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Impact of Dam Materials and Hydraulic Properties on Developing the Breaching Dimensions

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HIGHLIGHTS

- The 2D HEC-RAS models for the overtopping failure in a virtual dam were examined.
- The maximum breach width occurs in a short time with a side slope greater than 1:1 in the concrete face dam.
- The medium erodibility in each scenario gave a small width value and a long time for breach forming.
- Breach width and time are more sensitive to reservoir-filled capacity.

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ABSTRACT

Dam safety is an important issue as it directly influences environmental and life losses. Embankment material and embankment core are important factors that contribute to determining the size and hydraulic characteristics of the breach that occurs due to dam failure. The current topic is to present the analysis of the impact of the dam materials properties and hydraulic characteristics on breach dimensions due to overtopping failure using 2D-HEC-RAS software with the aid of RAS-Mapper. The analysis was made by Digital Elevation Model (DEM) conversed to a Triangular Irregular Network (TIN), then the 2D area of the dam was determined and the storage area boundary was calculated. Mosul dam in Iraq, considered one of the big dams that consist of different materials in the core and body, was selected as a case study to simulate the dam breach development due to overtopping failure. Six scenarios of dam failure were carried out for three types of dam materials (dam with corewall, concrete-face dam, and homogeneous zoned fill dam), each with high and medium erodibility. All scenarios were made for the reservoir elevation of 341 m which is considered the probable elevation for failure occurrence. The results showed that the minimum and maximum values of breach width were found to be 542 m and 1118 m, respectively in both cases of concrete-face dam type with a high erodibility and homogeneous zoned fill dam with medium erodibility rate. It has been illustrated that the medium erodibility in each scenario gives a smaller width for a long time, especially in homogeneous zoned fill dam type which is a good indication in engineering design. The analysis of sensitivity was carried out to examine the impact of pool volume at failure on breaching time and width of the breach. It showed that the breach width is more sensitive to reservoir fill capacity and there is a linear relationship between water volume reduction ratios and the breach width. Finally, tests of the six cases reveal that the proposed model is sensitive to soil conditions.

1. Introduction

Overtopping is the most common type of failure that occurs coming from high quantities of flood waves due to climate change or any other reason which makes water seep over the crest of the embankment dam and then cover most of the neighboring land [1]. This failure can occur in an embankment dam, levee, or dike when a flood level exceeds the design water levels. Therefore, predicting the breach properties and outflow hydrograph is important that will aids in developing the inundations maps and determining the most risk areas [2]. Usually, the presence of rigid or lean erodible materials has a significant impact on dam failures and then the propagation of flood waves that result in structural damage harm to the environment, and even human life loss, especially in densely populated areas [3,4]. Numerous dams' cores may be designed based on types of material such Dam- Corewall, Concrete-Face Dam and Homogeneous zoned Fill Dam. Also, the erodibility rate is an important factor in the design of embankment dams. Erodibility in non-cohesive soils is primarily influenced by grain size distribution, density, and form. The use of simulation models, such as 2D HEC-RAS software which is a 2D dynamic model developed by the U.S. Army Corps based on the Digital Elevation Model (DEM) which is a data file that represents a land topography. Numerous studies

