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FLOODPLAINS MODELLING DUE TO DAM BREAK

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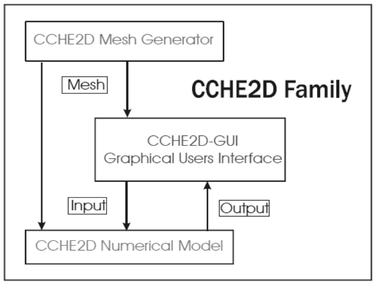
Graphical abstract



Abstract

The prediction of floodplains caused by dam break is very important to discuss for future planning and decision making for contingency evacuation planning and real time flood forecasting. The objectives of this study are (1) to determine the propagation of flood in the study area, in terms of water depth and velocity magnitude, and (2) to identify the potential area of high risk of flooding. The comparison of results using one point source input flood discharge (total discharge) and flood hydrograph have been carried out. The floodplain is simulated using software called CCHE2D_FLOOD model. A flood hydrograph due to dam break at Durian Tunggal Dam is used as a model parameters input. The simulation results showed that the higher flood depth for discharge hydrograph was 6.8 m, a bit lower than the sudden failure, which was 7.1 m. Meanwhile, the highest velocity predicted was 7.7 m/s. The total flooded area was approximately 48 km^2 and the potential risk happened at the residential area.

Keywords: Dam break, CCHE2D_FLOOD, floodplains modeling, flood hydrograph

Abstrak

Ramalan dataran banjir disebabkan empangan pecah adalah sangat penting untuk dibincangkan bagi perancangan masa depan dan membuat keputusan untuk perancangan pemindahan semasa kecemasan dan ramalan masa sebenar berlakunya banjir. Objektif kajian ini adalah (1) untuk menentukan penyebaran banjir di kawasan kajian, dari segi kedalaman air dan halaju magnitud, dan (2) untuk mengenal pasti kawasan yang berpotensi berisiko tinggi mengalami banjir. Perbandingan keputusan dengan menggunakan input sumber satu titik pelepasan banjir (jumlah pelepasan) dan hidrograf banjir telah dijalankan. Simulasi dataran banjir adalah menggunakan perisian yang dikenali sebagai model CCHE2D_FLOOD. Satu hidrograf banjir yang disebabkan oleh empang pecah di Empangan Durian Tunggal telah digunakan sebagai input parameter model. Hasil simulasi menunjukkan bahawa kedalaman maksima untuk kadaralir hidrograf adalah 6.8 m, lebih rendah dari kegagalan secara tiba-tiba, iaitu 7.1 m. Manakala, jangkaan halaju maksima adalah 7.7 m/s. Jumlah kawasan yang dibanjiri adalah lebih kurang 48 km^2 dan potensi risiko berlaku di kawasan penempatan.

Kata kunci: Empang pecah, CCHE2D_FLOOD, pemodelan dataran banjir, hidrograf banjir.

1.0 INTRODUCTION

Flood is a natural phenomenon and cannot be easily prevented. However, the impact of flooding can be reduced by improving forecasting flood system. The system is not only limited to hydrology and water profiles analysis but also how floods propagate in the channel and within the floodplains. By knowing how flood propagates within the floodplains, it may assist authorities to address some effect of flooding [7].

Flood inundation due to dam and levee breach often cause serious loss of life and property. To prevent the massive damages, the numerical model can be used to predict flood wave propagation and provide the information about the flood extent, flood wave arrival time and water depth, etc. Therefore, floodplain model is a useful tool for establishing flood control and dam operating strategies as well as developing evacuation plans and warning systems for the areas having potential flood risk [4].

