Hydrodynamic Dam Breach Modelling of Earthfill Saddle Dam

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KEYWORDS

- Dam break failure
- 1-D hydrodynamic modelling
- Dam breach parameter
- Dam break analysis

ABSTRACT

Dams have been built for many reasons such as irrigation, hydropower, flood mitigation, and water supply to support the sustainability of mankind since millennia. However, the huge amount of water stored behind the dam can seriously pose adverse impacts to the downstream community should it be released due to unwanted dam break event. Possible loss of lives and damages to properties due to dam failure are great that a proper Emergency Response Plan (ERP) and quantification of impacts become important requirement for a dam owner and operators. A study was conducted to specifically model the dam break for the Saddle Dam A located in Kenyir reservoir. The main purpose of the study was to establish dam breach characteristics in prediction of Saddle Dam A outflow hydrograph. Dam break modeling due to a breach were performed under two scenarios namely Probable Maximum Flood (PMF) scenario and Clear Day scenario. Prediction of dam breach parameters was conducted using Froehlich and Macdonald–Langridge-Monopolis (MDLM) predictor equations. The modeling was done via MIKE 11 1-D Hydrodynamic Model developed by Danish Hydraulics Institute (DHI). The peak outflow simulated due to Clear Day failure (CDF) was 152,130 m³/s whilst Probable Maximum Flood (PMF) yielded peak outflow of 208,543 m³/s.

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1. INTRODUCTION

Dam has been known as a key player in sustaining people’s lives. Dams are constructed for many reasons such as for irrigation and water supply, power generation, navigation and diversion, flood mitigation and other needs. Malaysia has nearly one hundred dams constructed for various purposes catering for human daily activities. However some of the dams can be rated as a high hazard which indicates that dam failure will probably result in loss of lives and major damages to property [1]. This is evident as most of these dams are constructed in the vicinity of highly dense populations such as traditional villages and fully developed township.

In the event of dam failure, the impounding water together with immense potential energy will storm through the downstream areas and damaging anything located in its path. The consequences could be extremely severe to the downstream populations. By conducting this study, loss of human lives can be estimated resulting from dam failure. The establishment of precise dam breach parameters and flood inundation map for a particular dam is essential in building and enhancing the community resilience towards disaster, stressing the ability to reduce the possible impact of a disaster as well as to effectively recovery following a disaster. The vital outcome of this study would be contributively towards the disaster management in the event of a dam break.

Prediction of dam breach in Malaysia is still very much in the realm of research despite the legal enforcement to conduct a dam breach study and impacts assessment for all new dams since 1989. Some dam owners and operators have taken step forward to conducting dam breach study to respond to the call as well as to maintain the good upkeep of their dams. The analyses would be important in the formulation of an Emergency Response Plan (ERP) which consequently coordinates the responsibility between dam owners, authorities and emergency agencies such as police and fire services in the preparations of evacuation plans, dam break and other flood warning systems, hazard classification of affected areas and post-flood actions.

Breach development and the resultant geometry have a fundamental control on the outflow hydrograph and the downstream migration of the flood wave. Breach simulation and breach parameter prediction contain the greatest uncertainty of all aspects of dam break analysis [2]. From the literature, the existing approaches used in predicting breach parameter can be based on the empirical method (case study method) or physically based model which is known as numerical model based on the principles of hydraulics and sediment transport to simulate breach development.

Numerous empirical equations have been developed from large databases on embankment dam failures. MacDonald and
Langridge-Monopolis proposed a breach formation factor, defined as the product of the volume of breach outflow and the depth of water above the breach invert at a time of failure [3]. Froehlich developed non-dimensional prediction equations for estimating average breach width, average side-slope factor, and breach development time [4]. Von Thune et al. used the data from Froehlich and Macdonald and Langridge-Monopolis to develop guidance for estimating breach side slopes, breach width and time of failure [5]. The United States Bureau of Reclamation also provide guidance for selecting ultimate breach width and time of failure to produce conservative, upper bound values introducing a factor of safety into the hazard classification procedure [6]. Numerical models on the other hand involve a computation process incorporating the development of a core algorithm such as BREACH model. Key parameters describing the impoundment geometry and materials properties are initially required. Cristofano invented the first physically based dam breach model assuming a trapezoidal breach of a constant bottom width [7]. Harris and Wagner applied sediment transport equation to dam breach flows, assuming breach erosion to begin immediately upon overtopping and proceed until the breach reached the dam bottom [8]. Brown and Rogers presented a breach model, BRDAM based on Harris and Wagner’s work, which was applicable to overtopping and piping induced breaches [9]. The BEED model developed by Singh and Scarlatos is a physically-based model simulating breach evolution and flood routing [10].

