Analysis of physical mechanisms of human body instability for the definition of hazard zones present in emergency action plans of dams. Case study: Santa Helena Dam, Bahia

Análise de mecanismos físicos de instabilidade do corpo humano para a definição de zonas de risco presentes em planos de ação emergencial de barragens. Estudo de caso: barragem de Santa Helena, Bahia

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ABSTRACT

The impacts caused by flood waves due to dam ruptures usually cause irreversible damages to the resident population, and, the loss of body equilibrium in floods contributes to aggravate this scenario. In this context, this work aimed to analyse the influence of consideration of physical mechanisms that cause instability in the human body on the definition of hazard zones. Therefore, it was developed simulation of the propagation of the flood wave due to the hypothetical rupture of Santa Helena Dam in Bahia, using the hydrodynamic model HEC-RAS. The results of flow velocities and heights were related and compared to different criteria of hazard zonings and mechanisms that cause body instability. It was verified that the consideration of instability mechanisms of the human body can contribute to hazard management, through the knowledge of areas in which different individuals may topple or slide. It was confirmed that in supercritical flow regimes is more likely for the individual to slide and that in subcritical regimes the individual will topple. Moreover, the consideration of parameters such as buoyancy force and the angle related to the human body's adaptive ability in a flooding influence on the definition of zones.

Keywords: Body instability; Dam break; Hazard zones.

RESUMO

Os impactos produzidos pelas ondas de cheias decorrentes de ruptura de barragens geralmente causam danos irreversíveis à população residente e a perda do equilíbrio do corpo nas inundações contribui para o agravamento desse cenário. Nesse contexto, esse trabalho teve como objetivo analisar a influência da consideração dos mecanismos físicos que causam instabilidade no corpo humano na definição de zonas de risco. Para isso, foi feita a simulação da propagação da onda de cheia decorrente da ruptura hipotética da barragem de Santa Helena na Bahia com auxílio do modelo hidrodinâmico HEC-RAS. Os resultados de velocidades e alturas de escoamento foram relacionados aos diferentes critérios de zoneamentos de risco e mecanismos que causam a instabilidade do corpo. Percebeu-se que a consideração dos mecanismos de instabilidade do corpo humano pode contribuir na gestão do risco, através do conhecimento de áreas em que os diferentes indivíduos possam tombar ou deslizar. Foi confirmado que em regimes de escoamento supercríticos é mais provável que o indivíduo deslize e que nos subcríticos que o indivíduo tombe. Além disso, a consideração de parâmetros como a força de empuxo e o ângulo referente à capacidade adaptativa do corpo humano em inundações influenciam na definição das zonas.

Palavras-chave: Instabilidade de corpo; Ruptura de barragem; Zonas de risco.

INTRODUCTION

The occurrences of failures and dam breaks generally unleash several damages to current population downstream valley, specially by flood waves and inundation caused by those disasters. Kobiyama et al. (2006), Freitas and Ximenes (2012), Quiroga et al. (2016) cite some possible consequences that may happen: damaging of the environment and infrastructure; health and mortality of human beings and animals; interruption of services; and disserving local economy.

Such phenomena are characterized for generating high flow velocities and water height, that compromise human security and result in the imbalance of the human body, which, in some cases, only slides, while others topple, possibly disabling the person and resulting in drownings.

According to ICOLD (1998), parts of the methodologies that guide the study on dam breaks are: elaboration of rupture hydrographs; the knowledge about induced waves dissemination; mapping flood zones; and, the creation of Emergency Actions Plans.

Mapping susceptible areas to flooding is part of the Emergency Actions Plans (EAP), and it is a largely used and useful alternative in hazard studies (MONTE et al., 2016). These maps contribute on the evaluation of damages and the establishment of communication procedures with the authorities, so they can plan their actions of rescue and improve the management of hazard and land use, defining evacuation routes and alert systems that are adequate (VISEU, 2006).

Such maps are elaborated from numerical results of the modelling of induced flood waves by dam rupture (LAURIANO, 2009) and watershed database.

Among the results from the modelling of dam rupture, those considered more important are flow velocity (v) and water flow height (h), because they cause harm to people's lives when they reach values capable of provoking drownings and other hazardous occurrences. The product of those variables is known as hydrodynamic risk (BALBI, 2008).

$$hv \qquad\qquad (1)$$

According to the National Water Agency of Brazil (ANA, 2016), one of the main characteristics that must be in flood maps is the establishment of flood zones boundaries.

An example of risk zoning based on results of numerical simulations of rupture waves is the zoning proposed by USBR (1988). Such proposition considers a diversity of danger curves based only on the analyses of two variables (flow height and velocity) for humans (adults, children), mobile structures (cars) and immobile (residences with foundation, without foundation etc).

In Brazil, there are not available legislations that describe criteria and methodologies in detail concerning definitions of hazard zonings for inundations as a result of dam breaks. The main laws related to water resources and dams are: the Law nº 9,433, January 8th of 1997, that founds the National Water Resources Policy, and the Law nº 12,334/2010 that establishes the National Dam Safety Policy (BRASIL, 2010). These do not mention the risk zoning. The resolution nº 236 from ANA, January 30th of 2017, and the Ordinance nº 70,389 from DNPM, May 17th of 2017, are the most recent documents that explain the definition

of those zones. Both confirm the need of a more detailed risk zoning present in the PAE, in a way that comply a flood study, with maps, identification of self-rescue zones (ZAS) and the vulnerable spots subjected to being affected. An example of hazard zoning study in Brazil is Menezes (2016), that discussed different criteria of hazard zonings to classify damages due to the rupture of Santa Helena Dam, from Bahia, located in the city named Camaçari (same study area addressed in this research). Therefore, Menezes (2016) applied two different methodologies, the Risk indexes and the Classification of Risks. His methodological process also complied the simulation of flood wave propagation in the unidimensional mathematical model HEC-RAS 4.1.0, and the mapping of flood areas.

When it comes to threatening human safety, variables related to fluid flow and to the physical attributes of the person at the moment of hazard during flood waves are important criteria to be considered in hazard zonings, because different bodies behave distinctively upon varied conditions of flow and terrain, and, by including these criteria, it is possible the establishment of more accurate risk zones (XIA et al., 2014).

One of the main factors that initiates the instability of a body in a flooding is the physical mechanism that act on the body at the instant of its interaction with the flow, that makes the body to topple or slide, caused by the action of several forces, such as dragging, weight, buoyancy and friction.

Researches that expatiate this theme in Brazil are rare, and there are not works that discuss the different physical mechanisms of instability of bodies through hazard zonings.

Some authors developed mathematical equations on the attempt to best represent the physical mechanisms of instability of the body and approximate the models to reality, by considering many criteria and hydraulic variables of instability of the human body in floods.

The most recent equations that are present in the literature cover aspects such soil roughness, body inclination in relation to the surface, specific mass of the body, specific mass of the fluid, dragging coefficients, parameters related to physical attributes of the body and even parameters of mobility, as proposed by Arrighi, Oumeraci and Castelli (2017).

For Milanesi, Pilotti and Ranzi (2015), in a review of criteria of hazard mapping there is a strong heterogeneity and fragmentation in relation to conditions and physical mechanisms considered in the instability analysis of the human body. However, although there are limitations and uncertainties related to studies of physical mechanisms that cause the instability of the human body, this work aimed to provide a general view of these processes, for a better comprehension of the related phenomena, and mainly, related to spatial distribution of the occurrence of the physical mechanisms of body instability in a floodplain.

The main target of this study is to evaluate the occurrence of physical mechanisms of human body instability (toppling and sliding), due to the hypothetical rupture of Santa Helena Dam, in Bahia, as a means of contribution to define risk zones required in Emergency Actions Plans of dams. Such consideration has not been yet made in the criteria of zoning currently used and there are no records of studies that discuss these physical mechanisms of human body instability as zonings criteria.

Hazard zoning

Balbi (2008) defines hazard zoning as the division of territory liable to be reached on the classified areas according to associated risk, magnitude of the damage, vulnerabilities and time alerts.

Hazard zoning is strongly associated to economic value of the properties, establishing severe conditions to plan use and control of the soil. Its study and definition are important to any extraordinary flood event, being the hazard zoning for dam break cases only one of its applications. In European countries, for example, hazard zonings are fundamental tools to safety programs against floods, above all to properties that are situated in risk areas, for the protection of the owners. Concerning the consequences, Richert (2017) affirms that variables such as submersion time due to flooding, velocities and maximum flow heights, flooded area and time space between floods are important to estimate the probability of consequences.

For Viseu (2006), hazard zoning should be defined in function of the flood wave characteristics, be it the maximum height reached by the water, the flow velocity or the flood wave time of arrival. The USBR (1988), reference in studies of dam security, classifies three hazard zones (Figure 1), they are: low hazard zone (if the person is subjected to low velocity and depth of water, being null the risks against life); high hazard zone (areas where there is the possibility of risking life); and, judgement zone (an uncertainty zone in relation to the lives in danger due to the impossibility to consider all the variables that interfere in threatening life and in the magnitude of the flood).

The definition and the knowledge of dangerous zones and potential areas to be flooded become essential, because they guide the development of measures and procedures to reduce hazard to life. The risks that a human life is subjected to in a flooding can be caused by different factors; besides the parameters previously described (water table height and flow velocity), they may also be caused by physical trauma, heart attack, possible drownings and loss of stability of the human body (JONKMAN; PENNING ROWSELL, 2008).

Physical mechanisms of human body instability

According to Arrighi, Oumeraci and Castelli (2017), the loss of equilibrium of a human body in floods is the result of the interaction between the water and the individual.

