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# Nonlinear Analysis of Dam Breaching Parameter

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***Abstract***
*The hydraulic structures such as dam and spillway always pose a devastating threat to the people living in the downstream of the dams where those structures are used for various purpose such as reservoir impoundment for generating hydroelectricity, fulfilling the demand of water supply for the hugely populated inhabitances of urban cities and supplying the demand of irrigation, for the navigation purpose and also for the flood control to protect the cultivated land of the communities.*
*Despite the increasing safety of dams resulting from the improved engineering knowledge and better construction quality, a full non-risk guarantee is not possible, and accidents may occur owing to natural hazards or human actions.*
*A dam can fail due to structural deficiencies in the original design or by external events that trigger conditions where it exceeds the dam capabilities. International bodies and emergency management agencies have identified a lack of awareness of the effects of dam failure outside of the dam safety community.*
*The failure of the dam due to the poor geological condition can cause a catastrophic failure on dams which hugely damages to the life & property of the downstream communities. Also, heavy thunderstorms such as PMF (Probable Maximum Flood) can cause to overtop the dam and the reservoir can empty within few hours of time which led to a devastating damages of the flood vulnerable inundation to the downstream communities of the dam.*
*The excessive seepage of the dam body can lead to a disaster of devastating flood damages which inundate with a high level of flood depth and an enormous amount of peak flood flow to a large area of the cultivated land and into the hugely populated urban cities in the downstream of the dam.*
*In some cases, the reservoir can breach due to the excessive amount of pressure rise due to the earthquake ground acceleration where this pressure cannot sustain by the dam body and it breaches. The earthquake ground acceleration can upheave or subsidence or even tear top to the bottom of the dam body and in the dam foundation which can cause a massive flood flow to the downstream of the dam that can sweep away the downstream inhabitance.*

***Key Words:*** *Dam Breaching, Breach Shape, Breach Development time, Downstream Peak Attenuation*

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## I. Introduction

Hydraulic works such as dams and reservoirs are of fundamental importance for human development since ancient times due to the great benefits provided by the storage of large water volumes, which were used for water supply for drinking, irrigation, hydro-electricity generation navigation, and other water storage purposes. The first dams known date back to 3000 BC in Mesopotamia. In recent times, as early as 1800 AD, technological progress has allowed the construction of large dams. The most impressive ones have been built within the last century, moreover, the number of dams has significantly increased according to water demand. In addition to supplying water and controlling floods, modern dams are often designed for power production.

However, despite its great benefits, the storage of large volumes of water poses serious risks for the downstream areas. Unfortunately, over the centuries, the history of retaining dams has been studded with disasters of various types, sometimes of great magnitude, with loss of human lives and destruction of downstream properties, agricultural lands, historical sites, industrial and productive settlements, and urban areas. Even though a time-related analysis shows that the frequency of failure of large dams has been reduced by a factor of four or more over the last forty years worldwide ICOLD Dam Safety 24th April 2021, dam incidents still occur at present with a non-negligible frequency. In the current year, the failure of the Rishiganga dam (India), recent incident of 60metre high concrete faced rock-fill dam of the 1,200 MW Teesta Stage III hydropower project in Chungthang, North Sikkim, was breached; the power house was submerged and the bridge connecting the power house washed away by a glacial lake outburst flood (GLOF) around midnight on 4th October 2023. Rockfill dam of Sikkim as mentioned induced by a glacier avalanche, caused a catastrophic flood in the downstream valley with many casualties and huge damages to four hydropower plants.

Moreover, the state of emergency was declared over toxic wastewater leaks in Florida due to the dreaded breach of the Piney Point reservoir. In this case a potential disaster was ultimately fortunately averted.

St Francis Concrete Gravity Dam was failed on 12th March 1928 due to the unanticipated adding of the dam height and the pressure behind the dam so its foundation could not sustain the addition stresses. As a consequences of its failure 400 people lost their lives in the casualties.

The Malpasset double curvature concrete arch dam was failed due to heavy thunderstorm. The reservoir level was drastically raised and within hours the bottom outlet gate being opened on 2 December 1959, the dam was failed without warning, almost 300 people died in the disaster.

On 9 October 1963, Vajont double curvature concrete arch dam, suffered a failure of its southern rock slope over an approximate length of 2 km. As a result of the devastating dam breaching; five village communities with 2,040 lives were lost due to the failure of the dam.

On February 9, 1971, the San Fernando earthquake with an estimated magnitude of 6.6 Richter scale occurred and the San Fernando earthen dam was breached catastrophically. To avoid the further damage of the life and the property during the presence of after-shocks, 80,000 people living downstream of the dam were evacuated over a single day and over 340 people were died.

In June 1976; 90 m high Teton rock-filled earth dam was constructed in a steep-walled canyon eroded by the Teton River in Idaho. It had a wide silt core, with upstream and downstream shells consisting mainly of sand, gravel, and cobbles. The dam failed due to excessive seepage and incompetence in resisting uplift pressure in the dam body. The flooding of the downstream regions after the failure of the dam resulted in the loss of 14 lives and caused an estimated loss property of the cost of $400 million.