More complex methods of hydraulic modelling have become more acceptable during the recent years, as window-based computer technology has emerged as the optimum graphical analysis tool. Hydrodynamic models are readily becoming commonplace for several reasons. First, computational speed and numerical modelling schemes have advanced far enough to solve the complete Saint Venant equations in an acceptable time period. Second, the growing availability of LiDAR and Aerial Laser Scanning is making high resolution topography datasets, the base input for all 2-D hydrodynamic models more readily available [11]. And third, the need for a more detailed investigation of flooding concerns is driving the use of hydrodynamic [11]. Some common 1-D river models include HEC-RAS, MIKE 11, and DAMBRK and 2-D models incorporate MIKE 21 and TUFLOW.

Sobey has developed a series benchmark tests for unsteady, one dimensional open channel flow models and the test ranged from simple reach model to looped networks [12]. In spite of computational dissimilarity for HEC-RAS and MIKE 11, both models successfully demonstrated the ability to model benchmark cases. But from rough discretization in some of the benchmark tests, MIKE 11 demonstrated an ability to respond more quickly to disturbances presented by the initial conditions. This study had therefore used the MIKE modelling package to simulate the dam breach event and to determine the outflow hydrograph to be routed to the downstream area and eventually to obtain the flood maps.

This paper will therefore discuss on the prediction of dam breach parameters and MIKE 11 model setup to generate outflow hydrograph under two scenarios namely Clear Day Failure (CDF) and Probable Maximum Flood (PMF).

2. STUDY AREA

Kenyir Hydroelectric Scheme is located East of Peninsular Malaysia, about 40 km inland from the coast and 60 km upstream of Terengganu River mouth and comprises of one main dam and eight saddle dams along the perimeter of Kenyir Reservoir. The scheme is mainly for hydropower generation operated by Tenaga Nasional Berhad (TNB), the largest utility company in Malaysia as well as for flood mitigation for Hulu Terengganu District.

The Kenyir reservoir catchment is formed by high hills to the south and west but the north east side is formed with a low ridge with several low saddles that are below the Full Supply Level (FSL) of Elevation (EL) 145 m. Therefore, eight homogenous earthfill saddle dams were constructed between 10 km and 15 km from the Kenyir Dam for the purpose of containing the Kenyir reservoir up to water level of EL 155 m. Among the eight saddle dams, Saddle Dam A (SDA) is the longest and highest with a maximum height of 52 m, embankment volume of 7 x 10^6 m^3 and the crest length reaches 2250 m. It is built with a crest level of EL 155 m and has the lowest part of the saddle at EL 110 m. Hence, the amount of water stored and its potential energy impounded behind SDA is the highest among all the other saddle dams. Therefore, SDA is considered in this simulation since it has the most severe, catastrophic impact to the downstream among all the saddle dams. Fig. 1 shows the location of Saddle Dam A.

![Location of Saddle Dam A](image)

Fig. 1. Location of Saddle Dam A

2.1 Prediction of Dam Breach Parameters

The breach parameters physically describe the breach shape as the breach depth or the vertical extent of the breach measured from the dam crest down to the breach height, breach width of the breach channel and breach side slope factor. The physical parameters are shown graphically in Fig. 2 while Table 1 lists the suggested breach parameters for earth dams. The height of the dam is denoted by h_d. These values can be used as reference for dam break simulation study [13].

The routine of obtaining outflow hydrograph using MIKE 11 software requires the prediction of dam breach parameters and setting up model that represents the actual layout on the ground. It is crucial for assigning appropriate breaching parameters since the parameters will affect the breach outflow hydrograph and consequences of dam failure. From literature
review, it is found that Froehlich and MacDonald & Langdrige Monopolis (MDLM) are the most suitable relations in predicting the breach parameters [15]. Both equations will be taken into account to calculate breach parameters. Table 2 shows the equations of both researchers used in this study while Table 3 shows the properties of Saddle Dam A according to scenarios. All properties were extracted from the sectional details of the dam and from the stage area and storage capacity curve.

