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Towards Resilient Flood Defenses: Assessing Tough Dikes Against Traditional Approaches

Bachelor thesis in civil engineering

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Towards Resilient Flood Defenses: Assessing Tough Dikes Against Traditional Approaches

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Abstract

This research aims to enhance flood protection by designing and evaluating resilient dike systems and comparing their effectiveness and costs with traditional dike structures. The focus is on a crucial section of the Pleij dike, which protects the city of Westervoort from the Rhine and Ijssel rivers.

The research begins with identifying the challenges in current dike designs and establishing the objectives. A comprehensive literature review is conducted to understand the mechanisms of dike failure and breaching processes. Innovative dike designs are proposed and modeled using D-Hydro software to simulate breach scenarios. The Schade en Slachtoffer Module (SSM2017) assesses these breach scenarios' direct damage and casualties.

A comparative analysis of various dike designs focuses on breach characteristics, cumulative water discharge, damage extent, casualties, and construction costs. The results show that tough dike designs can significantly mitigate damage and improve flood resilience compared to traditional designs, as evidenced by reduced water discharge and lower casualty rates in simulations. A sensitivity analysis is conducted to ensure the robustness of the findings.

The study concludes that integrating tough dike designs into future flood defense strategies is crucial for enhancing long-term resilience; however, further research is needed. The report provides recommendations for stakeholders on adopting these resilient designs to protect flood-prone areas better.

Table of Contents

List of Figures

List of Tables

1. Introduction

The Netherlands faces significant flood risks because much of its land is below sea level or in areas near rivers that can flood. These risks become even more significant over time because of climate change, which leads to rising sea levels and more frequent extreme weather events like storms and heavy rainfall (Robinson & Botzen, 2020). The Dutch approach to mitigating flood risk has traditionally relied heavily on hard engineering measures such as raising and strengthening dikes. While these measures have been influential in the past, there is growing recognition that a solely hard engineering approach may not be sustainable in the long term, especially in a country like the Netherlands with limited available space (Hegger et al., 2016). As climate change heightens flood risks, enhancing the country's defenses against flooding is imperative. While nature-based solutions are beneficial, they alone cannot fully mitigate the risk. Incorporating hard engineering methods is necessary, but relying solely on heightening and widening dikes poses environmental challenges and is unsustainable due to spatial limitations. Therefore, implementing new approaches is crucial. Strengthening dikes rather than simply enlarging them can play a pivotal role in effectively managing flood risks in the future (Rongen et al., 2022).

This research is commissioned by TAUW B.V, a European consultancy and engineering firm headquartered in Deventer, the Netherlands. The research is part of a large project called ‘’Taaie dijken klimaatrobuust ’’ led by HAN University of Applied Science with 12 practice partners from the government and water boards, knowledge institutions, and consultancy firms, including TAUW BV. The large project aims to generate practical insight into the climate robustness of tough dikes. It seeks to answer the primary question: To what extent do tough dikes contribute to the climate resilience of a dike, and how can a tough dike be designed?

1.2 Problem Statement and Research Objective

The challenge of reinforcing the Netherlands' dikes is the most significant since the Delta Works. By 2050, at least 2,000 kilometers of the 3,500 kilometers of primary flood defenses must be completed. However, only 219 kilometers have been completed so far (HWBP - 2023, n.d.). Future challenges are expected to be even more severe due to climate change. When flood risks exceed regulatory requirements, dikes are typically reinforced by making them wider and higher or by reducing the load through measures such as providing more space for water (Ministerie van Infrastructuur en Waterstaat, 2024). Another approach to reducing flood risk is compartmentalization (Asselman et al., 2008). However, current measures are insufficient, highlighting the need for research into a fourth option: strengthening the dike body and dike zone itself to ensure that the consequences of an unexpected breach are relatively minor.

This research aims to model several tough dike configurations using different dike body materials and compare them to traditional dike designs regarding damage consequences and construction costs. This research examines how much a tough dike design can reduce flood risk.

1.3 Research Questions

The objective of this research leads to several crucial questions that must be investigated and evaluated. Each question is an essential feature for better understanding the subject. Addressing these questions drives the research forward, developing results and contributing to the advancement of knowledge. The following is the primary research question for this study:

Which is more resilient, traditional or tough dikes?

This broad question necessitates addressing multiple sub-questions:

1. What distinguishes a tough dike from a traditional dike?
2. What elements can make a dike tougher?
3. How long does it take for a tough dike to fail compared to a traditional dike?
4. What is the difference in cumulative water discharge through the breach between tough dikes and traditional dikes?
5. Which dike causes more economic and social damage after a breach?
6. What is the associated flood risk of the designed dikes?
7. Which dike design is more expensive to construct?
8. Which dike design is the best?

These questions are essential for developing a comprehensive understanding of resilience of traditional versus tough dikes and determining whether tough dikes reduce flood risk.

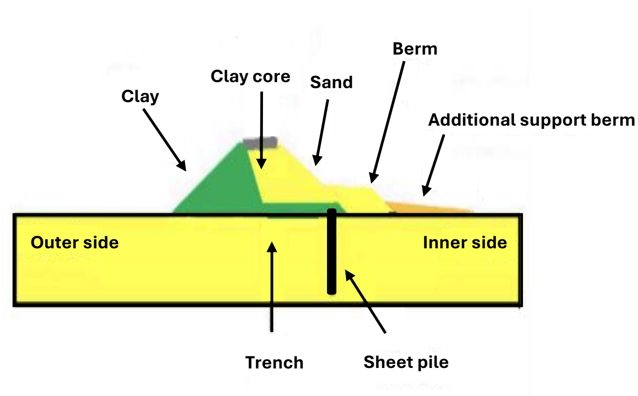
1.4 Scope of the Research

The main objective of this project is to develop and evaluate multiple tough dike designs, comparing them with traditional designs in terms of damage consequences and construction costs while adhering to Dutch guidelines. The dikes will be designed in the place of the Pleij dike in Westervoort in the Netherlands (see section 1.5 for more information). The toughness concept of dikes will be addressed based on knowledge gained by experts in the water safety field. A workshop about toughness in dikes will be attended; the results of this workshop will contribute to the answers to sub-questions 1,2 and 3. The progression of this breach will be modeled using D-Hydro software, utilizing a model provided by the Rijn and Ijssel waterboard. The results collected by the model will answer sub-question four and contribute to sub-questions 5 and 6. The Schade en Slachtoffer Module (SSM2017) will assess flood impacts, focusing on casualties and direct damage, with indirect damage excluded from the project scope. The outputs from the D-Hydro model will be used as input for the SSM model, and the results obtained from this model will be used to answer sub-questions 5 and 6. Estimating flood depth and water flow rate through a breach will begin with assuming an initial small breach. A social cost-benefit analysis will be conducted to analyze the results, and that will answer sub-question eight and the primary question. Finally, recommendations based on the findings of this research will be provided to stakeholders of the "Taaie dijken" project.

1.5 Case Study

The findings of this research, while developed explicitly for the Pleij dike in the Netherlands, can be applied to all dikes in the Netherlands and around the world. The dike designs will be developed for a specific dike section in the Netherlands, trajectory 48-1, known as the Pleij dike, which is about 2,621 kilometers long (Google Earth, n.d.). Figure 1a shows the dike section.

(a)



(b)

Figure 1: (a) The Dike section is in a yellow dotted line (Google Earth, n.d.). (b) Pleij dike cross-section.

The Pleij dike in Westervoort protects the city from two prominent rivers, the Rhine and the Ijssel. The Rhine, originating in the Swiss Alps, crossed multiple countries before reaching the Netherlands. The Ijssel River originates in Germany and flows into the Ijsselmeer in the Netherlands. Both rivers experience high water levels during winter (Ministerie van Infrastructuur en Waterstaat, 2024b). The cross-section of the current dike, featuring a clay core, a berm, a supporting berm, and a sheet pile, is shown in Figure 1b. Data for the dike section will be sourced from TAUW B.V. and Han University of Applied Sciences. This section of the dike is mandated to meet a minimum safety standard, capable of withstanding events with a probability of occurrence once every 10,000 years. Figure 2 depicts the safety standards assigned to all dike sections across the Netherlands, highlighting the Pleij dike section with a red circle.

Figure 2: Minimum safety standards for all dike sections. A red circle is added to highlight the case study area (Ministerie van Infrastructuur en Milieu & Rijkswaterstaat, n.d.)

2. Theory & Methodology

This section outlines the approach to addressing the research questions and the theory behind it. Initially, Figure 3 will present a schematic overview of the research flow. The methods employed include modeling studies and expert meetings. The methodology used to address the research questions will then be detailed.

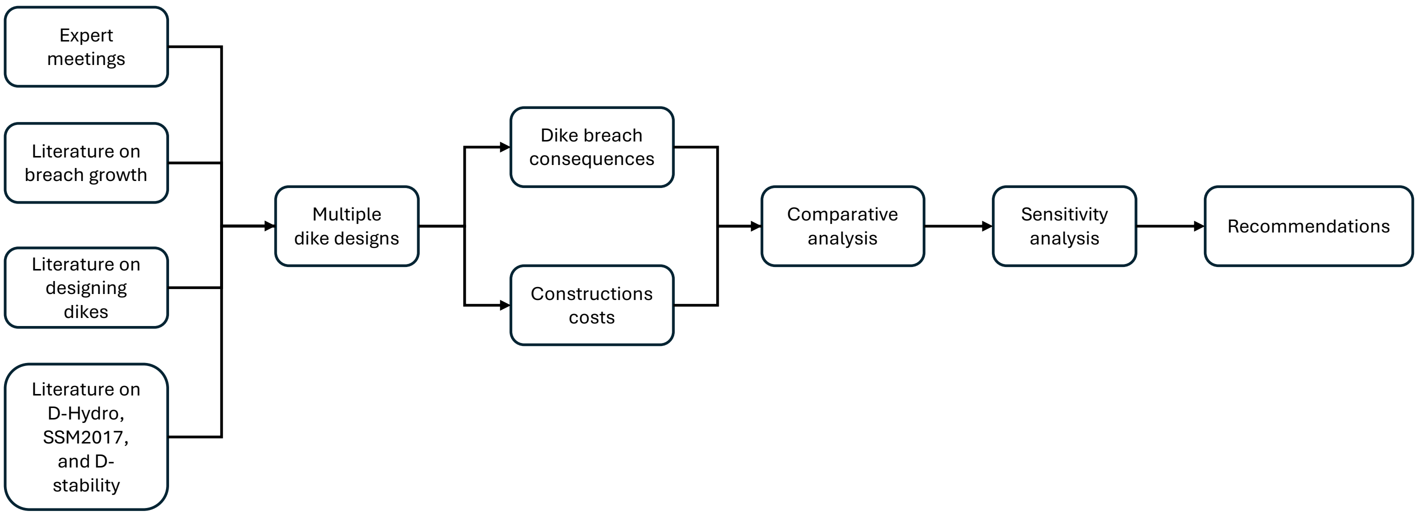


Figure 3: Schematic overview of the research flow

Following the flow chart outlined in the figure above will yield answers to the research questions.

2.1 Expert Meetings

To achieve the main objective of this research, it is essential first to understand what makes a dike tough. The expert meeting will explore the concept of tough dikes and their criteria. A workshop involved multiple experts from the water management sector, including representatives from waterboards, universities, and engineering firms. The list of workshop attendees is shown in Table 6 in Appendix A. This section presents the insights gathered from this workshop.

2.1.1 Dike Toughness

Several key questions about tough dikes were raised and discussed during the workshop. The discussion began with defining the essential characteristics that define a tough dike. The agreement among the experts highlighted the following criteria:

- Ability to withstand high water levels near the dike crest.
- Maintenance of a significant residual dike height to minimize inflow discharge.
- Slow erosion and failure, allowing the dike to deform while retaining a substantial residual height.
- Provision of sufficient time for evacuation post-failure.
- Development of additional cohesion even during failure.

This addresses the first research sub-question on what distinguishes a tough dike from a traditional dike. Additionally, the experts were asked to identify the three most crucial building blocks of dike toughness, the results of which are summarized in Figure 4.

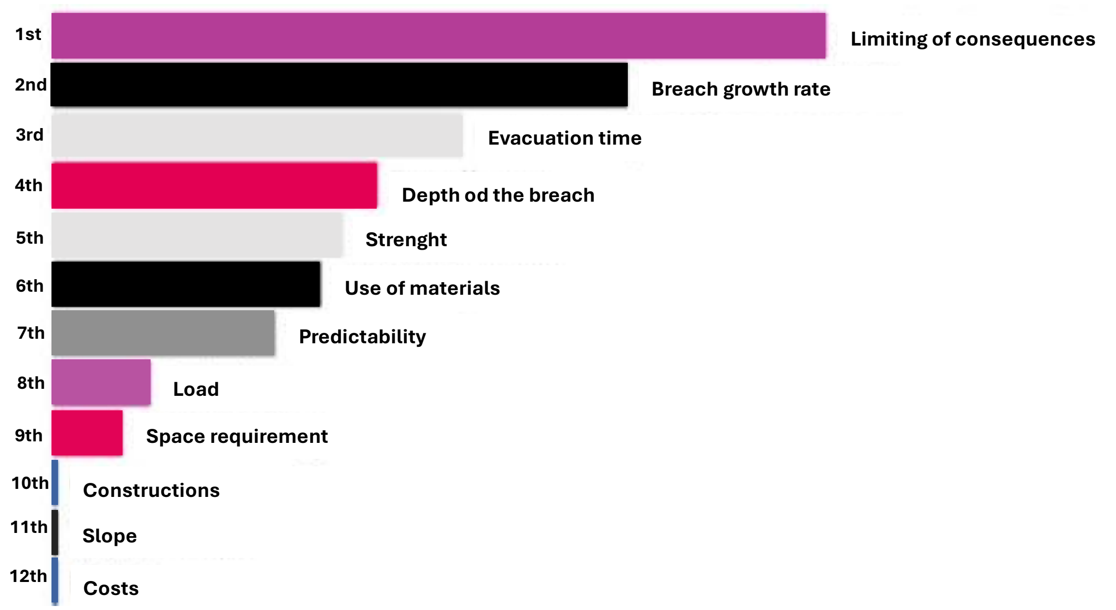


Figure 4: Expert answers regarding the building blocks of dike toughness during the workshop

Expert insights are essential to this study as they contribute not only as specialists but also as stakeholders. The primary focus of a resilient dike lies in its capacity to mitigate flood impacts, where breach growth and depth are crucial considerations. A dike design achieving a narrower and shallower breach allows for reduced water flow, potentially increasing evacuation time and minimizing overall consequences. Discussions on dike breach growth frequently highlighted the importance of material selection. Choosing the suitable materials is pivotal in dike design, significantly impacting stability and breach characteristics. In the Netherlands, dike construction primarily relies on materials such as sand, clay, and their combinations. Experts emphasize that breaches in clay dikes tend to be narrower than sand dikes due to clay's cohesive nature. Recently, discussions at the workshop highlighted the importance of breach depth in dike resilience. The current flood risk assessment assumes that breaches erode vertically from top to bottom, even in designs incorporating sheet piles. This raised questions about the role of intact sheet piles during flooding. If sheet piles remain intact, they can limit breach depth to their height, acting as a barrier. These discussions underscore the need for comprehensive dike design considerations, including soil type and incorporating structural elements like sheet piles.

Clay and sheet piles in a dike body are potential materials that make a dike tougher; these elements will be implemented later in the dike designs to answer the second research sub-question about what elements can make a dike tougher. After designing and modeling, it will be evident whether the consequences of those elements are as expected by the experts. A deeper understanding of the breaching process will guide improved design strategies and lead to more resilient dike structures.

2.1.2 Failure Path

For a breach to initiate, a linear sequence of events must occur; these events, from start to failure, describe the failure path of a dike section (Hardeman et al., 2023). This approach considers five steps to assess the probability of flooding with a failure path:

1. Formulating a story about the dike section: describing all relevant ways (failure paths) in which a flood may occur based on the properties of the system
2. Determining the critical failure paths: selection of those failure paths that will significantly contribute to the risk of flooding
3. Working out the critical failure path(s): working out sub-mechanisms in a failure path
4. Analysis of the critical failure path(s)
5. Determining the probability of flooding

Many possible failure paths could lead to flooding. When working with failure paths, it is essential to consider which ones are determined for the probability of flooding. Other failure paths are possible, but the probability of them leading to flooding is non-substantial (Hardeman et al., 2023). For this project's case study, Deltares has defined specific failure paths, with macro stability leading to dike breach being particularly relevant. Figure 5 illustrates a schematic of this failure path.

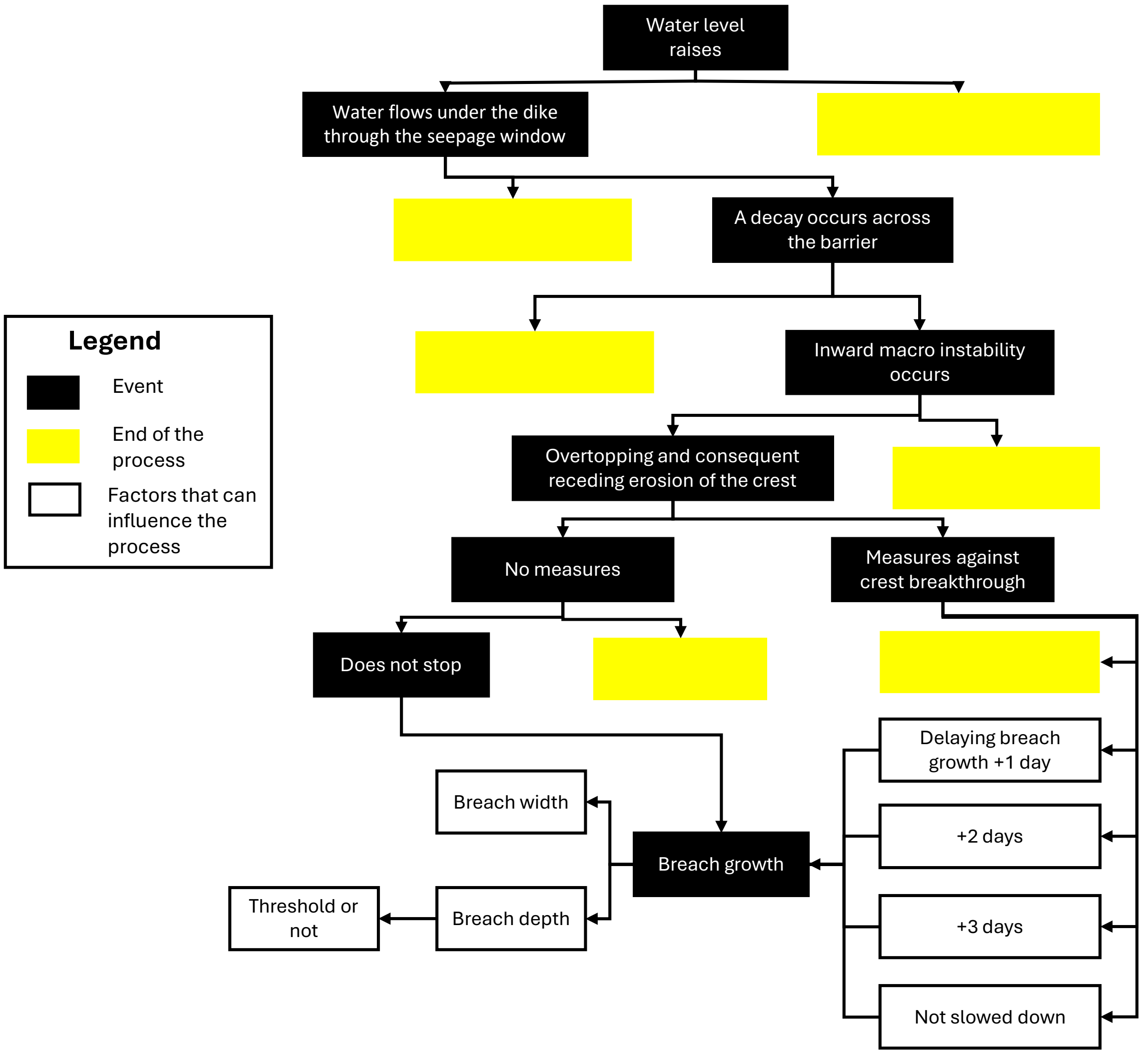


Figure 5: Failure path of the Pleij dike (Hardeman et al., 2023)

Each step depicted in the failure path must occur sequentially for a breach to initiate. The process begins with elevated water levels causing seepage beneath the dike, leading to erosion. This erosion can trigger macro instability, potentially followed by overtopping and backward erosion from the toe to the crest of the dike (Zhu, 2006). The duration of this backward erosion phase varies and requires further investigation. In some cases, measures can significantly delay breach growth, although this project does not consider such delays. Dikes are designed to withstand specific flood events, known as design standards, occurring at defined intervals. For the Pleij dike, this corresponds to a flood expected once every 10,000 years. Figure 6 illustrates the development and duration of such a flood wave. The data for the flood wave were delivered by the Rijn en Ijssel waterboard. This concerns a discharge wave for the entire month of November, which, in this case, is seen as the wettest month of the year. Current flood risk assessments assume dike failure at the peak of this wave. However, as discussed in section 2.1.1, dike designs incorporating tough elements may withstand the water pressure longer, potentially breaching after the peak or not breaching at all.

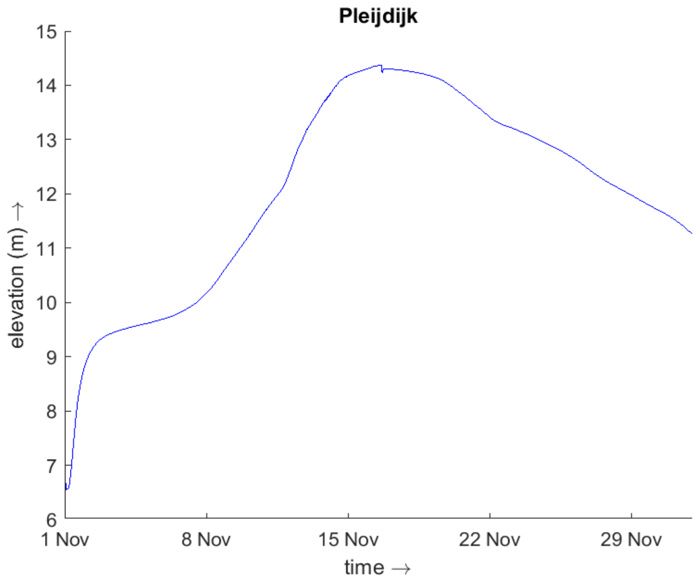


Figure 6: Flood wave 1:10000 years at the Pleij dike (Rijn and Ijssel waterboard)

Furthermore, the failure path analysis shows that once breach growth begins, the width and depth of the breach significantly influence the failure outcome, underscoring the importance of these parameters. The subsequent section will delve into the dike breaching process, focusing on the factors influencing breach growth.

2.1.3 Breaching Process

The width of a dike breach plays an essential role in determining its risk. The breach growth process has three phases (Verheij et al., 2003).

- Phase zero: the starting of the initial channel due to the erosive effect of wave overtopping or due to the sliding of the inner slope
- Deepening phase: The initial channel deepens into a breach with a bottom at a certain level, but does not become wider
- Widening phase: The breach no longer grows in depth but only in width

The duration of phase zero is uncertain, so current risk assessments in the Netherlands often overlook this duration, assuming breach initiation coincides with peak flood wave conditions (Verheij et al., 2003). During the workshop (see section 2.1.1), experts believed dikes reinforced with cohesive materials like clay may extend phase zero relative to those constructed with sand or other soil types. This observation stems from expert experience rather than experimental data, prompting discussions on potential future experiments by Rijn en Ijssel Waterboard and its partners. Given this uncertainty, this research will explore multiple scenarios modeling breach initiation at peak flood wave conditions 24 and 48 hours later. This approach will test the consequences of flood impacts under varying breach initiation assumptions and examine whether experiments in the future are necessary.

Water discharge through the breach can be quantified using Equation 1 (Verheij et al., 2003), which is implemented in the D-Hydro model; more about the implementation will be discussed in section 2.3.1.

$$Q = m * B * H * \sqrt{2 * g * (H)} \quad (1)$$

With:
m = discharge coefficient $(-)$
B = breach width (m)
H = Difference in height, $h_{water\ level} - h_{bottem\ of\ the\ breach}$ (m)
$h_{water\ level}$= outer water level (m)
$h_{bottom\ of\ the\ breach}$= depth of the breach (m)
g = gravitational acceleration (m^2/s)

As indicated by the formula, the dimensions of the breach, its width, and depth are crucial factors. A wider and deeper breach allows greater water flow, leading to more severe consequences. Equation 2 applies to breach width calculations for sand dikes, while Equation 3 applies to clay dikes. Both equations are implemented in the D-hydro model.

$$B_{Sand} = 1.2 * \frac{g^{0.5} * H^{1.5}}{u_c} * log\left(1 + \frac{0.04 * g}{u_c} t\right) \quad (2)$$

$$B_{Clay} = 1.4 * \frac{g^{0.5} * H^{1.5}}{u_c} * log\left(1 + \frac{0.04 * g}{u_c} t\right) \quad (3)$$

With:
H= $h_{outer\ water\ level} - h_{bottom\ of\ the\ breach}$ (m)
u_c= critical velocity (m/s)

The critical speed depends on the material type, as shown in Table 1.

Table 1: Strength properties of various soil types (Verheij et al., 2003)

Material type	u_c (m/s)
Grass, good	7
Grass, moderate	5
Grass, bad	4
Clay, very good	1.0
Clay with 60% sand	0.80
Good clay with little structure	0.70
Material type	u_c (m/s)
Good clay with a strong structure	0.60
Bad clay	0.40
Sand with 17% silt	0.225
Sand with 10% silt	0.20
Sand with 0% silt	0.16

This study will utilize two types of soil for dike designs: sand and clay, with corresponding critical speeds of 0.2 m/s and 0.5 m/s, respectively (Verheij et al., 2003). When a design combines both soil types, an average critical speed of 0.35 m/s will be assumed. Additionally, the breach depth is assumed to reach the bottom of the dike within 600 seconds unless a sheet pile is integrated into the design; in this case, the breach depth will be limited to the height of the sheet pile. The sheet pile acts as a barrier for flowing water and will be modeled to assess its impact on flood damage and casualties. The initial breach width for all designs is assumed to be 20 meters based on water board simulations and will remain unchanged.

Several parameters will be adjusted based on each design and scenario:

- Starting time of the breach
- Maximum depth of the breach
- Breach coefficient (1.2 for sand, 1.4 for clay, see equations 5 and 6)
- Critical velocity (0.2 m/s for sand, 0.5 m/s for clay, and 0.35 m/s for mixed soil)

At this point, sufficient knowledge about dike toughness, material utilization, failure paths, and the breaching process has been gathered. The following section discusses the methodology behind the design phase.