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have been carried out and developed in the field of the present research, such as Coleman et al. [5] who conducted flume experiments on a very large reservoir to evaluate the overtopping breaches of homogeneous non-cohesive embankments at a constant reservoir level. Because accelerating breach flows would have little effect on the flume walls, they assumed that the breach centerline in the experiments would be at the flume wall. It was discovered that embankment erosion was primarily lateral rather than vertical. Moreover, the study revealed relationships between breach outflow and breach width. While Chaudhry et al. [6] studied the influence of soil properties on the breaching process and breach flow in the laboratory to examine the effects of cohesively soft sediment on breach stages. The results showed that the peak discharge was reduced by 50% by that non-cohesive soft sediment (silt) and arrival time rise 7.5 times when compared to a levee created with compacted sand. While 15% of the peak discharge was reduced and 4 times increased the time to peak when the soil unconfined compressive strength doubled. Basheer et al. [7] implemented five breach prediction methods in the Mosul reservoir including different water levels to investigate the effect of breach parameters on outflows using 1D HEC-RAS software. The results showed that Froehlich equation was the most suitable procedure for estimating breach parameters. Lakhllifi et al. [8] developed a numerical solver (a finite volume method that is based on Roe's approximate Riemann solver) in 1D and 2D dam break cases. The results showed that the use of the mesh adaptation method to simulate these problems has considerably increased the accuracy and significance of simulation time-saving. Also, Ashraf et al. [9] assessed embankment dam breach parameters using laboratory modeling to provide a vision of the failure of embankments due to overtopping failure. Both cohesive and non-cohesive embankments were tested. Results indicated that in cohesive soil embankments, breach parameters should be determined based on both embankment dimensions and soil qualities. Sílvia et al. [10] proposed a set of core procedures and monitoring techniques in studies of dam breaching in case of overtopping failure. The first step involved the observation of breached model dams under different controlled hydraulic and geotechnical conditions. This test contributed to a better understanding of the influence of the relative compaction and water content of the earth-fill dams in the breaching process. Also, it was observed that earth-fill dams with similar water contents erode faster with high peak discharges. Hui et al. [11] studied the reduction in the celerity of dam break shock waves by applying both groyne and perpendicular piers based on Finite Volume Method. Different scenarios were applied including the set of groynes with different shapes and piers. The results explained that a single set of piers or groynes have no significance but when using the two groups together can reduce the celerity of flood wave. Abdulrazaq et al. [12] carried out a sensitivity analysis for Hamren Dam by implementing the 1D HEC-RAS program. The results illustrated that the outflow hydrograph is sensitive to the side slope of the breach, while the width of the breach is slightly sensitive to the peak discharge in contrast; the time of breach is insignificant for peak discharge.

While there are numerous studies focused on the investigation of the dam failures aspects for various earth dams, the aspects in the soil characteristics and the volume of the reservoirs that impact the design of the embankment dam were still needed more investigation. Based on the previous studies mentioned above, the current study was conducted to achieve the following aims: 1- Studying the impact of material types on breach dimensions when a virtual overtopping failure occurs, 2- Studying the sensitivity of hydraulic characteristics such as the volume of water storage in the reservoirs for breach dimensions, and 3- For both the above points, determination of the critical case for the design or grouted considerations.

2. Materials and Methods

2.1 Data collection

The present study focuses on the impact of material types and hydraulic properties on the design of the body and core of an embankment dam. The characteristics of the virtual dam in this study are considered the same case of hydraulic and material properties of the Mosul dam which is located north of Baghdad. Three types of dam materials were suggested in this work, dam with corewall, concrete face dam, and zoned earth-fill dam, each with two erodibility rates medium and high. The dam reservoir capacity is 14 x10^9 m^3 and the dam length and height are 3600 m and 113 m, respectively. Other details are illustrated in Figure 1. The hydraulic data of this study is considered the major factor in the procedure of dam breach simulation such as the dimensions of the dam, the water level of storage, and the capacity of the reservoir [13].

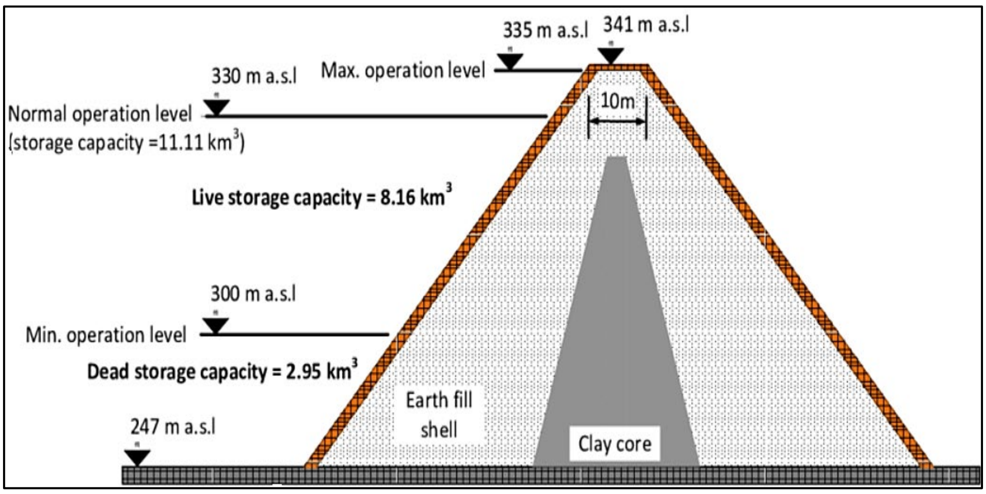


Figure 1: Cross section of Mosul dam [13]

The Digital Elevation Model (DEM) of the case study that was obtained from the USGS site and projection that was defined as UTM-WGS 1984-Northern Hemisphere and zone aid to determine the dam site and reservoir storage area to visualize the dam breach parameters as shown in Figure 2. Also, the analysis is taking into account the soil type to determine other hydraulic and geotechnical losses.

