EVALUATION OF HYDRAULIC PARAMETERS EFFECTS ON THE STABILITY OF DIKE EMBANKMENT DURING SPATIAL OVERTOPPING TESTS

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by

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LIST OF ABBREVIATIONS

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
AEV	Air Entry Value
ASCE	American Standard of Civil Engineers
ASTM	American standard for Testing and Materials
BSCS	British Soil Classification System
DST	Direct shear test
FOS	Factor of safety
FEM	Finite element method
FEMA	Federal Emergency Management Agency
GLE	General limit equilibrium
HAE	High Air Entry
HERU	Hydraulic Engineering Research Unit
LEM	Limit equilibrium method
LL	Liquid limit
ML	Low plasticity silt
OWC	Optimum Water Content
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USDA	United States Department of Agriculture
PWP	Pore water pressure

PSD	Particle size distribution
PL	Plastic limit
PI	Plasticity index
SWCC	Soil Water Characteristics Curve
SSR	Shear strength reduction
SP	Poorly graded sand
SML	Very silty sand with low plasticity silt
VWC	Volumetric water content
WRC	Water Retention Curve
kPa	Kilopascal pressure unit
lbs	Pound

LIST OF SYMBOLS

β_1	Constant side-slope angle
σ'	Effective normal stress
σ	Total normal stress
u_w	Pore water pressure
u_a	Pore air pressure
ψ	Matric suction
θ_n	Normalized water content
θ_r	Residual water content
θ_w	Volumetric water content
θ_b	Air entry value
λ	Pore-size distribution index
$\mathbb{S}_e$	Dimensionless Degree of saturation
$\mathbb{S}_r$	Residual degree of saturation
S_r	Degree of saturation
α	Function of the Air entry value
n	Slope of straight line segment in SWCC
m	Parameter control the residual water content
α_1	Curve fitting parameter
b_1	Curve fitting parameter
a_ψ	Curve fitting parameter
$C(\psi)$	Correction factor

k_w	Hydraulic conductivity for a specified water content
k_s	Saturated coefficient of hydraulic conductivity
k_{sat}	Saturated hydraulic conductivity
i_ψ	Hydraulic gradients
k_x	Coefficient of hydraulic conductivity in *x*-direction
k_y	Coefficient of hydraulic conductivity in *y*-direction
Q	Applied boundary flux such as evaporation, infiltration etc.
m_w	Slope of SWCC
τ	Shear strength of the failure plane
ϕ'	Effective angle of internal friction
c'	Effective cohesion
σ_n	Normal stress
σ'_n	Net normal stress
χ	Parameter assumed to represent the degree of saturation
q	Deviator stress
p'	Net mean stress
P	Vapour pressure of the air
P_o	Saturation vapour pressure at sample temperature
M	Slope of the failure
ϕ^b	Contribution to the shear strength due to matric suction
σ_1	Major principle stress
σ_3	Minor principle stress
τf	Shear strength of soil

τ_{mob}	Mobilized shear strength
c'_f	Effective cohesion parameter
$\emptyset'_f$	Effective internal friction parameter
ϕ'	Angle of slope failure
pW	Unit weight of water
RH	Relative humidity
R	Gas constant (8.31 J/mol K)
S	Total suction
°C	Celsius
°F	Fahrenheit
R	Universal gas constant
T	Absolute measured temperature
T	Kelvin temperature of the sample
uv	Partial pressure of pore water vapour in the specimen
u_{vo}	Saturation pressure of water vapour over a flat surface of water
b, r, m	Parameters of pore size distribution
x	Integration variable
M	Molecular mass of water
N_s	Base normal force of slice
W_x	Slice weight
F_m	FOS equations with respect to moment equilibrium
F_f	FOS equations with respect to horizontal force equilibrium
K_α	Dielectric constant of mass soil

C	Velocity of light in free space
t	Transit time for an electromagnetic pulse
L	Length of the probe
Fr	Froude number
hc	Critical flow depth
t	Time [s]
s	Seconds
h	Total hydraulic head
h	Hour
i	Hydraulic gradient
K	Hydraulic conductivity
$Q_{\circ}$	Inflow discharge (l/min)
Q	Volume flow rate of fluid
A	Cross sectional area