2.2 Dike Designs

First, the design guidelines will be utilized to develop multiple dike designs incorporating components that adhere to current safety standards (Fundamentals on Water Defences, n.d.). The existing height and crest width of the Pleij dike meet safety and design criteria at 15.58 meters and 5 meters, respectively (Arends et al., 2014), which will be maintained in the new designs. Given the focus on tough dike designs, the aim is to construct dikes that meet the criteria that define a tough dike (see section 2.1.1). Four dike designs will be made based on the findings of section 2.1, and the designs will differ in the materials and components used. As mentioned before, sand and clay will be the materials of the dike bodies. Furthermore, one dike design will implement a sheet pile in its dike body. The dike designs will be then as follows:

- Design 1 (Sand dike)
- Design 2 (Clay dike)
- Design 3 (Clay dike with a sheet pile)
- Design 4 (Sand dike with a clay core)

The crucial failure path of the Pleij dike (see Figure 5) demonstrates that inward macro instability is an important event. As a result, the designs' macro stability must be ensured, which will be accomplished using D-Stability software (for more information, see section 2.2.1). All designs must meet a specified safety factor, and the slopes will be changed accordingly. The following section will cover the methodology used to determine these safety factors.

2.2.1 Macro-Stability

Macro-stability refers to the potential for a dike to fail inward due to shearing on the landside caused by excessive groundwater pressure beneath and behind the dike. This failure mechanism occurs when there is an imbalance in the equilibrium of a soil mass. In slip plane analysis, this equilibrium hinges on driving and counteracting moments. To prevent macro-stability failure, the counteracting moment must exceed the driving moment (WBI et al., 2021). Figure 7 illustrates the characteristic circular slip circle associated with the macro instability of a dike.

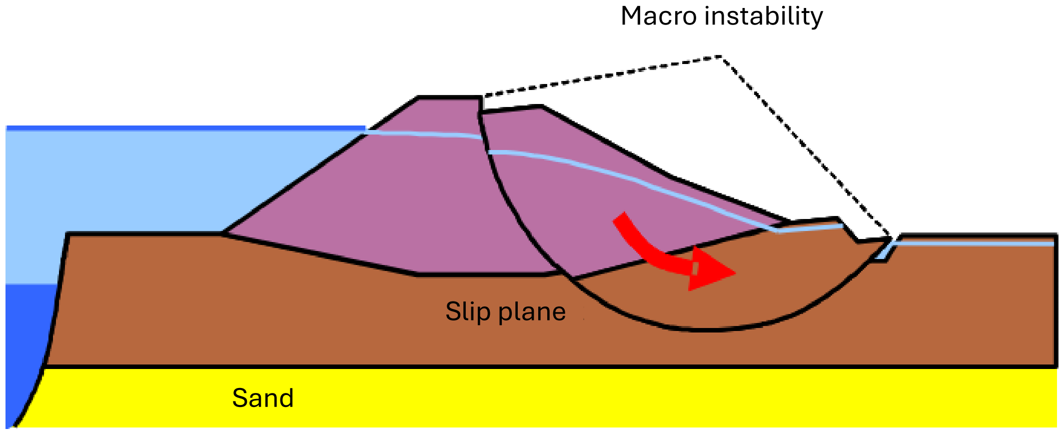


Figure 7: Macro instability of a dike (WBI et al., 2021)

Model

D-Stability 2024.01 is used to determine the dike's geometry. Semi-probabilistic analyses are performed at the water level at standard (WBN). Existing calculations of the Pleijkdijk delivered bij Rijn & Ijssel waterboard are used to design the different types of dikes. The delivered data contains the required information about the dike's foundation, corresponding materials, and strength.

Shear strength model

The dike design is determined using shear strength parameters according to the Critical State Soil Mechanics (CSSM) model. The strength parameters are copied from the current dike's calculations.

Safety factor

To ensure the dike design effectively mitigates inward macro-stability failure, it must meet a defined safety factor, which can be defined using equation 4 (WBI et al., 2021).

$$\gamma_r = \gamma_b * \gamma_d * \gamma_n \quad (4)$$

With:

γ_r = safety factor for the strength

γ_b = schematization factor, partial factor for the uncertainty of the soil structure, and the water (excess) stresses

γ_d = model factor, partial factor for the model uncertainty

γ_n = damage factor, a partial factor related to the standard height, flood failure, and length effect

Given:

γ_d = 1.06 (Uplift Van)

γ_n = 1.17 inwards, 1.08 outwards

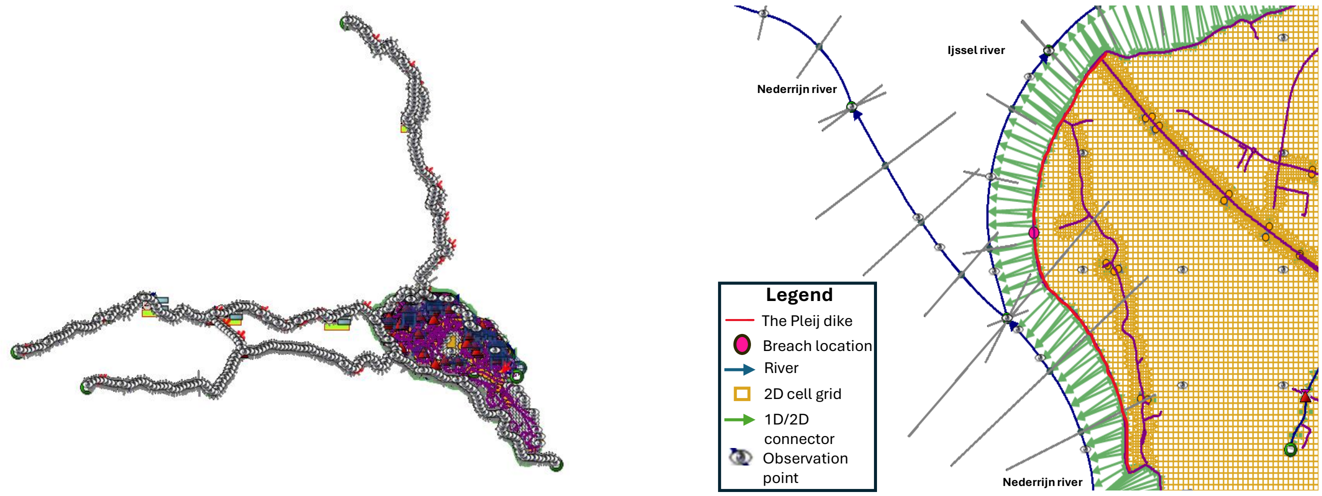
All the above factors are taken from Rijkswaterstaat except for the schematization factor. The schematization factor can vary from 1.0 to 1.3 (WBI et al., 2021). In this case, a schematization factor of 1,20 is chosen because sufficient information/data is available on the Pleij dike. However, there are still many uncertainties in the schematization of the design. This results in a safety factor of 1.49 for macro stability inwards and 1.37 outwards. The dike designs should have at least the mentioned safety factors in order to be stable. The dike designs will be validated using D-Stability, incorporating soil types provided by the Rijn and Ijssel waterboard. The water pressure distribution will be determined using the water net creator function in D-Stability. The outcomes of these designs will be presented in the results section. Following the completion of the dike designs, the dike breach of each design will be modeled. The following section will explain how this will be done.

2.3 Damage and Consequences

To answer the primary research question and examine the designs' resilience, the breach of each design will be modeled using D-Hydro modeling software. The simulation's outputs will answer sub-research question 4 about cumulative water discharge through the dike breaches. Furthermore, the model will provide the necessary input for the SSM2017 model, which will compute the direct damage, casualties, and affected individuals from the flood. The following two sub-sections will explain how D-Hydro and SMM2017 work, respectively.

2.3.1 D-Hydro Model

This section will explain the model used for simulating the breach of the designed dikes. The software used is D-Hydro, which is a software developed by Delatres. D-Hydro specializes in simulating various hydrological events such as floods, storm surges, hurricanes, wave dynamics, sediment transport, morphology changes, and ecological impacts (D-HYDRO Suite, n.d.). The Rijn and Ijssel waterboard provided the model and water discharge data, with specific adjustments for the dike breach scenarios. Figure 8a depicts the D-Hydro model within its graphical user interface, while Figure 8b provides a zoomed-in view of the model.



(a) (b)

Figure 8: (a) Dike section 48 D-Hydro model. (b) Zoomed-in view of the model.

The blue arrow line in the model indicates the Nederrijn River, which separates into two rivers: the Ijssel to the right and the Nederrijn to the left. The Pleij dike is presented by the red line in Figure 8b. A pink circle indicates the breach location, defined with x and y coordinates for the simulation. The hinterland is modeled as yellow grids that contain essential data such as elevation, roughness, and land use characteristics of the area.

The model operates as a 1D/2D hybrid, where the river is modeled in 1D and the inundation area in 2D. The simulation framework remains unaltered except for dike geometry and breach data adjustments, including critical velocity, initial breach width, and minimum breach height. The Verheij - van der Knaap formulation, detailed in section 2.1.3, simulates breach growth within D-HYDRO. Figure 9 shows the input file for this formulation. This formulation functions as a 2D feature in D-HYDRO, allowing the breach to expand along a specified line element from its center based on the growth formulation. Breach growth significantly influences water flow; wider and deeper breaches permit more water inflow. The model generates outputs in NetCDF files, including maximum water depth behind the dike, maximum flow velocities through the breach, total water volume passing through the breach, and breach width. The outputs will be utilized as inputs for the SSM2017 model to assess damage and casualty impacts, which will be further explained in the following sub-section.

```
[Structure]
id                     = Pleijdijk
type                   = dambreak
numCoordinates        = 201
xCoordinates          = 194047.051619119 194046.4
5 194011.5 194011.234375 194010.9375 194010.6406
194009.46875 194009.671875 194009.90625 194010.1
yCoordinates          = 440807.05516302 440809 44
441011.40625 441012.96875 441015.46875 441017.96
216.40625 441218.90625 441221.375 441223.875 441
StartLocationX        = 194007.659477455
StartLocationY        = 441054.310450892
T0 = 1351200                                        The starting time of the breach
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                 = 1
Algorithm             = 2
CrestLevelIni         = 15.5864954247726            Dike height
CrestLevelMin         = 10.0465                     Ground height
BreachWidthIni        = 20                          Initial breach width
TimeToBreachToMaximumDepth       = 600
F1                    = ?
F2                    = 0.04
Ucrit                 = ?
```

Figure 9: Needed parameters for breach growth simulation in D-Hydro

2.3.2 SSM2017 Model

The primary function of SSM2017 is to estimate the potential damage to infrastructure and the number of potential casualties during a flood event (Rijkswaterstaat Water, Verkeer en Leefomgeving, 2017b). Appendix D provides detailed information on the methodology used in the SSM2017 model. Figure 10 displays the interface of the software used for running SSM2017.

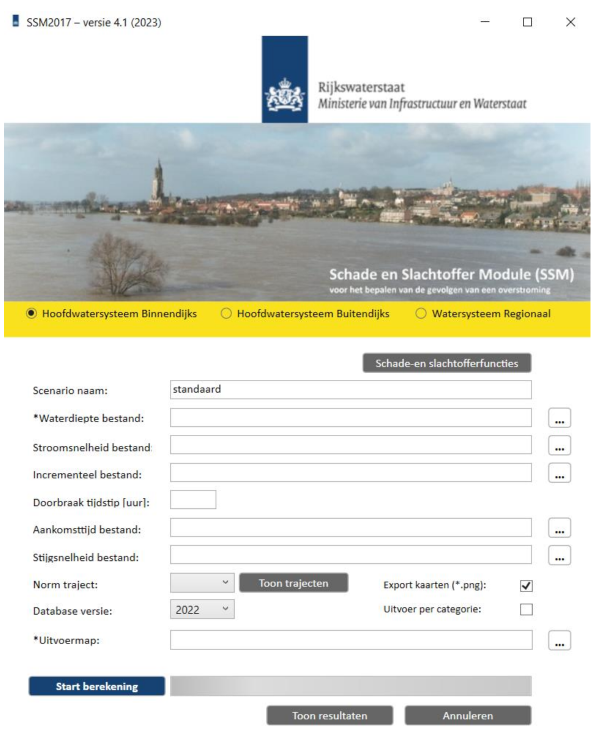


Figure 10: SSM2017 window

The software requires at least a water depth file to initiate the simulation. Additional files such as water velocity, arrival time of water, and ascent rate are optional and not mandatory. Due to time constraints, only the water depth and velocity files will be provided as inputs to the model. It is important to note that this approach may underestimate casualties in scenarios with rapid water ascent rates, a factor that will be considered during result analysis.

D-Hydro outputs are not directly compatible with SSM2017, as they need to be converted into ASCII (.asc) or GeoTiff (.tif) file formats. This conversion process can be facilitated using QGIS software, which converts mesh files to raster format and allows export to GeoTiff (.tif) files.

The primary outputs of the SSM2017 model include total estimated direct damage in euros, number of casualties, and affected population due to the flood event. These outputs provide answers to research sub-questions 5 and 6. Additionally, it generates an inundation map that visually represents the extent of the flooded area. The following section will detail the methodology employed to estimate construction costs.

2.4 Construction Costs

Construction costs for each dike design will be calculated for the entire length of the Pleij dike, which is 2.621 km (Google Earth, n.d.). The total construction costs include initial construction expenses and exclude periodic maintenance costs, which are standardized across all designs and thus do not affect comparative analysis. The construction costs comprise soil purchase and dike material expenses. Table 2 contains the applied unit prices (JDB Groep, 2024; Damwanden Laten Plaatsen Kosten | Grondverzet.nu, 2024):

Table 2: Prices for dike construction

Description	Price per unit
Supply and processing of dike material	€20 per m^3
Purchase of sand	€21 per m^3
Purchase of clay	€22.50 per m^3
Sheet pile installation	€200 per m^2

The results section will present the dimensions of each dike design and associated construction costs following the dike design phase. These findings address research sub-question 7. The following section will outline the methodology used for the comparative analysis.

2.5 Comparative Analysis

A comprehensive comparison analysis will address the research questions regarding the differences between each design's breach characteristics. D-Hydro outputs will be examined to compare each design's breach width and cumulative discharge. The damage and casualties of each dike design's breach will also be compared.

The subsequent step involves identifying the best dike design through a cost-benefit analysis (CPB et al., 2013). This analysis evaluates the costs and benefits associated with each design. Costs encompass construction costs (see section 2.4), while benefits are assessed by the level of hinterland protection against flooding, expressed as flood risk. In the Netherlands, an area's flood risk is determined by combining the probability that an area will flood and the consequences of the flood. Figure 11 shows a schematic representation of calculating the flood risk.

Figure 11: Schematic representation of flood risk calculation (Eems et al., 2018)

The probability of flooding is set at 1:10,000 years, aligning with the required safety standard for dike design. The consequences are calculated using the SSM model (see section 2.3.2); only direct financial damage will be considered for this analysis. The cost-benefit analysis involves computing the net present value of risk using Equation 5 (Rijkswaterstaat et al., 2021):

$$NPV_{risk} = \frac{R}{d} \tag{5}$$

With:

NPV_{risk} = Net present value [€]

R = Risk in year 1 [€]

d = Discount rate (= 0,0225) [-]

The best design is found at the economic optimum of costs and benefits. This economic optimum lies where the total costs are lowest, i.e., where the sum
costs and risk are the lowest. The results of this analysis address the primary research question and sub-question 8, which can be found in section 3.4. The following section will discuss the methodology used for the sensitivity analysis.

2.6 Sensitivity Analysis

Conducting a sensitivity analysis is essential for this research due to the assumptions made in breach modeling. This analysis evaluates the impact of these assumptions on the results by rerunning models with variations in assumed parameters. Each parameter will be adjusted by ±25% of its original value to test its sensitivity, once at 25% below and once at 25% above the chosen value. The 25% adjustment is chosen because it can reveal significant sensitivity in the model's output. Although adjusting the parameters in a range from -25% to +25% in as many steps as possible would yield more accurate results, the approach of using -25%, 0%, and +25% is selected due to time constraints and the significant runtime (24 hours) required. The sensitivity coefficient will then be calculated to quantify how sensitive the damage is to changes in the parameter. The sensitivity coefficient can be calculated using Equation 6.

$$Sensitivity\ coefficient = \frac{\Delta D}{\Delta P} \qquad (6)$$

With:
ΔD: Change in damage
ΔP: Change in parameter

Finally, the results will be analyzed to determine which parameters significantly impact the model's outcomes. This analysis will help identify critical assumptions that need careful consideration and provide insights into the model's robustness. The detailed results and their implications will be discussed in section 3.5.

3. Results

This section presents the project's outcomes, starting with the dike designs. This is followed by the results of the breach modeling using D-Hydro, the damage and casualty estimates from the SSM2017 model, and a sensitivity analysis to determine how variations in input values for a given variable affect the results.

3.1 Dike Designs

This section details the dike designs and the results from the D-Stability software, which was used to calculate the safety factors to ensure stable dikes. As outlined in the methodology section 2.2.1, the height of all designs is 15.58 meters. As described in section 2.2, four designs will be created, which are as follows:

- Design 1 (Sand dike)
- Design 2 (Clay dike)
- Design 3 (Clay dike with a sheet pile)
- Design 4 (Sand dike with a clay core)

The dikes' slopes were iteratively adjusted in the D-Stability software until the designs met the required safety factor. For consistency and accurate comparison, all designs lack a berm. Appendix B contains the D-Stability inputs for all designs, including geometry, materials, and water pressure. The macro stability results of the designs are shown in Figure 12.

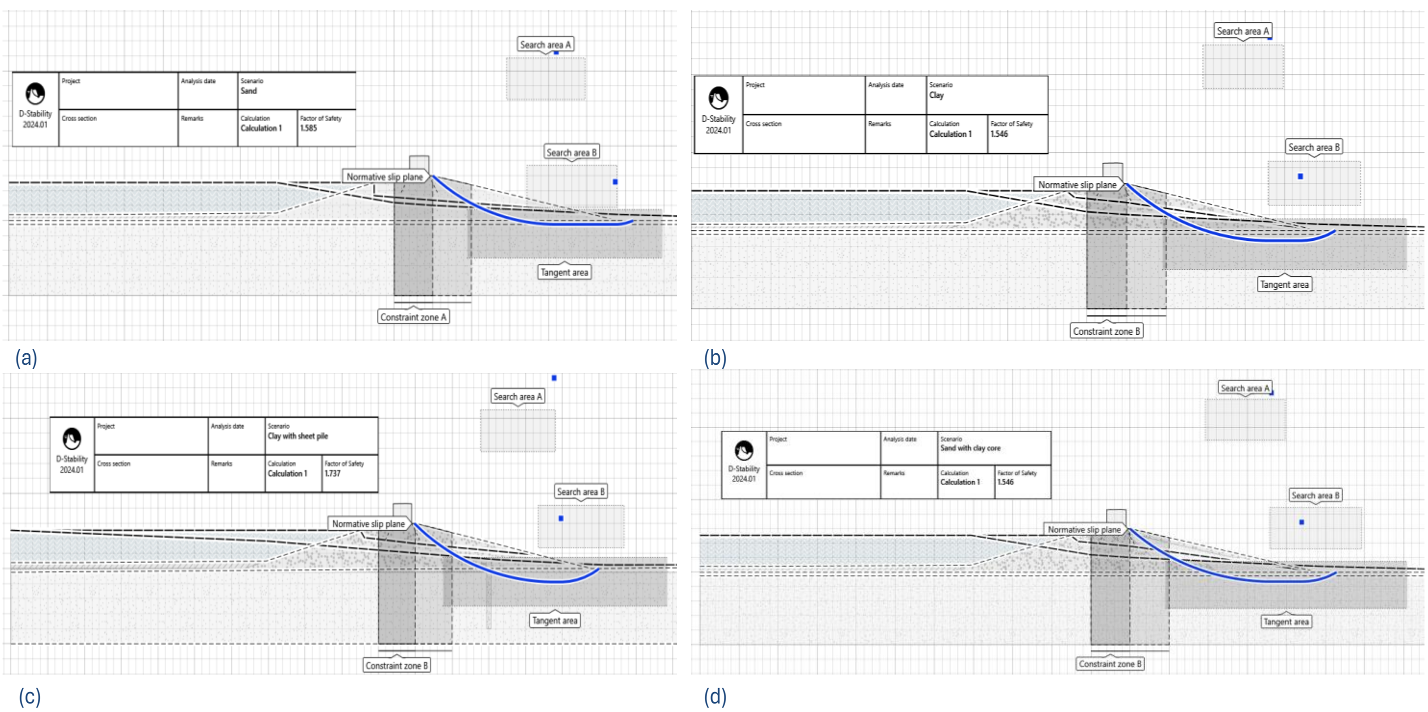


Figure 12. Safety factor results: (a) Sand dike design 1. (b) Clay dike design 2. (c) Clay dike with a sheet pile design 3. (d) Sand dike with a clay core design 4.

The required macro stability safety factor for all designs is 1.49, as determined in section 2.2.1. Firstly, all designs' initial inner and outer slope is designed as 1:3 slope. However, with the initial slopes, all designs achieved insufficient safety factors. Therefore, the choice is made to widen the outer slope to a 1:4 slope, which results in a sufficient safety factor. Figure 12 shows design 1 achieving a rounded safety factor of 1.59, design 2 achieving a rounded safety factor of 1.55, design 3 achieving a rounded safety factor of 1.74, and design 4 achieving a rounded safety factor of 1.55. The final designs are shown in Figure 13.

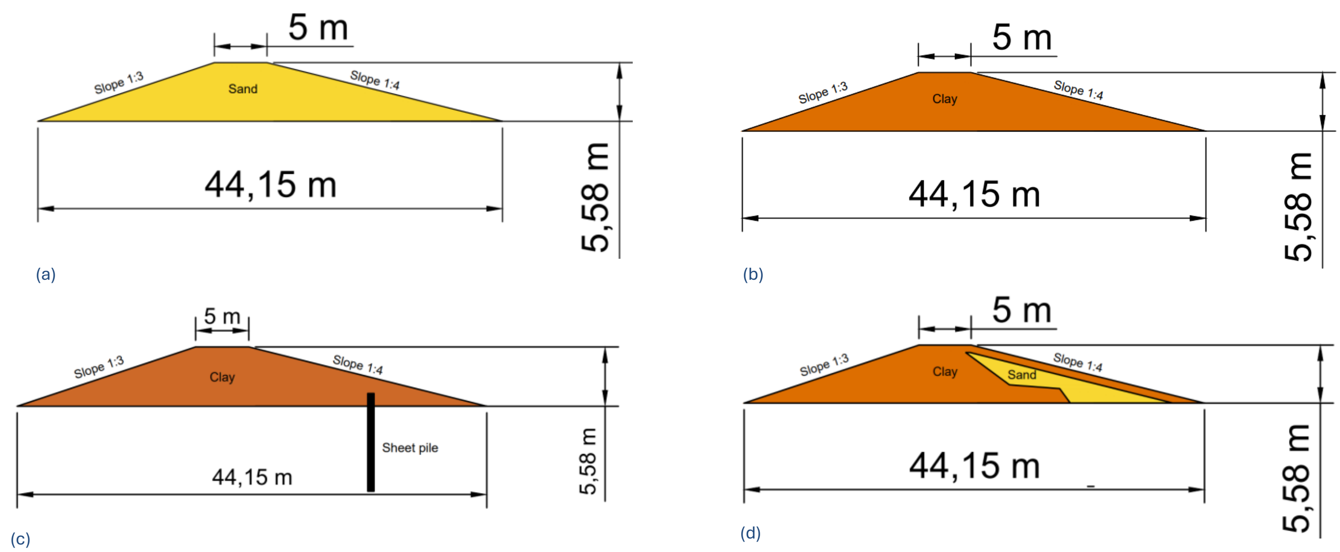


Figure 13. Geometry and materials used of all designs: (a) Sand dike design 1. (b) Clay dike design 2. (c) Clay dike with a sheet pile design 3. (d) Sand dike with a clay core design 4.

The designs in the figure above all have the same inner and outer slope, crest width, and crest height. All designs' crest width and height are maintained at the exact dimensions of the current dike, 5 and 5.58 meters, respectively (see section 2.2). The differences between the designs lie in the materials and components used in the dike body. Design 1 uses sand as the soil type for the dike body; designs 2 and 3 utilize clay; and Design 4 uses sand with a clay core. The choice is made to maintain the ratio and layout of sand and clay in design four as the ratios of the current Pleij dike. Furthermore, design 3 has a sheet pile implemented in its dike body, which has a length of 9.2 meters, of which 1.2 meters is above ground level. The breach of each design will be modeled, and the damage and casualties caused by each design will be calculated; this will be done in the following section.

3.2 Flood Consequences

This section will show and analyze the damage and casualty results. First, the dike breaches of the designs from the previous section are simulated using the D-Hydro model provided by the Rijn and IJssel waterboard. The methodology used for this can be found in section 2.3.1. Then, the results obtained from the SSM2017, which indicate the direct financial damage, casualties, and affected people, will be shown and analyzed. The methodology used for the SSM2017 can be found in section 2.3.2.

3.2.1 Breach Results

Breaching scenarios are modeled for the four dike designs. This is done to account for the duration of phase zero of the breaching process (for more details, see section 2.1.3). For Design 1, a sand dike, only one scenario is modeled: a breach starting at the flood's peak. Designs 2, 3, and 4, all with clay in their dike bodies, are modeled for three scenarios each. The first scenario has a breach starting at the peak of the flood wave, the second starts 24 hours after the peak, and the third starts 48 hours after the peak. The scenarios differ only in the input parameters for the breach structure file, which contains the necessary variables for the Verheij - van der Knaap formula. The breach structure input files of all designs and scenarios can be seen in Appendix C.1.2. The breach growth of all designs and scenarios can be seen in Figure 14. Moreover, each design's breach growth can be found separately in Appendix C.2.