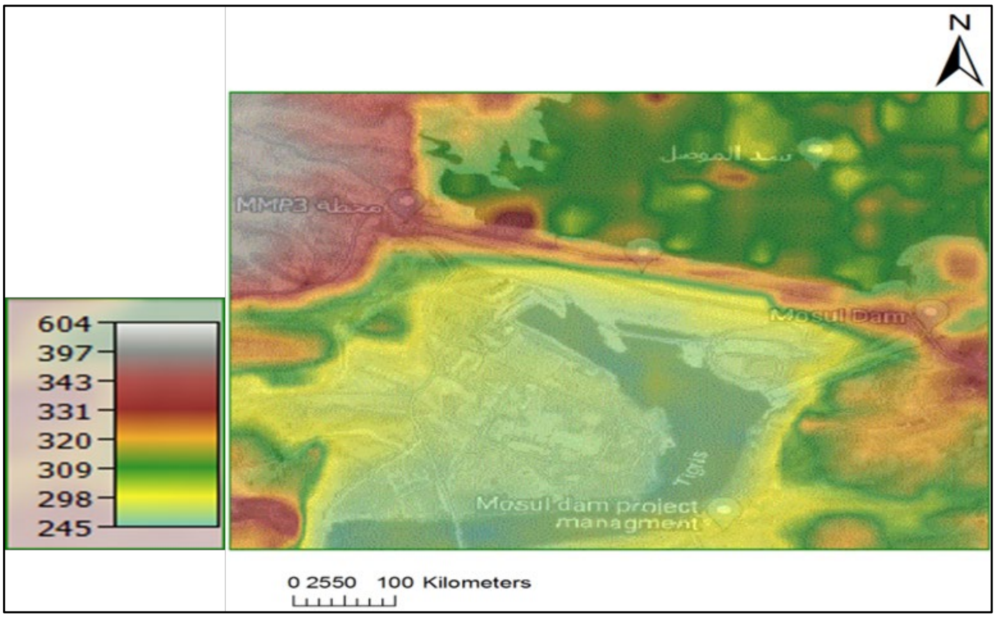


Figure 2: Location of Mosul dam (https:/earthexplorer.usgs.gov)

2.2 Modeling by 2DHEC-RAS software

One of the dynamic models created by the U.S. Army Corps of Engineers is the HEC-RAS software. Steady, semi-unsteady, and unsteady flows with one- and two-dimensional flow are possible to simulate in this model [14]. Three processes are involved in the dam breach modeling by using HEC-RAS software: (1) directing the inflow across the basin, (2) assessing the features of the dam breah, and (3) routing the flood wave downstream. In HEC-RAS software, the reservoir flood may be routed using whichever level of pool routing or unsteady flow routing [15].

2.3 Dam breach model

In the simulation of the dam breach, the section is typically represented by a trapezoidal shape [16]. Therefore, the breach depth, top width, bottom width, and side slope are geometric characteristics as shown in Figure 3. Two models are needed: the first is a hydrologic model and the second is a hydrodynamic model. The hydrologic model is used to determine the outflow hydrograph which is considered an initial boundary condition to a hydrodynamic model [17]. Many empirical equations are taken into account in 2D HEC-RAS software to calculate the breach parameters and formation time, such as Froehlich's (2008) approach as illustrated in Equations (1) and (2) [18].

$$B_{avg} = 0.27\, K_o\, V_w^{0.32}\, H_b^{0.04} \tag{1}$$

$$t_f = 0.0176\, \left(\frac{V_w}{g * H_b^2}\right)^{0.5} \tag{2}$$

Where: B_{avg} : average width of the breach (m), K_o : factor equal 1 for piping failure and 1.30 in overtopping mode, V_w: the mount of the reservoir above the breach's bottom level (m^3), H_b: the vertical distance between the dam crest and breach invert (m), t_f : time in T, and g: the acceleration of gravity (m/s^2). Another approach stated by Xu and Zhang (2009) to determine the other parameters of the breach, as illustrated in equations (3) and (4) [19]:

$$\frac{B_{ave}}{H_b} = 0.787\, \left[\frac{h_d}{h_w}\right]^{0.133} \left[\frac{V_w^{\frac{1}{3}}}{h_w}\right]^{0.652}\, e^{B_3} \tag{3}$$

$$\frac{t_f}{t_r} = 0.304\, \left[\frac{h_d}{h_w}\right]^{0.707} \left[\frac{V_w^{0.364}}{h_w}\right]^{1.1228}\, e^{B_5} \tag{4}$$