PENILAIAN KESAN PARAMETER HIDRAULIK TERHADAP KESTABILAN BENTENG TAMBAK SEMASA UJIAN LARIAN ATAS RUANG

ABSTRAK

Pembinaan benteng sungai sering dibina disebabkan oleh fungsi dan pontensinya dalam melindungi penduduk dan harta benda daripada kegagalan larian atas. Semasa kadar alir sungai yang tinggi, paras air boleh melebihi tinggi banteng dan menyebabkan kadar air larian atas. Feonomena ini menyebabkan kegagalan yang besar terhadap badan banteng disebabkan pengurangan kekuatan ricih tanah. Mekanisma ini melibatkan peningkatan kandungan air di dalam butiran tanah dan hubungkaitnya dengan pembentukan kegagalan saluran pelanggaran di hiliran dan huluan cerun adalah dipengaruhi oleh pelbagai aspek geoteknik dan hidraulik seperti kadar alir masuk, sudut cerun benteng, dan jenis tanah yang digunakan untuk benteng. Parameter ini perlu diambilkira di dalam kajian ini melalui eksperimen fizikal dan pemodelan berangka kegagalan larian atas. Beberapa siri pemodelan fizikal 2 dan 3 dimensi telah dijalankan terhadap model benteng homogen dibawah kesan parameter perbezaan kadar alir masuk, sudut cerun banteng dan jenis tanah. Fasa pertama kajian ini memberi tumpuan kepada pembentukan tekanan air liang dan kandungan air volumetrik kepada beberapa kumpulan titik sensor yang teragih disepanjang huluan dan hiliran cerun banteng. 12 sensor tensiometer dan domain masa reflektometer telah digunakan untuk mengukur magnitud tekanan air liang negatif (sedutan air) dan kandungan air volumetrik. Keputusan ujian eksperimen fizikal tersebut menunjukkan keberkesanan parameter yang digunakan bergantung kepada lokasi kumpulan sensor yang diletakkan dan juga sensor di cerun huluan yang menjadi tepu dengan sangat cepat. Fasa kedua eksperimen meliputi ujian larian atas 2-D untuk menyiasat penyusupan air pada arah menegak dan mendatar semasa proses peralihan paras air daripada hujung cerun huluan kepada permulaan puncak benteng. Paras air menepu badan benteng dengan lebih pantas pada arah mendatar berbanding arah menegak. Peningkatan paras air yang sangat laju juga mempercepatkan langkah permulaan kegagalan saluran pelanggaran pada puncak dan juga keadaan ketidakstabilan pada cerun huluan dan hiliran. Fasa ketiga pula meliputi pembentukan proses hakisan secara menegak dan mendatar semasa kegagalan benteng dimana dua kamera digital diletakkan dihadapan badan benteng dan juga di cerun hiliran untuk menangkap kegagalan secara hakisan tersebut. Hasil keputusan kajian menunjukkan kegagalan dominan di saluran rintis dan juga bahagian atas hiliran cerun adalah dalam bentuk hakisan secara menegak dan pembentukan kegagalan pada bahagian tengah benteng dan cerun huluan adalah disebabkan hakisan secara mendatar. Resapan sementara dan juga analisis kestabilan cerun telah dijalankan menggunakan kaedah unsur terhingga 2-D dan juga pengukuran bersandar masa dibawah kesan sudut cerun banteng dan jenis tanah. Pada masa kini, kaedah pemodelan berangka melalui pemodelan 2-D unsur terhingga tidak dapat secara matematik mensimulasi proses hakisan secara fizikal yang menyebabkan kegagalan larian atas benteng. Hasil keputusan analisis berangka menunjukkan partikel halus menyebabkan peningkatan kandungan air dan juga mengurangkan faktor keselamatan benteng. Rekabentuk benteng yang bersesuaian dan penyelenggaraan adalah bergantung kepada keadaan persekitaran hidraulik, dimensi dan jenis tanah benteng. Cerun bentung yang lebih landai dengan bahan banteng tanah tidak berjeleket adalah dicadangkan hasil daripada kajian ini.

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ABSTRACT

River dike construction has been widely used because of its potential in protecting people and properties from overtopping flow. During high discharge of a river, water level may exceed a dike crest and causes overtopping flow. This phenomenon has caused a large damage on dike body due to the reduction of soil shear strength. This mechanism involved an increase in water content within particles and its relationship with the development of breach channel failure in downstream and upstream slopes are affected by a series of geotechnical and hydraulic aspects, such as inflow discharge, dike slope and soil type, caused by overtopping failure. These parameters had been investigated in this study through physical experiments and numerical modelling during overtopping failure. A series of 3D and 2D physical modelling is conducted on a homogeneous dike embankment under the effect of inflow discharge, dike slope angle and soil type parameters.

The first phase focused on the development of pore water pressures and volumetric water contents for groups of points distributed along the upstream and downstream slopes of the dike embankment. Twelve tensiometer and time-domain reflectometer sensors were used to measure the magnitudes of negative pore water pressures (matric suction) and volumetric water contents. Physical experimental tests showed that a high inflow discharge resulted in a rapid increase in the amount of water content and a decrease in matric suction inside soil particles due to a high water velocity, whereas a

gentle slope and coarse sand soil increased the rate of water saturation. The second phase of the experiment involved a 2D overtopping test to investigate the water level infiltration in vertical and horizontal directions during the transition of the water level from the toe of the upstream slope to the beginning of the dike crest. The dike body was more rapidly saturated by the horizontal water level than by the vertical water level. The velocity of the two water levels increased the initiation of the breach channel failure in the crest and the instability state in the upstream and downstream slopes. The third phase included the progression of vertical and horizontal erosion processes during the dike breach failure. Two digital cameras were installed in front of the dike body and the downstream slope to capture the mechanism of failure caused by erosion. The dominant failure in the pilot channel and the upper part of downstream slope was vertical erosion, and the progression of breach failure in the middle of the dike and the upstream slope occurs because of horizontal erosion. Transient seepage and slope stability analyses (FOS) were performed using 2D finite element methods and time-history measurements under the effect of dike slope angle and soil type. The numerical model was limited by its inability to mathematically incorporate all physical processes governing an overtopping breach failure. The Numerical analysis revealed that a steep slope and fine particles increased the pore water pressure and reduced the FOS. Appropriate dike design and maintenance were dependent on surrounding hydraulic conditions, dimensions and soil types. A gentle slope and noncohesive materials with fine particles were preferable.

