IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Levee as a Flood Mitigation Option in Malaysia, Its' Susceptibility to Failure and Design Approach

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DOI: https://doi.org/10.30880/ijie.2019.11.09.024
Received 21 February 2019; Accepted 16 October 2019; Available online 31 December 2019

Abstract: Flooding is a major concern globally affecting many countries around the world, including Malaysia. As Earth undergo global climate change, intensified flood events are also expected to increase. One of the available structural flood mitigation measures is the implementation of levees. Effective and economical in preventing floods, levees can also be integrated into urban landscaping works and consequently improve the aesthetic appeal of the river frontage. However, levees also pose a critical risk as it can be catastrophic if any stretch of the levee structure fails. This paper summarizes the type of levee failures that can occur and discusses the basic design checks required thus providing levee designers an overview of the risks that needs to be addressed to ensure adequate levee design.

Keywords: flood mitigation, levee failure, levee design

1. Introduction

Flooding is one of the natural disasters occurring throughout the world with varied severity causing devastating losses to its' victims. Flood inundation causes loss of lives, property damages, disruption of traffic as well as decreased crop yield production. Based on the data set of 73 nations for annual deaths occurring from natural disasters between 1980 to 2002, Venezuela topped the average deaths per flood with 2,015.7330 followed by China (328.4300) and India (291.7245). Concurrently, Malaysia was ranked 54th with 7.5385 average deaths per flood [1]. Although the number of deaths due to flooding in Malaysia was not as critical when compared to other countries, the most frequent type of natural disaster that occurred between the year 1968-2004 was flooding which had mainly affected the eastern and northern part of Peninsular Malaysia [2].

Flooding occurs when part of the dry land area becomes submerged with excess water due to the overflowing of nearby water bodies and/or excessive urban runoffs. Climate change, rise of the sea levels, urbanization and deforestation are some of the factors that contribute to increased impact of deadly floods. However, flood occurrence can also be intentional as reflected in the 1938 Yellow River flood in China where the river dike was strategically breached to halt the approach of the invading Japanese armies. The intentional flooding had decimated approximately 500,000 people [3]. More recently in 2017, monsoon flooding had affected Nepal, India and Bangladesh between June to September and was described as the worst flood to hit South Asia in a decade killing more than 1,400 people [4]. Contrarily, the worst flooding event that hit Malaysia in 2017 occurred in November, affecting the northern states of Penang and Kedah with a death toll of at least 7 people [5]. Intensified flood events are expected to increase as Earth undergo global climate change.

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2. Levee as A Flood Mitigation Option

Structural flood mitigation in addressing flooding hazards includes the construction of dams, floodwalls, levees, revetments, pump stations and the deepening of river channels [6], [7]. The most economical flood mitigation option for reducing flood risks is the construction of levees, which are also known as dikes and earth embankments [8], [9]. Levees are defined as raised earth embankments built along rivers, lakes and seas to protect floodplains and low-lying areas from flooding [10]–[12]. Fig. 1 shows a schematic diagram of a levee structure by the river. A floodplain area protected by a levee system not only reduces the risk of flooding, but it will also subsequently attract development and thus increase the land value behind the levee [9], [13]. In urban areas, levees can also serve dual purposes where the design would integrate landscape works and improve the river frontage aesthetic appeal. This is usually done by creating landscaped greenery on the levee surface or constructing attractive flood walls with walkways.

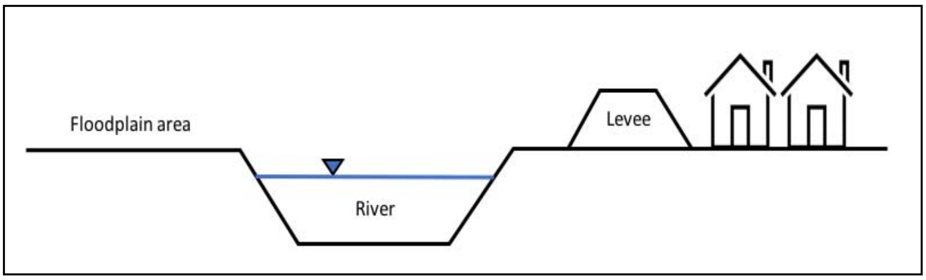

Fig. 1 - Schematic diagram of river levee

Setbacks when constructing levees include land acquisition, especially in urban and industrialized areas where the market value of land is generally higher than those of rural areas, not to mention the opposition and resettlement issues faced by local governments throughout the process [14]–[16]. In such areas, alternative to structural flood mitigation options are preferable, such as increasing the floodplain areas, improving stormwater management by restoring wetlands and implementing water retention ponds, as well as introducing ripraps in rivers to slow runoffs [17], [18].

In Malaysia, flood mitigation projects have been one of the key highlights tabled in the natinal budget every year. Between 2016 and 2018, a total of RM1.742 billion has been allocated to resolve flood problems in the country [19]–[21]. Some of the major levee implementation projects that has been completed in Malaysia can be found at Sungai Perai (Penang), Sungai Muda (Kedah) and Sungai Kerian (Perak, Kedah and Pulau Pinang). These levee projects have benefited the communities previously living in flood prone areas by reducing flood occurrences and improving their social-economic life. Fig. 2 and Fig. 3 show examples of the levee system built at Sungai Kerian and Sungai Muda respectively.

