Soil Erosion Morphology of An Embankment Failure

Z Mohamed Yusof\(^1\)*, A K Abd. Wahab\(^2\), Z Ismail\(^2\) and S Amerudin\(^3\)

\(^1\)Department of Water and Environmental Engineering, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Malaysia.
\(^2\)Centre For Coastal and Ocean Engineering (COEI), Universiti Teknologi Malaysia, Malaysia.
\(^3\)Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia.

*Corresponding author: zainabyusof@utm.my

Abstract. Embankments are essential infrastructure, are built to provide flood control. It also presents risks to property and life due to their potential to fail and cause catastrophic flooding. To mitigate these risks, authorities and regulators need to carefully analyse and inspect dams to identify potential failure modes and protect against them. This paper presents an embankment failure morphology, and the amount of erosion occurred due to overtopping flow. The breached morphology is analysed for an embankment slope of 1V:3H, using a medium sand grain size of non-cohesive soil in the laboratory. The embankment height is 0.1 m and tested with inflows rate of \(Q = 0.8 \times 10^{-3} \text{ m}^3/\text{s}\). Experimental results showed that the breached peak discharge is affected by the morphology of the embankment breached. The volume lost calculation of the embankment erosion was calculated using SURFER 8, indicating the volume of 0.0096 m\(^3\) with the peak breached discharge of 3.63 \(\times 10^{-3} \text{ m}^3/\text{s}\). The study concludes that the embankment volume lost is about 41\%, and the characteristics of the embankment failures influence its morphology patterns.

1. Introduction
Mechanisms that cause instability of compacted soils or embankment and any natural underlying foundation soils, particularly in soil response, are important mechanisms to look in details. Instability of the upstream or downstream slopes of the embankment is the main reason a dam can collapse. Factors such as the effect of pore water pressure affect the stability of the soil. These mechanisms are a measure of the performance of structural stability, which relates closely to the equilibrium between forces and momentum, and also to the mobility of soil strength involving concepts of soil shear strength and stress-strain response [1]. The pore water pressure is a dominant parameter resulting in the movement of water into the soil. The stability of the structure also is strongly related to the material used for the embankment. Other factors contributing to the failures as reported in the literature are lack of maintenance, settlement of the dam crest, earthquake loads and wrong design, for example in calculating the internal hydrostatic pressure, amongst others.

The process by which bed particles become entranced in a fluid is called erosion, which is the result of shearing stresses induced by the fluid flow on the particles. This occurs when the shear stress is high enough to overcome the force holding the particles together and then cause the removal of particles from
the bed surface. Erosion is one of the processes that cause a failure of a dam or embankment structure. When flow overtops the earthen dams, sediment or particles will be moved by the flow. The speed of flow and the amount of sediment transported downstream strongly depend on the type of soil, and the forces exerted on the particles.

The breach due to erosion is fundamentally different from the river sediment transport process, in particular. The driving forces resulting in breach embankment due to overtopping include the tractive force of the flow and gravitational effects. This study requires a good understanding of the erosion processes and breach formation mechanisms as critical factors to successfully develop a new physics-based breach model. Erosion processes such as head cutting, deepening, lateral widening, erodibility and overturning failures of soil masses are the characteristics of breached embankments that require a deeper understanding and detailed investigation experimentally and numerically. Even though many experimental tests have been carried out and numerical works performed, there are still uncertainties in evaluating the efforts. This includes the quantitative comparisons of breach model predictions and observed performance, leading to breach model evaluations in terms of ease of use, sensitivity to specific input parameters, consistency of results for different test cases and input data requirements. These issues have not resolved due to the nature of the breach and unreliable data observation during the failure.

2. Overtopping Failure

There are two causes of breach events, namely due to overtopping and piping failure [2]. Overtopping happens when the flow of water or flood overpass the highest level of the embankment dam. This scenario is said to initiate the breach due to overflow. As water level increases, the hydrostatic pressure behind the dam forces the water in the reservoir to pour down the downstream slope. The released of the water with large quantities will cause a disastrous effect on the downstream area. Overtopping could happen when extreme rainfall, where it will lead to more massive inflows into the reservoir. Besides that, other causes of overtopping are due to extreme waves caused by earthquake and surge, low maintenance of the dam structure, blockage in the spillway, and flood channel [9]. Besides, there are several other reasons which contribute in the overtopping of the dam [10]. The reasons are; a) insufficient design height for spillway crest or earth-fill dam, b) break down of gates, pipe outlets or spillways, c) lack of maintenance of the reservoir storage, and d) seismic activities that induced the seiches. Zhu et al. [12] listed some of the factors affecting the breach development process. The factors included profile and structure of the embankment, type of foundation (erodible or non-erodible), type of material (cohesive or non-cohesive), and causes of failures (overtopping, piping, slope sliding and seepage). The breach process influences by various factors: hydrologic, hydrodynamic, and geotechnical factors [13]. The process is complex due to the interaction between water and soil.