On July 2018, sudden breaching occurred to a 60m high concrete gravity Saddle Dam in Mekong Basin. The Dam was constructed for hydroelectric-power reservoir of southern Laos, caused catastrophic flooding after the breaching that resulted as a report indicated by the United Nations that 13,100 people were affected, 6000 evacuated, 13 died and 120 remain missing.

Hence it has reported that Overtopping flow is a prominent event of many or even most potential failure modes resulting from floods. Dams could have overtopped by a few millimeters to more than a meter without breaching, but other structures could fail quickly. Overtopping is a failure mode of concern since Costa (1985) reported that of all dam failures as of 1985, 34% were caused by overtopping, 30% due to foundation defects, 28% from piping due to seepage, and 8% from other modes of failure. Costa (1985) also reports that for earth/embankment dams only, 35% have failed due to overtopping, 38% from piping and seepage, 21% from foundation defects; and 6% from other failure modes.

Wider dissemination of awareness on risk factors affecting dam safety is constantly necessary due to the presence of old and new hazardous conditions that can have an adverse effect on stability and efficiency of retention barrages. Some examples of such adverse factors are dam aging and insufficient spillway capacity due to long-term alteration of weather patterns and exacerbated climatic extremes.

All these elements can increase dam-break flood risk in downstream areas, which is further amplified by growing exposure of human settlements and potential high vulnerability to flooding. For this reason, research related to the assessment of the hydraulic risk resulting from the failure of retaining structures is constantly ongoing and involves scientists from all over the world. Moreover, the lessons learnt by dam accidents and catastrophes in the past are still very relevant. Although there are countless works on the general subject of dam safety, only the ones that significantly helped in drafting the review are mentioned in this paper.

Among the possible aspects linked to the topic of dam safety, the assessment of flood hazard associated with a potential total or partial dam collapse is of key relevance and is strictly required by national technical guidelines worldwide. (ICOLD European Club). To this end, relevant flooding variables must be predicted by numerical models, which have seen a growing and unstoppable development for decades with the constant advances in computational techniques. For use in practical applications, dam-break numerical models must be efficient and robust, and capable to accurately track wetting and drying fronts and handle all the complexities that characterize unsteady free surface flows on real topographies. The verification and validation of these models are then necessary before the application to real case studies. Model verification can be performed by comparing numerical results with available analytical solutions of dam-break problems (which usually hold under the shallow water approximation, (Stoker, John Wiley & Sons, Hoboken, NJ, USA 1992

However, such analytical solutions, which in some countries have even influenced the promulgating of legislation on dams, deal with schematic geometries and cannot adequately represent the complex phenomena occurring on real topographies. On the other hand, numerical models can be validated against field or experimental data. Accordingly, in recent decades, great attention has been devoted to set up suitable databases from laboratory dam-break investigations.

Field data can be derived from the analysis of historical dam-break events. However, such catastrophic events are fortunately rather rare, and available data on flood dynamics are typically inaccurate and incomplete. Indeed, there is no targeted preparation or general attitude for collecting of a rich amount of information at the dam site and in the downstream areas during a calamitous event of this kind. Nevertheless, in some cases, data collected after or occasionally during the event (mainly maximum water depths and flood wave arrival times at selected locations, and extent of the flooded areas) are sufficient to set up interesting validation test cases, provided that all other essential data required to perform numerical simulations are available (i.e., the digital elevation model of the floodable area and, possibly, of the reservoir, and the input parameters defining the dam-break scenario).

The profession of dam engineering has a profound ethical responsibility to carry out its professional duties so that dams and reservoirs are designed, constructed and operated in the most effective and sustainable way, while also ensuring that both new and existing dams are safe during their entire lifespan, from construction to decommissioning.

In the event of the failure of Dams which causes a devastating threat to the people living in the downstream of the dams has to be studied in-depth for its mitigation. For the first instance it is needed to establish the modality of it's breaching. The failure of the Dams could be due to overtopping the flood from the crest of the Dam or it could be due to piping which is in the lower parts of the Dam body.

The overtopping model can happen when the reservoir level suddenly rises due to the excessive rain fall in the surroundings or could be due to the slope failure in the vicinity of the reservoir which can spill the reservoir level or could happen when there is a maxim peak ground acceleration which undulate the reservoir water level in spilling mode from the Dam crest. The piping modality could be when there is the excessive seepage in the bottom of the Dam where the foundation of the Dam is poorly constructed in an alluvial foundation. Also, the earthquake peak ground acceleration can tear the bottom of the foundation and the reservoir water starts seeping through the bottom of the foundation.

When there is a dam breaching the rapid outflow from the reservoir water will happen and flow of such rapid evacuation of the reservoir water will behave like rapidly varied unsteady flow. This flow estimation cannot be solved by the traditional way of solving the simultaneous equations but it needs to set up in-house computer model in order to estimate the extreme flood propagation in the downstream.

The dam breaching parameter like the breach opening and the timing of the breaching is a found to be a nonlinear behavior of the breach parameter form the different case study of number of dam failures cases. Therefore, the breaching behavior cannot be easily predicted to estimate the downstream peak flow for its extent of damage.

