2/9/2023

Feasibility of Aqueduct Construction in Spannenburg, Netherlands

Comparing Eared, Immersed and Piled Aqueducts using Multicriteria Decision Making Analysis.

Author: Nazir Saleh (s2602342)

Supervisor (UT) : Dr. Ing. Roland Kromanis and Ing. Gerrit Snellink

Supervisor (Province Friesland): Project leader. Dirk Walinga

UNIVERSITY OF TWENTE.

provinsje fryslân
provincie fryslân

Preface

This thesis is the result of my work carried out over three months, under the internal supervision of Dr. Ing. Kromanis (Roland) and Ing. Snellink (Gerrit) from the university of Twente and external supervision of the project leader. Drik Walinga from the province of Friesland. I am grateful to all supervisors for their guidance and support throughout this process. Their expertise and encouragement have been invaluable in shaping the direction and outcome of my work.

I also extend my heartfelt appreciation to mr. Sieds Hoitinga for providing me with the opportunity to undertake this research project.

It is my sincere hope that this thesis study will make a significant contribution to the field of civil engineering, and be of use to future researches in the area of Spannenburg.

Nazir Saleh ,February 2023

Abstract

This study presents a feasibility analysis of three aqueduct construction methods (eared, immersed, and piled) in the Spannenburg location in the Netherlands. The construction site presents challenges due to the proximity of a water purification company and site limitations such as clay bursting during the construction-phase. The study compares the construction methods based on environmental impact using LCA analysis, health and safety, effect on regular life, and ease of construction. The results of the study are derived from a Multi-Criteria Decision Making (MCDM) analysis, providing a comprehensive evaluation of the most suitable construction methods for the Spannenburg aqueduct project.

Contents

1. Introduction

An aqueduct is defined as man-made structures used to transport a water stream across an obstacle such as hollow, valley or natural streams through conduit or channels to convey water(Kamal and Khan, 2022). The technology of building and depending on aqueduct to transport water from their origin points such as lake or springs to where it was needed is known through the millennia, from prehistoric till today. Many ancient civilizations used aqueducts as a main conveyor of water in rivers such as the Chinese and Americans civilizations . Some civilizations used this technology mainly to supply water for their settlements and palaces as in the Mediterranean civilizations(De Feo *et al.*, 2013).

Constructing bridges and aqueducts is a well-known and reliable technology in the Netherlands to tackle traffic problems and water conveyance and it is estimated that civil infrastructure in general has a value of around EUR 318 billion. In numbers, there are around 85,000 bridges and viaducts, 83,000 culverts and 2,400 km of quays, while 7,800 pumping stations (Bleijenberg, 2021). However, many of these structures are facing two main issues, the first problem that these structures were built a bit later or directly after the world war two which means they are aged . Secondly, some of these structures cannot meet the high demand of traffic that increases from a year to another because they were designed based on old requirements. Thus ,they should be whether replaced or renovated.

The Spannenburg bridge 1952 in the province of Friesland, is one of these old civil infrastructures that the province of Friesland prefers to replace it with an aqueduct instead of renovation or replacing it with another bridge. The trigger for the decision of replacing a bridge with an aqueduct is that the province of Friesland is aiming to decrease the travel time between the province and Amsterdam and with aqueducts traffic can flow unimpeded. In other words, aqueducts are sustainable solutions for the delays caused by the interaction between the traffic in land and on water(Brolsma and Roelse, 2011). Moreover, the province of Friesland is a water sport destination for many sailors around the world thus constructing an aqueduct enhance a freedom of sailing. For the same reasons , the province of Friesland had what is called ‘’Frisian Lakes Project’’ aiming at making Friesland more attractive and water sports area(Waterman and Brouwer,2015).

1.1. Problem Definition

The Spannenburg bridge represented by the red line in figure 1 is located in the Prinses Margrietkanal in Friesland. The Rijkwaterstaat wants to replace it with an opening bridge (Friesland, 2022). However the province of Friesland are aiming at a better solution meaningly an aqueduct according to Dirk Walinga (project leader at the province). Near the Spannenburg bridge, there is a Drinkwater treatment facility. The dark blue in figure 2 shows the drinking water purification area and the light blue shows the groundwater collection area. Thus, construction in the area is constrained unless there is a good story explaining how the groundwater is preserved. The condition of constructing new structures in the area to preserve the clay layer(19m-NAP) and prevent leakage of the layer to the groundwater.