CHAPTER ONE

INTRODUCTION

1.1 Background

The dike is defined as a raised structure constructed from earth or other suitable material. A major benefit of river dike embankment construction is by ensuring the protection of lands from overtopping failure. The construction of river earth dikes can provide other benefits, such as drinking and irrigation, energy production and recreation purposes. The major effects of dike failure lead to high human casualties and substantial economic losses. Dike embankment failure worldwide occurs due to insufficient maintenance of dike components, soil properties, water discharge, insufficient spillway capacity and earthquakes. The earth-fill Bradfield dam in England has collapsed in 1864 due to overtopping failure and has caused the deaths of 238 persons. The Machhu Dam in India has been destroyed in 1979 due to the wave overtopping flow over the dam crest and has caused deaths of nearly 2000 people (Gee, 2008). The water level infiltrates the body of dike embankment and gradually reduces the resistance of soil materials due to the dike positions in preserving water in front of the upstream slope. The water level increases the water content and decreases the negative pore water pressure during water transmission in the dike crest. The overtopping flow results in the initiation of breach in the dike crest and moves down in the downstream slope. Subsequently, the erosion is extended in the upstream slope. The behaviour of dike “breach” failure is analysed by using either empirical or experimental methods. The empirical methods include different differential equations to approximate the breach channel discharges. The experimental tests investigate the mechanism of breach channel failure in small and large flumes. Although considerable effort has predicted the characteristic behaviour of dike embankments during overtopping failure, the effects of pore water pressure and volumetric water content and their correlations with the stability analysis of dike embankment and the initiation and advancement of erosion in the downstream and upstream slopes remain unclear. In this study, the effects of pore water pressure, volumetric water content and the infiltration of seepage flow in increasing the water saturation inside the soil particles are investigated. The mechanism of vertical and horizontal erosion processes is evaluated by using digital cameras under different hydraulic and geotechnical parameters. A slope stability analysis is conducted to assess the capability of dike slope to withstand against the gradual increase of water level in the upstream slope and dike crest. The input parameters of soil properties of cohesion and friction angle, soil water characteristic curve functions (SWCC), saturated hydraulic conductivity and dike geometry are required to calculate the accurate value of the minimum FOS. The results of the parametric tests are obtained in the laboratory. This study mainly evaluates the behaviour of water content saturation and the development of erosion, which will be discussed in details in the following section.

1.2 Problem statement

The river embankments are constructed to withstand against the water flow in rivers or lakes. They are subjected to different types of failures, such as overtopping, piping and side slope. These failures increase the rate of water flow seepage inside the particles of dike embankment and result in dike slope instability. The overtopping failure leads to gradually saturate the soil particles and may cause initiation of erosion process inside dike embankment. The erosion process is grouped into four distinctive mechanisms: concentrated leak, backward erosion, contact erosion, and suffusion. The suffusion mechanism is dependent on type of soil, soil texture while it occurs mostly in cohesion less soils such as poorly-graded materials for filter and drain layers and cores constructed from glacial tills (Bonelli, 2013). To analyse the effect of particle grain size for sand dike, three large-scale experiments were conducted at the Delft University of Technology (TUD) under constant head condition. The study stated that the larger grain sizes generally increases the erosion rate of sand dikes (Visser, 1998).

However, from series literature review that discuss the physical experimental tests, the author concluded that there is lack of understanding of how some important geotechnical and hydraulic parameters influence the development of matric suction, volumetric water content and the dike breach failure during overtopping failure. Examples of these geotechnical and hydraulic aspects include: different inflow discharges, different dike slopes angle for the upstream and downstream slope and soil types. These aspects are need to be considered in the physical experimental tests since they are govern the erosion process and side slope stability during overtopping failure. In this study, the comprehensive and extensive study on the effect of pore water pressure and volumetric water content and their relations with the development of water surface levels and the progression of erosion process inside homogeneous river dike have been analysed in details under the effects of inflow discharge, dike slopes angles and dike materials during spatial overtopping tests. The inflow discharges of (20, 30 and 40 l/min) represents the rate of water level in front of upstream slope that exposed higher pressure inside dike embankment. The increasing and decreasing of upstream and downstream slopes of (1V:2.5H and 1V:3H) has a direct relationship with the weight of dike embankment that resist the water pressure and the distributions of water flow seepage that saturated soil particles. The presence of fine particles of (coarse sand and very silty sand soils) governs the geotechnical properties of the non-cohesive dike embankments such as the hydraulic conductivity, permeability and porosity and thus control the time of overtopping failure occurrence and behaviour of erosion process.

Numerical models have been employed to simulate the breach failures of dike embankment during overtopping failure (Tingsanchali and Chinnarasri, 2001; Volz et al., 2012). These models use a series of differential equations in solving the nonlinearity behaviour of seepage mechanism at specified boundary conditions. The accurate prediction for the FOS is an indicator used for the stability of dike slope during water flow seepage (Li et al., 2009). Limit equilibrium and finite element methods are the common methods used to evaluate FOS through a numerical model. In this study, the numerical modelling was used to determine the development of pore water pressure and volumetric water content as well as the critical slip surface or FOS during overtopping under the effect of dike slope angle and soil type. The input parameters of shear strength and hydrological conditions are required in obtaining an accurate result prior to the determination of critical surface.

1.3 Objectives

This study conducts a series of physical experimental tests and numerical model, which aids in understanding the mechanism of seepage flow and erosion during overtopping failure. The thesis objectives can be summarised as follows:

1. To characterize the dike material properties by conducting a series of geotechnical laboratories tests.

The representative information for the dike embankment properties are essential prior to the physical overtopping test. A series of laboratory tests is required to identify the behaviour of a dike model during overtopping failure. Laboratory tests include sieve analysis, Atterberg limit, sand replacement method, constant head permeability, direct shear test and Dewpoint Potentia Meter tests. The sieve analysis and Atterberg limit tests were conducted to determine the soil classification of two soils used during overtopping tests. The constant head permeability was performed to identify the saturated hydraulic conductivity. The direct shear test was used to evaluate the shear strength parameter (cohesion and friction) while the WP4C test was used to determine the SWCC results. The results of sieve analysis, Atterberg limit, sand replacement method, constant head permeability and Dewpoint Potentia Meter tests are important in determining the water content distributions. The magnitudes of cohesion, friction and the pore water pressure (PWP), calculated from transient seepage analysis, are used to determine the slope stability analysis through the numerical model of SLIDE 2018.

2. To investigate the behaviour of dike embankment during spatial overtopping tests by incorporating the responses of matric suction, volumetric water content and water level distribution on a set of embankment dikes.