To be noted, a dam failure may involve a volume of water releases to downstream, particularly where a large dam is involved. Flood propagation is defined as the art of quantitatively describing the characteristic and evolution of the flow that is set up when a larger amount of water moves along the earth surface in an uncontrolled way [1]. That means the flow tends to moves to the lower elevation that would probably give higher potential of getting more floods at downstream when a dam collapsed. The amount of washout is so great that it overwhelms existing flood control or river control structures downstream of dam. The mere presence of floodwaters will certainly cause water related to damage in many area, and the high velocity of flow that will likely accompany such a flood event may also cause structural or erosion related damage [2]. There are many reasons the dam fails. Overtoping, piping, and seapage are the reasons where the dam fails to stabilise its structure leading to collapse [8]. For whatever reasons, the implication of the dam break must pay seriously attention to prevent death and loss of properties.

An overtopping occurs when the level of a reservoir exceeds the capacity or height of the dam. This can be caused by an inadequate or does not work spillway or by settlement of the dam crest. Overtopping occurs when water levels rise rapidly and without adequate warning. The result can compromise the structural integrity of the dam or it can quickly erode the land on either side of the dam, in effect disengaging the dam from its river slope embankment.

Floodplain mapping due to dam break is a sequences process; starting with hydraulic analysis and followed by geospatial process [10]. According to Federal Emergency Management Agency, overbank flooding occurs when downstream cannels receive more rain from their watershed than normal, or a channel is blocked by any ice jam or debris. For either reason, excess water overloads the channels and flow out onto the floodplain. Overbank flooding varies with the watershed's size and terrain. One measure of flood is the speed of its moving water, which is called velocity. Hilly or mountainous areas have faster moving water, so velocity can pose a serious hazard. In flat areas, the flood may move slowly, making its velocity less of a hazard. Flood depths vary, as do flood durations. Generally, the larger the river, the deeper the flood and the longer it will last. Depending on the size of the river and terrain of its floodplain, flooding can last for days and cover wide areas [11].

The use of numerical models to approximate physical problems is helpful in understanding the physics of the simulated components. As for floodplain due to dam break, the components of water depth and velocities are the main variables that need to be analysed accurately. This could be a major attention to modellers and researchers to do their estimation on the volume of flood to be considered in any hydraulic designs and also for emergency action plans.

2.0 CCHE2D_FLOOD MODEL

CCHE2D_FLOOD model was developed by the National Center for Computational Hydro-science and Engineering (NCCHE) at the University of Mississippi. The CCHE modelling analysis system is an integrated package for simulation and analysis of free surface flows, sediment transport and morphological processes. In addition to the numerical model itself, the software includes two components: a mesh generator (CCHE2D Mesh Generator) and a Graphical Users Interface (CCHE2D-GUI). The CCHE2D model is easy and efficient to use. Figure 1 illustrates in details the CCHE2D package family. The CCHE2D mesh generator allows the rapid creation of complex structured mesh system for CCHE2D model. Mesh geometry consists such as block boundaries, algebraic mesh, numerical mesh (use for smoothness the interpolation) and interpolation the bed elevation. Meanwhile, the CCHE2D-GUI is part of the simulation process. In CCHE2D-GUI consist initial condition and boundary condition, model parameter and run numerical simulation [6].

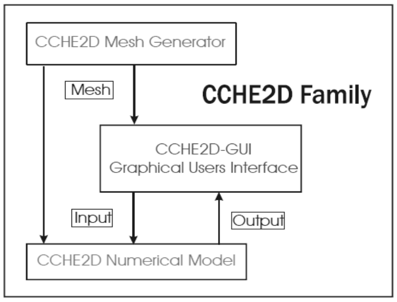


Figure 1 The CCHE2D_FLOOD family package

The CCHE2D model is a two-dimensional depth-averaged, unsteady flow and sediment transport model. It solves flow on a depth-averaged Navier-Stokes Equations (N-S). The equation is solved implicitly using the control volume approach for both steady and non-steady flow conditions. Boundary conditions can be specified to be specific discharge, total discharge or discharge hydrograph at any inlet. At an outlet, it could be set as an open boundary, water level surface, stage discharge relationship or stage hydrograph boundary condition [6].