Where: $Bave$: average breach width (m), Vw : reservoir volume at the time of failure (m^3), Hb: final breach height (m), hd : dam height (m),: 15 m, hw: height of water above the breach inverts (m), B_3 :factor that is a function of dam characterizes and B_5 : factor that is a function of dam properties,

Xu and Zhang stated that B_3 and B_5 are as in equations (4) and (5), respectively:

$$B3 = b1 + b2 + b3 \tag{4}$$

$$B5 = b4 + b5 + b6 \tag{5}$$

Where: b_1 equal to -0.041 and 0.026, for core walls and concrete faced, respectively, and -0.226 for homogeneous zoned-fill. b_2 is 0.149 for overtopping and -0.389 for piping. b_3 are 0.291, -0.14 for high and medium erodibility, respectively, and -0.391 for low erodibility. Also, b_4 values the ta vare -0.327, -0.674 for core walls, and concrete faced dams, respectively, and -0.189 for homogeneous/zoned-fill dams, b_5 are -0.579 and -0.611 for piping and overtopping, respectively, and b_6 are -1.205, -0.564 for high, medium, respectively, and 0.579, for low dam erodibility.

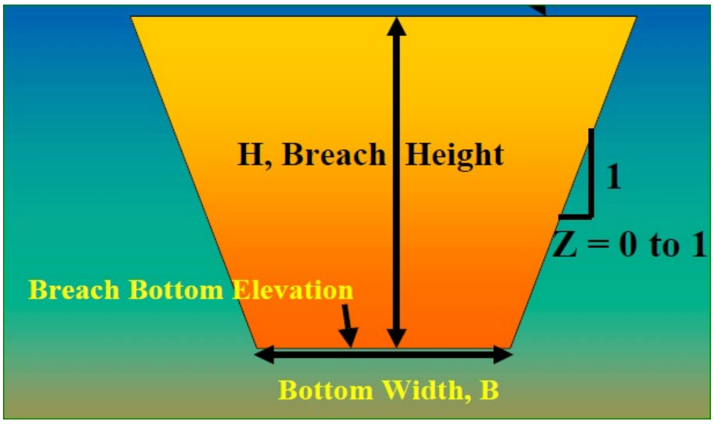


Figure 3: Scheme illustrating the breach dimensions [16]

3. Dam Break Visualization by Two-dimension HEC-RAS Model

In this work, the same conditions of Mosul dam are assumed and completely visualized using 2D HEC-RAS software with the aid of RAS Mapper. The dam breach at overtopping failure was analyzed by considering non-adequate spillway capacity. 2D area, reservoir, and dam are visualized in a Digital Elevation Model (DEM) that has been conversed to Triangular Irregular Network (TIN). The initial elevation of the reservoir is 250 m and the maximum level of 341 m as illustrated in Figure 4 [20].