The responses of matric suction and volumetric water content are required to be understood due to their effectiveness on the behaviour of unsaturated soil during overtopping failure. During the transient seepage flow, the volumetric water content accumulates due to the water flow that occupies the soil particles in vertical and horizontal directions of the upstream and downstream slopes. This condition decreases the matric suction and influences the behaviour of unsaturated soil and slope stability. Therefore, different geotechnical and hydraulic parameters, such as inflow discharge, dike slope angle and soil type and their correlations with the advancement of water content inside the dike were analysed. A small flume channel composed of PVC materials is constructed for the physical overtopping tests. The flume channel is supplied with a flowmeter and a sediment box to simulate the reservoir water level in front of the upstream slope and to collect the eroded materials at the end of tests.

3. To evaluate the movement of vertical and horizontal erosion in the upstream and downstream slopes by using digital cameras during 2D and 3D spatial overtopping tests.

The initiation of breach channel failure occurs due to the overtopping flow the dike crest. This event usually decreases the binding forces between the particles and leads to the gradual erosion on the downstream and upstream slopes. The effects of fine particles on the progression of erosion are frequently ignored due to their complexity behaviour during overtopping. Therefore, the presence of fine particles (clay and silt) within the constructed dike were analysed with the use of digital cameras to capture the progression of vertical and horizontal erosion. The vertical erosion responses are obtained under the effect of inflow discharge, dike slope angles and soil types while the horizontal erosion responses are measured under the effect of dike slope angle and soil type. The development of breach channel failure is not incorporated due to the limitation of numerical modelling.

4. To assess the distributions of pore water pressure and volumetric water content and the stability of dike slope assigned with the transient seepage flow conditions by using the conventional limit equilibrium method

The slope model was assigned with transient flow conditions that start from the toe of the upstream slope and end at the end of dike crest to evaluate the responses of pore water pressure, volumetric water content and FOS analysis. Van Genuchten equations were used to estimate the hydraulic conductivity function and volumetric water content functions of unsaturated–saturated seepage flow prior to slope stability analysis. The FOS of the dike model was obtained by using the conventional limit equilibrium method. The determination of FOS is essential in determining the influence of geotechnical parameters on slope instability. The effects of dike slope angle and dike material were considered in seepage and slope stability analyses.

1.4 Scope of the work

The dike embankment failures due to the overtopping flow over the dike crest are responsible for devastating disasters, which include economical and human losses and are of prime importance to our society. The overtopping failure is considered the common cause of failure in recent earth and earth-rockfill dams, and the main causes of dike failures are increased flood discharges during the previous years and insufficient maintenance and repair. Considering the improbability of eliminating the overtopping failure, understanding the dam behaviour during an overtopping failure remains a challenge. This study addressed the effect of governing hydraulic and geotechnical parameters on the mechanism of seepage flow and erosion under a series of 2D (Cruwez et al., 2018) and 3D (Altomare et al., 2018) spatial overtopping tests conducted at the Laboratory of Hydraulic and Civil Engineering in Universiti Sains Malaysia. Prior to the spatial overtopping tests, a series of geotechnical laboratory tests, such as sieve analysis, Atterberg limit field density, constant head permeability, direct shear test and SWCC test, was conducted to determine the dike embankment properties, and the latter was used as input parameters in the numerical analysis. This study extensively focused on the effect of inflow discharges, dike slopes angles and dike materials and their correlations with the advancement of matric suction, volumetric water content, water level infiltration and the widening of breach channel failure in the upstream and downstream slopes. Two types of dike soil were used to investigate the influence of fine particles (silt and clay) in the non-cohesive homogeneous dike embankment during 2D and 3D physical experimental tests. The tests were conducted in the small flume channel constructed from PVC materials equipped with sensors, digital cameras and flowmeter to simulate the behaviour of dike embankments due to overtopping failure. The sensors, which include a tensiometer and a time-domain reflectometer, are used to measure the negative pore water pressure and volumetric water content, respectively. The digital cameras were used to analyse the distributions of water infiltration levels and the progression of erosion processes. To complete the requirements of scientific research and the certainty in solving the seepage flow and slope stability problems, 2D seepage and slope stability analyses were conducted to determine the progression of pore water pressures and factor of safety (FOS) for the 1D dike physical model using the van Genuchten equation and limit equilibrium method. Only the effect of dike slope angle and dike materials was considered, and the effect of inflow discharge and erosion was not evaluated.

1.5 Research significance

In this study, the major importance of conducting a series of 2D and 3D spatial breach tests is by analysing the mechanism of seepage flow and erosion during overtopping failure in non-cohesive dike embankments through the determination of the combined effect of pore water pressures and volumetric water content and their influence on the initiation and widening of breach channel failure. This phenomenon was evaluated in depth under different geotechnical and hydraulic parameters to enhance the investigation of geotechnical engineering fields for dike embankment. To observe a fundamental process regarding the slope stability failure, a finite element numerical method was used to observe the seepage of water level inside the soil particles and its consequences in increasing the water content and reducing the shear strength of dike slope. The reduction of FOS analysis of dike slopes led to imminent economic and safety risk hazards. Thus, the investigation of slope behaviour failure could help the engineers to construct the dikes with proper dimensions and materials.

1.6 Limitations of the study

Despite the importance of conducting the physical tests and numerical modelling for analysing the mechanism of seepage flow and slope stability, the study have some limitations. Due to the characteristics of small flume channel and compaction method used during overtopping flow tests, it would be useful to conduct the 3D and 2D physical experiments in a wide hydraulic flume channel to analyse the behaviour of dike embankment model (matric suction and volumetric water content) and compared with prototype. Since the pilot channel is constructed in the side-wall of flume channel for measuring the responses of tensiometer and TDR sensors, the breach channel failure could be cut in the middle of dike embankment for evaluating the development of pore water pressure and the stages of erosion process.

1.7 Thesis outlines

Chapter 1: Explain the background of dikes embankments and the potential failures affecting them. The features of dike embankment, the inherent dangers in terms of economic and human losses due to overtopping failure and the description of slope stability analysis are briefly discussed. The scope and objectives of this research and the research significance are described.