2.1 Governing Equation

In the present study, the Shallow Water Equations (SWE) is used to model the propagation of disturbances due to floodplain. By assuming the depth of fluid is small in comparison to wave length of the disturbances. The equation of SWE is derived from the principles of conservation of mass and momentum where the independent variables are time, t and two spaces of x and y, respectively. Meanwhile, the independent variables are such as water depth, h and the two-dimensional fluid velocity fields; u and v. Therefore, the CCHE2D_FLOOD forms the conservative equation of two-dimensional shallow water equation (1), is written in [4], [5].

$$\frac{\delta U}{\delta t} + \frac{\delta F(U)}{\delta x} + \frac{\delta G(U)}{\delta y} = S(U) \qquad (1)$$

where U, $F(U)$, $G(U)$ and $S(U)$ are respectively the vectors of conserved variables, fluxes in the x and y direction, and sources which can defined as follows,

$$U = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix} \; F = \begin{bmatrix} hu \\ huu \\ huv \end{bmatrix} \; G = \begin{bmatrix} hv \\ huv \\ hvv \end{bmatrix} \; S = \begin{bmatrix} 0 \\ -gh\frac{\delta Z}{\delta x} - g\frac{u\sqrt{u^2 + v^2}}{C^2} \\ -gh\frac{\delta Z}{\delta y} - g\frac{v\sqrt{u^2 + v^2}}{C^2} \end{bmatrix}$$

where h = water depth; u = velocity component in the x direction; v = velocity component in the y direction; g = gravitational acceleration; Z = water level; C = Chezy's channel resistance coefficient [5].

2.2 Numerical Model

In general, the numerical model uses the planned upwind conservative scheme, which is based on finite volume method, as shown in Figure 2. The model employs a rectangular raster grid to identify the GIS raster topographic data.

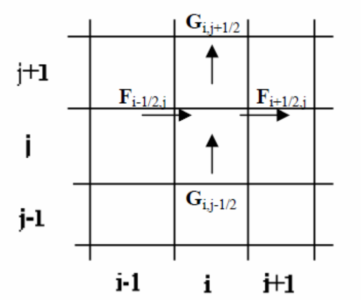


Figure 2 The numerical method of a cell centred grid

The conserved variables are then defined at the cell centres which represent the average value over each cell, whilst the fluxes are calculated at the interfaces between cells. The equation can be presented as follows,

$$U_{i,j}^{n+1} = U_{i,j}^{n} - \frac{\Delta t}{\Delta x_i}\left(F_{i+\frac{1}{2},j} - F_{i-\frac{1}{2},j}\right) - \frac{\Delta t}{\Delta y_i}\left(G_{i,j+\frac{1}{2}} - G_{i,j-\frac{1}{2}}\right) + \Delta t S_{ij} \qquad (2)$$

By integrating the equation (2) over the cell *i,j* with area of $\Delta x_i \Delta y_j$ and applying Green's theorem yields where $F_{i+1/2j}$, $F_{i-1/2j}$, $G_{i,j+1/2}$ and $G_{i,j-1/2}$ area the fluxes at the interfaces. Here upwind method is used to evaluate the inter-cell fluxes.

3.0 APPLICATION OF CCHE2D_MODEL

3.1 Site Description

Durian Tunggal Dam located at Melaka had been classified as a significant hazard dam and it can contribute of loose of life, property damage, economic losses, lifeline as well as environmental damage based on United States Army Corp Engineers (USACE) [3]. The Durian Tunggal Dam is the main water dam supply for Syarikat Air Melaka Berhad and has storage at full level of 32.60 Mm^3. It was constructed in 1974 at Simpang Gading and was subsequently raised in 1992. Initially it was built to regulate the flows of Sg. Melaka at the pump intake and water supply for Water Treatment Plant Bertam DAF at maximum 109 MLD since 1998. After 2003, the water contained inside the dam could be pumped to fill up Jus Dam at 100 MLD. It can also be released by gravity through siphon to the Durian Tunggal Intake for Water Treatment Plant Bertam I&II during drought season or wet season. This dam has a catchment area of 41.4 km^2 and an impounded area of 5.8 km^2. The location map of Durian Tunggal Dam is shown in Figure 3 while Figure 4 indicates the catchment area of the location study.