The study will further analyze the gap of the effect nonlinear behavior of the downstream peak flow impact in the presence of sediment flow and bed erosion of the mobile bed of the river valley. It will also analyze the time impact of time dependent phenomena like in instantaneous or a gradual long period of flow as which will be the critical case to the downstream uncertainty in generating peak flow.

## II. Literature Review

Brief Description of Dam Breaching

The procedure for estimating a potential dam breach mechanism and its behavior on the flood wave consequences requires the collection of information on dam characteristics, such as the type of construction, reservoir volume, and height and length in order to define and evaluate the impacts of a dam failure.

Numerous studies of dam failures have indicated that overtopping and piping are the two major failure modes of earth and rock fill dams (Adamo, N; Al-Ansari; Ali, S.H.; Laue, J.; Knutsson, S. Special Issue - Dam Safety Review 2020). The other causes of dam collapse are seismic vibrations, slop sliding, and sabotage incidents. (Singh A.K; Kothyari, U.C.; Ranga Raju, K.G Rapidly Varied Transient Flows in an Alluvial Rivers. J. Hydraul. Res 2004).

Overtopping failure is defined as water flowing over the dam crest, which leads to the erosion of the channel along the downstream face of the dam. Dam crest overtopping can occur in extreme flood events, Glacier Lake Out Burst Flood (GLOF), mismanagement of the spillway on these occasions, landslides of unstable slopes of the reservoir and the trapping of trees or other objects in the spillway, resulting in the insufficient operation of the dam.

Piping is an internal erosion process that leads to the occurrence of spot leakages on the body of the dam or its foundation and can be classified into backwards erosion, interior erosion, tunneling, suffusion and heave (Adamo, N; Al-Ansari; Ali, S.H.; Laue, J.; Knutsson, S. Special Issue - Dam Safety Review 2020)

The areas which concern such as the identification of the flooded area, which depends on shape and size of the basin, landscape, dam height, reservoir volume, land use/land cover map and dam failure scenario. The water depth and velocity constitute the most important factors to understand the water flow and flood procedure, which depends on the failure scenario, distance from the dam, and the topography of the inundation area. They directly affect the potential for damage to structures, loss of life and impact on the environment. As the depth of water inside structures increases, the damage increases. Nevertheless, even shallow water flowing at high velocity can considerably damage a structure, especially when the water carries debris. Excessive water velocity can lead to increased erosion and the loss of environmental assets (Solava, S.; Delatte, N. Lessons from the Failure of the Teton Dam. In Proceedings of the 3rd Forensic Engineering Congress, San Diego, CA, USA, 19–21 October 2003; pp. 178–189)

The final stage regards the identification of the flood wave's direct or indirect impact, determining the level of damage to structures, infrastructure and potential economic losses or loss of life, which depend on the depth and velocity of the water. The level of damage is not certainly an indicator of the potential for loss of life. Aspects that can affect the probability of loss of life include the distance between the dam and the infrastructure settlements as well as the existence of a warning system to alert the community of an actual dam failure in order to evacuate the area on time

Breach shape

The mathematical description of the interaction between dam material and water flow is not yet fully accurate determine (Morris, 2005). The opening formed in the structure during the failure process which is defined as breach shape that depends on the interaction. For accurate modelling, the soil parameters should be known. Nevertheless, they can be determined only with limited degree of accuracy. Assumptions are made concerning the breach shape in order to avoid the non-linearity inthe equations. Models usually predefine the shape of the breach. Constant breach shape and uniform erosion of the breach section throughout the whole breaching development time, is usually assumed. The breach cross section is often considered to be triangular, rectangular, trapezoidal or parabolic as shown Figure 1.

Johnson and Illes (1976), after analyzing the data from approximately 100 case studies concluded that the breach develops initially in '*V*' shape, three to four times wider than depth later developing in lateral direction once the apex reaches the hardest material of the dam core or its foundation.

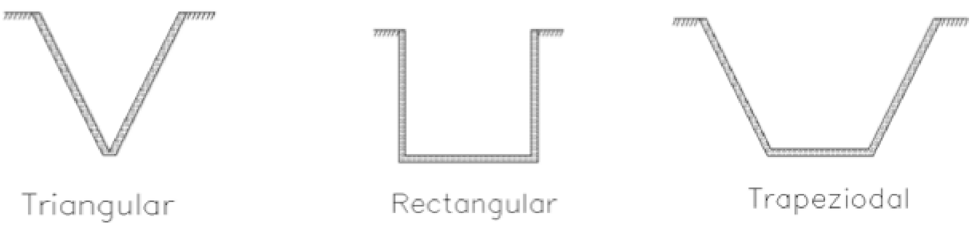



**Figure 1 Erosive patterns of various breach shapes**

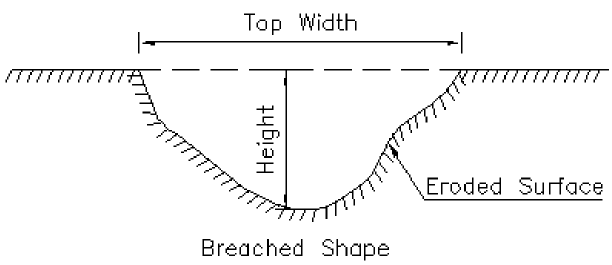



**Figure 2 Parameters of the breach opening shape**

The lateral erosion continues until either the dam is completely washed out, or the reservoir is emptied.