Singh [11] listed the percentage of several crucial factors that cause dam failure. Foundation and overtopping failure are the two reasons leading to the breached embankment. Besides piping and seepage, other possibilities that could also contribute to the percentage of failure due to foundation problem are excess pore water pressure, fault movement, and settlement. Xu and Zhang [14] compared the failure modes of dams indicated that the failure mostly occurred due to overtopping with the highest percentage (56%), followed by seepage erosion/sliding with the percentage of 35.6, failure due to sliding was about 5% and 3.4% for unknown causes.

Also, the study on embankment breaching has been carried out for ages by many researchers which involve large scale tests in the field and small-scale tests in the laboratory [3], [4], [5], [6], and [7]. The study of flow regimes and erosion zones of overtopped embankments is very crucial to identify the critical zone of the erosion to occur [8]. Findings from the study stated that there are three zones of embankment erosion due to overtopped flow, as depicted in Figure 1. Zone 1 is the region where less erosion might happen due to subcritical flow approaching the embankment, and the flow velocities and shear stresses above the crest are relatively low. Further along the crest, a so-called transition zone from subcritical to critical flow is observed (Zone 2). This zone exhibited high stresses due to the changes in the energy slope. Zone 3 is an area with a high potential for erosion. The flow starts to accelerate rapidly along the downstream slope, resulting in increased shear stresses at the downstream corner of the crest.
Hence, the objectives of this study are not only to investigate the breach grows and breach hydrograph when breaching takes place but most importantly, to calculate the volume lost due to the breaching. This can be done in the laboratory by analysing the breached patterns and recorded the breached hydrograph during the failure time.

3. Methodology

3.1. Laboratory Setup

An experiment was carried out to study the effects on sediment erosion in calculating an embankment volume loss of a non-cohesive embankment soil in a long channel located at Hydraulics and Hydrology laboratory, UTM. The schematic diagram of the channel setup is illustrated in Figure 2. Meanwhile, the soil properties of the embankment material were tested at the Geotechnical laboratory, UTM. The channel consists of the embankment, a v-notch weir, two video cameras and sumps for inlet and outlet of the water tank.

In this experiment, the breach initiated by initiating water reaches the notch in the centre of the crest of the embankment. The outlet discharge was measured using 90-degree v-notch weir, which is located at the open channel outlet. The formula to determine the outflow discharge, \( Q \), is given as Equation (1),

\[
Q = \frac{8}{15} C_d (2g)^{0.5} \tan \left( \frac{\theta}{2} \right) h^{2.5}
\]

where \( Q \) = outflow discharge (m\(^3\)/s); \( C_d \) = discharge coefficient; \( g \) = gravitational force (m/s\(^2\)); \( h \) = height of water (m).

A hydrograph is obtained after observation and calculation of an outflow discharge at the outlet. A point gauge is used to calculate the height of the water flowing through the v-notch weir, as shown in Figure 3. Maximum outflow and peak time are obtained after plotting the outflow graph against time. The outlet discharge was measured at the end of the flume, where the time delay had an effect on the outlet discharge. The discharge from the breach is generally assessed right after the breach along the embankment occurred.
The structure of the embankment was constructed with a dimension of 0.1 m height, 0.6 m width, and the slope of the embankment is 1V:3H, as depicted in Figure 4. The flowrate used is $Q_1 = 0.8 \times 10^{-3} \text{ m}^3/\text{s}$. The material of the embankment is medium sand with the grain size of the sediment ranging from 0.5 mm – 0.2 mm. A volume calculation estimated the volume of the embankment. Figure 1.5 shows the embankment set up of the compaction work and a notch location. The notch is built at the center of the embankment crest, acting as a weak point for the erosion to begin. The notch size is 10 mm height and 30 mm width.
Figure 5. Physical model setup; (a) soil compaction, and (b) A notch as a weak point of the embankment.

