HYDRAULIC FAILURES OF THE DIKE AROUND THE MUD VOLCANO LUMPUR LAPINDO

Final Report

Final thesis submitted to the Delta Academy Department of HZ University in the Netherlands as a part of the final year requirements in the Bachelor of Engineering in Civil Engineering program. Research took place in East Java Indonesia.

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Abstract:

This thesis has been written for a Living Lab project in Indonesia by Hilary Richards, a fourth year civil engineering student at the HZ University of Applied Sciences. This is a final thesis research report that is written on the dike around the Sidoarjo mud volcano. Fellow student, Tom van Mierlo, also conducted research on the mud volcano and during the set-up of the research has had a supporting role. The research is for Living Lab Water Indonesia – NL which is a partnership between Dutch and Indonesian universities and companies that work together on research projects based on real-life issues. Living Lab – Surabaya has been setup between ITS in Indonesia and the HZ in the Netherlands to focus on local issues such as the Lumpur Lapindo mud volcano. ITS hosted the students during their research period in Surabaya. The second host was Witteveen+Bos, civil engineering company, who provided technical guidance and support during the research period. The thesis is intended for readers interested in the research topic, the fundamental theory supporting the research and the method of how the research was conducted during the final thesis phase of final year civil engineering students of the HZ University of Applied Sciences in the Netherlands.

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BPLS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

In 2006 a mud volcano erupted in Sidoarjo, a town south of East Java's industrial hub, Surabaya. The volcano has continued to produce mud until the present day (2016) resulting in a mud depot of over 500 hectares. The mud has caused damage to the people living in the area and continues to bring destruction as it is not expected to stop within the coming years. This research thesis is on the post disaster management of the mud volcano, specifically the dike surrounding the depot. The mud depot is at its full capacity and that has resulted in an unstable dike. Flooding occurs outside the depot affecting important infrastructure and all mud is currently pumped away to the Porong river.

The objective of the research was to determine what hydraulic failures are present in the dike retaining the mud and design a solution to prevent these failures from occurring. The solution should improve ecological conditions by accommodating the mud so that pumping of mud to the Porong river is no longer necessary.

Currently the mud outflow from the mud volcano is 10 000m^3 and is comprised of hot water (70%) and fine sediment (30%). The outflow is expected to last for the next 26 years and the new solution therefore has a design life of 50 years. The geological conditions of the existing dike include underlying layers of clay and sand and the dike was constructed with pebbly-sandy soil.

The solution was designed in two phases where different failure mechanisms were analysed. The settlement, macro-stability and slip circle of the solution was analysed globally. The overflow, erosion of the outer slope and piping were analysed in detail. The requirements for the dike were based on Indonesian design standards and where these were not available were based on Dutch design standards. These requirements are stated in a functional and technical program of requirements as a result of the research.

Once the requirements were defined an alternative analysis was done on three solutions to accommodate the mud. The first was to create a depot within the current depot at the location were dredging is taking place. The mud would be separated into water and sediment with the water pumped away to the Porong river. The second solution was to create a new depot next to the existing one and to pump the mud there instead of to the river. After analysing the three solutions however the third solution was found to be the most viable.

The third (chosen) solution is a combination of the first two. It is a new depot next to the existing one which will act as a buffer zone where the sediment and water are separated. The sediment will be stored in the buffer zone and the water will be pumped away to the Porong river. This solution is able to accommodate the mud for required 26 years and has possibilities for testing and expansion.

The final design of the new solution determines the overflow and piping risk of the existing dike as well as the new dike design. The outcome is that the existing dike should be heightened to include a pipe through the dike to accommodate for overflow and a piping berm for piping risk. This in combination with the new design will reduce the risk of hydraulic failure in the existing situation.

The outcome of the research is based on limited information and the analyse done should be implemented for each cross section of the existing dike. The recommendation for further research and design of the separation of the mud is given if the chosen solution is to be realised. If the solution is not realised options to reduce the risk of hydraulic failure are provided for the existing dike.

1. INTRODUCTION

This research thesis is on the dike surrounding the Sidoarjo mud volcano in East Java, Indonesia that started erupting in May 2006. The focus of the research is on the hydraulic failures in the dike that was constructed to contain the mud. It specifically looks at the hydraulic failures that occur such as piping and overflow.

The research was led by Living Lab Water which is a combined organisation comprised of Dutch and Indonesian organisations. The organisations involved in the research were Witteveen + Bos Indonesia, ITS University and HZ University of Applied Sciences. The research took place in two locations in Indonesia, see figure 1.1, namely Jakarta and Surabaya. Jakarta is the location of host company Witteveen + Bos and Surabaya is the location of host University ITS. Witteveen + Bos Indonesia provided technical insight and quality control of the designed solutions and ITS provided local knowledge and expertise in dike structures and water management.

The aim was to find a way to accommodate the mud from the volcano, and prevent flooding and pumping of mud to Porong river. This chapter will discuss the motivation for the research, the objective, main question and the report structure of the thesis.

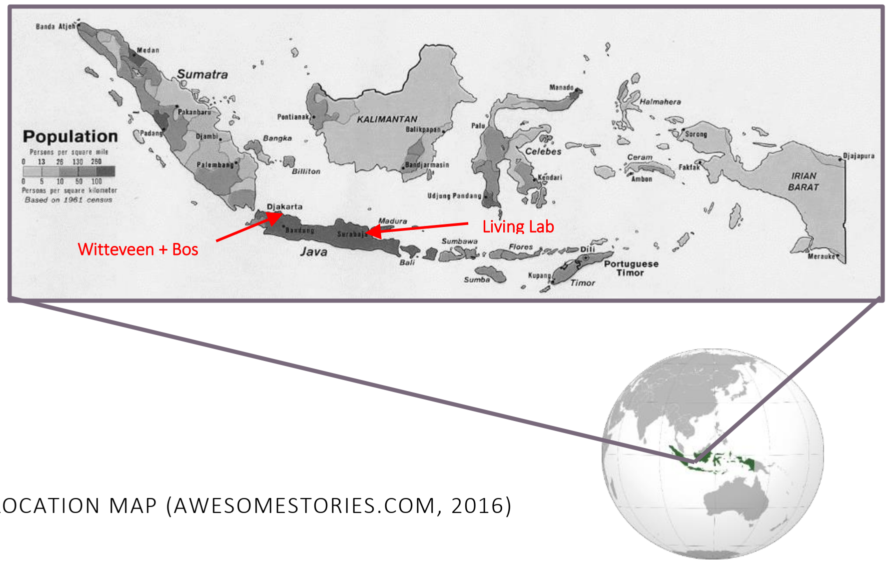


FIGURE 1.1, RESEARCH LOCATION MAP (AWESOMESTORIES.COM, 2016)

1.1 BACKGROUND

In 2006 a mud volcano erupted in Sidoarjo, a town south of East Java's industrial hub, Surabaya. The mud volcano has been producing mud since its eruption, reaching a peak of 180,000 m³ a day in 2011. It has since reduced to a fairly constant rate of 10,000 m³ a day. Ten years later the mud is still flowing and is currently contained by dikes (11 km perimeter) that surround the mud volcano and have created a mud depot of over 500 hectares. Currently the excess mud is pumped away to the nearby Porong river. The cause of the eruption is believed to be due to the combination of drilling by local company, Lapindo Brantas and an earthquake nearby the eruption site. He name of the mud volcano is a combination of these two things hence Lumpur Lapindo. The mud has already caused damage to the surrounding towns and businesses, displacing 40 000 people (Putro, 2012), and is not expected to stop within the next 26 years.

Next to the dike is Porong highway as well as the only railway connection between Surabaya and the rest of southern Java (see figure 1.2). These two access routes have been subject to flooding and dike breakthroughs as a result of the mudflow in the past. During heavy rainfall periods the road and railway have to be closed off for hours and sometimes days.

FIGURE 1.2: SATELLITE VIEW OF THE MUD DEPOT (GOOGLE MAPS, 2016)

1.2 PROBLEM ANALYSIS

Due to the fact that the Sidoarjo mud volcano has not stopped erupting, the dike surrounding the volcano has become insufficient and cannot contain all the mud. After many failed attempts to stop the mud volcano the decision was made to build a retaining dike. This dike was to hold all the mud however the volcano did not stop and it reached its capacity quickly.

The mud is at the same level as the dike and has to be discharged to the Porong river. Ideally the mud flows away naturally in the river to the ocean and does not negatively affect the water in the river. however due to its composition, sedimentation is occurring in the river effecting its discharge capacity and aquaculture is affected as O2 levels decrease.

Problem Statement:
The current dike around the depot experiences breakthroughs due to the mud pressures on the dike and water pressures in the system. Failures in the dike such as overflow from rainwater and piping are not being prevented. The flooding and seepage causes damage to the surrounding infrastructure. During heavy rain fall when flooding occurs, there is no system in place to discharge overflow water from the depot.

The main road, Porong Highway, and railway track that run alongside the dike (see figure 1.3) are currently at high risk of being affected or even damaged when flooding or dike failure occurs. Any excess mud coming out of the volcano that is pumped to Porong river is slowly filling up the river and reducing its capacity. The aquaculture is affected and there is an increase in the risk of flooding around the river. This is not a viable solution to discharge the mud from the volcano.

FIGURE 1.3: DIKE SEPARATING MUD AND ROADWAYS (HERMAWAN, 2013).

1.3 OBJECTIVE

The objective of the research is to determine what hydraulic failures, namely piping and overflow, occur in the current dike and design a dike solution that prevents flooding and water damage to the surrounding areas.

Main Question:
In order to carry out the final thesis research the following main question is answered:

To what extent can the risk of flooding due to piping and overflow of the dike around the Lapindo mud volcano in Surabaya, Indonesia be mitigated?

In the main question the overflow refers to the water that flows over the dike during heavy rainfall as well as the mud overflow that is being pumped to the Porong river. The risk of flooding therefore refers to the surrounding area, more specifically the Porong highway and railway next to the dike and the risk of flooding at the Porong river.

To further carry out the research the following sub questions are answered:
1. What is the current situation of the dike around the mud volcano?
2. What is the program of requirements for a dike design to prevent flooding?
3. Which dike alternatives can be used to prevent pumping mud to the Porong river?
4. What variants can be used to prevent piping and overflowing?
5. What is the most suitable alternative to prevent flooding?
6. How is the most suitable solution designed?

1.4 RESEARCH STRATEGY

The research was carried out in two locations in Indonesia namely Jakarta and Surabaya. The majority of the research was done in Surabaya at ITS University who have contact with local authorities responsible for the dike. Witteveen+Bos Indonesia provided support with the technical design and calculations. The thesis is by means of a theoretical research on dike calculations, failure mechanisms, flooding protection and site investigation with consultation with dike experts from ITS and Witteveen + Bos. Data was collected to determine the state of the current situation and from the assessment a solution was designed to prevent flooding and water damage outside the dike. The complete research strategy is explained in Chapter 3.

Due to time limitations of the thesis the other failure mechanisms in the dike were only considered but were not calculated as extensively as piping and overflow. Research on macro-stability and earthquake resistance was done on the dike by fellow researcher Tom van Mierlo. The designed solution has been analysed twice. Firstly three alternatives were designed globally and considered with variants for each failure mechanism. Secondly, once the most viable solution was chosen, the design was be calculated in detail. This design of the chosen solution forms the final product of the research.

1.5 REPORT STRUCTURE

The research report is comprised of six chapters namely Introduction, Theoretical Framework, Research Strategy, Results, Discussion and Conclusion. Chapter 2, Theoretical Framework, summarises key concepts that form the foundation of the design and research process. Chapter 3, Research Strategy, describes the work plan with project activities, products and planning guideline used to complete the research. Chapter 4, Results, summarises the outcome of the research and along with an explanation of the final design. Chapter 5, Discussion, includes an interpretation of the results of the research. Chapter 6, Conclusion, states the main aspects of the research and summaries the report with recommendations for further design.

The appendix of the report contains the extended information and details mentioned in the main research as well as a List of Symbols (Appendix A) and Additional Competences (Appendix B). Appendix B describes the challenges and opportunities of doing a final thesis abroad in Indonesia.

2. THEORETICAL FRAMEWORK

The foundation of the research and design of a dike solution depends on a theoretical framework that can be applied to the situation. This chapter will discuss the current system characteristics, applicable failure mechanisms to the research area, and design standards used in calculation methods. For a more detailed explanation of each sub-chapter see Appendix F.

2.1 CURRENT SYSTEM ANALYSIS

In order to design a solution to cope with the Sidoarjo mud volcano the current situation is assessed to determine what influential factors need to be adapted or reconstructed. The factors influencing the system include the mudflow of the volcano, the dikes around the depot, the soil conditions and the rainfall in the area.

2.1.1 Mudflow specifications

The daily outflow of mud varies every day and therefore it is difficult to calculate with an exact number. An estimation of 10,000m³ will be therefore used to calculate the system (Davies, Mathias, Swarbrick, & Tingay, 2011). The mudflow can be classified as a silt soil with high plasticity, see figure 2.1.

In order to further analyse the system it is important to know how long the mud volcano will last to determine the life span of the desired solution. The fact that the mud flow is declining does indicate that it will eventually stop however it is impossible to know when exactly. 26 years is an estimation that will be used as the predicted life span of the mud volcano.