MacDonald and Langridge-Monopolis (1984) observed from the collected historical dam failure events that in most of the cases the ultimate breach shape is of trapezoidal shape. It was concluded that for embankment dams, the breach shape can be assumed to be triangular up to the time the full erosion on the dam body is reached. Once the apex of the triangle reaches to a certain level then the breach develops in forming a trapezoidal section by extending to lateral erosion. The conclusions drawn from several field and laboratory tests performed is that breach sides preserve the vertical angle during the breach development (Morris, 2005). However, a factor influencing the conclusion can be that the rectangular initial breach shapeis predefined in all experiments. Data related to the progressing breach shape development (in time) during real dam failure events are still missing.

The parameters that specify the shape of a breach channel are: the breach depth $h_b$ or the vertical extent of the breach measured from the dam crest down to the breach bottom, width at the top $B_t$ and bottom $B_{bot}$ of the breach channel, and the breach side slope factor *z*.

Breach development in time

Breaching of a structure is a time dependent and nonlinear phenomenon. Water–soil interaction together with often non-homogeneous and specific material properties for each structure lead to the difficulty of accurately modelling the processes involved in breach development. Hydrodynamics effects, sediment transport mechanics, and geotechnical aspects are all present in the breach formation and their accurate modelling is very important for the accurate prediction of breach outflow. The development of effective emergency action plans and the design of early warning systems heavily rely on these prediction results.

Breach initiation time is defined as the time of duration starting with the first observable flow over or through the structure that might initiate warning, evacuation, or awareness, and ending with the start of the breach formation phase.

During the breach initiation phase, the outflow is relatively small, and if it can be stopped the structure might not fail. Typical breach initiation times may range from minutes, hours and to days. Especially piping failure might be preceded by a prolonged initiation phase. The breach formation phase is considered to begin at the point where the structure failure is imminent and ends when the breach has reached its maximum size. For small reservoirs, the peak outflow from a dam break may occur before the breach fully develops due to significant drop in reservoir levels during the formation of the breach, whereas in larger reservoirs the peak outflow may occur when the breach has reached its maximum size.

In the event of the breach formation phase, outflow and erosion are rapidly increasing; while for an earthen dam it might be possible to stop the breaching, it is unlikely that the outflow and failure can be stopped in case of a Rock fill dam. Several small springs were noticed near the right abutment of the Teton Dam, one day before its failure. All efforts made to close the sinkholes while the leakwas rapidly growing and failed. In contrast, small dam breaching can be stopped by human intervention.

The rate of breach formation depends on soil material properties such as cohesive, non-cohesive soils and embankment condition. Breach formation in embankment dams is highly dependent on the reservoir capacity and continues till either the reservoir is depleted or the dam can withstand further. According to the historical data, the breach formation phase for embankment dams ranges from 0.1to 4 hours (USBR).

Breach formation mechanisms and its process

Two breach formation mechanisms are identified: erosion and head cut erosion. The latter is the process of removal of structural material by the combined effect of the erosive force of water flow and by mass wasting. Laboratory experiments and observations of real Rock fill structure failures show that erosion is predominant for non-cohesive structures without a cohesive core. Head cut erosion is observed to be predominant during the breaching of structures with cohesive filling material, or with non-cohesive filling material but with a cohesive core.

