on the cascade question. An evaluation of cascade dam break was developed by Říha et al. (2020), but the equations used in that research were just the broad crest weir, and the results of the cascade dam break effect were superficially analyzed. In a very similar way, Cai et al. (2019) developed a study of the cascade dam break, but with the same approach as the broad-crested weir.

Visser (1995) obtain some geometrical evaluation of breach developed during dam break, studied some material's inertial forces according to precursor researchers of sediment transport, and verified sediments transportation according to hydraulic conditions in an approach to justifying the dam's material as the key to erosion during the rupture.

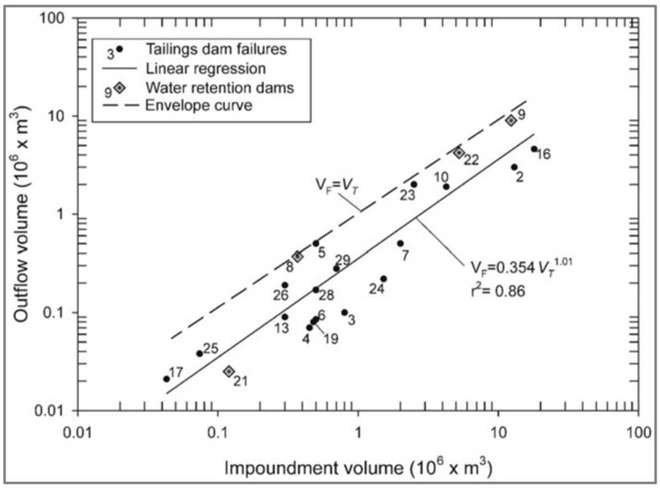

Figure 4. Impoundment volume and outflow volume [adapted from Rico et al. (2008)].

The sediment transport evaluation is quite interesting, although this research used synthetic material to represent the dam's materials, as quoted in Campos (2020) and Campos et al. (2020).

METHODOLOGY

The schematic drawing of Figure 3 shows the breach formation process that occurs in a dam located downstream of the upstream dam, where the first break occurs, to understand better the phenomenon of a cascade dam break and the portions of mass and energy involved.

For tailings dams, there seems to exist a relation between tailings storage and tailings released during the dam break, as shown in Figure 4.

With the inflow of the hydrograph (Figure 3 – Phase I) from the drainage area of the first upstream dam, a breach will occur (Cross-section AA, Figure 5 – Phase II) in this first dam. There will be the propagation of a hydrograph with greater volume and energy to the reservoir of the second dam (downstream). This second hydrograph has a much higher solids content, originating from deposited materials of the upstream reservoir and the first breach of the upstream dam, resulting in a hydrograph with higher volume and higher peak flow (Figure 5 – Phase II).

Equation 1 determines the volume from this very first dam break:

$$V_T = V_{HU} + V_{RL} + V_{ST} + V_{BR} \tag{1}$$

In Equation 1, V_T is the total volume (m³); V_{HU} is the hydrograph volume in upstream lake reservoir routing (m³), V_{RL} is the reservoir volume between the dam spillway inlet elevation and reservoir bottom (m³); V_{ST} is the sediment/tailings volume deposited in the reservoir mobilized in the rupture (m³), and V_{BR} is the soil and materials removed from the breach ($_U$ – Upstream and $_D$ - Downstream) during the physical process of breach formation (m³). Equation 1 also applies to tailings dams, changing sediment volume to tailings and sediment volumes. Each variable described above came from hydrological calculus and geometrical determination.

However, the outflow volume of sediments/tailings deposited in the reservoir is far away from being easily determined. On existing reservoirs, sediment or tailings strength parameters can be obtained from Cone Penetration Tests, even though these are not always easy to do considering reservoir access and safety issues.

When tailings or sediments strength parameters cannot be directly measured to determine their release with the dam break, or in the design phase, indirect methods can be used. Rico et al. (2008) suggested that tailings dam incidents release only a part of the tailings volume. So, one should evaluate the released volume as proposed by Rico et al. (2008):

$$V_F = V_T \tag{2}$$

$$V_F = 0.354\ V_T^{1.01} \tag{3}$$

In Equations 2 and 3, V_F is the total outflow volume from the reservoir during the dam break (m³), and V_T is the total volume in the reservoir (m³). However, if the reservoir is occupied mainly with water, V_F equals V_T (Equation 2). In the case sediments/tailings are significant in the dam reservoir, one should apply Equation 3, and the volume of sediments or tailings should be determined from bathymetry data compared to the original topography.

Recently, the Canadian Dam Association (2021) suggested that when direct estimation is not possible, the released material could be estimated as the volume between a 2º upstream slope plane from the breach bottom and sediment/tailings surface.

The arrival of the second hydrograph to the lake of the downstream reservoir (Figure 6 – Phase III) leads to the formation of a breach with significant characteristics of being larger, broader, and deeper (with a premise of even reaching beyond the natural terrain elevation), and with significant shorter formation time (cross-section BB).

During the routing process of the second hydrograph in the second reservoir (downstream breach, Figure 6 – Phase III), the hydrograph can be wholly smoothed or not, depending on the distance between the dam's structures, the reservoir volumes available for routing and outflow capacity conditions of the spillways.