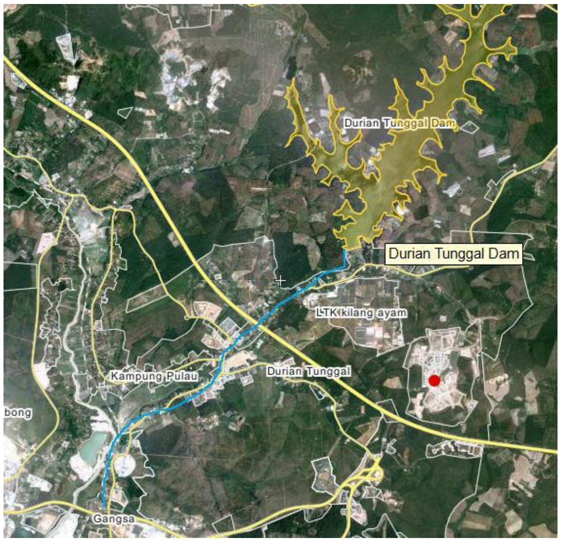


Figure 3 The location of Durian Tunggal Dam (Google Map). A blue line represents a river alignment for the study area

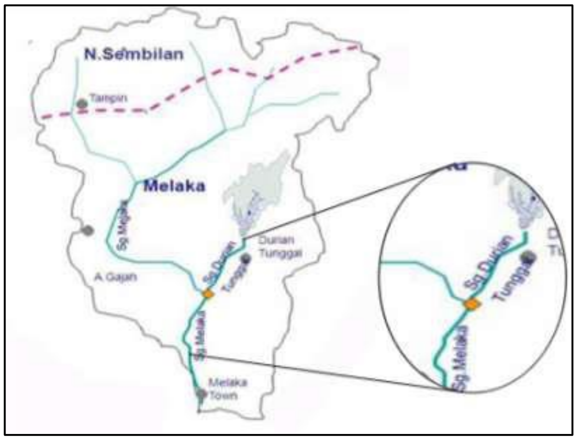


Figure 4 Catchment area of the study [3]

3.2 LiDAR Data

Light detection and ranging (LiDAR) is determined as a method of measuring ground surface based on transmitting laser signals by using all light (ultraviolet, visible, and influents) and collected those of million points by coded into point cloud. LiDAR with high resolution data have been used in generating the digital terrain model (DTM) which is important to support wide range of applications such as engineering, hydrology and floodplain management. In this study, the DTM data is about 3 m resolution, and this can be assumed as very high accuracy of topographic data.

3.3 Simulation Data

There are several parameters need to be determined in deal with CCHE2D model such as initial discharge, water surface elevation, bed roughness, etc. However, the most parameter needed in this study is the value of discharge when the dam is about to fail. Therefore, to get a realistic value of discharge due to dam break event, the study was relying on the previous research, reported by [3] for flood hydrograph analysis. The discharge due to dam break analysis was 14,557 m^3/s and the PMF inflow was 637 m^3/s. Therefore, the magnitude of flooding due to dam break analysis is about 23 times greater compared to PMF. The value would cause a catastrophic damage to the downstream area, lead to significant life losses and property damages up to Melaka town [3]. Figure 5 shows the hydrograph for dam break event of Durian Tunggal Dam [3]. However, in this study, a constant discharge of Q = 670 m^3/s and discharge hydrograph of the maximum outflow discharge of 670 m^3/s are also used to simulate the floodplains using the CCHE2D_FLOOD model.