Some studies were developed intending to raise the understanding of mechanisms that cause the loss of stability of the human body in inundations, for instance: Foster and Cox (1973), Abt et al. (1989), Endoh and Takahashi (1994), Karvonen et al. (2000), Lind, Hartford and Assaf (2004), Jonkman and Penning-Rowsell (2008), Rotava, Mendiondo and Souza (2013), Xia et al. (2014), Milanesi, Pilotti
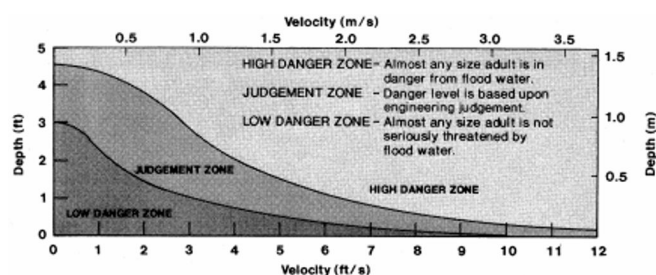
and Ranzi (2015) and Arrighi, Oumeraci and Castelli (2017). It was noticed that the factors that influence the most those mechanisms are hydrodynamic (velocity and depth of the water), physical attributes (weight, height), psychological conditions of the human being and topographic conditions of the place.

Over time, studies became less simplified, complying more criteria on the attempt to approximate to more realistic situations. In Brazil, few are the works that cover the analyses of those mechanisms, it is possible to cite Rotava, Mendiondo and Souza (2013) and Simões, Schulz and Luz (2016), with analyses that approach essentially the behaviour of different variables and parameters on the formulations of physical mechanisms of body instability and hydrodynamic hazard.

Jonkman and Penning-Rowsell (2008) affirm that few are the data about the dangerous circumstances that may occur in flood events considering the affected population, mostly those associated to depth and velocities of water that offer risk to life. Thus, the choice of adequate vulnerability criteria is fundamental (MILANESI; PILOTTI; RANZI, 2015).

The choice of criteria is complex, because there is a strong heterogeneity and fragmentation on the methodologies used by each study. Not having one that is fully satisfactory, then, should be selected the most suitable for the aim of the study considering also the data available for the work (MILANESI; PILOTTI; RANZI, 2015).

Simões, Schulz and Luz (2016) also verified similar difficulties, as those previously cited, in their study about dimensional analysis for human stability problems in channel flows, observing dimensionless groups, and affirming that the set of variables involved on human stability in flows is vast and rare are the data that are available in the literature about executed experiences.

Xia et al. (2014) reiterate the need to study human bodies instability in floods, because the security of people may be compromised in case the inundation exceeds the person's ability to keep standing or moving and, therefore, human stability should be of big concern in the management of areas prone to flooding. Thus, it is important the establishment of a quantitative methodology capable of evaluating the stability of the human body to provide, based on science, hazard management for these areas.

In accordance with Rotava, Mendiondo and Souza (2013) and Simões, Schulz and Luz (2016), several are the criteria of destabilization of a body and the consideration of physical aspects can be useful to estimate vulnerability levels of a person exposed to danger. In order for this to happen, a methodology can be represented by a mathematical model with values of active forces (Figure 2) in critical conditions to establish stability.
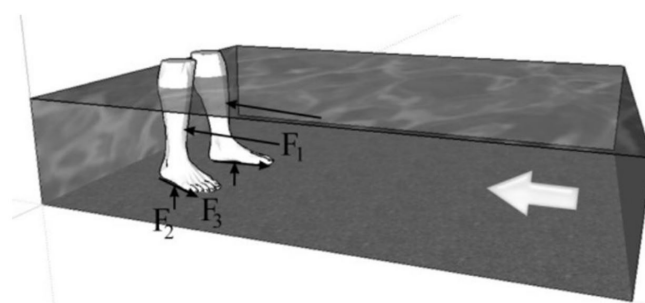

Figure 1. Danger curves by the relation between depth and velocity for adults, USBR (1988).

Figure 2. Active forces in a part of the human body. F_1 being the resulting force of the shear stress and the distribution of pressures caused by the fluid on the body, F_2 the buoyancy force and F_3 the force due to the friction on the soil, adapted from Simões, Schulz and Luz (2016).

The hydrodynamic hazard associated to people's instability in a flood situation is considered, by authors as Viseu (2006), USBR (1988) and Jonkman and Penning-Rowsell (2008), the product addressed in Equation 1. However, this function of empirical approximation is purely regressive and does not allow the establishment of an effective connection between hazard level and physical effects, such as instability for children or for adults (MILANESI; PILOTTI; RANZI, 2015).

Existing studies, such as Xia et al. (2014) and Milanesi, Pilotti and Ranzi (2015), indicate that human instability can be caused by two types of mechanisms, sliding and toppling (Figure 3). Sliding or friction instability happens when the drag force induced by the horizontal flow is greater than the friction resistance between the feet and the surface of the floor. On the other hand, toppling or moment instability always occurs when the moment caused by a flow approaches or exceeds the moment concerning the weight of the body.

For Milanesi, Pilotti and Ranzi (2015), a person's postural manoeuvres on the attempt to adapt to the flow may increase stability against toppling, which is different for the case of sliding, because the body mass distribution does not substantially alter the resistance over friction.

Milanesi, Pilotti and Ranzi (2015), as well as Jonkman and Penning-Rowsell (2008), Rotava, Mendiondo and Souza (2013) and Xia et al. (2014), analysed human stability considering involved forces during the interaction of water flow and the body, and moment equilibrium. For this, it was used a body made by cylinders, considering its sliding, toppling and drowning, in regard to high water levels.

One of the major differences from the work of Milanesi, Pilotti and Ranzi (2015), in relation to the previous ones mentioned, is that it was the first to include local slope for fluids of different densities, in situations that the floods could threat human life and it was verified that these variables significantly influence hazard factors and stability reduction.

In light of the countless works previously presented, that describe gradual change of the different formulations of body instability in floods, it was noticed that the current state of art presents robust equations, that consider a diversity of parameters and variables that seek to describe, in a most realistic approach, the interactions between the human body and the flows.

But, despite the amount of works already developed, those that relate those mechanisms to hazard zoning – in a way that the physical mechanisms of human body instability become incorporated to hazard zones definition – are rare.

Milanesi et al. (2014) was the most present work found in the literature with this purpose. Milanesi et al. (2014) expatiated different hazard zonings criteria for debris flow condition in three alpine watersheds, by elaborating maps as results of numerical simulation using the computational tool FLO-2D, with a 5 m resolution DEM (Digital Elevation Model). For this, were used hazard maps elaborated according to Japanese legislation, Swiss legislation, Austrian legislation, and, lastly, the hazard map considering human body instability.

For the elaboration of the last map, considering the instability of the human body, Milanesi et al. (2014) developed a simple conceptual model with a human being in orthogonal position on the floor, represented by cylinders of different sizes, having measured heights and weights, for the study of instability with debris flow.

Their analysis covered drag, friction and buoyancy forces and variables such as drag coefficient, local slope, specific mass of the fluid, volume under water, body weight and flow velocity.

Numerical simulation of flood waves

The equations that model the flow in free surface channels, in variable and varied regime, may assume different formats in function of the adopted simplification. There are one-dimensional Saint-Venant equations that represent the mass conservation principle and Newton's second law for the condition of incompressible flow, hydrostatic pressure distribution and uniform velocities distribution in cross sections. In two dimensions, the equations are obtained from the integration of the mass conservation equation
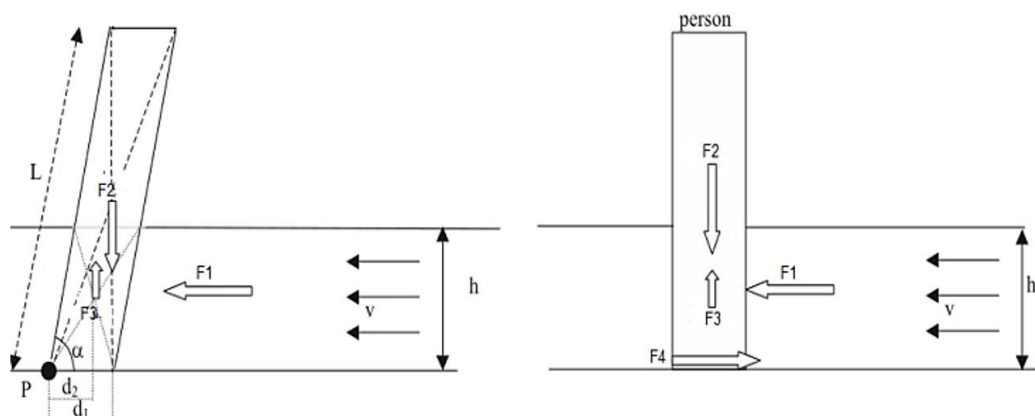

Figure 3. Representation of instabilities of a body by toppling and by sliding, respectively, adapted from Jonkman and Penning-Rowsell (2008). Which: F1 = horizontal force of the flow on the body; F2 = resulting force of the body weight; F3 = vertical buoyancy force; F4 = friction force on the soil; d_1 = person width, d_2 = distance of the articulation center of the person (point P) to the center of the vertical buoyancy force [m]; h = flow height; P = point where the person stands while tilts in the flow; v = flow velocity [m/s]; α = inclination of the person in degrees; and L = person's height [m].

vertically, and applying the same process (vertical integration) for the Navier-Stokes equations.

Examples of works that used one- and two-dimensional modelling to study floods and inundation are: Ribeiro Neto, Batista and Coutinho (2016) applied HEC-RAS (Hydrologic Engineering Center-River Analysis System) to aid the simulation of flood events for the Una River Watershed, in the state of Pernambuco; Haltas, Elçi and Tayfur (2016) used one- and bi-dimensional modelling, respectively, HEC-RAS 1D and Flo-2D to predict and analyse flood waves caused by the rupture of two dams located in Istanbul, in Turkey; Chiamulera et al. (2015) studied the calibration of the hydrodynamic one-dimensional and bi-dimensional model SOBEK for the Grande River Watershed, in Minas Gerais; Patel et al. (2017) confirmed the competence of the model HEC-RAS 5.0 for studies regarding mapping and management of floods through the simulation of flow discharged by the Ukai Dam; and Alzahrani (2017), who reiterates in his thesis the applicability of the bi-dimensional model HEC-RAS 5.0 to describe more accurately the flow behaviour of the flow of the Miami River and Bear Creek, in Ohio.