Fig. 2 - Sungai Kerian levee system

Fig. 3 - Sungai Muda levee system

An exemplar model of levee design and application can be found in the Netherlands, where a large part of the country is situated below the sea level. The country's flood prone areas along the main rivers, estuaries, Lake IJssel the North Sea has more than 50 major levee systems integrating both natural and man-made defences stretching approximately 3,300 km [22]. An absence of this exceptional flood defence system would certainly cause 60% of the country to be hit by flood incidences periodically [23]. The Netherlands commitment in preventing floods is reflected in their spectacular technological development, notably the Delta Works which was awarded the 2013 Awards of Excellence for Major Civil Engineering Project by the International Federation of Consulting Engineers [24]. The idea behind the series of projects comprised in the Delta Works was to reduce the Dutch coastline and manage water more effectively in order to avoid the repetition of the infamous 1953 North Sea flood which submerged 400,000 ha of land and caused 1,800 fatalities [17].

It is well understood that levee systems prevent excess runoffs and high flows of water from entering floodplain areas. However, no levee system can eliminate the flood risks completely [25]–[27]. In the process of designing a reliable levee system, it is good engineering practice to address all the risks that would affect the structural integrity of the levee leading to its' failure. Common methods in providing levees with additional protection and thus lowering flooding risks is by reinforcing levee with either concrete, steel or geotextiles. This paper will further discuss the susceptibility of levee failures and explore the basic design checks of river levee design.

3. Levee Failure

Levee failure is one of the contributing factors of flood disasters that occur every year around the world. Levee failure ensues when the levee system is incapable of achieving its design capability to provide protection as a flood defence system [28]. Examples of past catastrophic levee failures that involved a high number of deaths and huge economic losses include the 1421 St. Elizabeth's flood, the 1953 North Sea flood, the 1998 Yangtze River flood and the 2005 New Orleans flood [29]–[32]. Inadequate design, poor construction methods and lack of maintenance was a few of many reasons that can lead to the vulnerability of the levee system, causing it to break and fail [9]. According to the USACE Engineer Manual No. 1110-2-1913 [33], identified causes of levee failure were due to overtopping, surface erosion, internal erosion and slides within the levee embankment or the foundation soils.

3.1 Overtopping

Levee overtopping happens when flood or storm surge overflows the levee crown and creates fast flowing, turbulent water velocities on the landward side slope of the levee structure [34], [35]. This occurrence causes damage to the levee grass coverings, which in turn causes the underlying soil susceptible to scour and erosion. Prolonged overtopping will eventually lead to decreased crest elevation and possibly levee breach [36]. There are three types of possible levee overtopping: (a) wave overtopping; (b) surge overtopping; and (c) combined wave and surge overtopping [34]–[37]. Fig. 4 illustrates these three overtopping scenarios. Coastal levees have higher risk of overtopping occurrence when compared to river levees because of the varying sea levels based on the tidal phenomena and strong winds. When Katrina hurricane hit the city of New Orleans in 2005, the levee system surrounding the city was overtopped causing around 80% of the city to be submerged with approximately 1,300 fatalities [38], [39].

Recent researches in ascertaining that the levee system does not subside below design threshold include using space-based synthetic aperture radar interferometry (InSAR) which provides synoptic vertical land motion measurements [40]; and the Boussinesq wave model which uses a detailed hydrodynamic simulations of wave and surge overtopping [41].

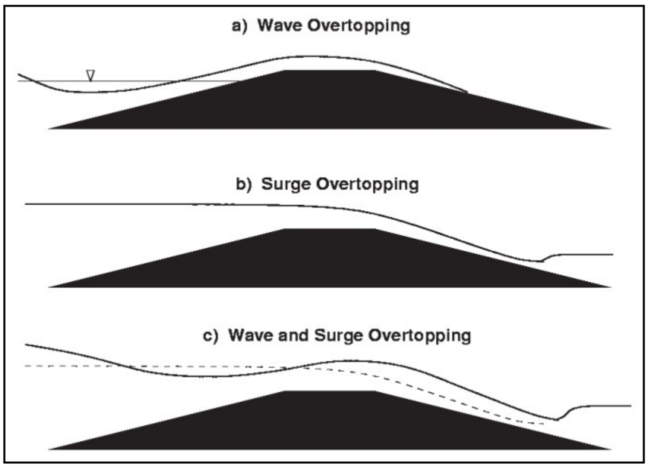

Fig. 4 - Possible levee overtopping scenarios [34]

3.2 Surface erosion

Soil erosion is the process of detachment and transport of soil particles caused by the energy transmitted from water and wind [42], [43]. The main factors that influence the erodibility of a soil or rock are the erosion rate, the velocity of the water and the hydraulic shear stress applied at the soil or rock – water interface [38], [44]. The Erosion Function Apparatus (EFA) can be used to measure in-situ erosion where erodibility of soils is categorized from very high erodibility (Category I) to non-erosive (Category VI) using the model as per equation (1), where ▯ =erosion rate (m/s); ▯ =water velocity (m/s); $(\tau - \tau_c)$=net shear stress (Pa); ▯ =mass density of water (kg/m^3); and all other quantities are
parameters characterizing the soil being eroded [38], [44]–[46]. These erosion categories can be presented in terms of velocity (Fig. 5) or shear stress (Fig. 6).

