Dam Break Analysis of Earthen Dam in Goa

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ABSTRACT

Dams are an integral part of the country's economy and development. Dams are confines built over a river to store water and construct a reservoir that serves various purposes. It is very important to have dam safety maintenance and monitoring. Therefore, dam breach analysis becomes an essential part of examining unforeseen repercussions posed to human habitat and environment by an abrupt release of water downstream of a dam. Every dam structure needs to be assessed whether built or proposed for the risk of collapse in essence to find out the precise consequences that would arise after the breach. The present study aims to find out the breach magnitudes of the Salaulim Dam located in the Sanguem taluka in Goa using the Hydrologic Engineering Centre's River Analysis System viz. HEC-RAS software. The dam is analyzed for the Probable maximum flood (Overtopping) scenario and the Clear Day Failure (Piping and internal erosion) failure scenario adopting the two-dimensional unsteady flow modeling. In the study, dam failures were simulated, and the average breach width, height, and side slope for the overtopping failure were 182 m, 30 m, and 1 respectively. The piping failure measured 0.7 degrees on the side, 28 meters high, and 143 meters wide. The highest velocity of the piping failure was 5.01 m/s, whereas the overtopping failure was 5.53 m/s. After the collapse, the water depth was found to be 21.12 meters and 13.17 meters, for overtopping and piping failures respectively. The peak discharge was 16002.502 m^2/s for overtopping while 18925.85 m^2/s for piping failure. These collapses would cause a tremendous amount of flood inundation in the downstream area. In addition to posing a risk to public health and safety, the floods would seriously affect infrastructure, livelihoods, and the environment. They would also cause property damage and interruptions to transportation.

Keywords: Earthen dam, Dam breach, HAC-RAS, Salaulim dam, Overtopping, Piping failure.

1.0 Introduction

A dam is a structure that is constructed over a river to hold water and create a reservoir for a variety of uses, such as flood control, irrigation, and electricity production. Building dams is essential to a nation's economic growth and development. Whether large or little, there are currently more than 57,000 dams in the world. There are currently 5,334 dams in India, 447 of which are very significant. Over the course of a dam's life, the flow of water is never guaranteed due to climatic change. Regular maintenance of the structure becomes crucial since certain dams that were previously deemed safe may not show the same level of safety. The 1975 failure of the Banqiao and Shimantan Dams resulted in the deaths of 26,000 people and the collapse of 5–6.8 million houses, despite the fact that dams are meticulously designed to prevent any failure options. These large structures can also fail and cause large damages to the downstream livelihood and the environment. Although dams are beneficial to civilization in many ways, some of the worst natural disasters have also been caused by floods that arise when dams fail. The safety of dams is a crucial topic. In order to prevent these dangers, safety plans and emergency flood plans for the dam were prepared in 2012 as part of the Dam Rehabilitation and Improvement Project. These plans require a thorough investigation of dam breaks, etc. The study on Dam Break Analysis is done using the Hydrologic Engineering Centre's River Analysis System viz. HEC-RAS [1] software. The gathered data is fed into the software and the results are generated.

2.0 Literature Review

Xiong (2011) [2] used the HEC-RAS dam break tool to simulate and analyze the Foster Joseph Sayers Dam break, considering three scenarios for Probable Maximum Flood conditions. The study found that dam breaches due to piping extended the period of high water surface level, increasing

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risk duration. The dam break had a greater impact on downstream locations, but changes in dam break parameters did not significantly affect downstream locations. In 2006, the Chaq Chaq Dam in Iraq was breached due to overtopping after 131.2 mm of rainfall over 24 hours. It was confirmed that the factors contributing to the dam's shortening life span included the dam's vertical construction in the same valley and the lack of compaction at the wall-embankment interface. The HEC-RAS model generated different breach hydrographs corresponding to different breach formation times, indicating a peak breach flood discharge of 979.2 m^3/s [3]. Sharma and Mujumdar (2017) [4] studied the dam break analysis of the Ajwa Sarovar Dam in Vadodara City, Gujarat, which flooded due to heavy rainfall. They conducted an unsteady flow analysis and ran a 24-hour simulation model. Peak discharges were generated for various locations downstream.