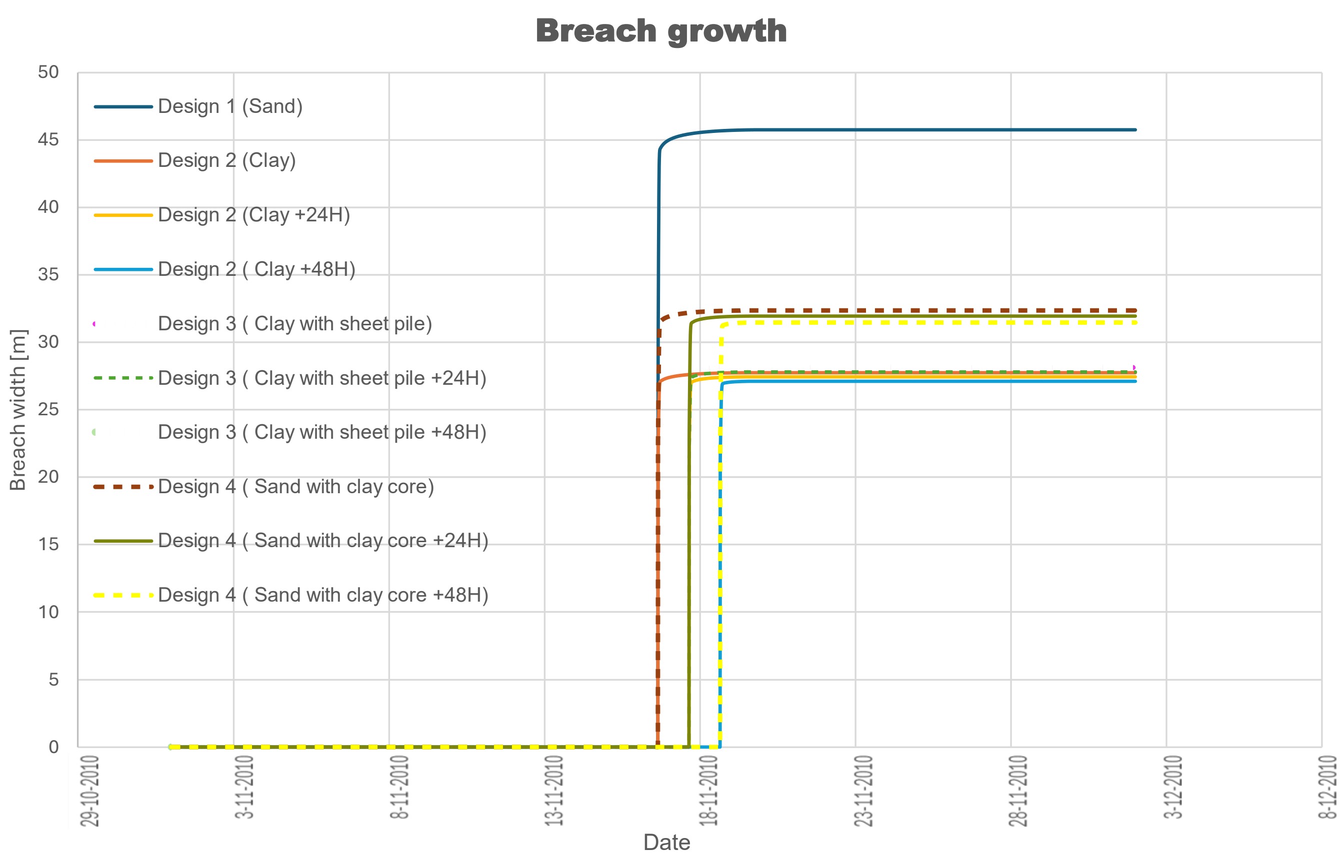


Figure 14: Breach growth of each design and scenario

The growth patterns of all designs and scenarios are very similar; the time it takes to reach maximum depth is remarkably fast, which will be further discussed in section 4. Furthermore, the maximum breach width can also be seen in Figure 64. The breach width of design 1 (Sand) is the widest breach among the designs; this is logical because sand has a lower critical velocity compared to clay (see Table 1); a lower critical velocity means that sand erodes by a lower velocity, making breach width wider compared to clay. The breach width of Design 4 (Sand dike with clay core) lies between Design 1 and the other designs, and the narrowest breaches are the ones of Designs 2 and 3 due to the cohesive characteristic of the clay, as expected in section 2.1.

The other designs have smaller breach widths due to the cohesive characteristic of clay, as expected in section 2.1. The narrowest breaches are the ones of the designs simulated 24 and 48 hours after the peak of the wave flood. However, the width of the breach is not the only factor affecting the water volume that flows through the breach. The starting time of the breach and depth also influence the discharge volume and, thus, the flood risk. The cumulative discharge through the breach of all designs is put next to each other, as shown in Figure 15.

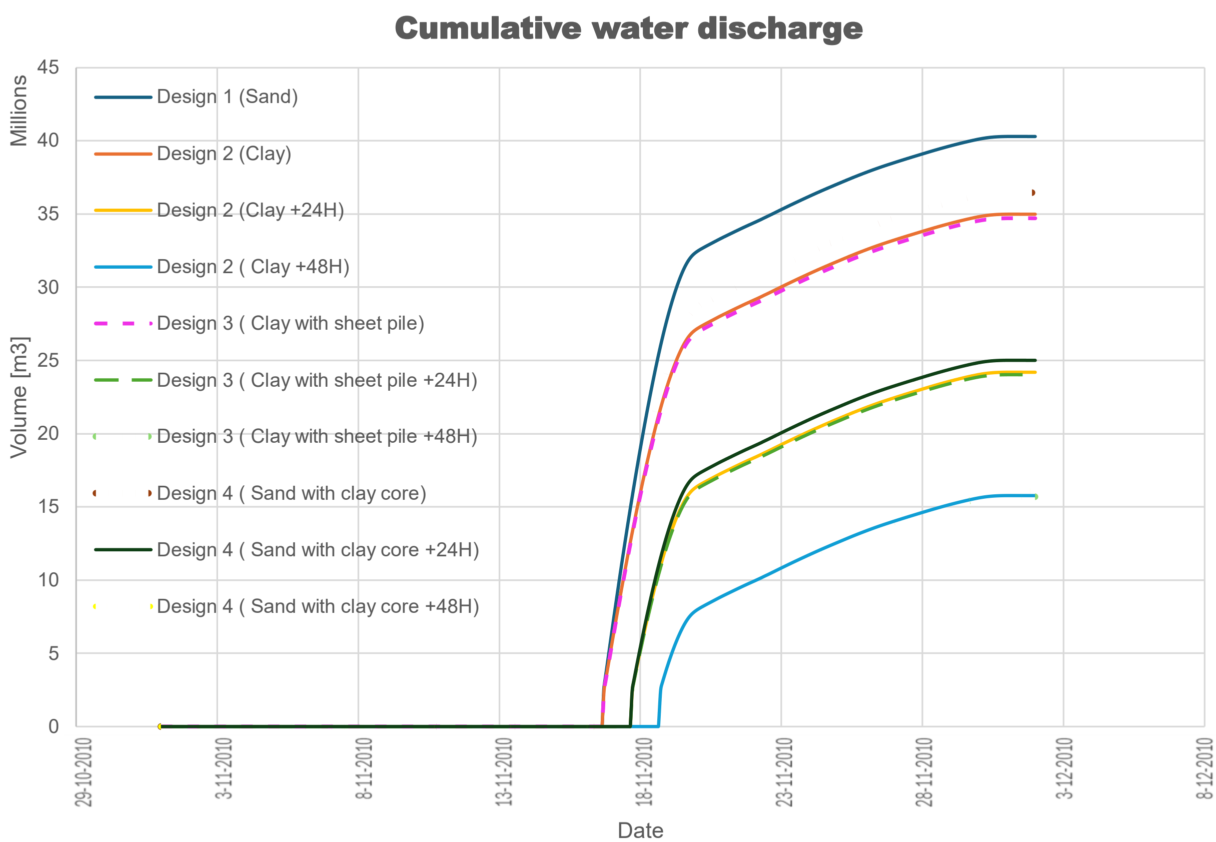


Figure 15: Cumulative discharge through the breach of all designs

The differences in discharge between the designs are significant, especially between the highest (Design 1) and the lowest (Design 3 Clay with sheet pile +48H). To clarify the difference between all designs and answer research sub-question 4, the total discharge through the dike has been plotted and shown in Figure 16.

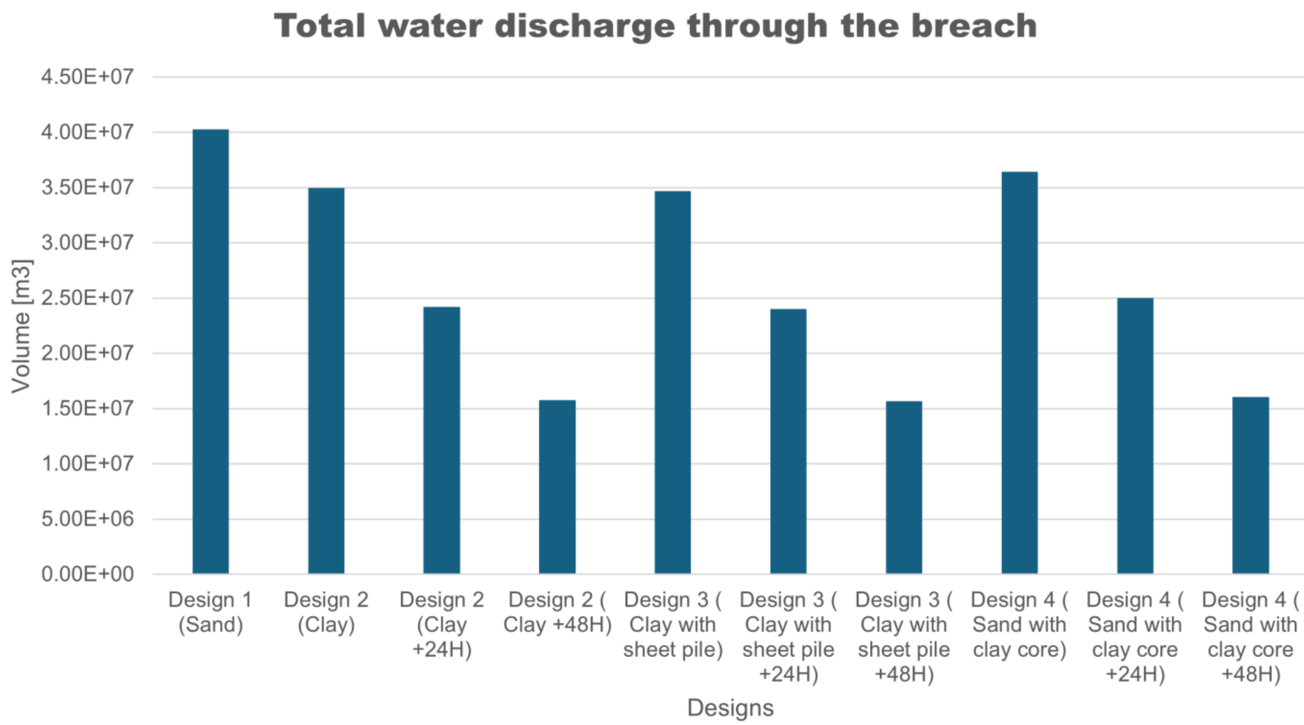


Figure 16: Total discharge through the breach

Design 1 demonstrates the highest total discharge through the breach, which aligns with its widest breach. Designs 2, 3, and 4 show similar results across both +24H and +48H scenarios. Designs simulated at +48H after the peak experience a significantly reduced discharge, specifically 61% less compared to Design 1. Similarly, designs simulated at +24H show a 40% reduction compared to Design 1. When comparing designs 2, 3, and 4 (with tough elements) that start breaching at the peak of the flood wave simultaneously with design 1, the discharge is only 12% lower, which is relatively minor. Of particular note is that the sheet pile wall does not significantly improve the breach width or total discharge; designs 2 and 3 show similar results. To assess the flood's impact on water depth in the hinterland, the maximum water depths following the flood for each design are compared in Figure 17.

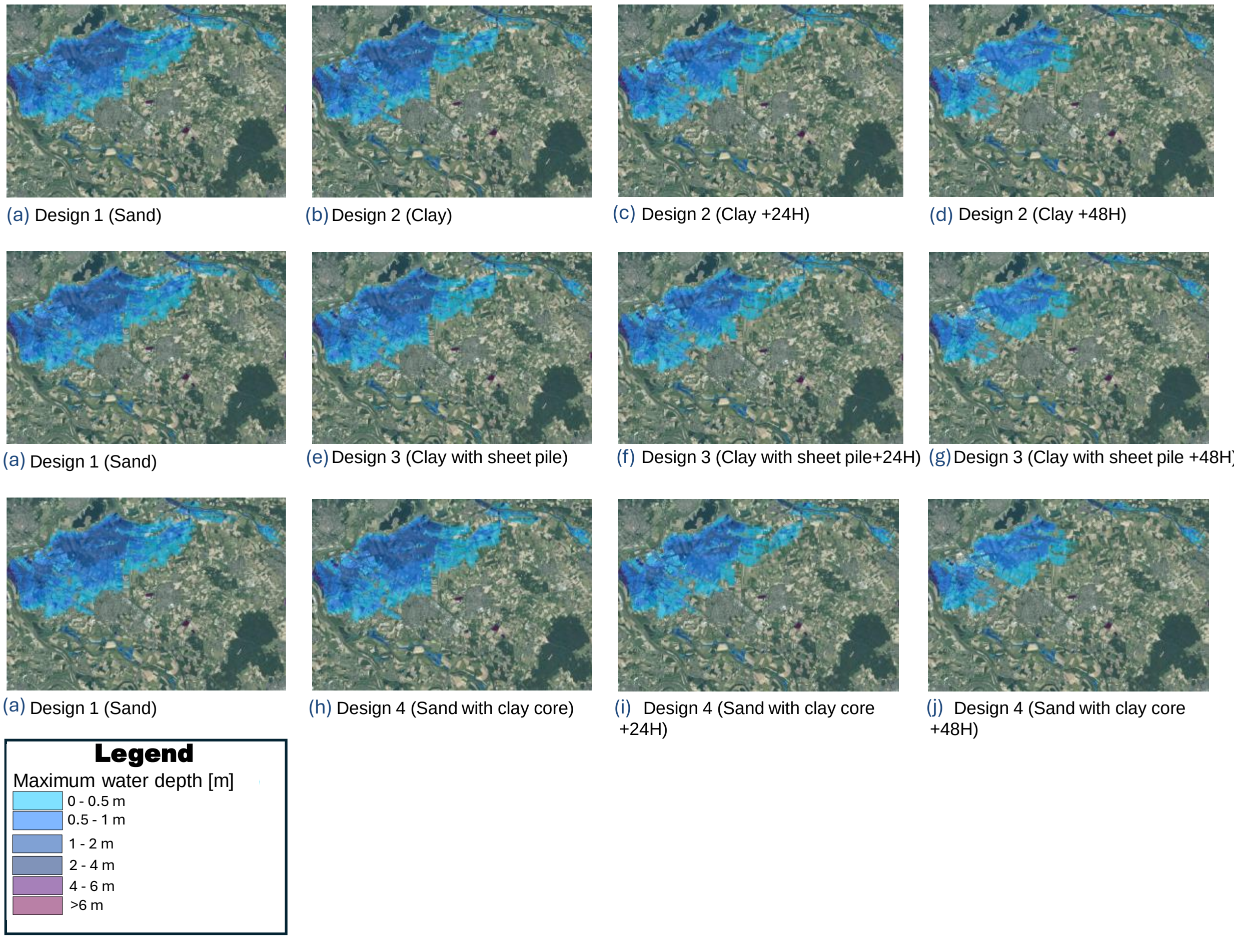


Figure 17: Maximum water depth maps of all designs

The maximum water depth maps visually represent the flood extent and depth of the dike designs and breach scenarios. Design 1, a sand dike, shows a large inundation area and significant water depths. However, compared to Designs 2, 3, and 4, the differences in inundation areas and water depths are minor (see Figure 17a,17b,17e,17h). This similarity is expected given the cumulative water discharges of design 2,3, which are only 12% compared to design 1, leading to comparable water depth maps. The delayed breach scenarios for Designs 2, 3, and 4 show significant reductions in the extent and depth of flooding. The water depth maps for the +24H scenarios are similar across these designs, reflecting the similar cumulative water discharge. The same pattern is observed for the +48H scenarios, where the delayed breach results in considerably less flooding extent and depth. The most noticeable differences in the water depth maps are between the +24H and +48H delayed and immediate breach scenarios. The delayed breaches show much less water depth, indicating a substantial reduction in flood impacts.

3.2.2 Damage and Casualties

Using the D-Hydro outputs as inputs for the SSM2017 model, as explained in section 2.3.2, the consequences of the flood, including direct financial damage, number of casualties, and number of affected people, are calculated. The SSM2017 model inputs are detailed in Appendix C.1.3.

The results for direct damage, number of casualties, and number of people affected for all designs and scenarios can be seen in Figure 18. The same results can also be seen in Table 13 in Appendix C.1.4.

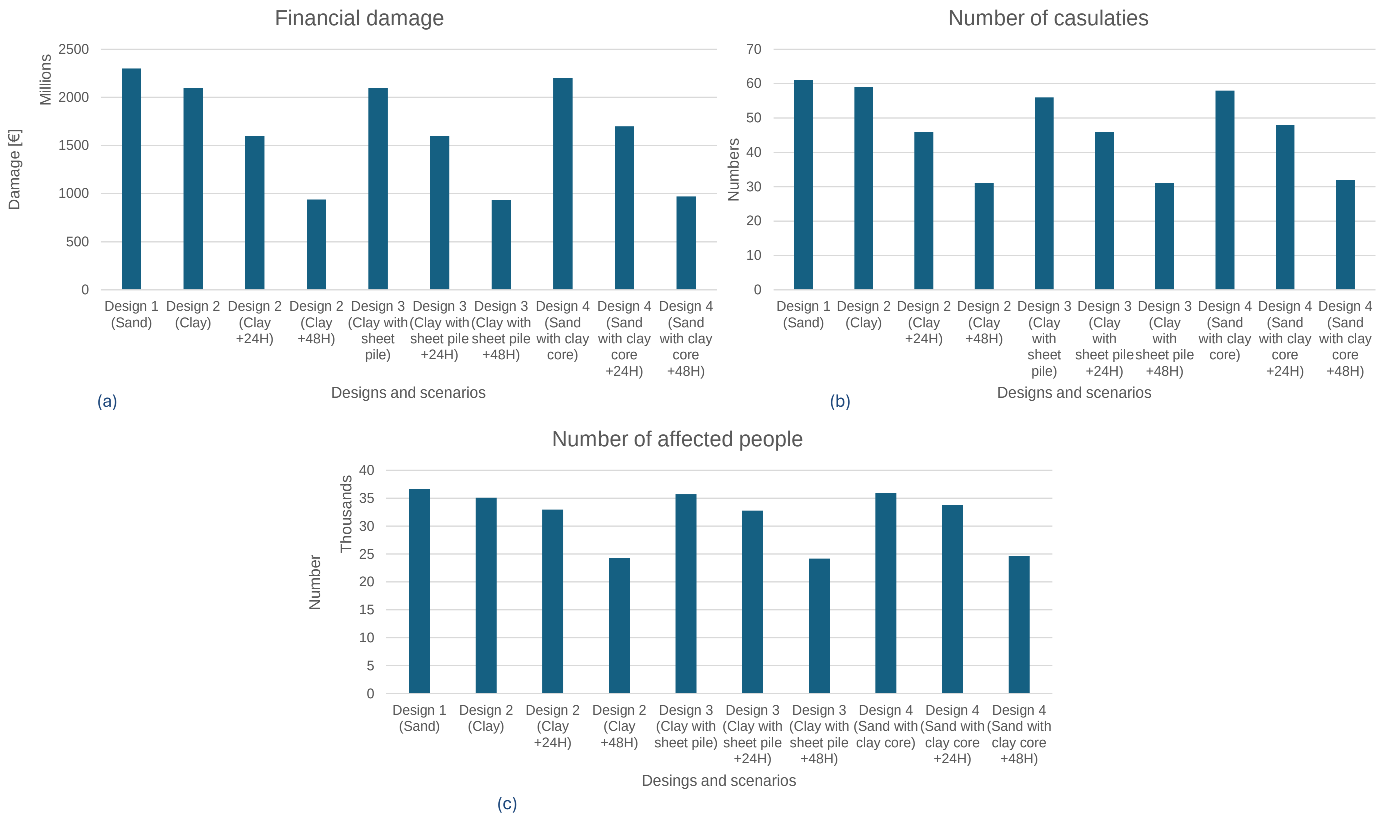


Figure 18. Flood consequences results : (a) Financial damage. (b) Number of casualties. (c) Number of affected people

The charts above illustrate the impact of different dike designs and breach scenarios on flood consequences. Design 1, a sand dike, consistently results in the most significant financial damage, number of casualties, and number of affected people, which answers research sub-question 5. However, the differences compared to other designs are not very large without considering delayed breach scenarios. This is because the difference in cumulative water discharge through the breach of the designs without breach delay is insignificant (see Figure 15), resulting in similar water depth maps and, thus, similar flood consequence results (see Figure 17). Design 2 (clay dike) shows improved performance over Design 1. When the breach is delayed by 24 hours, financial damage, casualties, and affected people decrease substantially. The 48-hour delay results in further reductions, demonstrating the benefits of delaying the breach. Design 3 (clay dike with sheet pile) performs slightly better than Design 2 due to the additional structural integrity provided by the sheet pile. Like Design 2, the delayed breach scenarios (24H and 48H) significantly reduce flood impacts. Design 4 (sand dike with a day core) also performs better than Design 1. Although it starts with higher initial impacts than the clay dikes, the delayed breach scenarios (24H and 48H) significantly reduce financial damage, casualties, and the number of affected people. With the 48-hour delay, Design 4 performs comparably to the clay dikes.

In summary, the flood consequences of all designs breaching at the peak of the flood wave are very similar, and the differences can be neglected. For designs 2, 3, and 4, delaying the breach by 24 or 48 hours significantly enhances their effectiveness in mitigating flood consequences.

3.3 Construction Costs

In this section, the construction costs of the dike designs will be calculated using the method described in section 2.4. Table 3 shows the dike profile and dimensions for each design.

Table 3: Dike dimensions of each design

	Design 1	Design 2	Design 3	Design 4
Outer slope	1:3	1:3	1:3	1:3
Inner slope	1:4	1:4	1:4	1:4
Crest width [m]	5	5	5	5
Crest height [m relative to ground level]	5.58	5.58	5.58	5.58
Cross-section [m]	137.14	137.14	136.42	Sand: 27.12 Clay: 110.02
Volume [m^3]	359443.94	359443.94	357556.82	Sand: 71081.52 Clay: 288362.42
Sheet pile [m^2]	-	-	24113.2	-

Table 4 shows the construction costs of each design, calculated using Table 3 and the prices mentioned in section 2.4.

Table 4: Construction costs of each design

	Design 1	Design 2	Design 3	Design 4
Supply and processing of dike material [M€]	7.19	7.19	7.19	7.19
Purchase of soil [M€]	7.55	8.09	8.05	7.98
Sheet pile installation [M€]	-	-	4.82	-
Total costs [M€]	14.74	15.28	20.06	15.17

The costs for each design are based on factors such as the volume of materials required and specific installation processes. The costs of the supply and processing of dike material are identical for all designs, at €7.19 million due to the same total volume. Considering the purchase of soil, the slight variations in soil costs are due to the different volumes and types of soil required for each design's specifications. The most significant difference comes from the sheet pile installation. Only Design 3 includes costs for sheet pile installation, amounting to €4.82 million. This addition makes Design 3 significantly more expensive than the other designs.

In conclusion, the main factors driving the cost differences are the purchase of soil and the inclusion of sheet pile installation. Design 1 emerges as the most cost-effective option, while Design 3 is the most expensive due to the additional sheet pile installation costs. The last answers research sub-question seven regarding which design is more expensive.

3.4 Comparative Analysis

This section compares the results from the D-Hydro simulations for each design by conducting a cost-benefit analysis to determine the best dike design. This analysis uses multiple parameters, including flood risk, net present value (NPV) of the risk, and construction costs. Flood risk is determined by multiplying the probability of flood (1/10000) by the consequences, and the NPV is calculated using Equation 5, as shown in Section 2.5. Construction costs are from Section 3.3. Table 5 summarizes the needed values for this analysis.

Table 5: Parameters needed for the cost-benefit analysis

Scenario	Damage [M€]	Risk [€]	NPV Risk [€]	Construction costs [M€]
Design 1 (Sand)	2300	230,000	10,222,222.22	14.74
Design 2 (Clay)	2100	210,000	9,333,333.33	15.28
Design 2 (Clay) +24H	1600	160,000	7,111,111.11	15.28
Design 2 (Clay) +48H	9400	94,000	4,177,777.78	15.28
Design 3 (Clay with sheet pile)	2100	210,000	9,333,333.33	20.06
Design 3 (Clay with sheet pile) +24H	1600	160,000	7,111,111.11	20.06
Design 3 (Clay with sheet pile) +48H	9300	93,000	4,133,333.33	20.06
Design 4 (Sand with clay core)	2200	220,000	9,777,777.78	15.17
Design 4 (Sand with clay core) +24H	1700	170,000	7,555,555.56	15.17
Design 4 (Sand with clay core) +48H	9700	97,000	4,311,111.11	15.17

The associated flood risk of each design and scenario is shown in the table above, which answers research sub-question six. The best design is found at the economic optimum of costs and benefits. This economic optimum lies where the total costs are lowest, i.e., where the sum of construction costs and NPV risk are the lowest. The values are plotted and can be seen in Figure 19.

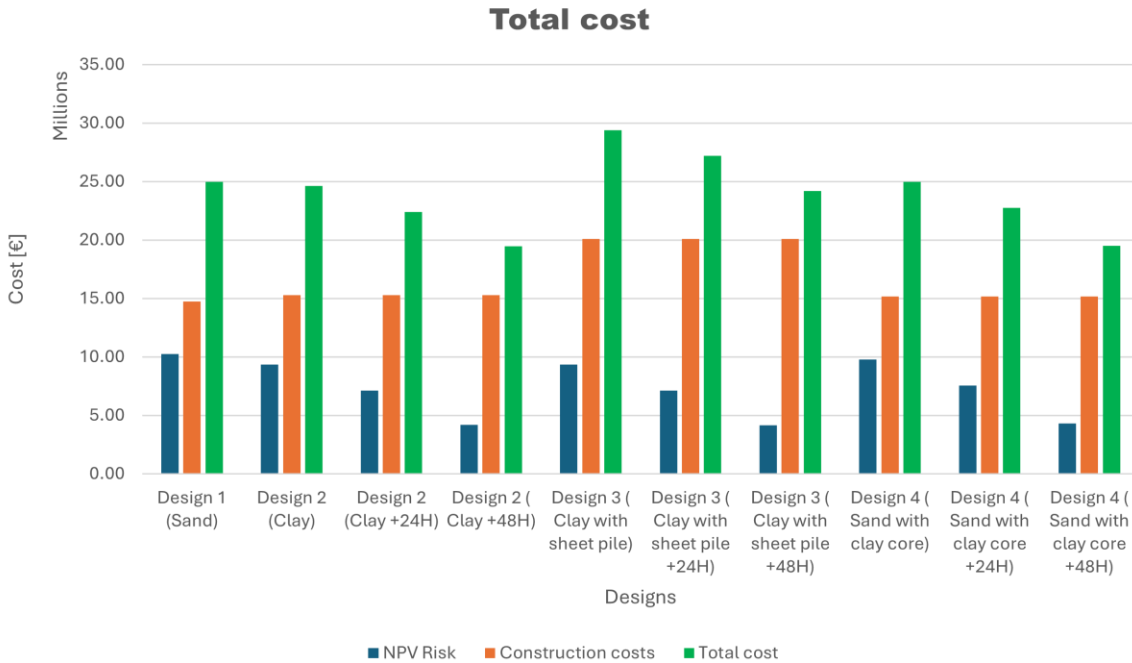


Figure 19: Total cost of all designs

Figure 19 shows several conclusions about each dike design's economic viability and risk management. The scenario "Design 2 (Clay) with +48H" has the lowest total cost of €19.46 million, making it the economically best design, which answers the research sub-question eight regarding the best design. This scenario balances construction costs and risk mitigation most effectively. On the other end of the spectrum, Design 3 proves to be the most expensive. The high construction cost due to the sheet pile installation contributes to its overall high expense, making it the least economical option despite its potential structural benefits.

