A hydrodynamic model of an embankment breaching due to overtopping flow using FLOW-3D

Z M Yusof[1,2], Z A L Shirling[1], A K A Wahab[1,3], Z Ismail[1,3] and S Amerudin[4]

[1] Department of Water and Environmental Engineering, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
[2] Eco-hydrology Centre, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.
[3] Centre For Coastal and Ocean Engineering (COEI), Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
[4] Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia

E-mail: zainabyusof@utm.my

Abstract. Embankment dam failures are concerning to many people in the society today, including dam engineers, federal, state, and local officials. The effects of dam failure may cause more harm than good; leading to the losses of lives, properties being damage, economic and environmental downfall. Embankment dam breaching is a complex process between hydraulics and soil erosion processes; until today it still requires more researches to be done. Many factors involved in embankment breaching such as cohesiveness of embankment material, compactness of the embankment soil material, height of the dam and slope of the dam. Through the help of simulation techniques such as computational fluid dynamics, it is possible to understand the behaviour of embankment breaching processes. In this research, modelling of embankment breaching with the aid of FLOW-3D allow us to open doors to plenty of experiments to breaching in the near future. This research focuses in analysing and comparing hydrodynamic parameters; breach outflow hydrograph, peak outflow rate Q_p and failure time t_f, and geometric parameters; breach depth H_b, and top breach width B_t, of the modelling breached embankment for different sediment diameter and inflow rates. Moreover, the research also investigates the velocity magnitude and breach width during the embankment breaching process.

1. Introduction

There are many types of embankment structures, such as dams, levees, dikes, and barriers. These structures are built by people or can be formed naturally along rivers, lakes, and coastal lines around the world. These structures are mainly built for flood defense, however, there are other applications such as for power generation, water supply, transportation, and sediment retention. Because these structures can sustain only limited safety levels and are subject to decay, they may fail owing to various triggering mechanisms [1-2], particularly with a high probability of failure under extreme conditions. These failures resulted in flood risks to people and property in the inundation area and cause an interruption of services provided by these structures. Concrete embankment dam will fail instantaneously, or break, the moment its entire structure or a portion of the structure, loses stability under certain number of loadings. An earth embankment, on the other hand, is likely breaching occur, due to erosion of its materials by water flow or wave action involving mixed-regime flows, strong sediment transport, and rapid morphological changes. The determination of earth embankment breach characteristics is quite complex and challenging, requiring predicting complex interactions between soil, water, and structure of the dam.

Embankment failures are normally associated with overtopping, pipping or seepage, foundation failure and structural defects. According to Costa (1985) [3], approximately 34% of dam failures are caused by overtopping, 30% by foundation defects, and 28% by piping. Overall, the most common causes of embankment failure are overtopping and internal erosion. Ralston (1987) [4] indicates that there are approximately 57 000 dams in the United States have the potential for overtopping and the leading cause of embankment dam failure worldwide is overtopping. According to research done from obtaining breaching parameters from regression analysis, Xu and Zhang (2009) [5] stated dam erodibility plays significant role in influencing the results of breaching parameters. Sand have high erodibility compared to clay which have low erodibility, and hence higher resistance to fast moving water. More in-depth study of the dam erodibility is required in order to understand embankment failure.

This research is conducted by using computational fluid dynamics software named FLOW-3D. The software utilizes the Navier-Stokes equation, in fluid dynamics coupled with the sediment scouring properties of soil. This coupling enables for the study of the complex breaching process of the embankment dam. There are two groups of breaching parameters: geometric and hydrodynamic. The breaching parameters are influenced by the embankment sediment sizes and inflow rates. Each breaching process is different for different embankments. Therefore, the analysis of breach hydrodynamic parameters; breach outflow hydrograph, peak outflow rate $\mathrm{Q_p}$ and failure time $\mathrm{t_f}$, and geometric parameters; breach depth $\mathrm{H_b}$, and top breach width $\mathrm{B_t}$ are important to investigate. The modelling breached embankment for different sediment diameter and inflow rates to determine velocity magnitudeand breach width during breaching process are also analysed.