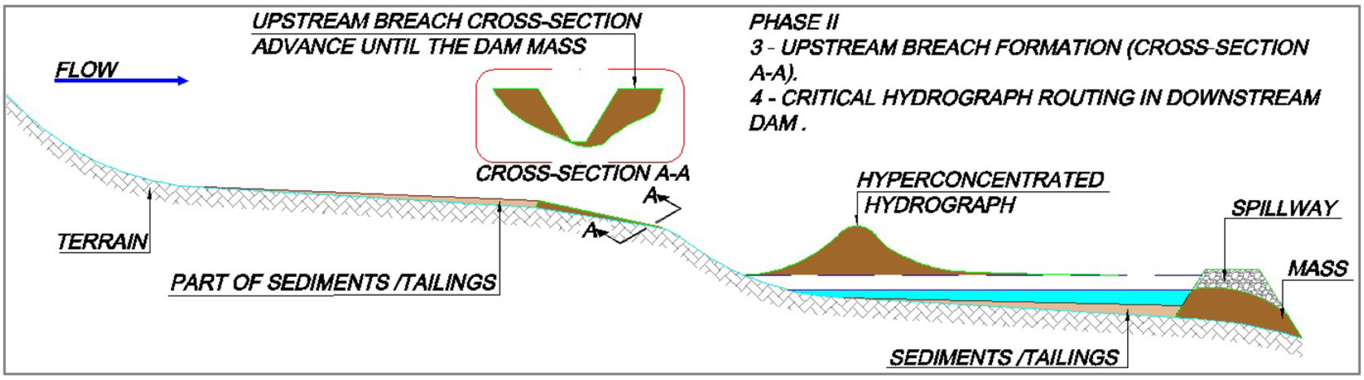

Figure 5. Preview of cascade dam break process – Phase II.

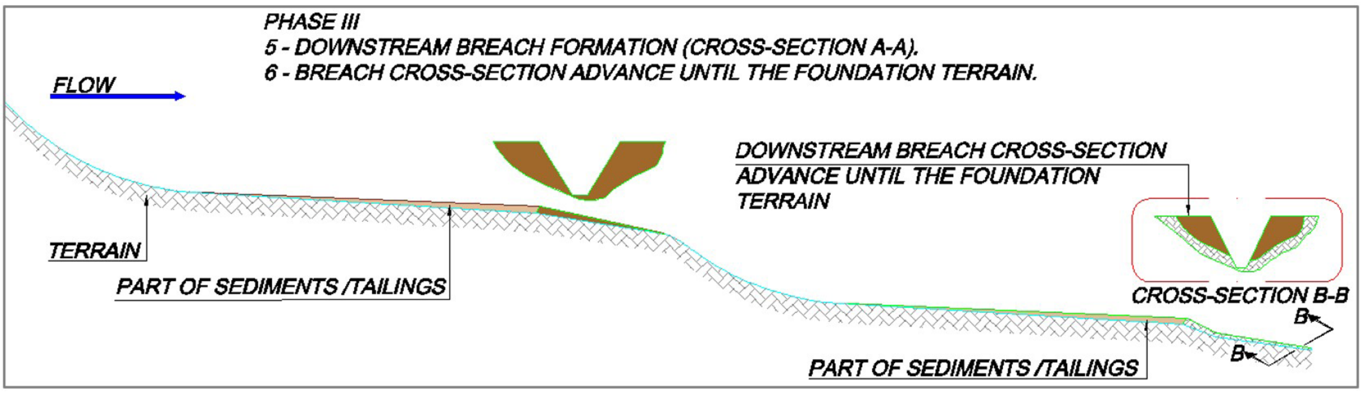

Figure 6. Preview of cascade dam break process – Phase III.

This research assumed that the distance between the dams is very short as a first premise, so that the passage of the second hydrograph, resulting from the sum of upstream volumes as proposed in Equation 1, will cause the rupture of the second dam, forming a more significant breach than that would occur in a single dam break. These assumptions are valid since the volumes involved are larger than that of a single dam break. Also, the proximity between the structures allows conserving a higher portion of flow energy, contributing to a greater breach in the second dam.

As cited by Luo et al. (2019), a wave from a rupture of the upstream dam will destroy the downstream dam to an extent proportional to the residual flow energy. Thus, the downstream dam will collapse if it cannot withstand the impact of the flood from the upstream dam break, resulting in a severe rupture.

The primary factors affecting a residual flow energy analysis in breach formation are (Figure 7):

- Dams' heights, assumed equal to maximum storage height (*Hwu* and *Hwd*, in m, for the upstream and downstream dams);
- The level difference between upstream and downstream dams (*Dud*, in m);
- Water, tailings, and sediment storage in both dams (*Vwu* and *Vwd*, in m^3, in the upstream and downstream dams' reservoirs).

When the first dam fails by overtopping, as shown in Figure 3, Figure 5, and Figure 6, an amount of potential energy stored in the upstream dam will dissipate as the following losses:

- An energy loss on the erosive process of the upstream dam breach (*hee*, in m);
- An energy loss on the erosive process of the downstream dam breach (*heed*, in m);
- An energy loss through the interaction between solid and liquid particles, and possible changes of regimes, in the course of the downstream valley, between the dams (*het*, in m);
- An energy loss through flow friction along the path to the downstream dam (*he'*, in m).

According to Powledge et al. (1989), when evaluating the hypothesis of the breach formation, one can describe this phenomenon in three regimes of hydraulic flow and erosion zones for the formation of breach by overtopping. In the dam crest, where subcritical to critical flow conditions occur, the energy slope, flow speed, and shear stresses are relatively low. Thus, erosion will occur at meagre rates. A transition to the supercritical flow occurs in the downstream portion of the crest. The energy slope and shear stresses are highest in this region, and erosion usually starts at the downstream slope, a few meters below the crest.