3.5 Sensitivity Analysis

This section investigates the sensitivity of assumed parameters in the D-Hydro model. The first parameter examined is the initial breach width, crucial for modeling breach growth using the Verheij-van der Knaap formula as detailed in section 2.6. A standard assumption of 20 meters is applied to all designs, necessitating sensitivity testing. The critical velocity parameter for design 4 (sand with clay core) is also assumed to be 0.35 m/s. For the initial breach width parameter, the D-Hydro model for design 2 (clay) will be rerun twice, varying the initial breach width by ±25%. The resulting outputs will then be fed into the SSM2017 model to assess how sensitive the flood consequences are to changes in the initial breach width. Figure 20 shows the sensitivity of the initial breach parameter on the financial damage results caused by design 2.

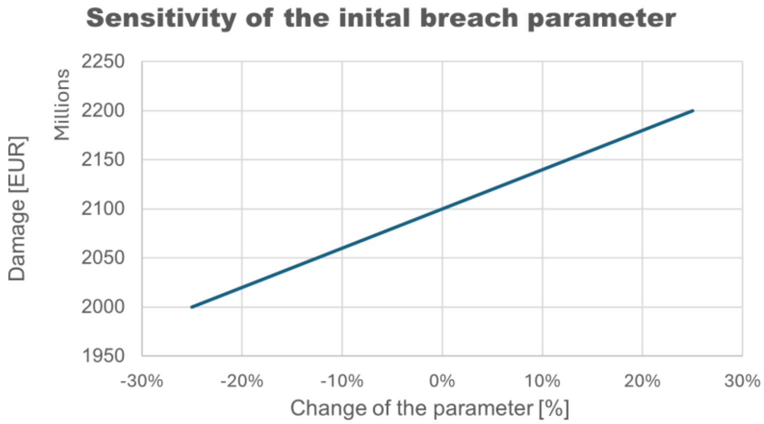


Figure 20: Sensitivity of the initial breach parameter in the damage results

The plot in Figure 20 exhibits a positive slope, indicating that the damage in euros increases as the initial breach parameter increases and vice versa. The sensitivity coefficient is calculated using Equation 6 to assess the damage's sensitivity to changes in this parameter. The sensitivity coefficient for a ±25% change in the initial breach parameter is 0.19, suggesting that for each 1% change in the initial breach parameter, the damage changes by approximately 0.19%. A similar analysis will be conducted for the critical velocity parameter of design 4, and Figure 21 shows the plot of those results.

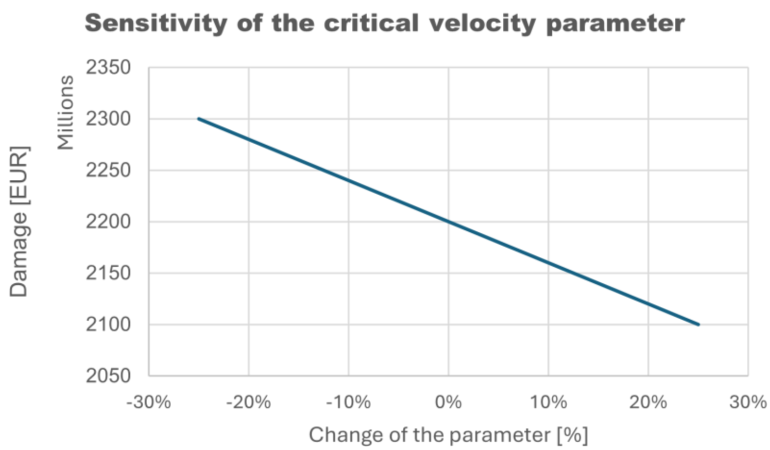


Figure 21: Sensitivity of the critical velocity in the damage results

Similar calculations are performed for the critical velocity parameter, resulting in a sensitivity coefficient of 0.18, indicating that for each 1% change in the parameter, the damage changes by approximately 0.18%. The outcomes for both parameters demonstrate moderate sensitivity, implying that variations in these parameters affect damage estimates, though not excessively. Understanding these sensitivities is pivotal for refining damage predictions' accuracy and making well-informed decisions regarding flood risk management. Future efforts to precisely estimate these parameters will mitigate uncertainty in damage outcomes, thereby enhancing the model's reliability.

4. Discussion

The results obtained in this study are based on a mix of literature and expert insights. An initial workshop with experts helped define the concept of toughness in dikes and gather ideas on designing tough dikes. Following this, multiple dike designs were developed, and their breach scenarios were modeled using a D-Hydro model to estimate the resulting damage.

Some results are not as expected, especially the difference between the resulting damage of the sand dike (design 1) and the dikes with clay in their dike body (designs 2,3 and 4) simulated to breach at the peak of the flood wave. Although the breach width of the clay dikes (28m) is narrower than the sand dike (46m), the flood impact of all designs is comparable, and the differences can be neglected. The expectation was for clay dikes to have more positive effects on the damage results. A possible explanation can be due to the size and height differences of the inundation area; the water level of the inundation area rises very fast after the breach, making the water level of the river equaling the water level of the inundation area, resulting in lower flow velocity and discharge which also explains the relatively small breach widths of the designs and the small size of the inundation area shown by the water depth maps. To verify this explanation, various dike sections with different inundation area characteristics (size and height differences) need to be modeled in the future.

On the other hand, the results of the dike design with the 24 and 48-hour delay scenarios are promising. The consequences of the flood were significantly reduced compared to the not-delayed scenarios. However, there are some limitations and uncertainties. The most significant uncertainty arises from an assumption based on expert experience regarding the duration of phase zero (the delay) in the breaching process. The experts believed that the duration of phase zero for dikes with cohesive materials in their dike bodies, like clay, can take longer than sand dikes. Thus, the dike withstands the high water levels longer, delaying the breach. However, due to the absence of experimental data to determine this duration, two scenarios were developed based on expert consultations: one assuming a 24-hour duration and the other assuming a 48-hour duration. These scenarios were only modeled for designs 2,3, and 4 due to the presence of clay in their dike bodies, while design 1 is of sand. These assumptions and the associated results can only be valid after conducting experiments to determine the duration of phase zero of the breaching process.

Another assumption involves the critical velocity for Design 4, which features a dike body made of sand with a clay core. The critical velocity was assumed to be 0.35 m/s, the average of the critical velocities for sand and clay. Sensitivity analysis indicated that this parameter does not significantly impact the results. However, only two parameter changes, +25% and -25%, made the analysis less reliable and can be improved in future research by taking a wide range of changes in the parameter. Furthermore, the sensitivity of the parameter was examined on the resulting damage, and since the differences were minimal in damage between the designs that were not delayed, possibly due to inundation area characteristics as discussed above. The parameter can be more sensitive for different case studies.

Unexpectedly, the sheet pile in Design 3, intended to act as a threshold for water and significantly reduce breach damage, did not perform markedly better than Design 2, which is identical except for the absence of a sheet pile. A higher sheet pile might yield better results, which should be considered in future projects.

Lastly, damage determination using the SSM2017 model was based solely on maximum water depth and velocity maps, excluding inputs like water arrival time and rise rate. This exclusion might have led to an underestimation of the damage. However, this potential underestimation would apply uniformly across all designs and scenarios, thus not affecting the comparative analysis. Additionally, the calculated construction costs may not be entirely accurate because the online prices reflect those available to individual buyers, whereas construction companies often receive different, typically lower, offers. Furthermore, maintenance costs were excluded. While these factors could lead to underestimations, they are not expected to impact the comparative analysis significantly. However, the costs are volatile over time, which can affect the cost-benefit analysis if this is done later in the future, which may lead to different outcomes.

5. Conclusion & Recommendations

5.1 Conclusion

The research on designing tough dikes has yielded valuable insights into the effectiveness of different dike configurations in mitigating flood risks. The findings from the D-Hydro and SSM2017 models, along with the sensitivity analysis, provide a detailed understanding of the performance of tough dikes compared to traditional designs. This conclusion summarizes the key findings of this research by addressing the research questions.

The main research question was, “Which is more resilient, traditional or tough dikes?” The results indicate that tough dikes are more resilient, as the designs incorporating tough elements caused significantly less damage than traditional ones.

The first sub-question was, “What distinguishes a tough dike from a traditional dike?” Insights from expert meetings suggest that a tough dike should have a higher ability to withstand high water levels near the dike crest, maintain a significant residual dike height to minimize inflow discharge, exhibit slower erosion and failure, allow more time for evacuation post-failure, and develop additional cohesion even during failure.

The second sub-question was, “What elements make a dike design tougher?” The results indicate that incorporating clay into the dike body makes the design tougher. This is evidenced by the reduced damage observed in designs 2, 3, and 4, which included clay, compared to design 1, which did not.

The third sub-question was, “How long does it take for a tough dike to fail compared to a traditional dike?” This question has no definitive answer due to the uncertainty surrounding estimating phase zero duration. Experts believe it may take 24 to 48 hours longer for a tough dike to fail, but this needs to be experimentally validated.

The fourth sub-question was, “What is the difference in cumulative water discharge through the breach between tough and traditional dikes?” The answer depends on the breaching process's assumed duration of phase zero. Assuming the same duration as design 1 (sand), the discharge of tough dikes is approximately 12% less. Assuming a 24-hour phase zero, the discharge is 40% less; for a 48-hour scenario, it is 61% less.

The fifth sub-question was, “Which dike causes more economic and social damage after a breach?” The results indicate that design 1, which does not incorporate tough elements, causes more economic and social damage.

The sixth sub-question was, “What is the associated risk of the designed dikes?” Table 8 contains the associated risks of all four designs and provides a detailed answer to this question.

The seventh sub-question was, “Which dike design is more expensive?” Tough dikes are more expensive, although the exact costs are uncertain due to factors discussed in the previous section.

The final sub-question was, “Which dike design is the best?” Based on the results of this research, design 2 with the +48H scenario is the optimum design.

In conclusion, tough dikes are very promising and can significantly reduce the risk of flooding. However, future experiments are necessary to determine the exact duration of phase zero and eliminate the uncertainties in this research's results.

5.2 Recommendations

Further research is necessary to enhance the precision and reliability of the results. Experiments to estimate the duration of phase zero in the breaching process of clay dikes are essential. Additionally, experiments to determine the critical velocity for soil types consisting of clay and sand are recommended, as many existing dikes have a sand body with an old clay core. HAN University of Applied Science is considering these experiments, but high costs, uncertainties, and spatial limitations have delayed their implementation.

As mentioned in the problem statement section, reinforcing 2,000 kilometers of the 3,500 kilometers of primary flood defenses by 2050 is a significant challenge. This research highlights the potential risk reduction offered by tough dikes. Eliminating the uncertainties of this research through targeted experiments could substantially impact flood risk management in the Netherlands, thereby helping to address this challenge.

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7. Appendix

A. Expert Meetings

Table 6: List of attendees at the expert workshop

Name	Job title
Helle Larsen	Senior advisor Technology and innovation at the Flood Protection Program (HWBP)
Oscar van Dam	Water safety program manager at STOWA
Martin Egas	Director at Ploegam BV
Martin Schepers	Leading expert at Aveco de Bondt
Martijn Kriebel	Water Safety & Geotechnical Advisor at Aveco de Bondt
Judith Paus	Water safety intern at Aveco de Bondt
Michelle Schouten	Water safety advisor at Hoogheemraadschap Hollands Noorderkwartier
Meindert Van	Expertise manager dike technology at Deltares
Mario van den Berg	PhD researcher in Coastal Engineering & Flood Risk at TU Delft
Barbara Bouman	Geotechnical advisor at TAUW bv
Ghaith Al Hussain	Third year civil engineering bachelor student at the University of Twente
Christien Veenstra-Huisman	Technical Manager Flood Protection Program (HWBP) at the Rijn and IJssel Water Board
Jeroen Kooman	Technical manager at the Rivierenland water board
Rik Beekx	Program director water at Dura Vermeer
Myron van Damme	Senior technical advisor at Rijkswaterstaat
Leo Zwang	Serviceline manager consulting / Commercial director water at Fugro
Frank den Heijer	Program manager flood defense asset management HAN University of Applied Sciences
Jan den Daas	Project leader sustainable river management at HAN University of Applied Sciences
Jeroen Rijke	Professor (lector) Sustainable River Management at HAN University of Applied Sciences
Maarten Podt	Researcher sustainable river management at HAN University of Applied Sciences

B. Dike designs / D-stability

This section contains each design's D-stability input, the geometry, the materials used, and the water pressure created by the water net creator.

