ANALYSING FLOW CHARACTERISTIC OF BREACHING EMBANKMENT USING LINEAR HYDRODYNAMIC POROUS MODEL

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DEDICATION

Knowledge is that which benefits not that which is memorised

Quoted by Imam Al-Shafié

Patience is a pillar of faith

Quoted by Umar ibn al-Khattab (RA)

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ABSTRACT

The study of the overtopping flow associated with breaching embankments is an essential part of water management, particularly for emergency planning. One of the mechanisms that triggers embankment collapse is overtopping. Therefore, it is crucial to identify the zones at risk where the overtopping failure is likely to occur and where the breach might form. The nature of the failure would significantly impact the breach discharge, the variation of reservoir water levels, and the resulting water levels in the downstream valley or floodplain. This thesis presents the characteristics of flow due to an embankment breaching caused by flow overtopping. Laboratory works were carried out to observe the embankment failure, how the erosion is triggered, and factors contributing to the failure. A dimensional analysis was performed to identify the variables involved to analyse the mechanism of the embankment failure. The development of an embankment breach model using Computational Fluid Dynamics (CFD) was carried out to model the failure patterns of a breaching embankment. This required specification of the breach formation and breach widening, and prediction of the resulting breach hydrograph. In this study, the embankment was modelled as a porous medium governed by a generalised form of Darcy's Law. The erosion is prescribed by systematically decreasing the porous embankment resistance in those areas where erosion is likely to occur linearly. Model validations were performed by comparing CFD simulations with measured data from experimental work in the laboratory for a 2D model. The Eroding models developed were conducted in 2D and 3D, using the Realizable $k-\varepsilon$ model and the Volume of Fluid (VOF) multiphase model to identify the free elevation surface. The 2D model results have shown good agreement with experimental data for free water surface and velocity profiles over a rigid embankment. For a porous embankment, the profiles displayed reasonable accuracy with that of a Rigid Model. The validations on the 2D porous embankment models gave reasonably good agreement on temporal breach patterns and free surface flow over the breached embankment. The results showed that the overflow volume predicted was close to the theoretical value. The percentage difference was around 13%. The study considered the mesh adaption technique using a grid refinement method. The results indicated that a 10% rule of refining and coarsening produced a difference of 6% (in peak flow of the hydrograph) compared to 10% rule of refining only technique. The 3D Eroding Models allow for the inclusion of lateral breach formation to predict flow features over a breached embankment and predict a breach discharge hydrograph. Three breach shape cases were simulated, namely the side-, trapezoidal, and triangle breach shapes. As a result, parameters such as velocity vectors at the breach area, free water surface profiles, and embankment volume lost during the breaching event were produced. The Eroding Model predicted that the initially triangular shaped beach produced 24% higher peak breach discharge compared with the trapezoidal shape. Comparisons of a maximum velocity at the breached area between the 3D Eroding Models and FLOW-3D simulation ranged from 11% to 52%. Meanwhile, the FLOW-3D simulation predicted more volume lost and peak discharge compared with observed data (Case Study E1) with a percentage difference of 42.7% and 30.2%, respectively.