Properties	Value
Water content, w	62.14%-73.29%
Specific gravity, G_s	2.71
Liquid limit, w_L	58.44%
Plastic limit, w_P	30.77%
Shrinkage limit, w_S	22.27%
Plasticity index, I_P	27.66%
Shrinkage index, I_S	36.17%
Liquidity index, I_L	1.13-1.54
% coarse grain	15.53%%
% fine grain	84.47%
% silt	30%
% clay	54.47%
Classification (USCS)	MH (High Plasticity Silt)

FIGURE 2.1: PHYSICAL PROPERTIES OF LUSI MUDFLOW (HANDOKO, 2015)

2.1.2 Geological conditions

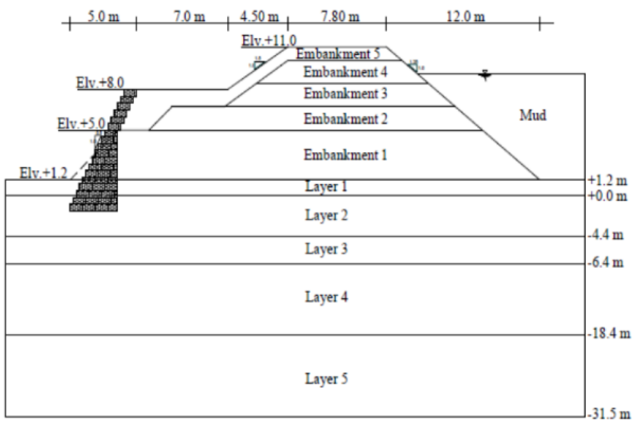


FIGURE 2.2: DESIGN OF EXISTING DIKE WEST (AGUSTAWIJAYA & SUKANDI, 2012)

A stability analysis of the dike was done in 2012 (Agustawijaya & Sukandi, 2012) looking at the vertical displacement of the existing dike. It shows that the dike structure was constructed in five phases, see figure 2.2. Initially embankment 1 was designed to be enough however when the mud kept on rising the dike was heightened each time until it was not possible anymore.

The dike core has been constructed with a pebble-sandy soil with the underlying layers defined in Table 2-1. The extended soil properties of the layers can be seen in Appendix C along with the drilling log (Appendix D) showing the composition of the layers. The grain size, weight density, porosity, water content, density index and organic matter content is taken from these data sources.

TABLE 2-1: SOIL PROPERTIES OF THE UNDERLYING LAYERS

Soil Type		Soil Properties													
Layer	Main Name	γ_{dry} (kN/m³)	γ_{sat} (kN/m³)	kx=ky (m/day)	kx=ky (m/s)	q_c Mpa	C'_p	C'_s	C_c	$C_{a5)}$	C_{sw}	E6 Mpa	ø'	C'	fundr kPa
8	Embankment	18.63	19.4	2.42x10-2	2.8E-07	15	500	-	0.008	0	0.003	75	26.97	10.06	n/a
7	Gravel	17	19	2.42x10-2	2.8E-07	15	500	-	0.008	0	0.003	75	32.5	n/a	n/a
6	Soft clay	14	14	6.9x10-4	7.99E-09	0.5	7	80	1.357	0.013	0.452	1	17.5	0	25
5	Sandy Clay	18	19	8.34x10-4	9.65E-09	1	140	1680	0.027	0.004	0.025	5	32.5	2	10
4	Sand	17	19	8.34x10-4	9.65E-09	5	200	-	0.021	0	0.007	25	30	n/a	n/a
3	Sandy shell	18	20	2.42x10-2	2.8E-07	12	600	-	0.006	0	0.002	30	30	n/a	n/a
2	Clayey sand	18	18	6.2x10-4	7.18E-09	1.5	20	240	0.237	0.005	0.079	3	22.5	10	80
1	Clay	17	17	6.9x10-4	7.99E-09	1	15	160	0.362	0.006	0.121	2	17.5	0	25

2.1.3 Hydrological conditions

The mud flow is a mixture of hot water and fine sediment that can either flow out in a gentle manor or be pushed out of the ground violently releasing steam and toxic gases. (Dimitrov, 2002). In the case of the dikes surrounding the Sidoarjo mud volcano the substance being held back is not water like that of most dikes that are designed. In this case it is a mix of water and silt. The forces that therefore apply to the dike have to be adjusted from water to a more suitable substance in this case “heavy” water. These properties will be used to calculate the mud pressure on the dike.

The design rainfall in the area that falls on the dike based on results in 2008 for a return period of 10 years is 145.6mm. For of two days for 10 day return period ranges from 162.4-186.8mm and a rainfall of 3 to 5 hours has a normal distribution curve. The peak rainfall occurs in January, March and April with rainfall higher in the northern parts compared to the south (ISJD, 2008).

The mud mixture is pumped away to the Porong river with a discharge of 0.8m³/s. The cross section of the Porong river can be seen in figure 2.3 showing the dimensions of the river and water levels. The water quality of the Porong river will not be assessed but the assumption is made that stopping pumping mud to the river will be beneficial for the ecological condition.

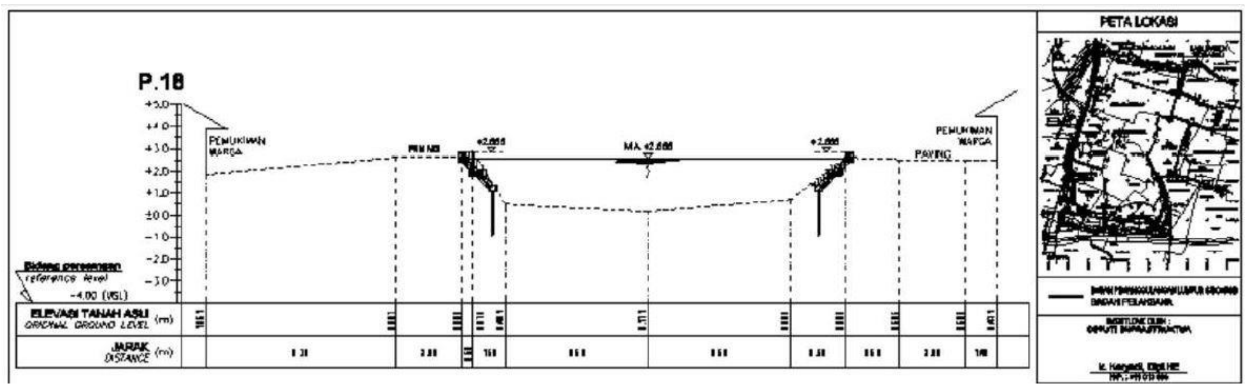


FIGURE 2.3: DIMENSIONS OF PORONG RIVER

2.2 APPLICABLE FAILURE MECHANISMS

The dike around the mud volcano is comprised of a sand core and is therefore similar to many lake dikes built in the Netherlands. An important step when analysing a dike is to determine what failure mechanism are present. This is usually after the soil layer conditions, geometry of the dike and the ground water flow have been defined (TAW, Technisch Rapport Waterspanningnen bij dijken, 2004).

Depending on the structure various failure mechanisms are applicable and these are further adjusted according to the circumstances. Usually the most attention is given to overtopping in dikes however due to there being no wave attack in the research area other failure mechanisms will be dominant. Figure 2.4 shows a summary of the types of failure mechanisms in dikes (TAW, Gondslagen voor waterkeren, 1998).

(A) – Overtopping
(B) – Wave run-up
(C) – Slip circle inner slope
(D) – Liquefaction (Sliding)
(E) – Slip circle outer slope
(F) – Micro instability
(G) – Piping
(H) – Erosion outer slope
(I) – Erosion foreshore
(J) – Settlement
(K) – Drifting ice
(L) – Collision from vessels

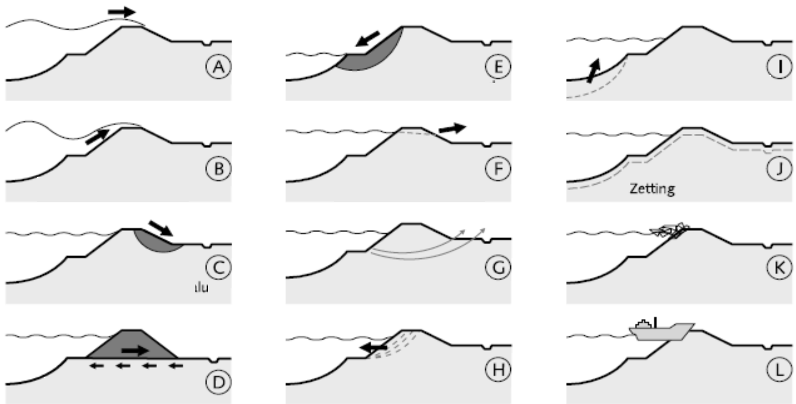


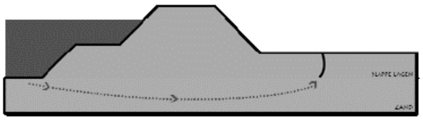
FIGURE 2.4: FAILURE MECHANISMS (TAW, GONDSLAGEN VOOR WATERKEREN, 1998)

The failure mechanisms that will be calculated in detail are overflow (overtopping) due to water flowing over the dike during heavy rainfall, micro-instability and piping. These are failure mechanisms associated with hydraulic pressures on the dike around the mud volcano and cause water and flood damage in surrounding areas. The other failure mechanisms present in the dike are slip circle of the inner/outer slope, liquefaction, erosion of the outer slope and settlement. These will be considered globally.

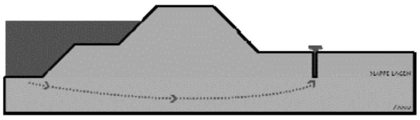
2.2.1 Piping

Piping occurs when there is seepage through the foundation of a dike and results in sediment transportation and erosion behind the dike. The erosion slows down however further erosion will take place if a critical hydraulic head difference is reached and can lead to the dike collapsing. The various phases of piping are illustrated in figure 2.5 showing from the start of the failure all the way through to total dike breakthrough.

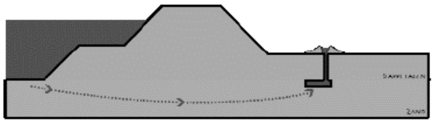
To determine the piping in the existing structure there are three piping rules that are used for standard calculations namely Bligh, Lane and Sellmeijer, see table 2-2). These rules are used as an initial assessment of piping in a structure. Advanced analysis needed is done using numerical piping modelling and MSEEP modelling program (Sellmeijer).



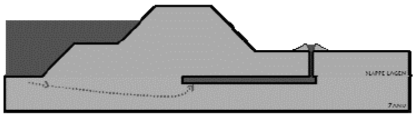
1) crack formation in top layer



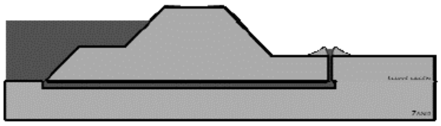
2) seepage/boil formation, beginning of erosion



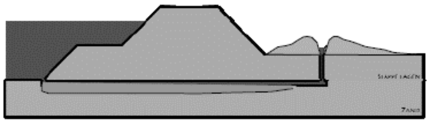
3) start of pipe formation due to receding erosion



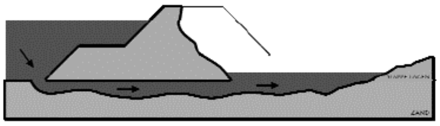
4) pipe formation due to backward erosion



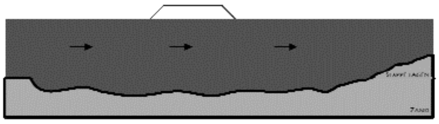
5) complete throughway pipe (piping failure mechanism)



6) expansion of the pipe



7) collapsing of the dike



8) complete dike breakthrough

FIGURE 2.5: TYPICAL PHASES OF PIPING (DELTARES, ZANDMEEVOERENDE WELLEN, 2012)

TABLE 2-2: THREE BASIS PIPIING RULES (SELLMEIJER)

Bligh $\frac{H}{L} = \frac{1}{C_{\text{Bligh}}}$	fine silty sand moderate fine sand course sand fine gravel course gravel	C_{Bligh} 18 15 12 9 4
Lane $\frac{H}{L_h} = \frac{\frac{1}{3} + \frac{L_v}{L_h}}{C_{\text{Lane}}}$	fine silty sand moderate fine sand course sand fine gravel course gravel	C_{Lane} 8.5 7 5 4 3
Sellmeijer $\frac{H}{L} = GRSF$	geometry factor $\mathrm{G} = \left(\frac{D}{L}\right)^{\frac{0.28}{\left(\frac{D}{L}\right)^{2.8} - 1}}$ rolling equilibrium $\mathrm{R} = \frac{\gamma_p'}{\gamma_w} \tan\vartheta$ sand properties $\mathrm{S} = \eta \frac{d}{\sqrt[3]{\kappa L}}$ 4 force factor $\mathrm{F} = 0.68 - 0.1\ln(S)$	D: aquifer height H: hydraulic head L: dike width γ_p: unit weight particles γ_w: unit weight water ϑ: bedding angle η: Whites constant d: particle diameter κ: intrinsic permeability

Once the effect of internal erosion is known, preventative measures can be taken. These include adding a new revetment layer to increase erosion resistance; placing a seepage barrier to stop piping from occurring; adding a ditch behind the dike; or drainage at the toe of the dike.

Variants to prevent piping from occurring include placement of clay in front of the dike (see figure 2.9a); adding a seepage barrier of clay box, concrete wall or film screen (see figure 2.9b); adding a piping berm and implementing drainage at the toe of the inside slope (see figure 2.9c and figure 2.9d).

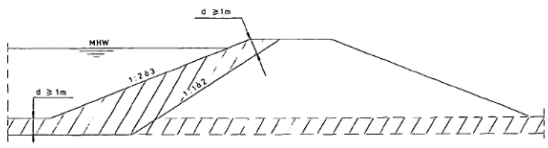


FIGURE 2.9A: CLAY PROTECTION LAYER (DELTARES, ZANDMEEVOERENDE WELLEN, 2012)

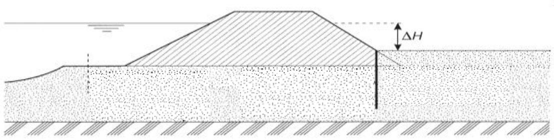


FIGURE 2.9B: BARRIER IN SOIL STRUCTURES (TAW, TECHNISCH REPORT WATERKERENDE CONSTRUCTIES, 2001)

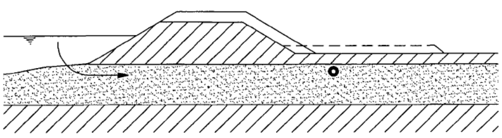


FIGURE 2.9C: FILTER CONSTRUCTION INSTEAD OF GENTLE SLOPE (TAW, HANDREIKING CONSTRUCTIEF ONTWERPEN, 1994)

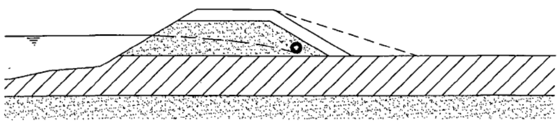


FIGURE 2.9D: DRAINAGE CONSTRUCTION INSTEAD OF A GENTLE SLOPE WITH DOTTED LINE AS POSSIBLE PIPING BERM (TAW, HANDREIKING CONSTRUCTIEF ONTWERPEN, 1994)

Once seepage and piping have already started occurring in the dike measures can be taken to limit further erosion. This can be done by implementing filter constructions at the toe of the dike or reducing the total head loss. This is done by means of a piping berm or placing sand bags at the places where signs of piping and erosion are evident.