2. Literature review

The role of embankment dam is to provide storage of water for irrigation which is important for agricultural production in many countries. The size of embankment dam may be small, medium, or large. The size is usually measured in terms of height or volume of water stored. Based on materials used in construction, a dam may be homogeneous or zoned earthfill, rockfill with earth core or concrete face or concrete that depends upon gravity, arch, or buttress resistance. Some dams are constructed with a combination of materials, such as earthfill, rockfill, masonry, and concrete. Most dams in Malaysia are earth-filled type due to it costing less in construction compared to the other types of dam [6].

Data collected by Association of State Dam Safety Officials (ASDSO) [9] between 2010 and 2019 shows that dam failure by overtopping ranked the highest for number of incidents, and followed by piping. Overtopping are a result of insufficient spillway capacity or an event of extreme flooding which causes water level to exceed design criteria. The water flow over the embankment from overtopping introduces tractive shear stress on the downstream surface. The erosion process begins at a weak spot where the tractive shear stress exceeds a critical resistance that keeps the soil material in place. The process will continue under the action of flowing water while soil materials are being transported downstream. The extent of breaching due to erosion usually depends on the duration of overtopping and the structure of the embankment. The erosion characteristics are different for granular and cohesive embankments. For granular embankments, the overtopping flow of water on downstream slope causes surface slip to take place quickly; hence result in granular materials to be removed rapidly layer by layer.

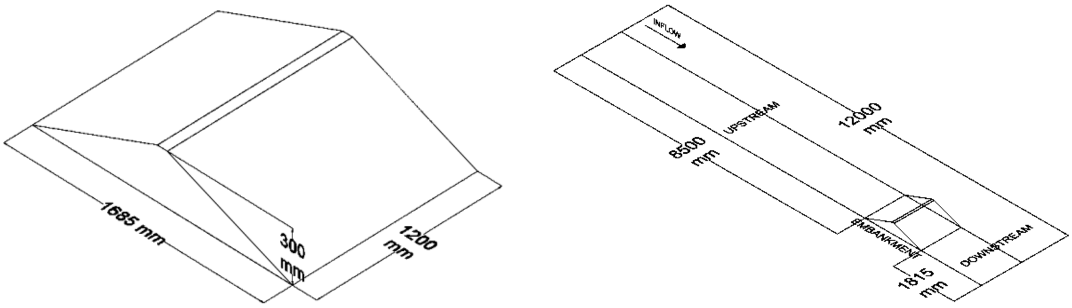
3. Methodology

3.1 Simulation Cases

There are two simulation cases for studying the objectives of this research, namely, Case 1and Case 2. The model setup of Case 1 allows the study of embankment breaching for various sediment sizes to be applied. There are three different sizes of sediment used, these chosen sediment size for this research are 0.1 mm for fine sand, 0.4 mm for medium sand and 0.8mm for coarse sand. Meanwhile, the model setup for Case 2 allows the study of embankment breaching for various inflow rates. Also, three different values of inflow rates are chosen; 0.006 m^3/s for low inflow rate, 0.012 m^3/s for medium inflow rate, and 0.024 m^3/s for high inflow rate.

3.2 Prepare Model Geometries and Dimensions

The embankment model used in this research is shown in Figure 1(a). The model is used for studying the properties of breaching through different sediment sizes (Case 1) and inflow rates (Case 2). Figure 1(b) shows model setup of the channel geometry with the embankment attached. The channel has a total length of 12 m with upstream and downstream lengths of 8.5 m and 1.815 m, respectively.



(a) (b)

Figure 1. (a) Embankment model and (b) Channel geometry and model setup.