ABSTRAK

Kajian aliran limpahan berkaitan pemecahan benteng amat penting dalam pengurusan air, terutamanya dalam menyediakan plan tindakan kecemasan. Salah satu mekanisma yang menyebabkan pemecahan benteng adalah limpahan air melalui struktur banteng. Oleh itu, adalah penting untuk mengenalpasti zon-zon yang berisiko di mana pemecahan benteng mungkin berlaku disebabkan limpahan ini dan lokasi pembentukkan pemecahannya. Sifat perpecahan benteng ini akan memberi kesan yang signifikan ke atas aliran air limpahan yang dihasilkan, perubahan aras air takungan dan menyebabkan kenaikan paras air di bahagian hilir. Tesis ini mengkaji ciri-ciri aliran akibat pemecahan benteng tanah yang disebabkan oleh aliran limpahan air. Penyiasatan di makmal telah mengkaji ciri-ciri aliran yang menyebabkan perpecahan benteng; bagaimana hakisan berlaku dan faktor-faktor yang mempengaruhi pemecahan benteng. Analisis tidak berdimensi telah dilakukan untuk mengenal pasti pemboleh ubah yang berkaitan yang menyebabkan perpecahan benteng. Pembangunan model perpecahan benteng dibangunkan menggunakan kaedah 'Computational Fluid Dynamics' (CFD) untuk memodelkan corak perpecahan pembentukan punca pemecahan benteng. Kaedah ini memerlukan spesifikasi pembentukan punca pemecahan dan kelebaran kawasan pemecahan dan meramalkan hidrograf aliran limpahan yang dihasilkan. Dalam kajian ini, benteng dimodelkan sebagai media berongga (berliang) yang alirannya dianalisis menggunakan Hukum Darcy dalam bentuk umum. Hakisan dibentuk dengan mengurangkan daya rintangan di bahagian benteng yang berkemungkinan terhakis secara linear. Pengesahan model dilakukan dengan membuat perbandingan keputusan model simulasi CFD untuk pemodelan 2D dengan data yang dicerap di makmal. Benteng dimodelkan secara 2D dan 3D menggunakan model berbilang fasa, iaitu menggunakan kaedah 'Volume of Fluid' (VOF) dan model aliran gelora 'Realizable Model' $k-\varepsilon$ untuk mengkaji ciri-ciri pembentukan air disebabkan pemecahan benteng. Hasil simulasi secara 2D bagi profil permukaan air dan kelajuan air bagi Model Benteng Tegar menunjukkan perbandingan yang baik dengan data yang dicerap di makmal. Bagi pemodelan benteng berliang, profil aliran menunjukkan persetujuan yang baik dengan Model Benteng Tegar yang tidak berlaku pemecahan. Pengesahan yang telah dilakukan bagi model 2D Benteng Berliang telah menunjukkan perbandingan yang baik, dari segi corak masa pemecahan dan aliran permukaan. Hasil kajian menunjukkan jumlah lebihan air menghampiri nilai teori dengan perbezaan peratusan sekitar 13%. Kajian telah menggunakan teknik pembentukan grid dengan kaedah penghalusan grid. Teknik penghalusan dan pembesaran grid sebanyak 10% menghasilkan perbezaan peratusan aliran puncak hidrograf sebanyak 6% berbanding dengan kaedah 10% penghalusan grid sahaja. Model Hakisan 3D mengambilkira pembentukan perpecahan benteng bagi simulasi aliran melalui benteng yang pecah dan seterusnya menghasilkan hidrograf aliran limpah. Tiga jenis bentuk perpecahan yang disiasat adalah jenis perpecahan sisi, trapezoid dan segitiga. Parameter yang dihasilkan adalah vektor halaju, permukaan air bebas dan isipadu kehilangan semasa perpecahan benteng berlaku. Hasil simulasi model 3D menunjukkan bentuk perpecahan awal jenis segitiga menghasilkan aliran limpahan 24% lebih tinggi daripada bentuk trapezoid. Perbandingan halaju maksimum di kawasan perpecahan benteng bagi semua Model Hakisan 3D dibandingkan dengan FLOW-3D adalah di antara 11% - 52%. Manakala, simulasi FLOW-3D menghasilkan lebihan kehilangan isipadu benteng dan kadaralir puncak berbanding data cerapan (Kajian kes E1) dengan perbezaan peratusan 42.7% dan 30.2%.

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LIST OF ABBREVIATIONS

ANSYS	-	Fluid Dynamics (CFD) Software Program Solutions
ASTM	-	American Standard Testing Manual
BEM	-	Boundary Element Method
BEED	-	Breach Erosion of Earthfill Dams
BREACH	-	An Erosion Model for Earthen Dam Failures
CAD	-	Computer-aided Design
CADAM	-	Concerted Action on Dambreak Modelling
CFD	-	Computational Fluid Dynamics
DAMBRK	-	Dam Break Forecasting Model
MyDAMS		Malaysian Safety Management Guidelines
UDF	-	User-Defined-Function
UDM	-	User-Defined-Memory
FDM	-	Finite Difference Model
FEM	-	Finite Element Model
FLOODsite	-	Integrated Flood Risk Analysis and Management Methodologies
FLOW-3D	-	CFD Software
FLUENT	-	Fluid Simulation Software
FVM	-	Finite Volume Model
HERU	-	Hydraulic Engineering Research Unit
HPC	-	High Performance Computer
IGES	-	Internal Graphics Exchange Specification
IMPACT	-	Investigation of Extreme Flood Processes and Uncertainty
N-S	-	Navier-Stokes
PDEs	-	Partial Differential Equations
PIV	-	Photogrammetric and Particle Images Velocity
QUICK	-	Quadratic Upwind Interpolation for Convective Kinetics
RANS	-	Reynolds Average Navier Stokes
RNG	-	Re-Normalised Group

SIMBA	-	SIMplified Breach Analysis (Computer Model)
SG	-	Specific Gravity
SST	-	Shear Stess Transport
STEP	-	STandard for Exchange of Product
VOF	-	Volume of Fluid
WinDAM	-	Windows Dam Analysis Modules