MATERIALS AND METHODS

The methodology of this study was structured in three steps: (i) Presentation of equations that physically describe instability mechanisms of the human body; (ii) Simulation of the flood wave downstream valley from Santa Helena Dam, on the bi-dimensional hydrodynamic model HEC-RAS 5.0; (iii) Elaboration of hazard maps against inundations, zoned based on presented criteria by the USBR (1988), the Brazilian legislation and the consideration of physical mechanisms that cause the instability of the human body.

Description of the study area

The study area is situated downstream Santa Helena Dam (Figure 4), located in the city of Camaçari, metropolitan region of Salvador. In December of 1979, the dam was built on the Jacuípe River having as primary purpose human supply, and, it currently supplies cities as Salvador, Lauro de Freitas, Simões Filho, Candeias, São Francisco do Conde and Madre de Deus (EMBASA, 2012).

Santa Helena is a homogeneous earth dam that has vertical sand drains, and has a crest of 260 m; it has two floodgates, the width of its spillway is 21.5 m and its maximum discharge is 1,750 m³/s considering a maximum level of 20 m (AMORIM, 2008).

In 1985, the dam broke and, according to specialized consultants, that happened due to rising of river level downstream the dam, that surpassed the conditions predicted in project, causing sub-pressure on the spillway channel slab and, consequently, its displacement or destruction (SSRH, 1985 apud Menezes, 2016).

Immediately downstream the dam (Figure 5), the valley is characterized as having intense medium and large vegetation, sand banks in a landscape that extends along great part of the river channel.

The figure highlights the Jacuípe River (blue contour) and the three downstream cross sections that were evaluated, in yellow. The first section is situated immediately after Santa Helena Dam,
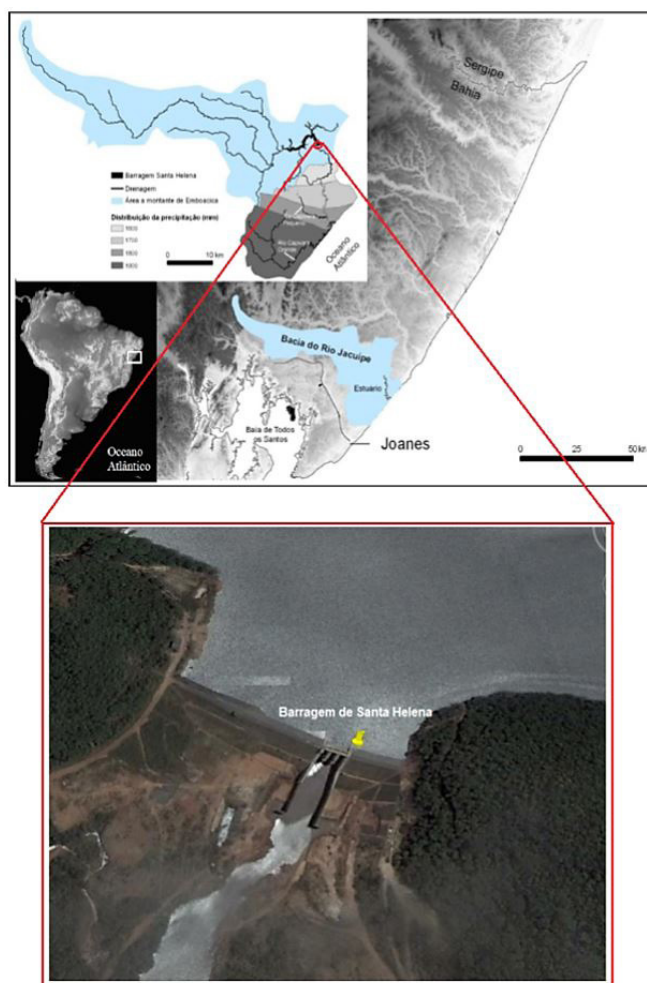

Figure 4. Location of the area and aerial view of the Santa Helena Dam (MENEZES, 2016).
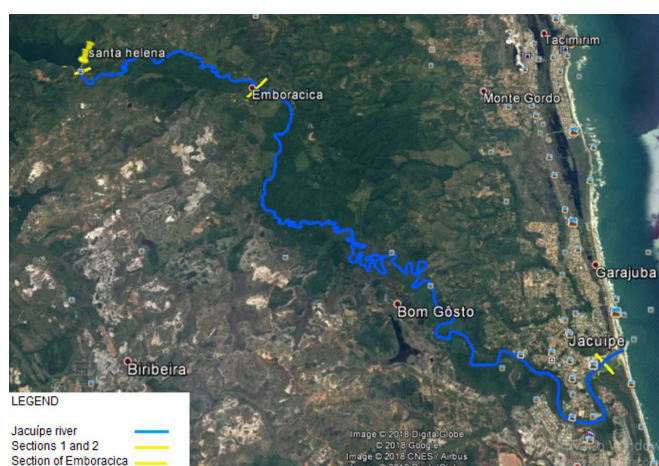

Figure 5. Location of the segment and sections of study, adapted from Google Earth (2018).

the second is located in the village Emboracica and the last one is in the city of Jacuípe. The sections from Emboracica and Jacuípe are present in areas prone to urban settlement.

Technical information related to the size of the dam, operational levels, geometric characterization of the breach of the dam rupture, time and peak discharge necessary to elaborate the hydrograph of rupture (Figure 6) were determined by Menezes (2016). The parameters of dam break were determined for a rupture scenario of a rainy day, using data regarding dam structure and information related to the accident that occurred. In order to define the most appropriate methodology to calculate breach parameters, Menezes (2016) compared several recommendations from authors and noticed that the one from ELETROBRÁS (2003) and the one from the United States (WASHINGTON, 1992) resulted in identical breaches, which could indicate a pattern set of more adequate breach for the case of Santa Helena Dam.

Menezes (2016) considered more adequate the hydrograph of rupture in parabolic decay for presenting more stability in the discretization of flow discharge along time, when compared to the simplified triangular hydrograph.
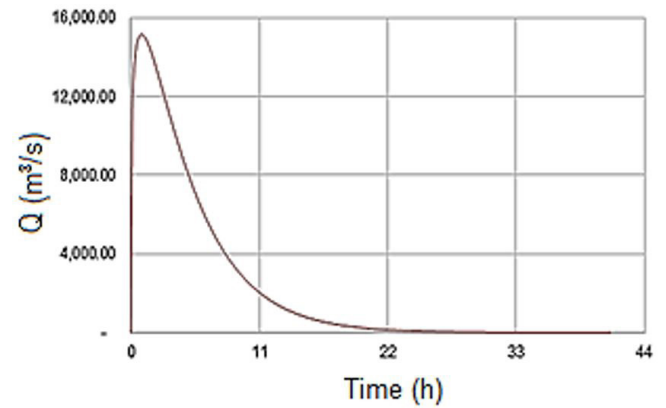
Methods

- Determination of equations that describe physical mechanisms of human body instability

Regarding instability mechanisms of bodies, Jonkman and Penning-Rowsell (2008) were the first ones to describe formulations of hydrodynamic hazard for toppling instability and for sliding instability, considering physical attributes of the human body such as individual mass (m), his height (L), average width of the body exposed to the fluid (B), tilt angle of the person in relation to flow direction (α), study area characteristics, friction coefficient (μ), and also, elements related to the flow, such as specific mass (ρ) and drag coefficient (C_D), disregarding buoyancy forces.

The relations of flow velocity and water height that represent moment instability and friction instability for Jonkman and Penning-Rowsell (2008) are, respectively, presented in Equations 2 and 3:

$$hv = \left(\frac{2mg\cos(\alpha)L}{C_D B \rho}\right)^{0.5} \tag{2}$$

$$hv^2 = \frac{2\mu g}{C_D B \rho} m \tag{3}$$

Xia et al. (2014) established equations that analysed body instability in inundations using experimental and theoretical analysis, with a channel of low depth and high velocity, considering toppling and sliding of bodies. It was also imagined a situation in which the individual would topple sliding, disregarding body inclinations (Figure 7).

Instability formulations for toppling and sliding were developed (Equations 4 and 5), observing the behaviour of the variation of profiles of propagation velocity and equations of incipient velocities were presented for every mechanism.

Their instability formulations were defined by means of the analyses of balance of moments and forces, active during body interaction with the flow, as Archimedes' buoyancy, drag force, weight force, friction force and normal force.

$$v = \alpha\left(\frac{h}{L}\right)^{\beta}\sqrt{\left[\frac{m}{\rho_s hL} - \left(a_1 \frac{h}{L} + b_1\right)\right]\frac{ma_2 + b_2}{L^2}} \tag{4}$$

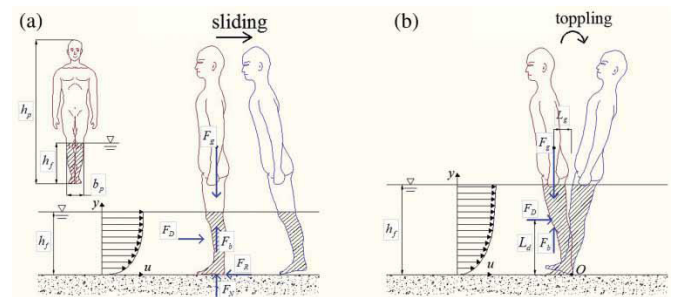**Figure 6.** Hydrograph of rupture of Santa Helena Dam.

Figure 7. Schema of actions of forces on an individual in a flood situation by sliding (a) and by toppling (b). F_D being the drag force; h_p the body height; h_f the water height; b_p the body width; F_G the weight force; F_N the normal force; F_R the friction force; F_b the buoyancy force; L_G the resulting moment of the weight force; and L_d the resulting moment of the drag force (XIA et al., 2014).

$$v = \alpha\left(\frac{h}{L}\right)^{\beta}\sqrt{\left[\frac{m}{\rho_s h^2} - \left(\frac{a_1}{h_p^2} + \frac{b_1}{hL}\right)\right]ma_2 + b_2} \tag{5}$$

Parameters α and β were calibrated according to the structure of a human body, friction force and drag force; a_1, b_1, a_2, b_2 are calibrated coefficients in function of the structure of the human body considered, h is the water height and ρ_s the specific mass of the fluid.