$$\frac{Z}{\ } \qquad \frac{\tau - \tau_c}{\ }^{m} \qquad (1)$$

$u = \alpha (\;)_2$

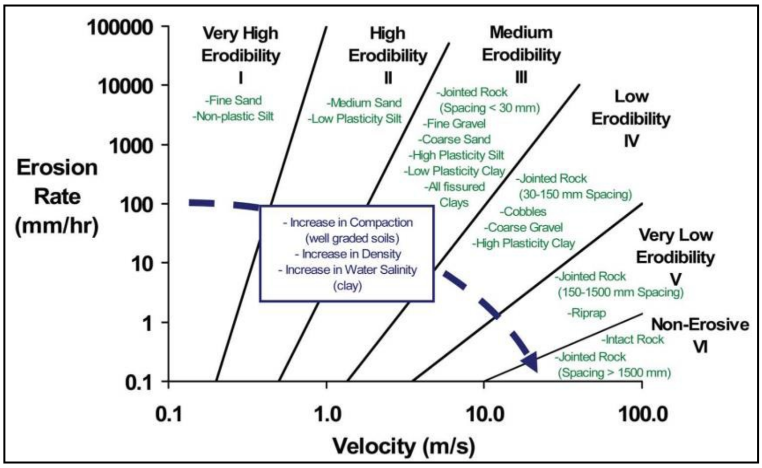

Fig. 5 - Erosion categories based on velocity (m/s) [44]

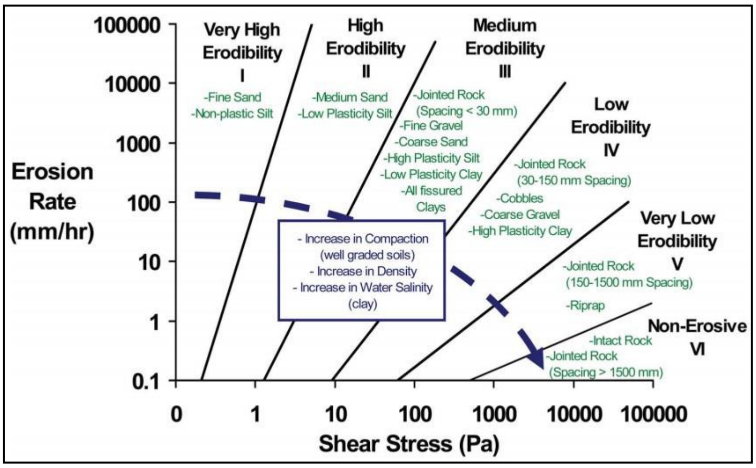

Fig. 6 - Erosion categories based on shear stress (Pa) [44]

As the topography of area varies from one levee location to another, the resistance of soil towards erosion plays a major part in determining the type of soil to be used for the construction of levees. The presence of grass covers on the levee slope surface can greatly increase its' erosion resistance, though it is interesting to note that the way of maintenance of the grass has little effect on the strength of the inner slope [47]. Other factors that may affect the erodibility of levees include soil compaction and cross section geometry.

3.3 Internal Erosion

Internal erosion in levees is described as the erosion of soil particles induced by hydraulic forces inflicted by water flowing through a body of soil or rock [48], [49]. When the body of soil can no longer resist the magnitude of the hydraulic forces (unstable core material), an initiation of seepage and piping can follow, progress and lead to its failure [50], [51]. This mode of failure is found to be the second most frequent cause of embankment failure after overtopping and the most recurrent cause of embankment structural failure [52]. Initiation mechanism of internal erosion such as backward erosion, contact erosion, concentrated leak and suffusion may be instigated either through the embankment, its foundation or embankment to foundation [50], [53].

Internal erosion failure can be difficult to detect whereby common detection methods rely on visual inspection limited to the external surface area of the levee. Alternative detection methods were developed by various researchers incorporating either/or a combination of multigeophysics, remote sensing, machine learning and ground penetrating radar [48], [54]–[58]. These research advancements enable early detection on the progression of internal erosion in levees and consequently provide additional warning time for the relevant authorities to avert and mitigate probable catastrophic failures.

3.4 Slides Within the Levee Embankment or the Foundation Soils

Slides failure can be categorized into upstream slides and downstream slides. Downstream slides comprise any form of sliding movement of the downstream slope such as sloughing (gradual sliding initiated by seepage within the embankment), through the embankment (slide area passes through the embankment only) and through the embankment and foundation (slide area passes through the embankment and the foundation); whereas upstream slides comprise any form of sliding movement at the upstream slope of the embankment with an addition initiation by drawdown of the water level [52]. Soil liquefaction triggered by earthquakes or other sudden change in the stress condition of soil can also cause slides, as illustrated in Fig. 7 when the 1995 Kobe earthquake in Osaka, Japan caused damage to the Yodo River levee [59]. Slump slides that occur along a long levee stretch can be difficult to detect and usually overlooked. They are usually identified by physical survey but there are also advanced tools using remote sensing data available to create a slide detection model [60]–[64].

Fig. 7 - Slides due to earthquake triggered soil liquefaction at the Yodo River levee [59]

4. Levee Design

Besides the obvious requirement of protecting flood plain areas, levee design consideration should be taken in terms of the economic and social aspects too. A responsible levee design should be built within the allocated budget and fulfil all the basic needs of the adjacent community including access for the future maintenance of the levee. There are three (3) failure mode checks that are typically being analysed which are overtopping, seepage and slope instability [65]. Some of the related design guidelines available for river levee design include United Kingdom's CIRIA C749 guide to EN 1997 Eurocode 7: Geotechnical design, The Netherlands's CUR-TAW Report 142 and United States' USACE Engineer Manual No. 1110-2-1913. Currently, levee design in Malaysia conform to the DID Manual Volume 1 – Flood Management.