Abhijith et al. (2017) [5] examined the dam break analysis of the Idukki dam in Kerala, a 168.91-tall arc dam supporting a 780 MW hydroelectric ability station. The authors used St. Venant's equations for unsteady flow in the HEC-RAS model and considered the overtopping mode of failure. The analysis showed maximum flow after 4 hours of break formation, then decreased with time. The depth of flow at different locations varied from 58.24m to 18.21m at the end of the reach. Balaji and Kumar (2018) [6] studied flood inundation maps for the Kalyani dam in Andhra Pradesh using the HEC-RAS model and GIS to predict water spread, depth, probable maximum flood, travel time, and plot to overflow succession. The output data was used to create flood inundation maps using GIS, aiding in disaster management planning. The study found that changes in barrier fracture parameters did not significantly control flow maximum water surface elevation, which could be influenced by factors such as initial stream shell distance, flood hydrographs, and gate breach elevation. Duressa and Jubir (2018) [7] studied Fincha Dam in Ethiopia using hydraulic models to analyze dam breach parameters and inundation map. The results showed that peak discharge from the overtopping mode of failure was more devastating than the piping mode, with dam breach parameters having a more pronounced impact than water level. The model provided an inundation map, guiding dam authorities and emergency management authorities to provide emergency action plans and plan future economic development activities.

Azeez et al. (2019) [8] conducted a study on dam break analysis and flood disaster stimulation of the Um Al-Khair Dam in Saudi Arabia, triggered by a 2011 rainfall storm. The study used a hydraulic modeling tool (HEC-RAS-2D) to set up a flood inundation model. The dam broke at 5:46 hours of simulation time, causing massive flooding in the downstream area. The simulation's accuracy was determined by comparing simulated water depths with observed locations. Khosravi et al. (2019) [9] conducted a dam break analysis of the Sefid-Roud Dam in Iran, analyzing 50 cross-sections across the river. The analysis showed flooding for 21 km downstream, with a maximum flood depth of 52m close to the dam and a peak velocity of 15m/s. The failure is estimated to risk the lives of around 3100 people, including destruction of the Tehran-Rasht Highway, rice farms, and olive orchards. High shear stresses in the flood waters are likely to cause heavy erosion and morphological changes to the river basin. Helwa et al. (2020) [10] studied the Old Aswan Dam in Egypt, which was widened and raised twice due to inadequate flood protection. The dam nearly overflowed in 1946, leading to the construction of the High Aswan Dam. A dam break analysis was conducted to study the hydraulic consequences of dam failure or large discharges in case of an emergency evacuation of Lake Nasser. The study considered eight dam breaching scenarios and examined the effect of changing parameters on the output hydrograph. The results showed that flood arrival and peak times depend primarily on initial flow values, with higher flow values having higher average velocities in the channel.

Kyaw (2020) [11] studied on dam break analysis for the North Yamar dam found that without an emergency spillway, a dam breach occurs with a peak discharge of 7,211 m^3/s and a peak elevation of 151.9 m. If an emergency spillway is present, no dam break occurs. The study also considered inundation mapping only for piping failure mode, as overtopping failure would not occur in this scenario. Bharatha et al. (2021) [12] conducted a dam break analysis using the Hydraulic Engineering Centre's River Analysis System (HEC-RAS) and HEC-GeoRAS on the Hidkal dam in Karnataka. They used a one-dimensional hydraulic model to predict breach parameters, flood hydrograph, peak flow, flood arrival time, and generate inundation maps. The study found that overtopping failure is more severe than piping failure. Abdulrahman et al. (2021) [13] conducted a hypothetical failure and risk assessment of the Khassa Chai Dam in Kirkuk, Iraq. The HEC-RAS software was used and regression equations to estimate breach parameters. It was concluded that overtopping is unlikely due to the large reservoir volume and large spillway capacity. The model domain was divided into upstream and downstream domains. The failure would result in an inundation depth of 3-18 meters, submerging most of Kirkuk's urban district. Sumira et al. (2022) [14] conducted a dam break analysis and flood inundation of the Sermo Dam in Indonesia, using two-dimensional HEC-RAS software. The dam overtopping and piping modes of failure were considered, resulting in a peak inflow discharge of 1276.6 m^3/s and a flood inundation area of 9394 hectares, and a maximum flood height of 17 m. The overtopping scenario affected 8 sub-districts, while the piping scenario affected six districts.

The primary focus of researchers investigating dam break analysis is on earthen dams and gravity. According to PMF, overtopping failure is the most frequent reason why dams burst. Another conceivable mode of failure is pipeline breakdown. Overtopping failure risk can be decreased with an ungated spillway. Dams and downstream regions suffer the most severe harm from overtopping failure. Floods have the ability to change human habitat and land up to 50 km downstream, and peak output is dependent upon breach criteria. A flow rate higher than 3 m/s has the potential to be disastrous. Plans for emergencies and flood control are essential since even a little incident can cause livelihoods to be permanently damaged. Water may be an ally or an enemy.