2.2.2 Overflow

Overflow is directly related to the flooding in the area around the Sidoarjo mud volcano. It traditionally occurs when water enters the protected area behind the dike due to a combination of high water and wave attack and the construction does not collapse, see figure 2.10. In this case water enters the protected area behind the dike during heavy rainfall periods when the mud depot fills up too high with water and the water flows over the dike onto infrastructure such as the Porong highway and railway. The lower lying area therefore flooded.

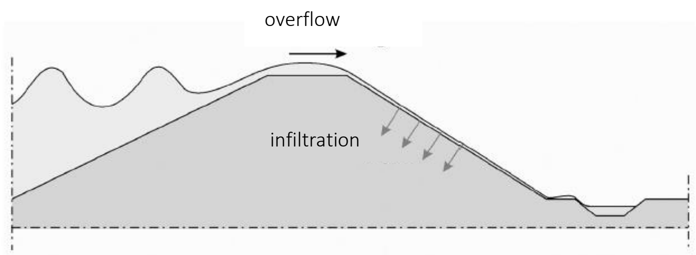


FIGURE 2.10: INFILTRATION DUE TO OVERTOPPING (TAW, TECHNISCH REPORT WATERKERENDE GRONDCONSTRUCTIES, 2001)

During infiltration of the inner slope a transition of the volumetric mass changes from γ_{dry} to γ_{wet}. The rate of infiltration depends on the amount of water flowing over the dike, the duration of the flow, and the permeability of the sand core. When the infiltration zone is saturated the water tension increases reducing the grain pressure therefore mobilising shear stress. The erosion from overflow deals with the shallow slip planes (see figure 2.11) in the top layer of the sand dike. In dikes made from more cohesive material deeper erosion will be present earlier than in less cohesive materials.

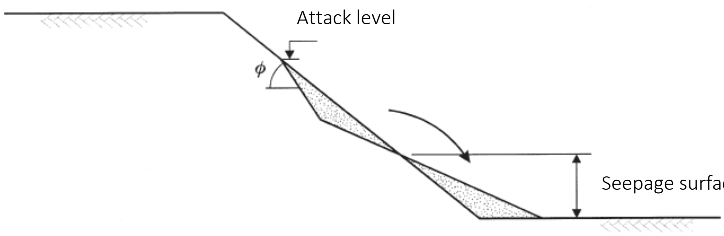


FIGURE 2.11: DAMAGE PLANES (TAW, TECHNISCH REPORT WATERKERENDE CONSTRUCTIES, 2001)

Variants to prevent overflowing from occurring include a drainage construction placed in the dike (see figure 2.14a), a discharge pipe placed over the top of the dike (see figure 2.14b), a discharge pipe placed through the dike (see figure 2.14c), or adding a revetment layer to increase erosion resistance.

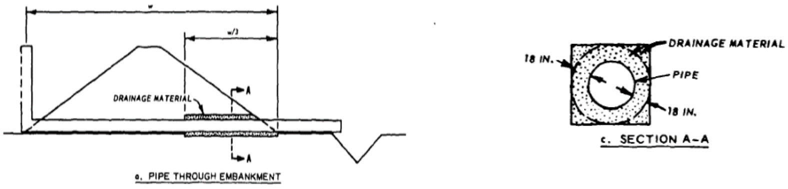


FIGURE 2.14A: DRAINAGE CONSTRUCTION THROUGH THE DIKE (HAMMER & BLACKBURN, 1977)

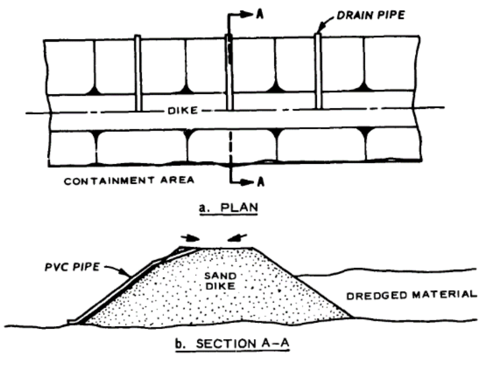


FIGURE 2.14B: DISCHARGE OVER THE DIKE (HAMMER & BLACKBURN, 1977)

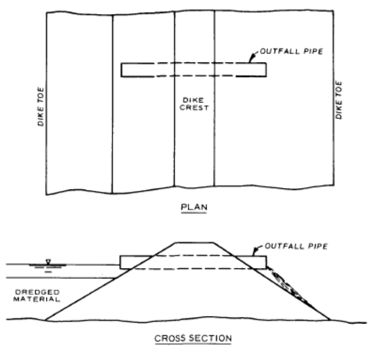


FIGURE 2.14C: DISCHARGE THROUGH THE DIKE (HAMMER & BLACKBURN, 1977)

2.3 SAFETY AND DESIGN STANDARDS

The soil conditions, available materials and pressures the dike has to resist will dictate the design and structure of the dike. It is important to recognise that a dike designed in the Netherlands will be different to one designed in Indonesia. Even in Java standards are different on each side of the island.

Standards used in the Netherlands are some of the most conservative in the world due to the risk of losing land to the sea that the country faces. Dikes have high safety because the chance of flooding and the damage it would cause in the country is very high. Comparing any dike to these standards therefore will result in an extremely low risk dike that can be adjusted to local conditions.

2.3.1 Eurocode 7: Geotechnical design

One standard used in the Netherlands is the Eurocode. It has been developed as the design standards for structures which is modified per country varying with local factors. Eurocode 7 specifically is on Geotechnical Design and shows design approach 3 that the Netherlands uses when designing for safety associated with uncertainty in loads. Load factors and partial factors are assigned for slopes according to soil parameters in the area (CEN, 2004).

2.3.2 Application of international standards

National standards are limited in terms of safety compared to those used in the Netherlands. This is because locally the threat and consequence from flooding is not as high and the social and economic risks the country faces is far lower when there are dike failures. When analysing the existing dike it is important to consider its current safety level and how it compares to that of safety standards in the Netherlands. The Dutch approach is very conservative so safety in the area will also depend on local requirements and the allowed risk involved with the flooding of the surrounding infrastructure. Standards that are available locally will be used however in the case where no standards are available Dutch standards will be used. This is done as suggestion from expert engineer at the local branch of Witteveen + Bos Indonesia as this is the approach the company takes when designing dikes in Indonesia.

3. METHODOLOGY

To research a viable dike solution and solve the problem of failures in the dike a design approach based on three elements was followed. This chapter will describe how each element was executed and the outcome is found in the Results chapter. Firstly a program of requirements was drawn up based on the functional and technical requirements. Secondly alternatives were drawn up, assessed and one solution was chosen based on a set of criteria. Lastly the final solution was designed in detail with technical calculations and drawings. For each part an appendix is available with details of the method and outcome.

To complete the research on time a work plan was created stating the communication during the project, the project activities and the products that were to be delivered. These sub chapters explain each of these aspects. A detailed timeline of the project can be found in Appendix E.

3.1 COMMUNICATION

During the research period communication was as follows with the involved organisations:

- HZ University via supervisor A. Repko through email and Skype meetings on progress and feedback of the final report and if the thesis met the requirements.
- ITS University via supervisor Pak. Wahyudi through email and weekly meetings for guidance and advise on local conditions and designing of the final dike solution.
- W+B Indonesia via supervisor T. Wilms weekly via email and Skype meetings for guidance and expert advice on local conditions and designing of the final dike solution.

3.2 PROJECT ACTIVITIES

To answer the main question and sub questions certain project activities took place. Each sub question has was made into a project activity and these are stated in this sub chapter. The sub questions were as follows (see Chapter 1):

1. What is the current situation of the dike around the mud volcano?
2. What is the program of requirements to prevent flooding?
3. Which alternatives can be used to prevent pumping mud to the Porong river?
4. What variants can be used to prevent piping and overflowing?
5. What is the most suitable alternative to prevent flooding?
6. How is the most suitable solution designed?

1. Current system analysis (answering sub question 1)

Determining client goals and wishes

To determine the client requirements an interview with the local governmental organisation - Sidoarjo Mudflow Mitigation Agency (BPLS) was held. They were responsible for constructing the original dike and monitoring the current one. For the detailed version of the lists see Appendix G.

Setting boundary conditions

- Rainfall conditions based on the rate of discharge and storm duration of 145 mm for return period of 10 years (ISJD, 2008) for a safety level requirement stated in client requirements.
- Soil and hydraulic conditions determined from data found in previous studies (Mazzini, et al., 2007) , (Agustawijaya & Sukandi, 2012) and provided by BPLS.

Determining starting points

- Daily mud outflow and duration of 15 000 m³/day and 26 years respectively (Davies, Mathias, Swarbrick, & Tingay, 2011).
- Determined design life span from duration of the mud volcano and a safety margin determined by the client requirements.

<u>Products:</u>
List of Boundary Conditions
List of Starting Points

2. Drawing up a program of requirements (answering sub questions 2)

A program of requirements was drawn up as an overview of the demands and specifications that the design has to fulfil. The requirements determine the functions that the dike solution needs to have. The detailed version of all requirements can be found in Appendix G.

Drawing up functional requirements
To determine the functional requirements of the new dike solution the wishes and goals of the client were considered as well as the objective of the research. The element functions of the dike were further defined according to the main functions of the dike with dimensional tolerances stated by the client.

Drawing up technical requirements
To determine the technical requirements the design elements, materials, viability and failure mechanisms were considered. The technical requirements of the design were found as follows:

- Assessing structural drawings of the current dike by contacting BPLS
- Determination of soil properties from Eurocode 7, specifically *"Tabel 2.b – Karakteristieke warden van grondeigenschappen"*.
- Partial safety factors for material factors determined from TAW design guide (TAW, Gondslagen voor waterkeren, 1998).
- Overall factors and design of geotechnical calculations determined from TAW design guide (TAW, Gondslagen voor waterkeren, 1998), (TAW, Technish Rapport Klei voor Dijken, 1996).
- Determine what the dimensions are based on function and materials.
- Determine how the elements need to be designed according to the applicable failure mechanisms (Deltares, Onderzoeksrapport Zandmeevoerende Wellen, 2012).

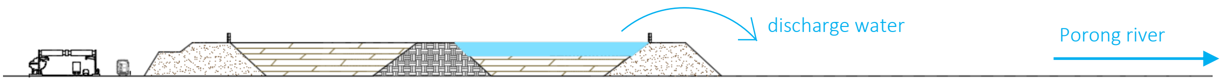
<u>Products:</u>
Functional Program of Requirements
Technical Program of Requirements

3. Setting up of alternatives and variants (answering sub questions 3 and 4)

To stop discharge of mud to the Porong river there are three options when designing a solution. First a dike can be built next to existing depot and the depot can be expanded. Secondly a dike can be built inside the existing depot where mud is being dredged away. Thirdly a buffer zone can be created before pumping away clean water. For the full details of how each alternative was designed see Appedix H and settlement tables in Appendix I. Each of these alternatives were designed with the following symbols:

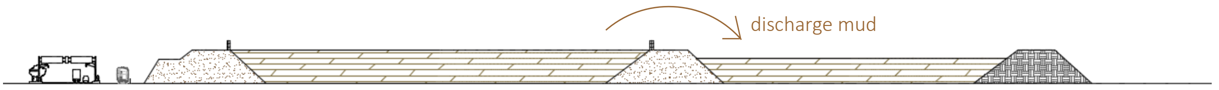
Alternative 1: Determine how a dike can be designed inside the existing mud depot

- A location was determined for the dike inside the depot according to current dredging activities.
- The dimensions of the new dike were based on the functional requirements and the cross-sections of the existing dike.
- The capacity of the new depot section was determined by using the predefined mud outflow and duration of 26 years.
- The settlement, subsidence and freeboard of the dike were based on a life span of 50 years.
- A piping resistance calculation was done according to Bligh and Lane.



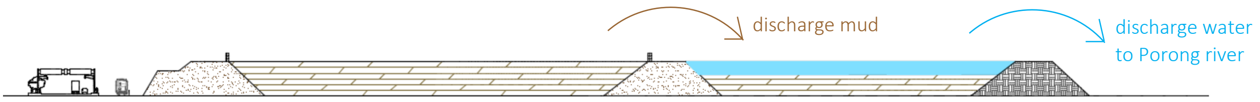
Alternative 2: Determine how a dike can be designed outside the existing mud depot

- The location possibilities were chosen according to future expansion possibilities in areas already defined as unsafe.
- The dimensions of the new dike were based on the functional requirements and the cross-sections of the existing dike.
- The capacity of the new depot section was determined by using the predefined mud outflow and duration of 26 years.
- The settlement, subsidence and freeboard of the dike were based on a life span of 50 years.
- A piping resistance calculation was done according to Bligh and Lane.



Alternative 3: Determine how a dike should be designed to create a buffer zone for the mud depot

- The location for a buffer zone determined by future expansion possibility near Porong river.
- The dimensions of the new dike were based on the functional requirements and the cross-sections of the existing dike.
- The capacity of the new depot section was determined by using the predefined mud outflow and duration of 26 years.
- The settlement, subsidence and freeboard of the dike were based on a life span of 50 years.
- A piping resistance calculation was done according to Bligh and Lane.