Powledge et al. (1989) assumed reduced flow velocity in the reservoir. However, specifically in the case of a cascade rupture, this initial condition is not valid since the arrival of the flood from the upstream dam break would lead to a considerable increase in flow energy, increasing velocities, and shear stresses.

Considering the Breach Formation Parameter (BFF - MacDonald & Langridge-Monopolis, 1984 – Equation 4) as an indicator of the accumulated energy in the upstream dam, one can evaluate the residual energy that would reach a downstream dam:

$$BFF = Vw.Hw \tag{4}$$

Where Vw is the reservoir volume (m^3) and Hw is the water depth in the reservoir (m). Vw can be assumed equal to the V_T, as proposed above, or V_F, according to Rico et al. (2008) or to Canadian Dam Association (2021), in which volumes parameters can refer to the materials stored, water, or tailings water mixture.

At first glance, BFF seems an unusual energy indicator as it does not have a unified system consistent (m^4) to flow energy (usually evaluated in m), which in open channel hydraulics uses a unit related to specific flow energy. Specific flow energy is the ratio of flow energy and its weight (Chow, 1959), so the conversion occurs by multiplying BFF by the fluid specific weight (γ, given in N/m^3), as from Vianna (1997):

$$E = \gamma H_w V \tag{5}$$

$$BFF = Vw.Hw.\gamma \tag{6}$$

In Equation 5 H_w is the water head relative to a *datum* (m), V is the storage (m^3), and E is the energy head (J). In Equation 6 H_w was approximated by H and V_w by V, γ is the specific weight (N/m^3), and then BFF has energy units.

Considering a point of analysis at the lowest point of the downstream dam, adopting a *datum* settled in the dam toe since all potential energy stored in the dam should pass by this point in case of rupture and breach development, or the energy that will act to create the breach in this dam, provided by a precedent upstream rupture, is given by Equation 7:

$$\Delta ER_u = \gamma_u (H_{wu} - h_{ee} - h_{eed} - h_{et} - h_{e'} + D_{ud}) V_u \tag{7}$$

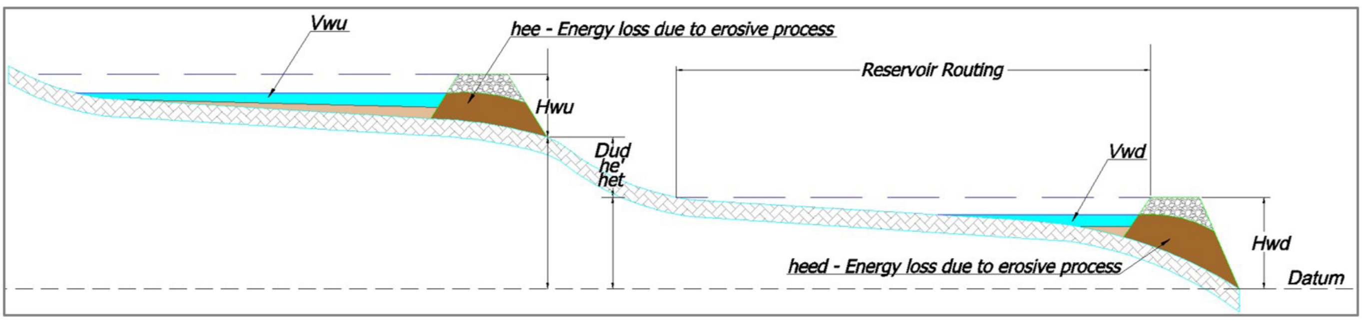

Figure 7. Energy factors and energy losses description.

In Equation 8, the term ΔER_u is the residual energy from upstream dam break (m), after discounting the energy losses and adding the level difference between dams, as defined previously, in Joules.

Thus, the amount of energy in the downstream dam that can lead to a dam break is approximated by Equation 8:

$$ERB_d = \Delta ER_u + E_d \tag{8}$$

Expanding this equation terms:

$$ERB_d = \gamma_u (H_{wu} - h_{ee} - h_{eed} - h_{et} - h_{e'} + D_{ud}) V_u + \gamma_d . H_{wd} . V_d \tag{9}$$

In Equation 8, E_d is the energy head (Joules) stored just in the downstream dam. The residual energy (ER_u) is the amount of potential energy converted into kinetic energy coming from the upstream dam, accentuating the breach formation in the downstream dam, as defined in Figure 7. Equations 8 to 10 are approximations of the conservation of mass and momentum, whether considering a bidimensional transitory approach, or energy conservation, whether considering a unidimensional permanent approach, as Bernoulli equation, from an upstream dam break.

The further downstream a dam, the more significant are energy losses, smoothing the upstream flood wave and preventing a cascade dam break.

With this concept, whether there exists enough distance between the dams, and/or there exists enough volume in the downstream reservoir to reduce the dam break upstream hydrograph, this methodology can be used to evaluate the safety of a pair of dams located in a cascade arrangement. That can be stated as ΔER_u gets closer to zero.

Despite being a basic approximation of energy in the formulations presented here, the volumes released during the dam break have a big influence and significance on the results and those should be considered in a bidimensional transitory model of the Saint-Venant equations. This approach leads to a more complete assessment of a downstream dam overtopping.

The energy associated with the upstream dam break wave depends mainly on the parameters:

- Volume of the upstream dam (m^3);
- Volume for downstream dam routing (m^3);
- Height of the upstream dam (m);
- Slope between upstream and downstream dams (m);
- Distance between dams (m).