4.1 Check Against Overtopping

The levee height design is based on the flood water level of the river section and the expected levee settlement within its' design life [66], [67]. Fundamentally, the levee height should be designed above the expected flood levels with consideration on combined wave and surge overtopping. Additional crown elevation with sufficient freeboard may be added to prevent flood or storm surge overflow due to the generated waves caused by wind [36], [68]. Freeboard is defined as the vertical distance between the surface of water elevation and crown of the levee elevation [69]. The various design guidelines' requirement for the levee height calculation is summarized in Table 1. Although CIRIA C749 guide to EN 1997 Eurocode 7: Geotechnical design did not specify its' minimum freeboard requirement, the guideline referenced [70], [71] for details of levee crest levels. In the case where the levee is designed to overtop, the resilience design of the levee is critical and levee strengthening is to be provided against erosion [37].

4.2 Seepage Analysis

Seepage analysis is required to understand the water flow and pore pressures within the levee that may trigger internal erosion and slides. The two types of seepage analyses are steady-state and transient, where transient analysis is applied for circumstances when the water level of the river is expected to fluctuate [72]. The determination of the pore water pressure or the phreatic line through the levee body is essential to further analyse the slope stability [73]. An increase of the pore water pressure will result in a decrease of the effective stress in the soil thus leading to a reduced factor of safety for the slope [74]. Determination of the phreatic line can be done using simple models, geometrical, analytical or numerical methods [73], [75]. Albeit complex numerical approach such as the finite element method provide a more thorough analysis, most geotechnical engineering practice adapt a simplified approach to determine the phreatic line [76], [77]. Fig. 8 illustrates a typical phreatic or seepage line that may be obtained for a levee structure. In the case where an embankment has a seepage exit face, seepage control must be provided to prevent piping. Various seepage controls to lower the phreatic line include toe drainage systems, cut-off walls, relief wells and deep mixing ground improvement [78]–[81].

Table 1 - Design requirement for levee height [33], [67], [84], [85]

Design guideline	Height of levee	Design water level	Minimum freeboard	Surplus height	Overtopping
CIRIA C749 guide to EN 1997 Eurocode 7: Geotechnical design	Not covered in the guideline.	Return period of at least 1% probability of being exceeded in the design life structure.	Not covered in the guideline	Not covered in the guideline.	To provide adequate protection and resilient level for levees that are designed to overtop.
CUR-TAW Report 142	Based on design water level, freeboard and surplus height.	Based on maximum high water level during 16,500 m^3/s discharge at Lobinth, where the Rhines enters The Netherlands.	0.50 m	To include the settlement of the levee within the next 50 years.	Freeboard provided up to the permissible rate of flow over the crest and inner slope of levee due to wave overtopping.
USACE Engineer Manual No. 1110-2-1913	Based on risk-based analysis (hydraulic uncertainties) and deterministic analysis (settlement, shrinkage, cracking, geologic subsidence and construction tolerances).	No additional remarks.	0.61 m	To be included in the deterministic analysis.	1V:6-10H on downstream slopes to minimize scour from overtopping. Overtopping to be avoided.
DID Manual Volume 1 - Flood Management	Based on design water level and freeboard.	Average Recurrence Interval (ARI) of 25-50 years for rural areas and 100 years for urban areas.	0.60 m	To be included in freeboard calculations.	Overtopping to be avoided.

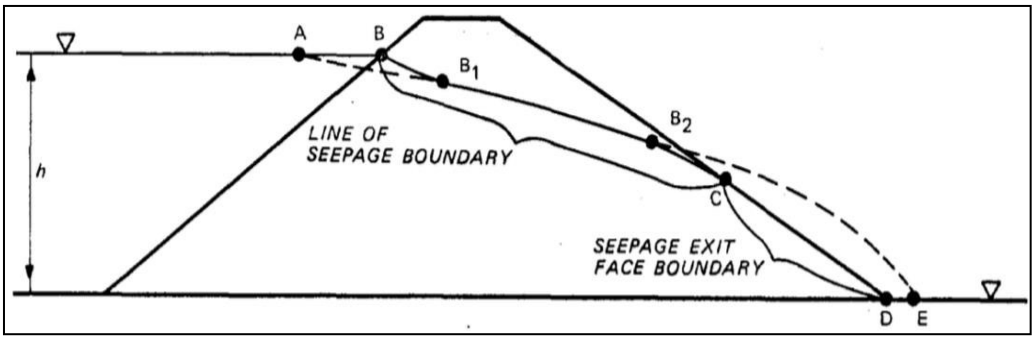

Fig. 8 - Line of seepage (BC) and seepage exit face (CD) for a homogeneous earth dam on an impermeable foundation [82]

4.3 Slope Stability Analysis

Slope stability analysis is performed to determine the factor of safety of the levee structure. It is an analysis of force and/or moment equilibrium which can be computed in respect of (1) total unit weights and boundary water pressures; or (2) buoyant unit weights and boundary water pressure – where the former of the alternatives is preferred as it is less complicated [83]. Limit equilibrium methods are widely used to determine the stability of earth slopes. Table 2 lists some of the well-known limit equilibrium methods and their respective equations of statics satisfied.

