Dam Break Analysis of Temenggor Dam Using HEC-RAS

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Abstract. Embankment dam is commonly built in Malaysia as it provides benefits to the local population, mainly agricultural activity and flood control measures. However, its massive potential energy reservoir would impose risk of sudden containment breach leading to loss of life and property at inhabited downstream area. This paper deemed to provide a dam break analysis of Temenggor Dam to generate breach hydrograph and inundation map as a result of dam break event under piping and overtopping failure. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) is capable to model 1-dimensional (1-D) and 2-dimensional (2-D) dam failure event by utilizing hydrological and terrain information generating unsteady-state flow simulation of the dam breach. The process for gathering and preparing data, estimating breach parameters, creating one dimensional and two-dimensional unsteady-flow model in HEC-RAS, performing a dam failure analysis for two dam failure scenarios and mapping the flood propagation are outlined in this paper. From 1-D analysis, it is found that the breach flow of Temenggor Dam failure can achieve 281,588 m^3/s for piping failure and 331,030 m^3/s for overtopping failure. 2-D analysis' breach flow attained 268,341 m^3/s and 328,869 m^3/s for piping and overtopping failure, respectively. Furthermore, the expected arrival time of flood wave at selected locations also presented in this paper. 1-D model produced comparable breach hydrograph result of Temenggor Dam against 2-D model with the advantage of significantly shorter simulation time requirement. However, 2-D model able to generate inundation map due to dam failure in wider area which can provide insight of flood hazard risk level and contribution for emergency action plan development.

1. Introduction

Dams are commonly known as mega structure which can provide essential needs for multiple purposes such as flood control, electricity generation, irrigation, water supply and recreation. Its impoundment system stores massive potential energy in providing benefits for human, but it would also impose risk of sudden containment breach leading to loss of life and property at downstream [1]. Since 1960, the incident of dam failure disasters occurred around the globe has instigated the necessity of forecasting, prevention, and mitigation plan for the event of failure at all constructed dams [2]. Therefore, a dam breach analysis is usually conducted to determine the ultimate discharge from a hypothetical breach of a dam under such events. Dam break analysis has been studied by many researchers using historical dam failure data and produced empirical equations as an estimation tool to predict failure time and breach flow. The use of geographic information systems (GIS) has become more common in dam break analysis. Terrain and land use information would improve the accuracy and reliability of hydraulic models by gaining capability in simulating a dam breach scenario and mapping the potential inundated area.

In 2014, Temenggor dam experienced risk of overtopping as a result of continuous rainfall and the villages situated at downstream was at risk during the period [3]. Early mitigation was carried by authority to release the reservoir in stages to avoid further catastrophic damages and human loss should the unexpected event of dam break occurs. This paper discusses the dam break analysis of Temenggor Dam by evaluating the dam breach parameter of Temenggor Dam based on dam failure scenarios, analyzing breach hydrograph for 1-dimensional (1-D) and 2-dimensional (2-D) model and proposing inundation map using GIS.

2. Methodology

This dam break study requires four major phases, which are data gathering, prediction of breach parameter and model simulation as shown in Figure 1.

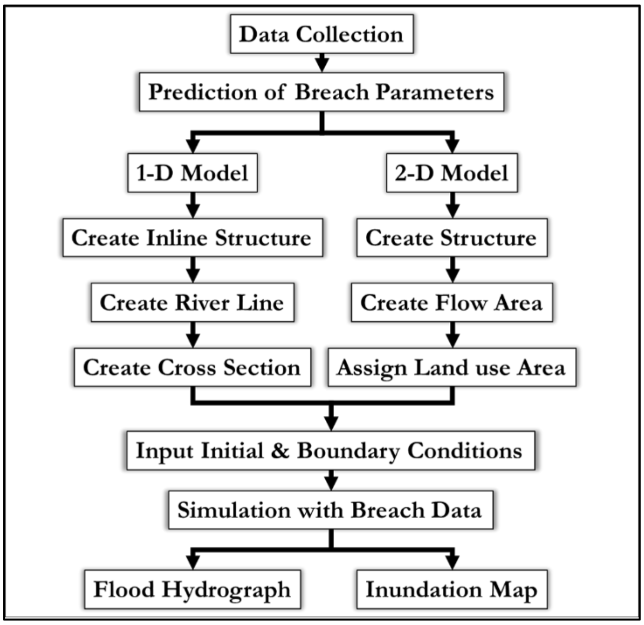


Figure 1. General Flow Diagram of Dam Breach Modelling

2.1. Study Area

The Temenggor Dam is a rock-filled embankment dam situated at latitude 5°24' North and longitude 101°18' East at Perak state. Commissioned in 1978, the dam is owned by Tenaga Nasional Berhad (TNB). Temenggor Dam is one of the cascading hydroelectric dams along Perak river where it is the upper most dam followed by Bersia Dam, which is approximately 19 km downstream from Temenggor Dam.