3.3 Model setup in FLOW-3D

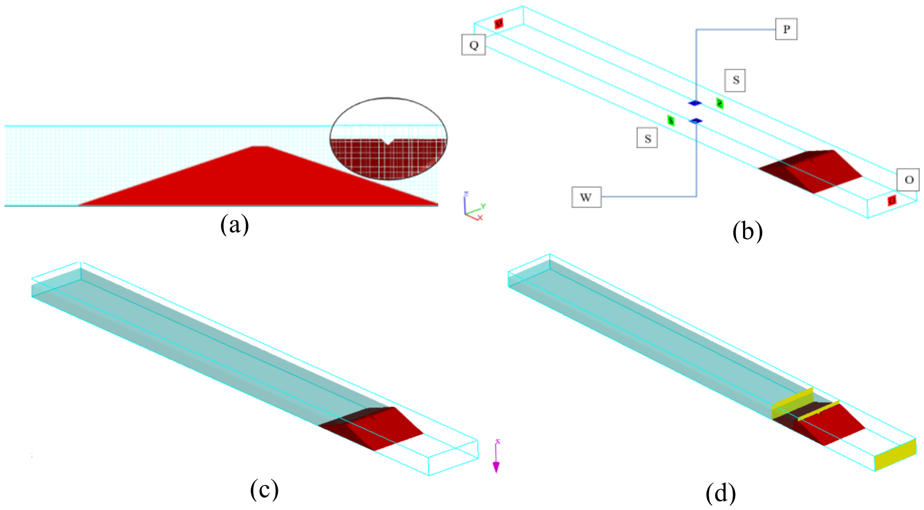
3.3.1 General settings. The general settings that required for the modelling of the embankment breaching are the Simulation Finish Time, Physics of the Model and Fluid Properties. For Case 1 and Case 2, the Finish Time was set to 400 s, the physical model setup are Sediment Scour, Gravity, and Viscosity and Turbulence. Density evaluation will be automatically selected when activating the Sediment Scour option. For example, in Case 1, the sediment diameter was set under the Sediment Scour physical model to be 0.1 mm (fine sand), 0.4 mm (medium sand), and 0.8 mm (coarse sand).

3.3.2 Meshing. The user imports geometry file before applying the mesh. All cell sizes in a mesh block are uniform in all directions. The finer the mesh, the more accurate the simulation would be. However, it requires a lot of computational power. Figure 2(a) illustrates the mesh size being applied for the model setup.

3.3.3 Boundary Conditions. Boundary conditions that are used in the model are Volume Flow Rate (Q), Outflow (O), Symmetry (S), Wall (W) and Specified pressure (P), as illustrated in Figure 2(b).

3.3.4 Initial Conditions. The initial state of the solution for transient fluid flow problems must be known in order to find a solution and, in a manner similar to what is done with boundary conditions, the initial conditions are assumed, approximating the true state at time t = 0. This research uses Fluid Regions to define areas of fluid at the upstream side of the embankment as shown in Figure 2(c).

3.3.5 Probes and Flux Surfaces. History probes are point measurement tools while Flux Surfaces are used to measure quantities that flow through them. Figure 2(d) shows the uses of Flux Surfaces at the upstream, middle of embankment, and downstream.



(a) (b) (c) (d)

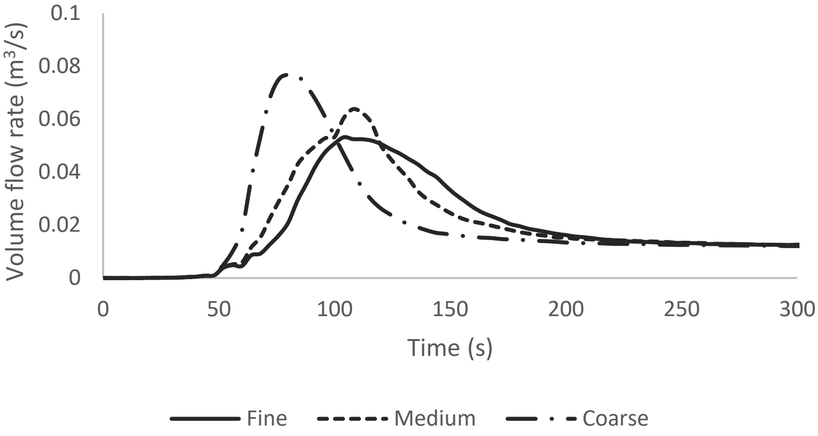
Figure 2. Modelling setup; (a) Meshing size, (b) Boundary conditions, (c) Initial conditions, and (d) Flux setup

