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DAM Break Analysis Due to Piping Failure Using HEC-RAS and HEC-GeoRAS

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Abstract: Angola has been actively building DAMs for the past few decades to meet various infrastructure requirements, but the country has never had a DAM demolished or failed. Based on the result attained from past studies, potential DAM Break scenarios and the ensuing flooding were not given much attention, therefore, the research mainly focusses on the analysis of both cases, by means of the Hydrologic Engineering Center River Analysis System (HEC-RAS), and the analysis of piping failure mode scenario which is frequently associated with dam break cases. For validation and forecasting of the DAM Break failure mode parameters, the hydrograph's linear Breakout-flow in the structure, located in Cunene Province, for both Froehlich and MacDonald & Langridge-Monopolis formulations was generated at different intervals in HEC-RAS using the empirical equations and numerical models of both Froehlich and MacDonald & Langridge-Monopolis. A high Probable Maximum Flood (PMF) inflow of 8.036 m^3/s is used as a reservoir input to determine whether the piping failure was conceivable, estimating that the spillway has demonstrated that it can handle the inundation caused by the PMF, turning the infiltration of the embankment impossible. Additionally, HEC-RAS was used to model piping failure. The resulting Break due to the piping failure was examined, and flood hydrographs were obtained at various cross-sections along the river.

Key words: Cunene, Calueque, DAM Break, Piping, HEC-RAS, HEC-GeoRAS, flood

1. Introduction

DAM failure, whether controlled or uncontrolled, is unavoidable because they are complex structures susceptible to several forces that can lead to failure. As per "Capítulo III, artigo 46 do Decreto-Lei 344/2007 de Outubro – Angola", there have been numerous initiatives to lessen the potential danger that DAMs pose as well as to offer emergency action plans in collapsing events. DAM Break analysis can offer fundamental flood event knowledge useful for managing floodplains, emergency response planning, and DAM building.

While enabling the control of fresh water flow and greatly simplifying lives, DAMs also inevitably and inherently pose a danger to both the environment and public safety as per DAM safety code Decree-Law 344/2007. Since the construction of the first DAMs, others have failed due to uncontrollable environmental factors, subpar engineering, or poor administration. Sadly, because there is so much potential energy involved, DAM failures frequently result in catastrophic events; they also, work towards the simplification of life in plenty of ways, presenting an uncontrollable and intrinsic threat to the environment and public safety.

Plenty of researchers and different organizations contributed their findings in the DAM Break analysis and its consequence; Based on data from historical DAM failure events, regression equations emerged in the prediction of Break geometry.

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On the other hand, designers or researchers are not performing such pre-event analysis as part of the initiative in Angola, which is actively involved in the development of DAMs. DAM Break modelling, however, must be a standard design method to determine its potential causes of failure and to simulate the breaking process to review design parameters. Map the area that will be flooded in the event of failure to demarcate any vulnerable areas, plan the downstream area for different infrastructures, notify the appropriate parties of the precautionary DAM safety plans, and create a hazard management system. As a result, in this research the pipe failure scenario is chosen using the empirical equations, the outflow hydrograph from the Break is routed.

2. Material and Methods

2.1 Study Area

The research is based in the village of Calueque, in the Naulila community, municipality of Ombadja, province of Cunene. It is about 12 km from the Angolan to Namibian border and about 195 km southeast of Ondjiva, passing through Xangongo.

The Calueque DAM is located in the Cunene River Basin, a transboundary basin containing its main flow in the Cunene River. It is considered one of the most crucial basins in Southern Africa. It covers approximately 106,500 km², crossing arid regions with relative population density. The DAM is formed by reinforced concrete and earth; its height is 19m high, with an expansion that includes the North Pumping Station aiming to infrastructure an Agricultural Perimeter and a water distribution network to about 2500 hectares, with a total potential of more than 11 thousand hectares is also seen as a gravity DAM type with spillways and hydraulic gates for flood control, complemented by an onshore dike, located in the downstream part of the Middle Cunene, about 540 km of the Gove DAM and 40 km upstream of the Ruacana DAM.

Additionally, the DAM consists of a Hybrid power source. One of the most crucial aims of the existence of Calueque DAM for the population residing in the rural areas as well as the suburbs of the neighboring country (Namibia) is to supply quality water through the open canal, thus fulfilling the country´s needs, and to improve the irrigation of some soils with the greatest agricultural capacity. Also, supply the electricity in the municipality of Ombadja, using the water stored in the reservoir of the Calueque Dam, thus eradicating part of the draught issues on the community.

The link provides more information: https://www.hec.usace.army.mil/publications/TrainingDocuments/TD-39.pdf. Digitization along the cross-section cut lines is performed downstream of the river from the DAM up to the downstream boundary of 40 km. Fig. 1 shows a cross-section cutline across the Cunene River and other geometric data in HEC-RAS.