Calculation for alternatives global design, loads and strength of the dike using the following sources:

- Eurocode 7: Geotechnical design.
- *"Leidraad voor het ontwerpen van rivierdijken"* in Dutch.
- *"Technish Rapport Waterspanningen"* in Dutch.
- Dike model made using D-GeoStability program of Deltares for current dike sections.

<u>Products:</u>

A design of how a dike is designed inside the existing mud depot.
A design of how a dike is designed outside the existing mud depot.
A design of how a dike is designed outside the existing mud depot to create a buffer zone.

4. Setting up criteria and analysis for alternatives and variants (answering sub question 5)

Setting up criteria

In order to select a solution various criteria were chosen that influence whether a solution is satisfactory and indicates the best choice. When designing a dike the costs, benefits, function and environmental impact have to be compared to each other. The materials used in the solution, the design of elements, durability and improved conditions influence the outcome. The following list is criteria for engineering designs For details about how the alternative was chosen see Appendix H:

- Requisite standard
- Structural integrity
- Implementability
- Resilience
- Control variability
- Reliability
- Adaptability
- Cost

Criteria analysis of alternatives

Once the criteria were set up each alternative was assessed individually. The advantage or disadvantage of each element was weighed against the criteria and what influence it had. This was done using a Cost Benefit Analysis approach as a way to determine what alternative is most suitable for the problem.

Products:

Cost benefit analysis of the alternatives and variants

A design choice of an alternative with the most suitable variant according to the analysis outcome.

5. Detailing, calculating and drawing (answering sub question 6)

Once an alternative was chosen according to the criteria analysis it was designed in detail, calculated and drawn. The detailed engineering was to verify that the solution is viable and that the failure mechanisms are prevented. The existing dike was checked for failures as well as the new design. For the extended explanation of the calculations see Appendix J and for drawings see Appendix L.

All calculations were using international as well as national references. Consultation was done with experts from Witteveen+Bos and ITS. Below the literature used for each calculation can be found. Calculations were done independently and then reviewed. The results of the calculations determine the adjustments or improvements that are to be made on the design.

Calculation of piping on the structures using the following sources:

- "Onderzoeksrapport Zeemmevoerende Wellen" in Dutch (Deltares, Zandmeevoerende Wellen, 2012).
- "Technisch Rapport Waterkerende Grondconstructies" in Dutch of TAW.
- "Grondslagen voor waterkeren" in Dutch of TAW.
- Dike model made using M-Seep program of Deltares.
- "Werkwijzer Piping bij Dijken" in Dutch by Rijkswaterstaat.
- Variants for preventing and controlling piping were designed (see Theoretical Framework).

Calculation of erosion on the structures using the following sources:

- "Technisch Report Waterkerende Constructies" in Dutch to determine erosion by overflow.
- "Leidraad voor het ontwerpen van rivierdijken" in Dutch to determine micro-instability in earth structures.
- Variants for preventing and controlling overflow were designed (see Theoretical Framework).

Technical drawing of the solution using the following sources:

- Technical drawings were done in AutoCad according to HZ University standards.

- An overview drawing was made to give an idea of the layout and placing of the design.
- Cross-sectional drawings were made showing the elements of the dike structures and variant solutions indicating materials.
- Detailed drawings were made showing connections between existing infrastructure and components of the dike solution.

Products:
A detailed calculation of the loads and strength of the dike solution.
A calculation of piping in the structure with and without the preventive measure variant.
A calculation of erosion on the structure with and without the preventive measure variant.
An overview drawing of the layout and placing of the dike.
Cross-section drawings at several locations of the dike.
Detailed drawings showing important feature of the new dike.

3.3 SCOPE OF THE THESIS

Due to the limited time to finish the research, boundaries were set for this final thesis. The list below shows the areas that will and will not be part of the final thesis:

- The thesis will be focused on a solution for the flooding risk on the infrastructure and the surrounding living area.
- The possibility to relocate houses to a location with lower risk of being flooded will fall outside of the scope.
- The relocation of the 'Porong Highway' will fall outside of the scope.
- The relocation of the railway behind the dike will fall outside of the scope.
- The research for another use for the mud from the volcano will fall outside of the scope.
- The possibilities to stop the mud flow completely will fall outside the scope due to all previous attempts from the municipality failing.
- The construction of a combi-wall will fall outside of the scope due to it not being technically realistic and steel prices in Indonesia are extremely high which concludes that this option will not be viable.
- There will not be a detailed calculation done on every relevant failure mechanism, only piping and overflow will be calculated in detail.
- No construction plan will be drawn up for the detailed solution.
- The research will fulfil the HZ University final thesis requirements of a final year civil engineering student.
- A design and calculation of the pumping system needed for the depot is not calculated.
- The method for separation of the mud into water and fine sediment will is outside the scope.

3.4 QUALITY CONTROL

In order to certify that the process and products of the research were at the required standard supervision and advise was taken from three institutions. The process and set up of the research and reports were assessed by HZ University and adjustments were made according to feedback, this ensures the report met the HZ University requirements. The second institution was Witteveen + Bos, an engineering company, and their advice ensure the products meet professional standards as they have work experience in the civil engineering field in the Netherlands and Indonesia. The final institution is ITS University which too provided guidance and support during the research and verified the calculations and designs that were made to make sure they are viable on a national level.

4. RESULTS

The outcome of the research is divided up into various products and the overview of the results are explained in this chapter. Firstly the requirements of the research and design are stated followed by the analysis of the three alternative design options. The chapter is finished by discussing the outcome of the detailed design of the chosen solution which includes calculation, modelling and technical drawings.

4.1 PROGRAM OF REQUIREMENTS

The final designed solution must meet certain functional and technical requirements that are determined by the client as well as national and international standards. This sub chapter will describe these requirements and an extended version can be found in Appendix G as well as the boundary conditions and starting points of the research.

4.1.1 Boundary Conditions

Hydraulic Boundary Conditions

- The design water level refers to the mud level that inside the mud depot of the new situation.
- Wave attack is not applicable to the situation.
- Ground-water level is taken as the polder water level in the area next to the dike.
- Rapid fall after high water is not applicable to this situation.

Rainfall

In addition to the design water levels, the influence of extreme rainfall has to be considered. The Probable Maximum Precipitation (PMP) in Porong of 507mm is used to calculate the required freeboard. The relationship between amount of rainfall and rise in water pressure is used to predict the effect of extreme rainfall.

Design life span

The design life span is 50 years which includes the assumption that the mud volcano will erupt for the next 26 years. The mud outflow is taken as 10,000 m^3 a day for the duration of the eruption (Davies, Mathias, Swarbrick, & Tingay, 2011).

Water discharge

The mud mixture is pumped away to the Porong river with a discharge of 0.8m^3/s. The water quality of the Porong river will not be assessed but the assumption is made that stopping pumping mud to the river will be beneficial for the ecological condition.

Additional loads

Loads that will not be calculated or are not applicable are chance of explosions, drifting objects, biological degradation, chemical degradation and vandalism.

4.1.2 Starting Points

To design a solution to cope with the current problems around the dike starting points are needed. Available information and data will be used when calculating aspects of the existing dike. This information includes the dike structure and soil properties of the foundation and core.

Geotechnical Aspects

The dike core has been constructed with a gravel and sand mixture and the underlying layers are defined in the Theoretical Framework chapter. The extended soil properties of the layers can be seen in Appendix C along with the drilling log showing the composition of the layers in Appendix D.

Crest level of existing dike

The crest level of the existing dike is taken from the cross sections of each alternative that show the original dike and the existing situation after settlement and subsidence. Originally the crest of the existing dike was at 11m and after subsidence it has been reduced by almost 2m in some places.

Slope protection of existing dike

A gabion wall using wire mesh and rocks was used to stabilise the dike near the Porong highway and railway at some locations. A higher gabion wall was used next to the highway as the risk of failure is greater at this location. The rest of the dike ring has little or no gabion wall.

4.1.3 Functional schedule of requirements

The ability of the dike to function primarily depends on the crest height. The rest of the elements are then put in place to keep the position and height of the crest in place. The dimensioning of the dike is done so that the dike can withstand loads acting on the dike, in this case the mud pressure and rainfall. The functional requirements are comprised of the structure functions and the element functions.

Structure functions

- Retaining dike: the primary function of the dike is to contain the mud that is erupting from the mud volcano. The capacity of the new solution will be based on the assumption that the volcano will be erupting for 26 more years.
- Flooding protection: the new dike solution will have to prevent flooding from occurring for a return period of 1000 years. This is done in order to protect infrastructure and living area behind the dikes from flooding from overflow.
- Ecological improvement: in order to improve the ecological situation of the Porong river the mud that is being pumped there has to be dealt with. Either the pumping of mud to the river is stopped or the mud and water is separated to reduce the toxic discharge to the river.
- Prevent breakthroughs: in addition to retaining the mud the dike solution should prevent dike failure specifically due to water pressures. The dike will be designed as a lake dike under Dutch standards. Micro-instability and piping will be calculated in detail and settlement and macro-instability will be calculated on a more global scale.

Element Functions

- Crest: at a level that prevents flooding and a high overflow discharge. The height is determined by the existing dike height and mud level plus a freeboard. The freeboard compensates for settlement, subsidence, rainfall and a safety factor for the design life of the dike.
- Core: the support structure that carries the various elements. The core itself has to be stable in carrying internal and external forces. The core usually cannot resist external loads such as over flows and is therefore protected with revetment.
- Outer Slope: usually defined as the slope in direct contact with water and/or waves, in this case the mud. The outer slope is used to reduce wave run-up however in this case this is not a threat to the outer slope. The slope should keep the dike stable and prevent erosion which results in instability

- Inner Slope: the slope affected when there is overflow or discharge or water over the dike. The function of the inner slope is to prevent excessive erosion of the dike. Infiltration of the over flow water also affects the local stability of the dike. The slope gradient is decisive for determining the safety against failure in the dike. An inner berm is used to further ensure the stability of the dike by reducing the slip circle and increasing the slip resistance.
- Revetment: depends on water attack on the dike and the change in water level. In this case the change in water level is low as there in no tidal influence. Revetment is therefore only necessary to prevent erosion if there is extreme rainfall over flow over the dike or locally erosion from water pressures.
- Ditch: placed behind the dike to positively influence the ground water level and water pressure in the dike. Implementing a ditch can create risk for uplifting or act as the exit point for piping therefore the leakage length is carefully considered when deciding the location of the ditch. The ditch is also a discharge vessel for rainfall or water flowing over the dike or discharged through a drainage facility.
- Foundation: the soil layers that the dike rests upon and is important when considering settlement and piping failure in the dike. The solution should compensate for the permeable layers that are underneath the dike as it presents the risk of allowing water flow.

4.1.4 Technical schedule of requirements

The technical design of the solution has to meet various requirements that are specific to the structural integrity. This sub chapter describes the requirements for the global design, the loads involved in calculations and the requirements for overflow and piping resistance. The global design of each alternative will follow the design standard of the Dutch system stated in Eurocode 7 and the guidelines of the Technische Adviescommissie voor de Waterkeringen (TAW). The dike will be designed as a lake dike under Dutch standards. Usually wave run up plays an important role in determining dike height however for a lake dike a surcharge of 0.1m is used.

Global Design

- Crest of the dike: should have a width of at least 3m, consideration for a maintenance path. The height of the crest should include a minimum free board 0.5m and accommodate for settlement, subsidence, extreme rainfall and safety.
- Revetment layer of the dike: if a clay revetment layer is used on the dike is should be at least 0.5m thick and calculation should be done on slope with the combination of the clay and grass type used.
- Slope: tested on the overflow discharge of 1l/m/s and using Joustra and Edelman check. If the slope is still not satisfactory it should be adjusted until it is satisfactory according to Bishop.
- Berm: height between 0.2 and 0.25 times the height of the dike with slope between 1:15 to 20 and should have satisfactory width for macro stability and acceptable piping resistance.
- A stability factor greater than or equal to 1.0.
- Settlement calculation using the Koppejan formula.
- Shear strength calculation using the formula: $\tau'_{kr} = c' + \sigma_n' \tan \phi'$.
- Geo-hydraulic aspects: calculation is done using a non-stationary flow and a capillary zone with degree of saturation S_w = 75%. The capillary rise (above the water table) in coarse sand is between 0.02-0.05 m, in moderately fine to medium coarse sand between 0.12 to 0.35 m, 0.70 to 1.50 m in silt and clay 2-4 m.

Loads on the dike

- Safety factors for shear resistance: inner slope: $\gamma_n = 1.1\ and\ \gamma_d = 1.0$ and outer slope: $\gamma_n = 1.0\ and\ \gamma_d = 1.0$.
- Permanent loads defined as: self-weight of the dike due to material used and soil pressure of the underground layers.
- Hydraulic loads defined as: extreme rainfall of 507mm, discharge over the dike fulfil 1l/m/s, decisive load as a combination of high water level and storm duration of t_s = 35hr, rapid fall of water level time = 0.5 t_s.
- Other loads defined as: traffic load for stability using a uniform load of 400kN per 12m converted to 13.3kN/m over a width of 2.5m, earthquake chance of failure for 1 in 100 years (SLS) and 1 in 3000 (ULS).
- Subsidence: the ground underneath the dike and surrounding the mud depot has subsided greatly since the eruption in 2006, 1.5 meters in three years in some places. It is clear that the subsidence is decreasing every year and is currently only a couple of centimetres per year. Subsidence effect on the dike height difference will be calculated at 1cm/year.

Overflow Resistance

- Over flow discharge: for an over flow discharge lower than 0.1l/m/s it can be assumed that infiltration is insignificant enough that no increased water pressure occurs and therefore no risk of failure.
- Grass cover: begins at the average high water level + 1m, outer slope at least 1:3 and the clay thickness is 0.8m, inner slope ideally is not steeper than 1:3 and clay layer of 0.6m, crest width is between 2 to 3m with a clay layer of 0.8m.
- Internal Erosion: filter protection shall be used when a ultimate limit state due to internal erosion occurs. This protection is a natural non-cohesive soil or geotextile.