B.1 Design 1

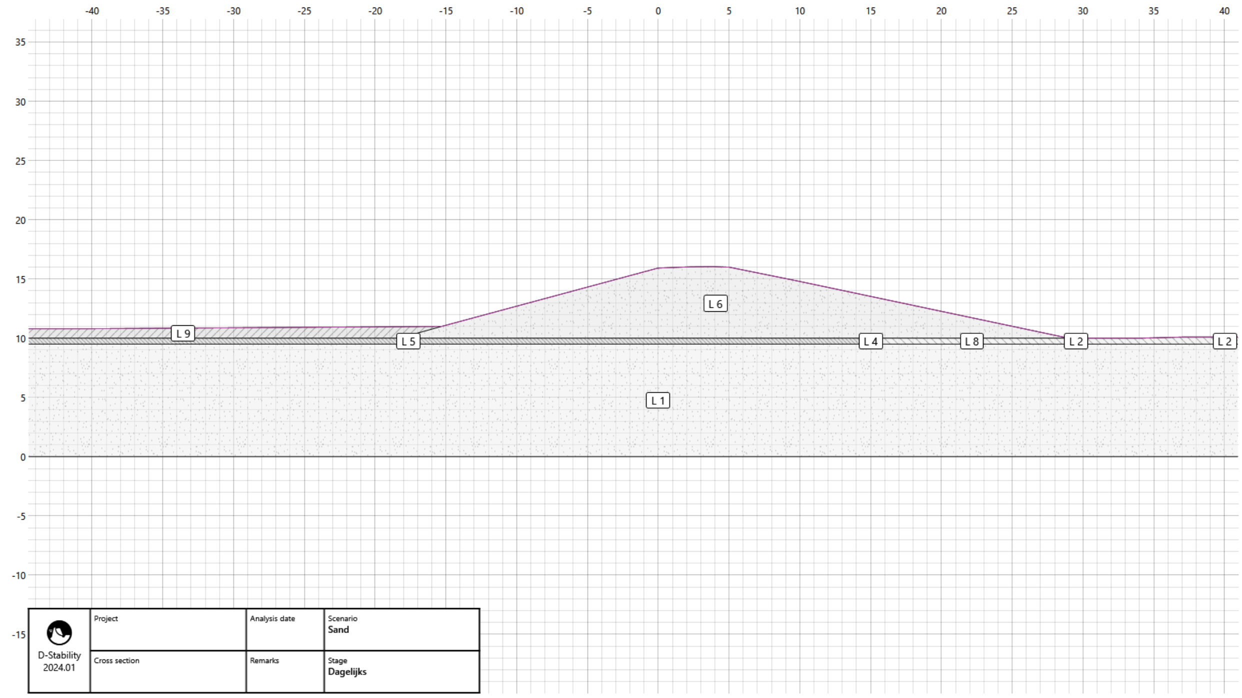

Figure 22: Geometry of Design 1

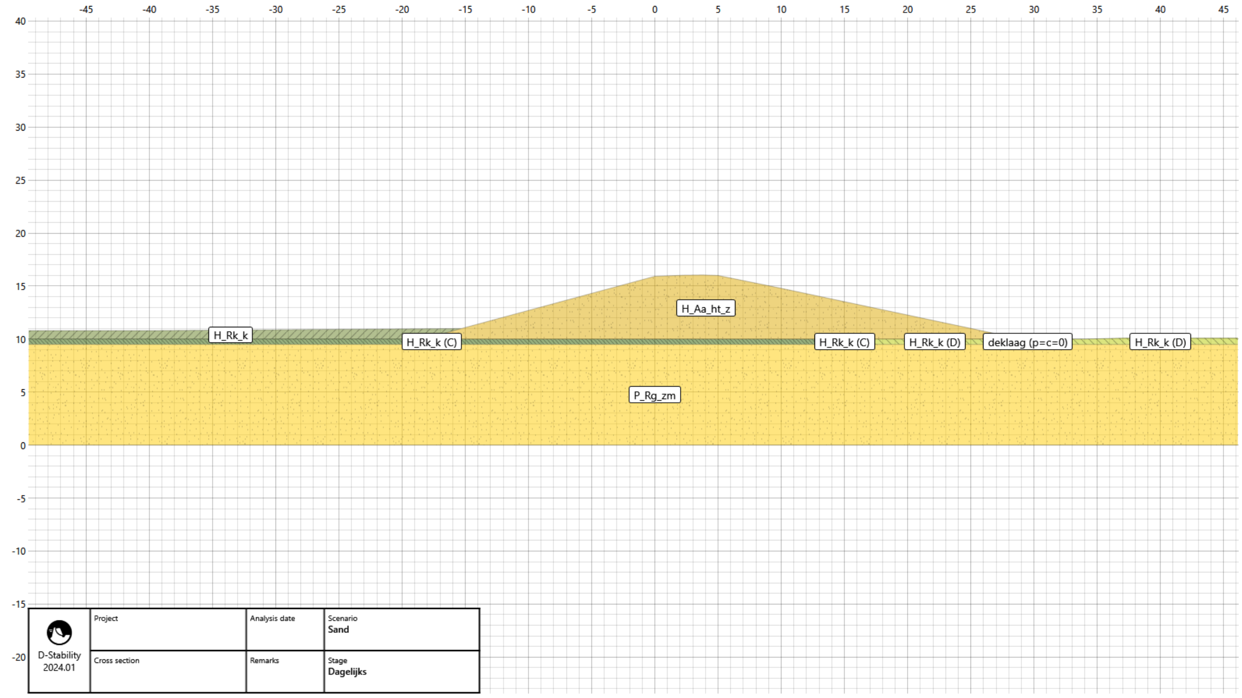

Figure 23: Used materials for Design 1

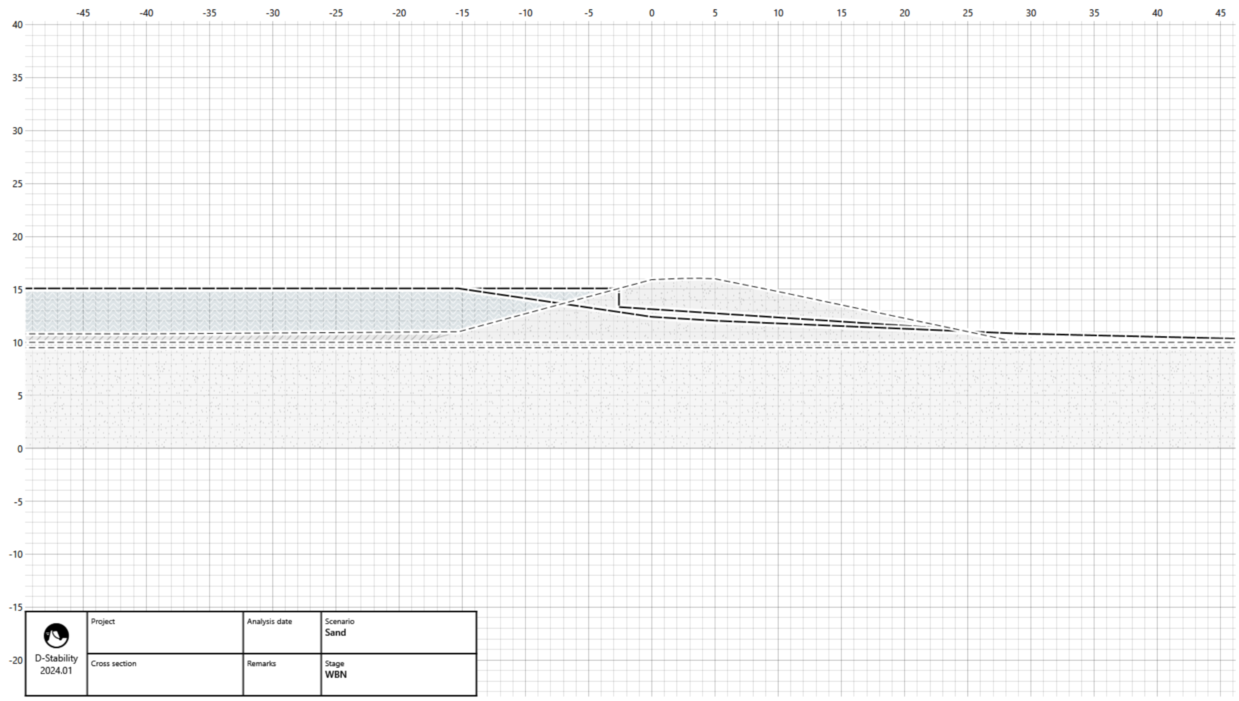

Figure 24: Water pressure of Design 1

B.2 Design 2

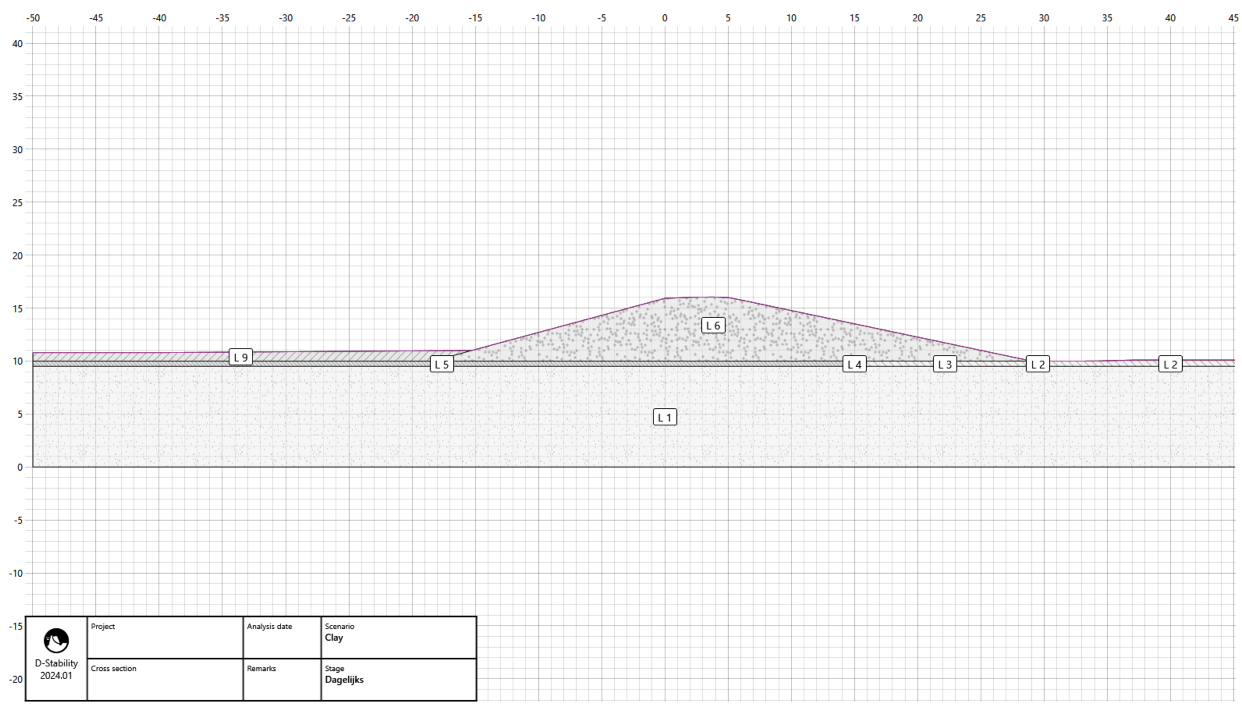

Figure 25: Geometry of Design 2

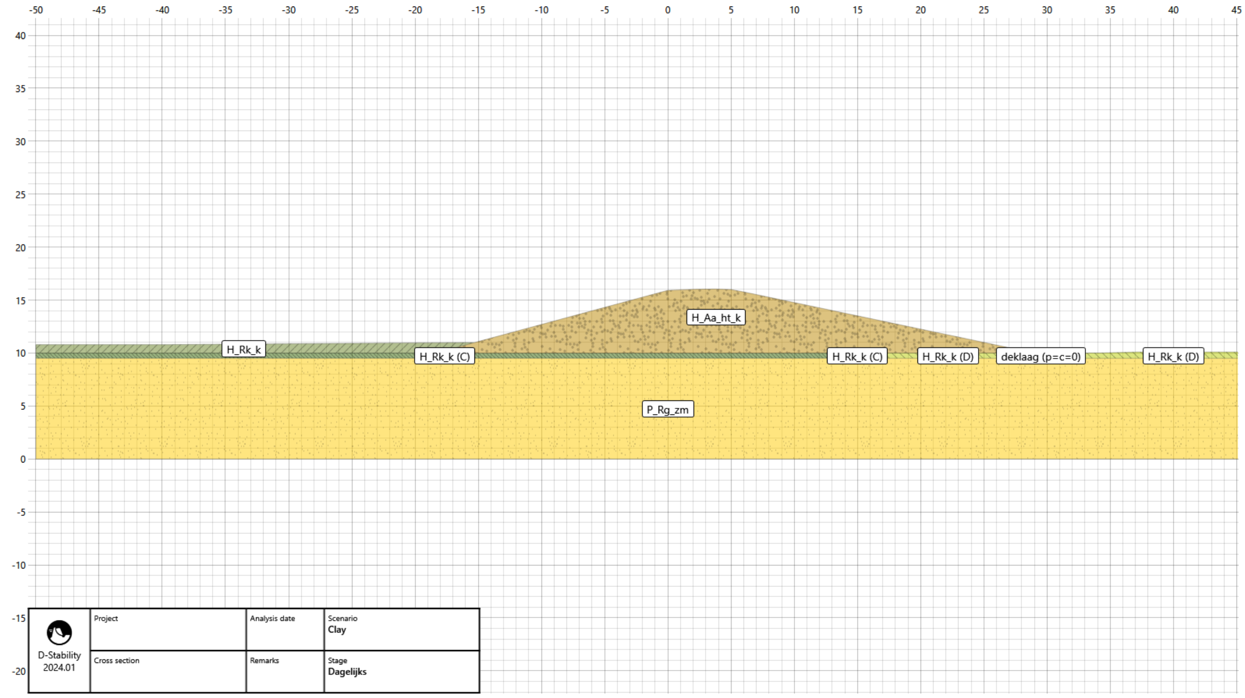

Figure 26: Used materials for Design 2

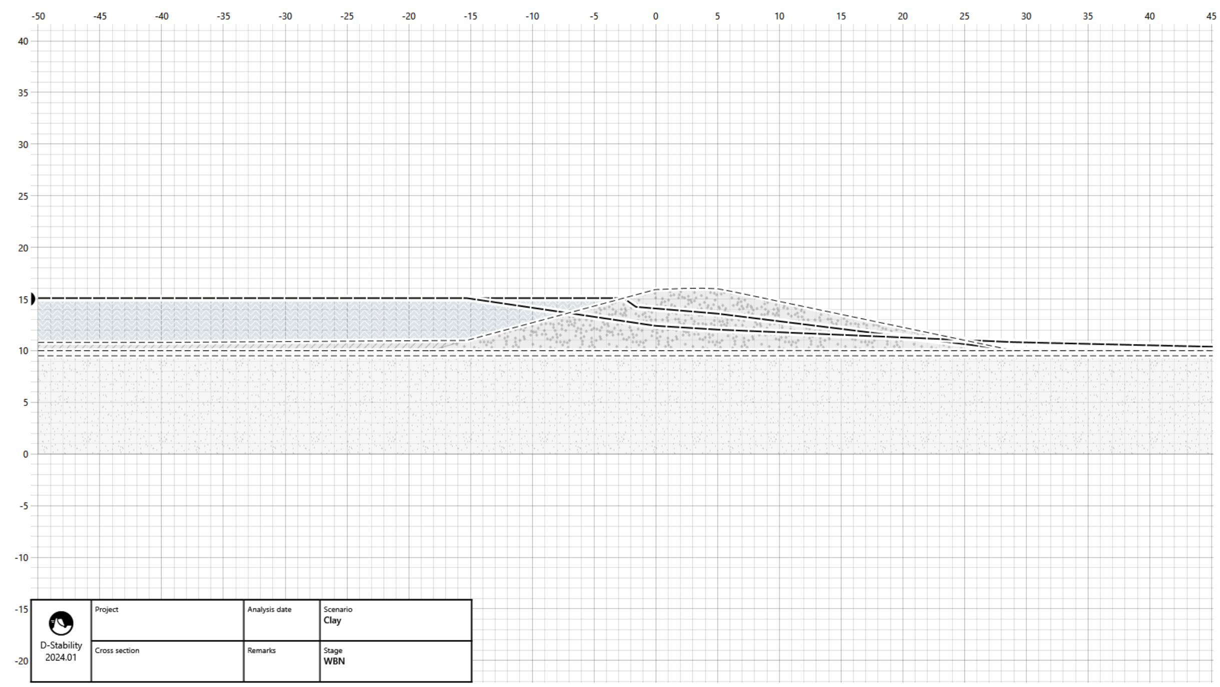

Figure 27: Water pressure of Design 2

B.3 Design 3

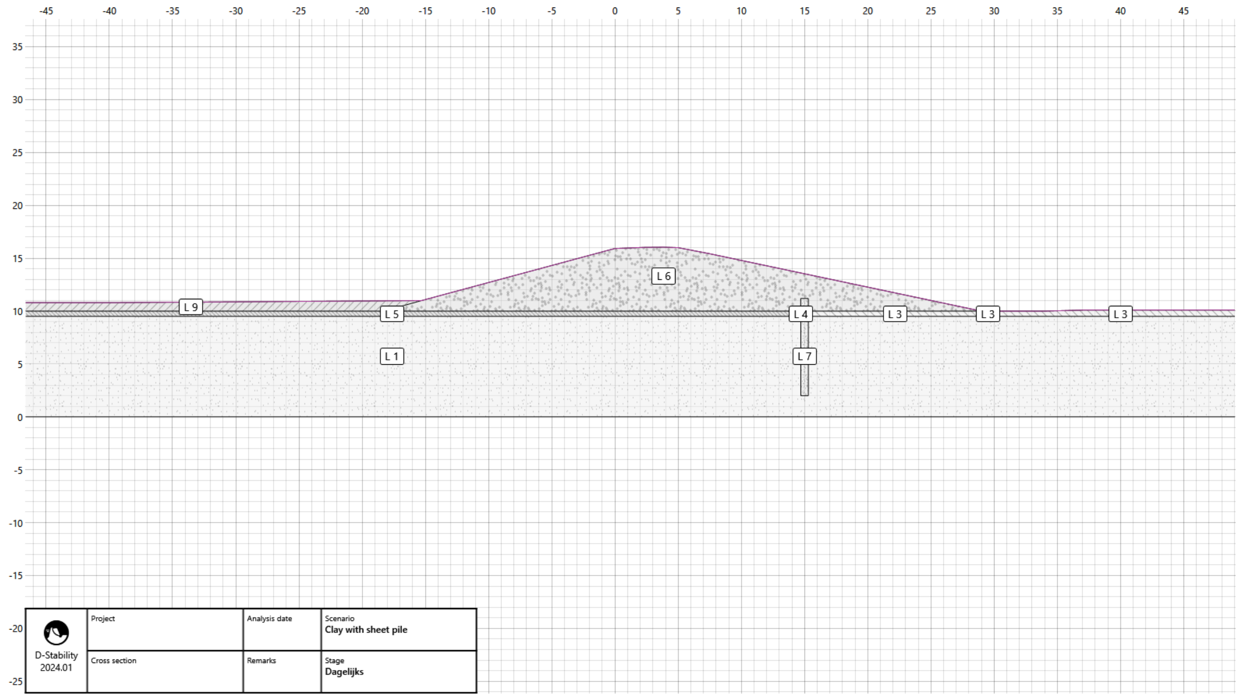

Figure 28: Geometry of Design 3

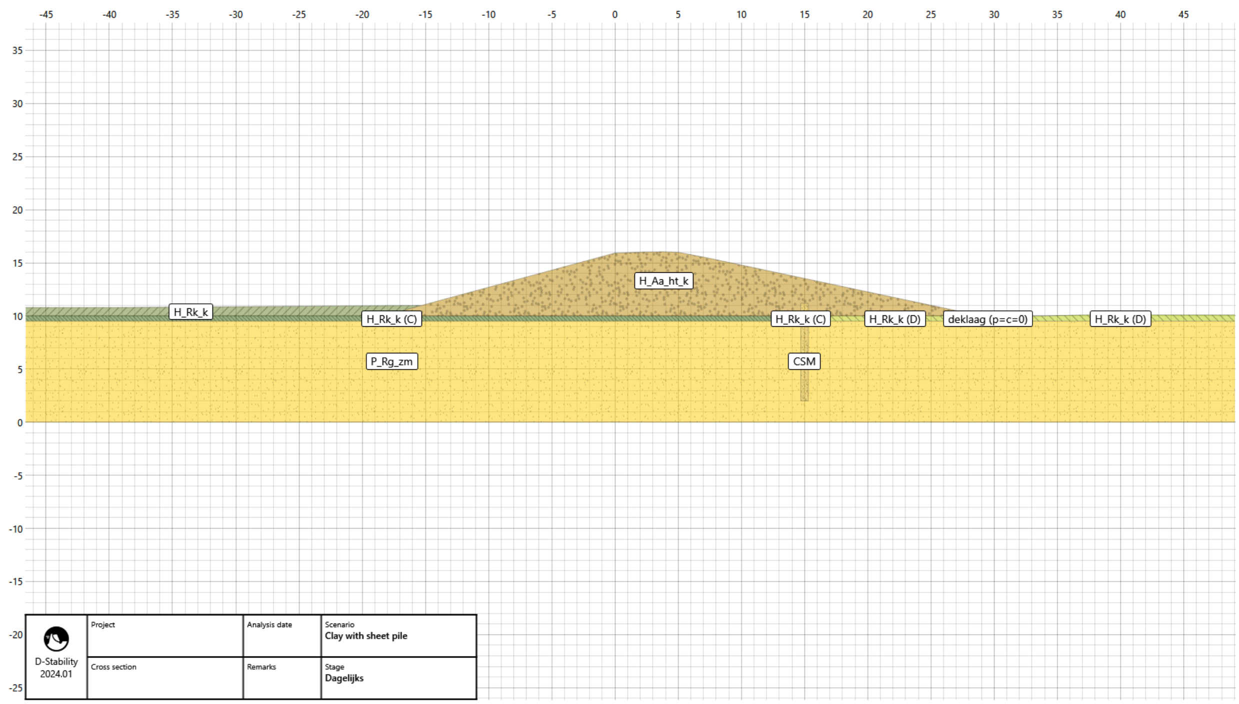

Figure 29: Used materials for Design 3

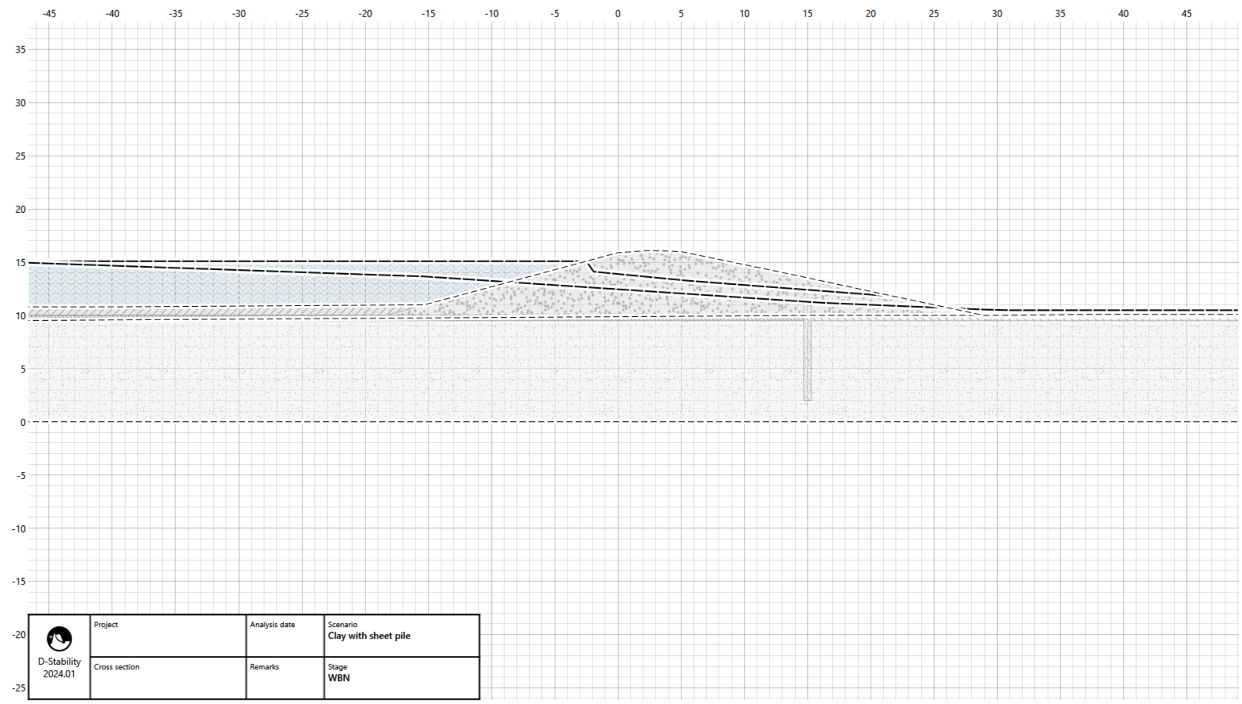

Figure 30: Water pressure of Design 3

B.4 Design 4

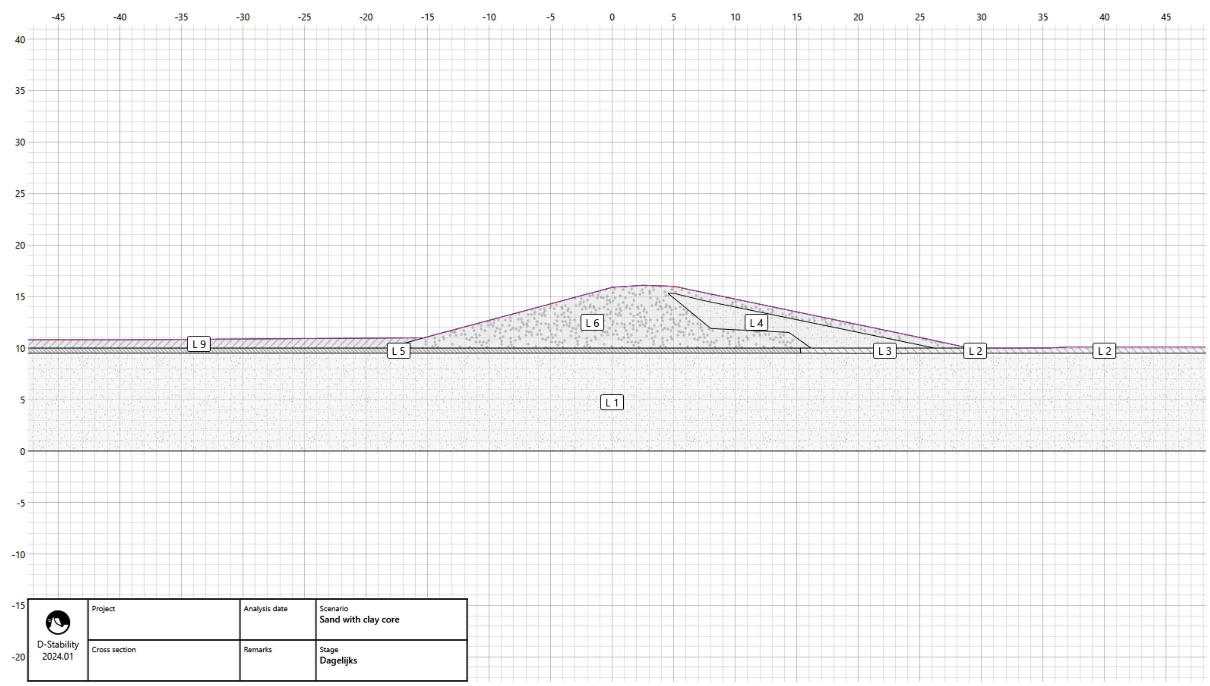

Figure 31: Geometry of Design 4

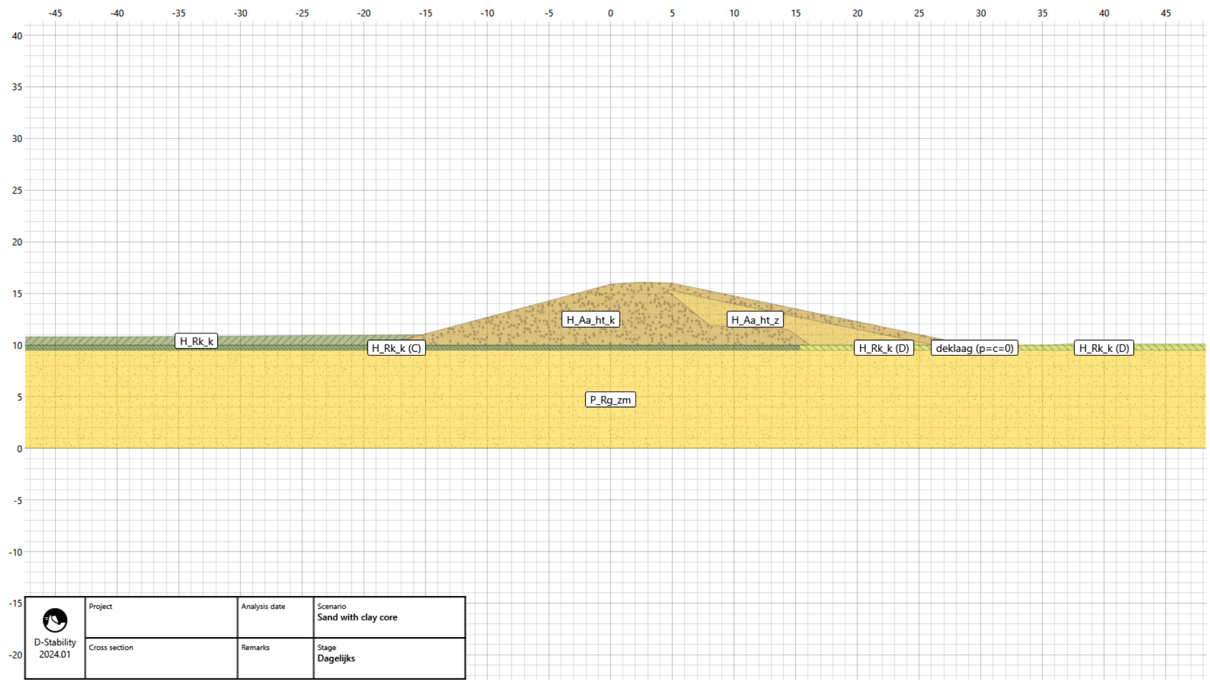

Figure 32: Used materials for Design 4

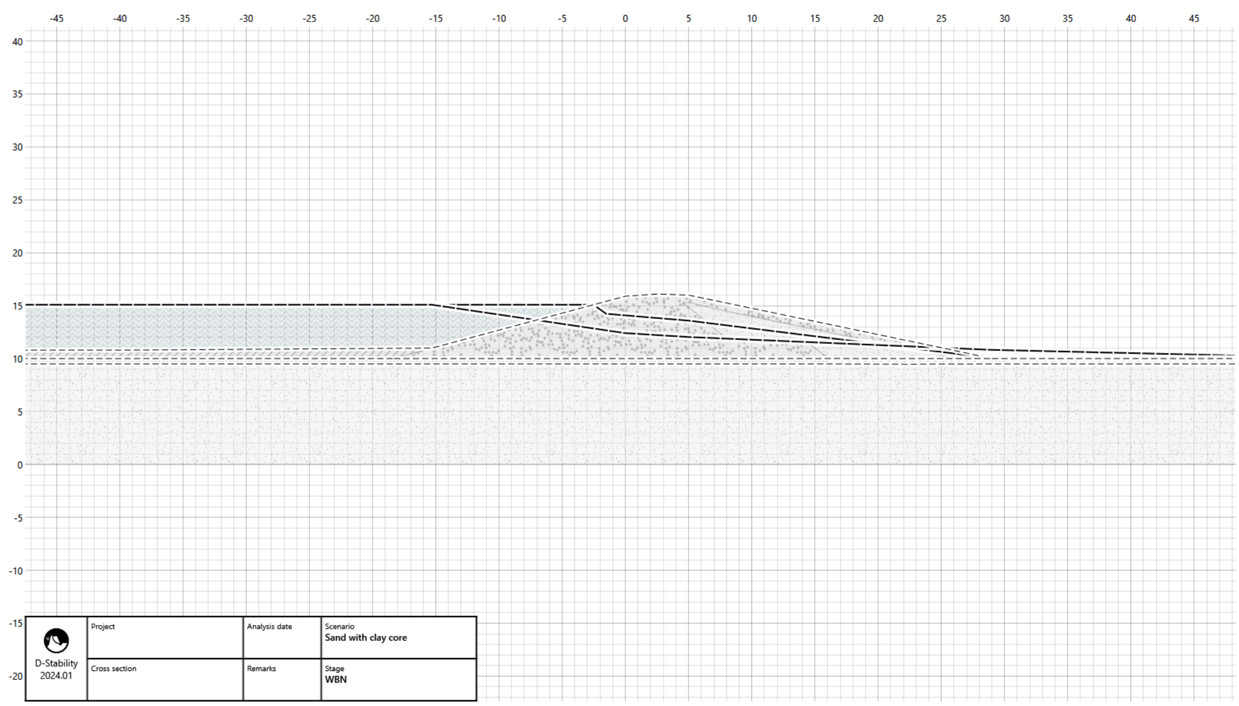

Figure 33: Water pressure of Design 4

C. D-Hydro Results

C. 1 Model Input

C.1.1 Discharge input

The Rijn and Ijssel waterboard delivers the discharge input. The probability of this discharge is 1 in 10,000 years, which is the dike's design standard. The used data can be seen in Tables 7 to 12.

Table 7: General information on the discharge input file

Key	Value
file Version	1.01
fileType	boundConds

Table 8: Discharge data of Hardinxveldboven

Water Level (m)	Discharge (m^3/s)
1.03	550
1.33	1401
1.768	2697
2.276	3997
2.679	5296
3.059	6473
3.623	8285
4.244	10165
4.631	11435
5.765	15400
6.222	17000

Table 9: Discharge data of Krimpen

Water Level (m)	**Discharge (m^3/s)**
1.227	25
1.387	309
1.556	753
1.75	1163
1.932	1579
2.108	2086
2.319	2758
2.527	3388
2.688	3812
3.748	6600
4.28	8000

Table 10: Discharge data of Ijsselmond

Water Level (m)	**Discharge (m^3/s)**
-0.02	50
0.067	400
0.171	800
0.328	1400
0.538	2200
1.009	4000
1.251	5000
1.462	6000
2.282	10000
2.692	12000

Table 11: Discharge data of Muendung_Lippe

Time (minutes since 2010-11-01 00:00:00)	Discharge (m³/s)
0	3303.210744
1440	3272.626652
2880	3272.963235
4320	3331.017753
5760	3406.212781
7200	3516.32472
8640	3750.558999
10080	4239.605158
11520	5010.794387
12960	5998.32528
14400	7363.897956
15840	9456.040152
17280	12173.2672
18720	14612.8331
20160	15715.62883
21600	16395
23040	16011.44352
24480	15452.50434
25920	14432.48388
27360	13160.36941
28800	11930.91985
30240	10808.69989
31680	9796.6412
33120	8947.728734
34560	8222.303813
36000	7361.743606
37440	6800.880307
38880	6245.23459
40320	5793.899966
41760	5361.655183
43200	4893.716169
44640	4400.808625

Table 12: Discharge data of OY_boundary_BocholterAa

Discharge (m³/s)
10

C.1.2 Breach Parameters

The used breach parameters can be seen in Figures 34 to 43.

```
[Structure]
id                    = Pleijdijk
type                  = dambreak
numCoordinates       = 201
xCoordinates         = 194047.051619119 19404
5 194011.5 194011.234375 194010.9375 194010.6
194009.46875 194009.671875 194009.90625 19401
yCoordinates         = 440807.05516302 440809
441011.40625 441012.96875 441015.46875 441017
216.40625 441218.90625 441221.375 441223.875
StartLocationX       = 194007.659477455
StartLocationY       = 441054.310450892
T0 = 1351200
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                = 1
Algorithm            = 2
CrestLevelIni        = 15.5864954247726
CrestLevelMin        = 10.0465
BreachWidthIni       = 20
TimeToBreachToMaximumDepth        = 600
F1                   = 1.2
F2                   = 0.04
Ucrit                = 0.2
```

Figure 34: Breach input parameters of design 1

```
[Structure]
id                    = Pleijdijk
type                  = dambreak
numCoordinates       = 201
xCoordinates         = 194047.051619119 194046.48437
5 194011.5 194011.234375 194010.9375 194010.640625 1
194009.46875 194009.671875 194009.90625 194010.14062
yCoordinates         = 440807.05516302 440809 440812
441011.40625 441012.96875 441015.46875 441017.96875
216.40625 441218.90625 441221.375 441223.875 441226.
StartLocationX       = 194007.659477455
StartLocationY       = 441054.310450892
T0 = 1351200
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                = 1
Algorithm            = 2
CrestLevelIni        = 15.5864954247726
CrestLevelMin        = 10.0465
BreachWidthIni       = 20
TimeToBreachToMaximumDepth        = 600
F1                   = 1.4
F2                   = 0.04
Ucrit                = 0.5
```

Figure 35: Breach input parameters of design 2

```
[Structure]
id                      = Pleijdijk
type                    = dambreak
numCoordinates          = 201
xCoordinates            = 194047.051619119 194046.
5 194011.5 194011.234375 194010.9375 194010.64€
194009.46875 194009.671875 194009.90625 194010.
yCoordinates            = 440807.05516302 440809 4
441011.40625 441012.96875 441015.46875 441017.9
216.40625 441218.90625 441221.375 441223.875 44
StartLocationX          = 194007.659477455
StartLocationY          = 441054.310450892
T0 = 1437600
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                   = 1
Algorithm               = 2
CrestLevelIni           = 15.5864954247726
CrestLevelMin           = 10.0465
BreachWidthIni          = 20
TimeToBreachToMaximumDepth        = 600
F1                      = 1.4
F2                      = 0.04
Ucrit                   = 0.5
```

Figure 36: Breach input parameters of design 2 (+24H scenario)

```
[Structure]
id                      = Pleijdijk
type                    = dambreak
numCoordinates          = 201
xCoordinates            = 194047.051619119 194046.4
5 194011.5 194011.234375 194010.9375 194010.6406
194009.46875 194009.671875 194009.90625 194010.1
yCoordinates            = 440807.05516302 440809 44
441011.40625 441012.96875 441015.46875 441017.96
216.40625 441218.90625 441221.375 441223.875 441
StartLocationX          = 194007.659477455
StartLocationY          = 441054.310450892
T0 = 1524000
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                   = 1
Algorithm               = 2
CrestLevelIni           = 15.5864954247726
CrestLevelMin           = 10.0465
BreachWidthIni          = 20
TimeToBreachToMaximumDepth        = 600
F1                      = 1.4
F2                      = 0.04
Ucrit                   = 0.5
```

Figure 37: Breach input parameters of design 2 (+48H scenario)

```
[Structure]
id                      = Pleijdijk
type                    = dambreak
numCoordinates         = 201
xCoordinates           = 194047.051619119 19404
5 194011.5 194011.234375 194010.9375 194010.6
194009.46875 194009.671875 194009.90625 19401
yCoordinates           = 440807.05516302 440809
441011.40625 441012.96875 441015.46875 441017
216.40625 441218.90625 441221.375 441223.875
StartLocationX         = 194007.659477455
StartLocationY         = 441054.310450892
T0 = 1351200
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                  = 1
Algorithm              = 2
CrestLevelIni          = 15.5864954247726
CrestLevelMin          = 11.2
BreachWidthIni         = 20
TimeToBreachToMaximumDepth       = 600
F1                     = 1.4
F2                     = 0.04
Ucrit                  = 0.5
```

Figure 38: Breach input parameters of design 3

```
[Structure]
id                     = Pleijdijk
type                   = dambreak
numCoordinates        = 201
xCoordinates          = 194047.051619119 194046.
5 194011.5 194011.234375 194010.9375 194010.64
194009.46875 194009.671875 194009.90625 194010.
yCoordinates          = 440807.05516302 440809 4
441011.40625 441012.96875 441015.46875 441017.9
216.40625 441218.90625 441221.375 441223.875 44
StartLocationX        = 194007.659477455
StartLocationY        = 441054.310450892
T0 = 1437600
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                 = 1
Algorithm             = 2
CrestLevelIni         = 15.5864954247726
CrestLevelMin         = 11.2
BreachWidthIni        = 20
TimeToBreachToMaximumDepth       = 600
F1                    = 1.4
F2                    = 0.04
Ucrit                 = 0.5
```