As all limit equilibrium methods does not consider strain and displacement compatibility, it is recommended to use methods that satisfies both moment and force equilibrium for a more accurate result of the minimum factor of safety [83], [86], [87]. A factor of safety greater than 1.0 signifies that a slope would be stable but due to the uncertainties involved in analysis, a higher value of factor of safety is preferred [88]. The minimum required factor of safety for various design guidelines is specified in Table 3. It is important to note that both the CIRIA C749 guide to EN 1997 Eurocode 7: Geotechnical design and the CUR-TAW Report 142 uses the partial factor of safety and limit states design approach, whereas both the USACE Engineer Manual No. 1110-2-1913 and the DID Manual Volume 1 - Flood Management uses an overall factor of safety design approach for its slope stability analysis [33], [67], [84], [85].

Table 2 - Equations of statics satisfied [86], [87]

Method	Moment equilibrium	Force equilibrium
Ordinary or Fellenius	Yes	No
Bishop's Simplified	Yes	No
Janbu's Simplified	No	Yes
Spencer	Yes	Yes
Morgenstern-Price	Yes	Yes
Corps of Engineers - 1	No	Yes
Corps of Engineers - 2	No	Yes
Lowe- Karafiath	No	Yes
Janbu Generalized	Yes (by slice)	Yes
Sarma – vertical slices	Yes	Yes

Table 3 - Minimum factor of safety [33], [67], [84], [85]

Design guideline	Minimum factor of safety	Condition
CIRIA C749 guide to EN 1997 Eurocode 7: Geotechnical design	1.0	All conditions
CUR-TAW Report 142	1.0	All conditions
USACE Engineer Manual No. 1110-2-1913	1.3	End of construction
	1.4	Long term (steady seepage)
	1.0-1.2	Rapid drawdown
DID Manual Volume 1 - Flood Management	2.0	All conditions

5. Conclusion

Due to global warming, flood occurrences are expected to increase and the economic benefits of implementing levee as a flood mitigation option in Malaysia outweighs the risk of flood losses. Mechanism of levee failures include overtopping, surface erosion, internal erosion and slides within the levee embankment of the foundation soils. The three basic design checks for levee systems are (1) check against overtopping; (2) seepage analysis; and (3) slope stability analysis. Malaysia's DID Manual Volume 1 – Flood Management, considers these three basic checks. However, it is important to note that levee design checks are not limited to these three criteria and in this aspect, the DID Manual Volume 1 – Flood Management lacks comprehensiveness especially to cater for the country's specific needs such as monsoon planning and agricultural needs. Other checks such as stress analysis and dynamic loading are recommended depending on the site conditions and external loads imposed on the levee system. In the authors' opinion, is advisable for levee designers in Malaysia to include other guidelines as their cross reference to ensure a reliable design approach.

References

[1] Kahn, M.E. (2005). The death toll from natural disasters : The role of income, geography and institutions. Review of Economics and Statistics, 87(2), 271–284.
[2] Mohamed Shaluf, I., & Ahmadun, F. (2006). Disaster types in Malaysia: An overview. Disaster Prevention and Management: An International Journal, 15(2), 286–298.
[3] Lary, D. (2001). Drowned earth: The strategic breaching of the yellow river dyke, 1938. War in History, 8(2), 191–207.
[4] Jain, R., & Wilkes, T. (2017). Worst floods to hit South Asia in decade expose lack of monsoon planning. Retrieved on December 31st, 2017 from https://www.reuters.com/article/us-southasia-floods/worst-floods-to-hit-south-asia-in-decade-expose-lack-of-monsoon-planning-idUSKCN1BC4QI.
[5] Davies, R. (2017). Malaysia – Severe Storm and Floods Leave 7 Dead, 10,000 Displaced. Retrieved on December 31st, 2017 from http://floodlist.com/asia/malaysia-penang-kedah-floods-november-2017.
[6] Brody, S.D., Kang, J.E., & Bernhardt, S. (2010). Identifying factors influencing flood mitigation at the local level in Texas and Florida: The role of organizational capacity. Natural Hazards, 52, 167–184.