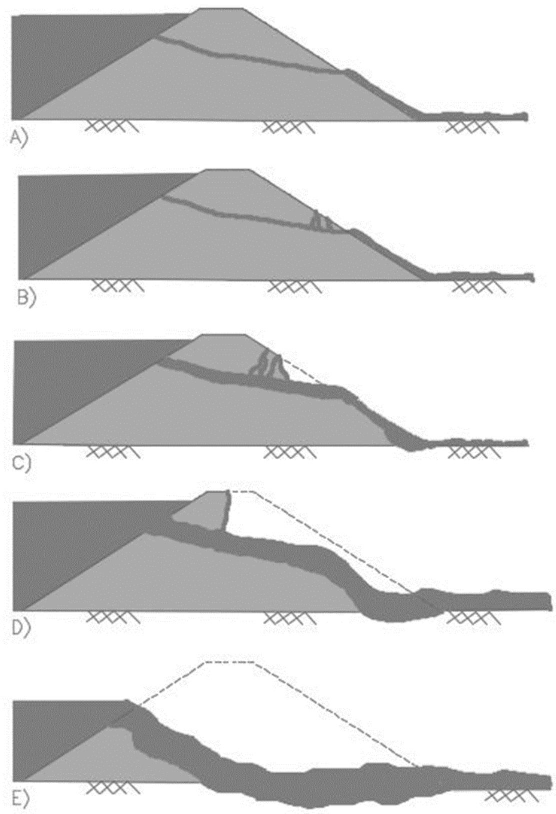



**Figure 3: Example Breach Process for a Piping Failure**

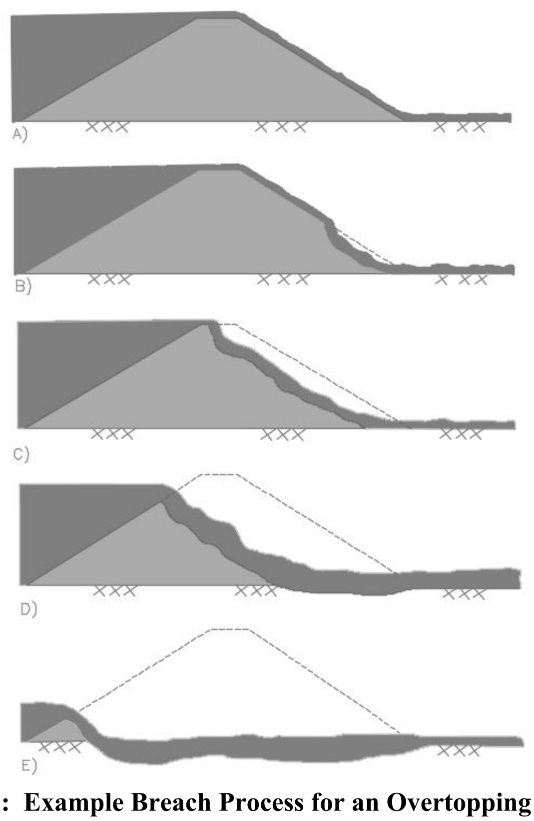



**Figure 4: Example Breach Process for an Overtopping Failure**

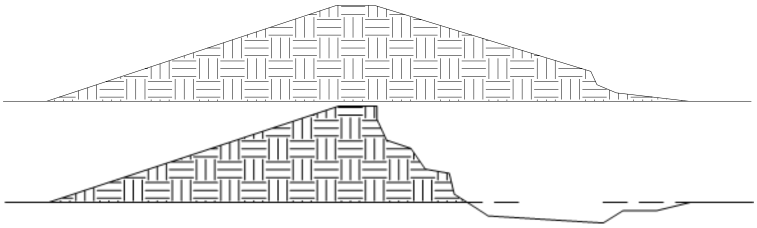


**Figure 5 Head cut erosion process in a cohesive soil embankment**

e.g. Ralston (1987); Dodge (1988); Powledge et al. (1989); Hanson et al. (1999); Morris (2005). By validating the modeling results versus field and laboratory experiments carried out during the breach models that predict breach growth considering the head cut erosion processes rather than only erosion, were argued to perform better (Morris, 2005) than the models that consider only erosion.

Modelling of the head cut erosion is not trivial, and while many experiments are carried out to gain insight into this process, the mathematical modelling of this process is just at the initial stages (see e.g. Temple and Hanson (1994); Temple and Moore (1997); Wu et al. (1999); Robinson and Hanson (1994); Hanson et al. (2001); Alonso et al. (2002)). Most breach models either do not consider head cut erosion, or consider this process using very simplified assumptions, usually modelling it asan energy dissipation process.

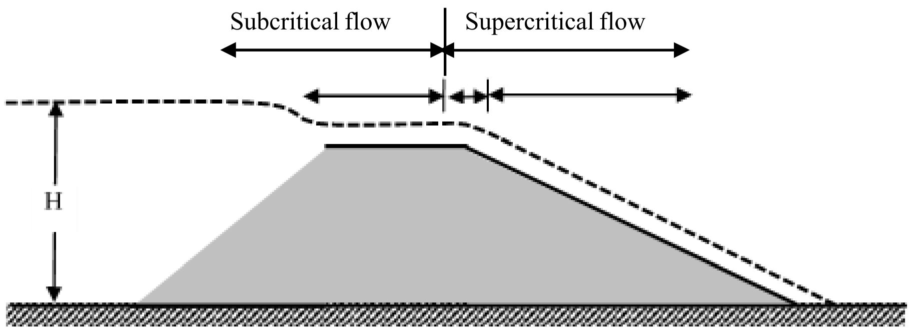
Erosion could be modelled using the sediment transport equations that are conventionally derived for steady subcritical flow conditions, specific types and certain diameter ranges of sediment (Yalin, 1972; van Rijn, 1993; Bogárdi, 1974). During structure breaching, the flow might develop into unsteady, supercritical flow and if these conditions apply, the use of unsteady non-uniform sediment transport equations is more appropriate. However, due to their absence the Meyer-Peter and Müller (1948); Exner (1925), Einstein–Brown (Brown, 1950), and the modified Meyer-Peter and Muller formula adapted by Smart (1984) are commonly used.

The rate of erodibility is given by:

$E_r = k(\tau - \tau_c)^a$

Where, $E_r$ presents the erosion rate, $k$ and $a$ are two correlation coefficients, $\tau$ presents the flowing water tractive stress and $\tau_c$ is the critical tractive stress for the erodible material.

The rate of erosion is commonly assumed to be uniform throughout the channel.




Different erosion rates

**Figure 6: Description of the flow over an embankment as from Powledge et al. (1989).**

section that is the submerged part of the breach channel sides is supposed to erode at the same rate as the unsubmerged part and the breach channel bottom. Most of the mathematical models deal with the homogeneous dams structures. The failure modelling of the heterogeneous structures is commonly done through averaging the characteristics of soil properties.