4. Results and discussions
The breaching process starts when the flow enters the notch as the result of overtopping flow, as seen in Figure 6(a). The water forces the embankment material to erode along the notch area. At the same time, the effect of hydrostatic forces behind the embankment triggers the embankment material to collapse instantly due to soil instability that causes advance failure. After the breaching process completed, as seen in Table 6(b), half of the embankment has been eroded by the stream and formed such bedlocks, as shown in Figure 7. The formation of sediment eroded to the downstream is varies based on the input of flow rates and compaction degree of the sediment.

The breached hydrograph is plotted to analyse the peak outflow and peak time during the breaching. Figure 8 shows the result of peak outflow, occurred approximately 105 s with a lagged time of 54 s. It took about 51 s to reach the peak flow, which is approximately $3.63 \times 10^{-3} \text{ m}^3/\text{s}$.
4.2 Embankment volume loss using SURFER 8. After the embankment completely breached, the embankment volume lost was calculated using a grids system. This can be done by marking the position of $x$ and $y$ in the laboratory. The sediment height of the breached embankment was measured using a point gauge based on a grid point, as shown in Figure 9. The data was plotted in 3 axes: $x_n$, $y_n$, and $z_n$ ($n = 1, 2, 3,\ldots$) whereby $y_n$ is sediment height at each point of the grid intersection of $x$ and $z$ axes. Each grid is fixed to 5 cm for $x$-axis and $z$-axis, whilst, the $y$-axis represents the height of the sediment recorded. The data is plotted into a 3D coordinate.
The analysis of volume loss was calculated using a SURFER 8 program. The SURFER uses contour a 3D surface mapping of embankment breached using shading and colours to emphasis the elevation data. The volume of the surfaces created for specific reference surface, \( z = 0 \) in SURFER 8 were calculated according to the rules of Trapezoidal rule, Simpson's rule and Simpson's 3/8 rule. The difference between these calculation rules depends on the different interpolation methods and grid ranges. A similar grid data taken from the experiment is used to analyse for the 3D surface modelling. When the embankment starts to breach, it continues to erode parts of the embankment. The process was initiated from the weakness part of the sediment. In this study, the final shape of the breached embankment due to overtopping erosion was almost symmetrical between both sides, which has a similar result found in Figure 10(b). It showed that a plot of surface breached morphology and breached hydrographs after the embankment was breached entirely. The heights of sediment remaining were recorded and plotted in SURFER 8 software for the volume loss calculation. The data was recorded for 5 cm interval.

![Figure 10. A 3D surface morphology using SURFER 8 of an embankment failure; (a) before and (b) after. The legend (in colours) represents the elevation in cm](image)

In details, the erosion pattern starts at the middle of the embankment and widens laterally before eroding vertically like a trapezoidal shape from a front view. This might due to the initial shape of \( v \)-notch built at the embankment crest to trigger the erosion. It started when the water flows through the notch to erode the crest until the embankment fails. The embankment fails due to hydrostatic pressures exerted on it, and this can be observed from the drastic changes in breached hydrograph produced. The existing volume of the embankment calculated from SURFER 8 is approximately 0.024 m\(^3\), which is close to the theoretical calculation value. After the failure, the remaining embankment volume calculated was approximately 0.014 m\(^3\) for all the calculation methods (rules) considered. The results indicate that the volume loss of the failure embankment due to erosion was approximately 0.0096 m\(^3\), as indicated in Table 1.

| Volume Calculation Method | Volume Before failure (cm\(^3\)) | Volume After failure (cm\(^3\)) |
|---------------------------|----------------------------------|-------------------------------|
| Trapezoidal Rule          | 23967.71                         | 14355.63                      |
| Simpson’s Rule            | 23969.18                         | 14357.01                      |
| Simpson’s 3/8 Rule        | 23969.03                         | 14357.44                      |
5. Conclusion
Findings from the experimental results showed that the percentage difference of volume loss for all methods calculated using SURFER 8 is less than 0.1%. This indicates that the accuracy of SURFER 8 in calculating the embankment volume loss for all three methods is in a good agreement. The percentage of embankment volume loss after the breach is approximately 41%.

6. References
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