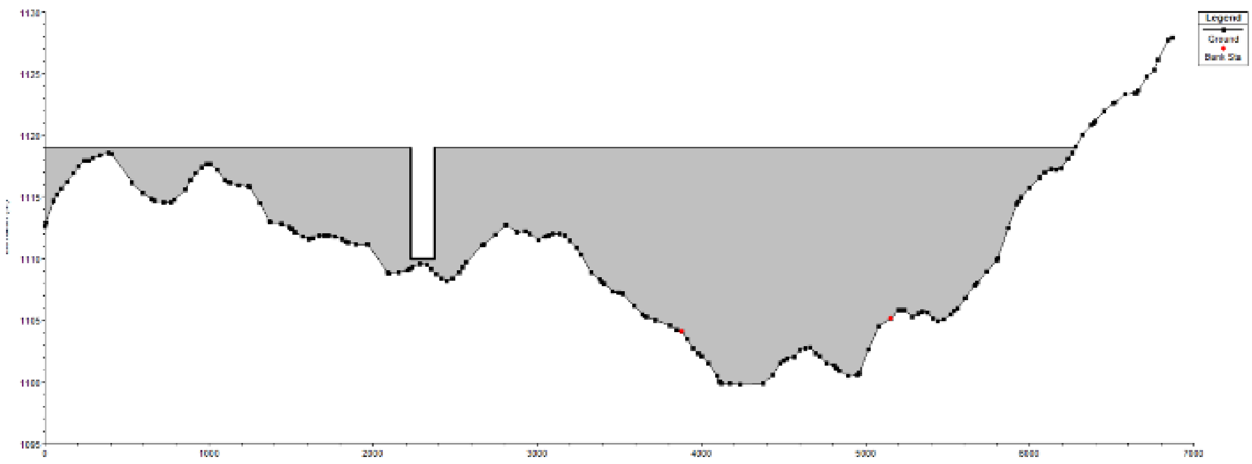

Fig. 1 The cross-sectional profile of Cunene DAM in HEC-RAS.

After the first crack in the DAM, large volumes of accumulated water are released. This creates a flood wave that moves rapidly along the watercourse, leading to a significant decrease in flow after the wave passes at 20, 30, and 40 km.

The database used in the analysis consists of hydraulic data, which results from the hydrological modelling collected from the Calueque Dam. The numerical modelling tool HEC-RAS was applied to attain the graphs presented in the research.

3. Methodology

The methodology used in this study entails data organization, collection, and data analysis using modelling software, as shown in Fig. 2 [1].

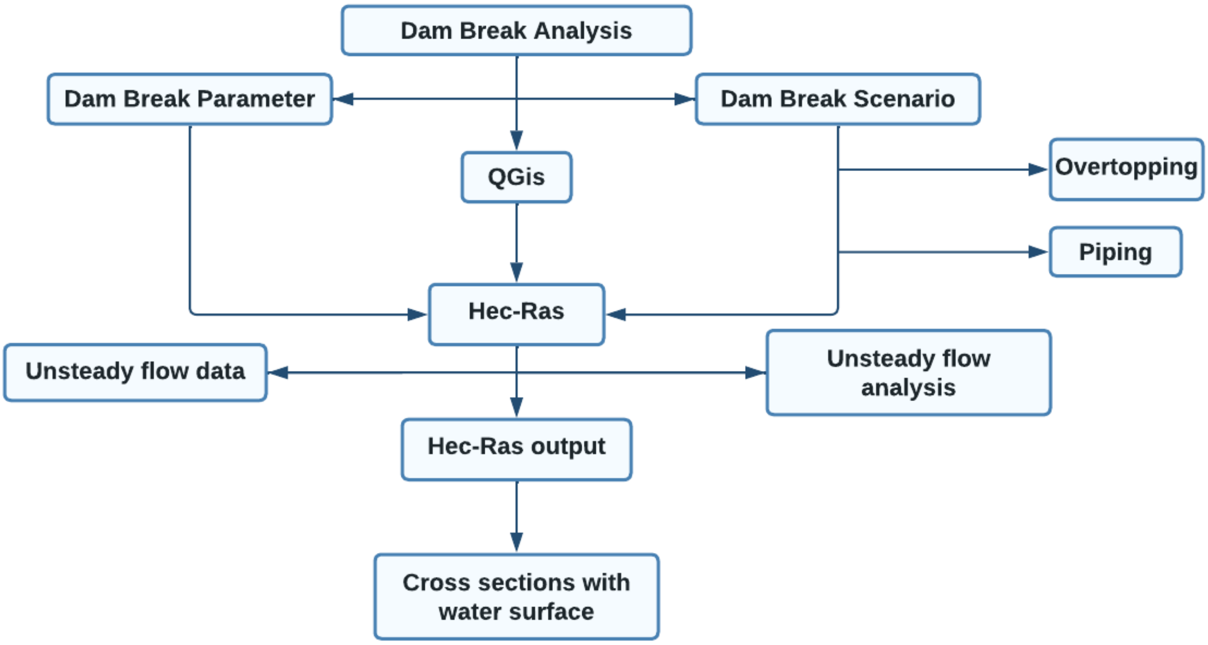

Fig. 2 Summary of the methodology of DAM Break Analysis.

3.1 Dam Break Parameters

3.1.1 Hydrological Modelling

To obtain flow rates, hydrological modeling was carried out using Arc SWAT software. The data used to parameterize the ARCSWAT model for the Calueque Dam watershed includes data such as: Elevation model; Land use; Type of soil; Climate data.

Data relating to topography were used to delineate the river basin and extract the river network.

The sub-basins were then cross-referenced with data on land use, soil type and slope and were subsequently divided into HRUs (Hydrologic Response Units). These values, when defined above 0%, give the model freedom to ignore all land uses, soil types and slopes that are present below the defined percentage. Climate data was obtained from GIOVANNI. This data is limited between January 1, 1981 and December 31, 2020, obtaining the flow rates generated by the model.