Figure 39: Breach input parameters of design 3 (+24H scenario)

```
[Structure]
id                     = Pleijdijk
type                   = dambreak
numCoordinates        = 201
xCoordinates          = 194047.051619119 19404
5 194011.5 194011.234375 194010.9375 194010.6
194009.46875 194009.671875 194009.90625 19401
yCoordinates          = 440807.05516302 440809
441011.40625 441012.96875 441015.46875 441017
216.40625 441218.90625 441221.375 441223.875
StartLocationX        = 194007.659477455
StartLocationY        = 441054.310450892
T0 = 1524000
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                 = 1
Algorithm             = 2
CrestLevelIni         = 15.5864954247726
CrestLevelMin         = 11.2
BreachWidthIni        = 20
TimeToBreachToMaximumDepth       = 600
F1                    = 1.4
F2                    = 0.04
Ucrit                 = 0.5
```

Figure 40: Breach input parameters of design 3 (+24H scenario)

```
[Structure]
id                      = Pleijdijk
type                    = dambreak
numCoordinates         = 201
xCoordinates           = 194047.051619119 1940
5 194011.5 194011.234375 194010.9375 194010.
194009.46875 194009.671875 194009.90625 1940
yCoordinates           = 440807.05516302 44080
441011.40625 441012.96875 441015.46875 44101
216.40625 441218.90625 441221.375 441223.875
StartLocationX         = 194007.659477455
StartLocationY         = 441054.310450892
T0 = 1351200
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                  = 1
Algorithm              = 2
CrestLevelIni          = 15.5864954247726
CrestLevelMin          = 10.0465
BreachWidthIni         = 20
TimeToBreachToMaximumDepth       = 600
F1                     = 1.3
F2                     = 0.04
Ucrit                  = 0.35
```

Figure 41: Breach input parameters of design 3

```
[Structure]
id                      = Pleijdijk
type                    = dambreak
numCoordinates         = 201
xCoordinates           = 194047.051619119 194046.
5 194011.5 194011.234375 194010.9375 194010.64(
194009.46875 194009.671875 194009.90625 194010.
yCoordinates           = 440807.05516302 440809 4
441011.40625 441012.96875 441015.46875 441017.9
216.40625 441218.90625 441221.375 441223.875 44
StartLocationX         = 194007.659477455
StartLocationY         = 441054.310450892
T0 = 1437600
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                  = 1
Algorithm              = 2
CrestLevelIni          = 15.5864954247726
CrestLevelMin          = 10.0465
BreachWidthIni         = 20
TimeToBreachToMaximumDepth       = 600
F1                     = 1.3
F2                     = 0.04
Ucrit                  = 0.35
```

Figure 42: Breach input parameters of design 4 (+24H scenario)

```
[Structure]
id                    = Pleijdijk
type                  = dambreak
numCoordinates       = 201
xCoordinates         = 194047.051619119 194046.48
5 194011.5 194011.234375 194010.9375 194010.64062
194009.46875 194009.671875 194009.90625 194010.14
yCoordinates         = 440807.05516302 440809 440
441011.40625 441012.96875 441015.46875 441017.968
216.40625 441218.90625 441221.375 441223.875 4412
StartLocationX       = 194007.659477455
StartLocationY       = 441054.310450892
T0 = 1524000
waterLevelDownstreamLocationX =194180
waterLevelDownstreamLocationY =441150
State                = 1
Algorithm            = 2
CrestLevelIni        = 15.5864954247726
CrestLevelMin        = 10.0465
BreachWidthIni       = 20
TimeToBreachToMaximumDepth        = 600
F1                   = 1.3
F2                   = 0.04
Ucrit                = 0.35
```

Figure 43: Breach input parameters of design 4 (+48H scenario)

C. 2 Breach Results

C. 2.1 Design 1

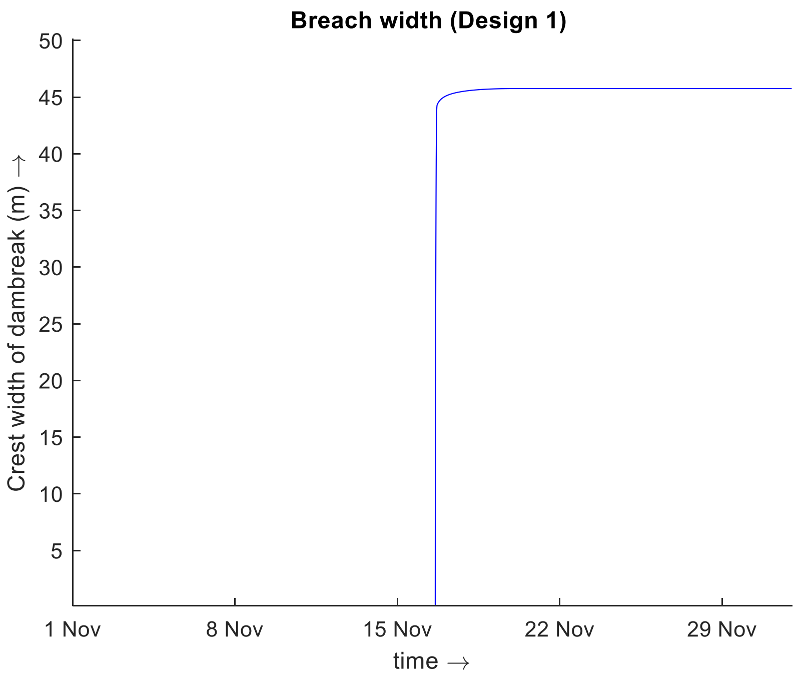

Figure 44: Breach width of design 1 (Sand)

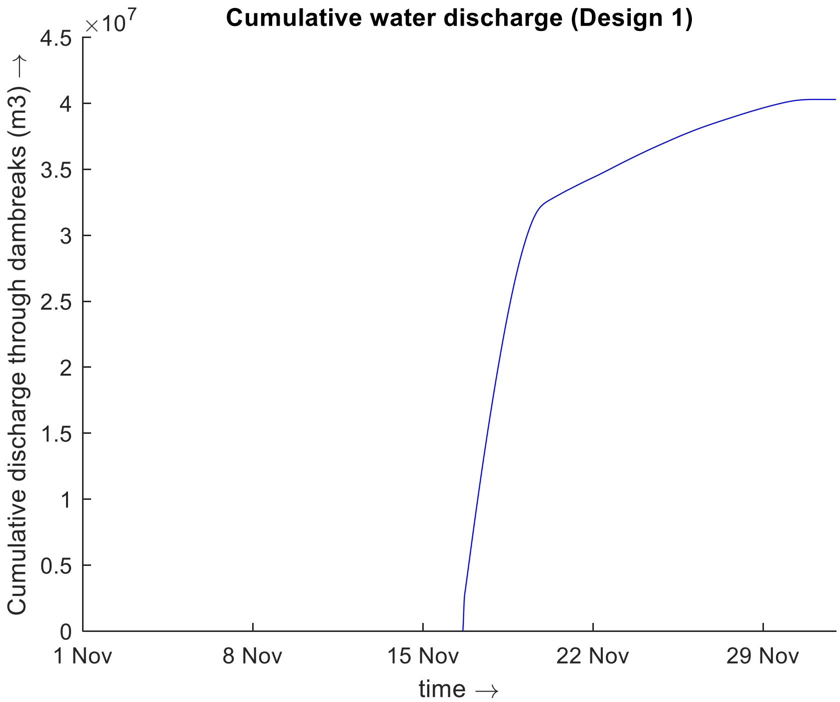

Figure 45: Cumulative discharge through the breach of design 1 (Sand)

C. 2.2 Design 2 (Clay)

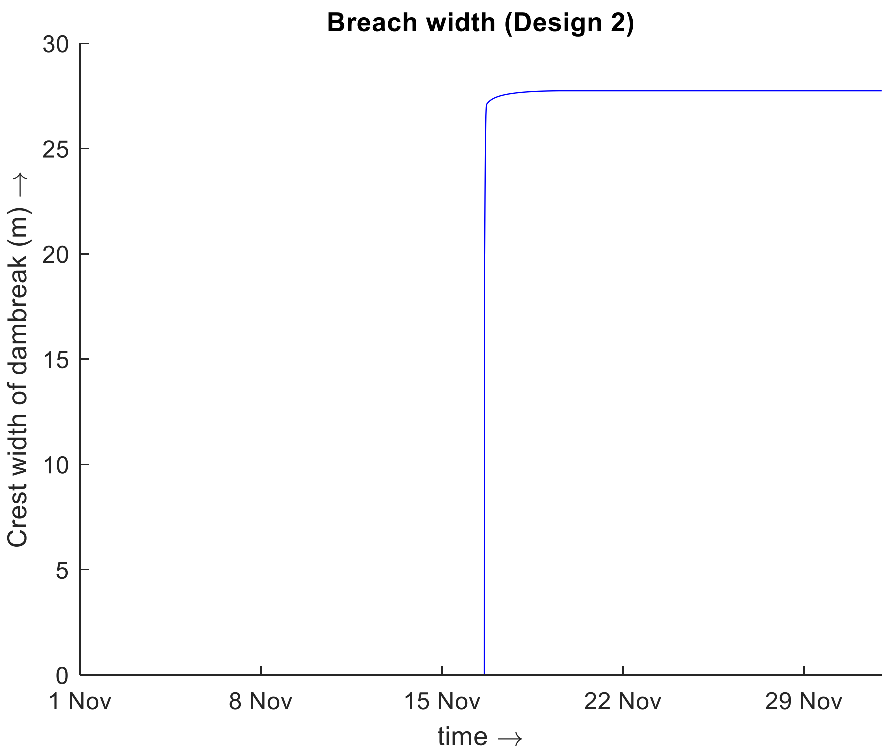

Figure 46: Breach width of design 2 (Clay)

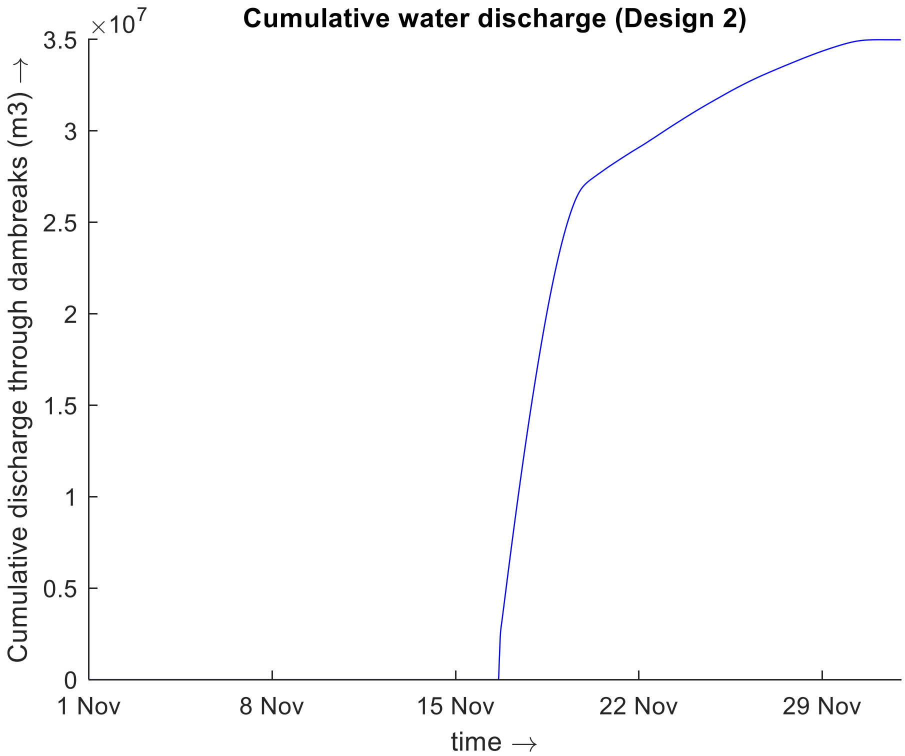

Figure 47: Cumulative discharge through the breach of design 2 (Clay)

C. 2.3 Design 2 (Clay +24H scenario)

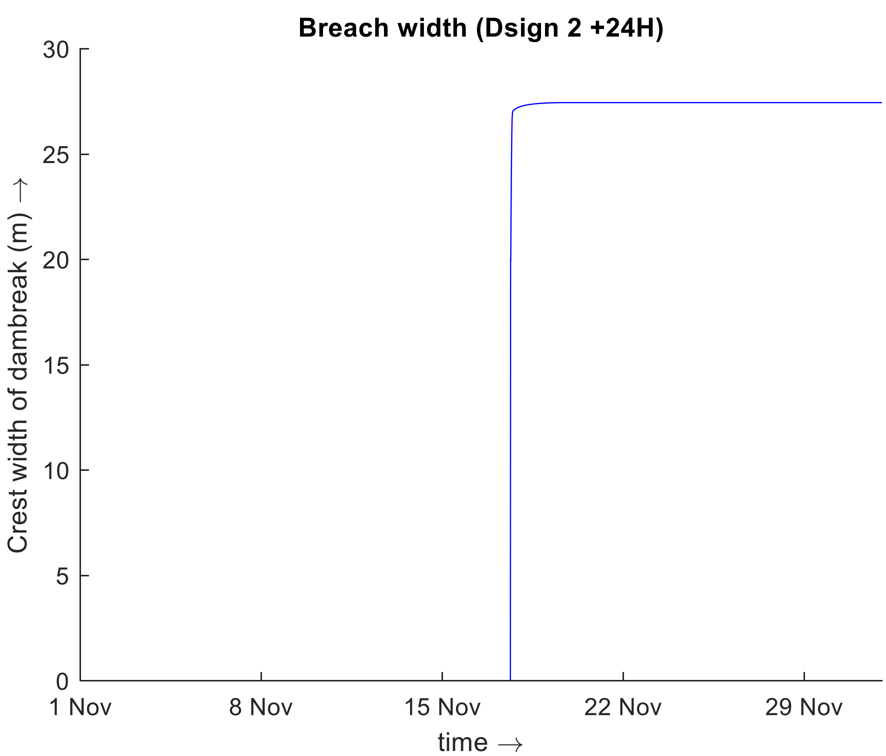

Figure 48: Breach width of design 2 (Clay +24H)

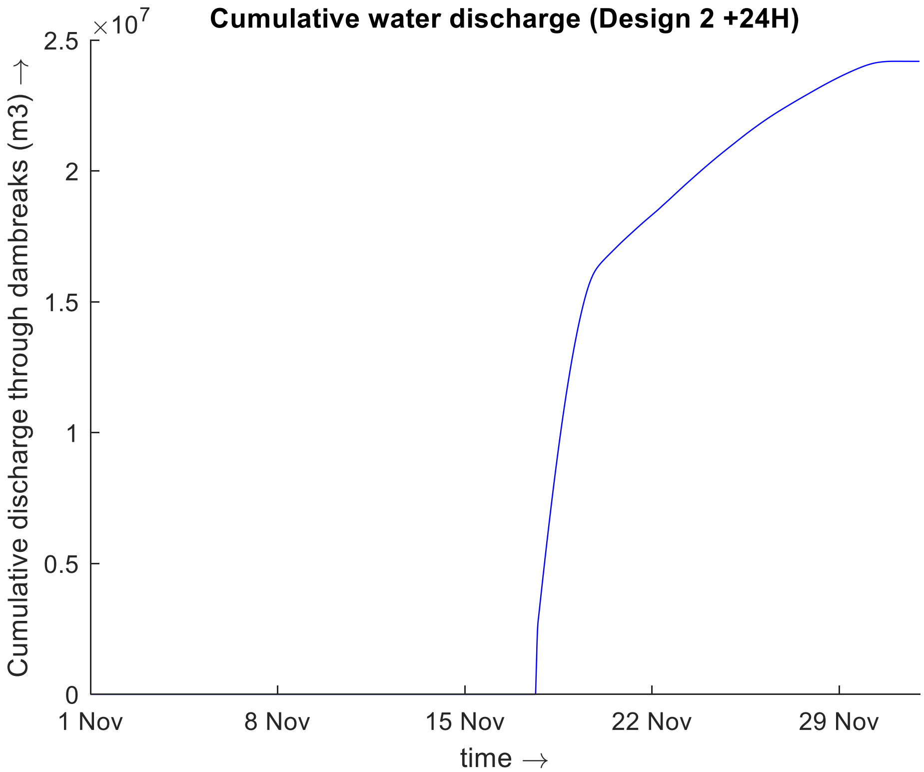

Figure 49: Cumulative discharge of design 2 (Clay +24H)

C. 2.4 Design 2 (Clay+48H scenario)

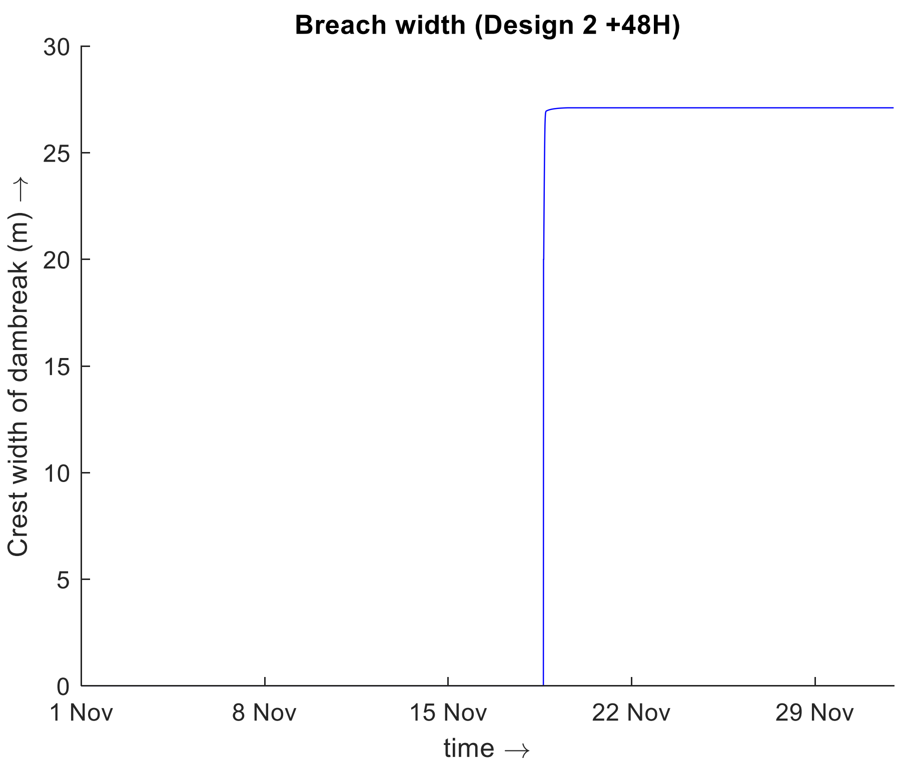

Figure 50: Breach width of design 2 (Clay +48H)

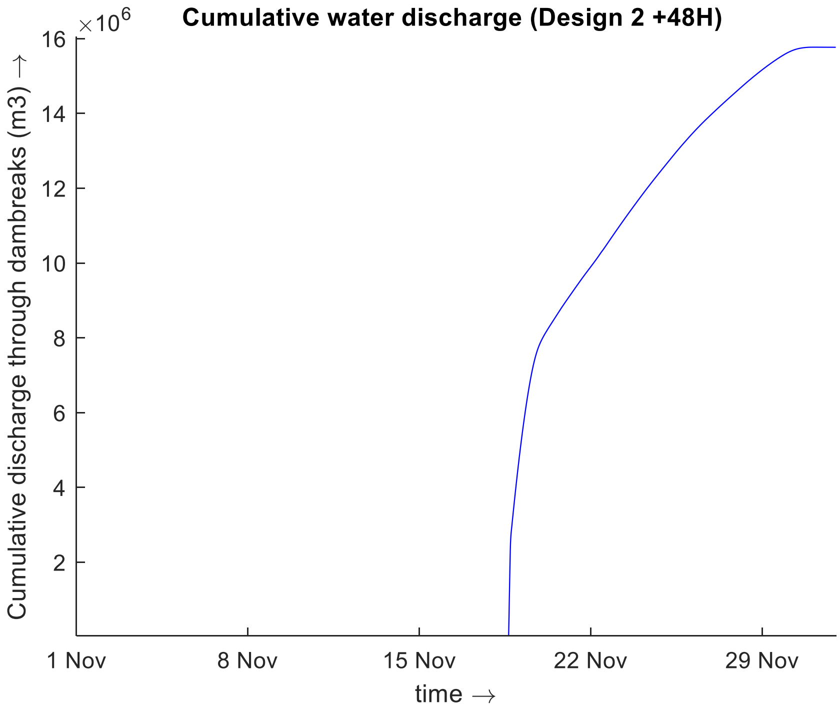

Figure 51: Cumulative discharge of design 2 (Clay +48H)

C. 2.5 Design 3 (Clay with sheet pile)

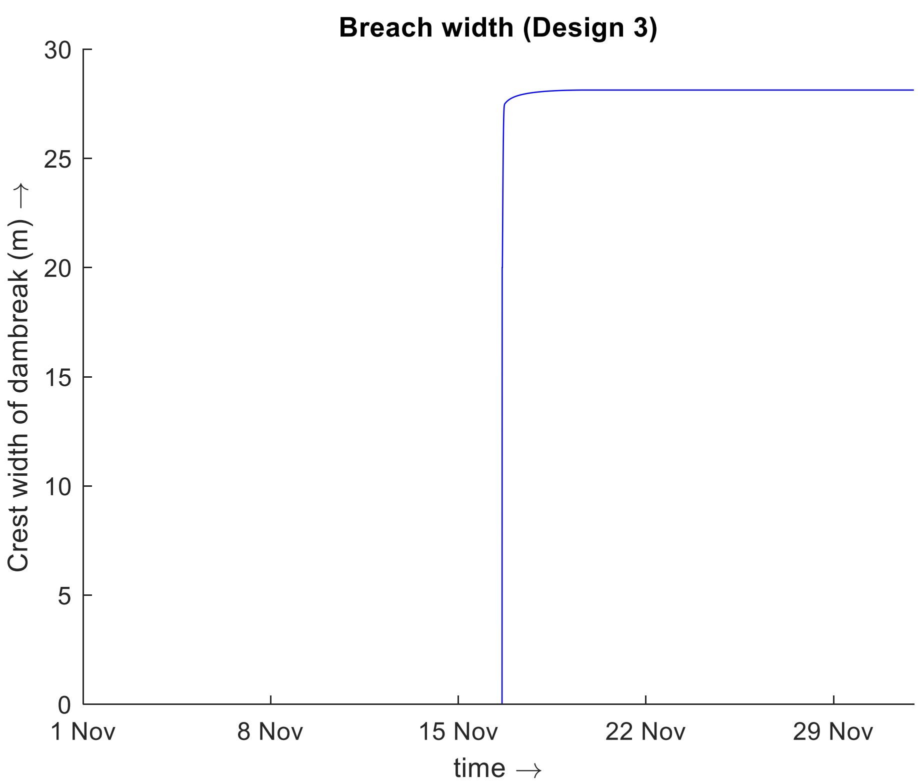

Figure 52: Breach width of design 3 (Clay with sheet pile)

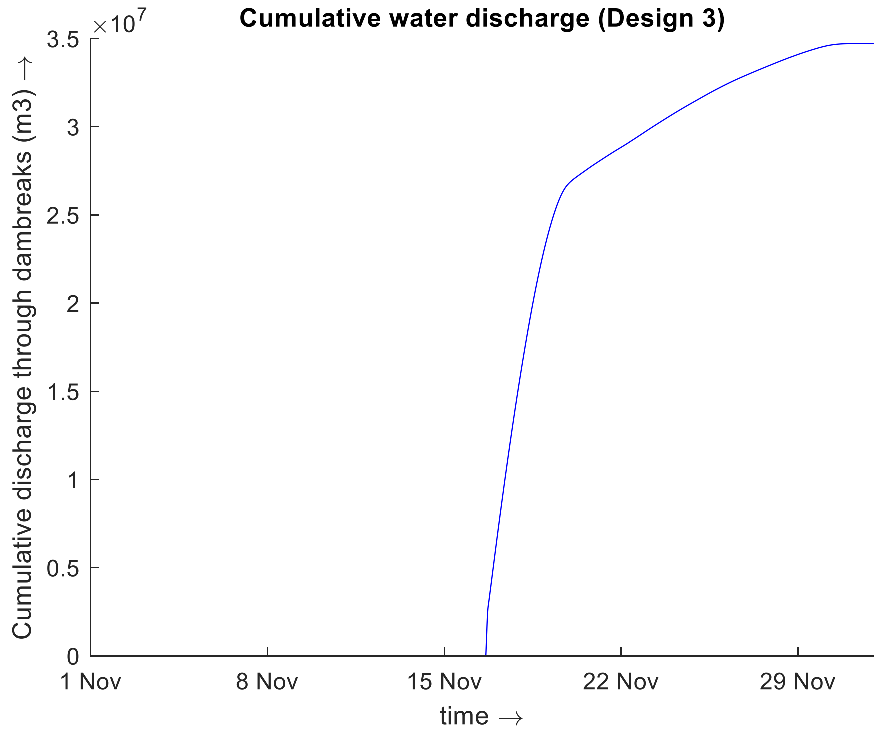

Figure 53: Cumulative discharge of design 3 (Clay with sheet pile)

C. 2.6 Design 3 (Clay with sheet pile +24H scenario)

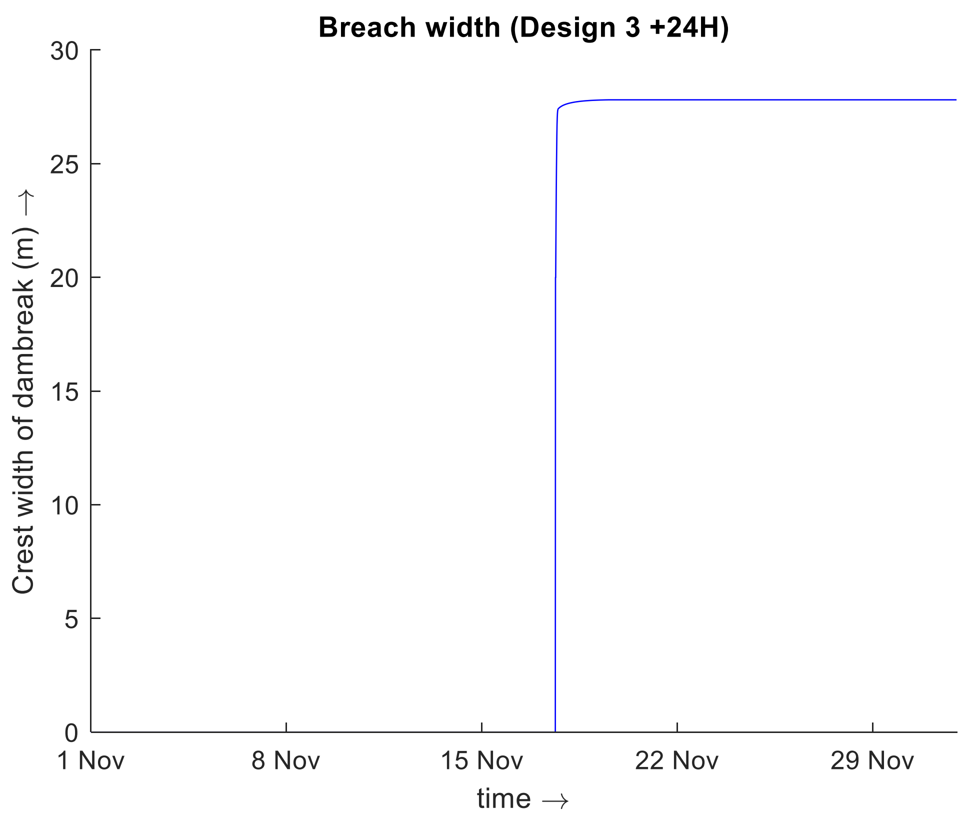

Figure 54: Breach width of design 3 (Clay with sheet pile +24H)