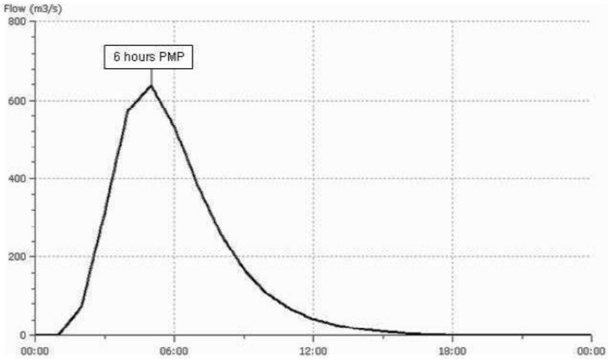


Figure 5 The predicted flood hydrograph of Durian Tunggal dam break event [3]

3.4 Initial and Boundary Conditions

The first task to develop the model is to define the boundary area, so-called domain area. This can be done by importing Bed Elevation into CCHE2D_Mesh model to create bed interpolation within the boundary area. The simulation results are based on calculation of 100 x 500 cells of mesh. The initial condition need to be specified such as initial water surface, bed roughness, time step and total time to simulate. In this study, bed roughness used is natural for the whole domain, which takes a value of 0.035. The boundary conditions are then set into inlet boundary and outlet boundary condition. The inlet boundary condition used in this study is based on two cases; (a) using total discharge and (b) discharge hydrograph. As at the outlet, the boundary condition is set to be opening (to allow the increment of water level). The inlet and outlet boundary conditions are shown in Figure 6.

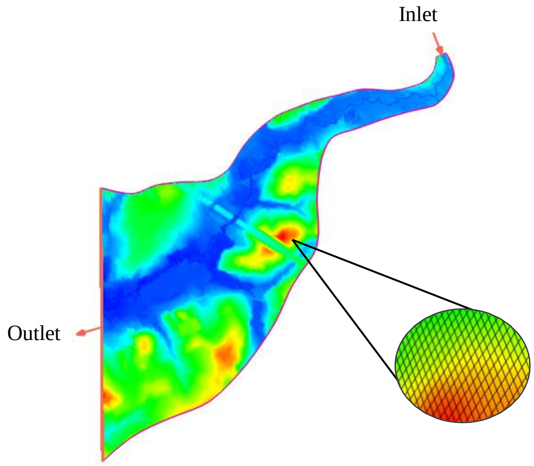


Figure 6 Location of inlet and outlet boundary conditions setup with the mesh size

4.0 RESULTS AND DISCUSSIONS

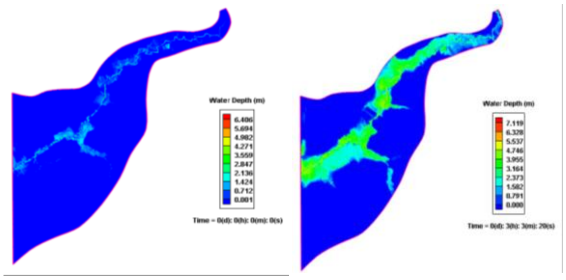
The result of the simulation can be visualized not only after the dam was completely failed, but also during the process of the breaching. Meaning, there is a progression of flood inundation during the time frame. The analysis is focusing on analysis of water depth and velocity magnitude for both cases considered; i.e. total discharge and discharge hydrograph.

4.1 Flood Depth

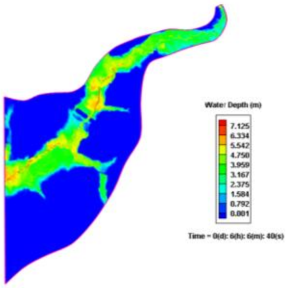
In this study, the flood depth is determined based on the value of water level when water propagates. The unit is in meter. The flood depth was calculated based on 0 hour, 3 hours and 6 hours event basis after the dam collapsed. The results of water depth in time are shown in Figure 7 and Figure 8 for total discharge and discharge hydrograph, respectively. The results have shown that the water depth increases during the failure and the value depends on the elevation of predicted water surface.

The simulation results indicated that the numerical model gave a realistic prediction of flood propagation in respect to time for both input discharges. The flood is propagated through the area of downstream when the dam failed. As the time increasing, the flood propagation is widely distributed in the domain. As for total discharge input, it is clearly seen in 1 hour that the flood is propagating when dam breaks immediately, which is faster than hydrograph discharge. The flood is continuously propagated until 6 hours of the simulation. Within 6 hours, the water has completely filled the downstream area that may cause massive damage of properties and lives. The maximum water depth of Durian Tunggal's river for total discharge, and discharge hydrograph are 7.1 m and 6.8 m, respectively.