Piping Resistance

- The piping resistance of the alternative designs should satisfy the Bligh and Lane requirements for leakage length. The detailed chosen solution should satisfy the Sellmeijer model.
- Rule of Bligh: leakage length (L) is greater than or equal to creep coefficient (c) x design drop (hydraulic head) across the dike (H).
- Rule of Lane: takes into account the vertical component leakage path.
- Sellmeijer Model: the relationship between critical head loss and a number of parameters that influence the geometry of the dike and material properties of the soil (layer exposed to erosion).
- Piping failure: where piping endangers the stability or serviceability of the hydraulic structure, prescriptive measures shall be taken to prevent the onset of the piping process, either by the application of filters or by taking structural measures to control or to block the ground-water flow. If a piping berm is used the thickness is chosen when the overpressure safety of 1.05 is reached.

4.2 ALTERNATIVE ANALYSIS

If the mud is expected to keep flowing for the coming 26 years with a daily outflow of 10 000m³ every day, then a total of 87 million m³ of mud has to be accommodated for. If the soil and water in the mud is separated this volume is 26 million m³. This chapter describes how the best alternative was chosen to achieve the solution. The perimeter of the existing dike can be seen in figure 4.1.

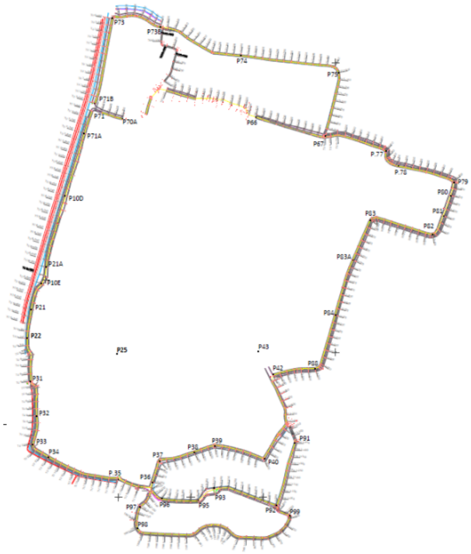


FIGURE 4.1: PERIMETER OUTLINE OF EXISTING DIKE STRUCTURE (BPLS, 2016)

To accommodate for more mud using a dike design there are a three options that can be combined with variants to prevent the failures from occurring. The three alternatives can be seen in figure 4.2 which indicates the variations and their expansion possibilities. The best alternative in combination with the best variant was analysed according to set criteria and the final solution was designed in detail.

Depending on the alternative different variants are used in combination to prevent piping and overflow from occurring. The variants that are mentioned relate specifically to the failure mechanisms that have to be prevented.

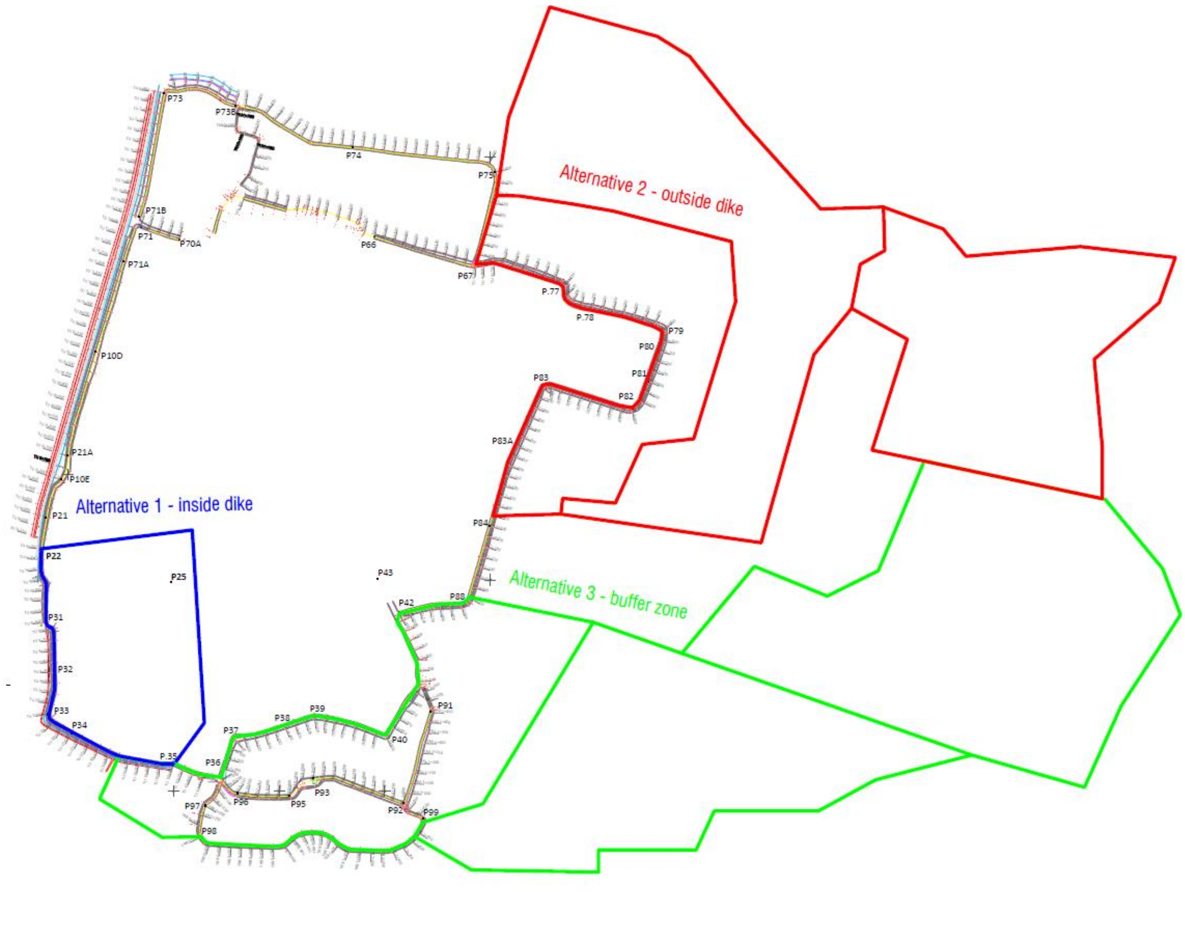


FIGURE 4.2: PERIMETER OUTLINE WITH EXPANSION POSSIBILITIES OF EACH ALTERNATIVE

4.2.1 Dike structure inside the depot

Alternative 1 is a dike inside the mud depot at the location where current dredging is taking place. This dike will cut off a small section inside the current mud depot. This section of the mud depot can be drained of water and creating extra space, to pump mud to, is the main advantage. The main disadvantage is that the new section will have to be drained and this involves determining a way to make space inside the current depot.

Global dimensioning of new dike:

- Mud Level: 7.8m
- Crest level: 11.55m
- Berm height: 8.65m
- Volume of sand and clay: 269 231m³; 18 903 m³
- Settlement calculation: 2.5m
- Piping calculation of existing dike: unsatisfactory
- Piping calculation of new dike: satisfactory
- Area: 733 930m²
- Dike length: 1 835m
- Mud capacity: 5 724 654m³
- Year till full: 5.3years

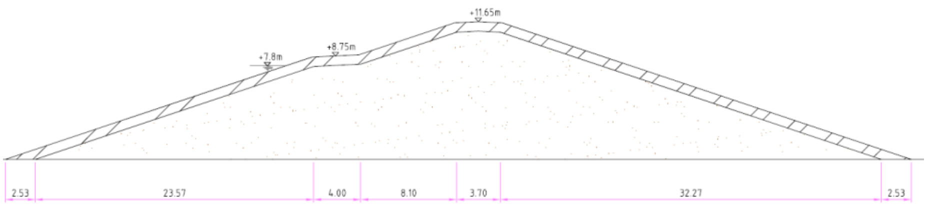


FIGURE 4.3: ALTERNATIVE 1 NEW DIKE CROSS SECTION

Assessment of the alternative includes global dimensioning (see figure 4.3) of the new dike section with a settlement and piping calculation as well as the capacity of the new depot. For further details of calculations see Appendix H.

4.2.2 Dike structure outside the depot

Alternative 2 is to build a dike outside the mud depot that connects to the existing dike and increases the capacity of the mud depot. The main advantage of this is that mud will not have to be pumped to the Porong river however the main disadvantage is that land will needed for the new extension and either people will have to be relocated or farmland will be lost.

Global dimensioning of new dike:

- Mud Level new dike: 9.1m
- Crest level: 13.12m
- Berm height: 9.95m
- Volume of sand and clay: 546 502m³; 34 173 m³
- Settlement calculation: 2.67m
- Piping calculation of existing dike: unsatisfactory
- Piping calculation of new dike: satisfactory
- Area: 4 131 312m²

- Dike length: 3 292m
- Mud capacity: 29 741 315m³
- Year till full: 8.1years

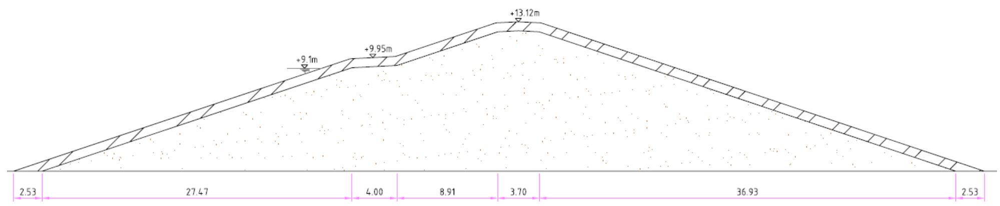


FIGURE 4.4: : ALTERNATIVE 2 NEW DIKE CROSS SECTION

Assessment of the alternative includes global dimensioning (see figure 4.4) of the new dike section with a settlement and piping calculation as well as the capacity of the new depot. For further details of calculations see Appendix H.

4.2.3 Dike structure as buffer zone

Alternative 3 is to create a buffer zone between the current depot and the pumping to the Porong river. Here a dike will also be built outside the current mud depot however the new area that is created will act as an area where the mud and water can be separated and the water can be pumped away. The main advantage is that the water that is pumped away will not be harmful to the environment. The main disadvantage is that land will needed for the new extension like in Alternative 1.

- Mud Level new dike: 6.9m
- Crest level: 10.51m
- Berm height: 7.75m
- Volume of sand and clay: 355 009m³; 27 574m³
- Settlement calculation: 2.26m
- Piping calculation of existing dike: unsatisfactory
- Piping calculation of new dike: satisfactory
- Area: 4 242 295m²
- Dike length: 2 651m
- Mud capacity: 29 186 990m³
- Year till full: 26.7years

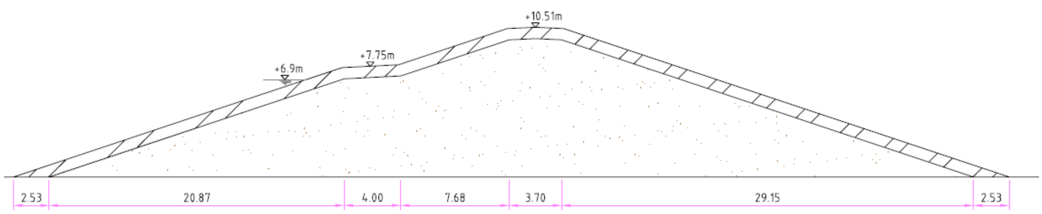


FIGURE 4.5: ALTERNATIVE 3 NEW DIKE CROSS SECTION

Assessment of the alternative includes global dimensioning (see figure 4.5) of the new dike section with a settlement and piping calculation as well as the capacity of the new depot. For further details of calculations see Appendix H.

4.2.4 Criteria Analysis

Each alternative has an analysis path to follow if it chosen and according to this path certain variants are applicable. Figure 4.6 shows the path of each solution and which variants are applicable.