LIST OF SYMBOLS

B	-	Breach Width (m)
B_0	-	Initial Rectangular-shape Width (m)
C	-	Material Dependent Constant
C_a	-	Empirical Coefficient
C_d	-	Discharge Coefficient
C_p	-	Pressure Coefficient
C_R	-	Embankment Resistance ($kgms^{-2}$)
C_{R0}	-	Embankment Initial Resistance ($kgms^{-2}$)
C_r	-	Courant Number
C_μ	-	Turbulence Model Constant
$C_{\varepsilon1}, C_{\varepsilon2}$	-	Model Constants
D_a	-	Darcy Number
D_i	-	Displacement Distance (m)
F_r	-	Froude Number
H	-	Headcut Overfall Height (m)
H_e	-	Embankment Height (m)
H_T	-	Total Energy Head (m)
H_t	-	Porous Media Thickness (m)
H_o	-	Overflow Energy Head (m)
I	-	Incoming Flow Rate (m^3s^{-1})
K	-	Porous Media Permeability (m^2)
O	-	Outflow Rate (m^3s^{-1})
P	-	Hydrostatic Pressure (Nm^{-2})
P_e	-	Peclet Number
P_k	-	Rate of Turbulence Production
Q	-	Discharge (m^3s^{-1})
Q'	-	Non-Dimensional Discharge
Q_o	-	Initial Discharge (m^3s^{-1})
Q_p		Peak Discharge (m^3s^{-1})
Q_{out}	-	Outflow Discharge (m^3s^{-1})

Q_L	-	Lateral Discharge (m^3s^{-1})
Q_B	-	Breach Discharge (m^3s^{-1})
R_e	-	Reynolds Number
R	-	Volume of Reducing Reservoir (m^3)
S_M	-	Source of Internal Energy
U_e	-	Erosion Rate (ms^{-1})
V_L	-	Volume Lost (m^3)
$\mathbf{U}(u, v, w)$	-	Velocity Vectors
b	-	Channel Width (m)
d	-	Particle Diameter (mm)
dt	-	Change in Time (s)
g	-	Gravitational Acceleration (ms^{-2})
h	-	Local Head Above The Dam Crest (m)
k_d	-	Detachment Coefficient ($ms^{-1}Pa^{-1}$)
q	-	Discharge per Unit Width ($m^3s^{-1}m^{-1}$)
q_c	-	Darcy Flux
t	-	Time (s)
u_b	-	Breach Velocity (ms^{-1})
v	-	Flow Velocity (ms^{-1})
y	-	Water Depth (m)
y_1	-	Water Depth Before The Hydraulic Jump (m)
y_2	-	Water Depth After The Hydraulic Jump (m)
y_o	-	Height of Free Surface Above The Embankment (m)
y_t	-	Tailwater Depth (m)
(x, y)	-	Coordinates x And y
τ	-	Local Bed Shear Stress (Nm^{-2})
τ_c	-	Critical Shear Stress (Nm^{-2})
τ_e	-	Effective Hydraulic Stress (Nm^{-2})
$\bar{v}$	-	Mean Velocity (m/s)
$\vec{u}$	-	Velocity Vector
ω_e	-	Angular Erosion Rate
ρ	-	Fluid Density (kgm^{-3})

θ	-	Channel Slope
γ_w	-	Unit Weight of Water (Nm^{-3})
γ_s	-	Particle Specific Weight (Nm^{-3})
Δt	-	Time Step Size (s)
Δx	-	Cell Size (m)
∇p	-	Pressure Gradient ($Nm^{-2}m^{-1}$)
α_a	-	Volume Fraction of Air
α_w	-	Volume Fraction of Water
μ	-	Water Viscosity ($kgm^{-1}s^{-1}$)
η	-	Porosity
$\sigma_k, \sigma_\varepsilon$	-	Turbulent Prandtl Numbers for k and ε
μ_t	-	Turbulence Viscosity ($kgm^{-1}s^{-1}$)

CHAPTER 1

INTRODUCTION

1.1 Background Study

Earthen embankment is a type of hydraulic structures or effective infrastructures constructed to retain water. This structure is always related with the risk of its failure due to aging, lack maintenance and extreme hydrological events resulted in a disastrous flooding downstream. In general, the causes of fatal embankment failures are due to loss of embankment material stability (shearing failure in the dam body or sub-base), overtopping due to insufficient spillway capacity, internal erosion and surface erosion caused by an instability embankment structure during the intensive rainfall. In practice, the above-mentioned types of failures are interrelated and statistics have shown that failure due to overtopping represents approximately 40% for all embankment dam failures (Saluja et al., 2018).