## III. Materials And Methods

**Simulation Models of Dam Failure Mechanisms**

The main values for overtopping and piping modelling failure mechanisms are related to the geometrical characteristics of the breach formed, which are (a) mean width (Bav), (b) bottom width (Wb), (c) height (hb), and (d) the height of the water from the bottom to the maximum free surface level (hw). These parameters were calculated utilizing the empirical equations of HEC-RAS and validated with the corresponding developed data from the Special Secretariat for Water (Greek Ministry of Environment and Energy) Saleh, H.; Allaert, G. Mitigating Urban Flood Disasters in Syria: A Case Study of the Massive Zeyzoun Dam Collapse. In

Proceedings of the World Water Week 2009, Stockholm, Sweden, 16–22 August 2009; Ghent University, Stockholm International Water Institute: Stockholm, Sweden, 2009; pp. 192–193.

HEC-RAS software was used to calculate the development of the breach. There are two breaching approaches to choose from user entered data (UED) and simplified physical with regards to the way that the input data are manipulated. For our purposes, the UED methodology was used for estimating geometrical and time characteristics, which incorporates regression equations based on observations of data from real failures. Most of the regression equations were developed from a small subset of the existing database of dam failures (108 historic dam breaches listed in the US Bureau of Reclamation report). The dams included in the analysis are a mixture of homogenous earthen dams and zoned earthen dams (Pilotti, M.; Maranzoni, A.; Tomirotti, M.; Valerio, G. 1923 Gleno Dam Break: Case Study and Numerical Modeling. J. Hydraul. Eng.2011, 137, [CrossRef]. Thus, the pick of the appropriate regression equation should be made with caution.

According to the analyses of the US Hydrologic Engineering Center (HEC) report (Hervouet, J.-M.; Petitjean, A. Malpasset Dam-Break Revisited with Two-Dimensional Computations. J. Hydraul. Res. 1999, 37 (CrossRef); there are several available techniques (which were taken under consideration in our study) such as (a) Froehlich and David 1995a, 1995b, 2008, (b) MacDonald and Langridge-Monopolis 1984, (c) Von Thun and Gillette 1990, and (d) Xu and Zhang 2009 ;Valiani, A.; Caleffi, V.; Zanni, A. Case Study: Malpasset Dam—Break Simulation using a Two-Dimensional Finite Volume Method.;J. Hydraul. Eng. 2002, 128, [CrossRef]; Bruschin, J.; Bauer, S.; Delley, P.; Trucco, G. The Overtopping of the Palagnedra Dam. Int. Water Power Dam Constr. 1982, 34, 13–19.; Petaccia, G.; Natale, L. 1935 Sella Zerbino Dam-Break Case Revisited: A New Hydrologic and Hydraulic Analysis. J. Hydraul. Eng.2020, 146, [CrossRef]

These studies provide detailed information regarding the selection of the most suitable model. The use of many different sets of equations to obtain a range of values for each parameter and to evaluate the corresponding output hydrographs produced during the failure has been suggested. The equation sets have been produced from a great variety of constructed projects of different scales.

In the present study, Froehlich's method (Valiani, A.; Caleffi, V.; Zanni, A. Case Study: Malpasset Dam Break Simulation using a Two-Dimensional Finite Volume Method. J. Hydraul. Eng. 2002, 128, 460–472. [CrossRef]) was selected as the most recent and representative method of this research after considering the HEC report and other evaluation research (Waltham, T. St Francis: The World's Worst Dam Site. Geol. Today 2018, 34, 100–108. [CrossRef]).

According to this method, Froehlich updated his breach equations based on the addition of new data, having utilized 74 earthen, zoned earthen, earthen with a core wall (i.e., clay), and rockfill datasets to develop a set of equations to predict average breach width, side slopes, and failure time. The height of the dam and the volume of the water at breach time, used for his regression analysis, ranged from 3.05 to 92.96 m (with 93% <30 m and 81% <15 m) and 0.0139 to 660.0 $m^3$ $10^6$ (with 86% <25 $m^3$ $10^6$ and 82% <15 $m^3$ $10^6$), respectively. The nonlinear regression equations analyzed from the database for the average breach width and the failure time are presented as Equations (1) and (2).

(1)

(2)

Where $B_{ave}$ is the average breach width (m), $K_o$ is a constant (1.3 for overtopping failures, 1.0 for piping), $V_w$ is the reservoir volume at the time of failure ($m^3$), $h_b$ is the height of the final breach (m), g is the gravitational acceleration (9.807 m/$s^2$), and $t_f$ is the breach formation time (s). According to the results of this analysis, the average side slopes should be 1.0 H/1 V for overtopping failures and 0.7 H/1 V for piping and seepage.