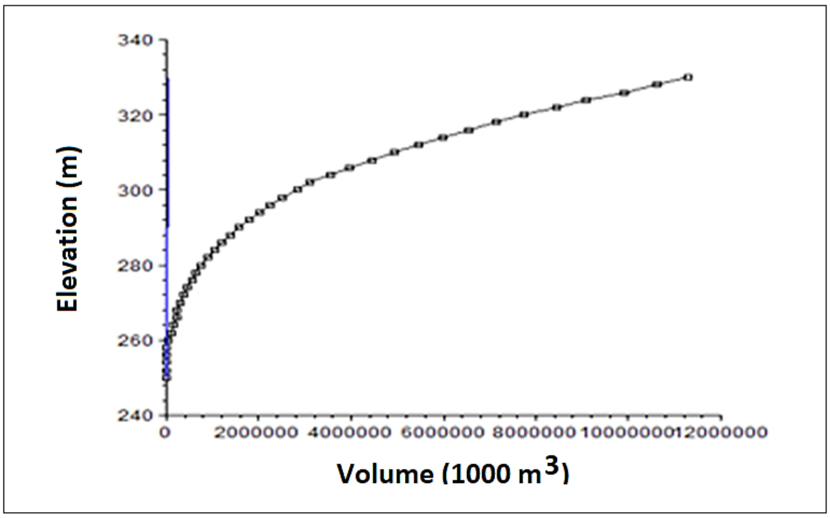


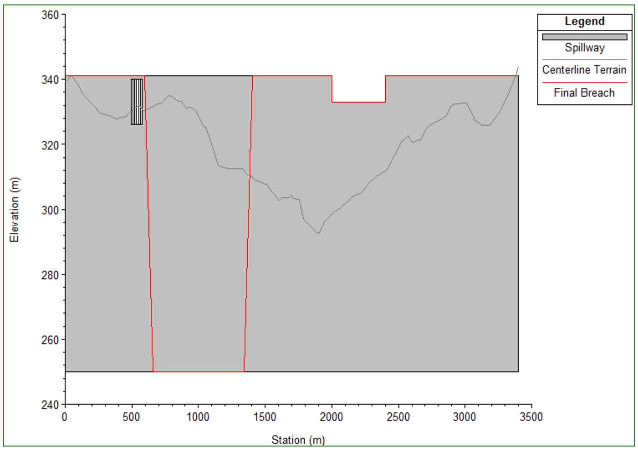
Figure 4: Volume - elevation curve of the reservoir [20]

The cross-section of the dam, volume-elevation curve of the reservoir, side slope, and width of the dam all are represented in the model, with consideration of the fully opened gate state.

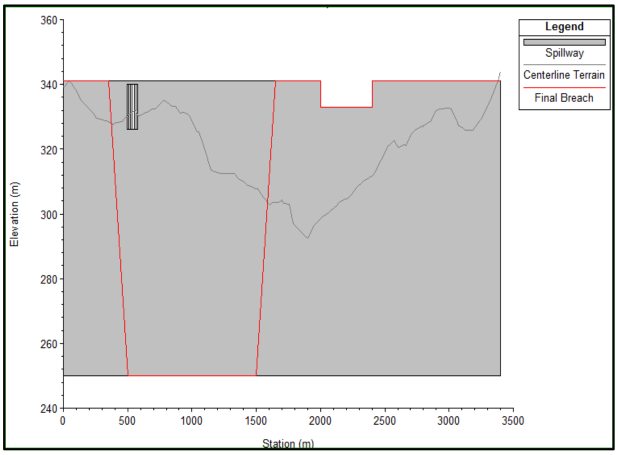
4. Results and Discussion

In this study, the virtual embankment dam breach due to overtopping failure occurring at a maximum elevation of the reservoir (341 m) was simulated. Six scenarios were applied based on the Xu and Zhang [16] approach with different core material types and erodibility rates (dam with corewall, concrete face dam, and homogenous zoned fill dam at both high and medium erodibility rates for each type) to show the change in breach dimensions in each case. Figure 5 explains the trapezoidal shapes of the breach for the three types of materials with medium and high erodibility rates. The figure shows that the homogeneous zoned fill dam can be considered less risky in both cases. While the concrete face dam case at a high erodibility rate is considered the worst case that permits it to pass off a huge flood flow. Also, the results show that the width of the breach is higher in a high erodibility rate than the medium erodibility rate. It is noted that maximum and minimum values of breach width are 1118 m and 542 m for the cases of concrete face type with a high erodibility and the homogeneous zoned fill dam with medium erodibility sequentially as illustrated in Figure 6.

Figures 6 to 8 explain the breach width, breach time, and side slope of the breach, respectively with the three types of embankment core materials of high and medium erodibility rates. The figures show that the greatest value of breach time and the side slope are 16 hr and 1.86, consecutively and the lowest values are 5.2 hr and 0.4 both occur in the case of concrete-face dam with high and medium erodibility serially. Moreover, the figures show that the increasing values of these parameters occur at a high erodibility rate. The average difference between the maximum and minimum values of both cases in the erodibility rate is approximately 0.8.