DAM break analysis entails routing the broken DAM's outflow hydrograph through the river downstream to its downstream boundary. To do this, there was an implementation of elevation data for the reservoir and the river’s cross-section, including the flood plain, and therefore, its analysis was simulated through the HEC-GeoRAS software from DEM (Digital Elevation Model) data of the location with a spatial resolution of 30 m x 30 m; after that, the model was exported to HEC-RAS software for a setup and simulation purpose as its source of elevation data.

PRECIPITATION: The breaking event of the Calueque Dam is taken into account when an extreme flood (probable maximum flood, or PMF) event enters the reservoir. This event is due to an extreme precipitation scenario determined by frequency analysis of historical precipitation data [3].

SOFTWARE: HEC-RAS and HEC-GeoRAS were used for the conjunction of hydraulic modeling, which includes a set of the QGIS tool (Fig. 3) and essential data such as Land use information and terrain data (Digital Elevation Model DEM). The HEC-RAS model solves the full Saint-Venant equations, and it is well suited for computing the flood wave propagation resulting from a DAM failure scenario [1]. Also, it is structured in 4 parts, namely, DAM Profile, DAM Break Data, Channel Cross-Section data, and the Unsteady Flow Analysis [1].

The propagation properties of the wave resulting from the intersection of the positive and negative surges can be described using equations developed by Saint-Venant. These equations form a coupled system of one-dimensional quasi-linear hyperbolic partial differential equations describing varied unsteady.

Below is a representation of the Saint Venant's 2D equations:

$$\frac{\partial H}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}=sources-\sin ks-conservation\ of\ \ in\ 2\mathrm{D}$$

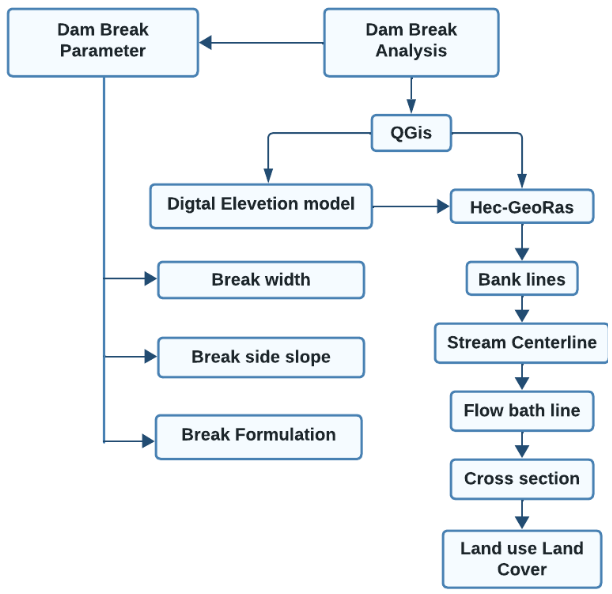

Fig. 3 Set of Qgis tools representation.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial H}{\partial x}+v_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-c_f u+fv$$

$$-conservation\ of\ \ momentum\ in\ 2\mathrm{D}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial H}{\partial x}+v_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-c_f v+fu$$

where,

t - time,

q - source/sink flux term,

u – velocity in x-direction

v- velocity in y-direction

g – acceleration due to gravity,

ν_t - horizontal eddy viscosity coefficient,

c_f - bottom friction coefficient

f - Coriolis parameter

3.1.2 Dam Break Side Slope

The characteristics of the rupture gap opening can be divided into two groups: geotechnical and hydrographic parameters (Fig. 4) [22]. The geotechnical parameters are responsible for the shape and dimensions of the rupture, and the hydrographic parameters are responsible for the rupture's formation time. Based on historical data [23]. It is described by the geometric parameters rupture height (Hb), average width (Bave), and lateral slope factor (Z), which are the elements of break formation.

Uncertainties and limitations in the break formation process significantly affect the determination of the water runoff rate and the potential for flooding downstream, pointing out that the size and time of formation of the rupture gap depends on the shape of the dam, the type of structure, the topography of the project site, the characteristics of the DAM foundation, the nature of the construction materials used in the project, the load in the reservoir, and the volume stored at the time of failure, all that explain the difficulty in predicting the shape and size of the fissure during rupture [24]. In this study, the data for the analysis of a DAM failure entailed three basic approaches: the analysis and comparison of resembling cases necessary to predict the gap parameters, the use of empirical equalizations based on previous DAM break cases, and the use of a rupture model with a physical basis, that employs the principles of hydraulics to simulate the development of the rupture.