As these parameters vary for each pair of dams under analysis, the possibility of a cascade dam break must be individualized and analyzed.

If the specific weight of the fluid is invariable for a pair of dams, Equation 10 turns into:

$$BFFR_d = H_{wu} - h_{ee} - h_{eed} - h_{et} - h_{e'} + D_{ud} + H_{wd} \tag{10}$$

Equation 10 assumes water flow. However, when the reservoir contains a significant amount of sediment or tailings storage or if the dam's embankment contributes significantly with solid during breach formation, it is possible to estimate an average specific weight considering water, embankment, and sediment/tailings specific weights:

$$\gamma_T = \frac{\gamma_w V_{HU} + \gamma_w V_{RL} + \gamma_{SST} V_{ST} + \gamma_{SBRU} V_{BRU} + \gamma_{SBRD} V_{BRD}}{V_{HU} + V_{RL} + V_{ST} + V_{BRU} + V_{BRD}} \tag{11}$$

In Equation 11, γ_T is the average specific weight of this mixture (N/m^3), γ_w is the specific weight of water (N/m^3), γ_{SST} is the specific weight of sediment or tailings stored in the reservoir (N/m^3), and γ_{SBR} is the specific weight of materials removed from the breach on the dam. To account for this specific weight change, Equation 10 turns into:

$$BFFR_d = \frac{\gamma_T}{\gamma}\left(H_{wu} - h_{ee} - h_{et} - h_{eed} - h_{e'} + D_{ud} + H_{wd}\right) \tag{12}$$

The general specific weight (γ_T) is very useful when evaluating the impact of a dam break wave to account for solids concentration influence. In a cascade dam break, γ_T estimates for both dams can be used on a weighted average, and this parameter is useful for non-Newtonian simulations.

An application of a flowchart summarizes the steps to carry out this evaluation (Figure 8), using simulation software (e.g., HEC-HMS and HEC-RAS) that can perform dam break and knowledge of the dams' soils, to determine if the downstream dam will fail after an upstream dam break wave passes through or not.

For a pair of dams, one can simulate the dam break (first step of Figure 8), using hydrologic software (e.g., HEC-HMS) to determine the smaller return period event that triggers a rupture, assuming a failure mode (piping, overtopping). Volume and spillway discharge curves for each dam are needed. The second step of Figure 8 considers routing of the previously determined upstream dam break hydrograph in the downstream valley and downstream dam reservoir, which leads to two possible outcomes (step three):

- The downstream dam overtopping does not overtop with the first smaller return period hydrograph from an upstream dam break. Step one is repeated until an overtopping occurs, as indicated in step four of Figure 8. If PMP (or another normative return period) is reached, the cascade dam break hypothesis is discarded, or, at least, unlikely.
- Overtopping of the downstream dam occurs with the upstream dam break hydrograph inflow, and step four indicates to move to step five of Figure 8.

If step five is reached, the downstream dam is at risk of a cascade dam break. Once an overtopping was possible, the previous analysis permitted to determine the associated return period, wave height through the crest, duration and shear stress levels.

With the downstream dam break hydrograph, from previous hydrological analysis, it is then necessary to run it in a hydraulic model (e.g., HEC-RAS) to verify important parameters, mainly velocity and shear stress.

From the hydraulic model results (velocity and shear stress) at a cross-section located in the crest or closer, an analysis of soil resistance to flow must be carried out, considering geotechnical properties (e.g., high or low plasticity, presence of sand, silt and clay). The analysis of these parameters will support a decision on whether or not a cascade dam occurs.

Briaud et al. (2008) developed extensive research on soils erosions resistance rate. They classified and grouped many kinds of soil erodibility, delimitating two main groups that are prone to failure overtopping and prone to resist overtopping (Figure 9).

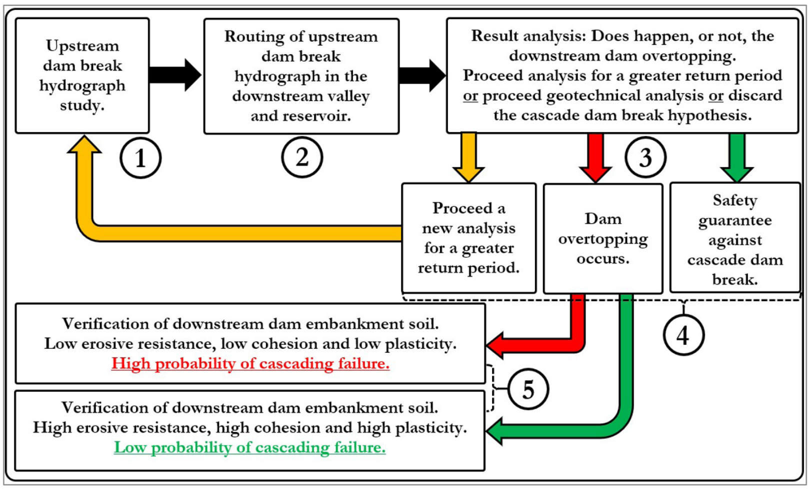

Figure 8. Flowchart for evaluating the occurrence of cascade rupture.