According to The British Dam Society (2007), there are over 3,000 embankment dams in the United Kingdom, some of which dated from the 9th Century. It is estimated that the average age of embankment dams in Britain is over 100 years. Meanwhile, in the United States, there are more than 90,000 regulated dams. According to the National Dam Inventory (USACE, 2016), about 85% are earthen dams and many of these dams have been built for the purposes of flood control, tourism, hydroelectric generation and irrigation (Sasanakul et al., 2019). These dams have an average age of more than 50 years, and some are older than 150 years (USACE, 2016). Aging and deterioration affect the stability and reliability of the dams to operate properly during extreme weather events, which may in turn endanger the health and safety of residents and property downstream. It has been reported that hundreds of them have suffered failures throughout history. The main purpose of an embankment dam is to retain water like other types of dam, but the structure relies on its compaction strength and weight to resist the flow of water, in the same way as a concrete gravity dam. Because of its age and earthen-filled material, an embankment dam needs to have regular maintenance to ensure strength, stability and safety.

Embankment breaching is a complex process affected by many factors such as the embankment height, slope, material, and flow. There is a strong coupling between flow hydraulics and the changing geometry of the breached structure (Hager and Unger, 2006; Hahn et al., 2000; Hanson et al., 2005; Hassan et al., 2004; Mohamed et al., 1999; Powledge et al., 1989). The process involves the sediment-deposition at the downstream due to water pressure behind the dam that causes the instability of the dam structure leading to collapse. The result of breach opening and sediment transport towards the downstream valley is a crucial aspect to consider when dealing with an embankment failure to prevent damages and deaths. An embankment erosion happens when shear stress by fluid flow on its surface is high and sufficient enough to overcome the force that holds the particles together. The rate of erosion, so-called erodibility differs from cohesive to non-cohesive soil. Factors such as grain size portion, density and grain shape influenced the erodibility for non-cohesive soil. Mechanism of erosion of the embankment failure is due to the flow of the water through the embankment material. For example, the failure due to overtopping is due to high stresses at the downstream embankment face near the toe, leading to high potential for erosion.

Breach parameters are obtained from simple regression equations based on dam and reservoir properties for embankment dams that fail by progressive erosion in most cases. Because real erosion processes are not modelled, the uncertainty of breach predictions is high. Inherent variation in the erodibility of embankment materials as a function of soil type and compaction and moisture conditions, and the effects of variability of embankment design, configuration, and geometry are factors increasing the uncertainty for embankment dams. The significant uncertainties associated with the simulation of breaches make it difficult to prevent the effects of dam failure accurately and to prepare for dam break flooding emergencies effectively.

Embankment breaches have been studied either using physical experiments, numerical model simulations, and field observations. Most publications focus on embankment breaching, but studies on the mechanism of overtopping failure are very limited due to the complexity of the erosion process (Freed, 1991; Singh, 1996 and Wahl, 2004). This include the determination of basic parameters that characterise the progress of the embankment failure such as time to failure, shape and size of the breach, progress of the failure and maximum breach discharge. The data can be obtained either based on historical observation or from the laboratory works. Without understanding the breaching process, one may overestimate the breached flood discharges. In this study, a numerical model is developed to simulate embankment breaching to understand and predict the consequences of what will happen when breaching occurred. Considering the complexity of the breaching process to resulting flooding, an approach of porous embankment is introduced to model the hydrodynamic of breach discharge in two-dimensional (2D) and three-dimensional (3D) flow model. This approach allows for a reliable dam break process model that would have the potential for the best outcomes.