3.0 Study Area

The Salaulim Dam, located in Sanguem taluka of Goa, is a composite structure of earth and masonry dam with an original capacity of 2.714 million cubic meters (MCM). It was constructed between 1979 and 2000 and is a key component of the Salaulim Irrigation Project. The Dam is illustrated in figure 1(a) below. The dam has a catchment area of 24 km^2 and has now a gross volume content of 234.361 MCM, an effective storage capacity of 227.157 MCM. The dam is unique and Asia's first ever type of spillway, Duckbill form spillway shown in figure 1(b), an ungated structure, is a popular tourist attraction. The reservoir has an estimated flood discharge of 1,450 cubic meters, with 126 MCM for irrigation and 101 MCM for domestic and industrial water use. The dam provides 220 million litres per day (MLD) of water for industrial and domestic use in South Goa.

(a)

(b)

Figure 1 (a) Salaulim Dam, Goa and (**b**) Duckbill Spillway at Salaulim Dam

4.0 Methodology

The Salaulim Dam is analysed under two conditions namely the overtopping failure and Piping Failure. Overtopping occurs when the water surface level in the reservoir becomes higher than the height of the Dam, the water pours over the top crest of the dam. The most frequent kind of failure is embankment dam overtopping caused by flooding. Internal erosion and piping in embankment dams are caused by concentrated seepage. Big holes get created in the ground as the seepage gradually erodes the dam. Erosion quickens as void increases. Internal erosion is the main cause of earthen dam failures. The

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breach parameters viz. the Breach Width (B), the time interval required for the breach (t), the side slopes of the breach, and the Breach height (H_B) are generated from the software.

The HEC-RAS software can do both overtopping and piping failure techniques enabled by the program, with the water surface, and duration, or specified time serving as the failure start. Water quality analysis, sediment transport calculations, unsteady flow simulation, and steady flow water surface computations are the four 1D river analysis components of the program. Utilizing the St. Venant equations for mass conservation and momentum conservation, HEC-RAS carries out 1D and 2D calculations. A 2D model solves the St. Venant equations along two dimensions as opposed to a 1D model's one-dimensional solution. The flow of the study is depicted in the chart below in figure 2.

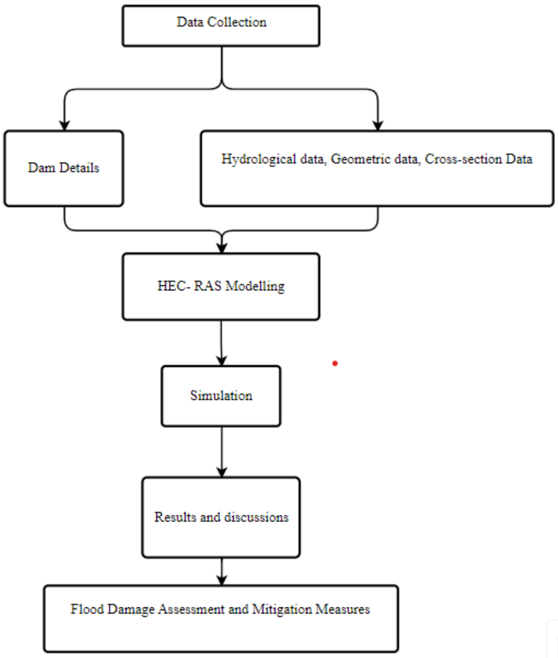


Figure 2 The flow chart of the analysis

4.1 Geometric Data

The geometry of the river is mandatory for all hydraulic modeling. Remote sensing data or field surveys can be used to obtain the river geometry data. Acquiring information by traditional survey methods provides precise river geometry, but it takes a lot of time and effort because a big region needs to be covered. On the other hand, since using remote sensing data reduces costs and saves time, hydraulic modeling has begun to use it more. The topographical map that was obtained from the USGS map in the projection file and was manually overlayed with the Geometric Data. After feeding the .tiff file into the program, ArcGis world image is overlaid over the projection. Storage areas work much like a place where water may be diverted. The storage space utilized in this analysis was designed with the reservoir of the proposed Salaulim Dam in mind. The reservoir's contours were sketched and designated as a "storage area." The area designated as "Perimeter 1" is the downstream region, often known as the 2D Flow area. Subsequently, an outline boundary that shows the direction of water flow past the downstream perimeter and the SA/2D connection, which is the dam, were added to this geometry.

4.2 Dam Breach Data

A number of factors are needed for the dam breach analysis, including the breach width, the ultimate elevation of the breach bottom, the duration of the breach, and the side slope of the breach. The breach parameters are found using the five primary regression equations: Froehlich (1995) [15], Von Thun & Gillete [16], Xu & Zhang [17], and McDonald et al. [18]. These parameters are estimated in this study using the Froehlich (2008) [19] regression equation. The overtopping failure and pipe failure breach parameters are obtained using the regression equation. For this study the breach parameters are determined using the Froehlich (2008) regression equation.