The results indicated that the numerical model gave a realistic prediction of flood propagation in time. It should be noted that the simulation results were based on calculation of 100 x 350 cells of meshes and $\Delta x = \Delta y = 1\,m$. As for the accuracy of model, the water depth could give higher possibility towards the elevation model created by LiDAR data.

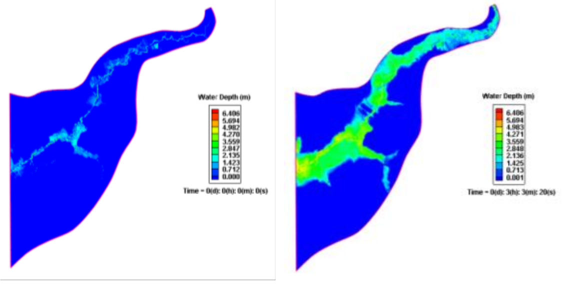


(a) t=0 hour (b) t= 3 hours

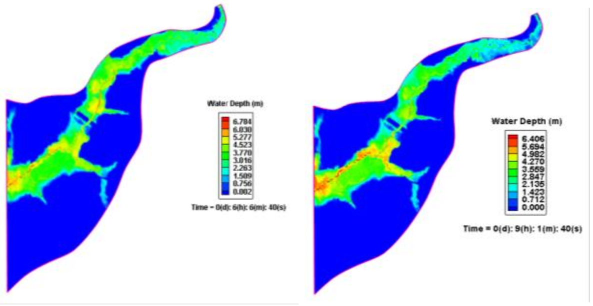


(c) t= 6 hours

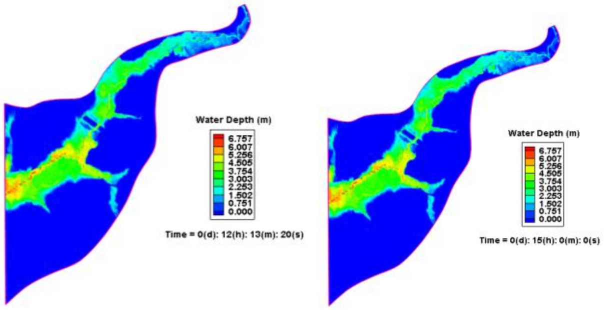
Figure 7 Floodplain water depths for total discharge, Q= 670 m^3/s; (a) t= 0 hour, (b) t= 3 hours and (c) t= 6 hours



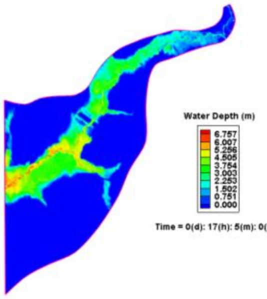
(a) t=0 hours (b) t= 3 hours



(c) t= 6 hours (d) t= 9 hours



(e) t= 12 hours (f) t= 15 hours

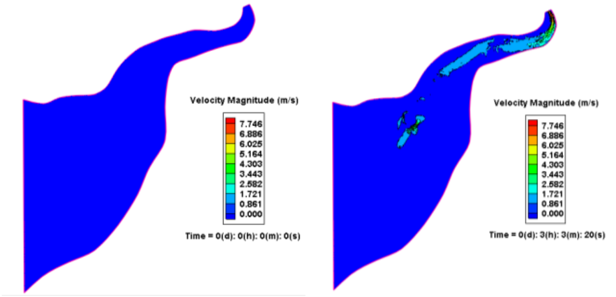


(g) t= 17 hours

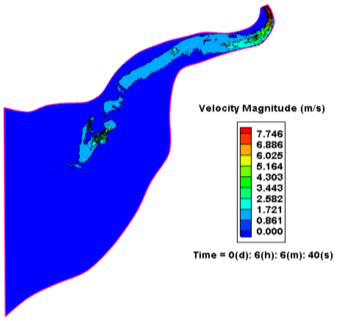
Figure 8 Floodplains of water depth for discharge hydrograph; (a) t= 0 hour, (b) t= 3 hours, (c) t= 6 hours, (d) t= 9 hours, (e) t= 12 hours, (f) t= 15 hours, and (g) t= 17 hours