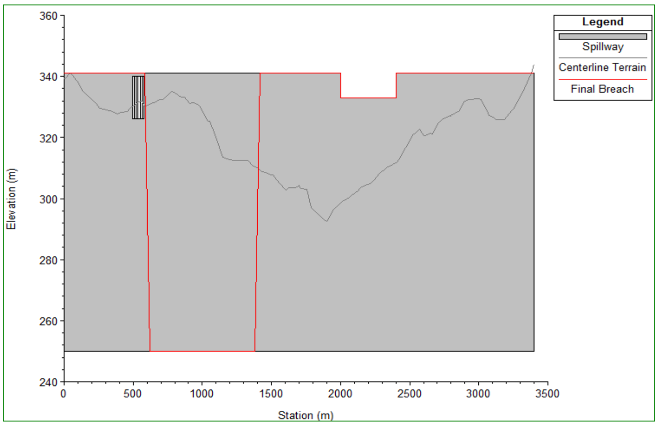


a. Medium earodibility

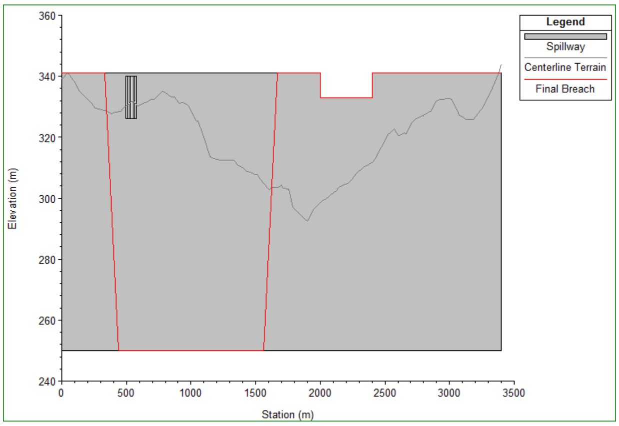


b. High earodibility

Dam with corewall

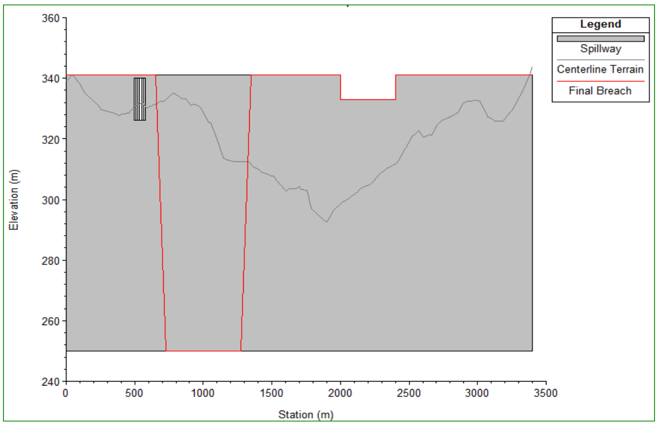


a. Medium earodibility

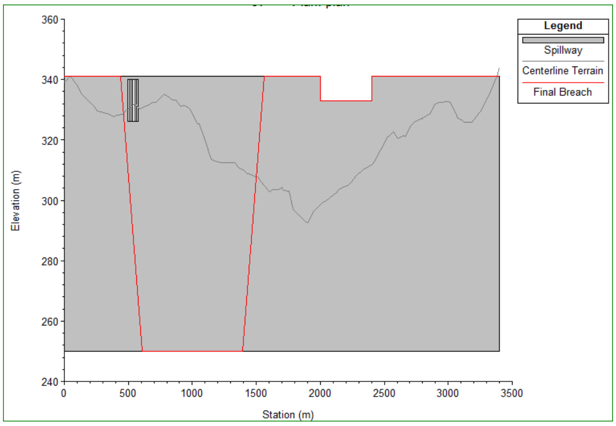


b. High earodibility

Concrete face dam



a. Medium earodibility



b. High earodibility

Homogeneous zoned fill dam

Figure 5: Formation of breach dimensions for embankment dam

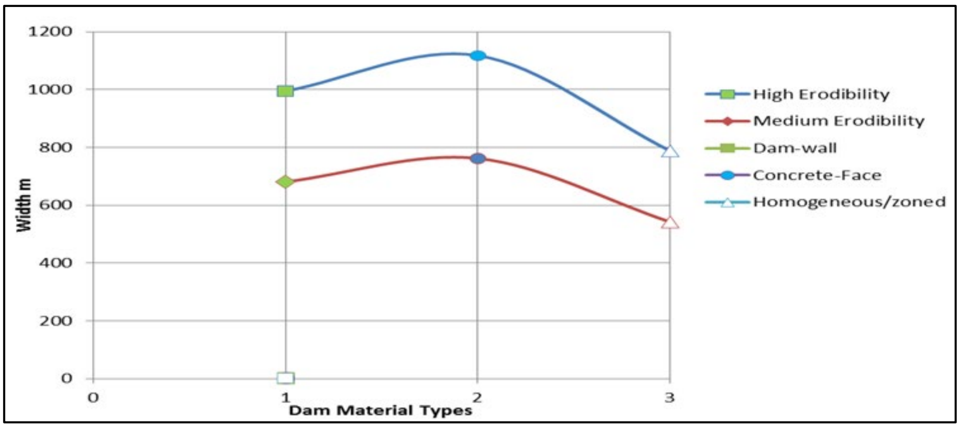


Figure 6: Variation of breach width with embankment core in high and medium erodibility rates

