# Feasibility of geotextile elements for dam construction in the North Sea

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# Feasibility of geotextile elements for dam construction in the North Sea

By

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in partial fulfilment of the requirements for the degree of

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TU Delft

# Preface

This bachelor thesis report concludes the final requirement in the fulfilment of the Bachelor of Science in Civil Engineering at the Delft University of Technology. Early in my studies I recognised that my main interest is in the field of hydraulic structures, making this thesis on the subject of a hydraulic structure an enjoyable experience.

The ALPHEUS project is aiming to create economically viable hydropower structures in shallow seas and environments with flat topography. The objective of my thesis is to verify whether a construction method using geotextile elements is feasible or not. The reader is expected to be familiar with basic concepts about the construction of civil structures. The report may be of interest for those that consider the use of geotextile elements in the construction of dikes, dams or coastal protection.

I would like to thank Ir. L.H. de Vilder, Ir. J.R. Moll and Dipl.-Ing. L. Jayasinghe for their supervision, guidance and feedback creating a pleasant cooperation.

Sjors Kremer
Delft, January 2023

# Abstract

The ALPHEUS project aims to realise a low head Pumped Hydropower Storage (PHS) in shallow seas and coastal environments with flat topography. This PHS concept will consist of a circular dam that creates a reservoir. This reservoir will be filled and emptied, generating energy in the process. To realise the project, a dam needs to be constructed in rough offshore conditions. Given the dimensions of the dam, traditional construction methods require huge amounts of transportation of material to the construction site. An alternative construction method, namely that of using geotextile elements, can be applied. However, due to a lack of practical experience and information on the design process the use of geotextile elements is often disregarded. The aim of this report is to verify whether a construction with geotextile elements is a feasible method or not. It does so by making use of the current known guidelines. The known guidelines do however not offer all required knowledge. Therefore other design principle from literature are implemented to generate a complete picture on all considerations in the design process.

After an exploration phase in which all safety considerations and failure mechanisms are outlined, the design process starts. The design process starts by providing a construction sequence that uses a single layered slope of geotubes that realises a steepness of 1:3. The sequence also has scour protection in the form of a self healing toe. With the sequence in place, the geotubes are tested safe against sliding and overturning due to waves and currents. The global stability of the structure is also tested safe for soil softening, bearing capacity and design wave heights.

Offering a construction sequence leading to a stable final structure, the strength of the geotextile is tested. The chosen geotextile offers sufficient strength against degradation and puncture from falling rock. An extensive geotechnical research should be executed to test the textile against erosion of fill, blocking, clogging and rupture during the filling of the geotube.

A final glimpse is on sand migration in and around the structure. Results show that sand migration during the construction period can be significant in storm situations. These values are significant up until a depth of 10 meters. Also, sand can migrate out from between geotubes. For both situations, different solutions can reduce or prevent material from washing out.

Following from the results, the use of geotubes does offer a feasible construction method. Some tests are based on assumptions on soil parameters. The values following from a geotechnical research are however not expected to alter the outcome of the conclusion. Due to a lack of proper information and clarity about the use, geotextile elements are often not considered. However, they are highly underappreciated and have a lot of potential.

# Contents

# Nomenclature

| | | |
|---|---|---|
| $b$ | Base width | *meter* |
| $b_c, b_q, b_\gamma$ | Reduction factors inclination of the base | - |
| $c^{'}$ | Cohesion coefficient | $kNm^{-2}$ |
| $c_v$ | Consolidation coefficient | $m^2s^{-1}$ |
| $C_u$ | Soil uniformity coefficient | - |
| $C_w$ | 2.0 (Empirical parameter) | - |
| $d$ | Drainage distance (= $D_k$ | *meter* |
| $d_{50}$ | Medium value of the particle size distribution | *meter* |
| $D$ | Diameter circle | *meter* |
| $D_c$ | Characteristic diameter geotube | *meter* |
| $D_k$ | Characteristic height geotube | *meter* |
| $D_x$ | Corresponding particle size | *meter* |
| $EAL$ | Energy Absorption Level | $kNm^{-2}$ |
| $f$ | Filling percentage | % |
| $g$ | Gravitational acceleration | $ms^{-2}$ |
| $G$ | Weight per length | $Nm^{-1}$ |
| $h$ | Height | *meter* |
| $h$ | Water depth | *meter* |
| $H_s$ | Significant wave height | *meter* |
| $i_s$ | Hydraulic gradient filling material | - |
| $i_c, i_q, i_\gamma$ | Reduction factors inclination of the load | - |
| $k$ | Wave number | $m^{-1}$ |
| $k_s$ | Hydraulic conductivity filling material | $ms^{-1}$ |
| $l_c$ | Length of tube parallel to wave direction | *meter* |
| $L$ | Length | *meter* |
| $L_0$ | Deep-water wavelength | *meter* |
| $M_e$ | Mobility parameter | - |
| $n$ | Porosity | - |
| $N_c, N_q, N_\gamma$ | Bearing capacity factor cohesion, surcharge and weight density | - |
| $O_{90}$ | Characteristic opening size geotextile | *meter* |
| $P_b$ | Pressure at base of geotube | $kPa$ |
| $P_s$ | Bearing pressure of the soil | $kPa$ |
| $q_b$ | Bed load transport | $kgm^{-1}s^{-1}$ |
| $r$ | Radius circle | *meter* |
| $s$ | Relative density | - |
| $s_c, s_q, s_\gamma$ | Shape factors of the foundation of the base | - |
| $T_d$ | Characteristic drainage period | *seconds* |
| $T_f$ | Tensile strength at failure | $kNm^{-2}$ |

| | | |
|---|---|---|
| $T_n$ | Characteristic compaction period | *seconds* |
| $T_p$ | Peak wave period | *seconds* |
| $u$ | (depth averaged) flow velocity | $ms^{-1}$ |
| $u_{cr}$ | Critical (averaged) flow velocity | $ms^{-1}$ |
| $u_{cr,s}$ | Critical current flow velocity based on Shields | $ms^{-1}$ |
| $u_{cr,w}$ | Critical wave velocity based on Komar and Miller | $ms^{-1}$ |
| $u_e$ | Effective (averaged) flow velocity | $ms^{-1}$ |
| $U_w$ | Peak orbital velocity | $ms^{-1}$ |
| $W$ | Width geotube | *meter* |

Roman classification

| | | |
|---|---|---|
| $\alpha$ | Slope angle of structure (ratio) | - |
| $\alpha$ | One dimensional compressibility of grain skeleton at deloading | $m^2N^{-1}$ |
| $\beta$ | Slope angle of the support of the geotube | *degrees* |
| $\beta$ | Coefficient related to vertical structure of velocity profile | - |
| $\gamma$ | 0.4 or 0.8 (irregular or regular waves) | - |
| $\gamma'$ | Volumetric weight | $kNm^{-3}$ |
| $\Delta_H$ | Pressure drop over geotextile | - |
| $\Delta_n$ | Reduction porosity in wave load | - |
| $\Delta_t$ | Relative density | - |
| $\varepsilon_f$ | Strain at failure | - |
| $\xi$ | Surf parameter | - |
| $\pi$ | 3.14159... | - |
| $\rho$ | Density material | $kgm^{-3}$ |
| $\rho_W$ | Density water (=1025) | $kgm^{-3}$ |
| $\phi$ | Friction coefficient between geotube and foundation | - |
| $\phi'$ | Internal friction angle of the soil | *degrees* |
| $\chi$ | Wave absorption correction factor | - |
| $\psi_0$ | Generation of overpressure at undrained load | $Nm^{-2}s^{-1}$ |
| $\Psi$ | Permittivity | $s^{-1}$ |

Greek classification

# Chapter 1

# Thesis Introduction

In this chapter, the blueprint of the report will be presented. The blueprint consists of relevant background information, specifying the problem statements, goals and the approach to work towards answering the main research question of the thesis.

## 1.1 Context

With climate change being the talk of the day, discovering and developing new ways of storing and generating energy is crucial in the current energy transition. Hydropower contributes with a total of 16 percent to the world's energy supply (Nunez 2019). Current hydropwer plants consist of three parts: a generator that produces energy, a dam that controls water flow and a reservoir that stores water. Typically, a hydropower plant is built on a river, where the dam blocks the water flow which creates a reservoir upstream of the dam. Also, dams are usually constructed in areas with a mountainous topography, which allows the water to flow down through the dam. The reservoir of the dam therefore acts as a battery, storing the energy. Currently, when there is a surplus of energy, the energy is used to pump water from from a low to a high elevated reservoir where it is stored again. When there is a need for energy, the water is allowed to flow back down to the lower reservoir generating electricity, creating a cycle.

This cycle of generating and storing energy, is only possible in environments with an elevated topography. In order to realise such a cycle in other topographies, the TU Delft is coordinating a new research program. The ALPHEUS program is looking into the feasibility of constructing a Pumped Hydropower Storage (PHS) in shallow seas and coastal environments with flat topography. The new PHS consists of a circular reservoir enclosed by a dam. For this research, the reservoir will be constructed in a yet to be determined place on the Dutch Continental Shelf in the North Sea. In stead of pumping water to a higher elevation, the cycle consists of filling and emptying the reservoir, generating and storing energy.

An important aspect in the feasibility of the project is the construction of the dam. The reservoir will have a diameter of 5 kilometres, which means huge amounts of materials will be required for the construction. Also, weather conditions can be rough during construction.

TenCate came up with solution in which geotextile elements are used for the construction of the dam. The elements are large geotextile bags that are filled with locally available materials which reduces the transport of material to the construction site. Also, the bags can be used to realise steeper slopes for the hard revetment, which also reduces the amount of material required (a slope of 1:3 can be created instead of 1:10). Therefore, the use of geotextile elements may provide a preferable alternative for the construction of the dam.

## 1.2 Problem analysis

The method of using geotextile elements is fairly new and because of a lack of application experience and design principles, developers often choose traditional construction techniques (Bernardini 2004). Whether geotextile elements form an alternative and what kind of elements they are, will be researched in this report.

Before the construction of the dam is started, there are multiple factors that influence the planning. Van den Herik developed a method for accurate placement of the elements. This method is however sensitive to the weather conditions. The strength and durability of the elements depend on a variety of factors, some better researched than others. Placement of the elements (where, when and how), the dimensions and the weather conditions all influence the construction sequence and final design of the structure. Because the knowledge about these factors is limited, the optimal construction sequence needs to be determined. The resulting final structure and construction sequence must be safe and stable, and therefore various tests according to design principles are required.

During and after the construction, waves and currents may cause materials to wash out, with the biggest uncertainty on locations between the geotextile elements. It might be necessary to take measures in order to prevent the washing out of materials and prevent failure during or after construction.

The elements are made of geotextile, failure of the geotextile can have big consequences for the safety of the structure. In the final construction phase, rock is dumped on the elements to create the revetment. An overview of the strength of the geotextile versus the dumping of the rocks is necessary to generate needed certainties about safely implementing the elements.