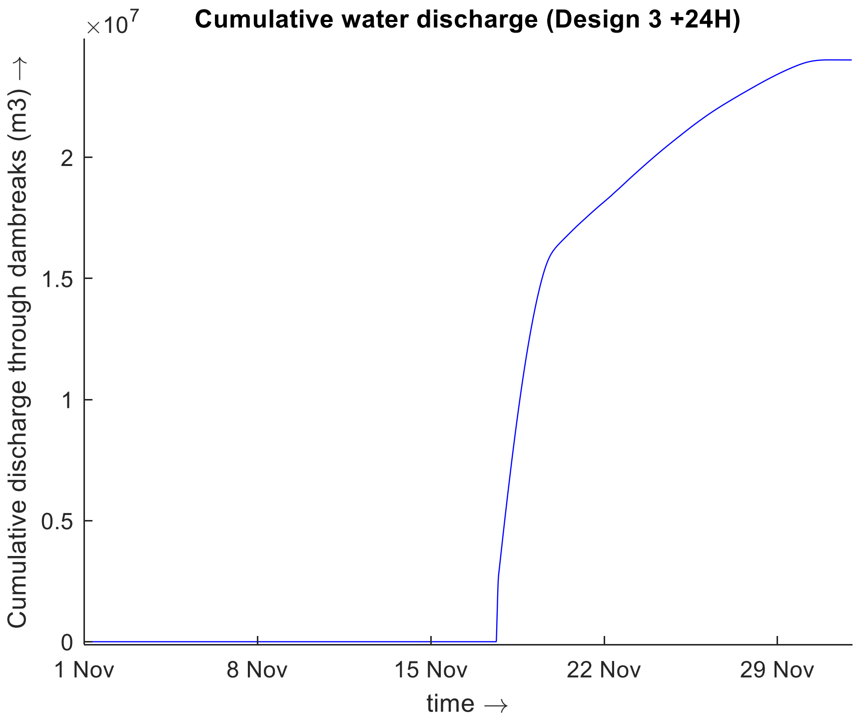

Figure 55: Cumulative discharge of design 3 (Clay with sheet pile +24H)

C. 2.7 Design 3 (Clay with sheet pile +48H scenario)

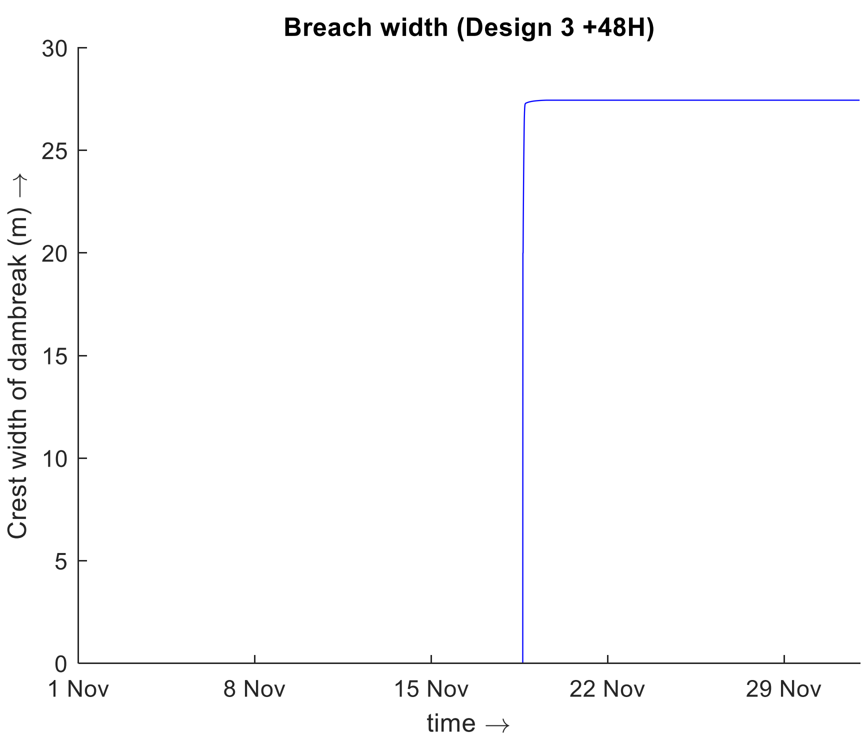

Figure 56: Breach width of design 3 (Clay with sheet pile +48H)

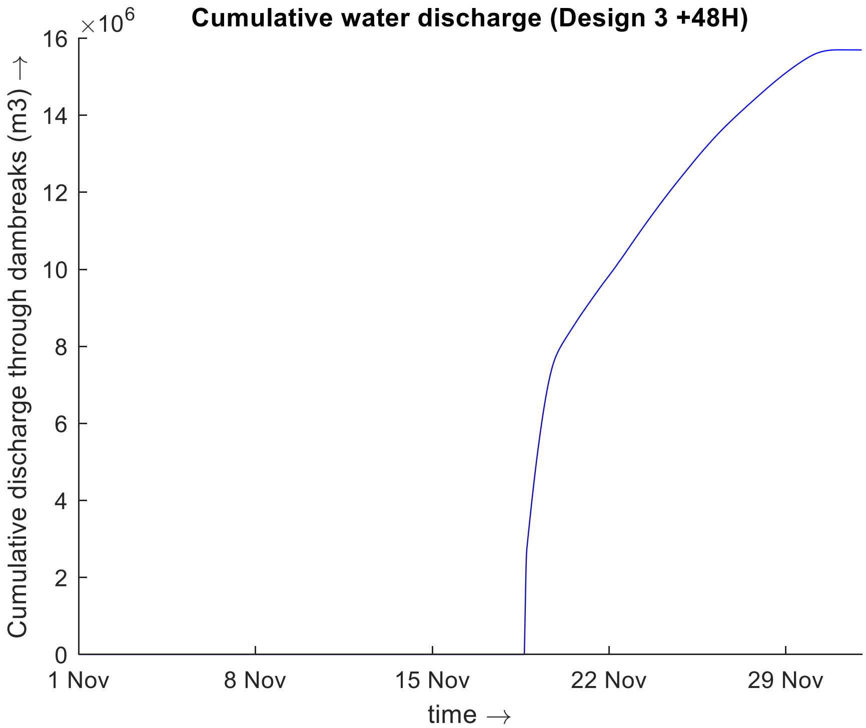

Figure 57: Cumulative discharge of design 3 (Clay with sheet pile +48H)

C. 2.8 Design 4 (Sand with clay core)

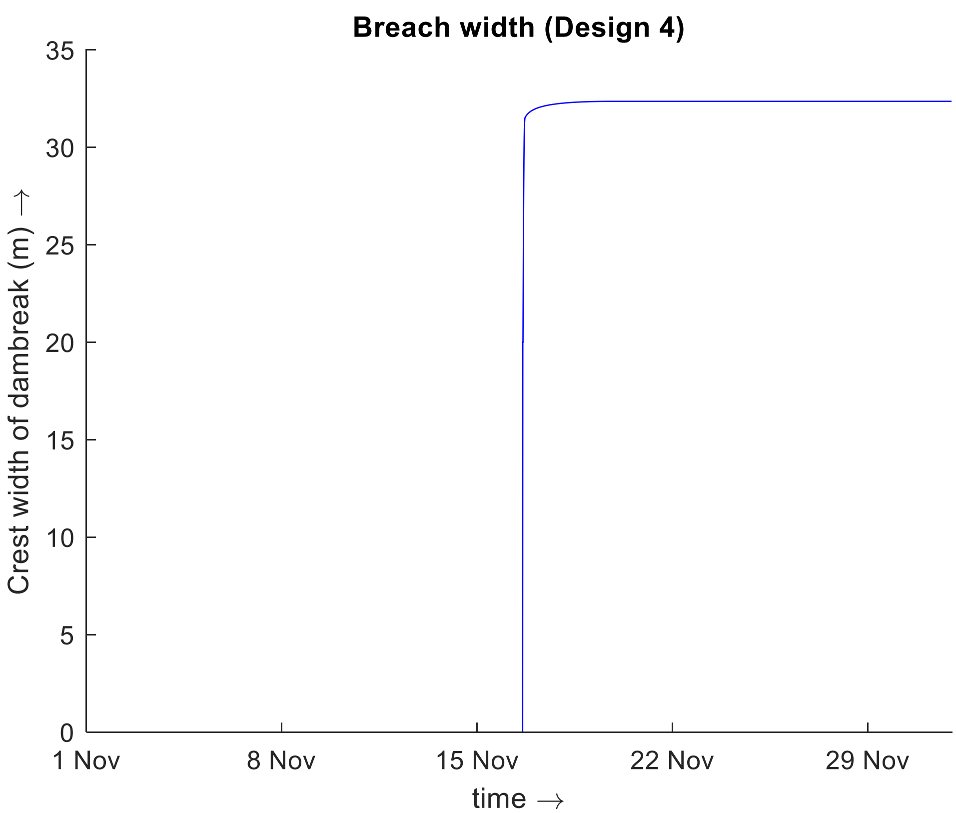

Figure 58: Breach width of design 4 (Sand with clay core)

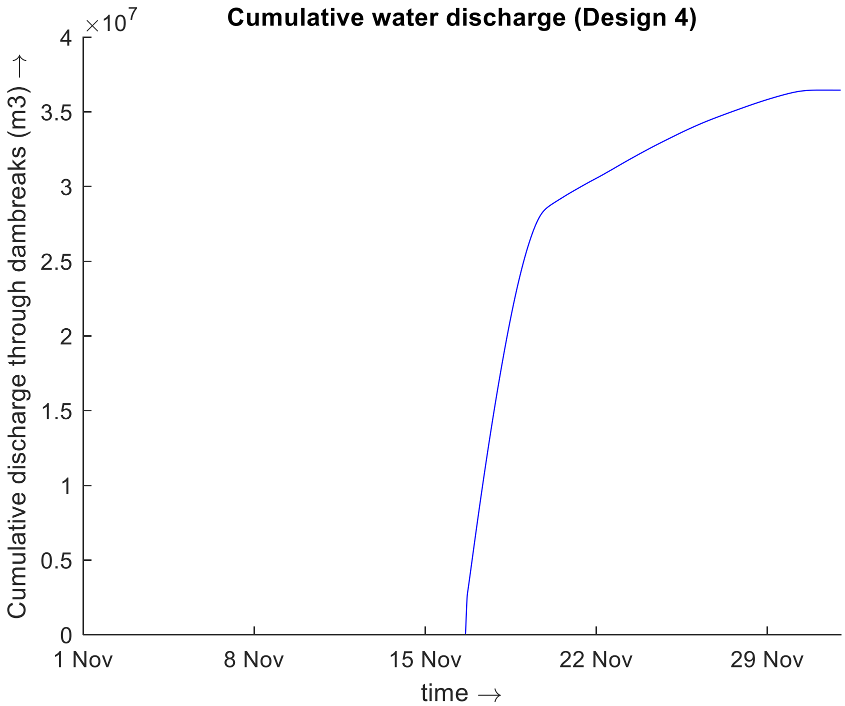

Figure 59: Cumulative discharge of design 4 (Sand with clay core)

C. 2.9 Design 4 (Sand with clay core +24H)

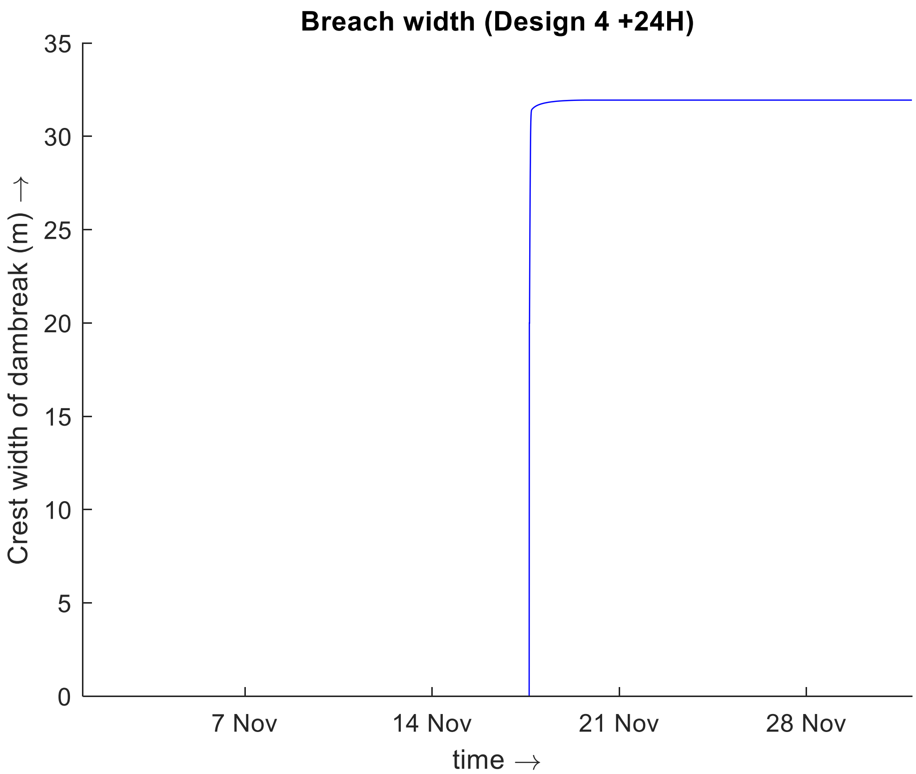

Figure 60: Breach width of design 4 (Sand with clay core +24H)

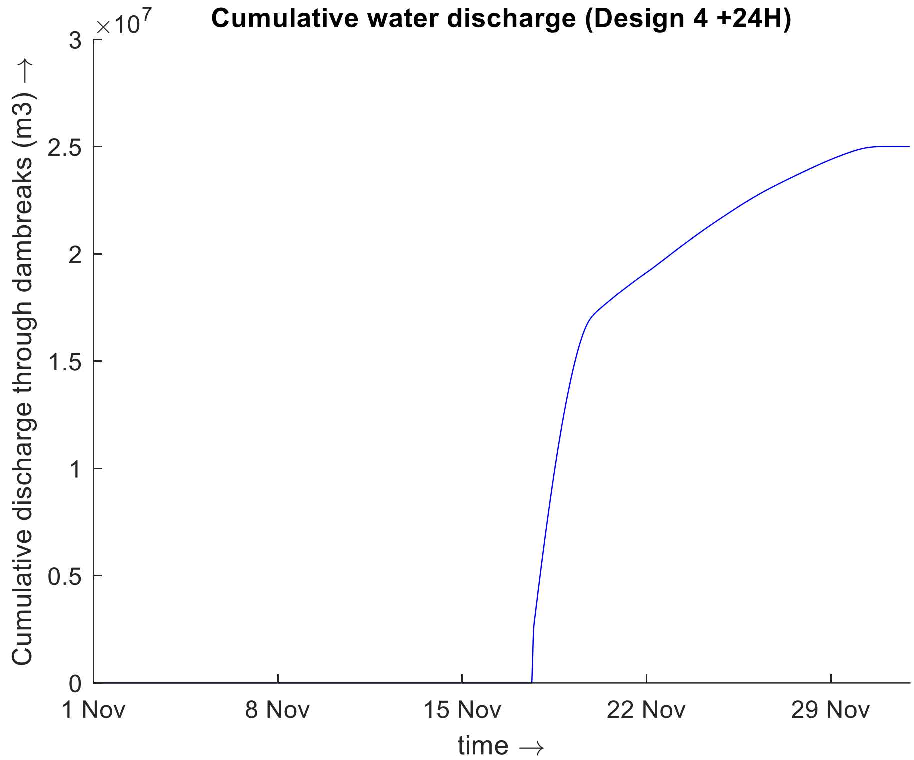

Figure 61: Cumulative discharge of design 4 (Sand with clay core +24H)

C. 2.10 Design 4 (Sand with clay core +48H)

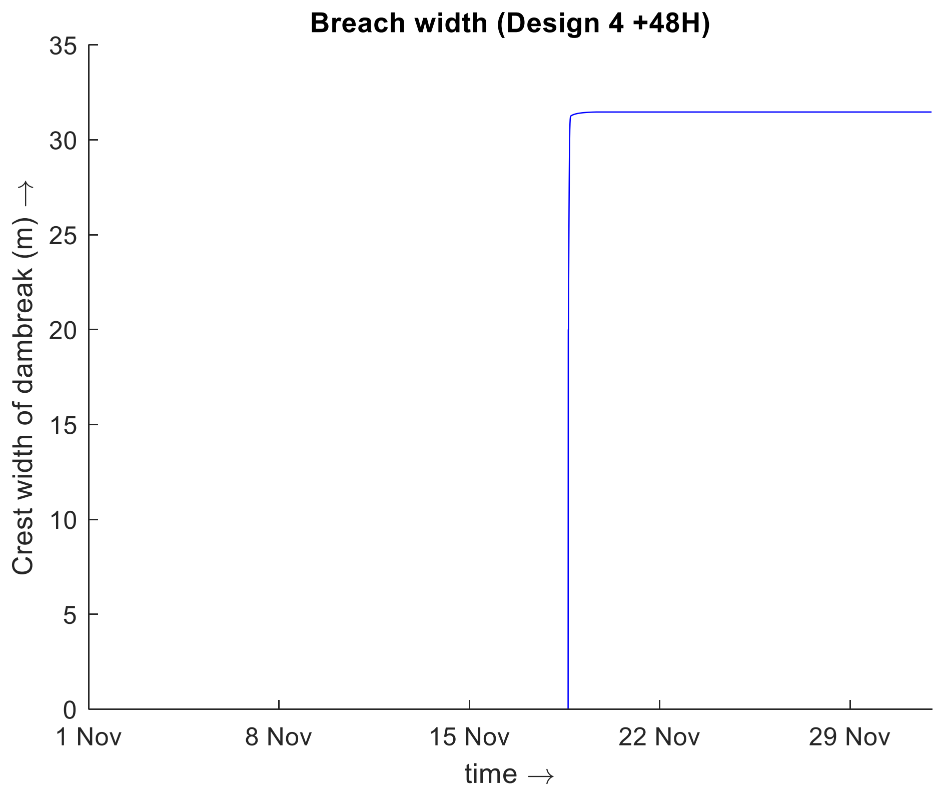

Figure 62: Breach width of design 4 (Sand with clay core +48H)

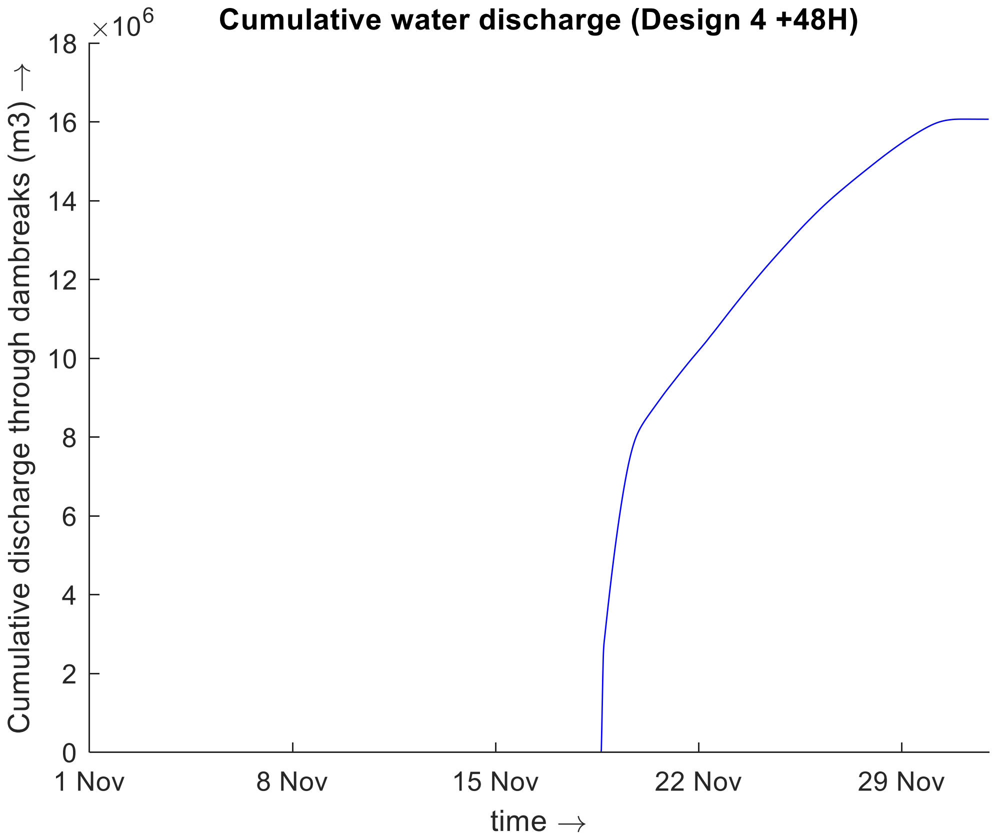

Figure 63: Cumulative discharge of design 4 (Sand with clay core +48H)

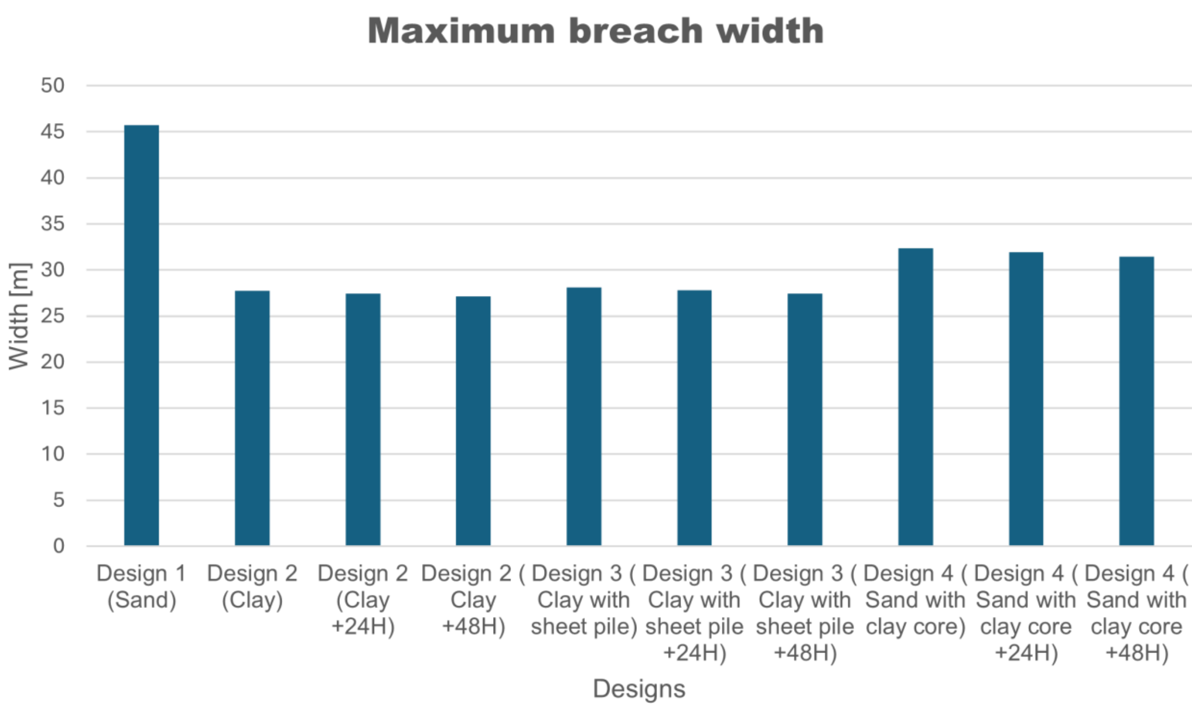

Figure 64: Maximum breach width of each design

D. SSM2017 Model

This chapter has been made using the document " Standard Method 2004 Damage and Casualties Caused by Flooding", DWW (2005). The SSM2017 model (damage and casualty module) is used in the Netherlands to assess economic damage and the number of casualties caused by floods. The module has also been used to develop water safety standards for dikes. The number of impacted residents and casualties is calculated assuming they stay home during the flood event. Two houses are considered: single-family homes (including farms and bungalows) and Apartments. Furthermore, the module calculates the economic damage, which can only be described in monetary terms. The estimated damage includes the following cases:

- Repair damage to immovable property owned or rented: inheritance and buildings.
- Repair damage to production resources, such as machinery, equipment, process installations, and means of transport.
- Damage to household contents.
- Damage due to the loss of movable property, such as raw materials, additives, and products (including crop damage).

When estimating the flood risk, vulnerable areas receive additional attention. Floods can inflict significant damage or casualties when they impact these areas. Institutions with large populations (often not self-sufficient), such as schools and hospitals, objects of great cultural-historical value, such as national monuments, and institutions that can pose a significant environmental risk in the event of flooding, such as Industrial Emission Directive installations, are all examples of vulnerable spots.

To estimate the consequences, the module uses a map indicating the maximum flood depth in each location. The depth is estimated based on the difference in elevation in the areas. Inputting the water's ascent and flow rates is optional; if not inputted, the module assumes a low ascent speed and flow rate, which do not influence the damage and victims. Furthermore, it is also optional to specify, for example, the minimum arrival time of the water associated with the simulation.

C.1 Damage Calculations

The module uses equation 7 to calculate the damage of a flooded area.

$$S = \sum_{i=1}^{n} a_i n_i S_i \quad (7)$$

With:

a_i = damage factor category i

n_i = number of units in category i
S_i = maximum damage per unit in category i
n = total number of categories

In this equation, S is the damage. The letter α stands for the damage factor category, which depends on the land use of an area. This value is between 0-1; some depend on the flood depth. The total damage in a given area is the sum of direct damage caused by operational interruptions and indirect damage in all categories identified in that location. Agriculture, homes, automobiles, and infrastructure are some examples of categories. Each category has units such as items, meters, or jobs.

C. 1.3 Model Input

This section will show the input of the SSM2017 model, which consists of the maximum water depth of each design and the maximum velocity. The inputs are shown in Figures 65 to 84.