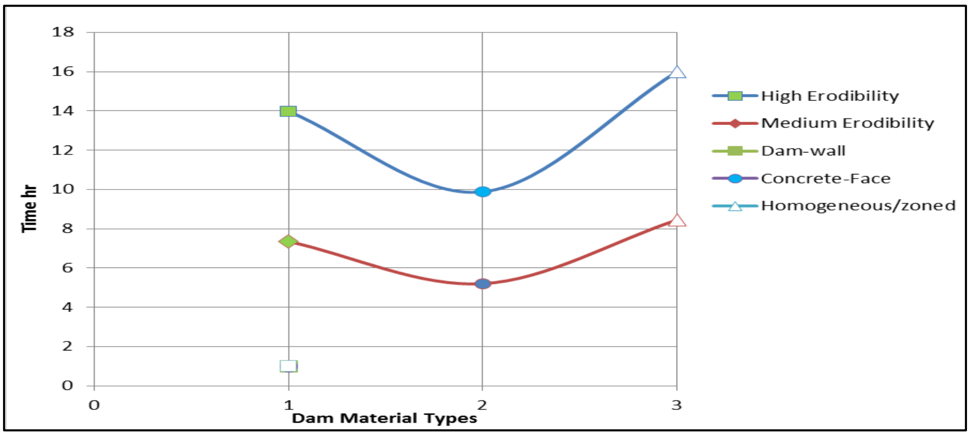


Figure 7: Variation of breach time with embankment core in high and medium erodibility rates

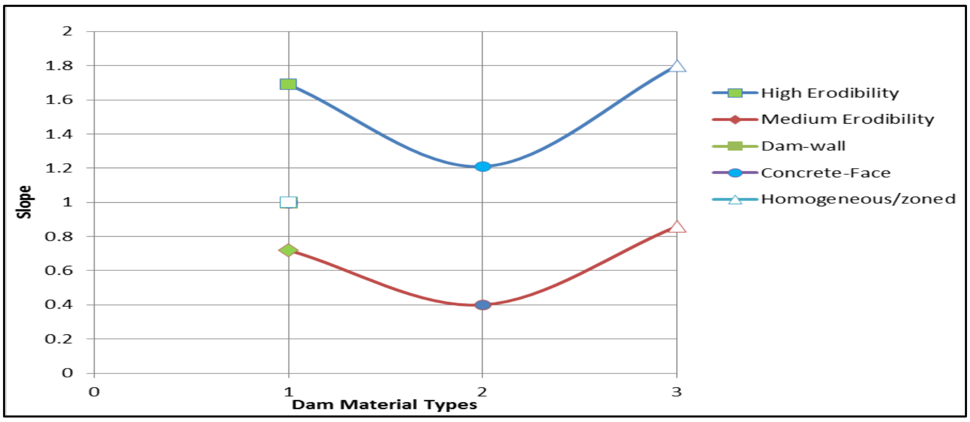


Figure 8: Variation of breach slope with embankment core in high and medium erodibility rates

Also, Figure 8 shows that the lowest values of side slope and time of the breach and high values of width occur in the case of concrete face dams with high and medium erodibility rates. In contrast, high values of side slope and time of the breach and lowest values of width in the case of homogeneous zoned fill dam with high and medium erodibility rate is considered the worst case because of reduction in the relative compaction.

A sensitivity analysis is applied with two scenarios depending on mathematical approaches modified by Froehlich [17] to examine the influence of more sensitive hydraulic factors (represented by the reduction of reservoir capacity) on breach width and time of completing breach as shown in Figures 9 and 10, respectively.

Figure 9 displays the relationship between the width reduction ratio and reduced water capacity ratios. It is noted that the maximum reduction in width ratio is 21% at 0.5 reduction capacity. Also, when the maximum reservoir capacity is reduced at a ratio of (10%), the width of the breach is increased slightly and there is approximately a linear relationship between the reduction ratio of the reservoir capacity and the width of the breach. While the 10% reduction ratio of the reservoir water volume caused the time of completing the full breach to decline linearly. Based on Figure 10, it is shown that the time of the completed breach will range between 14.34 to 10.3 hours when the reservoir capacity terminates reduced at a 50% ratio. In general, when the capacity is filled, there will be a need for more time and decrease with a shortage in the volume of water in the reservoir. The abrupt increase of water level in the lake causes a rushing of water during cracks which weaken the bond between soil elements. When water overflows, quick erosion will occur in the embankment soil.