Following from the context and problem analysis, the main research question of the reports is: *Is the use of geotextile elements a feasible method for dam construction in the North Sea?*.

To substantiate the feasibility, the main research question is divided into three subquestions:

1. *What is the best dam construction sequence using geotextile elements?*
2. *Is there a need for a mechanism preventing washing out of materials from between the elements?*
3. *What is the maximum load the geotextile can withstand from dumped rock?*

## 1.3 Approach

The aim of this report is providing a well-founded answer to the main research question, it does so by generating and applying design principles following from the sub questions. The conclusion includes answers to the research questions, a safe and stable design using the design principles (if possible) and recommendations for further research. The report is divided into two main parts: the exploration and design phase. The exploration phase will map out the fundamentals for the design phase.

**Exploration**

This phase is fundamental for the entire construction phase. First, the functions and requirements of the dam and the geotextile elements will be defined. These functions and requirements are the starting point of the research and provide necessary knowledge and background information. From there, the factors that will impact the building sequence and design (safety considerations) are mapped out. Examples are weather conditions, currents, locally available materials and failure mechanisms of the geotextile elements. The site investigation and different safety considerations will form the basis of the design process which starts in the next phase.

**Design**

Following form the different safety considerations, the design of the geotextile elements can start. Also, stacking sequence and placement variations will be tested for sufficient stability. The conclusion of this chapter gives the final building sequence and design that accounts for all the limiting factors and safety considerations. Also, following from the design sequence the need for a mechanism of washing out of materials can be researched. Finally with the construction in place, the strength of the geotextile can be tested. The conclusion of the design phase gives the final building sequence and design that accounts for all the limiting factors and safety considerations. After the design of the elements and dam, a short view on the maintenance of the dam is carried out.

# Chapter 2

# Phase 1: Exploration

In order to execute the research and design process the necessary knowledge is required. Also, prior to the construction of the dam various conditions have to be determined which will be fundamental for the design process.

The exploration phase consists of defining the functions and requirements of the dam and geotextile elements. Also, key dimensions of the dam and hydraulic (depth, waves, current) conditions have to be determined. These factors are of great importance during the construction itself and in the behaviour of the structure after construction. The chapter will be finalised by determining what the safety considerations are, which are based on all the relevant failure mechanisms.

## 2.1 Functions and Requirements

As previously mentioned, ALPHEUS is researching a feasible method for Pumped Hydropower Storages in shallow waters and environments with flat topography. An important aspect of the success of the project is the construction method of the dam. In order to design the PHS, the functions and requirements must be defined.

### 2.1.1 Circular Dam

The Pumped Hydropower Storage will consists of a circular reservoir, enclosed by a dam. In this case, the dam will be located in a yet to be determined place on the Dutch Continental Shelf in the North Sea. Conditions at the construction site are researched in chapter 2.2.

Following from the function of the dam, it can be classified. Classification is according to the function, hydraulic design and construction material (Patil 2021).

When constructed, the dam is required to do two things:

1. Allow the filling and emptying of the reservoir.
   When there is a need for energy, the reservoir is filled using turbines in the dam. The flow powers generators which produces energy. When there is a surplus of energy, the reservoir is drained into the North Sea (which works as the energy storage, or battery). The dam must therefore be able to host the turbines and generators.

2. Retain its stability.
   The dam must be a stable construction during the emptying and filling process. When the reservoir is empty, it must keep sea water out. When the reservoir is full, it has to remain a safe construction with water on both sides.

Following from the two functions of the dam, the classification according to the function is displayed in table 2.1:

| **Classification by:** | **Function** | **Design** | **Material** |
|---|---|---|---|
| Situation 1 and 2 | Storage dam | Non overflow dam | Geotextile elements |

Table 2.1: Classification circular dam (Patil 2021)

### 2.1.2 Geotextile elements

Geotextile elements have multiple applications such as breakwaters, dune protection and in land reclamation projects. The elements are made from geotextile which are filled with locally available sand. They come in forms of bags, mats, tubes and containers depending on their application (Bernardini 2004). The elements considered for this construction are geocontainers and geotubes, which will be placed in position with a new and more accurate method developed by Van den Herik.

Traditionally, geocontainers are filled in a split barge and dropped to their location. Because the dimensions of geocontainers are limited by the barge, they can only be filled for about 45%.

Geotubes are hydraulically filled and lowered to their location. The dimensions are not limited by the split barge and they can be filled to a higher degree, to about 80%. After the tube is placed, the water moves out of the tube and the filling material remains inside. Because the geotubes can be filled to a higher degree, they offer more stability. Therefore, geotextile elements considered for this construction are geotubes. More on their shape and dimensions will be discussed in the design process. An example of a geotube during it's filling process is shown in figure 2.1 (Indiamart 2023).

Figure 2.1: Example of geotube (Indiamart 2023)

Traditional construction methods for hydraulic structures mainly consist of dumped materials such as concrete , asphalt or sand. Since construction with loose materials is replaced with rigid geotubes, it is possible to realise steeper outer slopes for the revetment. This means a reduction of construction materials. (Bernardini 2004)

As the geotextile elements are filled with locally available materials, a lot of the construction materials do not have to be transported to the construction site which reduces the construction costs and environmental footprint.

With the ability to realise a steeper outer slope and use local materials for construction, the main functions of the geotubes is to reduce the required amount of construction material. In order to do this, the geotextile is not allowed to fail in the given conditions. Also, the geotubes must secure a stable structure during and after the construction. All considerations to ensure this are explained in section 2.4.

## 2.2 Site investigation

Construction will take place at a yet to determined place on the Dutch Continental Shelf. Factors of importance are water depth, wave height and direction, current speed and direction, and soil characteristics.

Important for the placement of the geotubes is the wave height. The maximum operating conditions for the placement method are with a maximum significant wave height $H_s$ of 1.0 meter. Conditions that are too rough can delay the construction. Also, waves may influence the stability of the structure (during and after construction) and cause materials to wash out.

Deltares performed a research about waves in the North Sea. One of the locations where the research was conducted was at the Europlatform, which is on the Dutch Continental Shelf. The research looked at wave heights over the period 1979 - 2001(Fockert 2011). This resulted in a wave rose shown in figure 2.2, which represents significant wave height $H_s$ and directions.

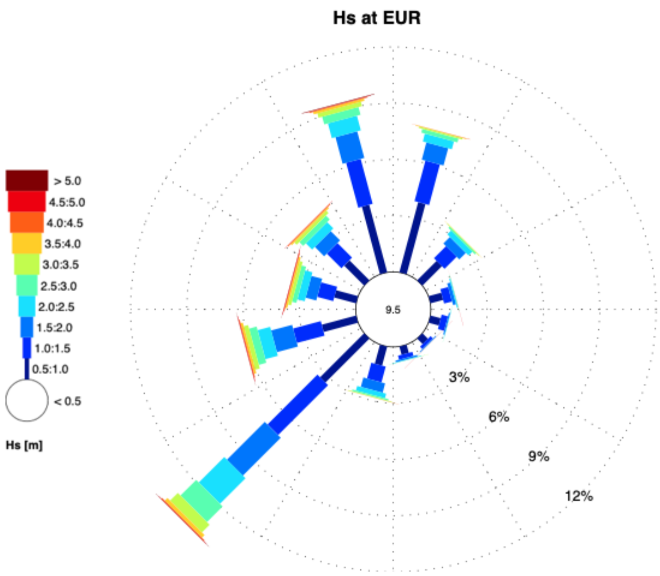



Figure 2.2: Significant wave height $H_s$ at construction location (Fockert 2011)

Because construction needs calm conditions, waves coming from the south east are considered for the remainder of the report. This is explained in more detail in section 2.4. Over a 1000 year return period, the maximum significant wave height $H_s$ is 4.0 meters. The maximum peak period $T_p$ is 7.8 seconds (Fockert 2011).

Magnitude of sea currents is of importance in stability and sand migration tests. Following from a research by Rijkswaterstaat, the residual current is heading north east (Giessen, Ruijter, and Borst 1990). However, the tidal current causes the highest velocities with 0.4 m/s at 22 meters depth, and 0.9 m/s at the top surface layer (Grasmeijer 2018). The water depth at the construction location will be 25 meters, so these velocities are useful in the stability tests. Basic soil properties of the location are also known, since the dam is built on sand with an underlying clay layer. With the basic soil properties known, general values will be assumed in the calculations of design process. Once the location is known, an extensive geotechnical research must be performed to obtain the definitive values.

## 2.3 Key dimensions

Key dimensions of the dam are the basis of the designing process of the geotubes, since they must be able to ensure the dimensions. As previously mentioned, the structure will be a circular dam. The diameter of the reservoir will be 5 kilometres, equation (2.1) gives us a total length of approximately 16 kilometres.

$$L_{dam} = 2\pi r \tag{2.1}$$

The PHS concept has a hydraulic head of 20 meters. This means that in operational function one (as mentioned in section 2.1.1) of the dam, the height difference between the sea side and the reservoir side must be 20 meters. Following from the site investigation, the water depth where construction will take place is 25 meters. Considered for the height of the dam are water depth, wave height and safety factors. The height of the dam is therefore set at 35 meters.

The project description provides a value for the inner slope, which is 1:10. The value for the outer slope is set at 1:3. Steeper is also possible, there is however a possibility of rock falling down the revetment (Booster and Vastenburg 2006). The values of the slope result in a foundation width of 250 meters. Important to note is that these dimensions are the starting point and might be altered during the design process.

## 2.4 Safety considerations

In order to design the dam using geotextile tubes, multiple factors must be considered to guarantee the safety of the structure. Safety concerns about the construction phase and the design of the geotextile bags will be discussed.

### 2.4.1 Environmental conditions

As previously mentioned, Van den Herik developed a method in which it is possible to place the geotubes with increased accuracy. The methods consists of lowering and guiding the containers from a ship, instead of dropping them. This method however is sensitive to the weather conditions, since the maximal allowed $H_s$ is 1.0 meter. In order to operate and achieve the required accuracy, weather and sea conditions must be calm. There are three possible options to cope with this problem.

1. A hybrid construction method.
   Following from the site investigation waves have a dominant direction. To create calm construction conditions, it is possible to combine different construction methods. In the dominant incoming wave direction (see figure 2.2) the dam can be partially constructed using caissons, which are less prone to environmental conditions. The dam with caissons will act as a breakwater which creates calm conditions to construct the remainder of the dam with geocontainers.

2. Construct breakwaters with geocontainers.
   Another possible solution to create calm conditions is by constructing breakwaters with geocontainers. They can be constructed in the dominant wave direction. This construction of these breakwaters however also needs calm conditions and because of the water depth, this is not a feasible solution.