Table 1. General Details of Temenggor Dam & Reservoir

General Details of Temenggor Dam & Reservoir	
Dam Type	Embankment Dam
Crest Level (m)	EL 257.56
Crest Length (m)	537
Height (m)	127
Catchment Area (km^2)	3,506
Full Supply Level or FSL (m)	EL 248.4
Storage at FSL (m^3)	6.05×10^9

Four downstream populated areas were selected as zones of potential danger in the occurrence of dam failure. These areas are located downstream of Bersia Dam and were determined based on its critical location and population size. Area 1 is the nearest populated area to Bersia Dam and Area 4 is the farthest location with biggest population. Area 2 and Area 3 is approximately same distance from Bersia Dam in which Area 2 is located near to the river channel while Area 3 is situated further in mainland. Figure 2 shows the location of study area and Table 2 outlines the information of each selected location.

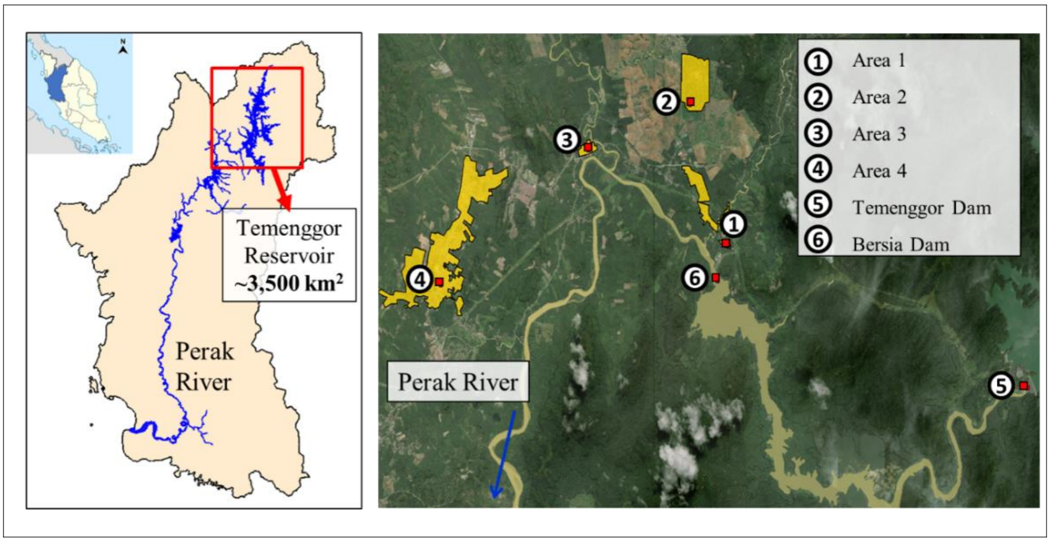


Figure 2. Location of Study Area

Table 2. Details of Selected Locations

Location	Distance from Temenggor Dam (km)	Category	Estimate Population
Bersia Dam	18.5	Infrastructure	-
Area 1	19.5	Village	> 1800
Area 2	24.5	Village	> 1700
Area 3	24.0	Village	> 830
Area 4	35.9	Town	> 12,000

2.2. Data Gathering

The effectiveness of analysis is highly dependent on the quality of the input data into the model. Dam and reservoir information are essential in the study to provide basic physical information which include structural dimensions of Temenggor Dam as well as its normal and maximum operating level, and storage-elevation curve of Temenggor Lake. The river cross section between Temenggor Dam until Bersia Dam from bathymetric survey is acquired from the dam owner. For hydrological data, Probable Maximum Flood (PMF) hydrograph for Temenggor Lake is used as an input for the maximum flood scenario. Topography and land use information are essential in inundation mapping in providing spatially and assigned roughness coefficient for the flood plain area. Figure 3 shows the Advanced Land Observing Satellite (ALOS) 30m Digital Elevation Map (DEM) and land use distribution map surrounding the dam area and its downstream.