**Evaluation of breach parameters**

The identification of highly influencing dam breach parameters is essential for fixing the breach during the numerical simulation. The breach width (w) and duration of the breach (T) are considered during the study, as they have a significant impact on the downstream peak flow. The 75 historical dams failed cases were studied, considering zonal fill dams to predict the dam breach width (W) and duration of failure (T). The data analysis was carried out to identify and eliminate the outliers from the collected data set. The relationship of highly influencing parameters i.e. volume of the reservoir in million $m^3$(V), dam breach height in meters (H), dam breach width in meters (W), and breach duration in hours (T) was considered to develop a relationship equation. To increase the accuracy of the prediction two cases were built and studied to perform a data set behavior analysis as follows:

Reservoir volume and breach depth ratio greater than 1 (V/H > 1)

The reservoir volume and breach depth ratio (V/H) for large volume reservoir dams were considered for the statistical analysis to build the relationship between the volume depth ratio (V/H) versus breach width (W) and breach duration (T).

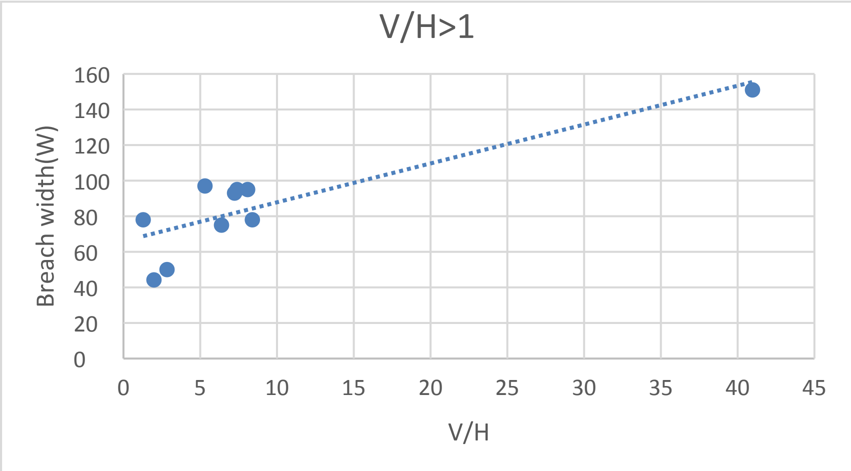



**Figure 7: Nonlinear- breach width prediction based on V/H > 1.**

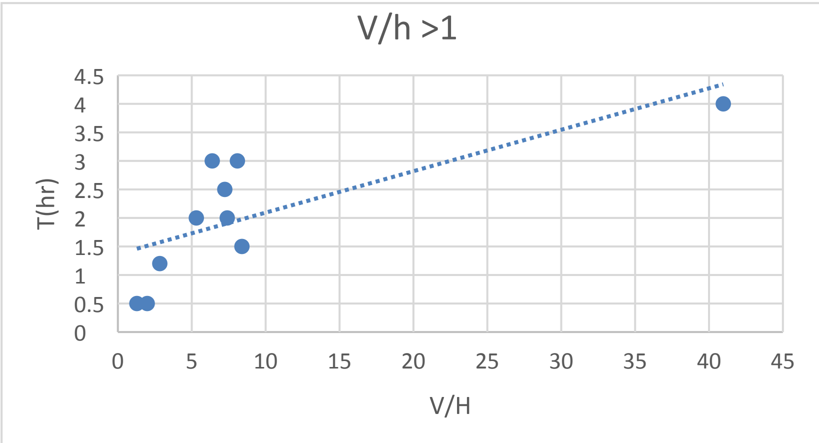



**Figure 8: Nonlinear- duration of failure prediction based on V/H > 1.**

The V/H >1 with the breach width (W) and time of the breach (T) were plotted as shown in Figures 9 and 10. The log nonlinear behavior was observed through the plot of the data set with R2 value greater than 0.7, within the range of acceptance value.

Reservoir volume and breach depth ratio less than 1 (V/H < 1)

The reservoir volume and breach depth ratio (V/H) for comparability less volume of reservoir dams were considered for the statistical analysis to build the relationship between the volume depth ratio (V/H) versus breach width (W) and breach duration (T).