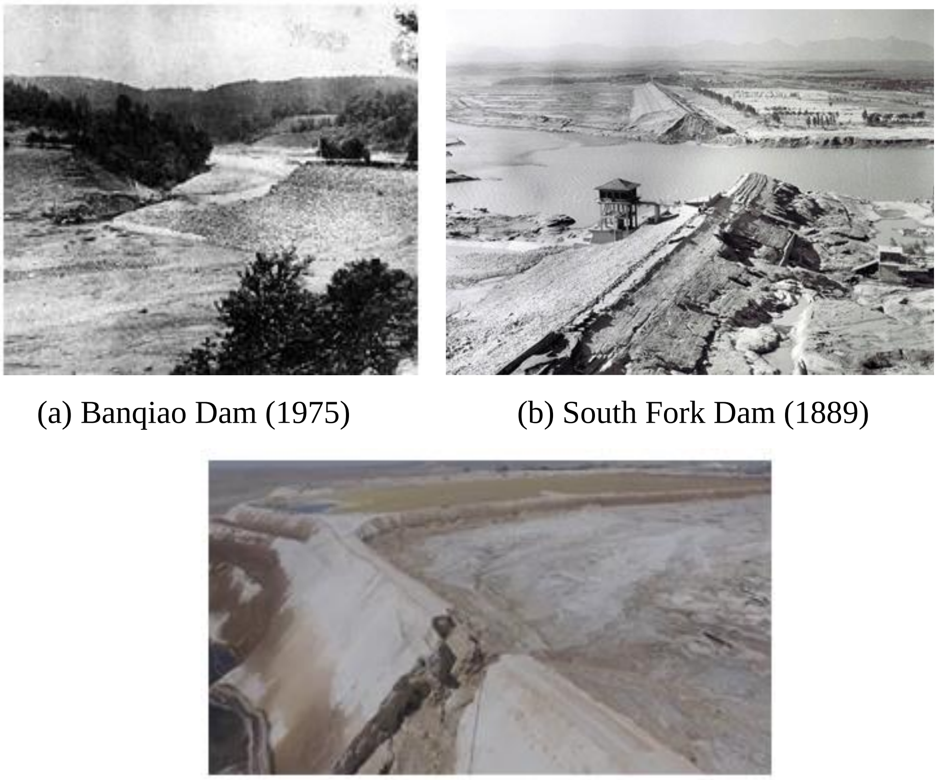
This study is to analyse flow characteristics of a porous embankment breaching due to overtopping. Several studies on porous media to characterise flow in open channels have been carried out, particularly on the behaviour of flow through the porous region, an application widely used in groundwater research. However, only a few of them comprehensively studied flow characteristics above the porous region, which is of interest. In other words, relevant literature on rigid porous regions was very difficult to obtain. This study therefore takes one step further to investigate quantitatively the characterisation of overtopping flow by the presence of porous media, as one of the new methods in modelling breaching embankments. The numerical approach undertaken is to model porous eroding embankment using ANSYS-FLUENT (hereafter FLUENT). In doing so, the embankment is assumed to be filled with porous material to allow sinks of momentum and turbulence to be specified. This study is also made to validate the capability of FLUENT in tackling the behaviour of overtopping flow over porous structures, particularly flow interaction at the interface of the fluid/porous region, which needs further investigation.

Indeed, modelling a breaching dam due to overtopping using a porous medium approach leads to a new approach in dam break analysis. A physical-based numerical simulation of breach model was replicated to propose a dynamic simulation of breached embankments using a porous medium approach. Therefore, the 2D and 3D Eroding Models are developed to model the patterns of breach embankment by lowering the embankment based on observation made from the experiments. The failure mode resulted exclusively from overtopping and it was governed by predefined lines and planes acting as surfaces of the embankment. Moreover, the porous eroding model has the capability to react instantly to the embankment surface failure to produce breach discharge.

1.2 Problem Statement

In practice, any dam or embankment that was designed and built to prevent flood, is in fact, acting as a boundary for an inundation area. When water has reached the embankment boundary, up to a maximum limit, the surplus capacity of water from the reservoir that spills over its banks may cause a collapse of the embankment. This is known as a breached embankment. The embankment is breached when part of it actually breaks away, creates a brink, and then allows a large opening for water to pass through it to flood the downstream valleys. The failure mode, whether sudden or gradual depends on the mechanism of the breach i.e. surface erosion or subsurface failure. For overtopping failure, the embankment surface has a potential to be eroded first rather than sudden breach i.e. due to piping, resulting the stored water washing out to downstream, thus causing catastrophic flooding. Indeed, with the urban and the increased frequency of extreme flood events, the behaviour of flood defences under these extreme conditions need to be investigated.

The historical local event of embankment breach happened in Malaysia was in 1883. The failure of the Kuala Kubu Dam destroyed the Kuala Kubu city in Selangor. The original Kuala Kubu Dam was established in 1780s to reduce the depth of the river for tin mining activities. The dam was about 1.6 kilometres long and over 91.4 meters wide. In 29 August 1883, a heavy downpour caused the dam to burst, which resulted in massive amounts of water flooding into Sungai Kubu. The embankment failed and as a result, the water flooded onto Kuala Kubu town and its surrounding area. The event killed 33 people and destroyed 38 houses. After 1883 event, there is no embankment or dam failure occurred but there are some incidents happened. The latest dam breach happened in October 2013 where 4 people deaths due to excess water released from the Sultan Abu Bakar Dam in Pahang during the Monsoon (DID, 2017). Meanwhile, the most dramatic examples of embankment breach were happened in South Fork Dam (1889) in Pennsylvania (USA), the breaching of Nanak sagar Dam (1967) in India and the worst failure in history was the breaching of Banqiao Dam (1975) in China (Zhu, 2006). The failure caused enormous losses to both human lives and economic properties. Figure 1.1 shows the images of the dramatic historical embankment failures due to overtopping flow.