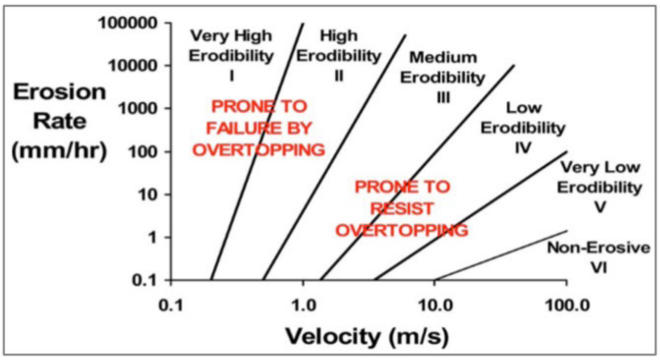

Figure 9. Guidelines for overtopping resistance [adapted from Briaud et al. (2008)].

Therefore, since the dam soil is very well characterized, defining the premise of a cascade dam break, or not, becomes a straightforward task.

Campos (2020) show in scale model tests that the Froehlich (2008) equations to determine dam breach parameters should be adapted in case of a cascade dam break, expanding breach average width by 40% and changing breach formation time by 70% (Equations 13 and 14):

$$\bar{B} = 1.40 \text{ x}0.27\; k_o\, V_W^{0.32} H^{0.04} \tag{13}$$

$$t_f = 0.70 \text{ x}63.2\sqrt{\frac{V_w}{gH^2}} \tag{14}$$

Where $\bar{B}$ is the average width of the breach (m), *ko* is a shape factor (1,3 on overtopping or 1,0 on piping failure modes), V_W is the reservoir storage at the time of failure (m³), H is the height of the dam (m), t_f is the breach formation time (h), and g is gravity (9,81 m/s²).

One possible application of the proposed methodology the evaluation of a future dam site considering an existing upstream dam, besides other factors such as valley morphology and geological conditions. Adequate distance between the dams can be determined to avoid a cascade dam break if the distance between them provides enough flood energy damping. Naturally, this damping will depend on local conditions such as shape and roughness of the downstream valley.

The cascade dam break methodology was originally developed for applications in a pair of dams, but the methodology can be extended to three or more dams, one pair at a time.

APPLICATION EXAMPLE

An application example developed to demonstrate the cascade dams break is presented in Figure 10 and Figure 11, and their respective data are listed in Table 1. There were developed two hydrologic simulations in HEC-HMS, first considering each dam break for each of the dams with parameters usually used for the structures (isolated structures - Table 1). Table 2 shows the parameter values needed to apply the herein proposed methodology for cascade dam break. Hydrological analyses determined that the critical storm duration is 180 min. Figure 12 illustrates the hydrological model (maps and elements) developed. Figure 13 illustrates the hydrological model drainage area and reservoirs lakes for the Upstream and Downstream dams' example. Green-shaded areas report to the Upstream dam, while orange shaded areas report to the Downstream dam. Those dams are located in Rio Piracicaba/MG.

Figure 14 shows hydrographs comparisons of single (usual) and cascade dam breaks of the Downstream dam. Focusing on the Downstream dam results, the dotted line refers to the usual dam break hydrograph, dashed line refers to the cascade dam break and the continuous line refers to the 1000-yr hydrograph, meaning for this flood the trigger was not activated (that flood did not pass over the crest). From Figure 14 it is clear the peak flow from a cascade dam break was 21% higher and 9 min earlier than single dam break values. These differences come from shorter breach formation time and wider breach width (comparing Tables 1 and 2), estimated using Froehlich (2008) and Campos (2020) breach equations.

Figure 15 depicts hydrographs generated according to the minimum formation time as proposed by Campos (2020) compared to Von Thun & Gillette (1990) and MacDonald & Langridge-Monopolis (1984) recommendations of 15 minutes minimum (lines symbology are the same as Figure 14).

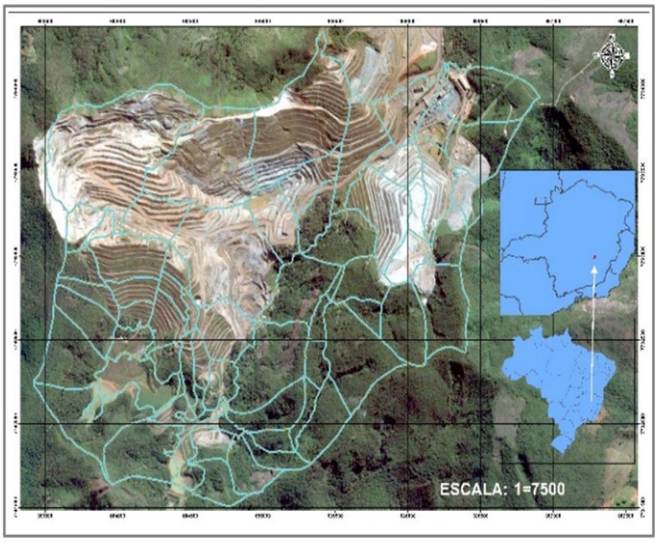

Figure 10. Example dams in panoramic view, in Rio Piracicaba/MG (source: Google Earth).