![Fig. 2. Parameter of an idealized dam breach [14]](image)

Table 1. Suggested Breach Parameter for Earth Dams [13]

<table>
<thead>
<tr>
<th>Source</th>
<th>Average Breach Width</th>
<th>Breach Side Slope (1V:ZH)</th>
<th>Breach Failure Time (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWS</td>
<td>1.0 to 5.0 h_d</td>
<td>Z = 0 to 1</td>
<td>0.1 to 2.0</td>
</tr>
<tr>
<td>COE</td>
<td>0.5 to 4.0 h_d</td>
<td>Z = 0 to 1</td>
<td>0.5 to 4.0</td>
</tr>
<tr>
<td>FERC</td>
<td>1.0 to 5.0 h_d</td>
<td>Z = 0 to 1</td>
<td>0.1 to 1.0</td>
</tr>
<tr>
<td>USBR</td>
<td>3 h_d</td>
<td>N/A</td>
<td>0.00333b</td>
</tr>
<tr>
<td>Boss Dambrk</td>
<td>0.5 to 4.0 h_d</td>
<td>Z = 0 to 1</td>
<td>0.5 to 4.0</td>
</tr>
<tr>
<td>Harrington</td>
<td>1.0 to 8.0 h_d</td>
<td>Z = 0 to 1</td>
<td>h_d /120 to h_d /180</td>
</tr>
</tbody>
</table>

Table 2. Equation for Breach Parameters

<table>
<thead>
<tr>
<th>Breach Parameters</th>
<th>MDLM</th>
<th>Froehlich (1995b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breach formation time, t_f (hour)</td>
<td>0.0179(V_o)^{0.164}</td>
<td>0.00254 (V_o)^{0.051} h_b^{0.15}</td>
</tr>
<tr>
<td>Average breach width, ( \overline{b} ) (m)</td>
<td>-</td>
<td>0.1803K ( \sqrt{V_o} ) ( w_b )^{0.19}</td>
</tr>
<tr>
<td>Breach side slope 0.5</td>
<td>1.4 for overtopping failure</td>
<td>0.9 for other failure modes</td>
</tr>
<tr>
<td>Average breach width (m)</td>
<td>0.53</td>
<td>0.607(V_o^{0.295} h_b^{1.24})</td>
</tr>
<tr>
<td>Simulated peak flow, Q_p (m³/s)</td>
<td>13.4 ( h_b)^{1.99}</td>
<td>6.071(V_o^{0.295} h_b^{1.24})</td>
</tr>
</tbody>
</table>

Table 3. Saddle Dam a Properties According to Scenarios

<table>
<thead>
<tr>
<th>Properties</th>
<th>CDF</th>
<th>PMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_o ), m³</td>
<td>11.1 x 10⁹</td>
<td>13.2 x 10⁹</td>
</tr>
<tr>
<td>( h_o ), m</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>( h_r ), m</td>
<td>35</td>
<td>( h_r ), m</td>
</tr>
<tr>
<td>( V_{er} ), m³</td>
<td>5.45 x 10⁶</td>
<td>5.45 x 10⁶</td>
</tr>
<tr>
<td>( h_d ), m</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>( K_o )</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 4. Calculated Breach Parameter for Saddle Dam A

<table>
<thead>
<tr>
<th>Leak Capacity</th>
<th>CDF</th>
<th>MDLM</th>
<th>Froehlich (1995b)</th>
<th>PMF</th>
<th>MDLM</th>
<th>Froehlich (1995b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average breach width (m)</td>
<td>609</td>
<td>-</td>
<td>644</td>
<td></td>
<td>-</td>
<td>644</td>
</tr>
<tr>
<td>Simulated peak flow (m³/s)</td>
<td>117,171.70</td>
<td>45,835.64</td>
<td>136,021.24</td>
<td>59,709.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The failure time computed for Saddle Dam A CDF scenario using MDLM and Froehlich are 5.07 hours and 17.42 hours. The shorter duration 5.07 will be adopted and considered reasonable for Saddle Dam A, which is of homogeneous earthenfill will erode much faster. For both scenarios, the maximum breach will occur corresponding to full length of dam height as Saddle Dam A is located at an elevation of 110 m which is higher than the original reservoir datum and it is susceptible to erosion as it consists of homogeneous construction materials. Average breach width is calculated to be 609 m by using Froehlich equation. From the literature review, most of an earthenfill dam will probably have a breach side slope of 1V:1H. By using the given suggested side slope, the bottom breach width is calculated to be 564 m. Breaching for Saddle Dam A PMF scenario was set to start when the reservoir water level reached its PMF level at EL 151.57 m. The dam breach section will be fully developed at 5.07 hours calculated using MDLM equation. For an average breach width, again using Froehlich gives 644 m. With the same side slope, 1V:1H, the bottom breach width is calculated to be 599 m.