[7] Brammer, H. (1990). Floods in Bangladesh: II. Flood mitigation and environmental aspects. Geographical Journal, 156(2), 158–165.
[8] Mizutani, H., Nakagawa, H., Yoden, T., Kawaike, K., & Zhang, H. (2013). Numerical modelling of river embankment failure due to overtopping flow considering infiltration effects. Journal of Hydraulic Research, 51(6), 681-695.
[9] Tobin, G.A. (1995). The Levee Love Affair: A Stormy Relationship?. Water Resources Bulletin: Journal of the American Water Resoursec Association, 31(3), 359–367.
[10] Van Looy, K., Honnay, O., Bossuyt, B., & Hermy, M. (2003). The effects of river embankment and forest fragmentation on the plant species richness and composition of floodplain forests in the Meuse Valley, Belgium. Belgian Journal of Botany, 136(2), 97–108.
[11] Dutta, D., Herath, S., & Musiake, K. (2000). Flood inundation simulation in a river basin using a physically based distributed hydrologic model. Hydrological Processes, 14(3), 497–519.
[12] Nakagawa, H., Utsumi, T., Kawaike, K., Baba, Y., & Zhang, H. (2011). Erosion of unsaturated river embankment due to overtopping water. Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), 67(4), II_1-II_4.
[13] Fell, H., & Kousky, C. (2015). The value of levee protection to commercial properties. Ecological Economics, 119, 181–188.
[14] Hussin, R., Abdul Rashid, R., & Yaakub, N.I. (2015). A preliminary study on compulsory acquisition of waqf land in Malaysia. International Conference on Waqf 2015 (Kuala Terengganu), 13.
[15] Ghatak, M., & Mookherjee, D. (2014). Land acquisition for industrialization and compensation of displaced farmers. Journal of Development Economics, 110, 303–312.
[16] Goswami, A. (2016). Land acquisition, rehabilitation and resettlement. Journal of Land and Rural Studies, 4(1), 3–22.
[17] Wenger, C. (2015). Better use and management of levees: Reducing flood risk in a changing climate. Environmental Reviews, 23(2), 240–255.
[18] Palmer, M.A., Liermann, C.A.R., Nilsson, C., Flörke, M., Alcamo, J., Lake, P.S., & Bond, N. (2008). Climate change and the world's river basins: Anticipating management options. Frontiers in Ecology and the Environment, 6(2), 81–89.
[19] Bahagian Fiscal dan Ekonomi. (2015). Bajet 2016. (Putrajaya: Kementerian Kewangan Malaysia), 45.
[20] Bahagian Fiscal dan Ekonomi. (2016). Bajet 2017. (Putrajaya: Kementerian Kewangan Malaysia), 22.
[21] Bahagian Fiscal dan Ekonomi. (2017). Bajet 2018. (Putrajaya: Kementerian Kewangan Malaysia), 54.
[22] Jongejan, R.B., & Maaskant, B. (2015). Quantifying flood risks in the Netherlands. Risk Analysis, 35(2), 252–264.
[23] Jonkman, S.N., Kok, M., & Vrijling, J.K. (2008). Flood risk assessment in the Netherlands: A case study for dike ring South Holland. Risk Analysis, 28(5), 1357–1373.
[24] International Federation of Consulting Engineers. (2013). Centenary Awards Celebrated in Barcelona 2013. Retrieved on December 31st, 2017 from http://fidic.org/node/3200.
[25] American Society of Civil Engineers. (2010). So, you live behind a levee! (Reston, Virginia.: American Society of Civil Engineers), 7-15.
[26] Florsheim, J.L., & Dettinger, M.D. (2007). Climate and floods still govern California levee breaks. Geophysical Research Letters, 34(22), 1–5.
[27] Pinter, N. (2005). One step forward, two steps back on U.S. floodplains. Science, 308(5719), 207–208.
[28] Simm, J., Wallis, M., Smith, P., Tourment, R., Veylon, G., Deniaud, Y., Durand, D., McVicker, J., & Hersh-Burdick, R. (2012). The significance of failure modes in the design and management of levees – A perspective from the International Levee Handbook team. Proceedings of the 2nd European Conference on Flood Risk Management (Rotterdam), 1–15.
[29] Kleinhans, M.G., Weerts, H.J.T., & Cohen, K.M. (2010). Avulsion in action: Reconstruction and modelling sedimentation pace and upstream flood water levels following a Medieval tidal-river diversion catastrophe (Biesbosch, The Netherlands, 1421-1750AD), Geomorphology, 118, 65–79.
[30] Gerritsen, H. (2005). What happened in 1953? The Big Flood in the Netherlands in retrospect. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 363(1831), 1271–1291.
[31] Plate, E.J. (2002). Flood risk and flood management. Journal of Hydrology, 267, 2–11.
[32] Jonkman, S.N., Maaskant, B., Boyd, E., & Levitan, M.L. (2009). Loss of life caused by the flooding of new orleans after hurricane Katrina: Analysis of the relationship between flood characteristics and mortality. Risk Analysis, 29(5), 676–698.
[33] U.S. Army Corps of Engineers. (2000). Design and Construction of Levees, EM 1110-2-1913 (Washington: U.S. Army Corps of Engineers), 1.1-8.11.
[34] Hughes, S.A. (2008). Levee Overtopping Design Guidance: What We Know and What We Need. Solution to Coastal Disasters, 867–880.
[35] Pan, Y., Li, L., Amini, F., & Kuang, C. (2013). Full-scale HPTRM-strengthened levee testing under combined wave and surge overtopping conditions: Overtopping hydraulics, shear stress, and erosion analysis. Journal of Coastal