(a) Banqiao Dam (1975) (b) South Fork Dam (1889)

(c) Nanak Sagar Dam (1967)

Figure 1.1 Dramatic historical embankment failures due to overtopping flow

Since the 1980s, computational methods have been in widespread use for routing floods caused by dam failure, and advanced 2D modelling capabilities are now popular. Most of these instruments are still focused on basic parametric representations of the flood wave-initiating breach occurrence. A user specifies the ultimate distance, depth and shape of the breach and the time needed for the development of the breach, and the model simulates the flow at the defined rate through the breach as it enlarges. For examples in BREACH, DAMBRK, BEED, etc. (Singh, 1996). The BEED model has been developed for earthfill dams to simulate the breach erosion. It incorporates the processes of surface erosion and slope sloughing to simulate breach enlargement (Singh et al., 1988). Moreover, efforts have been carried out by USDA and HR Wallingford in the United Kingdom, leading to advances in the field via two large projects: CADAM and IMPACT. Even though the projects were started years ago there is still poor understanding of erosion mechanism and a need for re-evaluation (Wahl, 2009).

The use of numerical modelling of free surface flows associated with breaching phenomenon is a fairly recent development in the field of river engineering. An analysis that includes fluid mechanics and embankment erosion is a complex problem, especially when defining boundary conditions to be coupled between flow and soil for hydrodynamic interaction. Aware of this concern, researchers have developed models to study breach problems and to produce the breach discharge hydrographs, leading to an extensive study of characteristics of breach models up to date. However, the available data on the numerous historical earth dam failures from the literature were limited and uncertainties, and sometimes contradictory to the source data of the same dam failure cases due to unreliable eye-witness reports (Wahl, 2004; 2009).

The knowledge of breaching processes in embankments is still in need of exploration, even though many scholars have come out with analytical, mathematical and experimental works. It is still uncertain which method could provide the best solution to describe the breaching process experimentally and numerically, in particular to predict breach discharge hydrographs, in view of the complex breach processes involved. The first version of the sandy embankment breach model studied by Visser (1998) gave a reasonable agreement with field data at the first stage of the breaching process, but it overestimated the breach growth at the end of the process. The results, however, provide improvement of breach models such as SIMBA, WinDAM and many other commercial models that have been developed by European and United State consortia (Hanson et al., 2005; Hassan et al., 2004; Temple et al., 2006). None of the models developed were able to model the breach hydrodynamics of the breach progression.

Thus, in 3D breach models, the headcut is constructed as an initiation to the breach so that the breach widening can be simulated laterally. As it was subject to flow, the headcut advances upstream along the embankment crest and at the same time vertically erodes the embankment. The growth process is modelled exclusively to investigate a process of surface erosion through a combination of vertical, lateral and headcut advance. This is not well understood at present because of the dynamic flow of the breach that triggers the erosion.

1.3 Aim and Objective of the Study

This study is aimed at understanding and analysing the flow characteristics associated with breach formation of a porous medium. The porous breach model to known later as an Eroding Model is developed to evaluate the ability of a CFD code, FLUENT, to model breach embankments and predict the breach discharge hydrograph and volume lost during the failure. To achieve the aim, several objectives are outlined as follows:

1) To investigate the processes involved in earth embankment breach through laboratory experiments including the effects of embankment slope, inflow rate, sediment gran sizes and breach widening. The experimental result is compared with FLOW-3D model.
2) To analyse and validate flow characteristics of overtopped embankments described by a Rigid Model compared to Intact Model to get a relationship of velocity profile, pressure distribution and shear stress profile at the interface of a porous and a rigid embankment.
3) To develop a two-dimensional computational model of an eroding embankment with specific feature of analysing free surface flow, breach patterns and breached outflow hydrograph during embankment drawdown.

4) To develop a three-dimensional computational model to simulate and study the breach characteristics from various type of headcuts.

1.4 Scopes of Study

Computational methods have been in widespread use for routing floods triggered by embankment failure. In the present study, the terminology used for each model development may refer to Section 1.8. The scopes of the study are:

(a) The physical model is conducted using a straight channel with a dimension of 12 m length, 0.5 m deep and 0.6 m width at the Hydraulics and Hydrology Laboratory, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia.

(b) The Eroding Model is developed to model a breach of a homogenous embankment dam. In the proposed model, it has been assumed that the embankment is not covered with grass on the downstream surface to allow water to flow freely at the embankment crest.