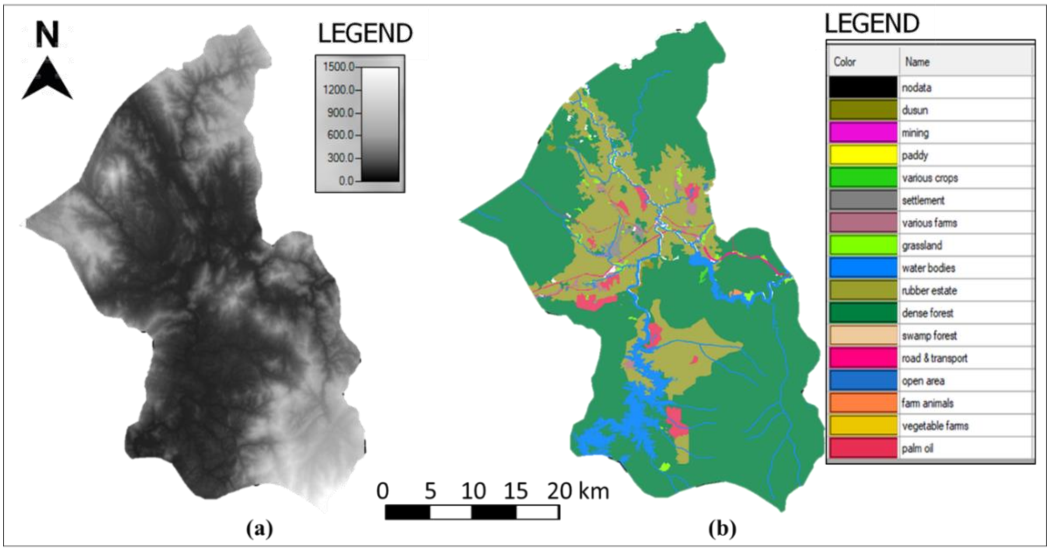


Figure 3. (a) ALOS 30m DEM and (b) Landuse Map

2.3. Estimating Breach Parameters & Failure Scenario

The estimation of the breach location, failure type, dimension, and development time are crucial in making reliable prediction of the peak discharge, outflow hydrographs and downstream inundation [4]. Several researchers have developed a set of regression equations using past historical data to determine the breach parameters such as breach width, breach formation time and side slope. Many dam break studies adopt empirical equations by Froehlich, MacDonald and Langridge-Monopolis (MLM) and Von Thun and Gillete (VTG) [5]. Peak discharge is also determined using regression equations of these methods which will be used for comparison purpose with that obtained from calculated peak discharge from simulation model.

The type of failure scenario that often associated with dam break cases are overtopping and piping failure. According to Sammen *et al* (2017), the number of actual cases for overtopping and piping failure was dominantly at 70.9% and 14.3%, respectively. Hence, this study will assume two possible scenarios, which are overtopping failure at PMF condition and piping failure during normal operation of dam. Overtopping occurs when uncontrolled flow of water is exceeding the crest level. The flow is similar to a flow over a broad-crested weir, where initial erosion occurs at bottom downstream section of dam and widen towards the crest level leading to breach of the reservoir. On the other hand, piping failure is associated with a gradual seepage at the internal dam structure, leading to a formation of significant hole at external face of the dam. Dam integrity would then be compromised when erosion takes place at the surface due to significant hydraulic flow at breach point.

2.4. 1-D and 2-D Simulation Model

Hydrologic Engineering Center's River Analysis System (HEC-RAS) is one of the approaches that is suitable to solve the dam break scenario having both 1-D and 2-D modelling capabilities. The dam break model in HEC-RAS includes the digitization of geometric information which essentially comprise river network, river banks, reservoir, structures, and flow area. Temenggor Dam is modelled using inline structure and connected to the first cross section of the river line. Bersia Dam is assumed to undergo instantaneous failure as the size of the dam is insignificant to take hydraulic impacts from the Temenggor Dam failure. Figure 4 shows the river profile between two dams and the first cross section of river after Temenggor Dam.