Milanesi, Pilotti and Ranzi (2015) also developed equilibrium of forces to establish instability conditions for body mechanisms (Figure 8).

The relation for stability is defined by Equation 6:

$$D + W_p \leq T \tag{6}$$

In which D is the drag force, W_p is the component of the weight force parallel to the drag force and T is the friction force. If the friction force is smaller, the person will slide.

The toppling mechanism is defined by the following relation (Equation 7):

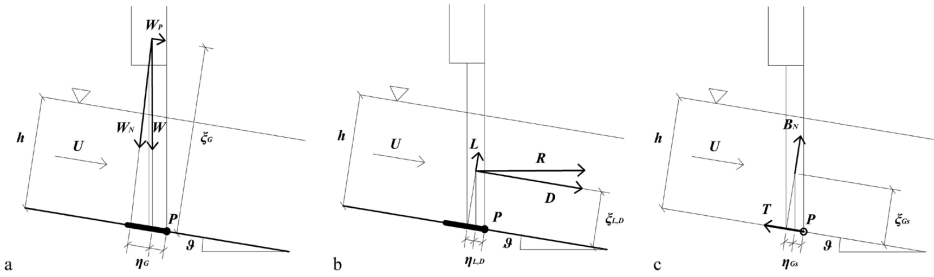$$D\xi_{L,D} + W_p\xi_G + B_N\eta_{GS} + L\eta_{L,D} \leq W_N\eta_G \tag{7}$$

Figure 8. Figures (a), (b) and (c) show active forces on the body and their applied spots, D is the drag force; W_p is the component of the weight force parallel to the drag force and T is the friction force; D and L are decomposed forces from the resulting force (R), relative to the forces of buoyancy and dragging; B_N is the buoyancy force on the submerged body; ξ_G and η_G are coordinates regarding the applied spots of the weight force on the centre of mass; and, $\xi_{L,D}$ and $\eta_{L,D}$ are coordinates of the application of D and L forces in relation to the soil and the heel, respectively (MILANESI; PILOTTI; RANZI, 2015).

In which, D and L are decomposed forces from the resulting force (R), relative to the forces of buoyancy and dragging, B_N is the buoyancy force on the submerged body, ξ_G and η_G are coordinates regarding the applied spots of the weight force on the centre of mass, and, finally, $\xi_{L,D}$ and $\eta_{L,D}$ are coordinates of the application of D and L forces in relation to the soil and the heel, respectively.

- Simulation of flood wave in the hydrodynamic model HEC-RAS 5.0

In this step, initially, information regarding the system dam-downstream-valley was gathered (topobatimetry, slope, Manning's coefficient), required for the numerical simulation of the flood wave propagation and analysis of the floodplain.

The topography of the terrain was provided by the Company of Urban Development of the State of Bahia – CONDER, in level curves, in CAD format, at scale 1:10000. Bathymetry was made available by the Baiana Enterprise in Water and Sanitation S.A – EMBASA, by means of 41 cross sections of the river channel, also at scale 1:10000.

In possession of these results, it was, then, proceeded the elaboration of the Digital Terrain Model - DTM by joining the area's topography and bathymetry in one of ESRI's Geographic Information System (SIG), the ArcGis, with the spatial reference UTM WGS, zone 24 (Figure 9).

The definition of the Manning's coefficient followed the proposition by Menezes (2016), having ranges of determined values from field observations and literature recommendations (Table 1).

Equation 8, presented below, is the differential form, obtained this form for the bi-dimensional flow in a channel (CHAUDHRY, 2008). Equations 9a and 9b correspond to resulting equations of the integration of Navier-Stokes' equations. For this, it is assumed that the vertical acceleration is negligible. These equations are named in a set of shallow water equations in two dimensions.

$$\frac{\partial y}{\partial t} + \frac{\partial (yu)}{\partial x} + \frac{\partial (yv)}{\partial z} = 0 \tag{8}$$

$$\frac{\partial (yu)}{\partial t} + \frac{\partial}{\partial x}\left(yu^2 + \frac{1}{2}gy^2\right) + \frac{\partial (yuv)}{\partial z} = gy\left(I_{ox} - I_{fx}\right) \tag{9a}$$

$$\frac{\partial (yv)}{\partial t} + \frac{\partial (yuv)}{\partial x} + \frac{\partial}{\partial z}\left(yv^2 + \frac{1}{2}gy^2\right) = gy\left(I_{oz} - I_{fz}\right) \tag{9b}$$
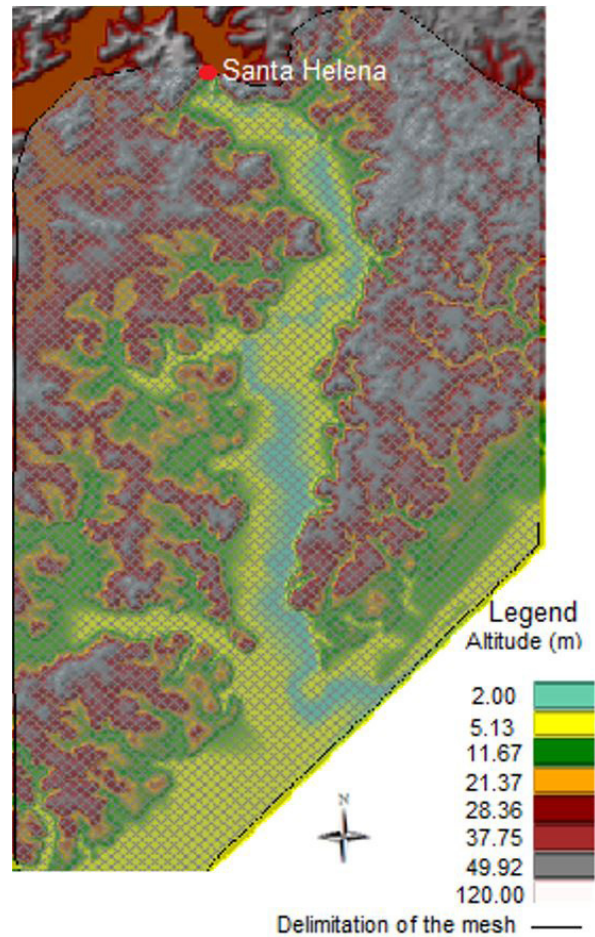

Figure 9. DTM (Digital Terrain Model) with delimitation of mesh to be modelled.

Table 1. Manning's coefficients used on the DTM, adapted from Menezes (2016).

Manning's Coeffients	Value
Floodplain with predominance of urban areas	0.15
Floodplain with predominance of rural areas	0.1
More winding areas of the main channel	0.05
Less winding areas of the main channel	0.03

Having the required data, it was proceeded the numerical simulation. Equating: Mass conservation and Newton's second law. DTM = Digital Terrain Model.

In these equations, u is the component on x of the velocity vector, v is the component on z of the velocity vector, in the xz plane, y is the flow height, g is gravity acceleration, t is the time, I_o is the bottom declivity and I_f is the declivity of the energy line.

The modelling of the system was developed using the free software HEC-RAS 5.0 (Hydrologic Engineering Center River Analysis System), in order to mathematically simulate the propagation of flood waves.

The mesh used covered the entire surface downstream the dam, in a domain that has 568,305 cells, each cell measuring in average 20×20 m, the largest cell covers an area of 723.69 m² and smallest one measures 304.02 m².

As input data, were used the terrain's DTM and the established Manning's coefficients.

The boundary conditions inserted were the hydrograph of the dam rupture on section 1 (Figure 5), and, on section 2, declivity, with a value of 0.00018 m/m.

The modelling of the system consisted in simulate the propagation of the flood wave caused by the hypothetical rupture of Santa Helena Dam. The simulation lasted in a total time of 16 h 45 min 32 s, from May 9th of 1985, with a time step equals to 20 s, to satisfy the CFL (Courant - Friedrichs – Lewy) condition.

• Test of the influence of Manning's coefficient

Aiming to analyse the influence of Manning's coefficient in the results of flow velocity and water height of the simulation of the flood wave propagation, due to the rupture of Santa Helena Dam, three tests were simulated for the scenario of the simulation of the break of Santa Helena Dam, with maximum values of flow during the simulated time. The values of Manning's coefficients adopted for each test are those presented in Table 2.

After simulation, information from all the tests was collected relative to twenty spots in different positions in the floodplain on the segment in study (Figure 10).

The influence of the variation of Manning's coefficients was also analysed in the definition of hazard zones in the floodplain, considering instability criteria for the human body. Therefore, hazard zonings were compared considering the occurrence of sliding of an adult, according to Manning's coefficients oriented by test 1 (maximum) and by test 3 (minimum) from Table 1. The instability equation of the human body for sliding used in this step was the one from Jonkman and Penning-Rowsell (2008), through Equations 2 and 3, which are relatively simpler and provide satisfactory results, when compared to other instability equations for the human body by sliding covered in this research.

• Generation of flood maps for different hazard zonings

The zoning oriented by the USBR (1988) followed the hazard classification for adults, in low, high risk and the judgement zone according to the thresholds presented in Figure 1. The zoning established, based on Brazilian legislation, was based on the ZAS and ZSS (Secondary Rescue Zone) elaborated considering Santa Helena Dam, and, finally, for the definition of hazard zones that consider physical mechanisms that cause instability of the human body, instability equations by sliding and by toppling were used, presented by Jonkman and Penning-Rowsell (2008), Rotava, Mendiondo and Souza (2013), Xia et al. (2014) and Milanesi, Pilotti and Ranzi (2015). The adopted characteristics relative to the physical attributes of the individual used in all the analyses

Table 2. Manning's coefficients used for the analysis of influence on the simulation.