4.2 Velocity Magnitude

A similar analysis was done for the velocity magnitude prediction. Time taken was 0 hour, 3 hours, and 6 hours, respectively. When the dam failed, the amount of water release to downstream can be represented in velocity magnitude profiles, as shown in Figure 9 and Figure 10 for total discharge, Q = 670 m3/s and discharge hydrograph. The results showed that the highest velocity predicted was about 7.7 m/s for both simulation and the lowest was 0.8 m/s. The highest velocity was observed at the upstream when the water is propagating to downstream. While, near the bridge piers, the velocity showed the higher value due to the narrower spacer towards the flood movement. In comparison with hydrograph flooplains' result, the velocity predicted was smaller i.e. at the upstream, as the flow reduces in time (see in Figure 10(f)).

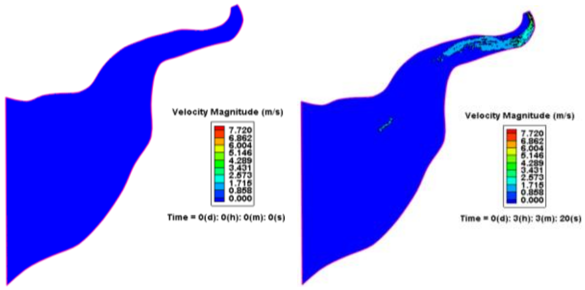


(a) t =0 hours (b) t = 3 hours

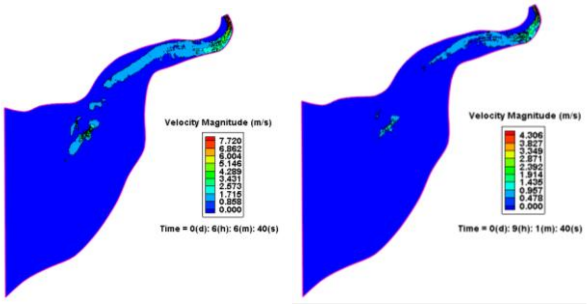


(c) t = 6 hours

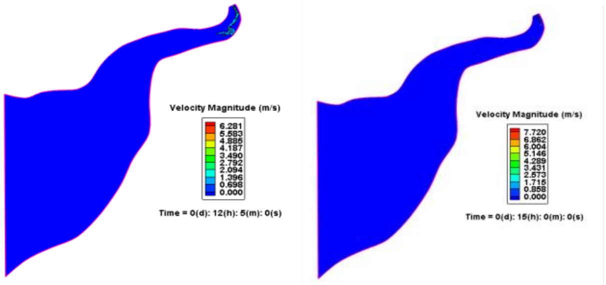
Figure 9 Velocity magnitude for total discharge, Q = 670 m^3/s; (a) t = 0 hour, (b) t = 3 hours and (c) t = 6 hours



(a) t =0 hours (b) t = 3 hours



(c) t = 6 hours (d) t = 9 hours



(e) t = 12 hours (f) t = 15 hours

Figure 10 Velocity magnitude for discharge hydrograph; (a) t = 0 hour, (b) t = 3 hours, (c) t = 6 hours, (d) t = 9 hours, (e) t = 12 hours, and (f) t = 15 hours

4.2 Flooded Area

Based on the result obtained from the flood propagation, an analysis on percentage difference of flooded area has been carried out. A comparison result of flooded area using total discharge and discharge hydrograph was carried out. Table 1 indicates the percentage difference of area affected by flood in hourly, until it reaches the maximum discharge. The analysis indicated that the percentage difference of flooded area for 3 hours is greater than 6 hours, which were 90.2% and 15.1%, respectively.