4. Results and discussion

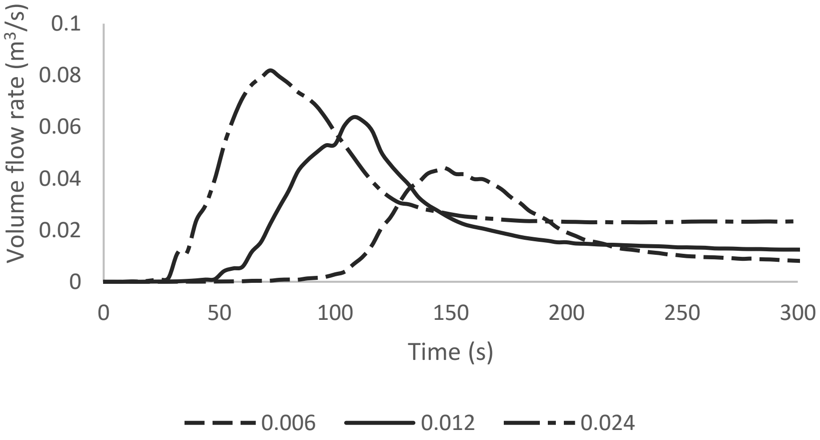
4.1 Breach outflow hydrograph and failure time

The peak outflow hydrograph for larger sediment sizes is greater than that of smaller sediment sizes. The peak outflow hydrograph for coarse sand with diameter of 0.8 mm is 0.0768 m^3/s, and for fine sand with a diameter of 0.1 mm, the peak is 0.0532 m^3/s. Meanwhile, for medium sand with diameter of 0.4 mm, the peak outflow hydrograph is 0.0638 m^3/s. As for the failure time, the coarse sand obtained a failure time of 80 s, while that of the fine sand has a failure time of 104 s. The failure time for the medium sand is 108 s which is almost as similar to the failure time for the fine sand. The modelling of Case 1, the embankment with different sizes of diameter of sediments, shows that the breaching occurs slower when the sediment used in embankments are finer as compared to larger sediment embankments. The fine sand seems to be more resistive to the erosion. This is because, finer sediments have greater suction pressure acting on it as compared to larger sediment. An increase of soil erodibility will certainly result in a decrease in failure time as shown in Figure 3(a).

Analyzing the result in Figure 3(b), the peak outflow resulted from inflow rate of 0.024 m^3/s is 0.0819 m^3/s, while inflow rate of 0.012 m^3/s resulted a peak outflow of 0.638 m^3/s. Whereas, the slowest inflow rate of 0.006 m^3/s resulted a smaller peak flow of 0.0439 m^3/s. The inflow rates of 0.024 m^3/s, 0.012 m^3/s, and 0.006 m^3/s resulted in failure time of 72 s, 108 s, and 148 s respectively. From this analysis of Case 2, the breaching process will complete much faster in the higher inflow rate case as compared to the lower. The erosion rate of the embankment during overtopping, which resulted in a higher peak outflow, is much greater in the case of the high inflow rate. This is because a large volume of fluid flowing over the embankment in high velocities produces great amount of shear forces, and the opposite is true for the low inflow rate case. Furthermore, the slope from higher inflow rate to lower inflow rate changes from a steep slope to a gentle slope.



(a)