3. Construct only in calm conditions.
   This option is dependent of the weather, which is predictable but uncertain. Research is done which concluded that there is an average of 40% workability rate over the year, with higher values in the summer months where the workability rate is 50-60 %. An option is to combine the hybrid construction method to increase the workability rate even further.

### 2.4.2 Geotextile tubes

In order to design a slope of geotextile tubes that is safe and stable, various failure mechanisms need to be assessed. The failure mechanisms can be divided into external and internal mechanisms (Lawson 2006). External failure mechanisms, shown in figure 2.3, affect the stability and performance of the entire structure. Internal failure mechanisms, shown in figure 2.4, affect the performance of an individual geotube. If all the possibilities are verified, the structure is deemed safe. Guidelines are offered for most of the mechanisms, some need more research.

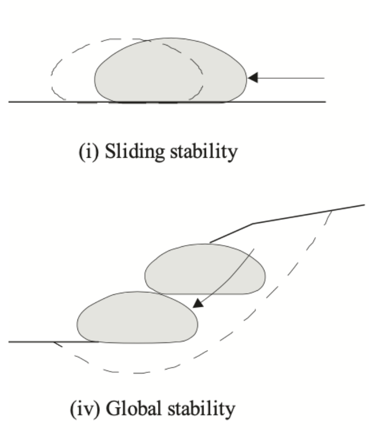



Figure 2.3: External failure mechanisms (Lawson 2006)

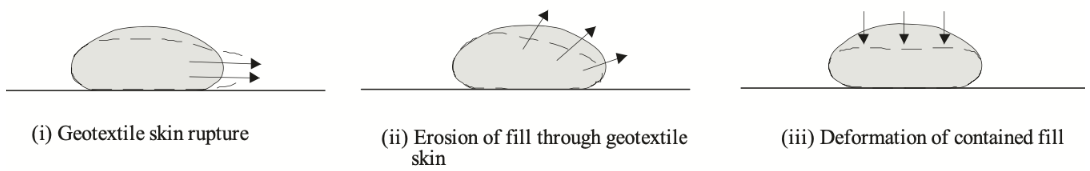



Figure 2.4: Internal failure mechanisms (Lawson 2006)

Sand migration is not only an internal failure mechanism, but occurs in more ways. While the dam is constructed, sand can start to migrate from the construction site overnight or after a storm. Also, when the geocontainers are placed without connections, there is a possibility for material to wash out through the space in between. These migration mechanisms need to be quantified in order to take countermeasures if necessary. How these mechanisms work is explained and researched in section 3.5.

Another important addition is an extension in the geotextile skin rupture verification. One of the final steps of the dam construction is creating the revetment. This is done by dumping rock on the outer slope, which can cause the geotextile to fail. A clear insight into this is necessary in order to create a safe revetment with dumped rocks.

All the safety considerations will be applied and tested in the design process, where they will be explained in more detail.

# Chapter 3

# Phase 2: Design

In this chapter, the design sequence will start. The process is started by setting the main dimensions of the geotubes. Next, using the dimensions of the dam and geotubes, a blueprint for the construction sequence is presented. The blueprint is firstly tested against all possible external failure mechanisms in order to verify the stability of the structure. Finally, the internal mechanisms will determine the strength of the geotextile. When necessary the dimensions of the geotubes or the construction sequence will be altered making this an iterative process.

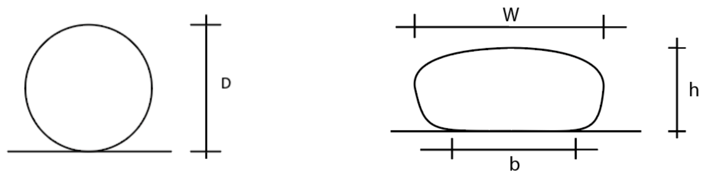
## 3.1 Dimensions geotubes

Fundamental for the construction are the dimensions of the geotubes. From these dimensions, the construction sequence and subsequently the failure mechanisms of the construction can be tested. Because of the scale of the project, the maximum dimensions of geotubes is desired in order to use the least amount of geotubes.

Figures 3.1a and 3.1b illustrate the parameters that are of importance in the design process. The dimensions of the geotubes are limited by the fabrication process. With help from TenCate, the maximum dimensions are set as shown in table 3.1. These dimensions of the geotubes are fundamental for testing the strength and stability of the construction sequence final structure amd geotextile. For now the dimensions are given, they are explained in more detail during the safety tests when necessary. The dimensions are also run through the TenCate Geotube Simulator, which is added to appendix B. Output of this simulation provides necessary values to test the internal stability.

| | | |
|---|---|---|
| $D$ | 5.0 | $m$ |
| $b$ | 4.43 | $m$ |
| $W$ | 6.3 | $m$ |
| $h$ (=$D_k$) | 3 | $m$ |
| $L$ | 60 | $m$ |
| $\Delta_t$ | 1.7 | $[-]$ |
| $f$ | 81 | % |
| $G$ | 272 | $kN/m$ |

Table 3.1: Dimensions geotube




(a) 100% fill (b) f % fill

Figure 3.1: Dimensions geotube

## 3.2 Construction sequence

Following from the dimensions of the dam and geotubes, a construction sequence needs to be determined. The sequence will be given and illustrated in this section, and tested on various stability mechanisms in the upcoming sections. The construction sequence focuses on the outer slope of the dam. The inner slope will be more flat (between 1:7 and 1:10) in order to maintain stability during the filling and emptying of the dam, and therefore does not require the use of geotubes. For this thesis, the construction sequence is divided into two parts, each explained in detail in the upcoming section:

1. Construction of the toe of the slope
2. Construction of the slope
3. Not included in this thesis: placement of a filter and revetment layer

#### Construction of the toe

The construction sequence works from the foundation on the sea bed upwards until the desired height is reached. Since the slope will be constructed using geotubes, the foundation of the slope (or toe of the dam) is crucial for the stability.

Deltares performed a research which resulted in a recommendation to use scour protection on the outer side of the geotextile elements (Deltares 2020). In order to prevent scour at the toe, a self healing toe (or 'Dutch Toe') will be applied (Coghlan et al. 2009). This consists of an extra row of geotubes under the seabed which are encapsulated by an extra layer of geotextile. Figure 3.2 displays the construction steps with a detail of the self healing toe. First a trench is created in figure 3.2a where the toe will be constructed. An extra layer of geofilter (coloured in red) is applied in the trench, encapsulating the outer geotube as shown in figure 3.2b. To finish the toe, geotubes are placed as shown in figure 3.2c and the toe is filled with dredged material. The geofilter is held in place by the weight of the geocontainers of the slope. It is possible to apply the geofilter over the entire height of the slope, more on this in section 3.4.

(a) Create a trench

(b) Place geotube encapsulated in a geofilter

(c) Stack geotubes and close toe with sand

Figure 3.2: Construction self healing toe

Another solution is to apply riprap protection (Maynord n.d.). However with riprap applied, geotubes can still move as show in figure 3.3 due to scour. Therefore the self healing toe is preferred and will be used for construction.

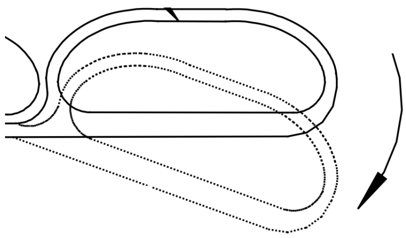


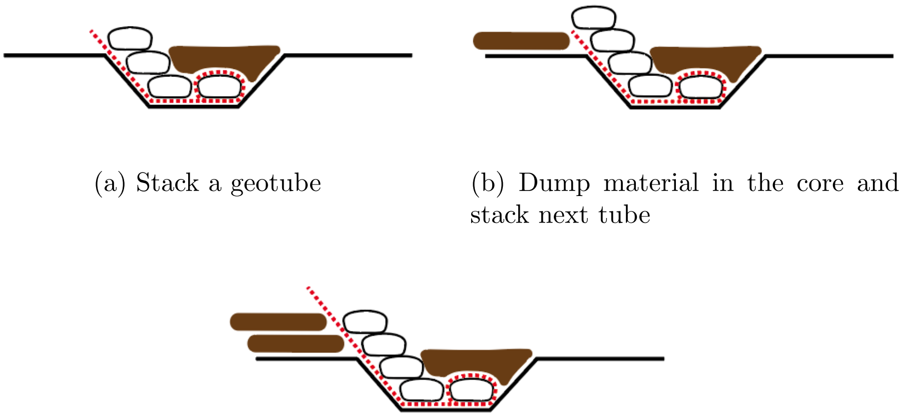
Figure 3.3: Detail self healing toe (Coghlan et al. 2009)

### Construction of the slope

With the toe in place, the slope can be constructed by stacking the geotubes. An important consideration is the application of a single or double layer of geocontainers. A single layer reduces the amount of geotubes drastically, it might however reduce the stability.

Stellenbosch University did research on the stability and stacking in a single and double layer revetment of geotubes (Baret 2013). The tests where performed with a slope of 33 degrees (instead of the 72 degrees that is aimed for in the design). However, the tests results in the single layer revetment were similar to the double layer revetment. Instabilities that followed from the tests indicated that the problems are causes of internal sand migration. However, a study from Deltares concluded that given the right filling degree, internal sand migration will not result in instabilities (Steeg and Vastenburg 2010). The same study from the Stellenbosch Universtiy also concluded that when the slope is increased, the design wave height for the construction increases (Baret 2013). Therefore a single layer of geotubes will be applied.

The geotubes will be stacked in such a way that the outer slope will be 1:3, which is a safe maximal slope (Bernardini 2004). After a geotube is placed on the lower one, material is added to the core of the dam, this is repeated until the desired height is reached. Figure 3.4 illustrates this process.



(a) Stack a geotube

(b) Dump material in the core and stack next tube

(c) Continue until desired height is reached

Figure 3.4: Stacking process geotubes

The geotubes will be stacked using a brick pattern as shown in figure 3.5. A brick patterns helps preventing shifting of geotubes since there is more contact area between all the geotubes, and therefore providing a more stable slope. During and after the construction, the geocontainers can lose stability and strength due to both internal and external mechanisms. This will be tested and verified in the upcoming sections.

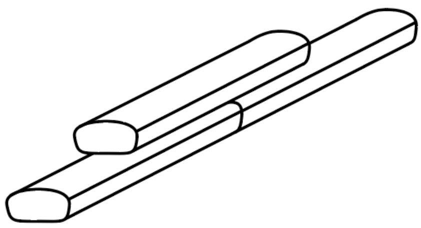


Figure 3.5: Stacking in brick pattern

## 3.3 Construction validation

In this section all the external failure mechanisms will be checked and verified. This will be done for during the construction and when construction is finished.