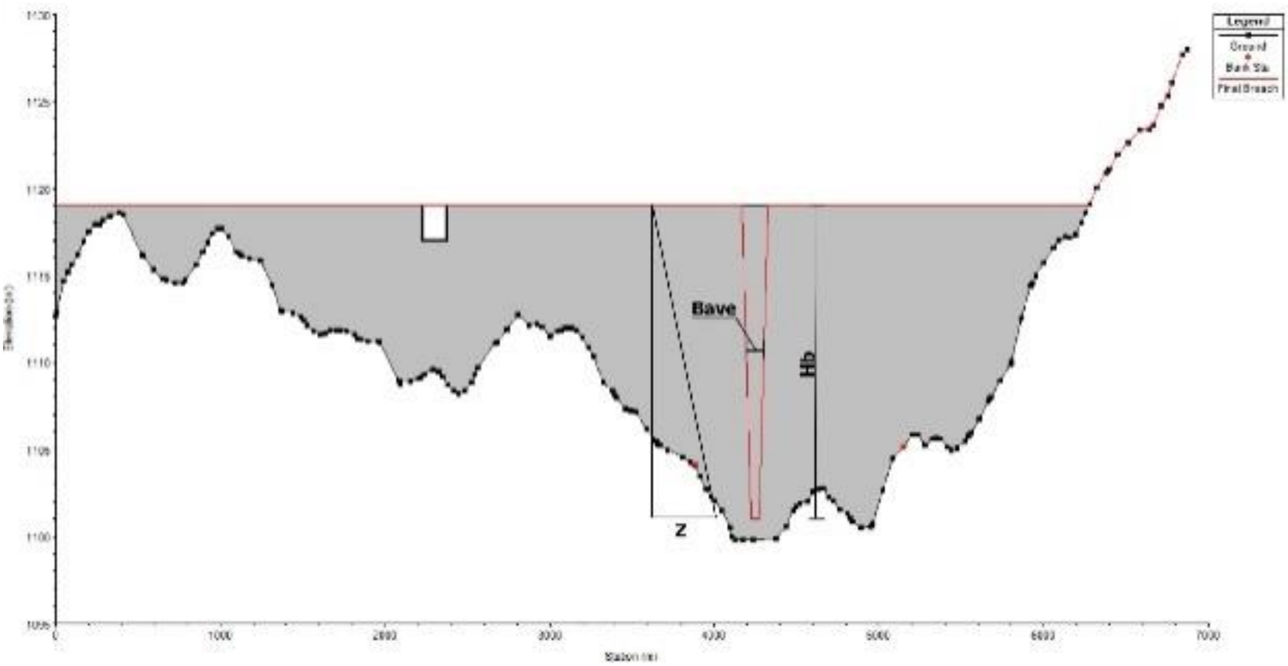

Fig. 4 Geotechnical parameters of the dam break.

3.2 Boundary Condition

The boundary condition is subdivided into two parts, namely, downstream and upstream boundary conditions.

3.2.1 Downstream Boundary

Normal depth is commonly used as a downstream boundary condition for open-ended rivers. Therefore, this thesis study uses Normal depth as a downstream boundary condition. The frictional slope of 0.012 is used as the normal depth for downstream boundary conditions [8].

3.2.2 Upstream Boundary Condition

The reservoir area upstream of the Calueque DAM can be modeled with cross-sections or by using a storage area. If a storage area is used, HEC-RAS uses level pool routing through the reservoir and unsteady flow routing downstream of the DAM. For this study, a storage area is used for upstream boundary conditions for DAM break simulation, and it is connected to the upstream end of the Cunene River.

The probable maximum flood is used as the reservoir's lateral inflow hydrograph and considered as inflow to the reservoir [8].

The upstream boundary condition given in HEC-RAS for DAM break analysis was the inflow hydrograph. The criteria for selecting inflow design flood for the safety of DAMs as per IS 11223 is shown in Table 1 [12].

The Calueque DAM consists of a storage capacity of 5234 m^3/s, with a height of 19 m above the foundation and 2600m of the total crowning development, and according to the Criterion for selection of design flood table above, the DAM is classified as intermediate. The unstable flow data used as a boundary condition in this study are normal depth and PMF inflow hydrograph. The PMF Inflow Hydrograph is used as an upstream boundary condition and Inflow Hydrograph boundary

Table 1 Criterion for selection of design flood (Source: HEC-RAS 5.0 Reference Manual).

Classification	Gross storage (MCM)	Hydraulic head (m)	Inflow design flood for safety of DAM
Small	0.5-10	7.5-12	100-year flood
Intermediate	10-60	12-30	Standard project flood
Large	>60	>30	Probable Maximum Flood

condition of the Cunene River. Normal depth is used as a downstream boundary condition and is also used as a downstream boundary condition for an open-ended reach [8].

The input data required were the Digital Elevation Model (DEM) of the river basin, DAM break parameters, spillway, and reservoir. All the geometric files were prepared from the DEM using RAS Mapper. DAM break parameters such as break width, Side Slopes (H: V), break Weir Coef, and break formation time were calculated using the different equations formulated [12].

3.3 Estimation of DAM Break Parameters

Various regression equations available for the computation of DAM break parameters are shown below:

Froelich (2008):

$$B_{avg} = 0.27 K_o V_w^{0.32} h_b^{0.04}$$

$$t_f = 63.2\sqrt{\left(\frac{V_w}{g h_b^2}\right)}$$

where,

B_{avg} = width of final break in m

t_f = break time in hrs

V_w = Reservoir volume at the time of failure in cubic meters

g = acceleration due to gravity

K_o = 1.3 for overtopping mode of failure

h_b = $height\ of\ final\ breach\ in\ meters$

Macdonald & Langridge Monopolis

$$B_{avg} = \frac{V_{er}}{\left(h_b \times W_b\right)}$$

$$t_f = 0.0179 V_{er}^{0.364}$$

where,

h_b = height of final break meters

W_b = bottom width of break in m

V_{er} = Volume of material eroded from the DAM embankment in cubic meters, which is given by:

$$V_{er} = 0.00348\left(V_{out} \times h_w\right)^{0.852}$$

where,

V_{out} = Volume of water that passes through the break at the time of failure in cubic meters.

h_w = depth of water above the break in meters.

3.4 Estimating Break Parameters & Failure Scenario

The estimation of the break location, failure type, dimension, and development time are crucial in making reliable predictions of the peak discharge, outflow hydrographs, and downstream inundation [6].