Table 1 The percentage difference of flooded area between total discharge (Q = 670 m^3/s) and discharge hydrograph from 1 to 6 hours duration. For discharge hydrograph the value Q is shown in brackets for each corresponding flooded area

Hours (hour)	**Area of flooded (m^2)**		
	Total Discharge (Q = 670 m^3/s)	**Discharge Hydrograph**	**Percentage difference (%)**
1	1969268	83890.8 (Q = 7 m^3/s)	95.7
2	16247152	1273776.7 (Q = 80 m^3/s)	92.2
3	24394111	2383304.6 (Q = 105 m^3/s)	90.2
4	32557392	23125515.3 (Q = 560 m^3/s)	29.0
5	40694119	32372172.1 (Q = 635 m^3/s)	20.5
6	48832823	41478599.8 (Q = 670 m^3/s)	15.1

In a case of total discharge input, the flood is rapidly propagated within 1 hour until 3 hours. This is due to the fact that the water in reservoir or the water at the upstream is flushing rapidly with a huge amount of water released to downstream. In comparison with flood hydrograph input, the amount of water released from the dam seemed to be gradually increased. As time goes, as to the maximum discharge, the amount of water propagated was nearly huge, close to the value of total discharge, Q = 670 m^3/s. From the calculation, it showed that the percentage difference in 6 hours is decreasing to 15.1%.

4.3 High risk of potential flooded area

The flood risk is defined as the probability of occurrence of flood and its increment is multiplied by its impact. It happens when the flood increases and changes rapidly. Flood risk is the flood hazard, resulted in an event of destruction of the area. The circles in Figure 11 show the potential areas of high risk flooding due to dam break when the outflow discharges at the rate of 670 m^3/s. From the simulation result, the inundation of water seemed worst at the areas of residential (as marked in red circles).

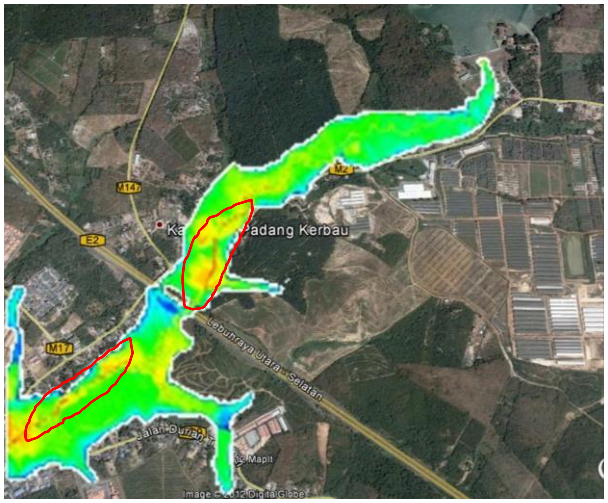


Figure 11 The potential areas of high risk flood due to dam break; shown in red circles

The risk is increasing because flood characteristic are changing due to rapid urbanization of catchments. The areas that have a potential of high risk flooded can be categorized as a hazard zone. When the impact of flood is increased meaning the impact of the flood in term of human health and economic losses has risen, and the planning of protection against flood can no longer be limited to protecting some isolated assets from certain types of danger.

5.0 CONCLUSION

The CCHE2D_FLOOD model is performed successfully to simulate dam break for Durian Tunggal Dam. From the result obtained, it can be concluded that the hydrodynamic model is very useful to predicting the flood propagation. The distribution of velocity magnitude as a result of point source inlet and flood hydrograph is helpful in analyzing the movement of floodplains. Identifying the location of flood risk area can also be done from the analysis. Results from the model can be utilized by prevention the consequences of damages and loss of life or action from authority and citizen could be taken immediately, in case a dam fails. In the other words, it takes an initiative approach to reduce the impact of disaster due to dam break. Finally, the analysis gave better information and early warning to provide better protection for local communities and citizens from the impact of dam break.

Acknowledgement

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