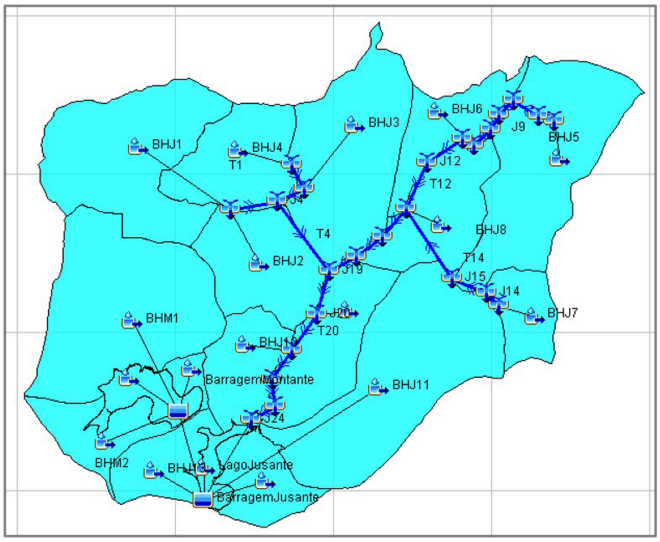

Figure 12. Upstream and downstream dams elements and map hydrology model.

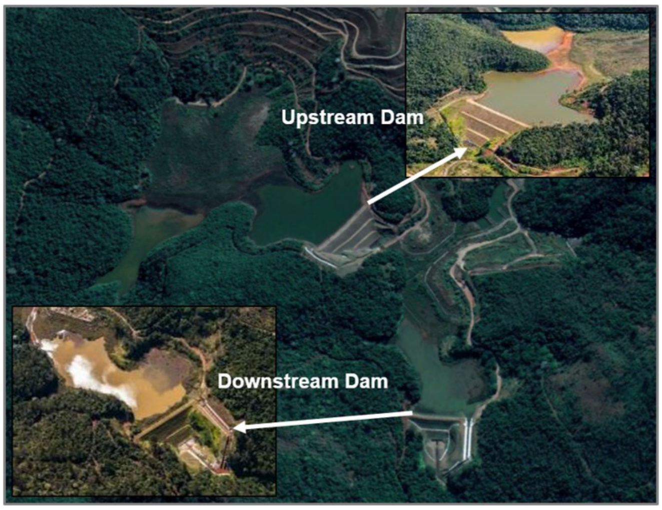

Figure 11. Example dams in panoramic view (source: Google Earth).

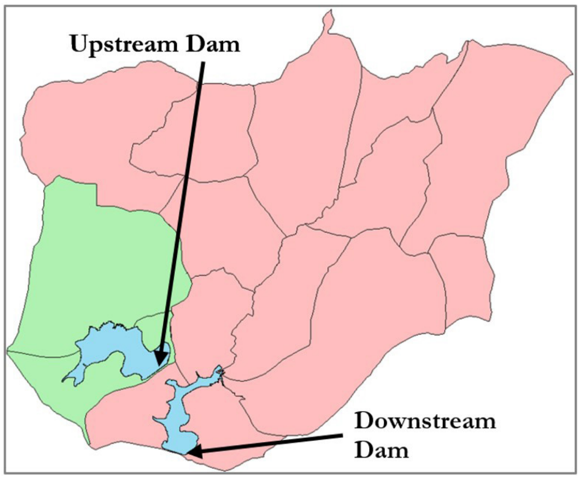

Figure 13. Upstream and downstream dams' drainage area and reservoirs lakes.

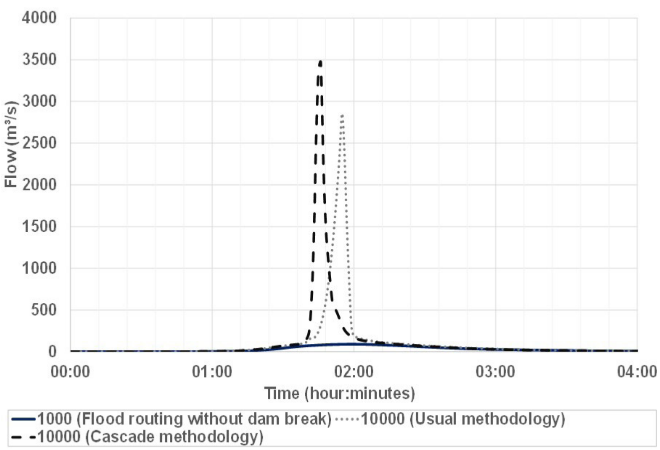

Figure 14. Hydrographs comparison of methodologies with minimum breach formation time according to Froehlich (2008) and cascade methodology.

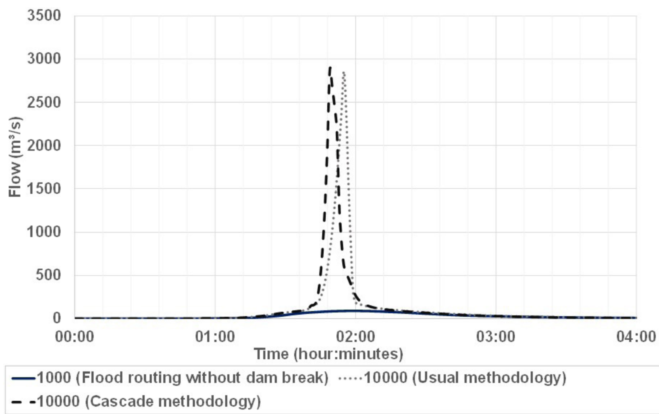

Figure 15. Hydrographs for comparing methodologies with minimum breach formation time according to Von Thun & Gillette (1990) and MacDonald & Langridge-Monopolis (1984) and cascade methodology.

Table 1. Study case characteristics on a single dam break.