### 3.3.1 External stability

The first event in the construction sequence is the construction of the toe. Since an encapsulated self healing toe is applied, the foundation is below the sea bed and the geocontainers will be buried (see figure 3.2). Sliding and overturning are therefore not considered an issue. Also, previous uses of geocontainers has shown that the weight distribution of geocontainers on (soft) soils is very efficient (Lawson 2006), and hence the bearing instability will not be an issue.

### General waves and currents

With the toe in place, the construction of the slope is started. Geotubes will be stacked on top of each other (see figure 3.4). During the stacking of the geotubes, the geotubes are prone to sliding and overturning in two situations: before sand is added to the core, and after the sand is added.

Sliding is possible in two directions. Away from the core which results in a gap between the dam, and into the core which results in geocontainers caving in the core of the dam. Both events should not happen during construction and are therefore checked according to guidelines.

First, sliding and overturning without sand in the core, as shown in figure 3.4a. This does not occur if the following is satisfied (Booster and Vastenburg 2006):

$$\frac{H_s}{\Delta_t D_k} \leq 2 \tag{3.1}$$

Using the values from table 3.1 and design principle 3.1, the maximum significant wave height $H_s$ can be calculated. The inequality, and thus no sliding and overturning, is safe for a **maximum $H_s$ of 10.15 meters.**

Second, sliding and overturning with the sand core, as shown in figure 3.4c. In this case, both mechanisms are caused by current flowing over the geotubes. Stability in the current for both mechanisms is ensured with the following inequality (Booster and Vastenburg 2006):

$$\frac{u_{cr}}{\sqrt{g\Delta_t D_k}} \leq 1.2 \tag{3.2}$$

Using the values from table 3.1 and design principle 3.2, the maximum current $u_{cr}$ can be calculated. The inequality, and thus no sliding and overturning, is safe for a **maximum $u_{cr}$ of 8.48 $m/s$.**

Following from section 2.2, both $H_s$ and $u_{cr}$ are very unlikely to happen during or even after the construction. Therefore safety is guaranteed for overturning and sliding (caused by waves and currents) for all the submerged construction steps.

### Waves and friction

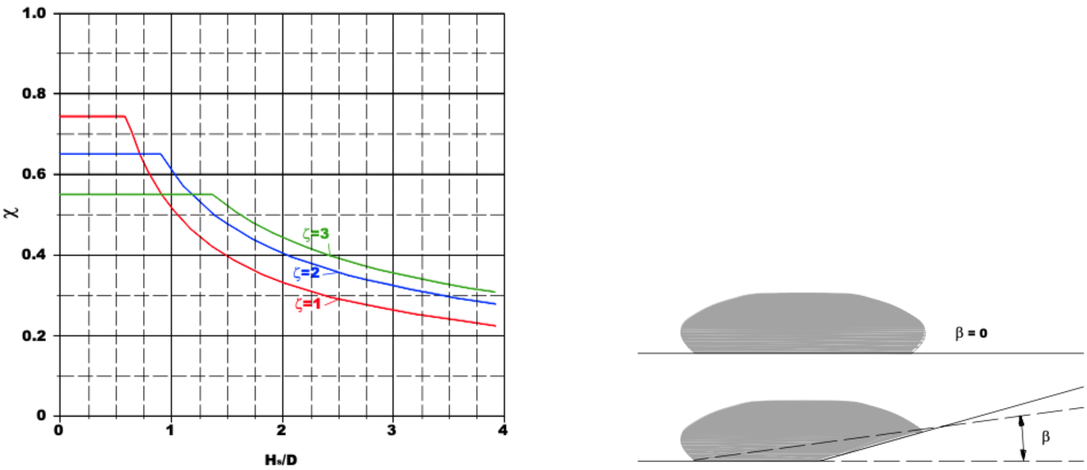
When the geotubes are placed on the outer slope, there is still a possibility that they start sliding. Geotubes are prone to the pulling and pushing forces of breaking waves, which can cause the tubes to slide out of the slope seaward, which can have big consequences for the slope. In the stability of the geotube against sliding, the friction between the geotube and the soil is found to be the most important parameter. Although there are multiple equations to test the stability, there is only one that takes the friction into account (Neves 2011).

The most critical part of the slope where this can occur is at the sea water level, since that is where the waves hit the slope and possibly displace the geotube. Whether the geotubes slide because of the wave forces is checked with the following formula:

$$\frac{\chi H_s}{\Delta_t \sqrt{bD_k}(\phi \cos\beta + \sin\beta)} \leq 0.65 \tag{3.3}$$

Unknowns in this formula are $\chi$, $\beta$ and $\phi$. $\chi$ and $\beta$ are to be determined according to figure 3.6. To make use of figure 3.6a, the surf parameter must be calculated first using equation 3.4. The friction coefficient $\phi$ between the tube and subsoil must be determined with tests when the subsoil is known.

$$\xi = \frac{\tan\beta}{\sqrt{\frac{H_0}{L_0}}} \tag{3.4}$$




(a) Design curve $\chi$ (b) Determination of $\beta$

Figure 3.6: Parameters for equation 3.3 (Neves 2011)

The construction of the dam will be finished with the final phase above water level. The stacking of geocontainers and adding material to the core will continue until the desired height is reached. The entire construction will be finished once the revetment layer is dumped on top of the geocontainers. This extra layer is not a part of the thesis and is not taken into account with the stability tests.

### Design wave height

In order to test the stability of a slope of geotubes, Wouters came up with a method to see if a single layered geotube construction is stable. The design wave height for the slope can be computed (using equation 3.5) for different wave periods an checked if these values ever occur (Baret 2013).

$$H_s = \left[\frac{2\pi}{g{T_p}^2}\left(\frac{(C_w D_c(\frac{\rho_{tube}}{\rho_W} - 1))^2}{\tan\alpha}\right)^2\right]^{1/3} \tag{3.5}$$

Where

$$D_c = l_c sin\alpha$$

Since all the variables are know, design significant wave height can be computed using different peak periods. Following from equation 3.5, $H_s$ and $T_p$ have a relation shown in figure 3.7.

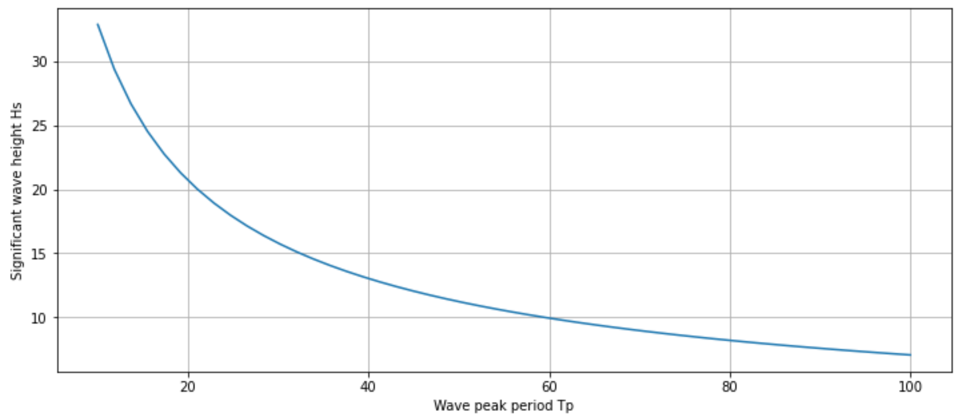



Figure 3.7: $H_s$ versus $T_p$

What is clear from figure 3.7 is that the wave peak periods have to be of unnatural values in order to form a hazard to the stability of the structure. Waves therefore form no danger.

### Soil softening

One of the global stability checks of the structure is done by verifying if the soil softens. Softening of the soil is not the case when the following inequalities hold (Booster and Vastenburg 2006):

$$T_d = \frac{D_k^2}{c_v} = \frac{\rho_w g d^2 \alpha}{k} << 300s \tag{3.6}$$

$$T_n = \frac{\Delta n}{(1-n)\alpha\psi_0} << 3000s \tag{3.7}$$

For now the $D_{20}$ of the soil at the construction location is assumed at $D_{20} = 63\mu m$. The other variables can be set at: $d = 3m, k = 10^{-5}m/s, n = 0.4, \Delta n = 0.01, \alpha = 3{\cdot}10^{-8}m^2/N$ and $\Psi_0 = 200N/m^2s$. Applying equations 3.6 and 3.7 with the assumed values results in $T_d = 272s$ and $T_n = 2778s$. This means that there is no soil softening with the assumed values. When the location is known, the exact values must be determined to accurately verify the failure mechanism.

### Stability subsoil

Important for the structure is whether the soil offers enough bearing capacity. If this is not enough, the foundation is unstable. The bearing capacity must be bigger than the pressure of the geotube at the base, this safety check is done using formula 3.8. The pressure at the base of the geotube results from the geotube simulator output.

$$\frac{P_b}{P_s} < 1 \tag{3.8}$$

Using the NEN-EN 1997-1 guidelines, the bearing capacity of the soil can be calculated using equation 3.9. (NEN 2005)

$$P_s = c^{'} N_c b_c s_c i_c + q^{'} N_q b_q s_q i_q + \frac{1}{2}\gamma^{'} N_\gamma b_\gamma s_\gamma i_\gamma \tag{3.9}$$

Where the bearing resistance can be calculated analytically using:

$$N_q = e^{\pi \tan\phi^{'}} \tan^2(45 + \frac{\phi^{'}}{2}) \tag{3.10}$$

$$N_c = (N_q - 1)\cot\phi^{'} \tag{3.11}$$

$$N_\gamma = 2(N_q - 1)\tan\phi^{'} \tag{3.12}$$

A faster approach is done by neglecting the reduction and uncertainty factors of equation 3.9. The equation then reduces to equation 3.13 which give a quick (less accurate) estimation (TenCate 2021).

$$P_s = c^{'} N_c + q^{'} N_q + \frac{1}{2}\gamma^{'} N_\gamma b \tag{3.13}$$

Using equation 3.13 and assuming $c^{'} = q^{'} = 0$, $\phi^{'} = 25°$, $N_\gamma = 9$ and $\gamma^{'} = 17$ $kN/m^3$ we find a $P_s$ of 338 $kPa$. This results in a safety factor of 0.16, which is safe. However, when the exact location and soil parameters are known, the bearing capacity can be accurately verified using equation 3.9. Also, models show that geosynthetic structures adapt very well to differential settlement and that these structures are not considered an alternative, but the preferable solution (Moayedi et al. 2011). Therefore, it is very likely that the bearing capacity with the accurate value will be sufficient as well and that settlement will not cause problems.

## 3.4 Internal stability

The internal stability of geotubes is dependent on the type of geotextile and the filling material. As shown in figure 2.4, the internal failure mechanisms consist of three parts: erosion of fill through the geotextile, rupture of geotextile and failure by deformation of fill. The latter will not be considered, since deformation of fill is not a risk with high filling degrees (±80% fill) (Steeg and Vastenburg 2010). In this section, requirements for the geotextile are provided. Important to note is that for this construction the location is yet to be determined. Therefore some design principles can not yet be applied.