The final bottom elevation is kept at 17 meters, while the centre station is kept at 400 meters left of the spillway. The preferred mechanism of failure is then selected. The information required to estimate the breach parameters in the two forms of failures is shown in table 1 below. After all the parameters have been confirmed, all that has to be done is "Breach this Structure".

Table 1 Input Data for calculation of Breach parameters

Mode of Failure	Input Data	value
Overtopping Failure	Top of Dam elevation	45 m
	Pool elevation at failure	42 m
	Breach bottom elevation	17 m
	Pool volume at failure	321641 m^3
	Dam Crest width	7.5 m
	The slope of US dam Face (H:V)	2
	The slope of US dam Face (H:V)	2
Piping Failure	Top of Dam elevation	45 m
	Pool elevation at failure	42 m
	Breach bottom elevation	17 m
	Pool volume at failure	321641 m^3
	Dam Crest width	7.5 m
	The slope of US dam Face (H:V)	2
	The slope of US dam Face (H:V)	2
	Initial Piping elevation	17 m

4.3 Flow Data and Boundary Conditions

The lateral inflow hydrograph of the reservoir served as the investigation's upstream boundary condition. For the purposes of the analysis, July 4, 2022, the day with the highest rainfall during the preceding 10 years (as mentioned in the collected data set), is taken into account. Conversely, the downstream boundary condition has a slope of 0.0004 and is set to normal depth. Calculating the lateral inflow for the dam simulation model involves making assumptions about the likely maximum precipitation in the area. The inflow hydrograph is replicated in the dam for about 1.2 days, or 29 hours. The inflow hydrograph is replicated in the dam for about 1.2 days, or 29 hours. The kind of dam collapse that is being discussed is a rainy-day failure rather than a sunny-day failure, which has more devastating consequences in the event that the dam fails quickly. The inflow peaks 1:20 hours into the experiment. It swiftly declines after reaching the peak because a dam breach is anticipated at this point, and the breach discharge spreads d/s as an outflow hydrograph. After 29 hours, the breakdown causes the reservoir's water to completely drain out of the dam, causing the inflow hydrograph to decrease to zero.

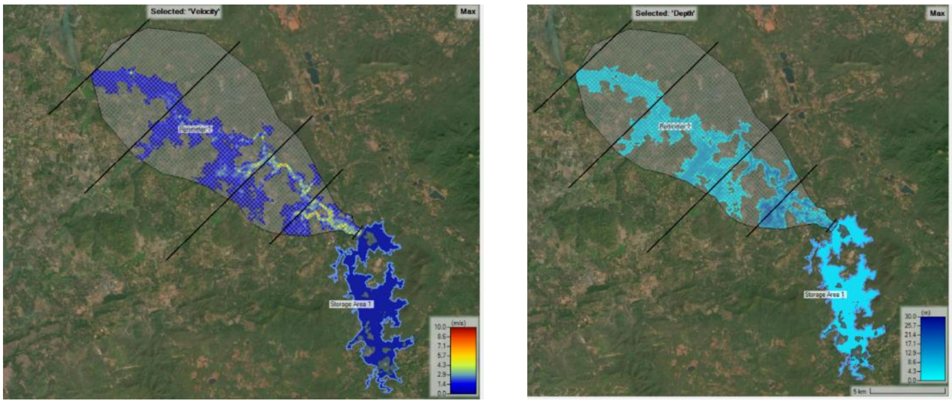
5.0 Results and Discussions

An examination of the Salaulim Dam overtopping and piping malfunctions were stimulated. The outcomes section, which is a clear description of the outcome at the moment of failure, was selected for breach SA2 (reservoir) once all of the unsteady flow simulations were finished. The water was then selected according to its depth and velocity, which reveal the breach discharge or flow that occurs after a dam fails as well as the maximum speed at which it flows. The largest and lowest flows at different simulation periods were noteworthy. It is possible to see flow at any given time with the RAS mapper. The following four primary influencing factors - velocity, water depth, flow discharge, and flow duration - may be mutually related in some manner and have a substantial impact on the repercussions of the dam break. Table 2 provides the critical values of dam break parameters under the two failure scenarios.