Research, 29(1), 182–200.
[36] Hughes, S.A., & Nadal, N.C. (2009). Laboratory study of combined wave overtopping and storm surge overflow of a levee. Coastal Engineering, 56(3), 244–259.
[37] Li, L., Pan, Y., Amini, F., & Kuang, C. (2012). Full scale study of combined wave and surge overtopping of a levee with RCC strengthening system. Ocean Engineering, 54, 70–86.
[38] Briaud, J.L., Chen, H.C., Govindasamy, A.V., & Storesund, R. (2008). Levee erosion by overtopping in new orleans during the Katrina hurricane. Journal of Geotechnical and Geoenvironmental Engineering, 134(5), 618–632.
[39] Ubilla, J., Abdoun, T., Sasanakul, I., Sharp, M., Steedman, S., Vanadit-Ellis, W., & Zimmie, T. (2008). New Orleans levee system performance during hurricane Katrina: London Avenue and Orleans Canal South. Journal of Geotechnical and Geoenvironmental Engineering, 134(5), 668–680.
[40] Brooks, B.A. (2012). Contemporaneous subsidence and levee overtopping potential, Sacramento-San Joaquin Delta, California. San Francisco Estuary and Watershed Science, 10(1), 1-18.
[41] Lynett, P.J., Melby, J.A., & Kim, D.H. (2010). An application of Boussinesq modeling to hurricane wave overtopping and inundation. Ocean Engineering, 37(1), 135–153.
[42] Yang, S., Lianyou, L., Ping, Y., & Tong, C. (2005). A review of soil erodibility in water and wind erosion research. Journal of Geographical Sciences, 15(2), 167–176.
[43] Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., & Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits. Science, 267(5201), 1117–1123.
[44] Briaud, J.L. (2008). Case histories in soil and rock erosion: Woodrow Wilson Bridge, Brazos River Meander, Normandy Cliffs, and New Orleans Levees. Journal of Geotechnical and Geoenvironmental Engineering, 134(10), 1425–1447.
[45] Briaud, J.L., Ting, F.C.K., Chen, H.C., Cao, Y., Han, S.W., & Kwak, K.W. (2001). Erosion function apparatus for scour rate predictions. Journal of Geotechnical and Geoenvironmental Engineering, 127, 105–113.
[46] Yuan, S., Tang, H., Li, L., Pan, Y., & Amini, F. (2015). Combined wave and surge overtopping erosion failure model of HPTRM levees: Accounting for grass-mat strength. Ocean Engineering, 109, 256–269.
[47] van der Meer, J.W., Steendam, G.J., de Raat, G., & Bernardini, P. (2008). Further developments on the wave overtopping simulator. Coastal Engineering, 1, 2957–2969.
[48] Planès, T., Mooney, M.A., Rittgers, J.B.R., Parekh, M.L., Behm, M., & Snieder, R. (2016). Time-lapse monitoring of internal erosion in earthen dams and levees using ambient seismic noise. Géotechnique, 66(4), 301–312.
[49] Polanco-Boulware, L., & Rice, J.D. (2016). Reliability-based three-dimensional assessment of internal erosion potential due to crevasse splays. Journal of Geotechnical and Geoenvironmental Engineering, 143, 04016111-1-04016111-12.
[50] Koelewijn, A.R., & Bridle, R. (2017). Internal erosion in dams and dikes: A comparison. Proceedings of the 25th Meeting European Working Group on Internal Erosion in Embankment Dams & their Foundations (Delft), 1–11.
[51] Yerro, A., Rohe, A., & Soga, K. (2017). Modelling internal erosion with the material point method. Procedia Engineering,. 175, 365–372.
[52] Foster, M., Fell, R., & Spannagle, M. (2000). The statistics of embankment dam failures and accidents. Canadian Geotechnical Journal, 37, 1000–1024.
[53] Fell, R., Wan, C., & Cyganiewicz, J. (2003). Time for development of internal erosion and piping in embankment dams. Journal of Geotechnical and Geoenvironmental Engineering, 129(4), 307–314.
[54] Rittgers, J.B., Revil, A., Planes, T., Mooney, M.A., & Koelewijn, A.R. (2014). 4-D imaging of seepage in earthen embankments with time-lapse inversion of self-potential data constrained by acoustic emissions localization. Geophysical Journal International, 200(2), 758–772.
[55] Mooney, M.A., Parekh, M.L., Lowry, B., Rittgers, J., Grasmick, J.,Koeliwijn, A.R., Revil, A., & Zhou, W. (2014). Design and implementation of geophysical monitoring and remote sensing during a full scale embankment internal erosion test. Geo-Congress 2014 Technical Papers. GSP 234 (Reston: American Society of Civil Engineers), 202–211.
[56] Fisher, W., Jackson, B., Camp, T., & Krzhizhanovskaya, V.V. (2017). Anomaly detection in earth dam and levee passive seismic data using multivariate Gaussian. 16th IEEE International Conference on Machine Learning and Applications (Cancun), 685–690.
[57] Fisher, W.D., Camp, T.K., & Krzhizhanovskaya, V.V. (2017). Anomaly detection in earth dam and levee passive seismic data using support vector machines and automatic feature selection. Journal of Computational Science, 20, 143–153.
[58] Pueyo Anchuela, O., Frongia, P., Di Gregorio, F., Casas Sainz, A.M., & Pocoví Juan, A. (2018). Internal characterization of embankment dams using ground penetrating radar (GPR) and thermographic analysis: A case study of the Medau Zirimilis Dam (Sardinia, Italy). Engineering Geology, 237, 129–139.
[59] Towhata, I. (2014). Geotechnical Earthquake Engineering: Damage Mechanism Observed. In: M. Beer, I. Kougioumtzoglou, E. Patelli, I.K. Au (eds) Encyclopedia of Earthquake Engineering (Heidelberg: Springer), 1–29.
[60] Dabbiru, L., Aanstoos, J.V., & Younan, N.H. (2015). Earthen levee slide detection via automated analysis of

synthetic aperture radar imagery. Landslides, 13(4), 643–652.

[61] Sehat, S., Vahedifard, F., Aanstoos, J.V., Dabbiru, L., & Hasan, K. (2014). Using in situ soil measurements for analysis of a polarimetric SAR-based classification of levee slump slides in the Lower Mississippi River. Engineering Geology, 181,157–168.

[62] Azad Hossain, A.K.M, & Easson, G. (2012). Predicting shallow surficial failures in the Mississippi River levee system using airborne hyperspectral imagery. Geomatics, Natural Hazards and Risk, 3(1), 55–78.