### 3.4.1 Geotextile

Important in the assessment of the internal stability is the geotextile of choice. Each geotextile has it's own properties and benefits. The GeoTube Simulator provided by TenCate had the GT1000M geotextile as input. GT1000M is a woven geotextile made of polypropylene yarns. This geotextile also is inert to biological degradation and resistant to naturally encountered chemicals, alkali's and acids (TenCate 2011).

For this reasons, GT1000M is a good fit to apply. To check the internal stability, the geotextile specific values as shown in table 3.2 and the output of the geotube simulator are relevant in the upcoming section.

| GT1000M | | |
|---|---|---|
| $T_f$ (axial or Machine Direction MD) | 175 | $kN/m$ |
| $T_f$ (circumferential or Cross Direction MD) | 175 | $kN/m$ |
| $\varepsilon_f$ (axial or Machine Direction MD) | 20 | % |
| $\varepsilon_f$ (circumferential or Cross Direction MD) | 20 | % |
| $T_{FS}$ | 88 | $kN/m$ |
| $O_{90}$ | 0.60 | $mm$ |

Table 3.2: Properties GT1000M geotextile (TenCate 2011)

### 3.4.2 Erosion of fill through geotextile

First, erosion of fill through geotextile will be discussed. This mechanism consists of two different parts. The characteristic opening size of the geotextile $O_{90}$ must be of a size that only a small percentage of the filling material can wash out. Also, the hydraulic conductivity of the geotextile must be sufficient to allow flow through the tube. Since the construction location is not yet known, the soil properties of the filling material is not yet known. When these properties are known, a comparison can be drawn with the known $O_{90}$ shown in table 3.2.

#### Characteristic opening size

There are known design principles to check the erosion of fill through the geotextile in two situations: stationary loads (currents) and dynamic loads (waves). They are verified with the following design principles, which need to be applied once the soil properties are known. (Booster and Vastenburg 2006):

Erosion of fill through geotextile in stationary loads:

$$O_{90} < 5D_{10}C_u^{1.2} \tag{3.14}$$

$$O_{90} < 2D_{90} \tag{3.15}$$

Where:

$$C_u = \frac{D_{60}}{D_{10}}$$

And erosion of fill through geotextile in dynamic loads:

$$O_{90} < 1.5D_{10}C_u^{1.2} \tag{3.16}$$

$$O_{90} < D_{90} \tag{3.17}$$

#### Hydraulic conductivity

The characteristic opening size influences the hydraulic conductivity of the geotextile. When the filling material is transported by water (during filling or after placement), it can block openings and clog pores in the geotextile. Blocking happens when particles block the pores of the geotextile, clogging happens when soil particles are trapped in between the fibres of the geotextile. Again, the principles (Booster and Vastenburg 2006) need to be applied once the soil properties are known.

Blocking of the characteristic opening size is safe when:

$$0.5 < \frac{O_{90}}{D_{90}} < 1.0 \tag{3.18}$$

Clogging of the geotextile pores is safe when:

$$\frac{O_{90}}{D_{15}} > 3 \tag{3.19}$$

### 3.4.3 Geotextile skin rupture

The geotextile can rupture due to multiple factors: skin rupture because of geotextile degradation, over pressure during filling, insufficient seam strength and insufficient puncture resistance. For all situations, the geotextile can be tested.

#### Over pressure

During the filling of the geotube, the caused over pressure must remain small enough to prevent rupture (Booster and Vastenburg 2006). Whether this is the case is verified with equation 3.20. Again, once the soil properties are known the over pressure can be verified.

$$\Delta H = \frac{k_s i_s}{\Psi} \leq 0.01m \tag{3.20}$$

Where:

$$i_s = \frac{\Delta H}{W}$$

#### Degradation

Degradation of geotextile can happen because of multiple factors. Factors that degrade the geotextile are UV radiation (only for unsubmerged geotubes), oxidation and seawater. To minimise the impact on the strength of the geotextile additives and stabilisers must be added during the production of geotextile. Current design principles have a premise of a lifespan of 50 years. However, with the right additives and strength reduction factors, a lifespan of 100 years is possible (Bernardini 2004). Since the geotextile is inert to biological degradation and is resistant to naturally encountered chemicals, alkali's and acids (TenCate 2011), additives to the geotextile are not required.

#### Seam strength

The factory seam strength of the geotextile is known (table 3.2) and can be compared to the occurring tensile forces in the geotextile. The occurring forces result from the TenCate Geotube Simulator. The biggest tensile force is in emerged conditions in circumferential direction. The safety factor for this situation is 1.72, which means the seam strength is sufficient.

### Puncture resistance

One of the final stages of the construction is dumping rock on the slope to create the revetment layer. When dumping takes place, the geotextile must have sufficient resistance to avoid puncture. The current CUR guidelines use a method in which the exerted energy of falling rock is compared to the energy the geotextile can absorb (the Energy Absorption Level or EAL). If the EAL is bigger than the exerted energy by the rock, the geotextile is considered safe (Jonker 2017).

Whether the EAL is sufficient, depends on the applied stone class. For each stone class, minimum required EAL's for the geotextile are given in table 3.3 and are derived from falling energy of rock. Assumed in this calculation is that the rock hits the geotextile with it's equilibrium speed (Jonker 2017).

| **Stone class ( NEN-EN 13883 )** | **EAL [kN/m]** |
|---|---|
| 90 / 250 mm | 3 |
| 5 - 40 kg | 3.5 |
| 10 - 60 kg | 7 |
| 40 - 200 kg | 9 |

Table 3.3: Required EAL of geotextile (Jonker 2017)

The Energy Absorption Level of the applied geotextile can be calculated using the following formula (Jonker 2017):

$$
\begin{aligned}
EAL &= \frac{1}{2}\left[\left[\frac{1}{2}T_f\varepsilon_f\right]_{\text{axial}} + \left[\frac{1}{2}T_f\varepsilon_f\right]_{\text{circ}}\right] && \text{for } \varepsilon_f \leq 60\% \\
EAL &= \frac{1}{2}\left[\left[\frac{1}{2}T_f\varepsilon_f\left(\frac{0.6}{\varepsilon_f}\right)^2\right]_{\text{axial}} + \left[\frac{1}{2}T_f\varepsilon_f\left(\frac{0.6}{\varepsilon_f}\right)^2\right]_{\text{circ}}\right] && \text{for } \varepsilon_f > 60\%
\end{aligned} \tag{3.21}
$$

If a composite geotextile (made of a membrane and fabric) is used, the two values may be added as follows:

$$EAL = EAL_{\text{fabric}} + EAL_{\text{membrane}} \tag{3.22}$$

There are additional requirements on the geotextile's strength, these are (Jonker 2017):

- Minimal required tensile strength in axial and circumferential direction is 35 kN/m for fabrics
- Minimal required tensile strength in axial and circumferential direction is 15 kN/m for membranes

If a composite geotextile is used, either the fabric or membrane must meet the mentioned requirements. Both tensile strengths should not be added. Other guidelines from the HZ University of Applied Sciences support these additional requirements.

The values where derived from field tests and give a minimal required tensile strength of 14 kN/m in both directions. In addition a minimal value of the required strain of the geotextile was derived. The minimal required strain against all classes dumped rock was found to be 22% (Bakker and Stee 2012).

When following the current CUR guidelines, the geotextile is safe for puncture from falling rock when the EAL value following from equation 3.21 is bigger than the required value given in table 3.3. An extra requirement of the geotextile could be a minimal strain of 22% following from the HZ University of Applied Sciences guidelines.

When applying formula 3.21 we see that the EAL of GT1000M is 17.5 kN/m, which means that the puncture resistance is **sufficient** for the heaviest stone class shown in table 3.3 according to the CUR guidelines. The tensile strength is also bigger than the minimal required according to the additional requirements. The geotextile does however not meet the requirements HZ University of Applied Sciences guidelines, since the maximal elongation is not sufficient. Since these are not official standardised guidelines, the puncture resistance of the geotextile is considered **safe**.

## 3.5 Sand Migration

Important for the safety of the structure is that washing out of materials should be limited to it's minimum. Washing out of materials can happen during the stacking process in construction or from in between the geotubes. Both options will be explained an researched in this section.

### 3.5.1 From construction site

When construction is stopped because of for example the weather conditions, materials can wash out during the steps shown in figures 3.4b and 3.4c. When this happens, new materials need to be added again which can cause delays in the planning. The washing out in this situation is caused by currents and waves. To get an insight in the magnitude of the sediment transport van Rijn (Rijn 2007) proposed a bed-load transport formula for steady flow, which can be used with or without waves. The formula reads:

$$q_b = 0.015 \rho_s u h (\frac{D_{50}}{h})^{1.2} (M_e)^{1.5} \tag{3.23}$$

Where:

$$M_e = \frac{u_e - u_{cr}}{\sqrt{(s-1)gd_{50}}}$$

$$u_e = u + \gamma U_w$$

$$U_w = \frac{\pi H_s}{T_p \sinh{(kh)}}$$

$$u_{cr} = \beta u_{cr,c} + (1-\beta) u_{cr,w}$$

$$u_{cr,c} = 8.5(D_{50})^{0.6} \log(\frac{12h}{3D_{90}})$$

$$u_{cr,w} = 0.95[(s-1)g]^{0.57} D_{50}^{0.43} T_p^{0.14}$$

$$\beta = \frac{u}{u+U_w}$$

$$s = \frac{\rho_s}{\rho_w}$$

If construction is delayed due to a storm, the bed load transport because of this storm can be calculated. Using the values in storm conditions for waves (Fockert 2011) (Holthuijsen 1995), currents (Giessen, Ruijter, and Borst 1990) (Caston 1974) and assumed soil characteristics as shown in table 3.4, the bed load transport is calculated over various depths using equation 3.23. These bed load transports are in the most dominant wave direction with storm conditions, and are therefore the most extreme values. Once the soil parameters are known, the values can be accurately calculated. The results of the instantaneous bed-load transport and that after a six hour storm over depth are shown in figures C.1 and C.2.

| | | |
|---|---|---|
| $u$ | 1 | $m/s$ |
| $H_s$ | 14 | $m$ |
| $T_p$ | 10 | s |
| $\rho_s$ | 2600 | $kg/m^3$ |
| $\rho_w$ | 1025 | $kg/m^3$ |
| $D_{50}$ | 220 | $\mu m$ |
| $D_{90}$ | 430 | $\mu m$ |

Table 3.4: Storm and assumed soil variables

With the calculated instantaneous bed-load transport $q_b$ (in [kg/s/m]), the total amount of washed out material over time for the given variables can be quantified over depth. To quantify the amount of lost material, equation 3.24 is used to calculate the volume after a specific time $\Delta t$ (a storm of six hours) over a specific length $L_{lost}$ (taken as the length of one geotube).