Several researchers have developed a set of regression equations using past historical data to determine the break parameters such as break width, break formation time and side slope. Many DAM breaks studies adopt empirical equations by Froehlich, MacDonald and Langridge-Monopolis (MLM) [5]. Peak discharge is also determined using regression equations of these methods, which will be used for comparison purposes with that obtained from calculated peak discharge from the simulation model.

The type of failure scenario that is often associated with DAM break cases are:

- Overtopping
- piping failure

Overtopping occurs when the uncontrolled flow of water exceeds the crest level. The flow is similar to a flow over a broad-crested weir, where initial erosion occurs at the bottom downstream section of the DAM and widens towards the crest level, leading to a break of the reservoir. On the other hand,

While the DAM experiencing seapage may appear in sound conditions there might be damages on the internal structure of the DAM. If there seem to be an increase in seapage flowrates, the flow is unclear and is causing internal erosion or carrying material then piping is likely occurring.

Piping is an erosion process that occurs inside the DAM whenever the seapage flow starts eroding embankment materials out of and away from the DAM. It starts at a downstream slope or toe and moves rapidly upstream to the impoundment this process tending to accelerate as the expanding larger opening or pipe allows for increase seapage flows. If left unattended, the seapage flow and progressive internal erosion will soon get out of control and with the expansion of both the internal pipe or void, the embankment structure above it collapses leading to a DAM embankment and a potentially catastrophic release of the stored water which leads to plenty of property damage and loss of life.

Piping failure is associated with a gradual seepage at the internal DAM structure, leading to the formation of significant holes, damaging the internal structure at the external face of the DAM. Its integrity would then be compromised when erosion takes place at the surface due to significant hydraulic flow at the break point.

The study, was based on piping failure for the prevision model of cracks as one of the methods that consider the circulation of water in the fine pores or small cracks in the soil, below or around the structure, which can lead to progressive and continuous erosion of the soil, slight failures in the structure and, eventually, collapses.

3.5 Rapid Failure: DAM Break Wave

DAM Break wave happened when in a complete annihilation of the Calueque DAM resulted in a highly turbulent, unsteady flow. The removal of the DAM in the creation of a retreating (negative surge) wavefront in response to the sudden reduction in flow depth [25]. When analysis was carried on the DAM splitting two bodies of water, the crossing of both the relatively slow-moving body of water and negative surge results of discontinuity of velocity were attained.

4. Results and Discussion

From these two (2) sets of values the one that gave the least break formation time was selected for the parameters. Manning's n values were assigned based on the LULC of the area. The geometric data of the DAM, spillway and reservoir were given as input into HEC-RAS. The PMF hydrograph, normal depth and initial elevation were input as the upstream boundary condition, the downstream boundary condition and the initial condition respectively. After conducting the DAM break simulation in HEC-RAS flood inundation maps were generated.

In this study, DAM break analysis of Calueque DAM was done using HEC-RAS software. The input data required were the Digital Elevation Model (DEM) of the river basin, DAM break parameters, Manning's n values and geometric data of DAM. The geometric files were prepared from the DEM using RAS Mapper. The DAM break parameters like break width and break formation time were computed using the different equations suggested by Froelich, MacDonald and Langridge Monopolis. From these two set of values the one that gave the least break formation time was selected for the parameters. The geometric data of the DAM was given as input into HEC-RAS. The PMF hydrograph, normal depth, and initial elevation were input as the upstream, downstream, and initial boundary conditions. After conducting the DAM break simulation in HEC-RAS flood inundation maps were generated [8].

Flood resulting from the PMF of Cunene River did not overtop the DAM during unsteady flow simulation. The PMF raised the water surface level of the reservoir to a level where it is below the crest of the DAM. Fig. 5 shows the maximum water surface elevation on the DAM profile during unsteady flow simulation.

Unsteady flow analysis due to piping of Calueque DAM in HEC-RAS is done after entering the necessary data for the simulation to begin. DAM Break parameters and boundary conditions in this case are the necessary data that are used as an input into HEC-RAS.

The starting water surface elevation for piping is taken at the crest of the spillway, since it is only used during flood events. Fig 7 shows water surface elevation before piping begins.