Chapter 2: Literature reviews related to research objectives. The detailed depiction for the definition of dike embankments, types of dike materials and the historical construction of dikes are illustrated. The literature reviews focus on describing the overtopping failure mechanism and constructing a laboratory model due to overtopping failure. The fundamental and comprehensive theory for the mechanism of unsaturated soil is presented, and the behaviour of seepage flow functions is discussed in details. The identified research gap of this study is presented.

Chapter 3: Discussion on the detailed information of dikes, flume channel geometries and the physical experimental test setup for 2D and 3D spatial overtopping. The comprehensive methodologies in describing the unsaturated–saturated seepage flow and slope stability analyses and numerical modelling are explained in detail.

Chapter 4: Presentation of the results of soil classification, laboratory tests and the responses of negative pore water pressure, volumetric water contents and water level distributions determined by physical tests. The vertical and horizontal erosions constructed in the small flume channel are investigated. In addition, FOS analysis is performed on the basis of stability analysis.

Chapter 5: Summaries of the conclusion of the research study with a list of references presented at the end of the study.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

The design and maintenance of dike construction have considerable impact on people's lives and properties (Kakinuma and Shimizu, 2014). These design include the observation of the erosion occurrence inside the dike during overtopping failure (Mizutani et al., 2013). Overtopping failures occur when water flow over the downstream slopes and continues until dike height gradually reduced due to erosion. During this process, water velocity increases (Visser, 1998). Dikes is an earthen embankment (gravel or sand materials) used to protect endangered regions and their population from seasonal floods. The dike body is much smaller than the dam and they are used for the protection of sea, river and lake water. The shape of dike embankment is trapezoidal with different geometrical dimensions and material characteristics provide their water retaining capacity. The most important dike elements are crest, outer slope (downstream slope) and inner slope (upstream slope). The crest of a dike is the highest part of it. Its height is depending on the design water levels, the increase of high water levels during the expected lifecycle of the construction, the local increases in the water levels and the strength properties of the soil that may lead to a settlement (TAW, 1999). The upstream slope is directly related with the sea or lake dike whereas it could resist the loading that is caused by the waves. The angle of the upstream slope has direct relations with the seepage of water flow and slope stability.

The presence of downstream slope is also important to overcome the wave of overtopping flow or during long period of precipitation. It is also essential in reducing the effect of lateral stability especially in cases of very high water levels. Due to the construction of dike embankment separate between the river and land, they are supposed to different failure modes due to water wave. Foster (2000) investigated different failure modes for most popular dike embankment prior to 1986. He stated that 136 dikes are failed out of 11.192 with average failure frequency of 1.2%. Other studies conducted by ICOLD, for 135 dams with more than 15 m height, imply that 72% of earthfill dikes and 28% of concrete dame were failed. There are four main causes of failure for dike embankment; overtopping, piping, erosion, seismic loading and slope instabilities. According to Singh (1996), the most common failure of dikes and earthfill dams is overtopping. For the past 300 years, 2,000 human lives have been lost from the collapse of earthfill embankments (Tsakiris et al., 2010). The embankment breach flow is one of the common problem occur in Bangladesh because of the unique topography, river system and rainfall pattern over the year. The mean annual rainfall within Bangladesh varies from 1250mm to 5700mm.

Over the years, the river channels are silted up with sediments composed of fine sands and silts causing a block of river flow and thus resulted in overbank flow and embankment failure. In Japan, most of the dike breach flood disasters occurred by heavy rainfall. In 2000, the heavy rainfall attacked Nagoya metropolitan area, and the city perfectly loss the function. In 2004, 10 typhoon hitting Japan islands due to heavy rainfall and caused dike breach at many rivers whereas more than 200 people were killed (Islam and Tsujimoto, 2012). Flood are common occurrence in Malaysia, but the recent monsoon flood from December 2014 to January 2015 was regarded as one of the more devastating flood to hit Malaysia in recent decades, with more than

10000 flood victims evacuated from their homes (Ismail and Haghroosta, 2014). In Sabah, Malaysia, the main factors causing slope failure (including embankment) are natural (geology, meteorology, topography and drainage system and human factors (lack of proper planning, human activities and communities' attitude) whereas failures in embankment are higher compared with other failures in rock slope (Roslee and Tongkul, 2018). .Floods usually occurs in Indonesia due to the local rainfall overwhelms the drainage capacity of the local canals and thus cause the local canals to overtop. However, the most dangerous overtopping embankment failure of January 2013 occurred in Jakarta due to the overtopping failure effect on WDC at Laturharhari and resulted in sending deluge of upstream water into the city centre whereas 41 deaths ensued (Bricker et al., 2014). Erosion is the main cause of dike failure (Al-Riffai and Nestor, 2011). Morris et al. (2007) suggested that the relationship between matric suction and volumetric water content during overtopping failure depends on various geotechnical and hydraulic properties of the dike soil, such as water content and dry density. Table 2.1 shows that overtopping failure is the main cause of huge losses in people's lives and finances. The breach channel is extended in horizontal and vertical directions up to the upstream slope as shown in Figure 2.1.