$$V_{lost} = \frac{m}{\rho} = \left(\frac{q_b \Delta t}{\rho_s}\right) L_{lost} \tag{3.24}$$

Since the bed load transport is the amount transported over one metre, the bed load can be translated into a height loss of the dam core. The lost amount of material and lost core height are shown in figure 3.8. The calculations are done up until a water depth of 3 meter, since one extra layer of geotube causes emerged conditions.

$$\Delta h = \frac{V_{lost}}{L_{lost}} \tag{3.25}$$

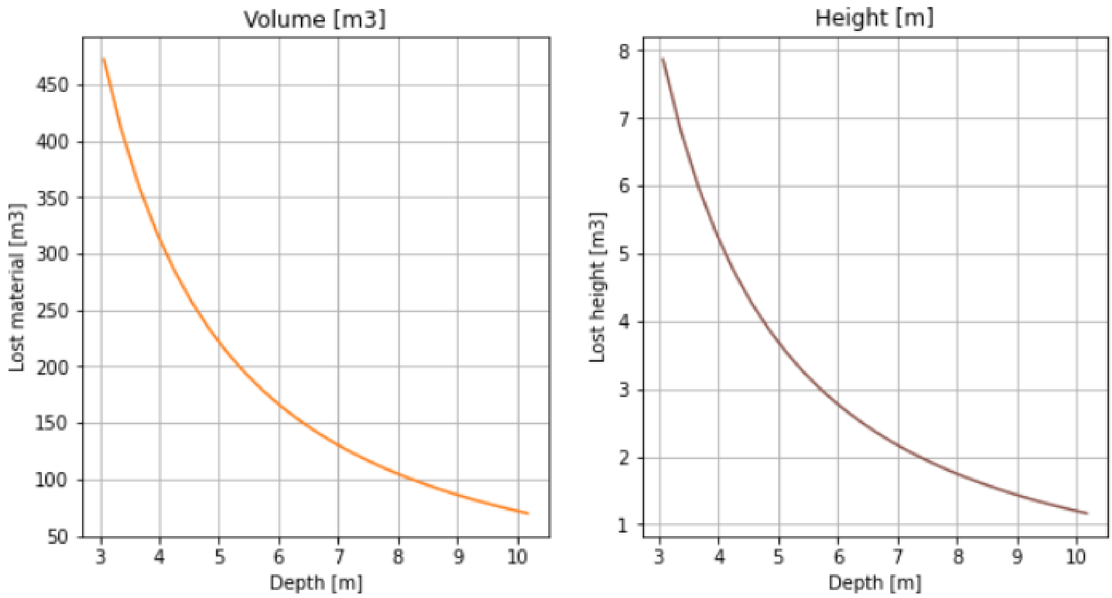



Figure 3.8: Lost volume and core height after a six hour storm

These losses, when such a storm occurs, are significant and need to be prevented or reduced to it's minimum. The losses are calculated for the construction stopped at the position shown in figure 3.4c. In the scenario of construction being at a water depth of 5 metres the lost material can be reduced with leaving the construction at the position shown in figure 3.4b. In this position, the geotube acts as a small wall that blocks and reduces bed load transport. Important to note that this preventing action is only safe for storm conditions where the $H_s < 10.15$ meters (resulting from equation 3.1. Another solution would be to plan the final 10 meters accoring to weather forecasts.

### 3.5.2 From connections

When the geotubes are placed, there is a possibility of spaces between the geotubes. These spaces form possible locations from where sand can be washed out from the dam. The location are marked red in figure 3.9. Usually, slopes are created by a double layer of geotextile elements which are stacked in a brick wise manner. This construction method removes the washing out mechanism, since all the spaces are blocked by the second layer of geotubes. However, since a single layer is applied, the mechanism needs to be prevented.

To cope with the sand migrating out, there are multiple options. The first option is to use regular geotubes and place them as close as possible to each other, this is shown in figure 3.10a. There is however an uncertainty about the quantity that migrates out, which is a risk for the structure. Therefore this is the most unsafe option.

The second option is to use flat-end tubes instead of regular tubes that are rounded on the sides. The difference is illustrated in figure 3.10 (Stephens, Dymond, and Plaut 2014). Flat end tubes can be connected to each other, which gives certainty to the space between the tubes. Although the risk is smaller than with regular tubes, there is still a risk of sand migrating out. Risks with a project of this scale always need to be avoided.

Another option is to apply a filter layer on the slope behind the locations marked red in figure 3.9. This can be done by stretching the geofilter that is used for the construction of the self healing toe over the entire slope, this might however mean higher construction costs and increased complexity during construction. Construction is more complex since during the construction there must be dealt with the geofilter floating over the depth of the construction site.

To reduce costs, geofilters can also be applied only behind or in front of the possible washing out locations. This option also has complexities to deal with. In this situation, the geofilter sort of acts as a connection between the geotubes. These geofilters can only be applied after the geotubes are placed in position, therefore it is very likely that divers are required. Divers need to sew, stitch or zip the geofilters. The presence of divers on the construction site brings risks, and the divers require a lot of expertise to place the filters.

There are multiple options to cope with this mechanism, which also can be combined. TenCate however advises to always apply some kind of geofilter behind the possible washing out locations, to gain certainties about the risks. The question which option to use is most likely a consideration of risk, costs and complexity. Geofilters sewed, stitched or zipped by divers may require new expertise. When a single layered slope requires too complex solutions for this mechanism, the application of a double layered slope is advised.

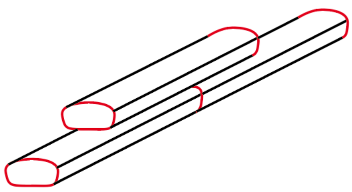
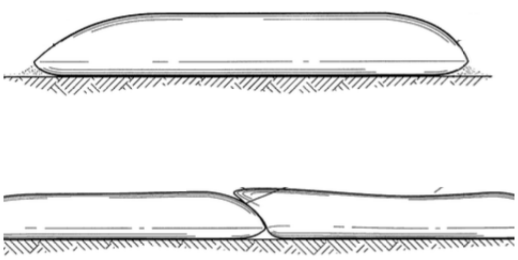
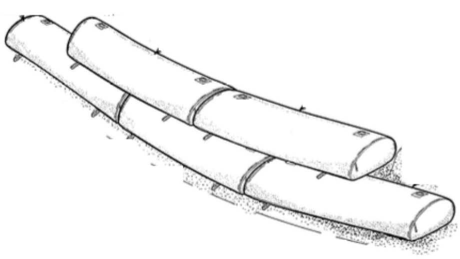


Figure 3.9: Possible washing out locations



(a) Regular geotube



(b) Flat end geotube

Figure 3.10: Regular and flat end geotubes (Stephens, Dymond, and Plaut 2014)

## 3.6 Maintenance

Once the construction is finished, monitoring of the structure is necessary in order to assure the quality. Though permanent monitoring is not necessary, annually, quarterly and post storm inspections are performed.

According to the KNMI, conditions considered a storm is when wind conditions reach an hourly average between 75 and 88 km/hour (KNMI 2023). After such events, post storm monitoring is performed. Such a report will include (Associates 2022):

- Are there displaced geotubes? If so, a photo documentation and location must be included in the report.
- Are there any exposed geotubes? If so, a photo documentation and location must be included in the report.
- Is waste present? Any washed up waste due to the storm must be removed.
- Conclusion on the general state and overall condition. Is the structure or are geotubes damaged, is repair necessary? Reparations can for example mean stitching patches over ruptures (Glick 2006).

Quarterly and annually include inspections include the previously mentioned elements, and add the following (Associates 2022):

- Did large erosion or settlement events occur? Erosion on the revetment layer or at the toe of the slope or sudden large settlements must be visually checked and documented. For a more accurate picture, bathymetric inspections can be performed.
- A summary of past inspection and an evaluation of the monitoring program. This may result in a recommendation to change the monitoring program.

# Chapter 4

# Discussion

Traditional construction techniques are often favoured over using geotextile elements by developers. To see whether a construction using geotubes is a feasible alternative for the construction of a dam in the North Sea, depends on the results of tests on various internal and external failure mechanisms (Lawson 2006). Due to a lack of experience and information, first the construction sequence using geotubes is determined. Since Van den Herik developed a new method that allows accurate placement of the geotubes, a predictable stacking sequence of a single layer of geotubes is achievable. However, the new placement method operates until a $H_s$ of 1.0 meters. This may mean a hybrid construction method using caissons in the dominant wave direction is necessary, operate only in the right conditions or both. With the construction sequence and placement of the geotubes known, various tests on the internal and external failure mechanisms have been performed.

Current official CUR guidelines (Booster and Vastenburg 2006) offer design principles for all internal failure mechanisms. In order to design the geotextile following these guidelines, the exact soil parameters have to be known. Once these are known, the characteristic opening size can be used to test the geotextile on erosion through fill, verifying the hydraulic conductivity and if the skin ruptures due to over pressure during the filling. With the choice of geotextile (GT1000M), no additives to reduce degradation are required and a lifespan of up to 100 years is achievable.

During the placement of the revetment layer, the geotextile is exposed to falling rock and may puncture. Current guidelines (Jonker 2017) to verify the puncture resistance result in a safety factor of 1.9 against stone class 40 - 200 kg. The margin suggests that a heavier stone class might be safe to use. The applied guideline is however under revision. For the time being an erratum is published ('Ontwerprichtlijn Geotextielen onder steenbekleding' - CROW), which contests the guideline used to verify the puncture resistance in this report. Since the erratum was not accessible during this thesis, the current (and still valid) official guidelines were applied. A lot of research is currently done in the strength against dumped rock of submerged geotextile elements. For a more accurate picture it is recommended to apply the recently published erratum.

To test the external failure mechanisms, CUR (Booster and Vastenburg 2006) provide basic principles to test against overturning and sliding. More extensive research in literature provided additional methods to obtain a more complete overview. This resulted in a need for scour protection using a self healing toe, a check against sliding and overturning using friction (which is neglected in the CUR guidelines), calculating the design wave height of the structure and checking the bearing capacity of the subsoil. With assumed general soil parameters, the calculations show that the geotubes are safe for all failure mechanisms. However, just like for the internal failure mechanisms, the exact soil parameters must be known for the right conclusion and a field test must be performed to obtain the friction coefficient between the geotextile and subsoil.

One of the two sand migrations, the bed-load transport, is calculated using the formula proposed by van Rijn (Rijn 2007). This formula shows significant loss of material during storm conditions up to a depth of 10 meters. The magnitude of material loss can be reduced by using a geotube as a wall, or planning the final 10 submerged meters according to weather forecasts.

With the geotubes in place, sand can migrate from between the ends where geotubes meet. With the new placement method of Van den Herik, placement is more accurate and these voids can be minimised. Since the magnitude of sand migrating out can not be determined, a preventing mechanism is always recommended according to TenCate. Flat end tubes, an extra filter layer, stitched, sewed or zipped geofilters on the washing out locations or a double in stead of single layer of geotube all provide a solution. Which to choose is a consideration of risk, costs and complexity.