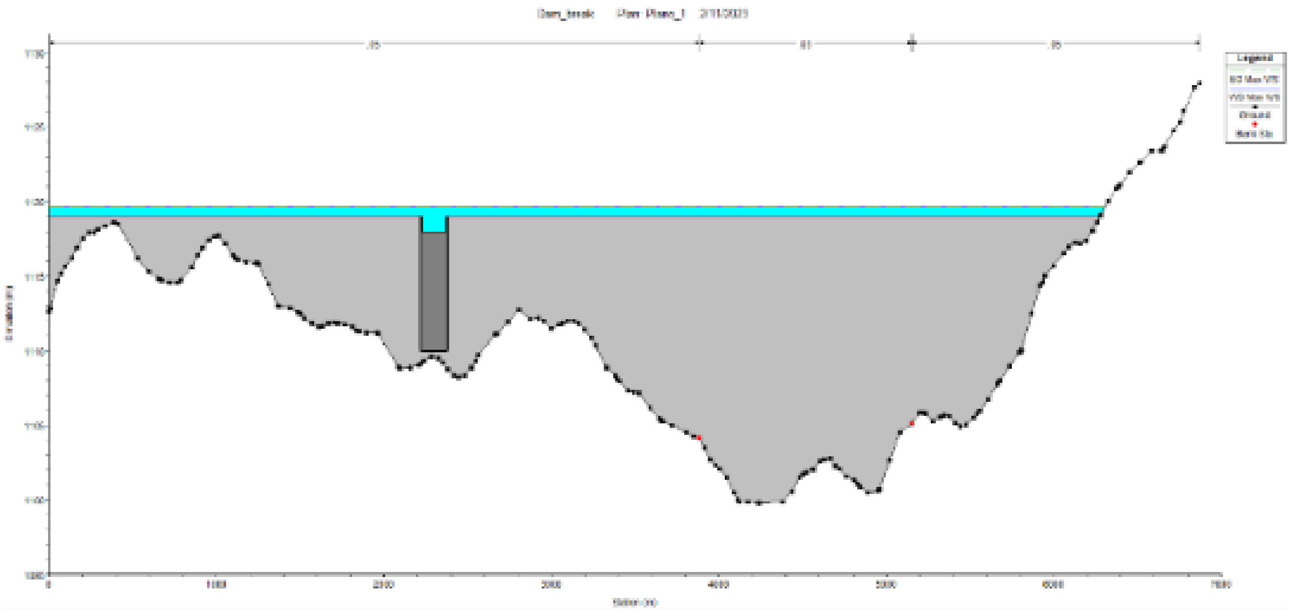

Fig. 5 Cunene DAM with maximum water surface.

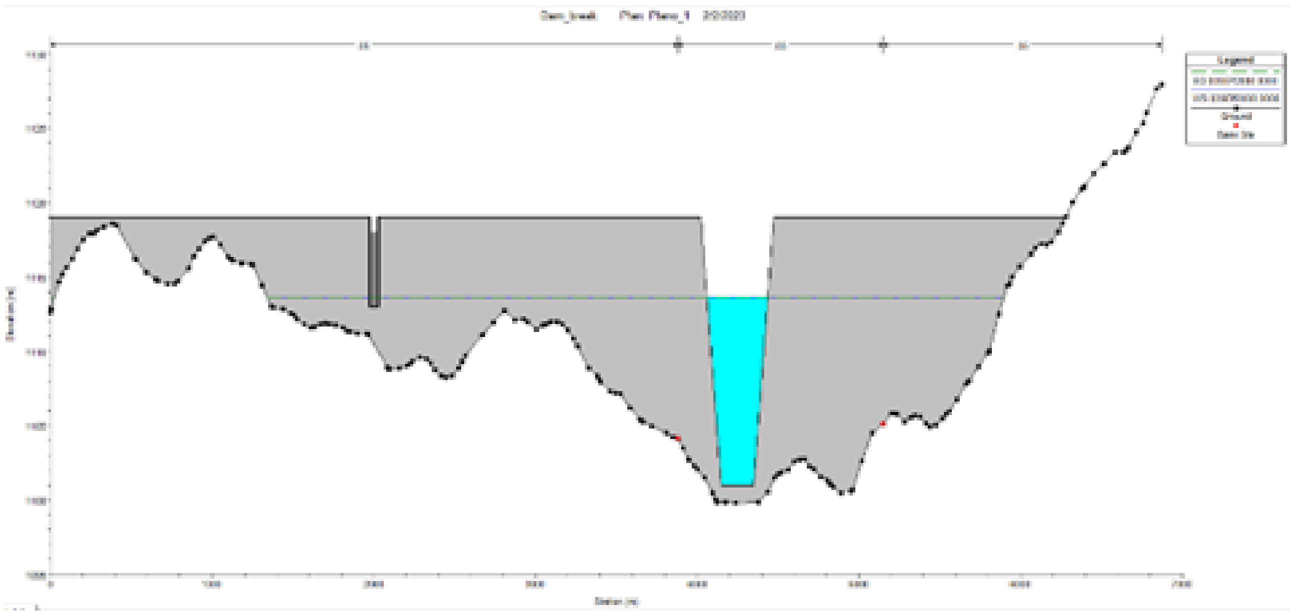

Fig. 6 Calueque DAM after the breaking.