(c) The storage capacity of the reservoir is determined by input velocity at the inlet where the water is pumped from that point. This setup will keep the velocity rate at the inlet the same, resulting in a reduction of the reservoir water level as breaching takes place. This approach, however, is useful to predict the breach discharge hydrograph, especially with data of reservoir water surface which sometimes is inconsistent with the reported outflow hydrograph.

(d) ANSYS-FLUENT is used to model the eroding porous embankment and validated with FLOW-3D software.

(e) The initial width, depth and shape of the breach and the time required for breach development are defined by the user.

1.5 Research Questions

In dealing with a fluid-structure interface, there is still a gap to model the breach embankment using a porous media approach accurately due to shearing stress and flow infiltration effect between the interface layer of porous medium and water. There are a few research questions need to be addressed;

(a) What are the parameters that influence the breaching embankment?

(b) What is the method to be adapted to model an Eroding Porous Embankment to analyse the breach flow characteristics?

(c) What is the correlation factor to model the erosion using a porous embankment due to slip boundary at water-soil interface?

(d) What are the outputs of different types of headcuts to initial breach for Eroding Model developed?

(e) Does the Eroding Model able to visualise breach patterns, breach flow characteristics and quantify the amount of breach discharges in 2D and 3D applications?

1.6 Significance of Study

Many scholars understand the important mechanisms that may trigger the collapse of an embankment dam. Dynamic interaction between the soil properties and the hydraulic behaviour of overtopping that causes instability of the soil is one of the main factor that warrants great attention to avoid the embankment collapses. One has to keep in mind that the failure of high-water defences has been an immediate cause of many inundations. The rate of inundation is theoretically governed by the discharge rate through the breach, which depends on the process of breach erosion. The breach discharge rate is the most important parameter for any modellers and policy makers when investigating the failure of an embankment. In any failure observations, it is crucial to be able to produce observed breach discharge hydrographs, not only to investigate the mechanisms that trigger the breach, but also to identify detailed breach patterns and predict the breach discharge.

Since the 1980s, models that simulate real erosion processes have also been available to predict breach growth in embankment dams, but have not seen widespread use. Most of these models were focused on primitive simplifications of erosion and breaching processes that, in case studies and experimental experiments, have proven to be inconsistent with subsequent findings of breach mechanics. A lack of ability to calculate the erodibility of embankment materials and a deficiency of models that efficiently integrate accurate erodibility measures has limited the implementation of the models. The need for enhanced modelling of embankment dam erosion and breach procedures is now motivated by many factors. Risk populations in areas directly below large dams continue to grow, the significant effect of warning time on flood effectiveness has been recognised. Also, the procedures for risk assessment are increasingly being used to cost of preventing in dam protection. Therefore, breaching process and breach phase modelling helps to address both of these needs by enhancing ability to predict the breach discharge hydrograph and timing of the dam breach discharge.

Thus, fundamental studies on breach discharge characteristics using a porous medium approach is an alternative to investigate how overflow may affect the embankment structure leading to lowering of the embankment and then visualise them in 3D applications. The proposed approach is a new method to analyse breaching embankments, particularly in analysing hydrodynamic flow over the breaching area and producing breach discharge hydrographs. It benefits to policy makers and government authorities in hazard mapping planning guidance for emergency evacuation.

1.7 Model Limitations

The present study consists of laboratory works and a numerical model development. The physical model is tested based on the erosion mechanism that causes the embankment to fail. However, due to the large complexity in driving the erosion process into the model development, the Eroding Porous Model only focuses on constant erosion rate for each time of breaching specified. In order to develop a linear erosion model of a lowering embankment, understanding the possible effects of using a variable erosion rate and time to breach are tested.

1.8 Terminology

The following terminology is to be used throughout the text.

(a) Zone – is a grouping of nodes, faces and cells, for examples the wall boundary zone and fluid cell zone.

(b) Domain – is a grouping of cell zones.

(c) Rigid Model – where the embankment is modelled using walls boundary condition without the embankment (the shape of the embankment is defined as rigid walls).

(d) Intact Model – where the embankment is modelled using a porous embankment. The model can be modelled either using a sub-domain or 1-domain approach.

(e) Porous embankment – where the embankment is present as a porous media, which has a porosity and resistance.

(f) Sub-domain approach – where the embankment domain is fixed and modelled using a porous medium. Breach patterns does not allow for the deposition process.

(g) 1-domain approach – where the embankment domain can be placed everywhere in the domain. Breach patterns does allow for the deposition effect.

(h) Eroding Model – where the embankment is modelled using a porous embankment, the extent of which is defined by a number of lines or planes. The line or planes can be moved with time.