With all tests performed, the results are promising and work towards a conclusion that the application of geotubes is feasible. The next steps would be to perform an extensive geotechnical research which maps out all required soil characteristics and getting more insight in the puncture resistance of geotextile using the recently published erratum (and/or field tests).

# Chapter 5

# Conclusion

The purpose of the research in this thesis is to verify whether using geotextile elements in the construction of a dam in the North Sea is a feasible method or not. In order to obtain the right conclusions, a construction using geotubes is designed according to various failure mechanisms. The main research question has been divided into three sub-questions in order to gradually work towards a conclusion.

The first question that needs to be answered is what the construction sequence looks like. Van den Herik developed a new method which allows accurate placement. Using this new method, literature and design principles show that a stable and safe slope can be constructed using a single layer of geotubes. This single layered slope does not reduce stability compared to a double layered slope. The maximal slope steepness, before rocks on the revetment start to slide, of 1:3 is applied and showed a design wave height of unnatural values. The geotubes on the slope are also tested against all known failure mechanisms. Although some tests are performed with assumed soil parameters, the tests indicate that the geotubes are safe to use in the given conditions and construction sequence.

Before the construction of the slope, scour protection at the toe needs to be implemented. A self healing toe is applied, which has big advantage compared to riprap since it's a self healing mechanism.

In the construction of the revetment layer rock is dumped on top of the geotubes, which can lead to puncture. An insight into the puncture resistance of the geotextile is the basis of the second sub question. Results from current guidelines show a significant safety factor of 1.9 against a stone class of 40-200 kg. Following these (still valid) guidelines, the puncture resistance of the geotextile is safe.

With the tested and verified construction sequence and geotextile strength, the final sub-question is whether it is necessary to prevent sand migrating out from in between geotubes. However, since the magnitude of this mechanism can not be quantified, it is necessary to always apply a preventing mechanism. Various options are possible, which one to apply is a consideration of costs and required extra expertise to place the preventing action.

Results on the sand migrating from the construction (overnight or after a storm of six hours) show that significant amount of material can be lost. During a storm of six hours and construction being in submerged conditions up until a depth of 10 meters, lost material ranges from 60 to 460 $m^3$ over the length of a single geotube. Countermeasures are possible in forms of using a layer of geotube as a blocking mechanism during a storm, or planning the final 10 meters using weather forecasts.

The conclusion on the feasibility of the use of geotubes depends on a lot of different factors and variables. Following from all the applied design principles, the geotubes are a feasible method for dam construction in the North Sea. Important to note is that some design principles are applied with assumed (general) soil parameters. Once these are known a definitive conclusions can be drawn. However, since the margins are high the definitive soil parameters are not expected to alter the conclusion. Also, sand migration (both mechanisms) can be reduced or prevented and possible inaccurate results in the puncture resistance verification can be solved by using the newly published erratum. Since the safety factor is of 1.9, there is a lot of margin and the (more strict) method proposed in the erratum is not expected to alter the conclusion.

# Appendix A

# Planning

This overview visualizes the planning for the upcoming period. All the activities, deadlines and working hours are indicated.

| Week | Date | Time | Activity |
|---|---|---|---|
| 2.1 | 14 November 2022 | 10.45 | Kickoff presentation |
| 2.1 | 16 November 2022 | 15.00 | Meeting ir. Moll |
| 2.1 | - | - | Assignment: Information Literacy 2 |
| 2.1 | - | - | Setting up Overleaf |
| 2.1 | - | - | Writing CH1: Workplan |
| 2.2 | 21 November 2022 | 10.30 | Weekly feedback meeting |
| 2.2 | 21 November 2022 | 23.59 | Deadline: Information Literacy 2 |
| 2.2 | 21 November 2022 | 23.59 | Deadline: Workplan |
| 2.2 | - | - | CH3.1 - CH3.4 preparation |
| 2.3 | 28 November 2022 | 13.00 | Weekly feedback meeting |
| 2.3 | - | - | CH2.4 |
| 2.4 | 5 December 2022 | 13.30 | Weekly feedback meeting |
| 2.4 | - | - | CH3.1 - CH3.4 validation |
| 2.4 | 9 December 2022 | 12.00 | Deadline: Interim Report |
| 2.5 | 13 December 2022 | 10.00 | Interim presentation |
| 2.5 | 13 December 2022 | - | Deadline: Peer reviews |
| 2.5 | - | - | CH3.5 |
| 2.6 | 19 December 2022 | 11.00 | Weekly feedback meeting |
| 2.6 | 23 December 2022 | 18.00 | Deadline: Essay ethics |
| 2.6 | - | - | CH4 |
| 2.7 | 9 January 2023 | - | Weekly feedback meeting |
| 2.7 | 10 January | 11.00 | Deadline: Pitch ethics |
| 2.7 | - | - | CH5 |
| 2.8 | 16 January 2023 | 12.00 | Deadline: Final report |
| 2.8 | 18 January 2023 | 15.00 | Final presentation |
| 2.8 | 20 January 2023 | - | Self evaluation |
| 2.8 | 20 January 2023 | - | Uploading final documents to onstage |

# Appendix B

# Output Simulator

The output of the GeoTube simulator provided by TenCate is presented for submerged en emerged circumstances.

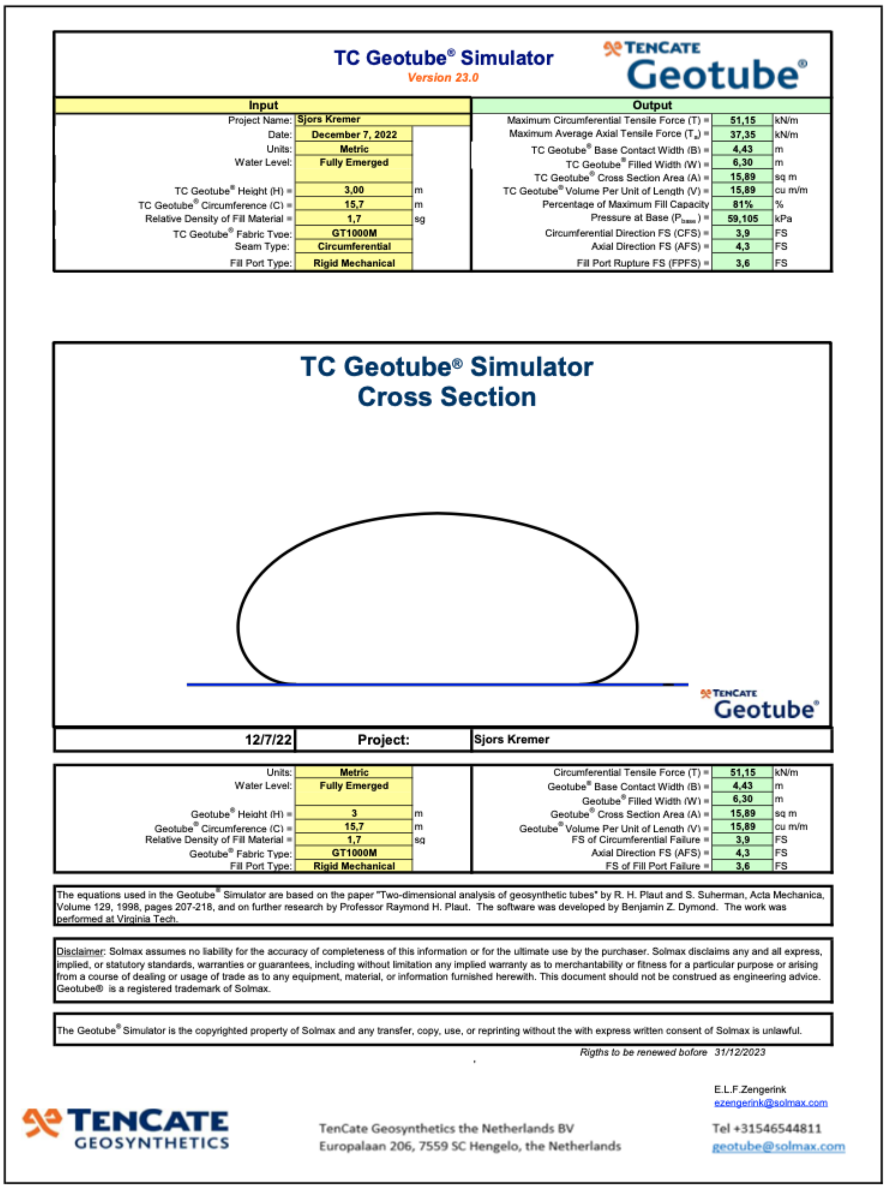
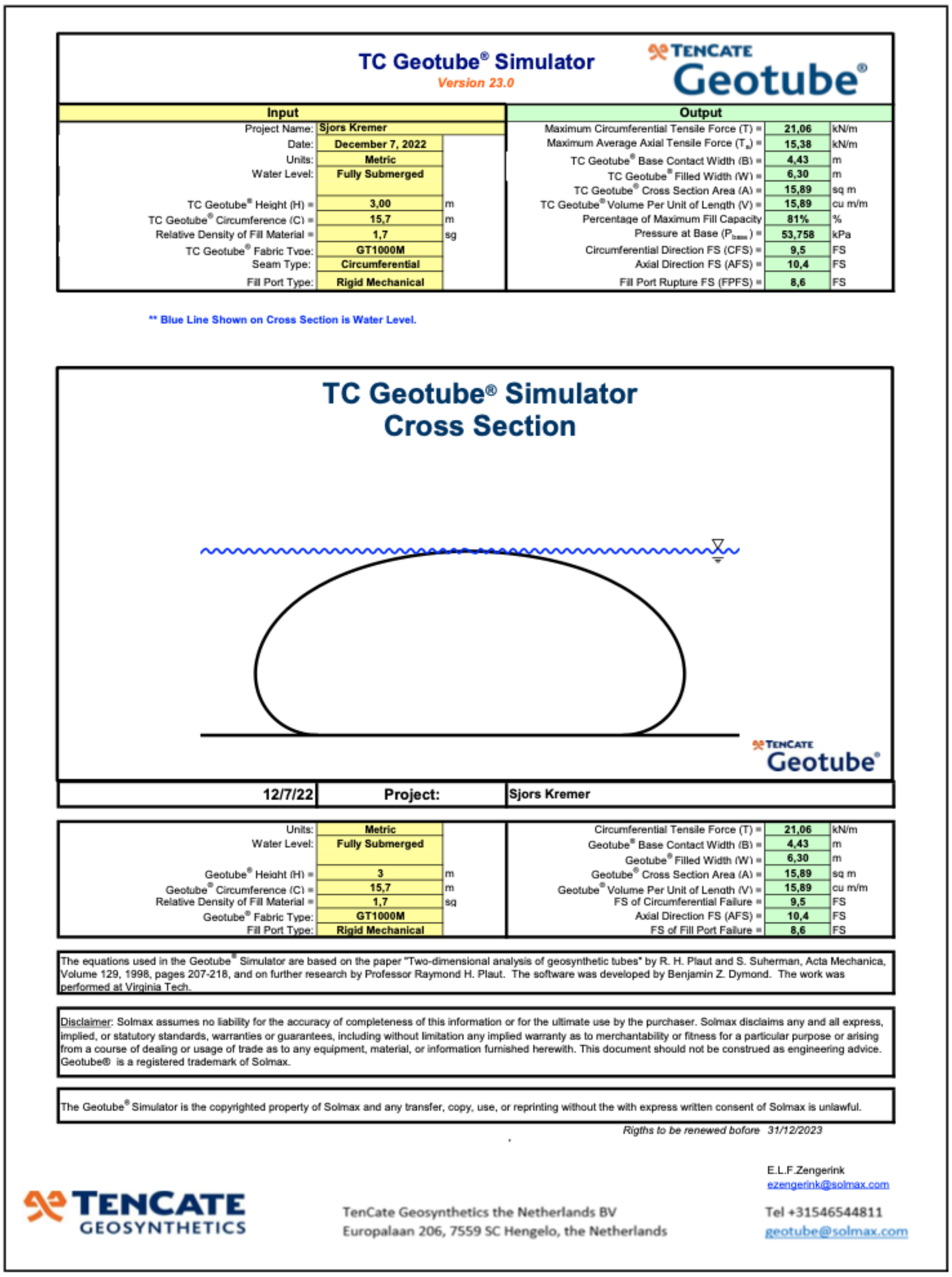