Variable	Upstream dam	Downstream dam	Note
Crest elevation (m)	688.00	660.70	1
Invert elevation (m)	657.00	637.20	1
Dam height (m)	31.0	23.5	1
Dam width (m)	201.0	134.0	1
Dam length (m)	135.0	81.0	1
Reservoir volume (m^3)	800,200	400,000	1
Breach Formation Factor (1000 m^3.m)	24,806	9,400	Equation 4
Breach formation time (min.)	15.0	15.0	3
Breach formation time (min.)	9.7	9.1	2
Average breach width (m)	31.2	24.7	2
Breach height (m)	31.00	23.50	2
ko coefficient [3]	1.3	1.3	2
Breach lateral slope (V/H):	1.0	1.0	2

1: ANM: Classification of Brazilian Mining Dams - Base Date January/2019: SIGBM extraction for classification - updated on 01.23.2019.pdf. 2: Adopted according to Froehlich (2008). 3: Based on minimum breach time formation as proposed by Von Thun & Gillette (1990) and MacDonald & Langridge-Monopolis (1984).

Table 2. Study case characteristics cascade dam break parameters applied to downstream dam.

Variable	Downstream dam	Note
Breach formation time (min.)	6.3	2 (Equation 14)
Breach formation time (min.)	10.5	4 (Equation 14)
Average breach width (m)	34.6	Equation 13
Breach height (m)	23.50	1
ko coefficient	1.3	2
Breach lateral slope (V/H):	1.5	3

1: ANM: Classification of Brazilian Mining Dams - Base Date January/2019: SIGBM extraction for classification - updated on 01.23.2019.pdf. 2: According to Froehlich (2008). 3: Adopted according to cascade methodology. 4: Calculated on minimum breach formation time proposed by Von Thun & Gillette (1990) and MacDonald & Langridge-Monopolis (1984) applying cascade methodology equation.

The peak flow from a cascade dam break of the Downstream dam was 1% higher and 6 min earlier than single dam break values.

It should be noticed that the volumes in any of the dam break hydrographs are the same [usual dam break hydrograph according to Froehlich (2008), cascade dam break hydrograph and 15 minutes minimum hydrograph according to Von Thun & Gillette (1990) and MacDonald & Langridge-Monopolis (1984)], since it was assumed that the complete dam's height will breach, the complete volume of both dams will be released, but the amount of energy varied, since the flow rate over time varied.

Figures 14 and 15 were developed using SCS Curve Number and SCS Unit Hydrograph methods, to transform rain to flow, and Puls reservoir routing method with HEC-HMS dam break adjustment parameters, as well mentioned.

CONCLUSIONS

Flood arrival time and peak flow can change significantly according to the methodology adopted and if a dam fails alone or from an upstream rupture. Even for a single event, differences occur between different breach equations available in the literature, which raises if a cascade dam break evaluation is done.

Also, differences in dam-break analyses come from hydrological parameters (sub-basin area, lag-time, loss parameters, reservoir volume, and discharge curve), leading to an extensive possibility. These aspects reinforce the importance of proper engineering judgment in the composition of model scenarios and dam break simulations, which will feed an emergency preparedness plan. It is worthwhile to remind that dam-break modeling does not restrict to software simulation. It must encompass engineering analysis.

To turn the analysis of a cascade dam break more accurate and precise the methodology presented was developed, tested and it should reassure the of this methodology to adequately described this phenomenon.

The formulas presented in Equation 6 to 12 lined up the foundation of cascade dam break, presented here, in an energy approach, and this conduct to some gross errors, since this evaluation is just conceptual based. Those equations did not consider the momentum or other inertial forces and even was not developed as a derivative of time. The Equations 6 to 12 objective was just delineated the amount of energy that's really involved in a cascade dam break.

According to the results of the application example, peak flow from a cascade dam break evaluated at the Downstream dam was 21% larger and 9 minutes earlier than single dam break analysis values, which agree to the results of physical model's laboratory tests developed by Campos (2020) and Campos et al. (2020). The results of the application example refer to a specific pair of dams, highlighting that even if one could be classified as a small dam, it has significant height and volume, and a cascade dam break results can be significantly different from an isolated rupture.

The methodology developed can also be used to obtain the adequate distance between the dams, focusing on avoiding a cascade dam break, as stated, since ΔER_u gets closer to zero, or effectively the hydrograph coming from an upstream dam break can be completely damped in the downstream valley and downstream dam's reservoir passing through its spillway, without the downstream overtopping. This evaluation can be developed by tests of pre chosen locations using hydrologic software (e.g. HEC-HMS) to verify that, in case of an upstream dam break, the downstream dam will not be overtopped, in that way determining the safety distance by tests, since it depends of variety of hydrological and topographical parameters it is not equatable.

The methodology can be expanded to more than two dams, and the evaluation of cascade dam break can be done either.

The equations herein proposed can be added with volumes, specific weight, and parcels of energy and energy losses from anymore dams as necessary.

The detailed physical model's laboratory tests, measurements, and somehow important materials details, which validated results used to develop the proposed equations, can be found at Campos et al. (2020).

As demonstrated, using the cascade dam break methodology hydrograph peak discharge is earlier and higher, which means the rupture wave should reach some point earlier and higher than usually foreseen. The use of cascade dam break methodology can provide elements to an earlier alert system and flood delineation more accurate, and that means, this use can save lives.

To demonstrate the theorical hypothesis of cascade dam break an unidimensional expression was used and to demonstrate the example a hydrological and bidimensional hydraulic software model were used. The precision of the software are adequate to demonstrate the problem, but it has some representative limitations, as it cannot represent issues related to turbulence or even all three dimensions involved in the dam break problem. Besides, it is known that the dam break occurrence has more complex phenomenon, and the equations demonstrate herein are a basic approach, thus, being those the limitations of the research.