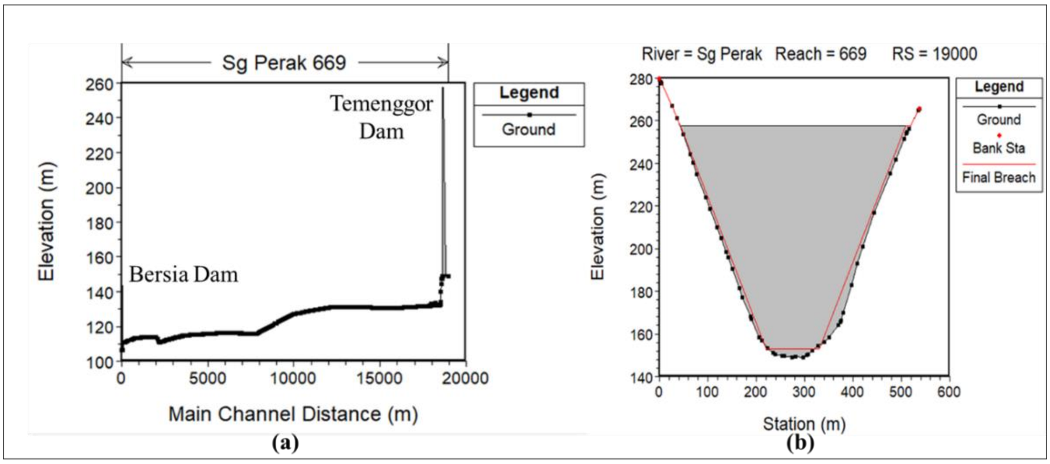


Figure 4. View of (a) Longitudinal Profile and (b) River Cross Section

For 1-D model, the fundamental geometry data includes the river reach, bank line, flow path line, inline structure and storage area. Then, a number cross section along the downstream channel until Bersia Dam is drawn by using interpolation tools between the actual cross sections. The reservoir is modelled as storage area with storage-elevation curve. Level pool routing method is used to simulate the breach between reservoir and breach point as it is assumed the reservoir level is horizontal during the drawdown. The channel roughness, Manning's n coefficient, of 0.035 is defined while for the overbank floodplain, coefficient of 0.16 is assigned.

For 2-D model, 2D flow area polygon is created around the affected downstream area due to the dam break event and extends further than Bersia Dam to downstream area. DEM and land use map is geo-referenced and exported to GIS to delineate the spatial data and surface roughness within the flow area. Values of Manning's n coefficient are assigned to define the surface roughness based on the individual land use type. Figure 5 shows the 1-D and 2-D's geometry model of downstream area of Temenggor Dam set up in HEC-RAS.

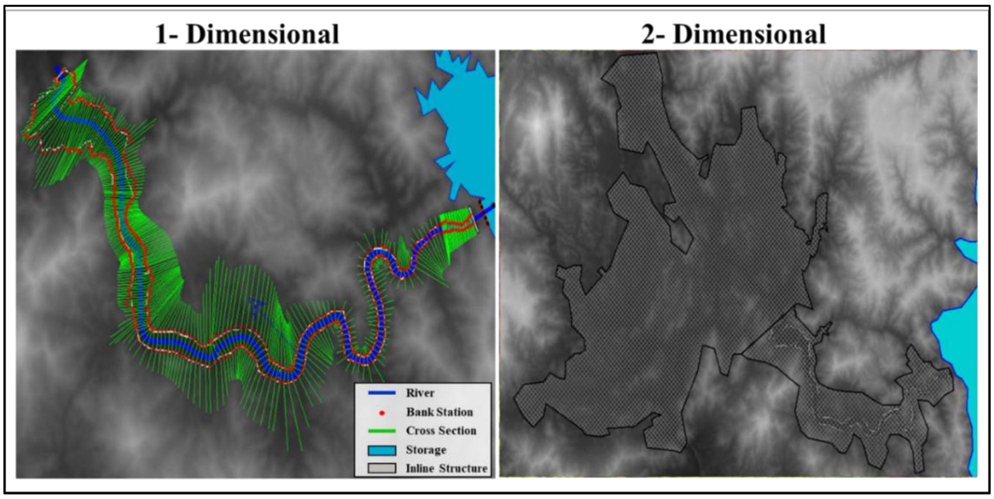


Figure 5. 1-Dimensional and 2-Dimensional Geometry Model in HEC-RAS

Boundary condition is necessary to define both upstream and downstream in 1-D and 2-D models. At upstream boundary condition, the storage is defined as inflow in addition to PMF inflow hydrograph into the reservoir for overtopping scenario. For downstream boundary condition, normal depth is used at frictional slope of 0.05. In addition to boundary conditions, initial condition must be defined in unsteady flow simulation. Initial value of upstream flow of the reach and initial reservoir elevation are required before executing the simulation.