Figure B.1: GeoTube Simulator emerged



TC Geotube® Simulator
Version 23.0

TenCate Geotube®

| Input | | | Output | | |
|---|---|---|---|---|---|
| Project Name: | Sjors Kremer | | Maximum Circumferential Tensile Force (T) = | 21,06 | kN/m |
| Date: | December 7, 2022 | | Maximum Average Axial Tensile Force ($T_a$) = | 15,38 | kN/m |
| Units: | Metric | | TC Geotube® Base Contact Width (B) = | 4,43 | m |
| Water Level: | Fully Submerged | | TC Geotube® Filled Width (W) = | 6,30 | m |
| | | | TC Geotube® Cross Section Area (A) = | 15,89 | sq m |
| TC Geotube® Height (H) = | 3,00 | m | TC Geotube® Volume Per Unit of Length (V) = | 15,89 | cu m/m |
| TC Geotube® Circumference (C) = | 15,7 | m | Percentage of Maximum Fill Capacity | 81% | % |
| Relative Density of Fill Material = | 1,7 | sg | Pressure at Base ($P_{base}$) = | 53,758 | kPa |
| TC Geotube® Fabric Type: | GT1000M | | Circumferential Direction FS (CFS) = | 9,5 | FS |
| Seam Type: | Circumferential | | Axial Direction FS (AFS) = | 10,4 | FS |
| Fill Port Type: | Rigid Mechanical | | Fill Port Rupture FS (FPFS) = | 8,6 | FS |

** Blue Line Shown on Cross Section is Water Level.

TC Geotube® Simulator
Cross Section

TenCate Geotube®

| 12/7/22 | Project: | Sjors Kremer |
|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Units: | Metric | | Circumferential Tensile Force (T) = | 21,06 | kN/m |
| Water Level: | Fully Submerged | | Geotube® Base Contact Width (B) = | 4,43 | m |
| | | | Geotube® Filled Width (W) = | 6,30 | m |
| Geotube® Height (H) = | 3 | m | Geotube® Cross Section Area (A) = | 15,89 | sq m |
| Geotube® Circumference (C) = | 15,7 | m | Geotube® Volume Per Unit of Length (V) = | 15,89 | cu m/m |
| Relative Density of Fill Material = | 1,7 | sg | FS of Circumferential Failure = | 9,5 | FS |
| Geotube® Fabric Type: | GT1000M | | Axial Direction FS (AFS) = | 10,4 | FS |
| Fill Port Type: | Rigid Mechanical | | FS of Fill Port Failure = | 8,6 | FS |

The equations used in the Geotube® Simulator are based on the paper "Two-dimensional analysis of geosynthetic tubes" by R. H. Plaut and S. Suherman, Acta Mechanica, Volume 129, 1998, pages 207-218, and on further research by Professor Raymond H. Plaut. The software was developed by Benjamin Z. Dymond. The work was performed at Virginia Tech.

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*Rigths to be renewed before 31/12/2023*

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Figure B.2: GeoTube Simulator submerged

# Appendix C

# Bed-Load transport

Results from the bed-load transport calculations.

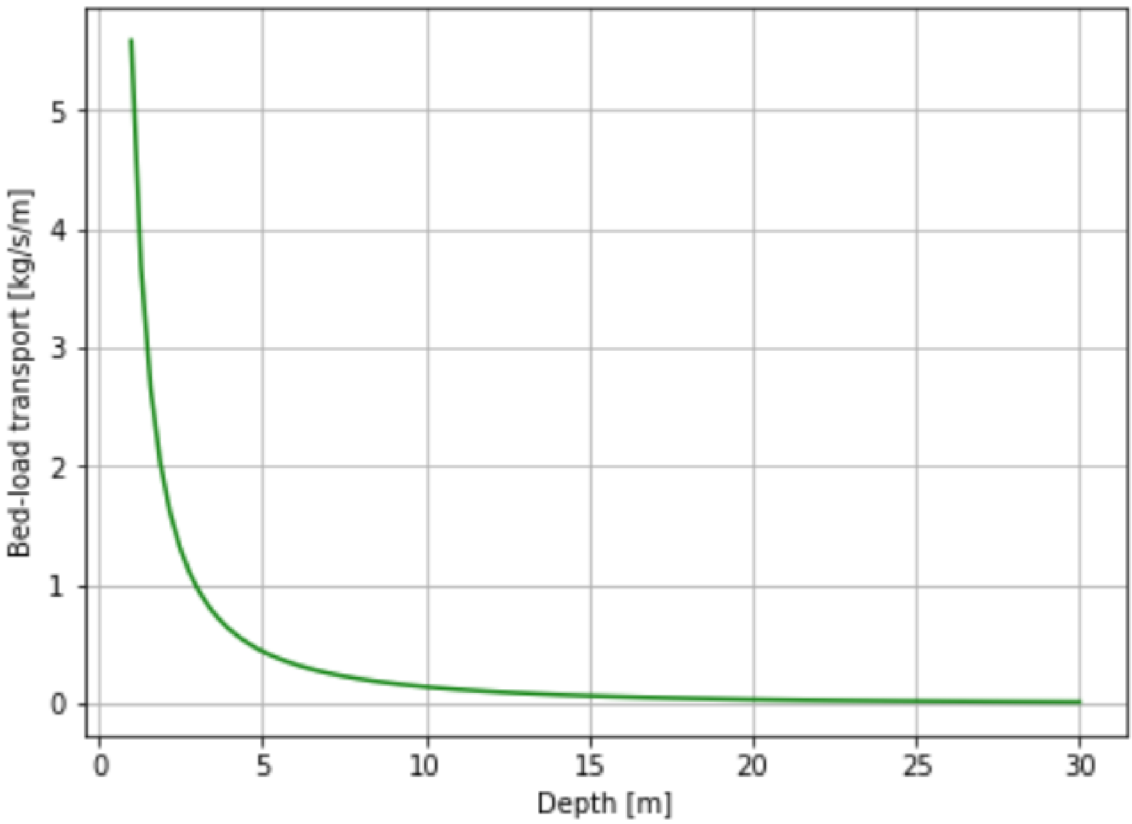


Figure C.1: Bed-Load transport over depth in storm conditions $[kg/s/m]$

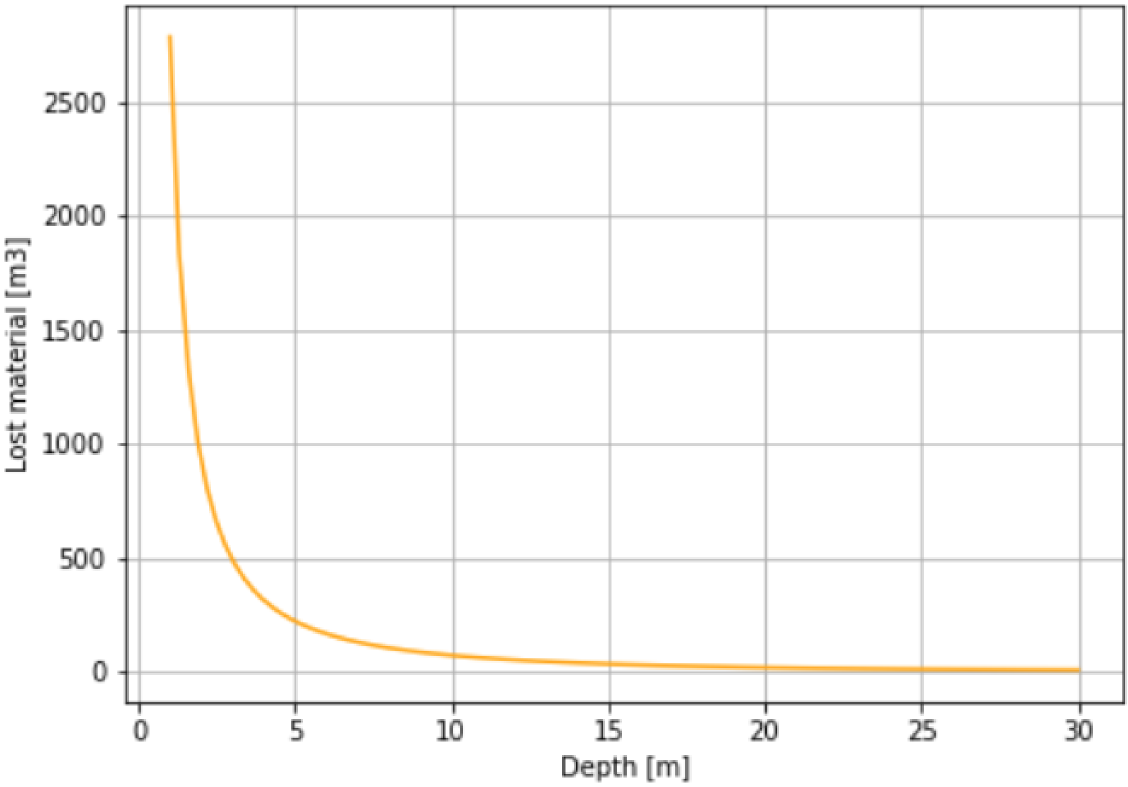


Figure C.2: Lost amount of material [$m^3$]

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