Manning's Coefficient	Test 1	Test 2	Test 3
Riverbed	0.05	0.03	0.01
Rural area	0.1	0.1	0.1
Urban area	0.15	0.15	0.15

LEGEND
Flooded plain
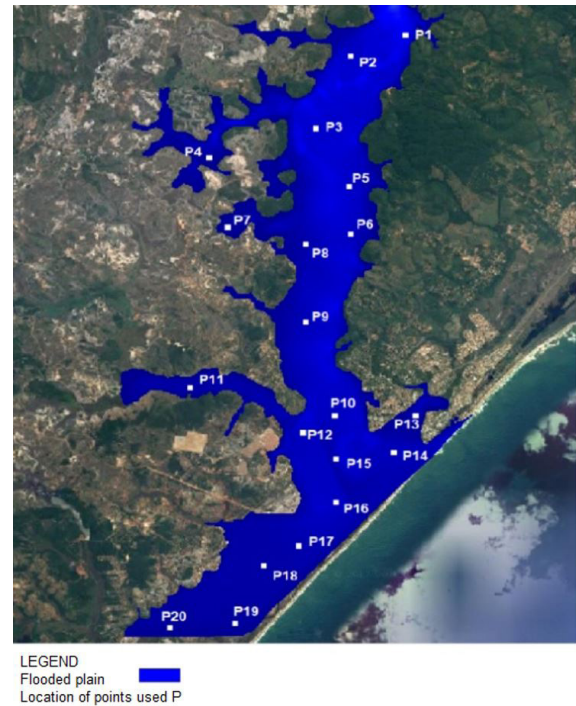Location of points used P

Figure 10. Cutting of the floodplain highlighting sampling spots (P) of the hydraulic variables for the sensitivity test.

of this research were: height equals to 1.71 m, mass equals to 60 kg, average body width equals to 0.26 m and leg diameter of 0.13 m. Such values were adopted as they were similar to the ones considered by Milanesi, Pilotti and Ranzi (2015), Jonkman and Penning-Rowsell (2008) and Xia et al. (2014) in their works.

In possession of the values of the instability thresholds for sliding and for toppling of a human being, hazard zones in the floodplain were delimited, indicating potential areas where the person is prone to slide or to topple.

• Evaluation of hazard zoning results

The evaluation of results occurred after being defined all hazard zonings in the floodplain, according to criteria of the USBR, 1988; Brazilian legislation and considering physical mechanisms of body instability. Therefore, the different hazard zonings were compared and the flooded area results were analysed, as well as the different zonings extensions and the occurrence of sliding and toppling in every mapping.

RESULTS AND DISCUSSIONS

After simulating the process of flood wave propagation due to the rupture of Santa Helena Dam, it was obtained the floodplain for the results of height (Figure 11) and maximum

velocities of the flow (Figure 12). In Figure 13, flow velocities and heights are represented in function of time for the section in Jacuípe during the propagation of the flood wave.

According to the hazard classification presented by Viseu (2006), on 27.19 km² of the flooded area with flow height less than or equals to 4 m, the risk at them is classified as medium. Even if being classified as medium hazard, it is essential greater attention on the zone, mainly due to the possibility of permanency of people with their mobility reduced, such as disabled people, elderly and children.

For the section in Jacuípe, in approximately 57% of the simulated time for the scenario of maximum values, flow heights remained above 2 m. Besides that, maximum velocity surpasses 2m/s, being classified as medium hazard.

- Test of influence of the Manning's coefficient

The results obtained from the 20 selected spots in the described simulation in Table 2 are presented on Figures 14 and 15, for the tests according to the defined Manning's coefficients in Table 2.

It is verified in Figure 14 that the results referred to flow heights present lower variations when compared to the variations of flow velocity from test 1. Test 1 presented flow heights superior than the ones from test 2 at 17 spots, wherein 4 spots exhibited heights that surpassed 1 m of water.

The results from test 3 presented 18 spots with flow heights lower than the ones from test 1, and from those 18 spots, 10 of them also showed flow heights greater than 1 m of water. At the spot labelled P8, the height surpassed approximately 2.8 m in test 1.

Still in Figure 14, it is noticed that spots 4, 7 and 14 presented results considerably different from the others. Such discrepancy can be attributed to the location of those spots, because spots 4 and 7 are situated in areas that are more distant from the main flow channel, resulting in smaller discharges and higher pressure drop. The greatest value for height and velocity of the flow at spot 14 was probably due to the fact that it is located above the main flow channel, having more accentuated depths in the terrain.

Figures 16 and 17 present the definition of hazard zones considering the instability of the human body by sliding for an adult, guided by the use of Manning's coefficients from test 1 and test 3. In this step, the instability equation for the human body for sliding and their classification thresholds were from Jonkman and Penning-Rowsell (2008).

When compared, Figures 14 and 15, it was verified that the adopted values for the Manning's coefficients influenced the definition of hazard zones. The reduction of Manning's Coefficient
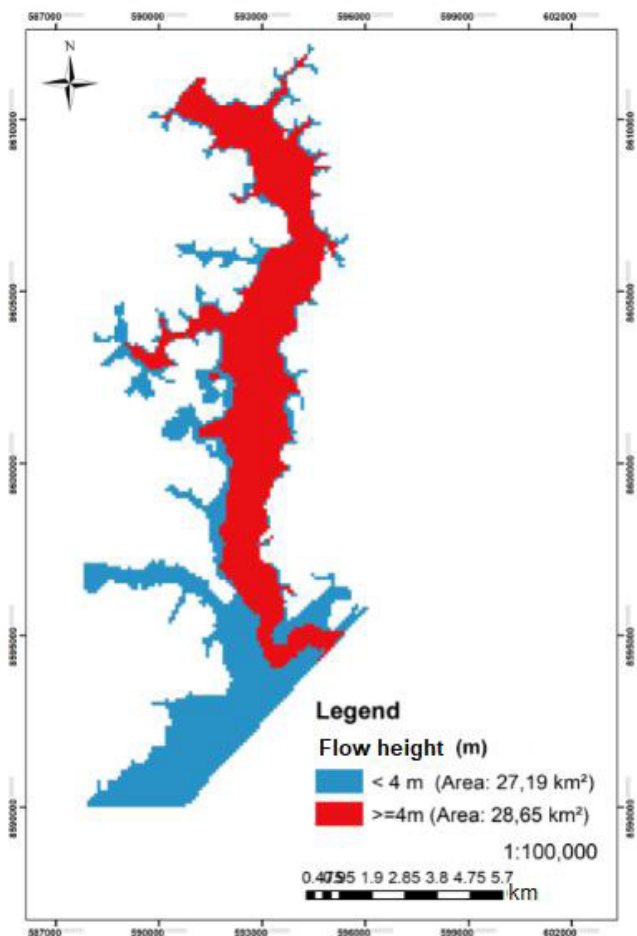

Figure 11. Values of maximum heights of flow from the simulation of the wave caused by Santa Helena dam break.
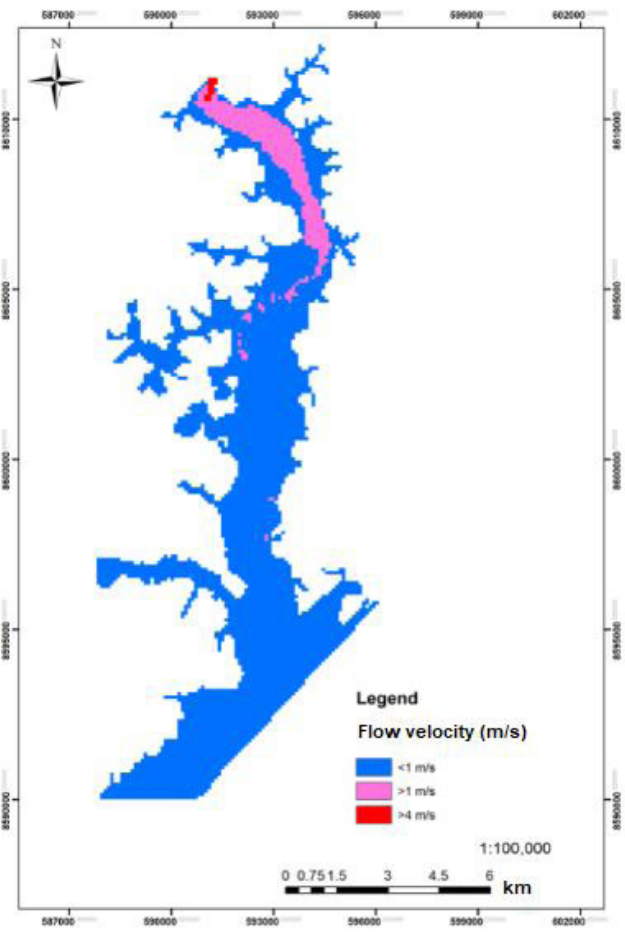