The simulation of dam break was carried out for 24 hours period. The results obtained are presented in the form of breach hydrograph and inundation map. From hydrograph results, the magnitude of peak discharge is compared against the peak flow calculated using empirical equations. In addition, the inundation map is analyzed by acquiring water depth and velocity profiles at critical locations.

3. Results and Discussion

The breach parameters were determined using regression equations yield as shown in Table 3. It is observed that for both overtopping and piping failure, the breach width exceeds the maximum width of upstream cross section invert. Hence, it is assumed that the maximum shape of breach would have the same shape as the first upstream cross section of the river.

Table 3. Calculated breach parameters for Temenggor Dam

Breach Parameter	Piping Failure				Overtopping Failure			
	Froehlich (1995)	**Froehlich (2008)**	**MLM**	**VTG**	**Froehlich (1995)**	**Froehlich (2008)**	**MLM**	**VTG**
Bottom Breach Width, W_b (m)	494	366	1734	241	731	503	2227	264
Breach Formation Time, t_f (hr)	5.91	4.17	10.13	2.16	6.56	4.60	11.07	2.34
Peak Flow, Q_p (m^3)	1.32×10^5	-	2.62×10^5	-	1.58×10^5	-	2.96×10^5	-

3.1. 1-D Breach Model

Steady-state flow during normal condition was carried out as mean of calibration and its output is used for initial condition for unsteady-state flow. Figure 6 shows the water level in Sg Perak between Temenggor Dam and Bersia Dam during normal condition and after the dam break event.

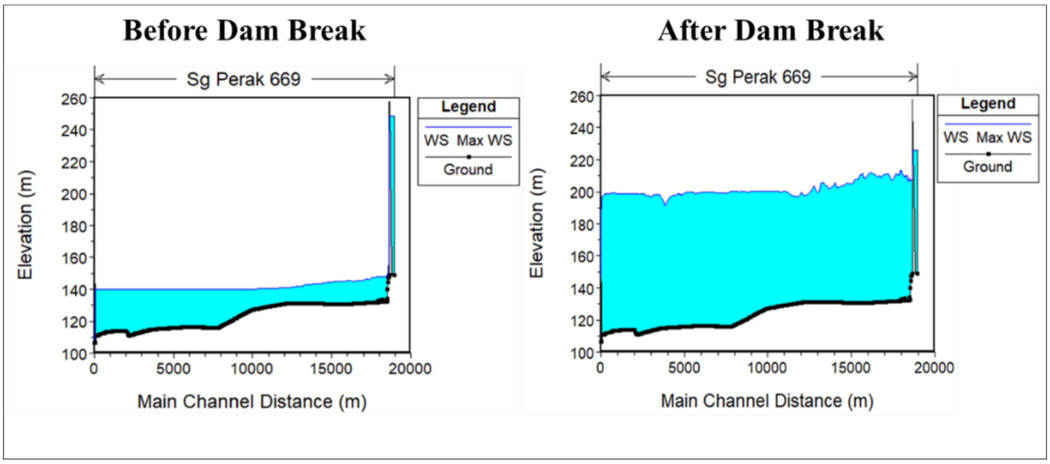
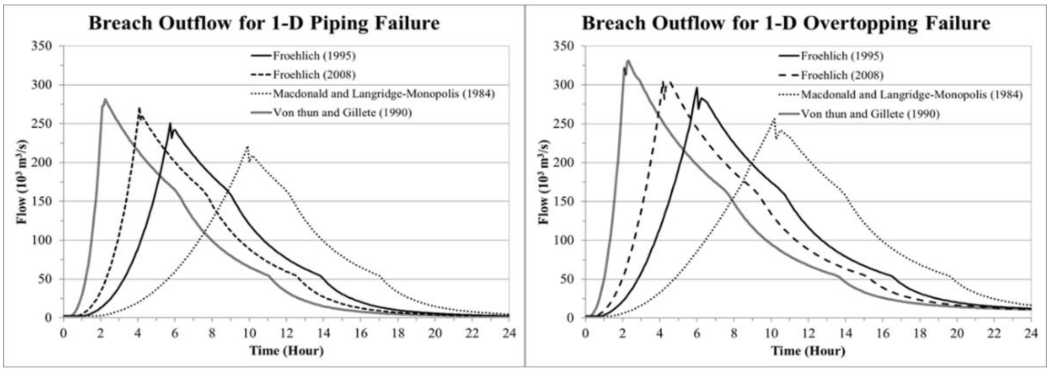