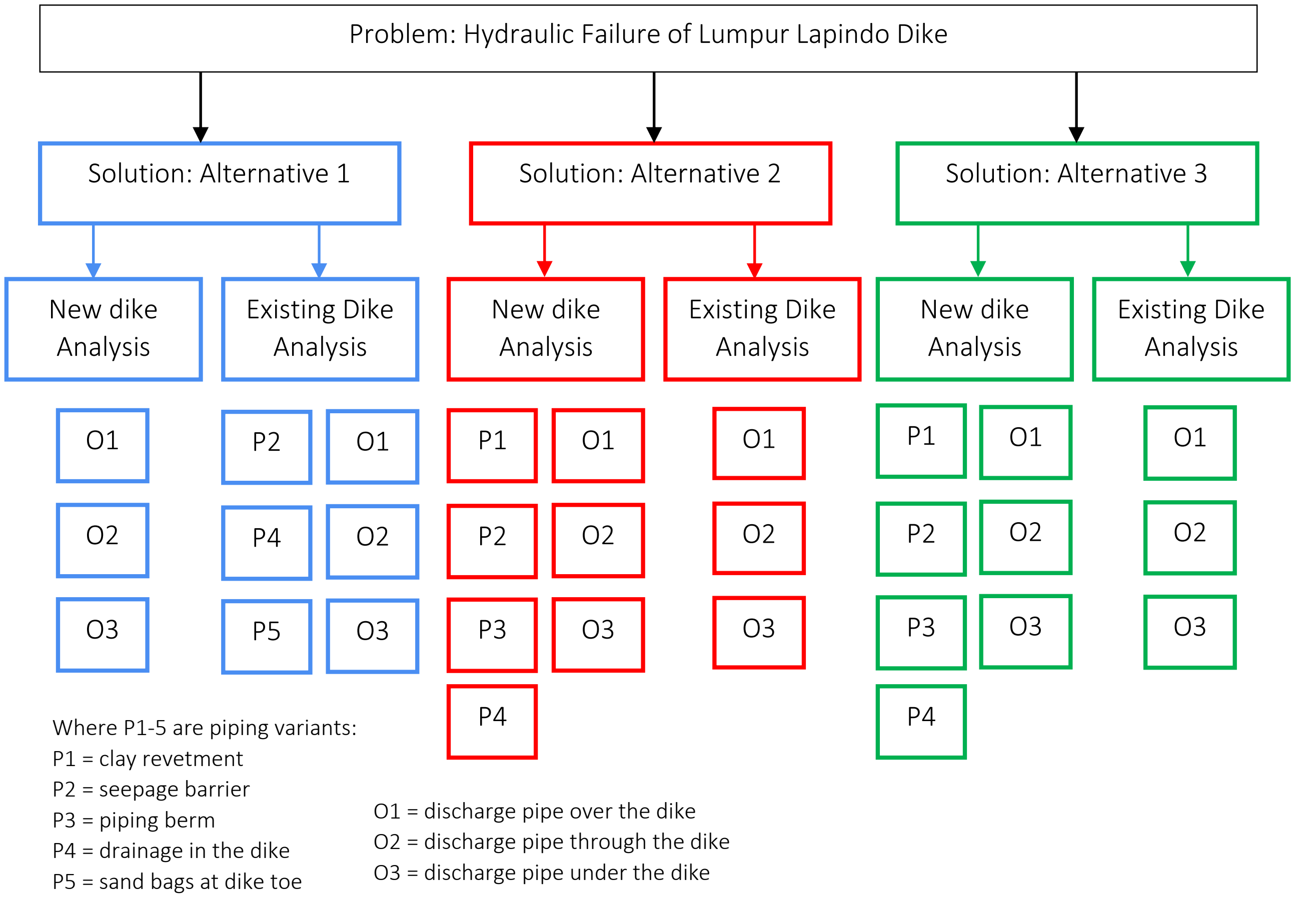


FIGURE 4.6: ANALYSIS PATH PER ALTERNATIVE SOLUTION

To determine which alternative is the best solution this path is considered and a criteria analysis is done looking at 8 criteria specific to engineering designs. Each alternative was given a weighting per criteria from 1 to 5 with 5 being very important and 1 less important (see Table 4-1). Within each criteria each specific factors are also rated. The rating is totalled for each criteria and multiplied by the importance. The alternative with highest score is the most suitable as the solution (see Table 4-2). Below is a description as to why each criteria was scored the way it was. For a detailed explanation of each factor and its rating see Appendix H.

1. **Requisite standard**

   This criteria is given an importance of 5 as this is one of the main requirements of the client and the research. If the solution does not fulfil this criteria then it cannot function to the required standard.

   1.1. Retaining mud – Alternative 3 scored highest here due to the fact that it can accommodate the most mud followed by 2 and then 1

   1.2. Flooding resistance – Alternative 3 scored highest here as it will increase the flooding resistance the most and control the water outflow to Porong river.

   1.3. Ecological improvement – Alternative 3 scored highest here as it is the solution that will create the space that no mud has to be pumped to the Porong river for the entire duration of the expected eruption period. The other alternatives improve the situation temporarily.

2. Structural integrity
   This criteria is given an importance of 5 as this is also one of the main requirements of the research. If the solution does not fulfil the resistance to the failures in the dike then it is not a suitable solution.
   2.1. Piping resistance – Alternative 2 and 3 score the highest as they both reduce the piping problem in the existing dike by creating a new depot. Design considerations can be taken when designing the new dike.
   2.2. Over flow resistance – Alternative 2 and 3 score the highest here as well. Implementing preventative solutions are more favourable than trying to solve the current problems.
   2.3. Settlement – the amount of settlement and extra sand that will be needed for the new design is lowest for Alternative 1 and therefore it scores the highest.

3. Implementability
   This criteria was given an importance of 4 as it will determine if the solution can be used in locally. The idea may be good however if it cannot be implemented easily there is little motivation to design it.
   3.1. Separation of sediment and water (Alternative 1 and 3) – Alternative 1 and 3 score low here as they require a technique in separating the mud and water so that water can be pumped to the Porong river that is not harmful. Alternative 2 scores very high as it does not require any techniques to separate the mud.
   3.2. Rerouting pumping system to Porong river – All the alternatives score low here as they all require rerouting of the pumping system that is in place.
   3.3. New pumping system to new depot section – All the alternatives score low here as they will all require a system to either pump from the existing depot to the new one or from the new one to the Porong river.
   3.4. Dewatering current depot (Alternative 1) – Alternative 1 scores low here as it is the only solution that requires dewatering part of the current depot and building a new dike in the current depot which is technically very challenging.

4. Resilience
   This criteria is given an importance of 2 as withstanding a first attack or loading is more important than its ability to withstand a second. The solution is for a natural disaster and therefore any situation that usually is seen as extreme is not as severe in this case.
   4.1. Extreme rainfall – All the alternatives are given the same score for resilience as they are not specifically designed for this however it is important to consider in the design.

5. Control environmental variability
   This criteria is given an importance of 4 as it is a main requirement of the client as the main affected area that is at risk is directly next to the dike. The highway and railway are extremely important to keep assessable and to reduce the risk of damage.
   5.1. Porong highway and railway access – All the alternatives scored the same for this criteria as they all provide a solution to reduce the risk of flooding and damage. The solutions differ however they are all able to achieve the same result.

6. Reliability
   This criteria was given an importance of 5 as it is critical that the dike does not fail often. The maintenance should not be high as in practice in the area maintenance will only be implemented if it is minimal. The dike is protecting important infrastructure and communities and should be reliable.

6.1. Maintenance – Alternative 2 scored the highest as it does not require any treatment of the mud and therefore the method of separating the mud does not have to be maintained. Alternative 3 scored the lowest as it requires extra maintenance for the separation as well as the pumping to the river and new dike that is built.
6.2. Resistance to breakthroughs – All the alternatives scored the same as they are designed to be equally resistant to breakthroughs however the implementation of these measures differs for each alternative.
6.3. Damage from breakthrough – Alternative 2 scored the highest here as a breakthrough would mean damage to the main highway and railway therefore it has a higher importance and should be chosen as the risk of damage is greatest.

7. Adaptability

This criteria is given an importance of 2 as is not a defining requirement of the research or the client. The possibility for future construction or extension is necessary however if a design solves the problem that is currently occurring then it is seen as a viable solution.

7.1. Expansion possibility – Alternative 2 and 3 has the possibility to expand and increase their capacity to hold the mud. Alternative 1 does not have this option and therefore scored low.
7.2. Mud flow increase – Alternative 2 and 3 are also able to accommodate more mud in the event that the mud does not stop erupting in the future. These alternatives can be heightened or the area that they take up can be extended.

8. Cost

This criteria was given an importance of 3 as it is one of the deciding factors when a design is chosen or not however is not a main requirement of the research or the client.

8.1. Dike construction (length and materials) – Alternative 1 scored the highest as it has the shortest dike length and height and therefore less construction time and materials. Alternative 2 scored the lowest as the length of the dike is the longest with the lowest capacity of mud ratio.
8.2. Land acquisition (Alternative 2 and 3) – Alternative 1 scored the lowest as no costs are required to acquire land and no compensation to local communities is needed.

TABLE 4-1: WEIGHTING PER FACTOR FOR EACH ALTERNATIVE

Criteria	Importance	Alternative 1	Alternative 2	Alternative 3
Requisite standard (total)	5	8	9	15
Retaining mud capacity		2	3	5
Flooding resistance		3	4	5
Ecological improvement		3	2	5
Structural integrity	5	13	13	14
Piping resistance		4	5	5
Over flow resistance		4	5	5
Settlement		5	3	4
Implementablity	4	4	12	8
Sediment and water separation		1	5	1
New pumping system		1	1	1
Rerouting current pupming system		1	1	1
Dewatering current depot		1	5	5
Resilience	2	5	5	5
Extreme rainfall		5	5	5
Control environmental variability	4	5	5	5
Porong highway and railway access		5	5	5
Reliability	5	8	8	5
Maintenance		3	4	2
Resistance to breakthroughs		1	1	1
Damage from breakthrough		4	3	2
Adaptability	2	2	9	9
Expansion possibility		1	4	5
Mud flow increase		1	5	4
Cost	3	15	8	10
Dike construction (length)		5	3	4
Dike construction (material volume)		5	3	4
Land acquisition		5	2	2
TOTAL		60	69	71

Alternative 3 has the highest score after the weighted criteria have been summed up followed by Alternative 2 and then Alternative 1. The area that Alternative 3 scored significantly more in is requisite standard due to the fact that with this alternative the accommodation of mud is for a duration longer than 26 years. This is possible if the mud is separated into soil and water with the water pumped away to the Porong river. This separation of the mud is the reason that Alternative 3 scores low in the Implementability and Reliability criteria. Alternative 2 and 3 also have a much higher score for adaptability due to the fact that they both have large expansion options and the solution can be tested and implemented in phases, with Alternative 1 this is not possible.

TABLE 4-2: IMPORTANCE AND FINAL SCORE FOR EACH ALTERNATIVE

	Requisite standard	Structural integrity	Implementablity	Resilience	Control environmental variability	Reliability	Adaptability	Implementation	Weighted total
Importance	5	5	4	2	4	5	2	3	
Alternative 1	40	65	16	10	20	40	4	45	240
Alternative 2	45	65	48	10	20	40	18	24	270
Alternative 3	75	70	32	10	20	25	18	30	280

4.3 DETAILED ENGINEERING

The chosen solution is designed in detail for the existing dike sections and the new dike design. The dike sections are analysed by modelling the dike sections in MSeep and D-GeoStability to compare hand calculations to the results. The detail results and method of calculation is found in Appendix J.

4.3.1 Piping calculation

The first step to determine if piping is a possibility in the designed solution a blow-out check is done. If the outcome is unsatisfactory further analysis is done. In this case the situation is modelled using the Sellmeijer method and checked with MSeep. If the outcome is still unsatisfactory the design has to be adjusted.

1. Blow-out check:
   $$condition: \frac{\sigma_g}{\sigma_w} = \frac{\gamma_{sat} - \gamma_w}{\gamma_w} * \frac{d}{\phi_{z,g} - h_p} \geq 1.2 * \gamma_b$$
2. Sellmeijer method:
   $$condition: \frac{\Delta H_c}{\gamma_n \gamma_b} > (\Delta H - 0.3d)$$
   $$therefore: \Delta H_c \geq 9.438m$$
   $$with\ \Delta H_c = L\, F_{resistance}\, F_{scale}\, F_{geometry}$$

New Dike Section:

1. $\frac{\sigma_g}{\sigma_w} = 0.3 < 1.2$ Unsatisfactory therefore subject to blow-out and piping
2. $\Delta H_c \geq 9.438m$ with $\Delta H_c = 20.03m$ therefore satisfactory

Existing Dike Section 3a:

1. $\frac{\sigma_g}{\sigma_w} = 0.69 < 1.2$ Unsatisfactory therefore subject to blow-out and piping
2. $\Delta H_c \geq 2m$ with $\Delta H_c = 6.45m$ therefore satisfactory

Existing Dike Section 3b:

1. $\frac{\sigma_g}{\sigma_w} = 0.4 < 1.2$ Unsatisfactory therefore subject to blow-out and piping
2. $\Delta H_c \geq 7.7m$ with $\Delta H_c = 11.05m$ therefore satisfactory

4.3.2 Overflow calculation

To determine if the dike is satisfactory against overflow the slope of the dike has to be analysed to determine if it is resistant should overflow occur. The dike should have a freeboard that is large enough to satisfy a resistance to the rise in water level of PMP rainfall. A sensitivity analysis was done for this calculation and are discussed in Chapter 5.

1. Determination of maximum overflow discharge.
2. Joustra and Edelman slope check on overflow discharge:

$$\tan\emptyset \;\geq\; \frac{\gamma_d\,\gamma_{m,\emptyset}\,\gamma_n\rho_g\sin\alpha - \gamma_{m,\emptyset}\,\gamma_{m,p}\,\dfrac{C}{\gamma_{m,c}\,d}}{\rho_g g\cos\alpha - \rho_w g\,\cos\alpha}$$

3. Slope check using Bishop method (see sub-chapter 4.3.4).

4. Shear strength check:

$$\cos\alpha \geq \frac{\gamma_d\,\gamma_{m,p}\,\gamma_n\rho_w(h-z)}{\rho_g d}$$

5. Microstability check:

$$\frac{2cd}{\gamma_{m,c}} + \frac{\rho_g g}{\gamma_{m,p}}\Delta xt\,\cos\alpha + \frac{\rho_g g}{\gamma_{m,p}}\Delta xd\,\sin\alpha\frac{\tan\phi}{\gamma_{m,p}} \;\geq\; \gamma_d\,\gamma_n(\Delta h - \frac{1}{2}\Delta x\sin\alpha)\frac{\rho_w g}{\gamma_{m,p}}\Delta x$$

New Dike Section:

1. Maximum overflow discharge: 0.59l/m/s is satisfactory.
2. Not applicable due to step 1 being satisfactory.
3. Slope is stable with safety factor of 1.87.
4. $\cos 18.44° \geq 0.89$ therefore satisfactory shear resistance.
5. $8527.98 \geq 5465.72$ therefore satisfactory microstability.

Existing Dike Section 3a:

1. Maximum overflow discharge: 0.98 l/m/s is unsatisfactory
2. Joustra and Edelman slope check on overflow discharge: $0.315 \geq 0.192$ therefore satisfactory.
3. Slope is stable with safety factor of 1.78.
4. $\cos 23.13° < 2.88$ therefore shear resistance is unsatisfactory.
5. $6584.04 \geq 5376.1$ therefore satisfactory microstability.

Existing Dike Section 3b:

1. Maximum overflow discharge: 0.81 l/m/s is unsatisfactory
2. Joustra and Edelman slope check on overflow discharge: : $0.32 < 0.42$ therefore unsatisfactory.
3. Slope is unstable with safety factor of 1.24.
4. $\cos 41.3° < 2.88$ therefore shear resistance is unsatisfactory.
5. $5549.14 \geq 4955.76$ therefore satisfactory microstability.