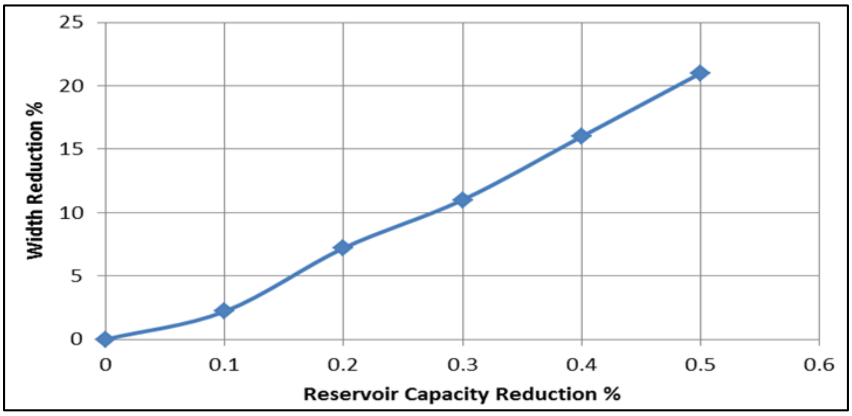


Figure 9: Sensitivity analysis for width and volume reduction ratio

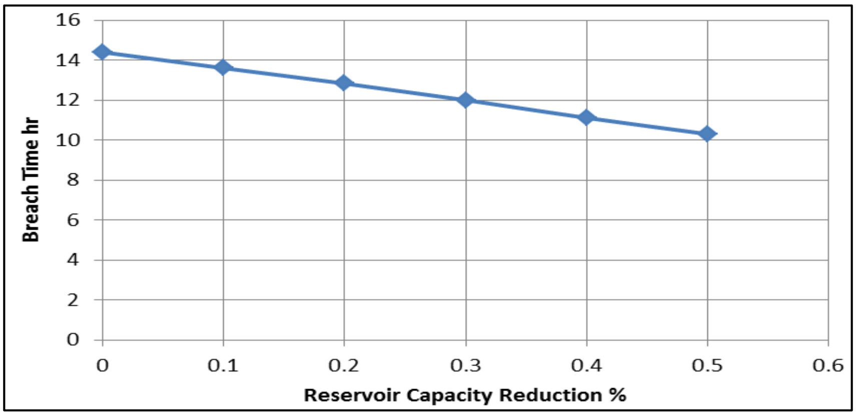


Figure 10: Sensitivity analysis for time and volume reduction ratio

5. Conclusions

The following conclusions can be drawn based on this topic:

1) The 2D HEC-RAS models for the overtopping failure in a virtual dam were examined. It is drawn that the maximum breach width occurs in a short time with a side slope greater than 1:1 in the concrete face dam case at a high erodibility rate which is considered the worst case that permits to pass a huge flood flow. In contrast, the minimum breach width and delay time occurred in the homogeneous zoned fill dam type. In fact, this gives a good indication to take into account in designing dams and is a strength in safety processes too.
2) The medium erodibility in each scenario gave a small width value and a long time for breach forming, especially in homogeneous zoned fill dam type which is a good indication in engineering design. Moreover, the average difference in width, time, and side slope between medium and high erodibility are 305, 6.46, and 0.91, respectively.
3) One of the most crucial characteristics is soil erodibility, and analyses of the six cases reveal that the proposed model is sensitive to soil conditions. Lower relative compaction conditions were shown to cause earth-fill dams to erode more quickly and show greater peak flows.
4) It is necessary to use additives or reinforcing materials, such as soil cement, natural or geosynthetic fiber, etc., to improve the geotechnical qualities of embankment material. Compaction energy has a greater impact on the breach time than compaction moisture content, while compaction moisture content has a greater impact on the breach width.
5) Finally, breach width and time are more sensitive to reservoir-filled capacity, and the results show a linear relationship between reduction ratios of water stored with width and time of the breach.

Author contribution

All authors contributed equally to this work.

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Data availability statement

Not applicable.

Conflicts of interest

The authors of the current work do not have a conflict of interest.

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