Figure 12. Values of maximum flow velocities of the simulation of the wave caused by Santa Helena dam break.
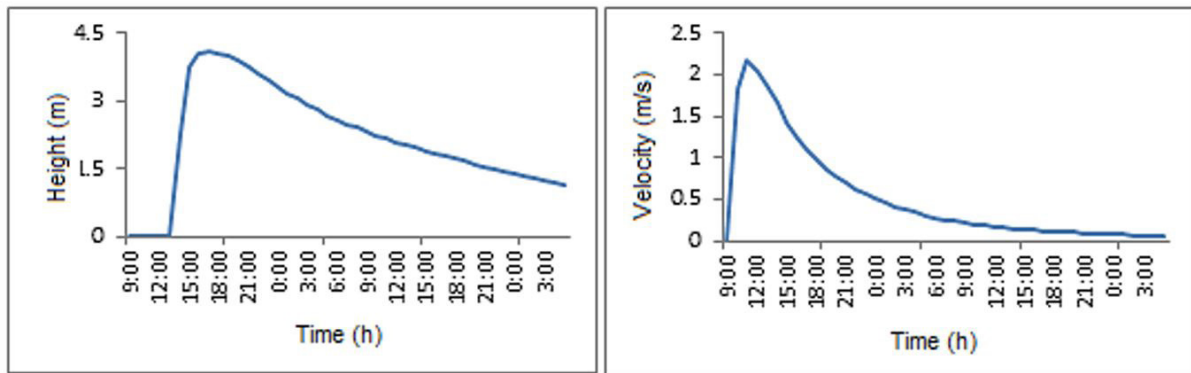
Figure 13. Behaviour of height and velocity of the flow during the flood wave propagation on the section from Jacuípe.
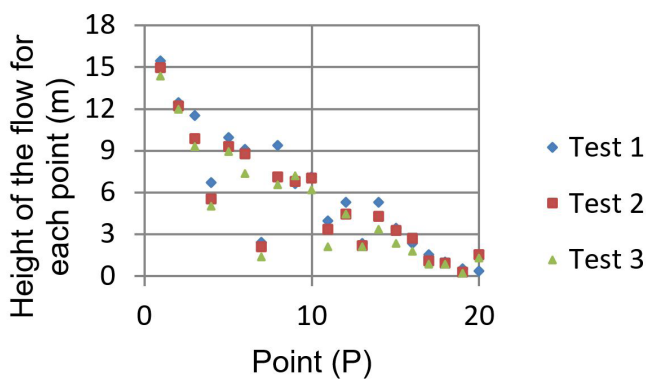

Figure 14. Behaviour of flow height during the flood wave propagation on the section from Jacuípe.
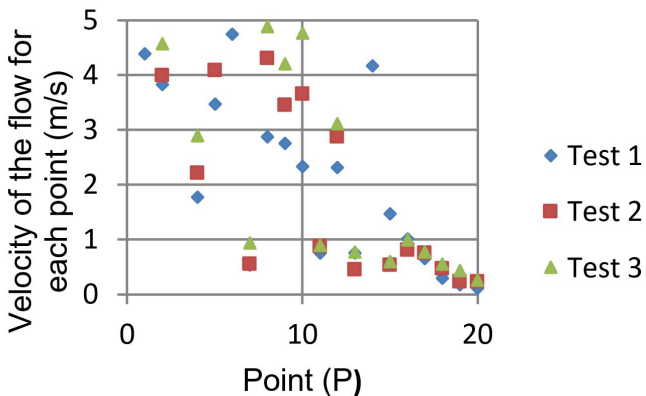

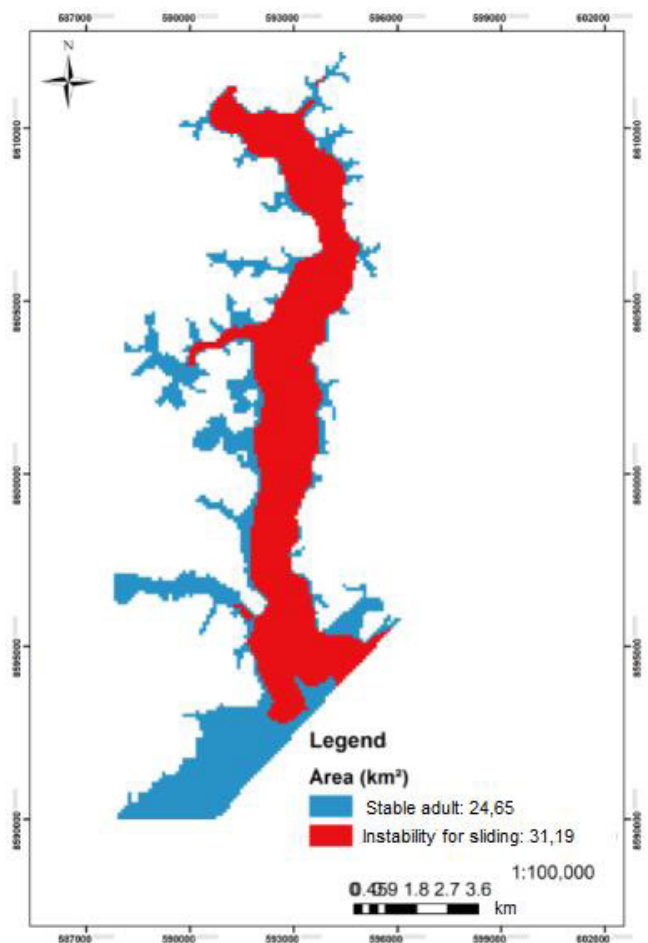**Figure 15.** Behaviour of flow velocity during the flood wave propagation on the section from Jacuípe.

Figure 16. Hazard zonings for sliding according test 1.

on test 1 in relation to test 3 increased in 8.05 km² the hazard zone for sliding instability of an individual.

- Generation of flood maps zoned according to different criteria

The results of different propositions of hazard zonings in this work, USBR (1988), Brazilian legislation - Law 12,334/2010 and EAP, and zones that consider physical mechanisms that cause human instability in floods are presented as follow. USBR (1988):

The hazard zoning suggested by the USBR (1988) for inundation maps classify the zones in lower hazard, high hazard and judgement zones, by means of the values of depths and water heights. Figure 18 corresponds to hazard zoning for adults.

In the map, the high hazard zone prevails with area equals to 41.22 km². The judgement zone, with area equals to 7.14 km², is of great importance in this study, because the level of risk associated to these zones is determined from the decisions made by the responsible engineer, and thus conflicts of interests may
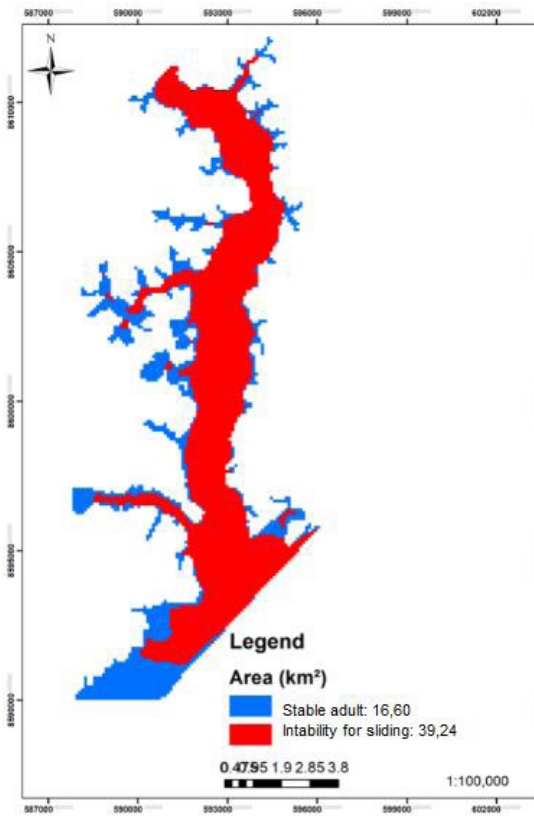
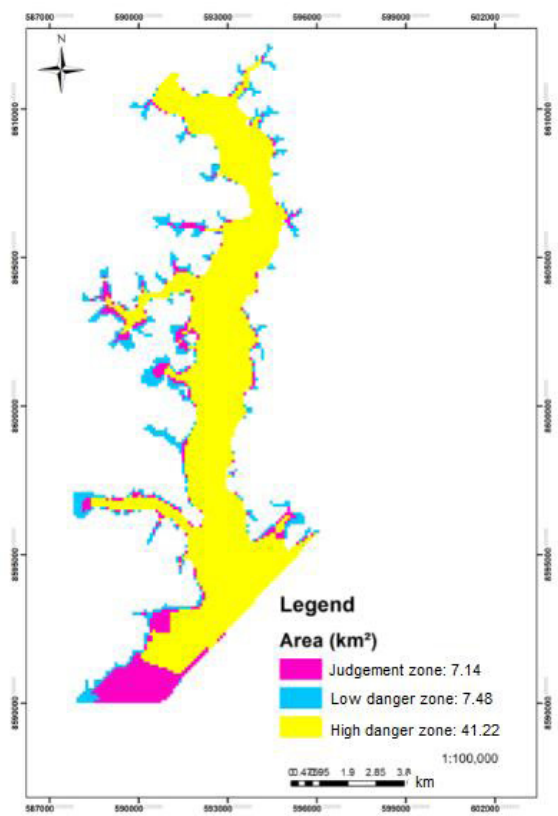**Figure 17.** Hazard zonings for sliding according test 3.

Figure 18. Hazard mapping considering the proposition by USBR (1988) for adults.

occur, as well as infringements of criteria and, in emergency situations, and inadequate judgements and the knowledge of bodies instability on that zone may contribute to the rescue in emergency situations.

The low hazard zones were considered with hydrodynamic hazard lower than or equals to 0.09 m²/s, the judgement zone with hydrodynamic hazard greater than 0.09 to 0.16 m²/s and high hazard zones with hydrodynamic hazard above 0.16 m²/s.
Brazilian legislation - Law 12,334/2010 and EAP:

In Figure 19 is presented the self-rescue zone (ZAS), referring to a distance of 10 km from downstream dam toe.

The region of the watershed that is far from the dam with a radius of 10 km and is contained on elevated areas susceptible to be reached by the flow are of responsibility of the entrepreneur of the dam, he is the one who must take the required emergency actions. Besides this area, at the ZSS, the hazard level should be analysed considering the impacts on the population and on the environment from the impacted areas, thus, demanding further studies of the functionalities of each urban space from the impacted cities.