Figure 6. Water Surface Level at Temenggor Dam's downstream before and after dam failure

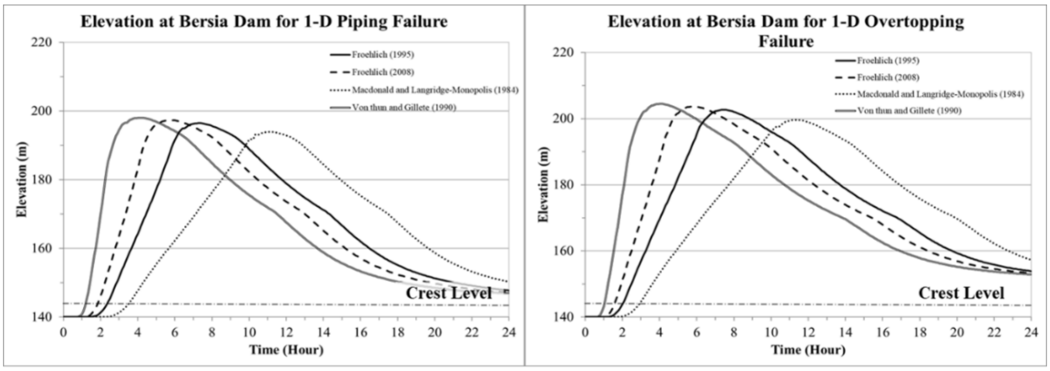
Figure 7 shows the breach outflow for 1-D model. For piping failure scenario, output result gave the peak discharge is found to be between 221,490 m^3/s and 281,588 m^3/s whereas for overtopping failure scenario, the peak discharge is between 256,308 m^3/s and 331,030 m^3/s. The arrival time to overtop Bersia Dam after the Temenggor Dam's breach as shown in Figure 8 is found to be 1.2 - 3.4 hour and 1.0 – 2.8 hour for piping failure and overtopping failure, respectively.

IOP Conf. Series: Earth and Environmental Science **479** (2020) 012041 doi:10.1088/1755-1315/479/1/012041



(a) (b)

Figure 7. Breach hydrograph for 1-D Temenggor Dam's (a) piping and (b) overtopping failure

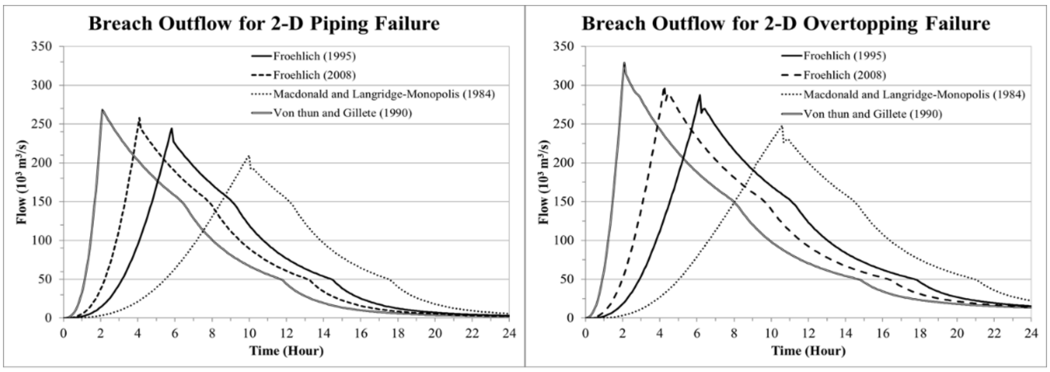


(a) (b)

Figure 8. Bersia Dam's elevation for 1-D Temenggor Dam's (a) piping and (b) overtopping failure