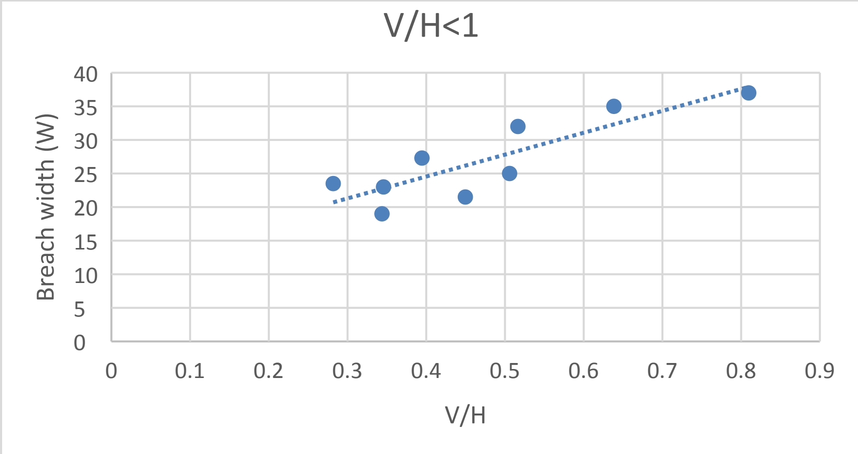



**Figure 11: Nonlinear- breach width prediction based on V/H < 1.**

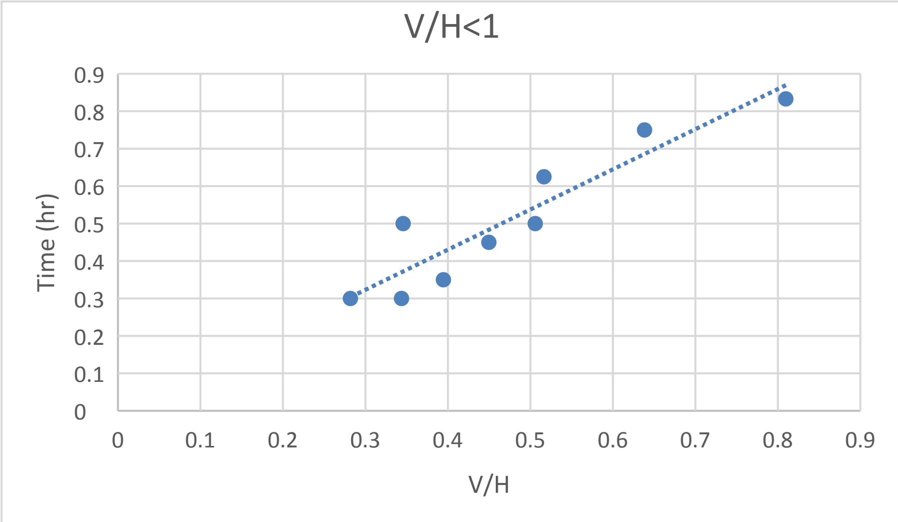



**Figure 12: Nonlinear- duration of failure prediction based on V/H < 1.**

The V/H < 1 with the breach width (W) and time of the breach (T) were plotted as shown in Figures 11 and 12. The log nonlinear behavior was observed through the plot of the data set with $R^2$ value greater than 0.7, within the range of acceptance value.

## IV. Conclusions

The dam breaching could occur due to various reasons such as the enormous flood generated by the Glacier Lake Outburst (GLOF) at the event of the climatic changed condition which accelerate the catastrophic flooding behind the dam, less compatible of dam to sustain the hydrostatic and dynamic thrust in natural condition, due to the poor geological condition in the periphery of the dam axis and a high magnitude of the earthquake ground acceleration triggering may cause the failure of the dam.

From the study it shows that these failures are mainly due to overtopping and piping in the dam body which will lead to a total breaching of the dam of any type rock fill or of concrete or of even earthen dam in a rapid development of time of breaching.

Hence it has reported that Overtopping flow is a prominent event of many or even most potential failure modes resulting from floods. Dams could have overtopped by a few millimeters to more than a meter without breaching, but other structures could fail quickly. Overtopping is a failure mode of concern since Costa (1985) reported that of all dam failures as of 1985, 34% were caused by overtopping, 30% due to foundation defects, 28% from piping due to seepage, and 8% from other modes of failure. Costa (1985) also reports that for earth/embankment dams only, 35% have failed due to overtopping, 38% from piping and seepage, 21% from foundation defects; and 6% from other failure modes.

The Dam breach mechanism can be discussed on its failure modality either in overtopping mode or in piping mode the main concern area is its breach shape, breaching development time and its failure nature as how it develops in time in overtopping and piping mode. The other important factors need to be considered during the breaching is as how quickly developed its formation mechanism of breach width depth and its cutting slopes in the dam and the downstream peak flow for protecting the lives and properties of the people in downstream of the dam.

The increasing importance of the evaluation of dam safety has led to the development of sophisticated computer programs that can estimate the potential hazards of dam failures. One limitation on the use of these programs is the accuracy of the input data for the geometric and temporal characteristics of the dam breach.

Data on a number of historical dam failures is recommended be collected as attached in the annex of the report and these data has to be analyzed to develop relationships which would form the basis of a methodology for estimating the geometric and temporal characteristics of breaches. All types of dams including rock fill/earthen or concrete gravity dams in which breaches are formed by erosion of the embankment material and that may have failed partly due to erosion and partly due to sudden collapses· caused by instabilities needs to be studied. The breach characteristics of the any types of dams needs to be compared to determine whether there are any consistent differences.

From analyses of the data on historical dam failures it is concluded that:

For any type of dam, the breach shape can be assumed to .be triangular with 2V:1H side slopes if the breach does not extend to the base of the embankment and trapezoidal with 2V: l H side slopes if additional material is washed away after the breach reaches the base of the dam. This breach shape should only be assumed if the breach size is less than the embankment size.

For any type of dam, the volume of embankment material removed during a dam failure can be used to estimate the peak breach outflow hydrograph. The time for breach development can be estimated using the relationship of the volume of material remove during the breaching event.

The increasing importance of the evaluation of dam safety has led to the development of sophisticated computer programs that can estimate the potential hazards of dam failures. One limitation on the use of these programs is the accuracy of the input data for the geometric and temporal characteristics of the dam breach.

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