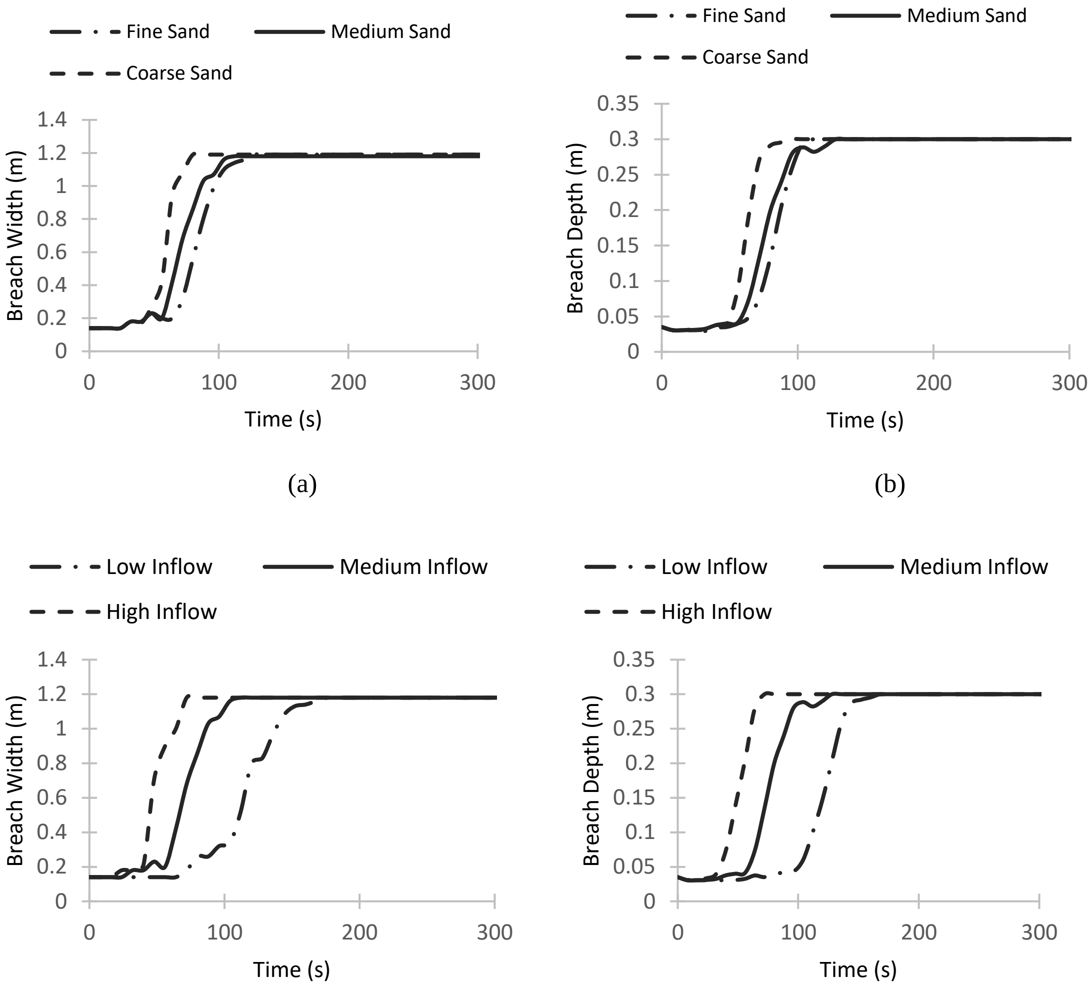


(b)

Figure 3. Outflow hydrograph for Case 1 (a) for different sediment sizes, and Case (b) for different inflow rates.

4.2 Breach Depth and Breach Width

Case 1 of coarse sand of 0.8 mm diameter, the breach size is the largest at time intervals of 60 s, 80 s, and 100 s. Meanwhile, the fine sand of 0.1 mm diameter has the smallest breach size at time intervals of 60 s, 60 s, and 100 s. This is because fine sand has higher resistance to erosion as compared to coarse sand, thus fine sand breach size is much smaller than coarse sand. The coefficient of erosion for fine sand is much higher as compared to coarse sand, the increase interlocking of soil particle and inter-particle bonding in finer sand, makes sand resistive to erosion. Figure 4(a) and Figure 4(b) shows the results of breach width and breach depth against time, respectively. For coarse sand, the breach width and breach depth occurred predominantly earlier. On the other hand, for fine sand, the breach width and breach depth occurred predominantly later. Case 2, the high inflow rate produces significantly larger breaching size compared to the medium and low inflow rates. Thus, the rate of erosion for the case of high inflow rate is significantly higher. High fluid flow velocity from the high inflow rate, causes the embankment to experience high tractive shear stress which quickly exceeds the resistivity of the soil. The opposite is true for the low inflow rate as the low inflow rate produces lower velocity flow, thus a lower tractive shear stress and slower rate of erosion. Figure 4(c) and Figure 4(d) show that the high inflow rate causes the breach depth and breach width of the embankment to breach predominantly earlier compared to medium and low inflow rates.