[63] Han, D., Du, Q., Aanstoos, J.V., & Younan, N. (2015). Classification of levee slides from airborne synthetic aperture radar images with efficient spatial feature extraction. Journal of Applied Remote Sensing, 9(1), 097294-1-097294-10.

[64] Azad Hossain, A.K.M., Easson, G., & Hasan, K. (2006). Detection of levee slides using commercially available remotely sensed data. Environmental and Engineering Geoscience, 12(3), 235–246.

[65] Fu, Z., Su, H., Han, Z., & Wen, Z. (2018). Multiple failure modes-based practical calculation model on comprehensive risk for levee structure. Stochastic Environmental Research and Risk Assessment, 32(4), 1051–1064.

[66] Haddad, O.B., Ashofteh, P., & Mariño, M.A. (2015). Levee layouts and design optimization in protection of flood areas. Journal of Irrigation and Drainage Engineering, 141(8), 04015004.

[67] Centre for Civil Engineering Research and Codes & Technical Advisory Committee on Water Defences. (1991). Guide for the Design of River Dikes: Volume 1 - Upper River Area (AK Gouda: CRC Press), 1-212.

[68] Tung, Y.K., & Mays, L.W. (1981).Optimal risk-based design of flood levee systems. Water Resources Research, 17(4), 843–852.

[69] Pan, Y., Kuang, C.P., Li, L., & Amini, F. (2015). Full-scale laboratory study on distribution of individual wave overtopping volumes over a levee under negative freeboard. Coastal Engineering, 97, 11–20.

[70] Kirby, A.M., & Ash, J.R.V. (2000). Fluvial freeboard guidance note. (Bristol: Environment Agency), 1-78.

[71] Gaines, R., Mars, S.S., Perlea, M., Simm, J., Wallingford, H., & Wielputz, M. (2013). The International Levee Handbook. (London: Construction Industry Research and Information Association), Chapter 9

[72] Fredlund, M., Lu, H.H., & Feng, T. (2011). Combined seepage and slope stability analysis of rapid drawdown scenarios for levee design. Geo-Frontiers Congress 2011 (Dallas), 1595–1604.

[73] Yan, Z.L., Wang, J.J., & Chai, H.J. (2010). Influence of water level fluctuation on phreatic line in silty soil model slope. Engineering Geology, 113(1–4), 90–98.

[74] Perri, J.F., Shewbridge, S.E., Cobos-Roa, D.A., & Green, R.K. (2012). Steady state seepage pore water pressures influence in the slope stability analysis of levees. GeoCongress 2012 (Oakland), 604–613.

[75] Gaines, R. (2013). The International Levee Handbook. (London: Construction Industry Research and Information Association), Chapter 8

[76] Sun, G., Yang, Y., Cheng, S., & Zheng, H. (2017). Phreatic line calculation and stability analysis of slopes under the combined effect of reservoir water level fluctuations and rainfall. Canadian Geotechnical Journal, 54(5), 631–645.

[77] Huang, M., & Jia, C.Q. (2009). Strength reduction FEM in stability analysis of soil slopes subjected to transient unsaturated seepage. Computers and Geotechnics, 36(1–2), 93–101.

[78] Soong, T.Y., & Koerner, R.M. (1996). Seepage induced slope instability. Geotextile and Geomembranes, 14(7–8), 425–445.

[79] Yang, D.S., Luscher, U., Kimoto, I., & Takeshima, S. (1993). SMW Wall for Seepage Control in Levee Reconstruction. 3rd International Conferences on Case Histories in Geotechnical Engineering (Missouri), 487–492.

[80] Mansur, C.I., Postol, G., & Salley, J.R. (2000). Performance of relief well systems along mississippi river levees. Journal of Geotechnical and Geoenvironmental Engineering, 126(8), 727–738.

[81] Porbaha, A., Shibuya, S., & Kishida, T. (2000). State of the art in deep mixing technology. Part III:Geomaterial characterization. Proceedings of the Institution of Civil Engineers - Ground Improvement, 4(3), 91–110.

[82] U.S. Army Corps of Engineers. (1986). Seepage Analysis and Control for Dams, EM-1110-2-1901 (Washington: U.S. Army Corps of Engineers), 6-1.

[83] Duncan, J.M. (1996). State of the art: Limit equlbrium and finite-element analysis of slopes. Journal of Geotechnical Engineering, 122(7), 577–596.

[84] Department of Irrigation and Drainage Malaysia. (2009). DID Manual: Volume 1 - Flood Management (Kuala Lumpur: Jabatan Pengairan dan Saliran), 1.1-13.8.

[85] Pickles, A. & Sandham, R. (2014). Application of Eurocode 7 to the design of flood embankments (London: Construction Industry Research and Information Association), 1-51.

[86] GEO-SLOPE International Ltd. (2012). Stability Modeling with SLOPE/W: An Engineering Methodology (Alberta: GEO-SLOPE International Ltd.), 1-238.

[87] Duncan, J.M., & Wright, S.G. (1980). The accuracy of equilibrium methods of slope stability analysis. Engineering Geology, 16(1-2), 5–17.

[88] Duncan, J.M., Wright, S.G., & Brandon, T.L. (2014). Soil Strength and Slope Stability, 2nd Edition (New Jersey: John Wiley & Sons, Inc.), 1-336.