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Systematic review on the use of digital terrain models in dam rupture simulations

Abstract

The study of hypothetical dam failure simulates the flow of the volume released by a dam in partial or total collapse. The calculations of wave propagation over the ground downstream of the eroded dam are performed by fluid hydrodynamic simulation programs. In this sense, the input data of the simulation model can be summarized in the physical characteristics of the fluid, the propagation hydrograph and the digital terrain model (DTM). Thus, this systematic review aimed to seek current bibliographic sources around the topic of simulation of hypothetical dam failures, with emphasis on the topographic representation of the valley through which the wave propagates, as a subsidy for simulating the failure of Dam B1, in Brumadinho, MG, Brazil. The results were classified according to categories in order to better differentiate the multidisciplinary content of the topic addressed.

Keywords: dam, digital terrain model, failure, mining, tailings, rupture

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Abbreviations: DTM, digital terrain model; HEC-HAS, hydrologic engineering center- river analysis system; LIDAR, light detection and ranging; NDSP, national dam safety policy

Introduction

According to[1] based on recent research carried out in the literature, there are 769 tailings dams registered in Brazil, where 425 of them are included in the National Dam Safety Policy (NDSP) and 344 are not under the control of NDSP. Due to the high environmental, economic and social risks associated with dams, studies that address this topic are of special interest to the populations affected by these structures, hence the motivation and possible relevance of the research carried out in this work. In this context, it is important to mention the rupture, in January 2019, of the mining tailings dam B1, of the Córrego do Feijão Mine, belonging to the mining company Vale, located in the municipality of Brumadinho - MG that caused the biggest[2] accident in terms of victims of the Brazilian mining history. This dam B1 failure event impacted a large part of society, making the social, environmental and economic consequences much broader than the area directly affected. Therefore, this study is of special interest to the agents involved in the management and operation of dams, because from the analysis of the results obtained in these simulations, the Emergency Action Plans are prepared, which determine the emergency procedures to be adopted in the event of a possible dam collapse.

The hypothetical failure study aims to investigate the flow of the volume retained by a dam through the valley downstream, when this structure suffers some type of failure that causes its partial or total collapse. Currently, these simulations have been carried out in 2D hydrodynamic models, where the rupture hydrograph is propagated over the Digital Terrain Model (DTM) of the valley downstream of the dam. As a result, information such as the inundation area, depth, velocity and the arrival time of the rupture wave is provided in continuous data format. Relief features can fulfill the function of hydraulic control causing, for example, backwater or wave spread. Thus, the reliability of the results provided by the model is directly related to the quality of the input DTM, which leads several researchers to consider it as the most important input element of the simulation, which is pointed out in[3,4] and[5] These authors, as well as[6,7] and[8] used the computer program HEC-HAS (Hydrologic Engineering Center- River Analysis System) which was developed by[9] widely used in the simulation of water dam failure, and, from version 6.0 onwards, it also started to represent the propagation of non-Newtonian fluids, describing in a more appropriate way tailings dam failure events. In preventive and operational terms of displacement and movement of the dam due to the pressure of the material accumulated in it, it is worth mentioning a recent work published by[10] where these authors used geodetic methods combined with the use of Global Navigation Satellite System (GNSS) and surveying total station.

The HEC-RAS model uses the bathymetric sub grid calculation method Figure 1, in which the information on hydraulic radius, volume and section area of the cells of the calculation grid, represented by the blue lines, are previously calculated from the topography, represented by the gray mesh. In this pre-processing, some topographic details are lost, however information with sufficient precision is preserved to ensure that the sparse numerical method can explain terrain influence through mass conservation.[9] Due to this characteristic of the HEC-RAS model and considering the availability of data and real information about the B1 dam event that allows comparing results, the purpose of the study was to investigate whether the spatial resampling of DTM from high-precision surveys, such as scanning laser, would imply a significant difference in the results obtained in the B1 dam rupture simulations. The research has an exploratory character to observe the response of the hydrodynamic model in relation to the variation in the spatial resolution of the, DTM, as input data. In addition, it is possible to mention some recent searches about the dam break or hydrologic studies by several authors as[11,12] for example. The interdisciplinary character of the study presented the need to search

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the literature for the most current studies on the topics addressed. Therefore, a systematic review was carried out seeking a historical and methodological overview of several works, taking into account a comprehensive academic database, such as the Brazilian system of CAPES Periodicals.