Table 2 Critical output values of the dam break analysis

Parameters	Overtopping	Piping
Maximum Discharge of the breach	16002.65 CMS	14925 CMS
Time of initiation of breach	00:00 hours	00:58 hours
Arrival time of Peak discharge after initiation of dam breach	01:58 hours	02:40 hours
Maximum water depth	20.80 m	15.95
Maximum velocity	5.53 m/s	5.01 m/s
Full breach width	184 m	143 m

As shown in figure 3 (a and b), the program creates the visual representation of the flow of water downstream in terms of velocity and depth. Breach development occurs steadily and progressively over time. The dam is simulated, and the breach formation completely develops by 01:58 hours, taking around 2 hours to reach a full width of 184 meters. The water's greatest recorded velocity as it surges towards the downstream side is found out to be 5.53 m/s, while its lowest recorded velocity is 1.52 m/s. The depth of the water decreases from its maximum value near the dam as it flows away from it. The highest depth ever measured is 20.80 meters at the dam just after the break. The reservoir would take 10 hours to drain in this kind of failure. There has been a noteworthy and consequential release water downstream. Figure 4 illustrates the discharge representation. 16002.65 CMS is the peak discharge at the failure that has been recorded.



(a) **(b)**

Figure 3 (**a**)the flow of water with respect to velocity and (**b**) the flow of water with respect to depth during overtopping failure

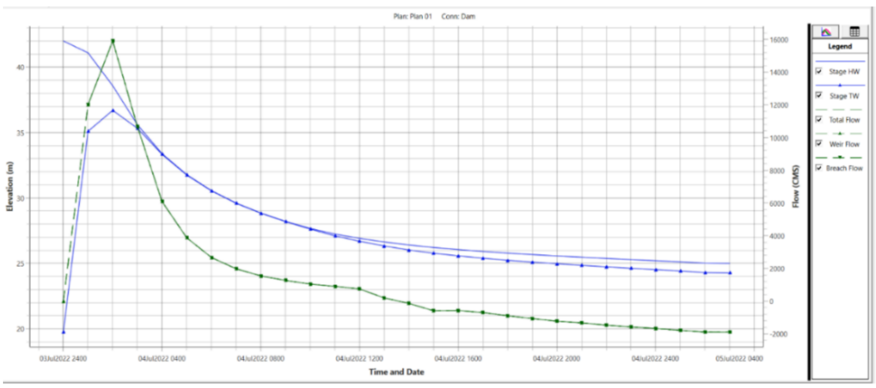
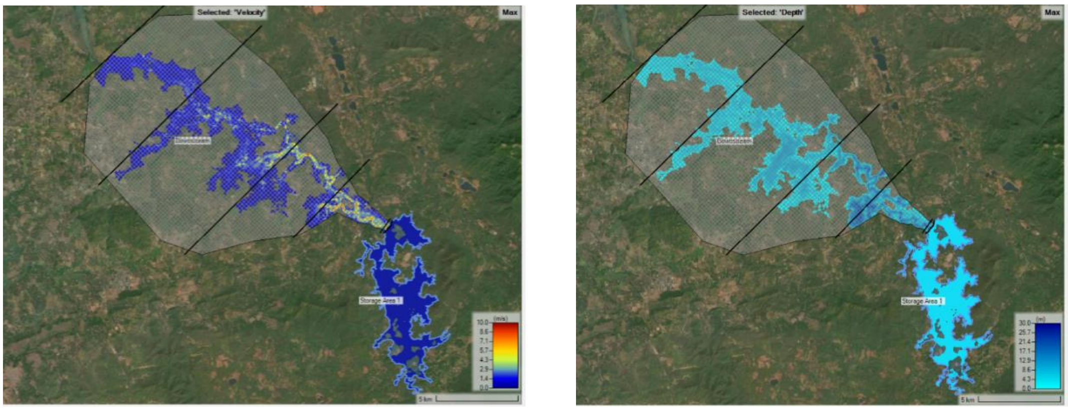


Figure 4 The Stage Hydrograph (HW and TW) for Overtopping Failure

The piping failure, like the overtopping failure, has a breach dimension provided by the regression equation of Froehlich (2008) [19]. Over time, breaches grow gradually and slowly. The dam is intended to fail at 00:58:36 hours, and as time passes, the structure grows to its greatest width of 143m. Figure 7 shows the Inline structure of the Dam at Centreline of 400m for Piping failure. The dam entirely breaks in 2 hours after the simulation; Figure 5 (a and b) shows a visual depiction of the water flow velocity and depth. The water surges towards the downstream side with a maximum velocity of 5.01 m/s and a minimum velocity of 0.024 m/s. The depth of the water decreases from its maximum value near the dam as it flows away from it. The greatest depth ever measured is 15.95 meters, which was recorded 3.8 km away from the dam after the break. After 10 hours, the piping issue causes the reservoir to empty. There's been a significant leak. Figure 6 depicts flow of the discharge. During the collapse, a peak discharge of 14925 CMS is observed.