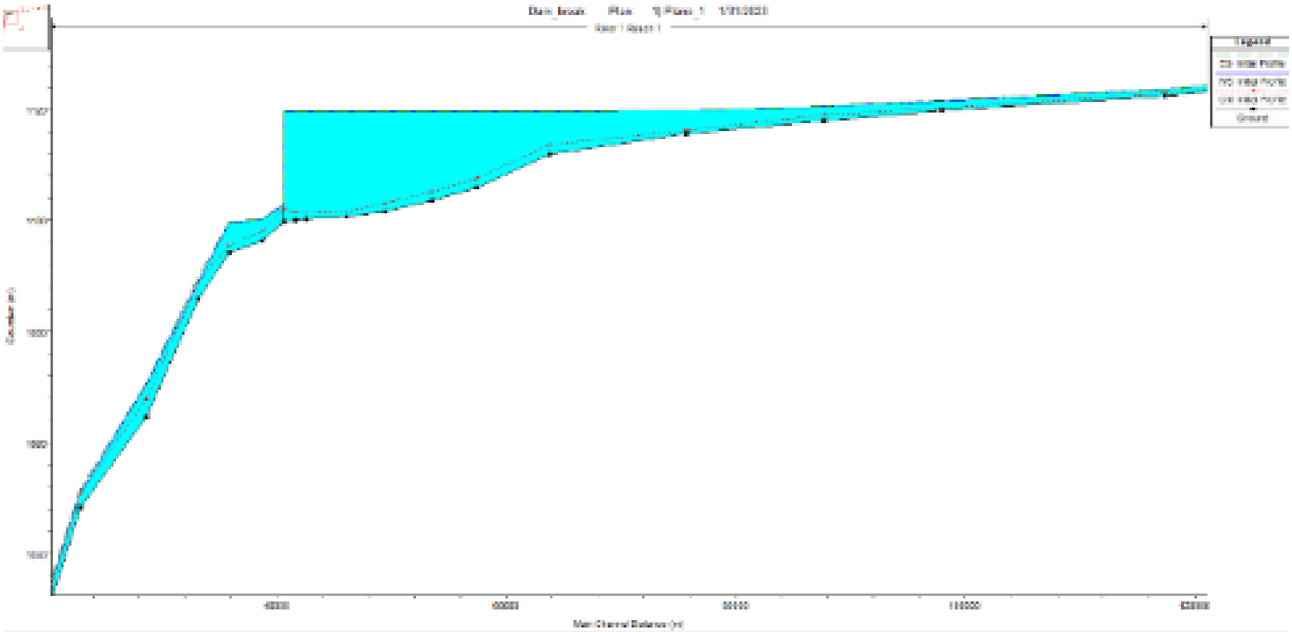

Fig. 7 Water surface profile of Cunene River.

Fig. 8 shows hydrographs in the in-line structure and at 20 km, 30 km, and 40 km from the DAM by Froehlich (2008), MacDonald, and Langridge-Monopolis, respectively. The behavior of streamflows at 20 km downstream of Calueque DAM at time intervals, 0:00 am, 05:00 am, 10:00 am, 15:00 pm, and 20:00 pm are 7111.858, 4316.093, 4316.672, 3562.277 and 3559.573 m/s^3, respectively, while according to Froehlich the maximum Break outflow hydrograph record occurs at 1:00 am and minimum at 20:00 with 3925.038 and 3187.811 m/s^3 respectively.

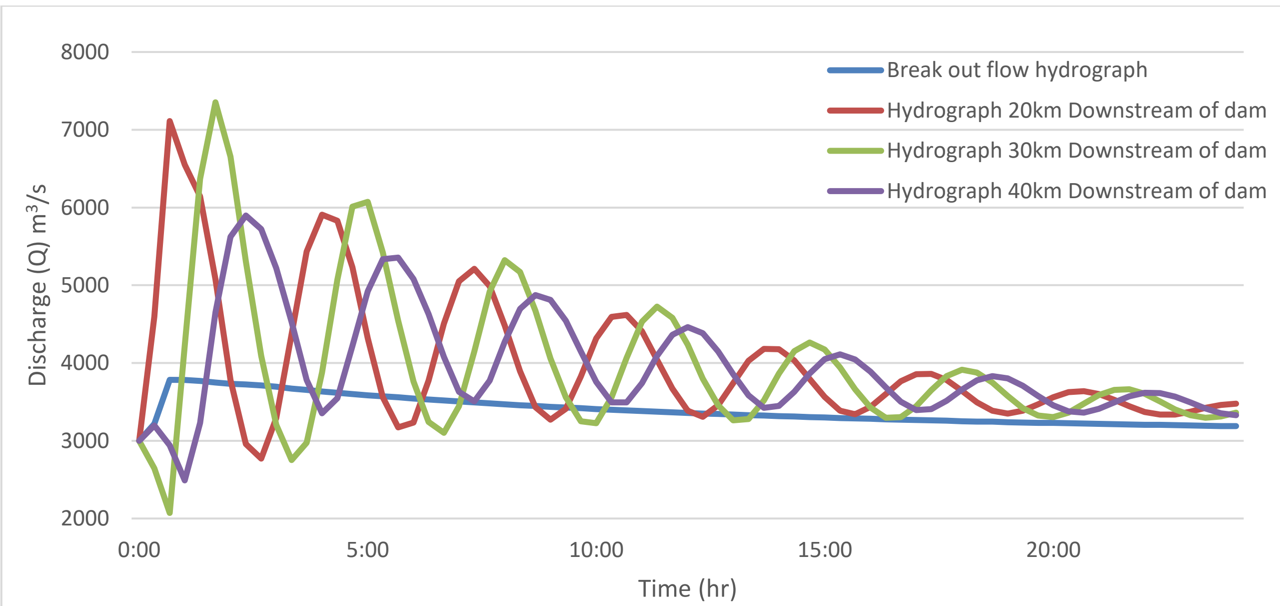

Fig. 8 Hydrographs after unsteady flow analysis Froehlich (2008).

The behavior of streamflow at 20 km downstream of Calueque DAM at time intervals, 0:00 am, 05:00 am, 10:00 am, 15:00 pm, and 20:00 pm are 2999.999, 4331.678, 3102.672, 3548.267 and 3165.259 m/s^3, respectively, while according to Macdonald and Langridge-Monopolis, the maximum Break outflow hydrograph record occurs at 1:00 am and minimum at 20:00 with 3919.738 and 3212.648 m/s^3 respectively as per Fig. 9.