(i) Non-deposited Eroding Model – where the breached embankment does not consider the sediment deposited. The model uses the sub-domain approach.

(j) Deposited Eroding Model – where the breaching embankment considers the sediment deposited downstream using 1-domain approach.

1.9 Thesis Outline

This chapter provides an overview of the study, consisting of the aims and objectives to be achieved. These include the importance of the study, the problems underlined throughout the study to be addressed and improved, and the methodology used to model a breaching embankment using the new porous medium approach. Chapter 2 presents a general theory of flow over hydraulic structures in open channels and reviews some studies of breaching embankments due to overtopping both in experimental work and numerical modelling. Most of the breaching embankment literature identify erosion as the main mechanism of collapse and a few papers discuss breach patterns. Reviews on the evolution of breach progression are less widely discussed. Also, it describes the numerical modelling techniques using the CFD package, FLUENT. The choice of mesh resolution, initial and boundary conditions, turbulence models, and multiphase models are discussed.

Chapter 3 explains the methodology to model an eroding porous embankment using a delimiter line approach in lowering the embankment in 2D model. A description of delimiter lines (predefined lines) and their movement via translation and rotation are presented step-by-step. A similar approach is used to determine a lateral breaching for a 3D Eroding Model. In contrast to the 2D model which uses lines to define the extent of the embankment, the 3D model uses planes to describe the embankment surfaces.

Chapter 4 discusses the results of breaching mechanisms in a laboratory. Parameters such as the effects of embankment geometries, hydraulic characteristics and soil grain sizes leading to the breaching are analysed. Breaching outputs such as embankment volume lost, breached patterns, breached hydrograph and breached velocity are also analysed and compared with FLOW-3D. Sensitivity analysis on CFD techniques to simulate a Rigid Model and Intact Models (sub-domain and 1-domain approach) are carried out. These are: using walls to model the embankment and using a porous region by predefined three delimiter lines to model the porous embankment. The results such as free surface profiles, velocity, pressure and wall shear stress are discussed and compared with Fritz and Hager (1998), that investigated flow over a rigid embankment.

Chapter 5 presents the results of Eroding Models using the delimiter line method to model eroding embankments in 2D. The results of eroding models including breached outflow hydrographs are then discussed and model validations are made against data of two series of experimental work: non-deposited and deposited models of Lüthi (2005) to replicate a pattern of breached embankments. In the 3D Eroding Model results, breach flow characteristics in terms of free surface, velocity profile at breach, embankment volume lost, breach discharge hydrographs and breach shape are presented and validated with FLOW-3D.

Chapter 6 presents a conclusion of the study and highlights a few recommendations of model improvement for future research.

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LIST OF PUBLICATIONS

List of Indexed Journals

1. **Zainab Mohamed Yusof**, Ahmad Khairi Abd. Wahab, Zulhilmi Ismail and Shahabuddin Amerudin (2020) Soil Erosion Morphology of an Embankment Failure. *In IOP Conference Series Proceeding publication: Material and Science Engineering, 5th International Conference and Advance Technology & Applied Science in Conjunction with 6th Malaysia-Japan Joint International Conference (ICaTAS 2020)*, Issue 1051, Paper No. 012045, pp 294 - 302 (Indexed by Scopus).
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3. **Zainab Mohamed Yusof**, Ahmad Khairi Abd. Wahab, Zulhilmi Ismail and Shahabuddin Amerudin (2021) 'Erosion Morphology of a Breached Embankment Due To Overtopping Flow', *International Journal of Integrated Engineering (IJIE) - Special Issue 2020: Micropollutant Research Centre (MPRC)*, Penerbit UTHM (In Press – Indexed by Scopus).
4. **Z. Mohamed Yusof**, M. F. Mohd Mokhtar, A. K. Abd. Wahab, Z. Ismail and S. Amerudin (2021) *Breached Hydrograph Analysis of Kaolin Embankment Failures*. In Community, Environmental and Disaster Risk Management (CEDRM) Book Series: Sustainability and Water Quality Assessment Techniques – An Insight in Asia, through 4th International Conference of Water Resources (ICWR 2018), Vol (25), Emerald Publisher (Accepted for Correction – Indexed by Scopus).

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1. **Zainab Mohamed Yusof**, Ahmad Khairi Abd. Wahab, Zulhilmi Ismail and Shahabuddin Amerudin (2020) Soil Erosion Morphology of an Embankment Failure. *5th International Conference and Advance Technology & Applied Science in Conjunction with 6th Malaysia-Japan Joint International Conference (ICaTAS 2020)*, September, Kuala Lumpur.
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