The presented theory used hydrological methods and software to be demonstrated, since, in summary, it proposes the adjustments of the dam break hydrograph equations that limit the breach formation geometry and the formation time. In addition, to this demonstration by digital means, the laboratory tests results that corroborate the proposed method can be found in Campos (2020).

REFERENCES

Alhasan, Z., Jandora, J., & Říha, J. (2015). Study of dam-break due to overtopping of four small dams in the Czech Republic. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, *63*(3), 717-729. http://dx.doi.org/10.11118/actaun201563030717.

Briaud, J.-L., Chen, H.-C., Govindasamy, A. V., & Storesund, R. (2008). Levee erosion by overtopping in New Orleans during the Katrina hurricane. *Journal of Geotechnical and Geoenvironmental Engineering*, *134*(5), 618-632.

Cai, W., Zhu, X., Peng, A., Wang, X., & Fan, Z. (2019). Flood risk analysis for cascade dam systems: a case study in the Dadu River Basin in China. *Water*, *11*, 1365. http://dx.doi.org/10.3390/w11071365.

Campos, R. G. D. (2020). *Proposta de uma metodologia para obtenção de parâmetros de brechas em rupturas de barragens em cascata utilizando modelagem física* (Doctoral dissertation). Universidade Federal de Minas Gerais, Belo Horizonte.

Campos, R. G. D., Saliba, A. P. M., Baptista, M. B., Biscaro, V. H. B., Sá, J. M. M., Passos, D. T., Coelho, S. A. S., & Mamani, J. A. G. (2020). Breach parameters for cascade dams' breaks using physical, empirical and numerical modeling. *Revista Brasileira de Recursos Hídricos*, *25*, e30. http://dx.doi.org/10.1590/2318-0331.252020190109.

Canadian Dam Association. (2021). *Tailings dam breach analysis*. Ontario: Canadian Dam Association. Technical Bulletin.

Carvalho, E. (2007). *Segurança de barragens – aspectos hidrológicos e hidráulicos*. Rio de Janeiro: Comitê Brasileiro de Barragens.

Chow, V. T. (1959). *Open channel hydraulics*. New York: McGraw-Hill.

Colorado. Division of Water Resources. Dam Safety. (2010). *Guidelines for dam breach analysis*. Denver: Division of Water Resources.

Froehlich, D. C. (2008). Embankment dam breach parameters, and their uncertainties. *Journal of Hydraulic Engineering*, *134*(12), 1708-1720.

Froehlich, D. C. (2016). Predicting peak discharge from gradually breached embankment dam. *Journal of Hydrologic Engineering*, *21*(11), 04016041.

Luo, J., Xu, W., Tian, Z., & Chen, H. (2019). Numerical simulation of cascaded dam-break flow in downstream reservoir. *Water Management*, *172*(2), 55-67.

MacDonald, T. C., & Langridge-Monopolis, J. (1984). Breaching characteristics of dam failures. *Hydraulic Engineering*, *110*(5), 567-586.

Pereira, P. N., Santos, R. P., Ferreira, W. F. V., Guimarães, R. D. S., Martins, J. R. S., Fadiga Junior, F. M., & Santos, R. C. P. (2003). Modelação da propagação de cheias ocasionadas por rompimento de barragens na cadeia de geração do Rio Paranapanema. In Comitê Brasileiro de Barragens (Org.), *XXV Seminário Nacional de Grandes Barragens* (pp. 1-15). Rio de Janeiro, Brazil: Comitê Brasileiro de Barragens.

Powledge, G. R., Ralston, D. C., Miller, P., Chen, Y. H., Clopper, P. E., & Temple, D. M. (1989). Mechanics of overflow erosion on embankments. II: hydraulic and design considerations. *Journal of Hydraulic Engineering*, *115*(8), 1056-1075.

Rico, M., Benito, G., & Diez-Herrero, A. (2008). Floods from tailings dam failures. *Journal of Hazardous Materials*, *154*, 79-87.

Říha, J., Kotaška, S., & Petrula, L. (2020). Dam break modeling in a cascade of small earthen dams: case study of the Čižina River in the Czech Republic. *Water*, *12*, 2309. http://dx.doi.org/10.3390/w12082309.

Saliba, A. P. M. (2009). *Uma nova abordagem para análise de ruptura por galgamento de barragens homogêneas de solo compactado* (Doctoral dissertation). Universidade Federal de Minas Gerais, Belo Horizonte.

Vianna, M. R. (1997). *Mecânica dos fluidos para engenheiros* (3. ed.). Belo Horizonte: Imprimatur.

Visser, P. J. (1995). *Application of sediment transport formulae to sand-dike breach erosion*. Delft: Delft University of Technology. Communications on Hydraulic & Geotechnical Engineering Report no. 94-7.

Von Thun, J. L., & Gillette, D. R. (1990). *Guidance on breach parameters*. Denver: US Bureau of Reclamation. Unpublished internal document.

Wahl, T. (1998). *Prediction of embankment dam breach parameters. A literature review and needs assessment*. Denver: US Bureau of Reclamation. Dam Safety Research Report DSO-98-004.

Wahl, T. L. (2004). Uncertainty of predictions of embankment dam breach parameters. *Journal of Hydrologic Engineering*, *130*(5), 389-397.

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