Table 2.1: Selected dike failures due to overtopping flow (Singh and Quiroga, 1988; Weiming et al., 2011; Serre at al., 2017)

Date	Name	Fatalities
1889	South Fork Dike, Massachusetts	2200
1972	Orós Dike, Brazil	125
1975	Banqiao Dike, China	85600
1979	Machhu II Dike, India	2000
1998	Yangtze River Dike, china	‹2000
1999	Languedoc Dike, France	36
2005	New Orleans dike, USA	1118
2010	Vendée dike, France	41

Figure 2.1: Side view of final breach channel on downstream slope (left) Morris, 2002b (right) Morris, 2002c

The types of dike embankments include river dikes, coastal dikes, earthfill dams and rockfill dams. The dangerous of overtopping failure for dike embankment is dependent on scale of earthfill dike, dike materials, height of reservoir water level in the upstream slope, loss of life and economic loss. Between 1900 and 1969, the percentage failure rate for earthfill embankments constructed in Western Europe was 1.2%, second only to buttress dams, while 74% of construction failures were attributed to earthfill dikes in China and other parts of the world (Costa, 1985). Dike embankment heights are directly related to potential failure, whereas about 83% of dike failures in the US occur in dike embankments lower than 15 m (Zhang, 2009). Small reservoir size can also be considered a high risk for embankment breach during overtopping failure. The Archus Creek Dam, which is 7 m high, was breached by a five-year return period storm which produced only a little amount of precipitation (11 cm) for a few hours (Newhouse et al. 2010). Overtopping failures also increase the potential hazards of dike embankments, with hazards categorised as low, significant and high, as shown in Table 2.2 (FEMA, 2004). Breach channel failure increases the possibility of potential hazards. Of the 85,000 dams in the US, more than 15,000 have high risk hazards, while approximately 4,000 dams are considered unsafe (ASCE, 2009). An accurate analysis of potential hazards requires flood mapping and hazard mitigation teams and insurance and asset management companies to assist in hazard assessment and prevent risks

Table 2.2: Hazard potential classification System (FEMA, 2004)

Category	Loss of human lives	Economic loss
Low	Non expected	Low; limited to owner
Significant	Non expected	Yes
High	Probable. One or more expected	Yes, although not necessary for this classification

This chapter provides an overview of the current literature related to the failure of dike embankment from overtopping, and it concludes with a description of dikes, dike materials and dike construction. Overtopping flow behaviours and regimes are highlighted, and two types of planar and spatial breach failures with selected physical experimental tests are covered. Finally, the mechanics of seepage flow in unsaturated soil, soil water characteristic curve (SWCC), shear strength and slope stability and its interaction with dike properties are demonstrated.

2.2 Description of dike construction and overtopping breach

2.2.1 Dike definition

A dike is an embankment constructed from earth or other suitable materials to prevent or reduce the effects of water damage on people and property, control flow in conjunction with a floodway and provide power generation and sediment retention (Costa, 1985; Foster et al., 2000). Dikes have simple construction designs and are constructed from loosely placed sediments like gravel, sand, silt and clay. Dikes have no cores, and surface seals are built into the embankment body that is temporarily exposed to high water pressure. Despite their similarities, dike and dams have major differences in engineering design and objectives, differences that play important roles in determining the main functions of these structures. Dike embankments are shorter compared to dams. Earth dams have generally larger upstream–downstream head differences compared to dikes (Zhu, 2006) as shown in Figures 2.2. Dikes usually have poor foundations because they are constructed on heterogeneous soil often taken from the vicinity of a river bed (Schmocker et al., 2011).

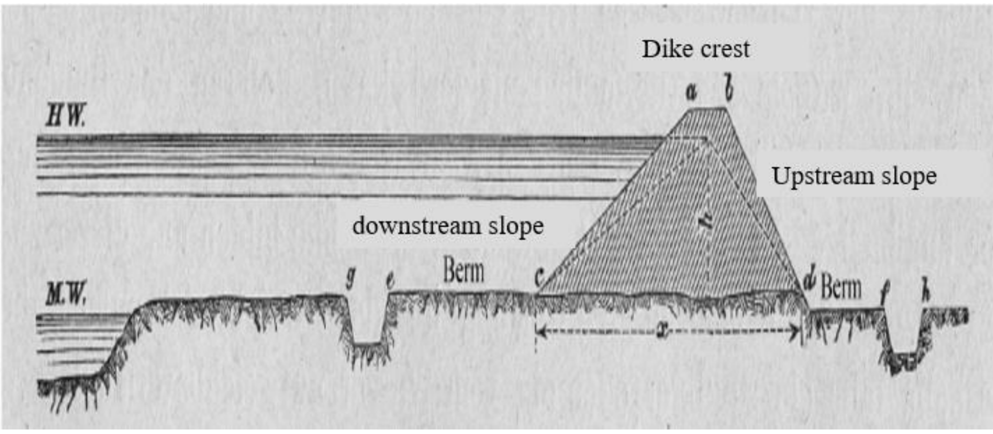


Figure 2.2: Component parts of dike embankment (Kreuter, 1921)

2.2.2 Characteristics of dike materials

A dike is usually constructed in a trapezoidal cross-section shape. The dike body is composed of earth-filled materials, such as cohesive soil (silt or clay), or non-cohesive materials (gravel or sand). Most earthfill dams are constructed with homogeneous materials, which increase the number of modern dams with impervious cores (Jansen et al., 1988). The preferred material for dike embankment construction is fine-grained soil, which is dependent on water content and the degree of compaction (Brown, 2004). Dikes can contain a homogeneous material, such as sand, or composite materials containing two or three types of soil. The dike body usually contains homogeneous sand or gravel or composite materials depending of dike design (Dupont et al., 2007; Wu and Wang, 2008). Seepage problems that start on the downstream slope of a dike embankment can also be decreased using drainage elements, such as toe drains, on the base of the upstream slope (Coleman et al., 2002; Pickert et al., 2004). The toe drain should be designed properly with appropriate particle gradation to avoid an increase in pore water pressure between different soil materials and prevent the migration of fine particles through overtopping failure as shown in Figure 2.3.