(a) (b)

(c) (d)

Figure 4. Results of Case 1; (a) Breach width, (b) breach depth against time, and results for Case 2; (c) Breach width, (d) breach depth against time.

4.3 Velocity magnitude during breaching process

In the breaching process, the velocity plays an important role in the erosion and scour of the embankment, the widening and deepening process of breach, and the flood propagation process in the downstream, etc. [7]. At $t = 40$ s, the maximum velocity reached is 0.339 m/s. Meanwhile, at $t = 60$ s, the maximum velocity reached is 0.7109 m/s. Right before breaching begins, the embankment undergoes incipient motion which is the initiation of surface erosion. The initiation of surface erosion greatly depends on the properties of the soil. At $t = 80$ s and $t = 100$ s, the maximum velocity reached are 1.145 m/s and 1.245 m/s. As the velocity increases rapidly, so as the erosion rate, as can be observed from the breach parameters of breach depth as shown in Figure 5. At t = 120 s and $t = 140$ s, the maximum velocity reached are 1.042 m/s and 0.952 m/s. The velocity magnitudes of these time intervals are lower than that of $t = 80$ s and $t = 100$ s. As breach depth increases, and the height of the embankment reduces, the downstream slope angle of the embankment decreases.

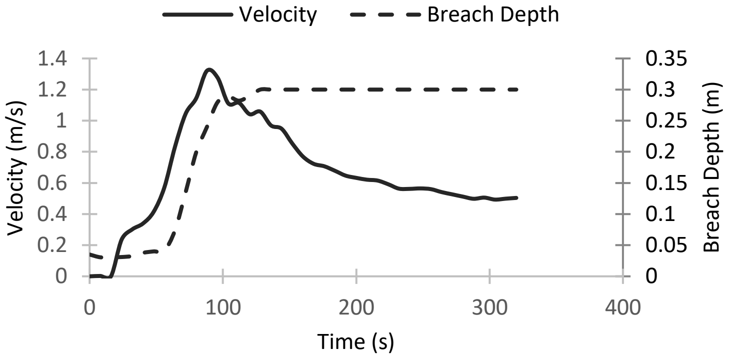
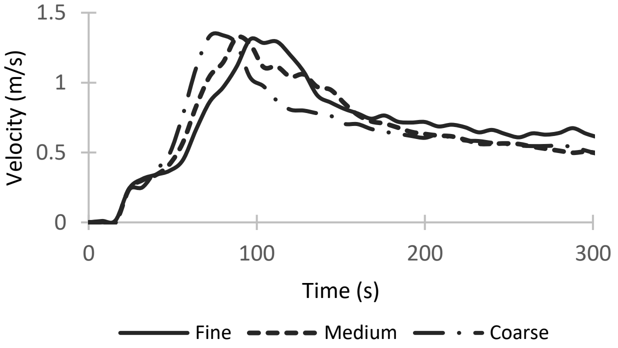
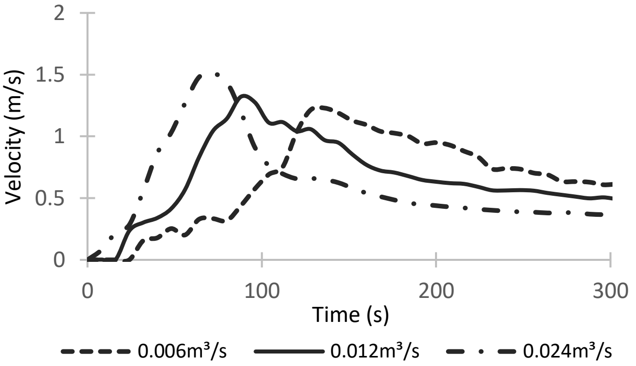


Figure 5. Relationship between a breach depth and velocity against breaching time.

Case 1 shows that the sediment size does not influence the peak velocity, however there are subtle difference to its failure time. This is because, the maximum velocity is determined by the height of the embankment [8], shown in Figure 6(a). For Case 2, the influence of different inflow rates shows difference to the peak velocity magnitude and failure time shown in Figure 6(b). This show that peak velocity and failure time are influence by inflow rates. The higher the inflow rate during breaching, the higher its peak velocity. The modelling results of velocity magnitude of the embankment are also shown in Figure 7.