4.3.3 MSeep Modelling

This computer program is used to analyse the groundwater flow for the dike cross sections, 3b and the new dike design. The geometry is imported form D-GeoStability with the soil properties as defined in Appendix C. After the geometry has been created the boundaries of the model can be defined. To determine the groundwater flow in the structure the potential boundaries are entered. The first boundary is where the mud level is in relation to the dike. The second boundary is at groundwater level on the opposite side of the dike.

The program then determines the groundwater flow based on the permeability in each soil layer and the difference in pore pressures. This is done for each mesh element that is defined by the program with the following inputs and outputs:

1. Input: potential boundary lines – these lines are defined by the boundaries corresponding with water levels. In this case this refers to the mud level on the one side of the dike and the ground water (-1m) on the opposite side of the dike. The mud is modelled as water as this is the least favourable condition.
2. Output: Contour potentials – this output shows the pattern of the potential change in the dike and the underlying layers. The potentials decreases as you move from high water level to low water level (groundwater level).
3. Output: Contour velocities – this output shows the groundwater flow in each layer as well as the dike. In layers that have low permeability no water will flow. This output shows where the water is able to enter the dike and where the exit point it. This indicates the potential for piping.
4. Output: pressure levels – this output shows the change in pressure through the dike and the underlying layers. The deeper you go in the soil the higher the pressure.

The contour velocities output is shown in figures 4.7 – 4.9 and the rest of the inputs and outputs are shown in Appendix J.

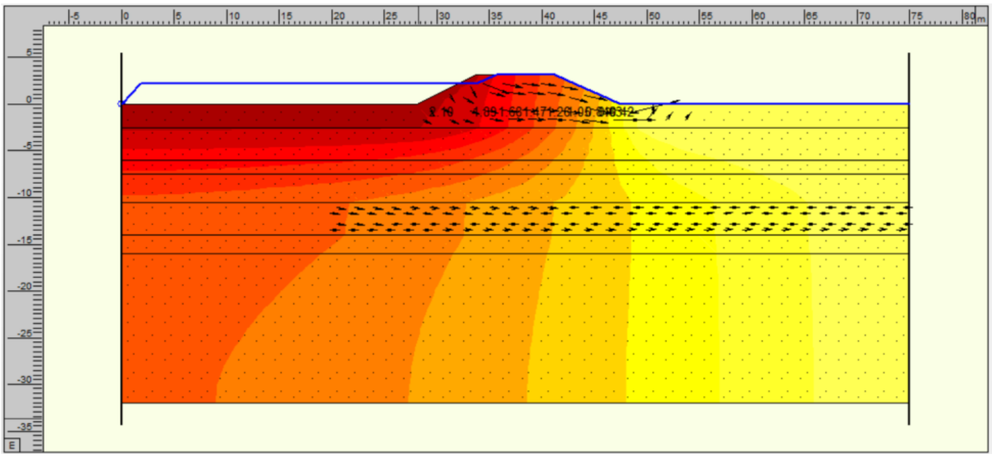


FIGURE 4.7: CONTOUR VELOCITIES DIKE SECTION 3A

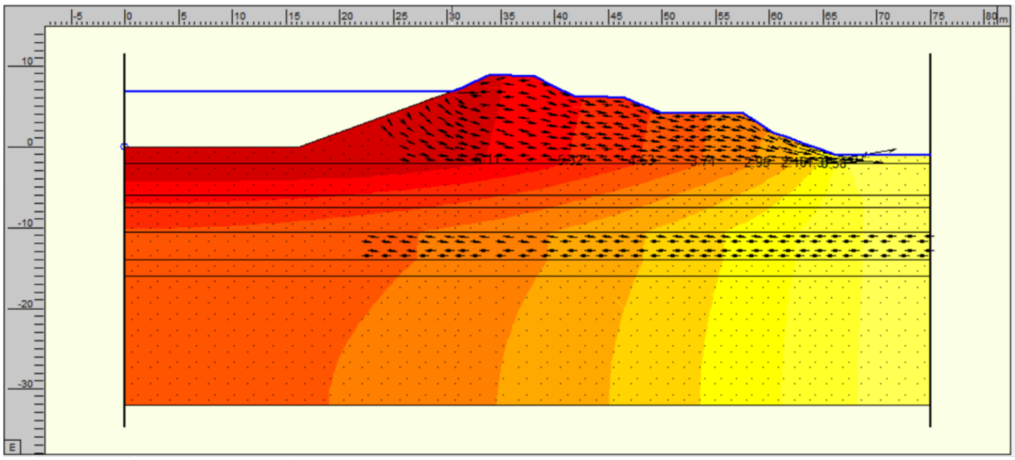


FIGURE 4.8: CONTROU VELOCITIES DIKE SECTION 3B

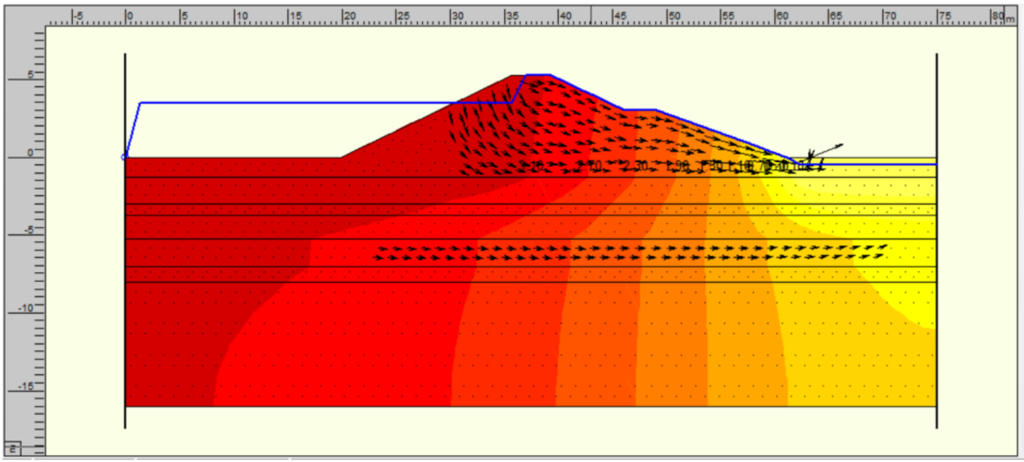


FIGURE 4.9: CONTOUR VELOCITIES NEW DIKE DESIGN

It is clear from the models that sand layers in the underground are able to allow for groundwater flow. Water is also able to flow in the dike body and an exit point is seen at the toe of the dike. The adjustments and design options can be seen in sub chapter 4.3.5 as well as Chapter 5.

4.3.4 Stability modelling

Each cross section was modelled in D-Geo Stability which is a program that determines the stability of a dike sections. The input into the program includes the soil properties defined in Appendix C and the geometry of each section. The stability analysis was done on the new dike design and cross sections 3a and 3b. This was to determine if the dike is stable or not.

The program gives the following as output:

1. Stresses in geometry
2. Critical slip circle
3. Total and shear stress
4. Piezometric pore pressure
5. Safety factor

The most important output are stresses in geometry, the critical slip circle, piezometric pore pressure and the safety factor of the dike. The can be seen for cross section 3a, cross section 3 in Table 4-3 which summarises the output for each model. All results can be found in Appendix J.

TABLE 4-3: D-GEOSTABILITY MODEL OUTPUT SUMMARY

Cross section:			3a	3b	New design
Stresses in geometry	Due to water	kN/m²	324.58	364.03	362.74
	Due to soil	kN/m²	612.15	715.33	760.5
Critical slip circle (radius)	Radius	m	12.72	24.5	20.34
	Co-ordinates	m	(45.46; 6.73)	(55.50; 18.45)	(51.13; 17.34)
Total stress	Maximum	kN/m²	138.675	110.767	103.443
	Minimum	kN/m²	8.5	8.5	7.094
Shear stress	Maximum	kN/m²	17.532	40.106	44.296
	Minimum	kN/m²	1.953	3.713	6.149
Piezometric pore pressure	Maximum	kN/m²	55.882	69.986	77.034
	Minimum	kN/m²	0	0	0
Safety over view			1.78	1.24	1.87

The outcome of the stability models show that cross section 3a and the new dike design are stable (figure 4.10 and 4.11) however cross section 3b (figure 4.12) is below satisfactory stability. In the figures the safety overview is shown as the outputs from D-GeoStability, green indicates sufficient stability and yellow indicates below satisfaction.

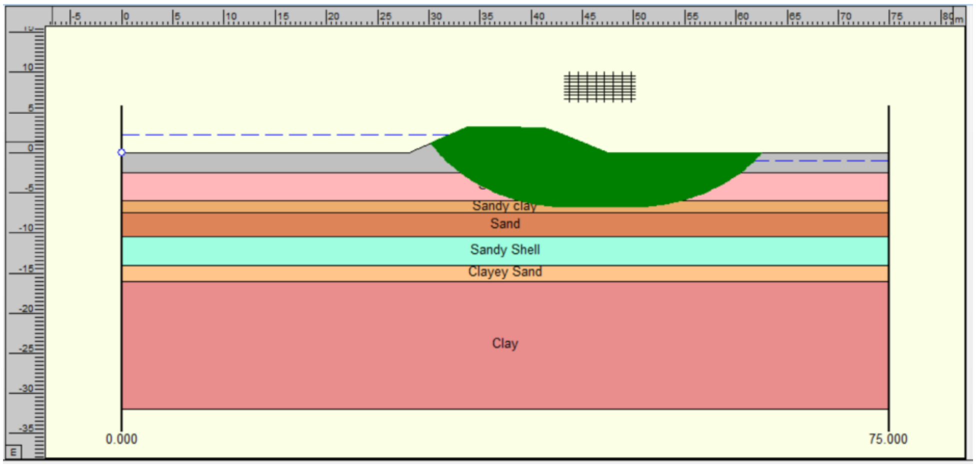


FIGURE 4.10: STABILITY CROSS SECTION 3A

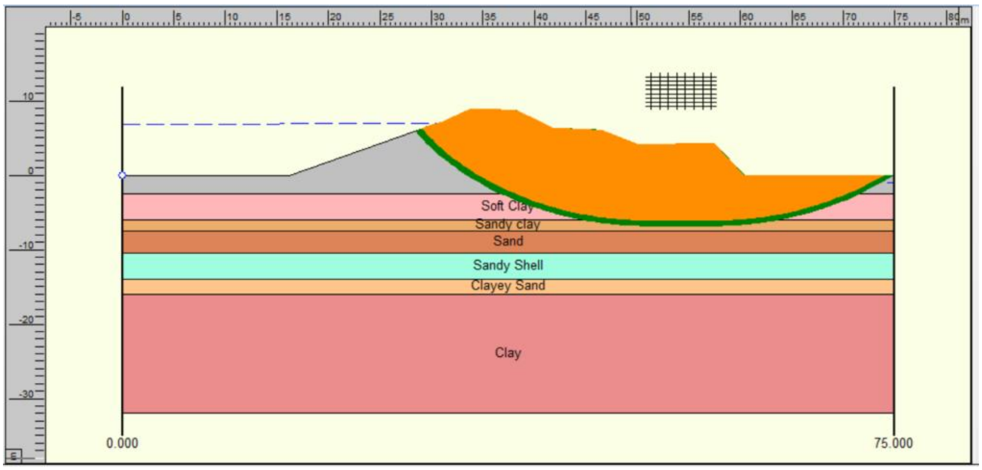


FIGURE 4.11: STABILITY CROSS SECTION 3B

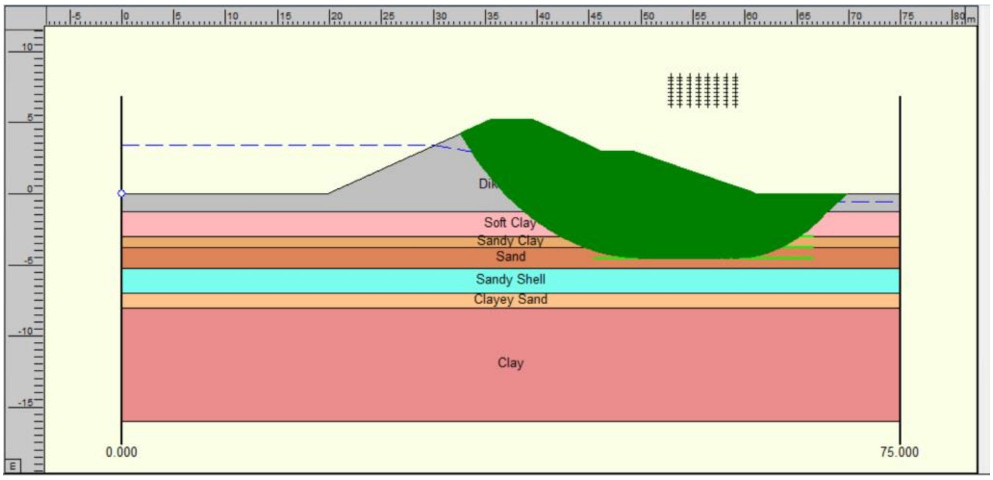


FIGURE 4.12: STABILITY NEW DIKE DESIGN

4.3.5 Technical Design

The design of the final solution is shown in Appendix L where the details of the design are illustrated using AutoCAD drawings. The drawings that are included are:

1. *DRAWING 000 – Location overview (Connection to existing dike sections)*

This drawing shows a top view of the entire mud depot site and shows where the buffer zone will be located. It indicates how the new dike will be connected to the existing dike and where the cross sections are taken from. It is important to note that for the existing dike section Variant combination 2 and 3 are only applicable if the new buffer zone is not implemented.

2. *DRAWING 001 – Variant Combination 1 (Cross-section A-A'; C-C')*

This drawing shows the designed solution of a new dike design (section A-A') and the berm to be implemented of the existing dike section 3a (section C-C'). This illustrates the first variant combination for dike section 3a. Details of the pipe through the dike are shown. This pipe is for overflow and eventual transport of the water from the depot to Porong river.