(a) **(b)**

Figure 5 (**a**)the flow of water with respect to velocity and (**b**) the flow of water with respect to depth during piping Failure

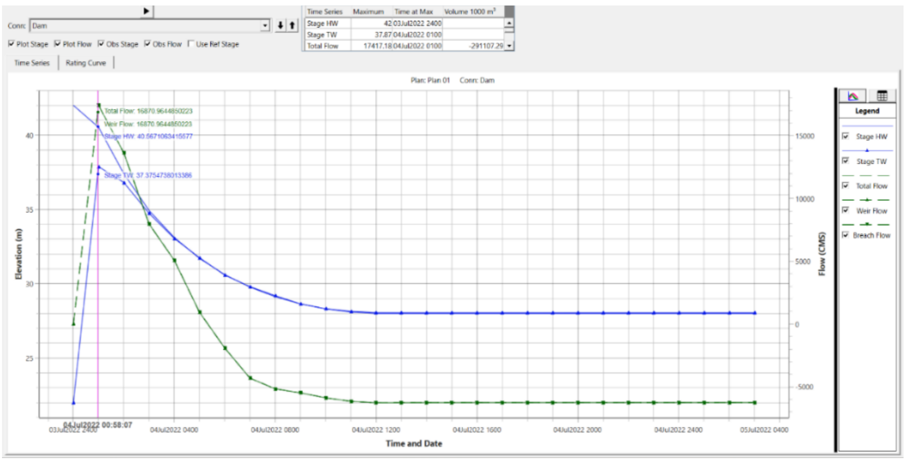


Figure 6 the Stage Hydrograph (HW and TW) for Piping Failure

The overtopping failure is more critical since the peak discharge values are higher than that of peak discharge in piping failure. A similar trend was seen in Duressa and Jubir (2018) [7], Bharatha et al. (2021) [12], Sumira et al. (2022) [14], Mattas et al. (2023) [20] and Psomiadis et al. (2021) [21]. However, the velocity of the flow, in both cases would be devastating to the habitat as the velocity is higher than 3 m/s in downstream area. As the water flows forward its velocity and depth decreases and is validated through the literature review.

6.0 Comparison between the Failure modes at various distances along the downstream path

Understanding how the four primary factors – discharge, depth, velocity, and time—interrelate to determine the catastrophic flooding that happens when a dam fails along a downstream channel. This correlation facilitates an examination of the mitigation techniques and disaster preparedness. Failure possibilities are contrasted with one another along the escape pathway based on the criteria mentioned above.

6.1 Velocity

The flow velocity decreases as the water recedes from the dam as can be seen from figure 7. The piping failures decreased from 5.01 m/s to 1.52 m/s, while the overtopping failure's velocity reduced from 5.53 to 1.58 m/s by the time the flow passed 20 km downstream. This might be due to energy dissipation processes that help lower the flow velocity as the floods move downstream, such as turbulence, eddy formation, and flow expansion. As the distance grows, these processes cause the flow's kinetic energy to be converted into different types of energy, such as heat and turbulence, which causes the flow's velocity to decrease. It is also clear that overtopping failures produce a higher velocity than pipe failures.

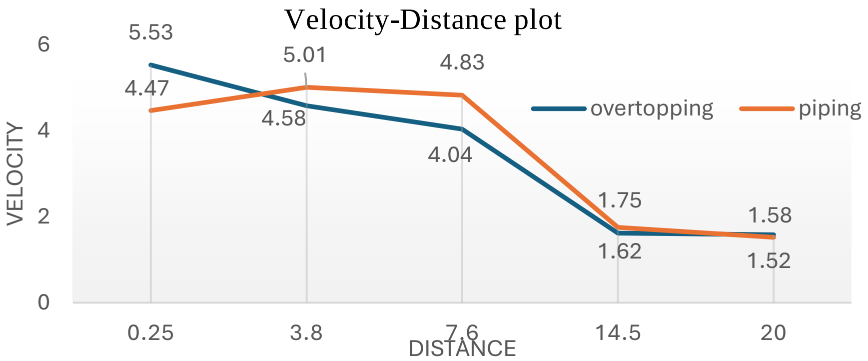


Figure 7 Velocity v/s Distance plot

6.2 Depth

A flood wave crosses the river channel downstream after a burst dam releases floodwaters. As the flood wave recedes from the breach site, frictional losses, dispersion, and lateral spreading cause the water depth to drop. The volume of water discharged, the river slope, and the roughness of the river channel all affect how quickly the water depth drops with distance. This is corroborated by the depth-distance map in figure 8, which