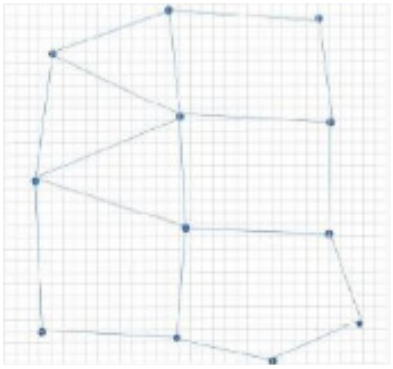

Figure 1 Calculation mesh and bathymetric sub-mesh. Source.[9]

Material and methods

The development of the literature review followed structured steps, based on the systematic review methodology proposed by[13] which was adapted for the purposes of this work. Thus, the bibliographic research was structured according to Figure 2. From then on, the emphasis was defined on the three main axes of search, namely: topographic representation, hydrodynamic modeling and dam failure. The intention of this thematic association was to facilitate the direction for bibliographic materials that have an interrelationship of the thematic axes in their contents. In organizing the search protocol, Table 1, the CAPES/MEC Portal (CAPES journals) was chosen because it has an integrated database, with topics ranging from "references and abstracts of academic and scientific works to technical standards, patents, theses and dissertations, among others, covering all areas of knowledge".[14] Regarding the date of publication, preference was given to the most recent publications, classified in annual intervals, with a maximum limit of 3 years, and using Portuguese, English and Spanish languages. Keywords were selected which, combined with the use of special characters and Boolean operators, formed the search expressions. Table 1 presents the details of the established search protocol. The selection of the material took place through a careful analysis of the search responses and the application of possible filters to better direct the results and, consequently, optimize the choice of bibliographic references that best linked to the proposed theme. From the citations found in the researched publications, new references were incorporated, expanding and continuously improving the research.

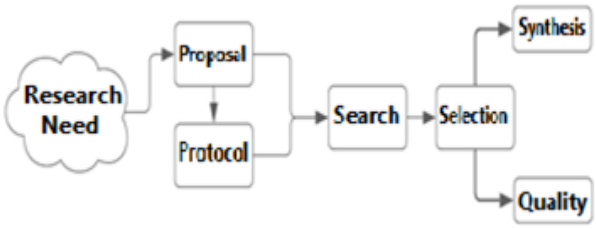

Figure 2 Structure of the bibliographic research. Source: Authors (2022).

Table 1 Systematic review protocol. Source: Authors (2021)

Date of Research	**28/01/2021**		
Local	CAPES Portal		
Language	Portuguese, English and Spanish		
Keywords	Brumadinho Disaster – Digital Elevation Model – Dam Break – Hydrodynamic Models		
Search Expressions	a) Brumadinho OR "Córrego do feijão" OR "B I dam" b) dam (break* OR fail* OR collaps* OR breach*) c) DEM OR DTM OR DTS OR terrain OR "terrain model" OR "digital elevation model" OR "digital terrain model" d) disaster OR accident OR event OR ocurrence OR collapse e) evaluat* OR assess* OR rat* OR compar* OR quali* f) Stud* OR simulation OR map*		
Search Form	a AND d	b AND f	c AND e
Motivation	Rupture of B I	Rupture Studies	DTM Analysis
Year of Publication	2019 – 2021	2021	2021
* - Search all variations of word suffixes			
" " - Search identical term			
( ) - Term Grouping			

Results

Table 2 presents the results obtained in the systematic searches. From the search formulations carried out, a total of 2006 titles were initially obtained. The main selection criterion was the approach close to more than one of the three established motivations. For example, the three titles selected in DTM Analysis, Table 2, present DTM studies applied to the simulation of flood events, whether natural or as a result of a dam collapse. The selected titles provided new authors, which were added to the initial results. Other sources used were publications by national authors, who in recent years have been developing research in the scope of fluid hydrodynamic simulation. In this sense, in addition to the works by[3] and[4] central references on the subject, articles dedicated to the evaluation of hydrodynamic models and for studies of retro analysis of dam failures were also selected. Due to the thematic diversity that make up the universe of hypothetical

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dam failure studies, the three main axes initially established were divided into classes in which the 51 selected bibliographic references were distributed. Table 3 and Figure 3 show the distribution of titles according to the topic addressed. It is worth noting that a reference can have its content pointed to in multiple classes.

Table 2 Systematic review protocol. Source: Authors (2021)

Search Form	a AND d	b AND f	c AND e
Motivation	B1 Rupture	Rupture Studies	DTM Analysis
Year of Publication	2019 – 2021	2021	2021
Result	192	611	1.203
Selection	5	2	3

Table 3 Classification of selected titles by thematic axis. Source: Authors (2021)

Thematic Classes	References
Literature Review	2
GIS	13
DTM	20
LIDAR	15
Hydrodynamic Model	31
Rheology	15
Dam	23
Córrego do Feijão	13