3. *DRAWING 002 – Variant Combination 2 (Cross-section B-B';C-C')*

This drawing shows the recommendation if no buffer zone is implemented. Changes for the existing dike sections 3a (section C-C') and 3b (section B-B') are shown in detail. For dike section 3a this is variant combination 2 using sand bags and for dike section 3b it is variant combination 2 using a discharge pipe through the dike.

4. *DRAWING 003– Variant Combination 3 (Cross-section B-B';C-C')*

This drawing shows the second recommendation option for if no buffer zone is implemented. Changes for the existing dike sections 3a (section C-C') and 3b (section B-B') are shown in detail. For dike section 3a this is variant combination 3 using a discharge pipe through the dike and for dike section 3b it is variant combination 3 using a subsurface drain in the dike.

5. DISCUSSION

The results of the research are comprised of various products which include a program of requirements, alternative analysis and detailed engineering. This chapter will discuss the outcome of these products and to what extent they are reliable. A sensitivity analysis was done for parts of the research to indicate what effect change in the permeability and soil values of the dike has on the microstability and piping resistance. Recommendations for solutions and further research can be found in Chapter 6.

The research strategy was defined before the research started and was maintained throughout the duration of the research. Available information and language barriers delayed the analysis of the current situation however this time was made up during the buffer zones planned in at the beginning.

5.1 DIKE MODELLING

The outcome of the dike modelling supports the calculations that were done and provides further insight to the stability of the existing dike sections and the new dike design. This sub chapter will discuss the results of the models that were made in D-GeoStability and MSeep and what they mean. The models were modelled as a pebbly-sand dike without a clay revetment layer. The extended explanation of the models is found in Appendix J.

D-GeoStability modelling:
The most important outcome of this modelling is the safety factor of the dike. Cross section 3a and the new dike are satisfactory and therefore no further calculations are made. Cross section 3b has a safety factor lower than 1.5 and is therefore is not satisfactory. In the chosen solution dike section 3b will become obsolete and this therefore does not present a problem. In a new depot is not built the stability of the dike will have to be assessed according to accompanying research (van Mierlo, 2016).

MSeep modelling:
Contour potentials
As you move from high water level to low water level in the models the potential lines decrease as the potential is higher at high water level. At the toe of the dike the lowest potential is reached. Cross section 3a has the lowest water level and therefor has the lowest maximum potential height.

Contour velocities
In the cross section models the ground water flows through the dike and for each cross section the exit point is found at the toe of the dike. The fact that water can move through the dike and underlying sand layer indicates that there is a possibility for piping and this therefore has to be validated. For the new dike design an impermeable clay layer is added which prevents the water flow in the dike.

Pressure levels
The pressure levels in the dike cross sections increase with depth below the surface meaning the underlying soil layers have the highest pressure levels. A higher dike and water level will result in a higher pressure the deeper you go. Here cross section 3a has the lowest pressure.

*additional note: the new dike design was scaled by a factor of 0.5 so that it did not extend beyond the limitations of the modelling programs. Results in the figures and Appendix J are based upon the scaled model.

5.2 RELIABILITY OF RESULTS

Assumptions were made based on previous studies and available data from BPLS. These include the expected duration of the mud volcano, the estimated daily outflow of mud, the soil layers below the foundation of the dike and the material that the existing dike is made of.

Specifications of the mud volcano:
The duration and outflow of the mud volcano influenced the required space for mud during the alternative analysis and therefore played a role in determining which alternative was chosen. If the volcano was to stop in the near future it may not be needed to find a solution to stop pumping the mud to the Porong river. It is however still necessary to determine which hydraulic failures are present in the existing situation.

Geotechnical information:
The soil data that was made available was limited to one point in the dike and therefore the results are based on one source. The permeability of the dike and underlying layers is important for determining whether water flows through these layers and if it transports sand as well. Changes in this data could result in the existing situation to be critical or in the same way completely safe. The revetment and clay layer on the existing dike is also assumed as it is not defined In the provided data. It is clear from site visits that there is some clay and grass however the quality and strength is not known. This affects whether the dike is able to cope with overflow failure during heavy rainfall (see figure 5.1).

FIGURE 5.1: EVIDENCE OF PREVIOUS OVERFLOW OVER THE EXISTING DIKE (AGUSTAWIJAYA & SUKANDI, 2012)

Schematisations of existing dike cross-sections:
The alternative analysis and detailed engineering was done based on dike cross sections provided by BPLS however for each alternative one cross section was made with two dike sections for each. This means in total only 6 cross sections were analysed and two in complete detail. If there is little variation in soil properties and dimension changes in the dike this is not a problem however drastic differences could result in different results.

5.3 SENSITIVITY ANALYSIS

To determine the effect of the change in the soil properties a sensitivity analysis was done for the shear strength and microstability of the slope as well as for change in the creep factor for the piping resistance of the dike. The complete analysis can be seen in detail in Appendix K .

Overflow resistance:

The overflow calculations were done using fresh water properties for the overflow material with a density of 1000kg/m³. In reality there is a possibility that the overflow discharge over the dike is not only fresh water. To determine what effect the change in water density has on the dike the calculations were done for salt water, heavy water and mud.

Figure 5.2 shows the results for the microstability sensitivity for cross section 3a where it is clear that for fresh and salt water the dike is satisfactory as the results are below the limiting value line. When mud is tested on the dike however, the dike fails with certain x values (where x represents change in width of the slope section at risk). This change sensitivity analysis has been done for the shear strength analysis, Joustra-Edelman analysis and microstability with the results found in Appendix K.

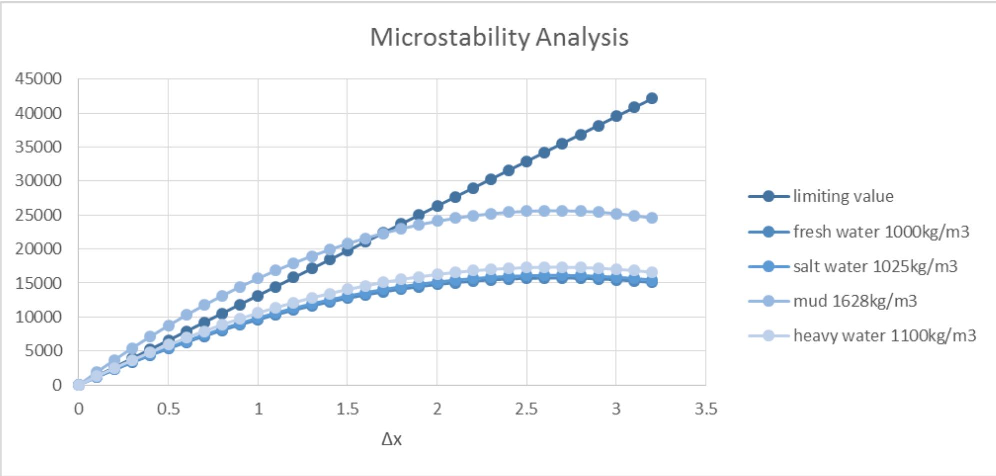


FIGURE 5.2: GRAPH SHOWING THE MICROSTABILITY ANALYSIS OF DIKE SECTION 3A

Piping resistance:

The permeable layers in the drilling log are the sand layer (defined as clean loose sand) and the sandy shell layer (defined as slightly silty). For the calculations the layers were combined as the permeable layer in which water can be transferred. In reality the water will follow the path of least resistance which is the sandy-shell layer. To determine the effect that the creep factor has on piping, a sensitivity analysis was done with $C_{Bligh} = 18, 15, 12$ and $C_{Lane} = 8.5, 7, 5$ (see outcome in Table 5-1).

TABLE 5-1: PIPING ANALYSIS USING BLIGH AND LANE RULES

Depot details	Dimensioning					Leakage length			Piping Calculation					
									Bligh			Lane		
Alternative	Dike Section	Crest (m)	Mud level (m)	Freeboard (m)	H (m)	Lh (m)	Lh with ditch (m)	1/3Lh+Lv (m)	$C_{Bligh} = 18$	$C_{Bligh} = 15$	$C_{Bligh} = 12$	$C_{Lane} = 8.5$	$C_{Lane} = 7$	$C_{Lane} = 5$
1	1a	7.81	4.59	3.21	4.59	40	52	41.53	82.66	68.88	55.10	39.03	32.14	22.96
	New	11.55	7.80	3.75	7.80	72.3	84.3	74.90	140.40	117.00	93.60	66.30	54.60	39.00
	1b	10.25	7.77	2.47	7.77	52.6	70.6	55.19	139.91	116.60	93.28	66.07	54.41	38.87
2	2a	12.00	9.09	2.91	9.09	50.3	62.3	53.33	163.57	136.31	109.04	77.24	63.61	45.44
	2b	9.54	7.20	2.34	7.20	48.9	60.9	51.30	129.58	107.99	86.39	61.19	50.39	36.00
	New	13.12	9.10	4.02	9.10	81.72	93.72	84.75	163.80	136.50	109.20	77.35	63.70	45.50
3	3a	3.13	2.13	1.00	2.13	19.44	31.44	20.15	38.34	31.95	25.56	18.11	14.91	10.65
	3b	8.77	6.88	1.89	6.88	49.9	61.9	52.19	123.84	103.20	82.56	58.48	48.16	34.40
	New	10.51	6.90	3.61	6.90	66.06	78.06	68.36	124.20	103.50	82.80	58.65	48.30	34.50

insufficient leakage length
sufficient leakage length
only sufficient when ditch is at 12m

6. CONCLUSION AND RECOMMENDATIONS

The main objective of the research was to determine how the risk of flooding due to hydraulic failures in the dike around the mud volcano could be mitigated. This was determined by answering various sub questions to determine the most viable solution according to the requirements. The sub questions cover the current system analysis, program of requirements for the design, an alternative analysis and detailed engineering of the chosen solution.

The current situation around the mud volcano consists of a dike structure that was built to retain the mud flowing out of the volcano. The depot is at its maximum capacity and currently all mud is pumped to the Porong river. The existing cross sections are subject to overflow during rainfall and at some locations the dike is at risk of piping.

The requirements of the new solution is to retain the mud with a dike structure with a life span of 50 years based on an outflow of 10 000m³/day and improve the ecological state of the Porong river. The new design prevents overflow in the case of PMP (probable maximum precipitation) in the area and is resistant to dike failure if overflow occurs. Furthermore the design is resistant to piping determined using Dutch design principles.

The best alternative is to create a buffer zone between the existing mud depot and Porong river. This is the most suitable way to achieve the requirements for a new dike solution. The mud will be stored in the buffer zone and separated to so that only the water is pumped to the Porong river. The new depot has the option to expand if the initial concept is successful and therefore will be sufficient to contain the mud for the expect eruption of 26 years. The new dike design has a freeboard to accommodate for heavy rainfall combined with an impermeable layer as protection against piping through the dike.

If a new dike is not constructed the existing dike structures have to be combined with overflow and piping variants to prevent hydraulic failures (see recommendations). With these adjustments to the existing dike sections or constructing the new solution the hydraulic failures can be prevented.

6.1 RECOMMENDATIONS

The outcome of the research shows that changes need to be made in the current situation. Overflow causes flooding due to water flowing over the dike as well as from the Porong river where the mud is pumped to. Water is able to flow under and through the dike and as a result the piping resistance of the existing situation is below a satisfactory standard.

Buffer zone with mud separation:
The recommendation is to construct a new dike and create a buffer zone depot where mud and water can be separated. This will solve the overflow and piping failures at cross section 3b and only a piping and overflow variant is needed at cross section 3a. Here the dike is heightened with a pipe through the dike for discharge of overflow water from the depot to a ditch behind the dike (see DRAWING-001). The new dike design is protected with an impermeable clay layer with a bulk density greater than 1600kg/m³. In order for this solution to be viable further research is needed to determine how to separate the mud so that water can be discharged to the Porong river. The pipelines from the river need to be rerouted to the new buffer zone and a design for pumping the mud to the buffer zone needs to be made.

Piping and overflow variants for existing dike sections:
If a new buffer zone is not created and the mud is pumped to the Porong river then improvements on the existing dike sections need to be made. A combination with an overflow variant and piping resistant variant can be used. In table 6-1 the summary of variants can be seen that were considered.

TABLE 6-1 PIPING AND OVERFLOW VARIANTS

Piping Variants:		Overflow Variants	
P1	clay revetment	O1	discharge pipe over the dike
P2	seepage barrier	O2	discharge pipe through the dike
P3	piping berm	O3	discharge pipe under the dike
P4	drainage in the dike		
P5	sand bags at dike toe		

The variant combinations that have been design (Appendix L) include:

1. Cross section 3a with variants P5 + Cross section 3b with variant P1 and O1 (DRAWING – 002).
2. Cross section 3a with variant P3 and O2+ Cross section 3b with variants P4 (DRAWING – 003).

The recommendation is to implement one of these combinations if no new depot system is implemented to pump the mud to. For sufficient resistance to slope erosion and microstability the clay used should have a bulk weight greater than 1600kg/m^3. The dike section 3b should also be stabilised and further research for this is needed.

Analysis for each dike cross section:
The analysis was done on only a few dike cross-section. As recommendation this analysis should be done on every cross section around the entire dike depot to determine other points of weakness. These cross sections can be modelled and calculated using the programs previously mentioned in the research such as MSeep. These models should be tested with geotechnical data at each cross section and not based on only one drilling log showing soil properties of the underlying layers. Tests should be done on the slopes of the dike using water and mud to determine how the slope can be resistant to mud overflow as well as fresh water overflow from heavy rainfall.

If these recommendations are followed and the existing situation is researched thoroughly the hydraulic failures that are present can be reduced and prevented.

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A. LIST OF SYMBOLS

B. ADDITIONAL COMPETENCES

C. SOIL PROPERTIES EU7 AND TABLE

D. DRILLING LOG BPLS

E. PLANNING

F. THEORETICAL FRAMEWORK

G. PROGRAM OF REQUIREMENTS

H. ALTERNATIVE ANALYSIS

I. SETTLEMENT TABLES

J. DETAILED ENGINEERING

K. SENSITIVITY ANALYSIS

L. DRAWINGS