2.2 Simulation of the Breach Outflow Hydrograph

In this study, the core system is the dam break (DB) module which is used to model the dam breach process. The hydrodynamic (HD) module which represents the heart of MIKE 11 is used to calculate the outflow, flows and water level of channels and rivers. To setup the model for this study,
parameters such as river network, cross sections, boundary data, time series and hydrodynamic need to be created.

The network for this study was setup using the network editor which is a central unit of MIKE 11 model. Branches and points were inserted indicating the river network and dam structures. In this study, two branches have been created to represent the Sg. Terengganu, Sg. Telemong and spillway of the main dam. The first point for all branches represented the Kenyir reservoir whilst the last point indicated the downstream of Sungai Terengganu and Sg. Telemong. Dam structures were described based on dam height, crest length, and crest height whilst Spillway structure was described using the spillway coefficient, height, width and level. Points were inserted along the channels and defined as chainage, by assigning specific cross section which was described in the cross section file. Fig. 3 shows the entire network of Kenyir reservoir whilst Fig. 4 shows the close-up of Saddle Dam A branch network of Sg. Telemong. Fig. 5 represents the dam data of the main dam and Saddle Dam A.

![Fig. 3. Network branch of Kenyir Reservoir](image)

![Fig. 4. Close-up network branch of Saddle Dam](image)

The river cross-section extracted from SRTM data were inserted in the model to join the entire network while Kenyir storage and capacity curve was used to represent the reservoir. In the boundary section, the breach parameters and the inflow hydrograph in time series were inserted into the models. The upstream of the dams were specified as ‘Inflow’ boundary type and downstream as ‘Water level’. Dam is specified as ‘Dambreak’ where the dam breach parameters in time series were inserted. For PMF scenarios, PMF inflow hydrograph (Fig. 5) was inserted in the model but for the CDF scenarios, there was no inflow discharge was inserted hence; time series consist of zero value was created and inserted into the model. For hydrodynamic part, initial water level for need to be justified in order to run a hydrodynamic computation. The river beds were assumed to be packed clay with the recommended Manning’s (M) equals to 30 [16].

![Fig. 5. Probable Maximum Flood (PMF) Hydrograph](image)

For Saddle Dam A, the breach was assumed to start when the reservoir level was at EL 145 m. The dam breach section would be fully developed in 5.07 hours after the initiation of dam break with a breach side slope of 1V: 1H and bottom breach width of 564 m. The peak discharge was simulated to be 152,130 m$^3$/s and the breach hydrograph is shown in Fig. 6. There was no outflow discharging through the spillway as the dam was simulated to breach at full supply level. Breaching was set to start when the reservoir water level reached its PMF level at EL 151.57 m. Time of failure equalled to 5.07 m with 1V: 1H breach side slopes and 599 m breach bottom width. The dam break peak discharge was simulated to be 208,543 m$^3$/s as depicted in Fig. 7.

![Fig. 6. Breach outflow hydrograph for Saddle Dam A CDF scenario](image)
3. CONCLUSIONS

Dam could fail due to various causes such piping, overtopping, foundation and many others. In the case of dam break modelling, it is important to predict the breach parameters accurately. Prediction is limited by the number of reported and analysed cases whilst the physical model was not cost effective to support the prediction of these parameters. Literature review revealed that Macdonald and Langridge-Monopolis (MDLM) and Froehlich were the best predictor equations. From the result, the peak outflow discharge due to failure of Saddle Dam A considered small as compared to the peak outflow discharge of Kenyir dam [17]. This analysis would help the formulation of EAP for Kenyir Dam and to assist the relevant authority to react in any unlikely event of dam failure. Consequently, it will improve the community state of preparedness and resilience in reacting towards a disaster hence improving the authority disaster management policy and procedures. Since there is very limited modeling data available on the behaviour of dam breach parameters in Malaysia hence there is clear need for further research work on this subject.

REFERENCES

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