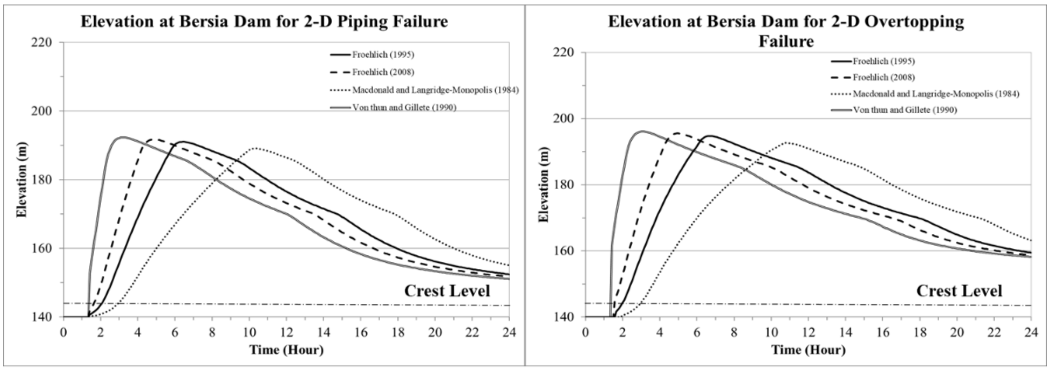
3.2. 2-D Breach Model

Figure 9 shows the breach outflow for 2-D model. For piping failure scenario, output result gave the peak discharge is found between 209,497 m^3/s and 268,341 m^3/s whereas for overtopping failure scenario, the peak discharge is between 247,940 m^3/s and 328,869 m^3/s. The arrival time to overtop Bersia Dam as shown in Figure 10 is found to be 1.4 - 2.8 hour and 1.4 – 2.8 hour for piping failure and overtopping failure, respectively.



(a) (b)

Figure 9. Breach hydrograph for 2-D Temenggor Dam's (a) piping and (b) overtopping failure



(a) **(b)**

Figure 10. Bersia Dam's elevation for 2-D Temenggor Dam's (a) piping and (b) overtopping failure

3.3. 1-D and 2-D HEC-RAS Model Comparison

The breach hydrograph and the arrival time at Bersia Dam between 1-D and 2-D results are found to be similar profile and manner in general based on the result obtained. The larger peak flow value was observed in the 1D model due to the simplified representation of Manning's roughness coefficient and limited channel geometry's area defined in 1-D model. On the other hand, in 2-D model, the flow characteristics is represented by cell sizes, hence able to increase the geometry of flow area and spatially define the roughness coefficient and hydraulic properties in more realistic way. While comparing results among those dam break models, 1-D hydrograph gave value of peak flow higher than 2-D hydrograph of 2.4% – 5.4% for piping failure and 0.7% – 3.3% for overtopping failure.

It is also observed that the time to overtop Bersia Dam for 1-D's piping failure is longer 15 minutes in average compared to 2-D result. On the other hand, for overtopping failure, both models show almost same arrival time at Bersia Dam.

With small margin of difference with 2-D model, 1-D hydrograph result can be used for dam break analysis of Temenggor Dam and flood propagation up until Bersia Dam as the flow area between the dams is primarily uni-directional with minimum slope of the terrain. Furthermore, 1-D model able to reduce substantial amount of simulation time and output files while requires lesser input data into the model.

3.4. Inundation Map

Figure 11 and 12 shows the result of inundation map from 2-D simulation model which delineates maximum water surface elevation and velocity, respectively. Map results show the flood propagated for area coverage of 186.5 km^2, reaching a distance of more than 30 km from Temenggor Dam. Table 4 summarizes the wave propagation arrival time, maximum depth and maximum velocity at respective critical locations for both piping and overtopping failures.

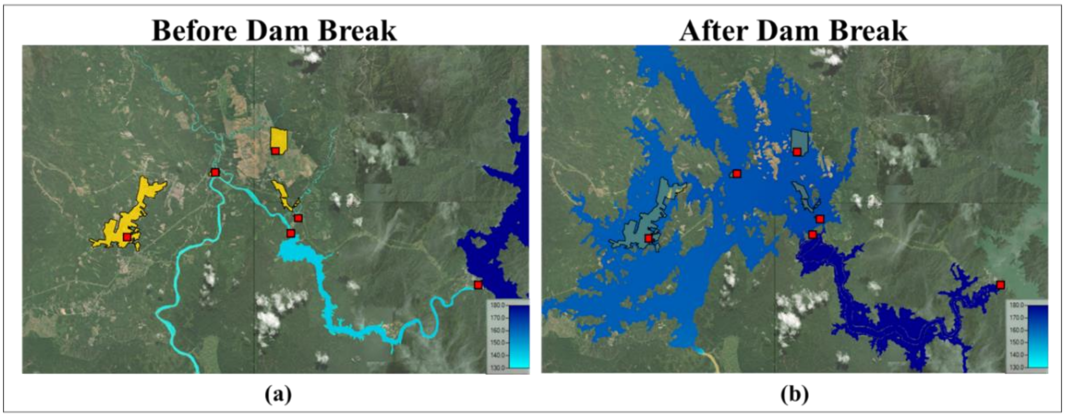


Figure 11. Water Surface Elevation for (a) Normal Day and (b) Temenggor Dam Break Event