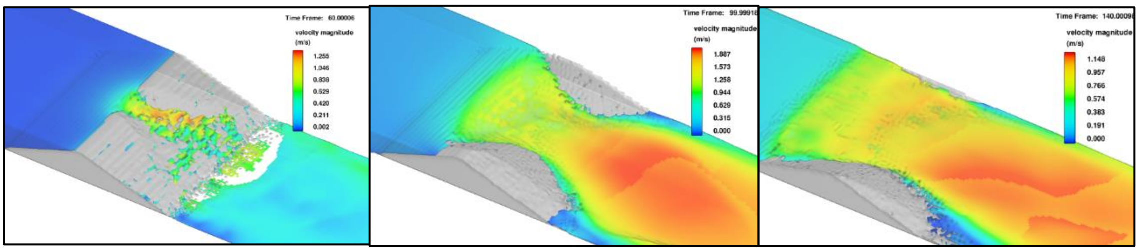


(a)



(b)

Figure 6. Velocity against time graph for (a) Case 1 and (b) Case 2



(a) (b) (c)

Figure 7. Modelling results of velocity magnitude of the embankment at time interval (a) 60 s, (b) 100 s, and (c) 140 s.

5. Conclusion

The peak outflow hydrograph is higher and has shorter failure time for embankment with larger sediment sizes and lower peak outflow hydrograph and longer failure time for embankment with finer sediment sizes. Finer particles are able to provide greater surface area of contacts between other particles, thus having increase interlocking between soil particles, and hence higher resistances to soil erosion. Meanwhile, larger inflow rates give larger peak outflow hydrograph and shorter failure time, and vice versa for lower inflow rates. Embankment dam with large sediment sizes will have larger breach depth and width as compared to embankment dam with finer sediment size at end of the breaching process. Meanwhile, the end breaching parameters of breach depth and breach width increases with the values of inflow rates. The changes in inflow rates show significant changes to the end breaching parameters. The velocity magnitude during breaching process follows a slightly similar graph trend to the breach outflow hydrograph, where the graph of velocity magnitude to time shows a peak value at certain time intervals. The difference between sediment sizes does not influence the peak velocity during the breaching process.

References

[1] Foster M, Fell R and Spannagle, M (2000) The statistics of embankment dam failures and accidents *Can. Geotech. J* **37(5)** 1000–1024.

[2] Allsop N W H A, Kortenhaus A and Morris M W (2007) *Failure mechanisms for flood defense structures* FLOODsite Rep. T04-06-01 FLOODsite Consortium ⟨www.floodsite.net⟩.

[3] Costa J E (1985) *Floods from dam failures* Open-File Rep. No. 85-560, USGS, Denver, 54.

[4] Ralston D C (1987) Mechanics of embankment erosion during overflow *Hydraulic Engineering, Proc* 1987 National Conf. on Hydraulic Eng. ASCE Reston VA 733–738.

[5] Xu Y and Zhang L M (2009) Breaching parameters of earth and rockfill dams *Journal of Geotechnical and Geoenvironmental Engineering* **135(12)** 1957–1970.

[6] Mat Lazin N A (2013) Erodible Dam Breaching Patterns Due to Overtopping. Johor Bahru: Universiti Teknologi Malaysia.

[7] Zhao G. et al. (2015) *Flow hydrodynamics in embankment breach Journal of Hydrodynamics* **27(6)** 835-844.

[8] Powledge G R, Ralston D C, Miller P, Chen Y H, Clopper P E and Temple D M (1989) Mechanics of overflow erosion on embankments II: Hydraulics and design considerations *Journal of Hydraulic Research* 115(8) 1056–1075.

[9] ASDSO (Association of State Dam Safety Officials) (2020) Lessons learned: From Dam Incidents and Failure. https://damfailures.org/lessons-learned/high-and- significant-hazard-dams-should-be-design-to-pass-an-appropriate-design-flood-dams-constructed-prior-to-the-availability-of-extreme-rainfall-data-should-be-assessed-to-make-sure-they-have-ad/, retrieved date 15th July 2020.