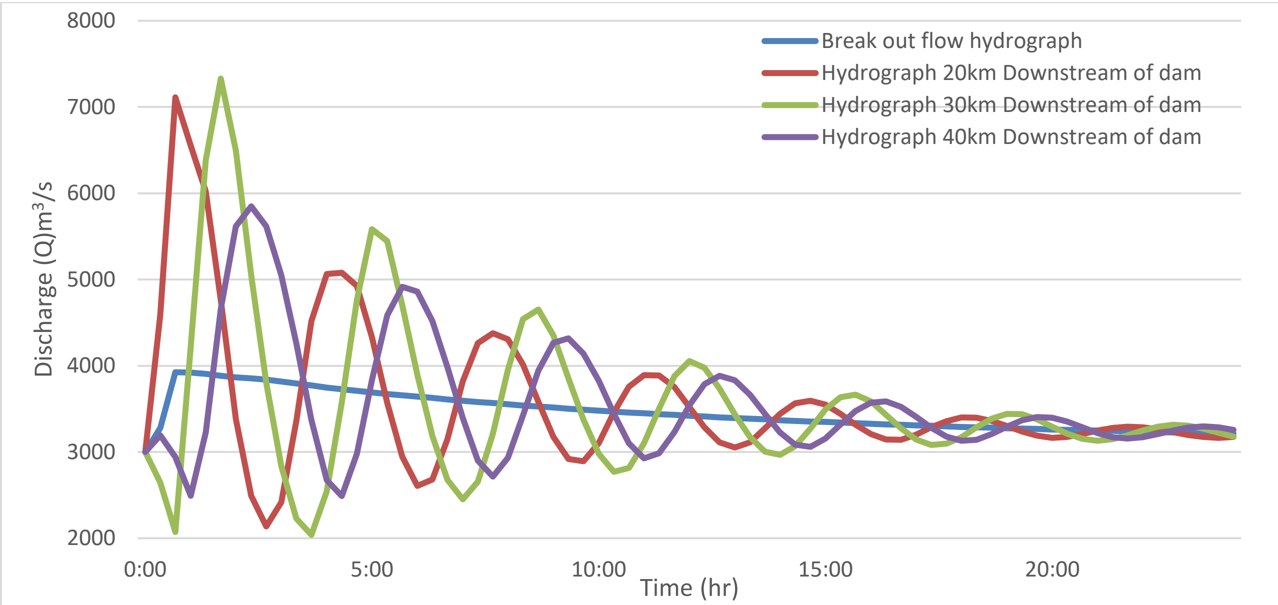

Fig. 9 Hydrographs after unsteady flow analysis for MacDonald and Langridge-Monopolis (1984).

When observing the Breakout flow hydrograph for both Froehlich (2008) and MacDonald and Langridge-Monopolis (1984) formulations it is observed in Fig. 10 below that, according to Froehlich the maximum Break outflow hydrograph record occurs at 1:00 am and minimum at 20:00 with 3925.038 and 3187.811 m/s3 respectively whereas, according to Macdonald and Langridge-Monopolis the maximum Break outflow hydrograph record occurs at 1:00 am and minimum at 20:00 with 3919.738 and 3212.648 m/s^3 respectively.

3.4. Flood Mapping

The information related to the infrastructures and buildings of the cadastral mapping, as well as the classes of the vegetation cover map, were digitized in information plans using the Qgis software.

The vegetation map with the original classes has been reclassified to order them in ascending order of vulnerability.

The lower the vegetation, the greater its vulnerability to occupation, as shown in Figs. 11, 12.

According to the results obtained in the model, agricultural areas, shipyards, Calueque airport, road number 295, and villages will not be directly affected by the large volumes of water.

The presentation of the affected areas after DAM break and flooding as shown in Table 2.

Having analysed the parameters have been in a limited range the flood mapping results in the early stage of DAM piping failure depicts a tremendous uncertainty. As the flood spreads furthermore downstream of the Calueque DAM, the uncertainty gradually decreases. When creating flood mapping there should be an inclusion of emergency plans, and an application of conservative value of flood routing simulation parameters which will not have great increase on the flood inundation areas far from the DAM, not causing unnecessary waste and loss in emergency scheduling; and thus, the approval of conservative parameter values is recommended when simulating flood routing for areas distant from the DAM.

When simulating flood mapping it is crucial to adopt adequate break models and regression analysis ensuring the accuracy of the results.

4. Conclusions and Recommendation

4.1 Conclusions

After choosing a failure situation, a DAM Break is modeled. Piping is the failure scenario chosen for this research because they account for the majority of historical DAM failures. According to this research, the Calueque DAM does not have sufficient free board and spillway capacity to safely pass the PMF inflow of the Cunene River without any cracks.

According to the results, the formulations of both MacDonald and Langridge-Monopolis (1984) Break outflow hydrographs were found to be conservative and reliable, and then the formulations were selected for inundation mapping in QGis and HEC-RAS's unsteady flow analysis.

QGIS Software can detect elevation differences anywhere depending on the quality of the DEM, and, therefore it was clearly detected that 12.523 hectares of land are affected by the DAM Break from the drawn flood and the aerial map.

4.2 Recommendation

Angola has several DAMs for hydropower, irrigation, and water supply, but the study of DAM Breaks has received little to no focus there. However, it is crucial for reducing the loss of life and property as a result of the DAM Break inundation. More research on DAM Break studies will be required in this nation in the future. In the case of a DAM Break, potential infrastructure developments in flooded towns must take emergency situations into consideration. This might include having sufficient waterways for building bridges. The relevant flood management and mitigation offices may also need to plan emergency drills for these circumstances.

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