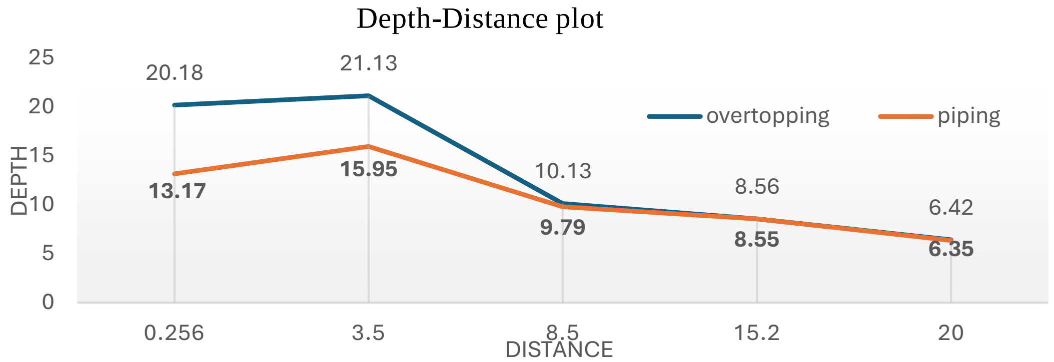


Figure 8 Depth v/s Distance at D/S

6.3 Discharge

Higher flow discharge rates and more water releases result in more extensive flooding across a larger region. Longer floodwater journey lengths and greater flow discharge rates make the infrastructure downstream of the dam more vulnerable. Overtopping failures yield the highest discharge values at a variety of distances, as seen in figure 9 below. The two types of failure show a discernible difference in

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values close to the dam; however, the fall in overtopping failure happens faster, whereas the decline in pipe failure happens more gradually.

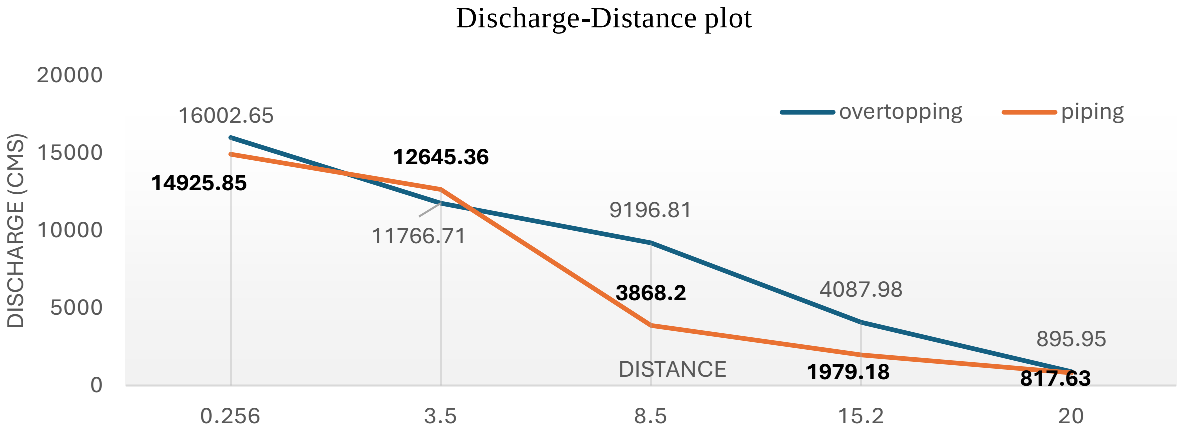

Figure 9 Discharge v/s Distance

6.4 Duration of flow

Floodwaters spread throughout time and move downstream at different speeds depending on time. Numerous variables, including geography, channel features, and the amount of water discharged, affect the flood path and extent. Determining the amount of flood inundation and identifying risk regions are made easier with a solid understanding of the connection between time and distance. Figure 10 illustrates the relationship between time and distance. The data set clearly shows that the region would flood in three hours because, in the case of a pipe breakdown, the flow would reach the downstream more quickly.