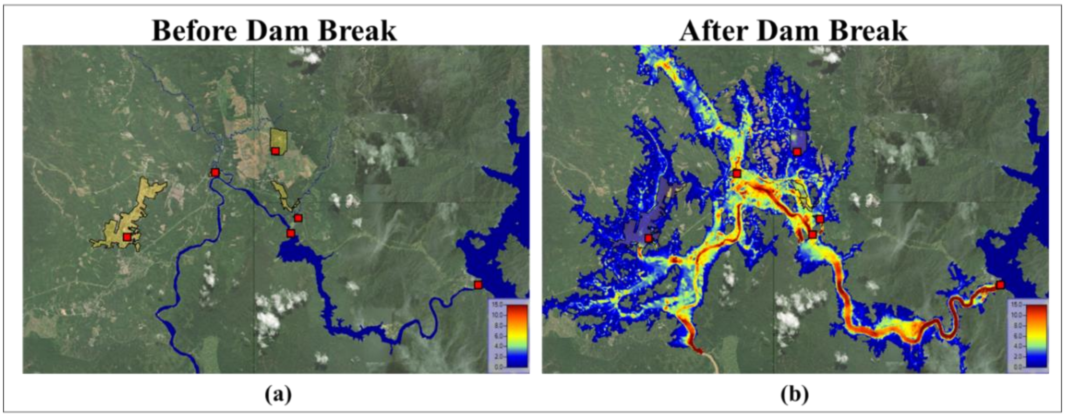


Figure 12. Water Stream Velocity for (a) Normal Day and (b) Temenggor Dam Break Event

Table 4. Summary of Inundation Map for Piping and Overtopping Dam Failure

	Piping Failure			Overtopping Failure		
Location	Arrival Time (hr)	Max Depth (m)	Max Velocity (ms^{-1})	Arrival Time (hr)	Max Depth (m)	Max Velocity (ms^{-1})
Bersia Dam	1.42	52.1	28.6	1.42	56.1	29.4
Area 1	1.58	36.5	1.57	1.58	39.4	2.73
Area 2	2.25	24.5	0.94	2.00	27.3	1.43
Area 3	2.08	33.7	1.96	2.08	37.7	2.24
Area 4	3.33	23.5	1.19	3.08	26.3	1.44

Based on the results in Table 4, both type of failures depicted the same arrival time of flood wave to Bersia Dam, and subsequently propagated to Area 1 after 9 minutes. It can also be observed that for piping failure, Area 3 would receive the flood wave earlier than Area 2 despite equal distance from Bersia Dam but situated differently from the river channel. However, for overtopping failure, both Area 2 and Area 3 are expected to experience the flood wave around the same time. Area 4, the highest population area, is predicted to be flooded 3 hours after the Temenggor Dam's failure.

In addition, overtopping failure exerts higher depth and velocity than the piping failure due to the higher volume of reservoir at initial breach time, which stores more potential energy and leads to higher hydraulic velocity towards downstream.

4. Conclusion & Recommendation

Despite dam break event is a complex and unpredictive event, disaster mapping and risk assessment is important as it can be used as primary information in developing proper prevention and mitigation measures. With the utilization of empirical equations and HEC-RAS simulation tool, this study able to provide an overview of sequential event in predicting the breach formation time of Temenggor Dam and flood propagation along downstream areas. Residents in Area 1 would be prioritized in evacuation plan due to the short response time after the failure of subsequent dam. It can also be inferred that the speed of the flood wave into populated areas as a result of Temenggor Dam failure is almost identical as flash flood with speed of 0.79 to 2.58 ms^{-1}[10]. Calibration of breach simulation result was not included in this study as there is no historical failure of Temenggor Dam, hence it is possible to use occurrence of any flash flood event at downstream area due to the similarity of flood propagation. Analysis and simulation of embankment dam breach events and the resulting floods are critical to differentiating and reducing threats due to potential dam failures. Development of effective emergency action plans requires accurate prediction of inundation levels and the time of flood wave arrival at downstream critical locations.

Acknowledgement

The author would like to express sincere appreciation to Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia for support in this study and TNB Research Sdn. Bhd. in providing data and information required for this study.

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