The knowledge of these information can contribute on the definition of evacuation routes and shelters for people at the ZAS.
Zoning considering physical mechanisms of human body instability:

Instability formulations were applied considering sliding and toppling of the body, described by three authors: Jonkman and Penning-Rowsell (2008), Xia et al. (2014) and Milanesi, Pilotti and Ranzi (2015).
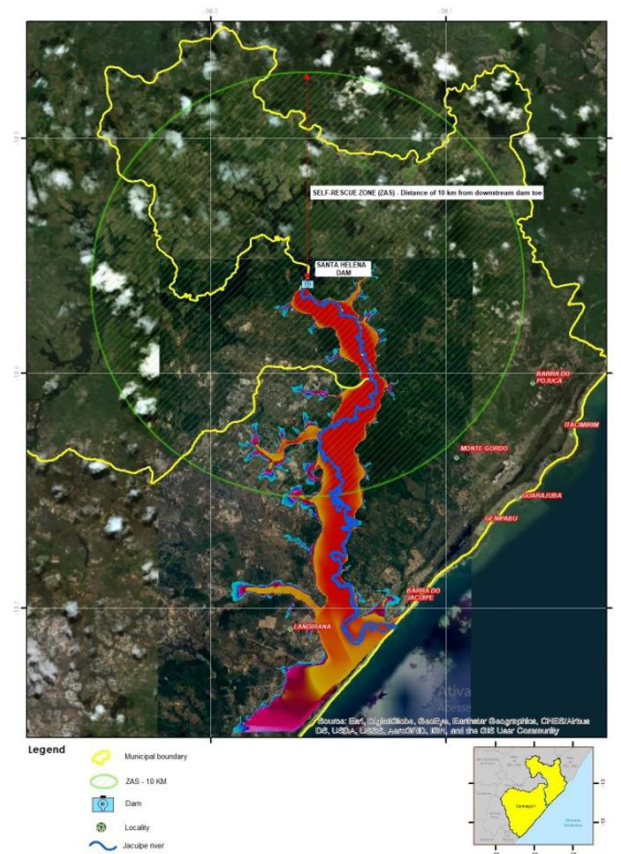Jonkman and Penning-Rowsell (2008):

Figure 19. Hazard mapping considering Brazilian legislation criteria.
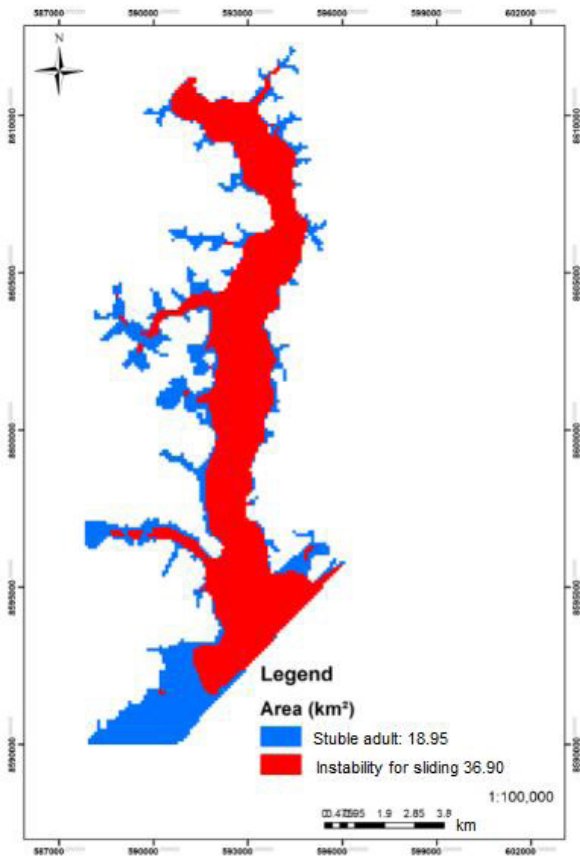
Figure 20. Hazard mapping considering the thresholds of sliding instability for adults in accordance with Jonkman and Penning-Rowsell (2008).
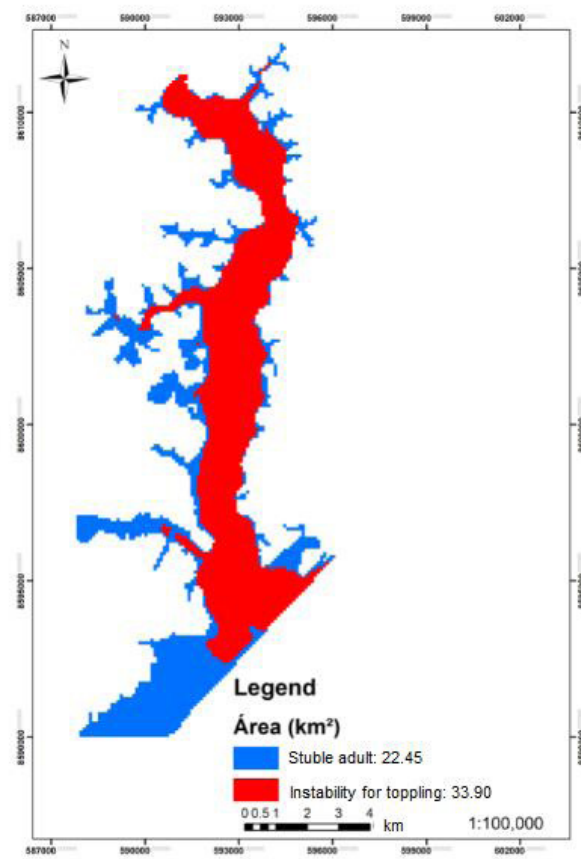

Figure 21. Hazard mapping considering the thresholds of toppling instability for adults in accordance with Jonkman and Penning-Rowsell (2008).

The physical mechanisms of sliding instability and moment instability were described by relations of velocities and water heights. The hydrodynamic hazard to sliding (hv^2) represented friction instability and hv moment instability. For this research, local gravity was defined as 9.81 m/s^2, specific mass of fluid as 1000 kg/m^3, drag coefficient of the flow was equal to 1.1 and body inclination in relation to the soil was an angle of 75°. Zoned results from the simulation according to criteria by Jonkman and Penning-Rowsell (2008) are presented in Figures 20 and 21.

According to developed formulations by Jonkman and Penning-Rowsell (2008), the body will suffer toppling when the hydrodynamic hazard is greater than or equals to 1.1 m^2/s, and it will slide when it is greater than or equals to 0.3 m^3/s^2.

Based on comparison of the hazard areas in Figures 16, 18 and 19, it is verified that in every zone considered as high hazard by USBR (1988) the individual will topple or slide. On the other hand, the zone considered as the judgement one, it was not observed body instability.

Xia et al. (2014):

Similar to Jonkman and Penning-Rowsell (2008), both toppling instability and sliding instability are made by equilibrium of forces and moments, but, they also consider various parameters related to the physical attributes of the body and his clothing in the wet area.

In this research, parameters α and β, present in equations, represent empirical coefficients calibrated in the Sediment Research
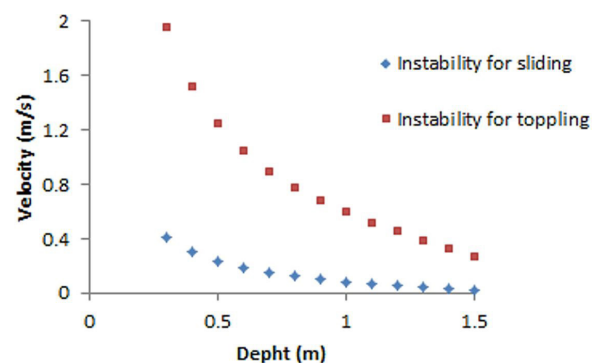

Figure 22. Hydrodynamic hazard (hv) for sliding instability and toppling instability.

Laboratory from Wuhan University in China. For the case when the body is susceptible to slide, α and β are equal to 7.975 $m^{0.5}s^{-1}$, 0.018, and for conditions in which the body topples, equal to 3.472$m^{0.5}s^{-1}$ and 0.188.

The values of a1, b1, a2 and b2 also present in the equating of moment instability and sliding instability, relative to physical attributes of the human body were equal to *0.633*; *0.367*; *$1.015 \times 10^{-3} m^3 kg^{-1} and -4.927 \times 10^{-3} m^3$*, respectively to both instability mechanisms.

In Figure 22 is presented the curve that relates values of velocities and water depths sufficient for the body to slide and topple.

Based on the Froude number (Fr) calculated from Figure 20, in view of the formulation presented by Porto (2006) for free conduits, considering water depth equals to hydraulic height of

the section, sliding instability starts in supercritical flow regimes (1<Fr≤1.16) with heights up to 0.3 m, in which they present higher velocity and lower depth of water. Above 0.3 m, the subcritical flow regime prevails. Toppling instability was recorded in subcritical flow regimes for the entire analysed period, in which flow velocity is smaller and water depth is higher, therefore, there is a higher probability of the body to topple (0.13≤Fr<1). The hazard zoning considering hazard thresholds proposed by Xia et al. (2014) are presented in Figure 23.

In 52.36% of the flooded area the individual is susceptible to slide or topple, then, it may be the method for hazard classification that best favours safety, when compared to USBR (1988), Jonkman and Penning-Rowsell (2008), Xia et al. (2014), and the definition of zones recommended by the Brazilian legislation.
Milanesi, Pilotti and Ranzi (2015):

For this analysis, it was adopted a diameter of each leg equals to 0.13 m; the angle formed by the inclination of the body in relation to the surface equals to $\pi/2$; and the surface angle in relation to a horizontal axis equals to 0°. Figure 24 illustrates the different relations of hv that satisfied the established instability conditions by toppling and sliding.

The Fr calculated from Figure 24 to different instability mechanisms of the human body indicate that the body subjected to high flow velocities in low depths (Fr>1) will tend to slide to the entire height of the resulting flow, as opposed to toppling, which usually occurs in high depths and low velocity (Fr<1), being identified considering a water height of 1 m. The zoning considering these physical mechanisms are exhibited in Figure 25.