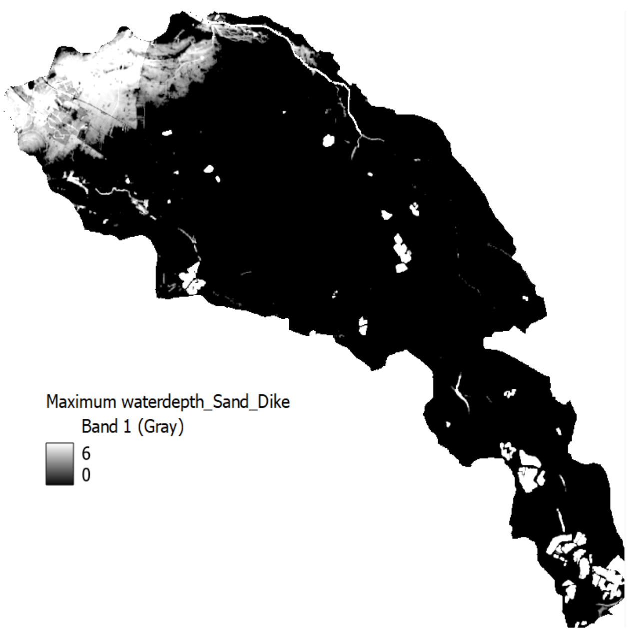

Figure 65: Maximum water depth of design 1

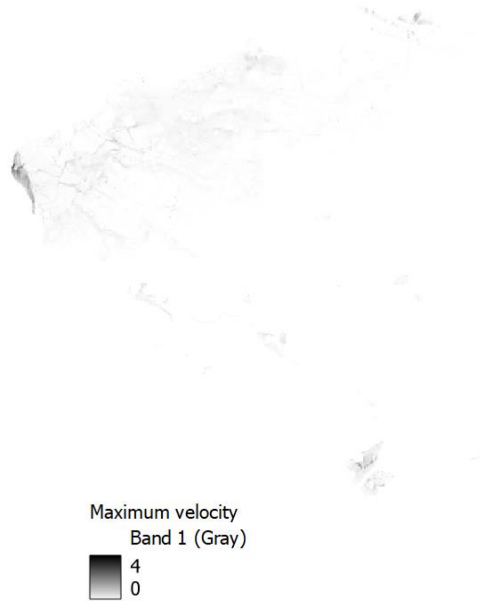

Figure 66: Maximum velocity of design 1 (Sand)

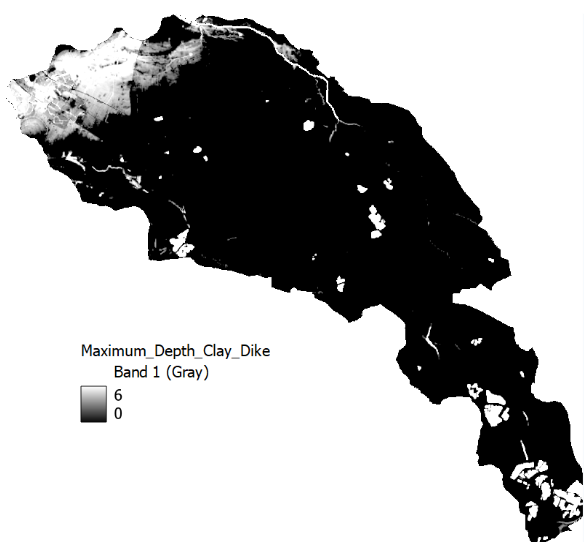

Figure 67: Maximum water depth of design 2 (Clay)

Figure 68: Maximum velocity of design 2 (Clay)

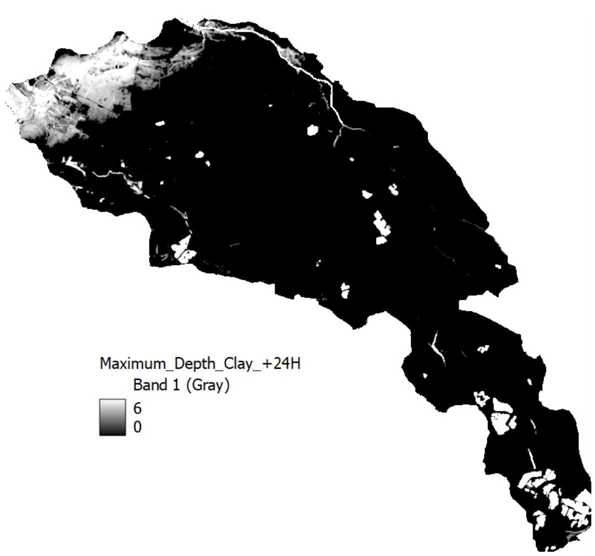

Figure 69: Maximum water depth of design 2 (Clay +24H)

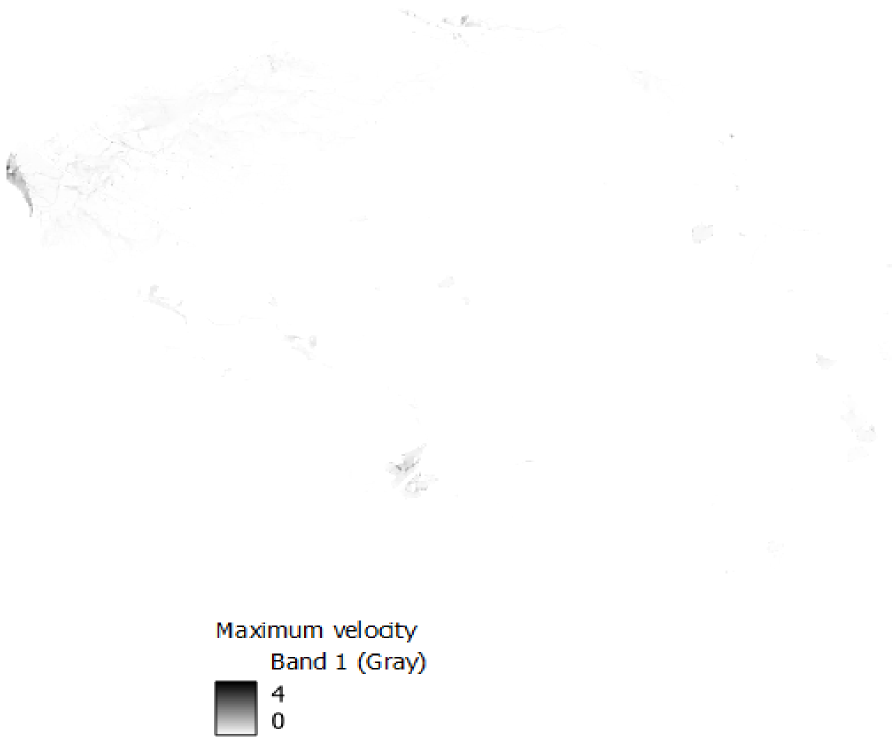

Figure 70: Maximum velocity of design 2 (Clay +24H)

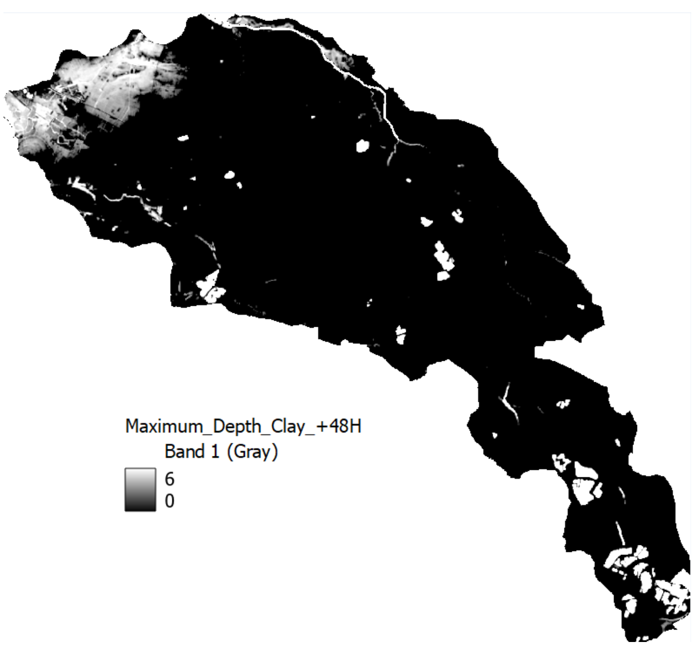

Figure 71: Maximum water depth of design 2 (Clay +48H)

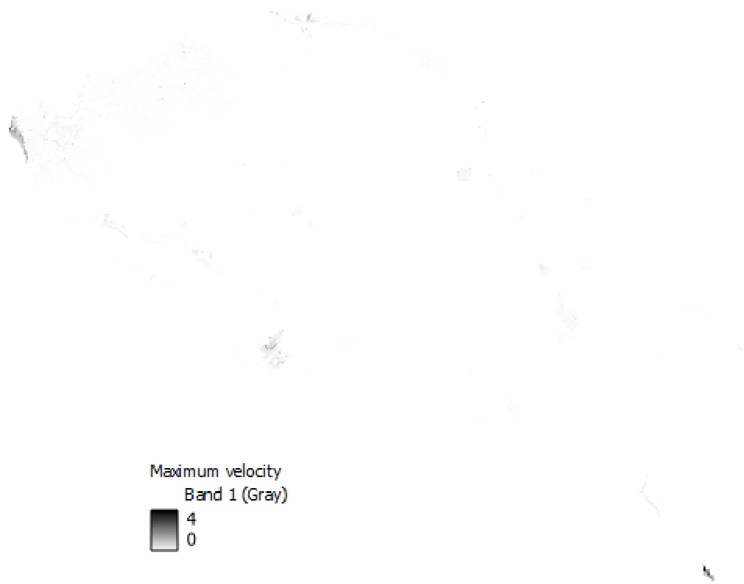

Figure 72: Maximum velocity of design 2 (Clay +48H)

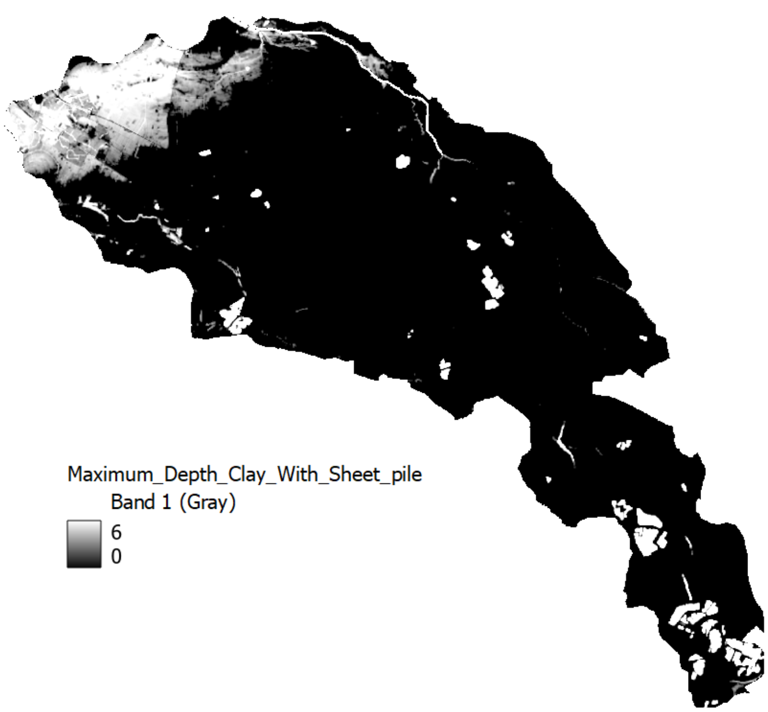

Figure 73: Maximum water depth of design 3 (Clay with sheet pile)

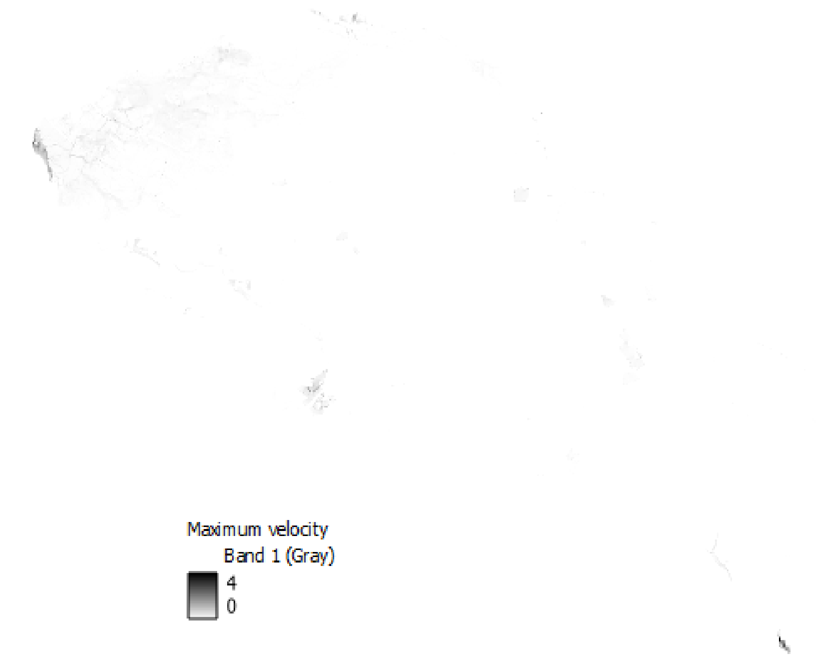

Figure 74: Maximum velocity of design 3 (Clay with sheet pile)

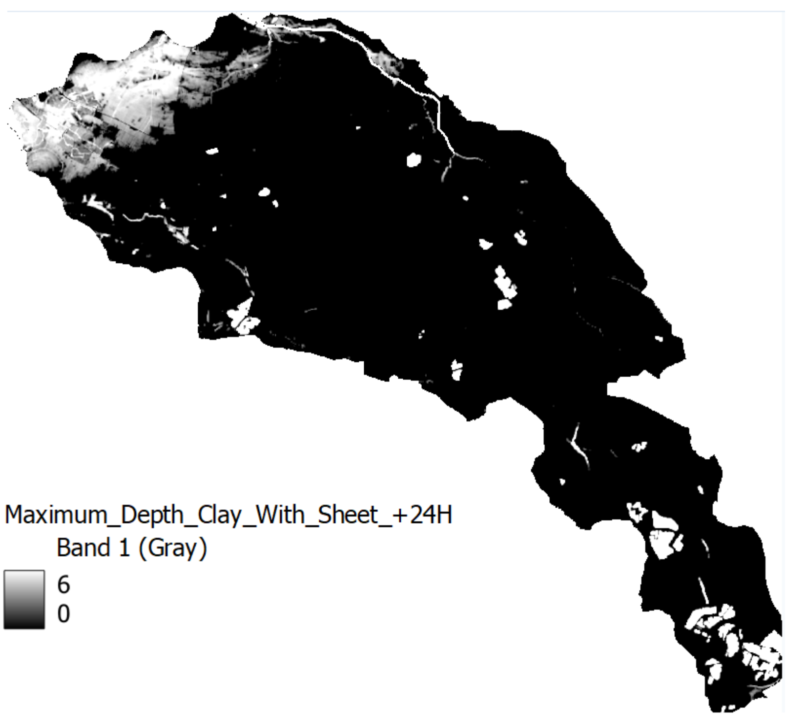

Figure 75: Maximum water depth of design 3 (Clay with sheet pile +24H)

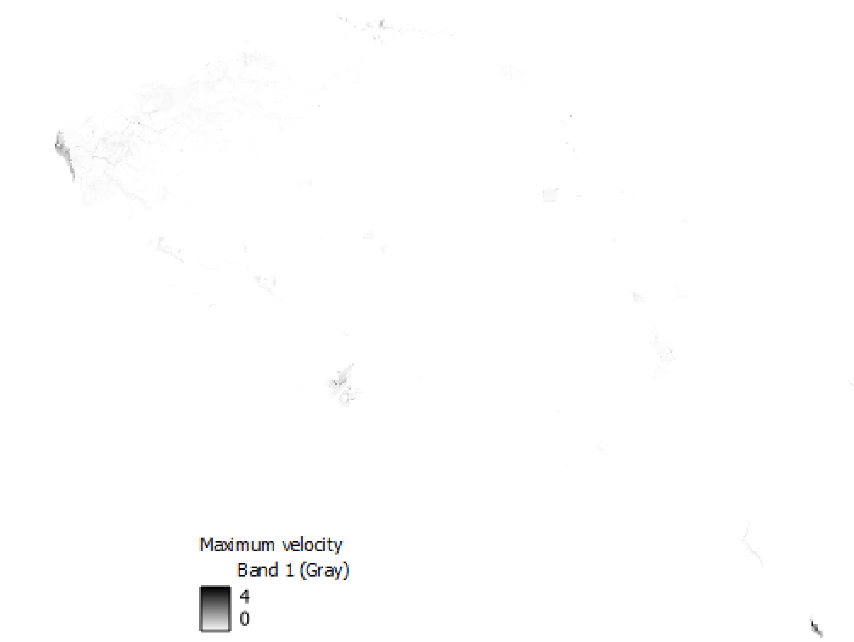

Figure 76: Maximum velocity of design 3 (Clay with sheet pile +24H)

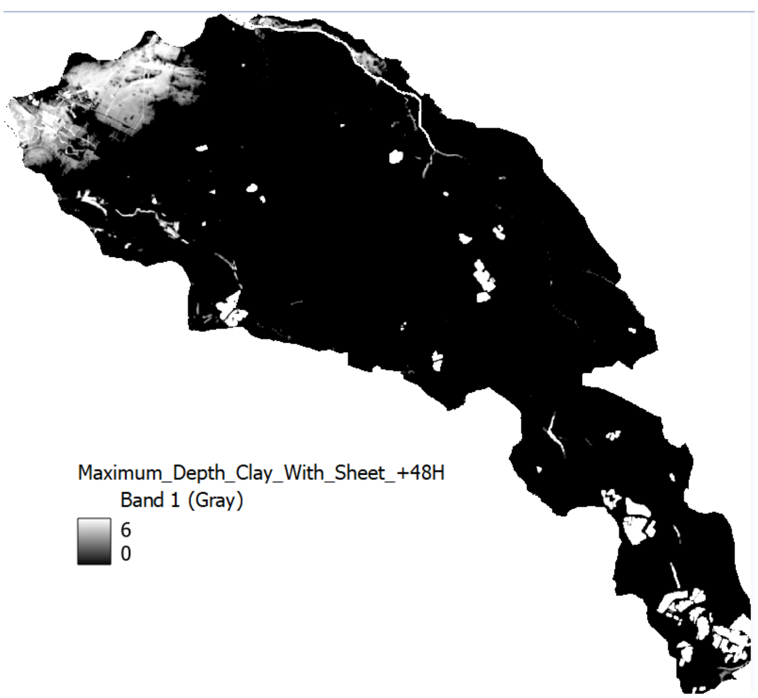

Figure 77: Maximum water depth of design 3 (Clay with sheet pile +48H)

Figure 78: Maximum velocity of design 3 (Clay with sheet pile +48H)

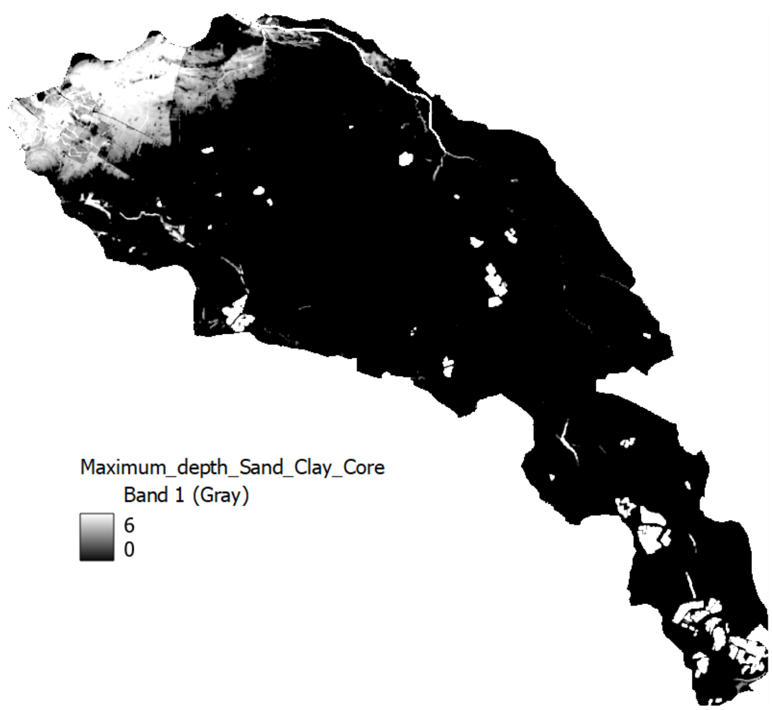

Figure 79: Maximum water depth of design 4 (Sand with clay core)

Figure 80: Maximum velocity of design 4 (Sand with clay core)

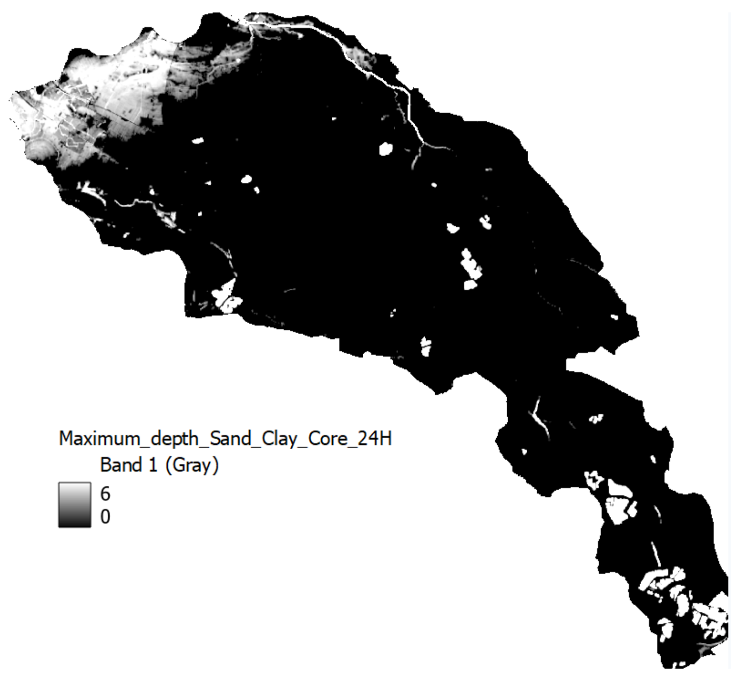

Figure 81: Maximum water depth of design 4 (Sand with clay core +24H)

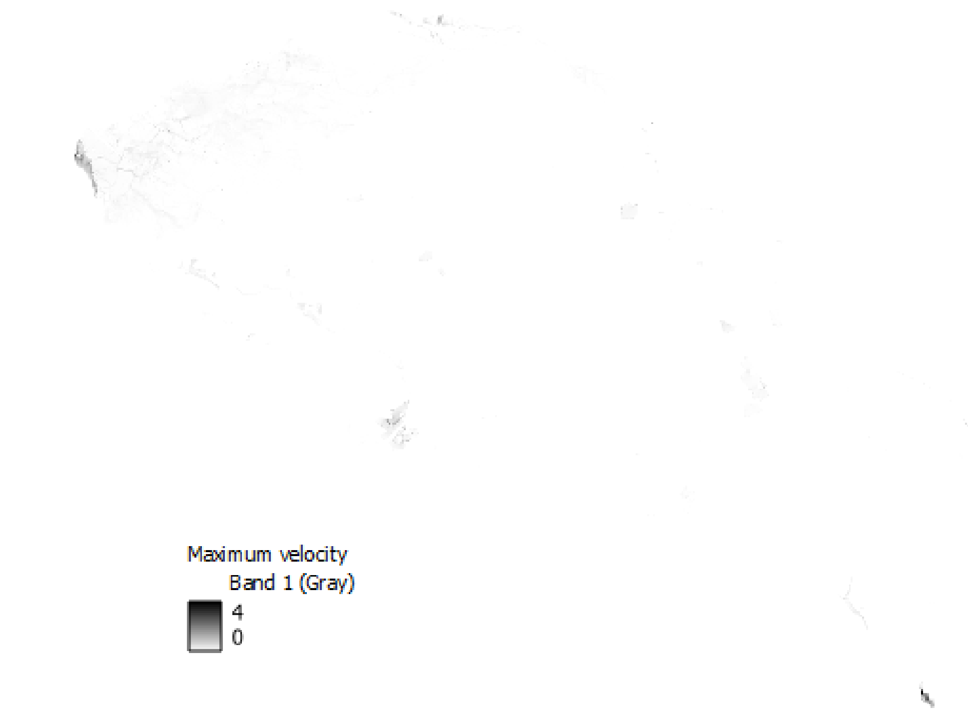

Figure 82: Maximum velocity of design 4 (Sand with clay core +24H)

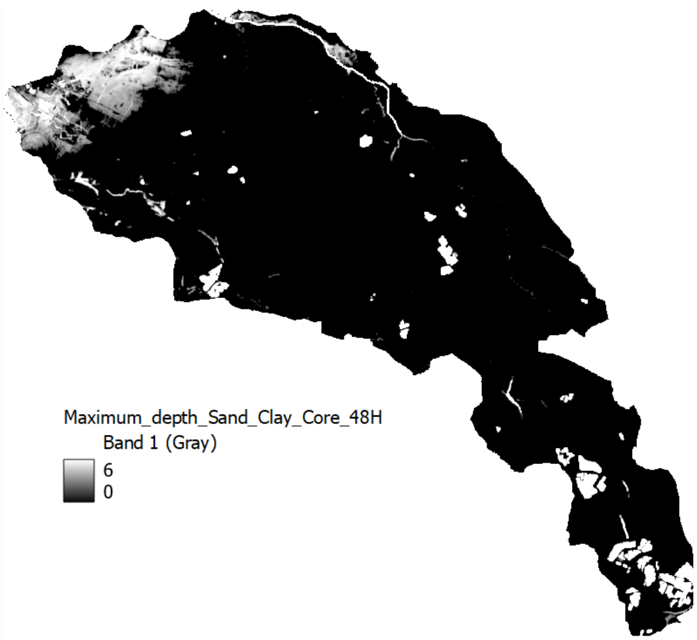

Figure 83: Maximum water depth of design 4 (Sand with clay core +48H)

Figure 84: Maximum velocity of design 4 (Sand with clay core +48H)

C. 1.4 SSM2017 Output

The flood consequences, direct damage, and the number of affected people can be found in Table 13.

Table 13: Direct damage, number of casualties, and number of affected people results

Scenario	Direct damage [M€]	Number of casualties	Number of affected people
Design 1 (Sand)	2300	230,000	10,222,222.22
Design 2 (Clay)	2100	210,000	9,333,333.33
Design 2 (Clay) +24H	1600	160,000	7,111,111.11
Design 2 (Clay) +48H	9400	94,000	4,177,777.78
Design 3 (Clay with sheet pile)	2100	210,000	9,333,333.33
Design 3 (Clay with sheet pile) +24H	1600	160,000	7,111,111.11
Design 3 (Clay with sheet pile) +48H	9300	93,000	4,133,333.33
Design 4 (Sand with clay core)	2200	220,000	9,777,777.78
Design 4 (Sand with clay core) +24H	1700	170,000	7,555,555.56
Design 4 (Sand with clay core) +48H	9700	97,000	4,311,111.11