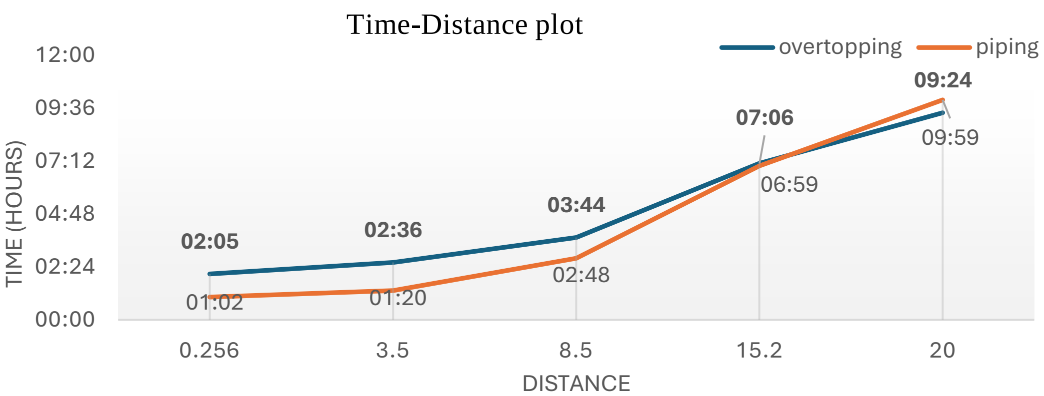

Figure 10 Discharge v/s Distance

The data indicates that overtopping failure will be more catastrophic since all the parameters connected to dam breach show bigger values for each element, despite the fact that overtopping failure takes a lot longer to breach than pipe failure. The factors and their impacts suggest that overtopping failure is more dangerous and harmful to the environment, infrastructure, and means of subsistence in downstream areas, even in the event that piping failure occurs before overtopping failure.

6.5 Flood Inundation

Flood inundation is the process by which water overflows onto land and submerges regions. In this case, the floods were brought on by the dam failing. Roads, bridges, and trains that flood can cause disruptions to transportation networks, making it more difficult for people to move about and for emergency services to respond promptly. Knowing how river flow rates impact flood travel durations makes it simpler to plan evacuation routes, organize gathering places, and notify the public of evacuation orders. Flooding may also lead to electrocution, drowning, or accidents that result in harm or death. According to this study, Sanguem, Bamansai, Vorkotto, Dando, Zanoda, Nagem, Cacora, Curchorem, and Macasana are the communities that are most at risk of flooding. The Zuari River frequently floods the places along its banks, deepening the water and causing it to penetrate the surrounding area. There might be imminent modifications to the river path as a result of this sudden entry of water.

6.6 Mitigation Measures

To decrease the effects of flooding, a variety of structural and non-structural techniques are frequently employed, including mapping floodplains, land use planning, constructing levees and floodwalls, putting up drainage systems, installing flood forecasting and warning systems, and starting public education and awareness campaigns. Emergency Action Plans (EAPs), which include information on procedures, evacuation routes, and communication mechanisms for local authorities, emergency services, and dam operators, are essential for an effective reaction to incidents involving dam failure. The resilience of dams to collapse can be enhanced by structural retrofitting and upgrades, which may include constructing emergency spillways, reinforcing embankments, putting erosion control measures in place, or increasing spillway capacity. For the purpose of identifying any issues and guaranteeing structural soundness, dams require routine maintenance and inspections. When a dam exhibits unusual behaviour, such as increased seepage or deformation, early warning systems can detect it and notify the public downstream as well as the appropriate authorities. Implementing setback laws and accurately mapping floodplains are two land use planning techniques that can lessen the chance of flooding brought on by a failed dam. Flooding can also be lessened by enforcing setback laws, preserving natural floodplains, and restricting buildings in high-risk regions.

7.0 Conclusions

Dam breach analysis is necessary in order to investigate the possible downstream effects of an unexpected water release. The River Analysis System (HEC-RAS) of the Hydrologic Engineering Centre is used to assess the extent of dam breaches, including piping and overtopping scenarios. In order to identify probable failure situations, the study correlates variables including breach parameter prediction, impacted region identification, peak discharge, flow velocity, depth, and flood duration. This reduces the possibility of disastrous outcomes and guarantees dam safety. The present research leads to the following outcomes. The study examined how water flow is affected when a dam fails. The average breach width, height, and side slope following the overtopping collapse were 184 m, 30 m, and 0.7 m, respectively. In contrast, the piping collapse had a side slope, breach width of 143 meters, and heights of 28 meters. The simulation of both failures began at 0:00:00, with the dam overflowing at 2 hours into the simulation and the pipes initiating at 00:59:36. The highest velocity of the pipe failure was 5.01 m/s, whereas the overtopping failure was 5.53 m/s. After the collapse, the flood water depth was 21.12 meters in case of overtopping failure and 13.17 meters, for piping failure. The overtopping produced a peak discharge of 16002.65 CMS at the failure, while the piping failure has a discharge of 14925.85 CMS. Gathering from the study the critical mode of failure is overtopping failure posing a greater risk to infrastructure, the environment and the habitat downstream. It is anticipated that Sanguem, Bamansai, Vorkotto, Dando, Zanoda, Nagem, Cacora, Curchorem and Macasana may be severely affected by flooding. Authorities should combine structural and non-structural techniques, such as mapping floodplains, land use planning, erecting levees, floodwalls, drainage systems, and flood forecasting and warning systems, to lessen the consequences of dam collapse floods.

Conflict of Interest

The authors declare no conflict of interest.

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