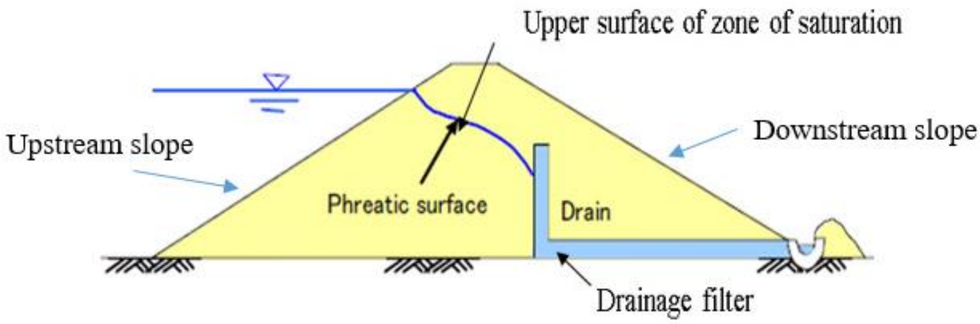


Figure 2.3: Homogeneous dike showing the upstream, downsteam slopes, and toe drain (Kunitomo, 2000)

2.2.3 History of dike construction

The dikes embankments have been constructed to prevent the occurring of overtopping failure (Xu and Zhang, 2009). The first dams were simple earth walls created from soil adjacent to rivers and oceans. Dikes, however, have been subjected to a series of dangerous failures due to deficiencies in knowledge on hydrology, hydraulics, and geotechnical information (Singh and Scarlatos, 1988). A dike is designed based on a location's record of the highest or most recent flood that occurred. Recent developments in river engineering have contributed significantly in constructing dikes with appropriate geometrical specifications, therefore increasing good services in navigation routes and protecting settlements and agricultural lands from flooding, as shown in Figure 2.4 (Albers, T. 2014).

Figure 2.4 Ancient dike's construction in California, USA, 1928 (Albers, T., 2014)

The first rudimentary dikes were built in Europe during the early Middle Ages, particularly in the 9th century on the Rhine River and in the 12th century on the Elbe River. In the Netherlands, the first dike was constructed in the 13th century. Large dikes with two simple fence walls backfilled with loose soil material were also being built in the Netherlands and Germany at the time. Dikes from the Middle Ages have varied soil content which originated from local barrow areas. Knowledge on the challenges and dangers surrounding dikes and the required engineering steps to counter failures developed during the 18th century. The first book to describe the construction requirements of dikes was first published by Albert Brahms (1692–1758), and it is still used as a reference today. The Linth structure in Switzerland was one of the most important water projects in 1784. It served as a diversion for the Linth River into Lake Walen and a canal between Lake Walen and Lake Zurich. The diversion was useful to overcome flooding, which threatened nearby towns, and protect agricultural land. Dike construction increased in the 19th century with the development of the steam engine, which revolutionised vehicles and construction equipment. Different canal constructions were initiated all around the world, such as the Suez Canal, which opened in 1869, and the Panama Canal, which opened in 1914. These canals have contributed primarily to water diversion projects. According to scientific curriculum and engineering designs, specific guidelines are used in the planning of dike construction (USACE 2000a), and the general shape of dikes has not changed over the years. Figure 2.5 shows a typical cross section of a dike embankment (DWA, 2011) with basic components, such as body, crest and land and water berms.

In the Netherlands, dike geometry characteristics are controlled by three main features: geometry of the sea, rivers and lakes. The forms of dike geometry differ from site to site and are primary dependent on the loading on these sites. Storms, with their short durations and high wave attack degrees, play a major role in shedding loads on lake dikes. The parts of a dike, such as its outer slope, crest height and revetment, should be designed properly to withstand the external water load. The inner slope and berm of river dikes should be well maintained to prevent piping failure resulting from long periods of high water loading.

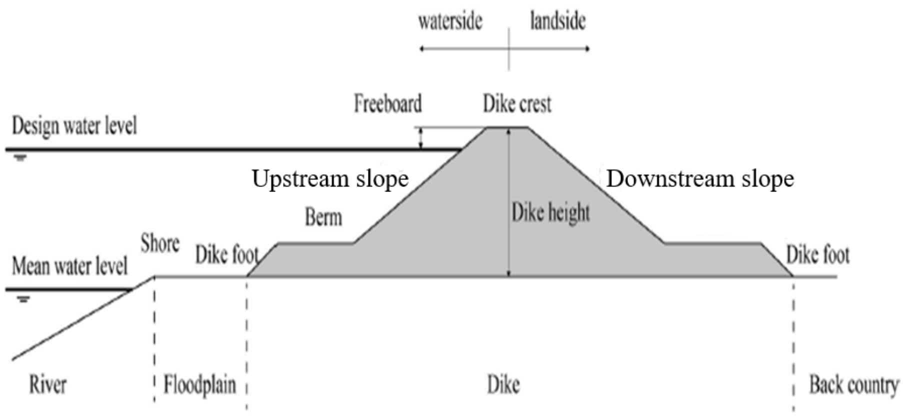


Figure 2.5 Dike's side view of dike embankment, DWA (2011)

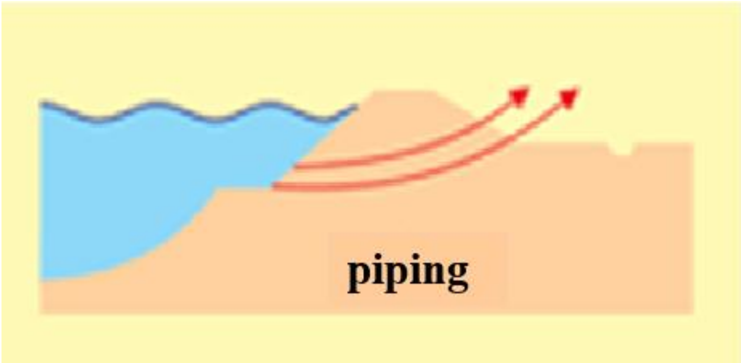
The revetment along the upstream slope prevents or reduces the effect of erosion on the widening dike breach channel. In the Netherlands, the different types of revetments are grass, rocks, blocks and asphalt. Dike geometry and classification play important roles in the distribution of revetment types. Aside from the usual single revetment, a dike can use a combination of two types of revetments, such as blocks with filters on clay, grass on clay and asphalt on sand. Design guidelines specify the information needed for dike construction (USACE, 1979; USBR, 1988). These guidelines also provide information on water level design to determine the freeboard and the required dike crest elevation. The dike cross-section is defined based on the crest width, dike slope and possible berms and maintenance tracks. Seepage control is controlled either by the dike body or by additional elements in the construction system, such as spillways (Kirkpatrick, 1977). Once all the above-mentioned information has been considered, dike stability, hydraulic and structural safety and usability should be determined.