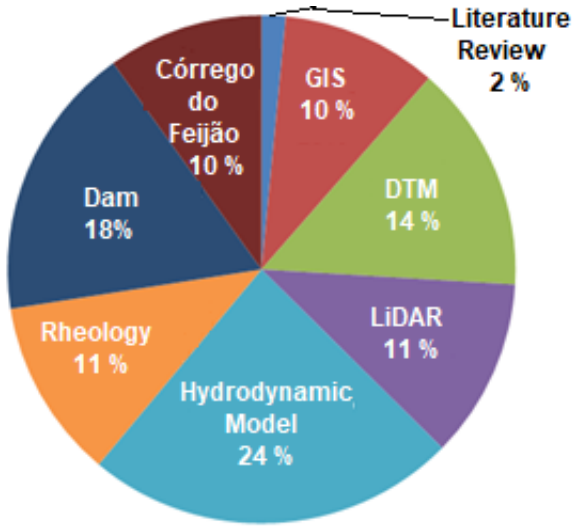

Figure 3 Thematic distribution of titles. Source: Authors. (2021).

Discussion

Based on the classification of references, it was possible to select the titles with the greatest contribution to the study. Regarding hydrodynamic models, the publications of the United States Army Corps of Engineers[9] explain all the equations contained in the HEC-RAS (Hydrologic Engineering Corp – River Analysis System) simulation program, version 6.0. A considerable update introduced in this release is the ability to represent the propagation of hyper concentrated fluids. The other elements of the model such as the input and output boundary conditions, computational time, simulation time interval, calculation mesh determination and other information about the functionality of the program are covered[15] mathematically describes the use of the bathymetric sub-grid by the algorithm of determination of dry or wet surface by hydrodynamic models. In[8] there is a sensitivity analysis of the HEC-RAS model, version 5.03, where the input data were changed in order to observe the effect on the results of speed and depth of the patch as well as flow and time of wave peak. From the observed results, he states that the topography is not always the most important data on the simulation result, and the use of low resolution topography may be admitted depending on the morphological characteristics of the valley through which the wave propagates[16] used the HEC-RAS in the Al-Khair dam failure simulation and reached a correlation coefficient of 0.57 between the simulated and observed phenomenon.

On the topic of Dam, the works by[17] propose a methodology for the evaluation of dam failures, considering the geotechnical characteristics of the tailings.[2] evaluated the methods used in dam failure studies through the retro-analysis of the São Francisco dam failure, using the HEC-RAS and FLO-2D model, and concluded that the topographic representation tends to be the main agent in determining the flood spot by simulation,[18] who presents the theoretical basis of rupture studies, carried out a retro-analysis of the Fundão dam failure considering different models and simulation hypotheses, drawing attention to the sensitivity of flood prediction by the model in relation to the quality of the input data. In the studies by[7] and[8] analyzes of uncertainties in studies of simulation of dam failure are addressed. Regarding the Córrego do Feijão class, the titles dedicated to Dam I were prioritized, among which[19] who, after an extensive investigation into the technical causes of the collapse of Dam 1, concluded that the event was due to the liquefaction of the material in the massif. About Rheology, the physical characteristics of the material and the behavior of the mobilized tailings flow was described by[19] As a classic reference on hyper concentrated flow,[20] investigate the nature of hyper concentrated sediment flows presenting the principles as well as the classification based on the physical characteristics and concentration of non-Newtonian fluids.[4] classified the gravitational movement of the mass mobilized by the collapse of Dam 1 from the energy level at, debris avalanche, sediment flow and mud flow, and from this classification established different zones of destructive capacity.[17] contemplates the characterization of the rheological properties of the tailings flow.

[3]and[4] considers three scenarios to simulate the rupture of B1. Each scenario is composed of a different DTM, one from a LIDAR survey, another from the SRTM mission and the ALOS project. The conclusion presented is that the DTM scenario from LIDAR presented a superior event prediction capacity when compared to the other scenarios.[21] reviews the use of DTM derived from LIDAR surveys in forecasting flooded areas and reinforces the assertive capacity of the forecast made using this type of data.[6] in his assessment of the use of DTM available online for modeling floods, found that there is a tendency to overestimate flooding when this type of resource is used. Regarding the DTM theme,[22] presents a review of methods for evaluating the quality of digital elevation models with the use of reference data and without this use, based on criteria established for the use of this data by the user.[23] presents proposals for the evaluation of the altimetric accuracy of LIDAR data.[24] propose a new method of positional quality control of digital maps in which the sample size is determined as a function of the data population size. Finally, the search protocols were based on the methodology proposed by[13] as a systematic review of the knowledge developed over time in the field of medical sciences.

Conclusion

The methodological proposal provided satisfactory results in the selection of references with contents that present a greater correspondence with the interdisciplinary nature of the researched

topic. For additional studies on this subject, we suggest the application of the methodology in research with different themes and evaluation of the obtained return.

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Conflicts of interest

There is no conflict of interest.

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