The hazard areas of instability for the human body by sliding decreased by 5.05 km² and by toppling, approximately, 4 km² when compared to the ones from Xia et al. (2014). That is probably due to the consideration of the angle between the person and the surface in the equations, which refers to the ability of the body to adapt to the flow and to attempt to keep standing, lowering the risk.
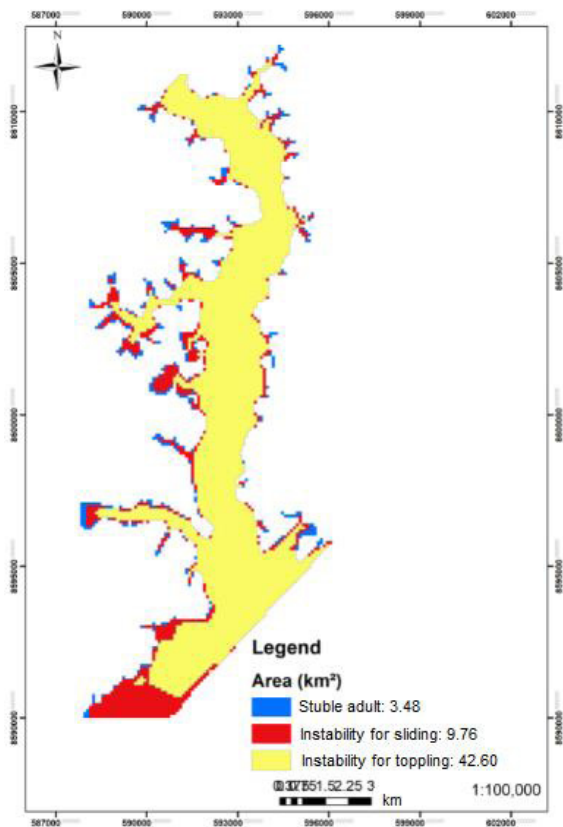

Figure 23. Hazard zoning for sliding and toppling in accordance with Xia et al. (2014).
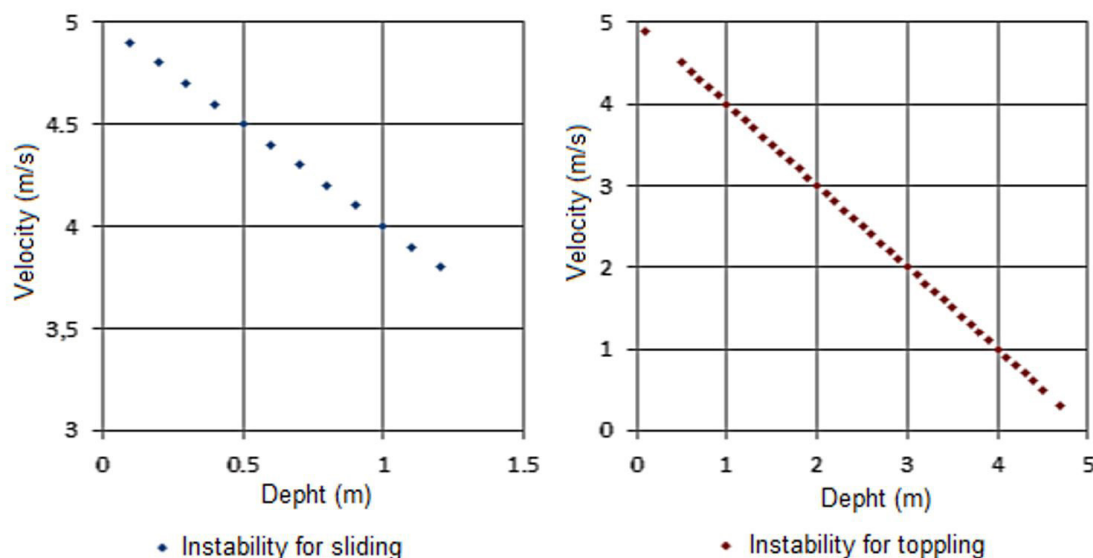

Figure 24. Hydrodynamic hazard (hv) in order to occur instability by sliding and toppling in accordance with Milanesi, Pilotti and Ranzi (2015).
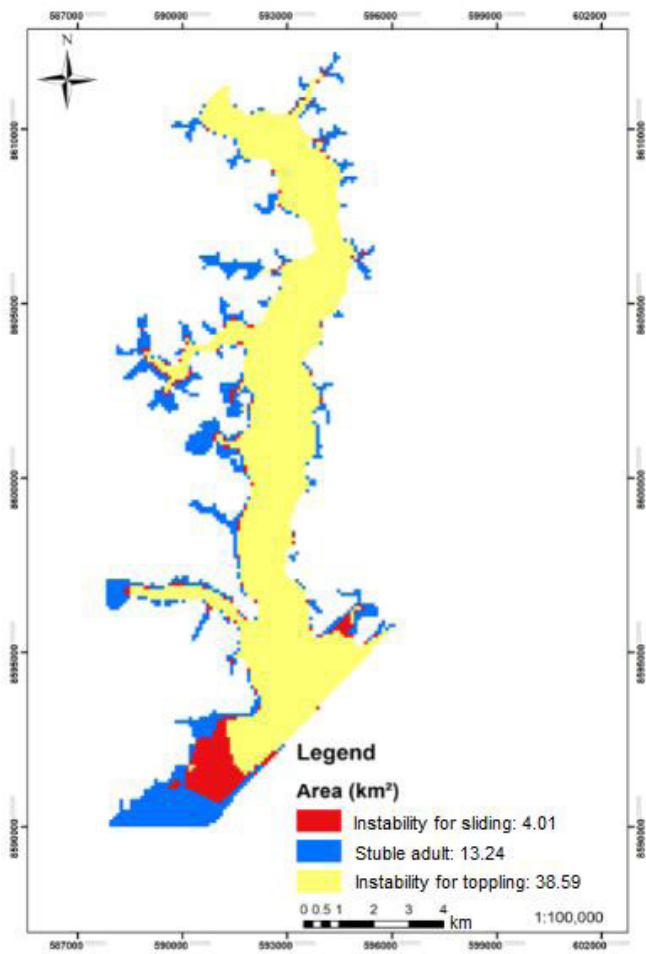
Figure 25. Hazard zoning for toppling and sliding in accordance with Milanesi, Pilotti and Ranzi (2015).

Comparing Figure 23 to Figures 18, 19 and 21, it is verified that this zoning presented similar areas of instability of the body, then, it is possible to consider it as the "intermediate" of the previous zonings. The zoning proposed by Xia et al. (2014) presented 18% of hazard area (considering zones with instability for the body by sliding and toppling) superior to Milanesi, Pilotti and Ranzi (2015) and 29,52% superior to Jonkman and Penning-Rowsell (2008).

CONCLUSIONS

The focus of this work was to analyse the influence of physical mechanisms that cause instability to bodies in floods, due to dam breaks, using different hazard zoning. The results here presented confirm that the consideration of toppling instability and sliding instability, on the definition of hazard zones, contributes to hazard management, minimization of impacts and disaster prevention.

In view of the Law 12,334/10 that qualifies the Dam Safety Plan, where should be contained the EAP, and, consequently, a satisfying hazard zones mapping, the consideration of different

hazards to human beings in a flood situation, including loss of equilibrium, may ensure more safety to the lives of the population.

After hypothetical simulation of the propagation of the flood wave caused by Santa Helena Dam rupture, in the bi-dimensional hydrodynamic model HEC-RAS 5.0, it was observed that if the flood imprint was zoned considering only the technical criteria recommended by the Law 12,334/2010 or by USBR (1988), with hydraulic variables (water velocity and depth), socioeconomic aspects or ZAS and ZSS, those can put at risk the lives of different people, mainly because each individual has physical attributes (mass, height) different from the other, and that's why they behave distinctively when facing inundations, toppling or sliding in varied positions.

When the influence of surface roughness is analysed during the simulation of the water flow on the propagation of the flood wave caused by the hypothetical rupture of Santa Helena Dam, through the test of Manning's coefficient variation, it was noticed that the Manning's coefficient influences the results of the hydraulic variables flow velocity and height in the simulation. In the majority of the analysed spots, as higher it was the Manning's coefficient value adopted in the simulation, lower it was the flow velocity and higher it was the water height. Moreover, the reduction of Manning's coefficient from test 1 to test 3, from 0.05 $m^{-1/3}.s$ to 0.01 $m^{-1/3}.s$, only in the river channel produced a rise of 20.51% in hazard zoning, considering the human body instability by sliding.

Three quantitative methods of mechanisms of bodies instability were compared in order to analyse the sensitivity of the established hazard zones, and it was verified that the equations which included the buoyancy force and the angle between the person and the surface (due to the attempt to keep standing in a flood) were the ones that resulted in bigger variations of hazard zones, as Equations 4 and 5, proposed by Xia et al. (2014), presenting zones almost 30% higher to the most simplified ones as those from Jonkman and Penning-Rowsell (2008).

From the three methods applied, the method oriented by the instability equations by Jonkman and Penning-Rowsell (2008) was the one that presented more stability zones for the body (81% more than the method by Xia et al. (2014) and 30% more than the method by Milanesi, Pilotti and Ranzi (2015)).

Through the analysis of the Froude number and hazard zoning, it was confirmed that toppling usually occurs in subcritical flow regimes, low velocity and high water heights, different than the sliding, which are more susceptible in supercritical flow regimes, that present high velocity of flow and low water heights.

Hazard zones using the classification of USBR (1988) do not present higher variation when compared to the zones that consider instability mechanisms of the body, but, still, the application of criteria that recognise the loss of human equilibrium may contribute for a better definition of the judgement zone, as it specifies areas where the body could slide or topple. For example, in the entire judgement zone, according to instability criteria adopted by Xia et al. (2014), was noticed hazard for the body to slide, and, in approximately 5% of the area, to topple.

Thus, it is concluded that the knowledge of potential areas where the human body may come to topple or slide is an important information for the knowledge of hazard managers

and civil defence, because, by means of it, they will be able to act and aid for a better hazard management and safety actions.

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Authors contributions

Luan Marcos da Silva Vieira: Equations survey of body instability mechanisms, simulation of the HEC-RAS 5.0 hydrodynamic model, data and results analysis.

Andrea Sousa Fontes: Determination of the study methodology, support in the analysis of results and research supervision.

André Luiz Andrade Simões: Support in the analysis of results and research co-supervision.