2.3 Types of dike failure

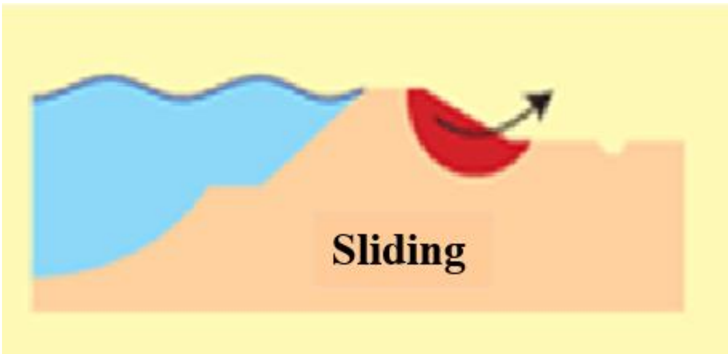
Increasing the percentage of water content inside dike's soil particles is occurred due to severe failures such as slope instability, earthquake loading, overtopping and piping. The causes of these failures is due to downed tree of on levee slope, animal burrows, Seepage through pervious levee material, Seepage following tree root paths, lack of maintenance, poor construction, poor spillway efficiency, earthquake, Corrosion and piping around riser and conduit, and the heavy rain. Although earthquake failure is uncommon, it induces an increasing internal pore water pressure and reduces the strength of materials and slope stability (Foster et al., 2000; Zhang et al., 2009). The collapse of soil could be occurred in downstream and upstream slopes and can lower the crest significantly. Piping failure is the penetration of water level inside dike soil due to the weakness of the upstream slope, consequently causing the successive removal of large particles along the base of dike embankment (Linsley and Franzini, 1964). A long path of water upstream starts inside the dike owing to increasing pore water pressure, and thus, backward particle erosion occurs at the toe of the downstream slope, helping to form conduits inside the dike (Omer, 2006).

Slope instability is one of the most common failures that occur inside dike embankments for upstream and downstream slopes during transient water flow and sudden drawdown. For the latter case, the sudden drop in water prevents water from flowing out of particles faster, consequently causing a slow reduction in water content. The failure occurs due to reduced soil strength for cohesive and non-cohesive dike materials. Therefore, understanding the behaviour of pore water pressure and matric suction under different types of soil is essential (Blight, 1997). The effect of rainfall infiltration on the saturation of saturated–unsaturated dike embankment models and leading to dike slope collapse has also been studied by researchers (Lumb, 1962; Mein and Larson, 1973; Sun et al., 1998; Thielen et al., 2005; Huang et al., 2014; Orlandini et al., 2015; Sumi et al., 2016). (Huang et al., 2014) have studied the mechanism of Chiuliao levee failure due to an extreme rainfall event during the Typhoon Morakot. They analysed the failure mechanism based on the variation in water levels in both sides of levee. They have observed main four failure mechanism. The first mechanism includes the determination of FOS of slope under the hydrostatic condition and various water levels.

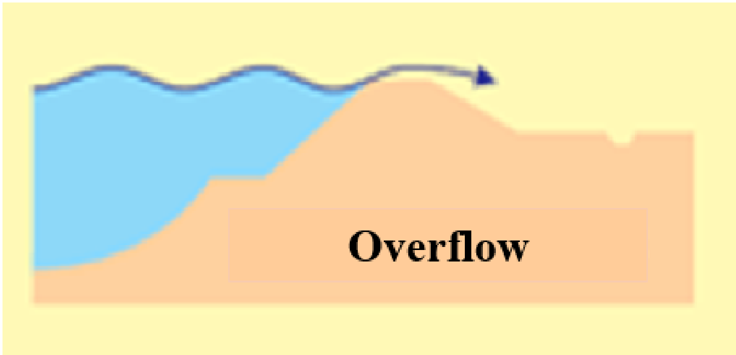
The FOS of levee slope is stable and cannot fail. The second mechanism includes the FOS analysis under steady state condition. The levee slope may fail due to attachment of water level near the levee crest. The third and fourth failures involves the sliding and overturning failure of levee foundation. The occurrence of sliding failure in levee foundation is highly predicted compared with overturning one. (Sumi et al., 2016) conducted series of vibration loading experiments for different moisture content to clarify the relationship between the volumetric water content with elapsed time after rainfall and the scale of slope failure. The rainfall behaviour were simulated using an artificial rain while model slope was subjected to seismic wave loading using a shaking table. The results show that the volumetric water content has a significant effect on the slope stability in which it leads to the occurrence of sliding failure and soil collapse when the percentage of water content is low. On the other hand, when the volumetric water content is high, the settlement failure in the dike crest is occurred without eroding the sliding surface. Continuous maintenance and risk evaluation can reduce the potential failure of dike slopes during the saturation of water infiltration (Aryal and Sandven 2005; Aryal et al., 2004). Figure 2.6 shows the sketches for overtopping flow, piping and sliding inner slope failures



(a)



(b)



(c)

Figure 2.6: Sketches of (a) piping failure; (b) sliding inner slope; and overtopping flow failures (Rebour et al., 2016)