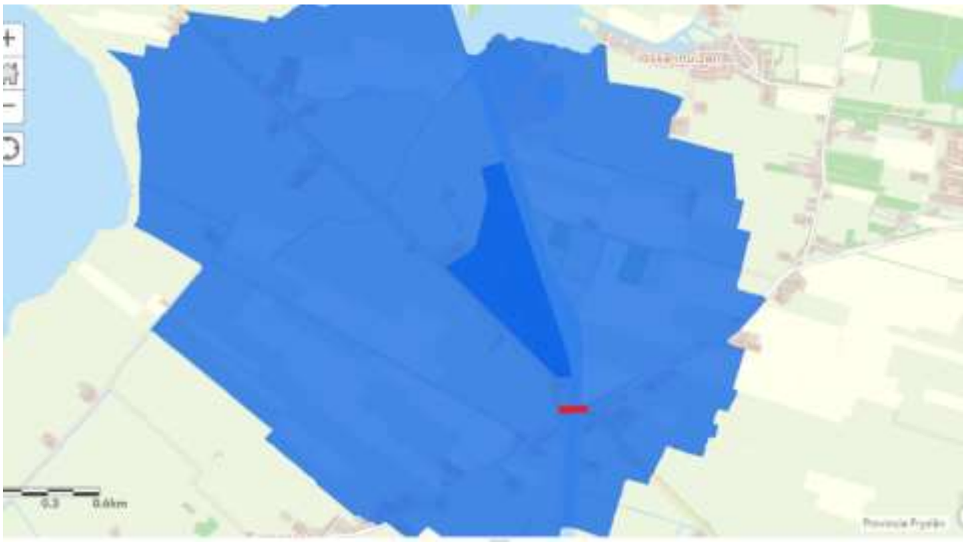


Figure 1-Groundwater and Purification area

1.2. Research questions

In this feasibility study, we investigate different aqueduct construction methods and see what is the optimal method to realize with preserving the clay layer as possible.

What is the best construction method for an aqueduct in Spannenburg ?

- What are the soil characteristics underneath the Spannenburg aqueduct ?
- What are limitations of constructing foundation at the location of Spannenburg?
- What ancient construction methods were used in area ?
- What are the criteria of the best construction method ?

1.3. Scope

The scope of this study is limited due to the short period of the study (10 weeks). Moreover, it is a feasibility study to compare strong and weak points of aqueduct three construction methods. Then choosing the best construction method that can be applied to replace the bridge of Spannenburg. Thus, the study is not meant to make detailed design and structural analysis of the aqueducts rather to make a feasibility study to find suitable construction method.

1.4. Structure of the report

The report is structured into thirteen chapters, each serving a specific purpose in presenting the findings and conclusions of the study. Chapter 2, entitled "Methodology," provides a comprehensive explanation of the methodology employed to address the problem at hand. Chapter 3, "Study Area Overview," offers an in-depth examination of the region under investigation, including its geographic and cultural context. Chapter 4, "Aqueduct Characteristics," provides a thorough examination of the physical and functional properties of the aqueduct. Chapter 5, "Construction Methods," outlines various construction methods applied to the Spannenburg project. Chapter 6, "Construction Site Preparation," describes the preparation process for each construction method applied. Chapter 7, "Comparison Criteria," defines the criteria used to compare the various construction methods. Chapter 8, "Multi-Criteria Decision-Making Analysis," is an application of the decision-making analysis aimed at selecting the best construction method. Chapter 9, "Retaining Wall Design," outlines the design of the retaining wall for the selected construction method. Chapter 10, conclusion of the report. Chapter 11, "Conclusion," serves as the conclusion of the report, followed by the references in Chapter 12 and appendices in Chapter 13

2. Methodology

Figure 2 shows the methodology that is used to accomplish the research aim. Firstly an investigation of the soil type and characteristics is needed to predict the behaviour and engineering properties of the foundation. Then the aqueduct characteristics are defined based on the current bridge in the location, for instance, the number of vehicles and bike lanes. Afterward, the aqueduct is designed based on different construction methods. Finally, the construction methods are evaluated based on environmental consequences, feasibility, and other criteria to suggest a proper construction method for an aqueduct in Spannenburg.

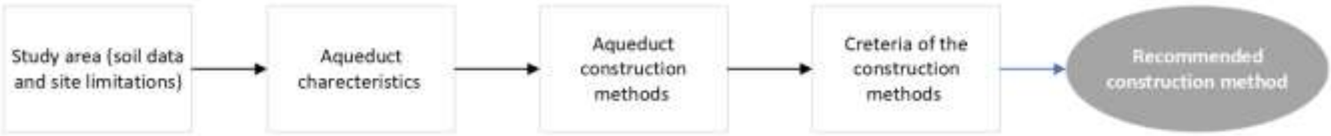


Figure 2-Research methodology

3. Study Area

The lemmer-Delfzijl canal is considered as one of the most important canals in the Netherlands in terms of shipping and sailing sports as it provides navigable connection between the Ijsselmeer lake and the Ems estuary and it also supports the Netherlands as major maritime hub as large ships can bypass the shallow Wadden Sea (Brolsma and Roelse, 2011). Moreover, the canal is popular destination for recreational boaters and sailors as it provides access to the Wadden Sea and the Ijsselmeer lake. It is also used to host sailing events such as the national and international regattas, and for training purposes. In the province of Friesland, the need to provide a seamless passage for boats and ships and to minimize potential traffic disruptions has led to the consideration of replacing the Spannenburg bridge with an aqueduct. Figure 3 gives an overview of the project area. The pushpin indicates the location of the aqueduct and the red area indicates the location of the Drinkwater treatment company. The Prinses Margrietkanal runs along the Spannenburg bridge to the Koevordermeer and it continues over the Prinses Margrietkanal in the A7 at Uitwellingerga to the Sneekermeer.

There is a T-junction on both sides of the new aqueduct, on the west side the N354 crosses the Gaestdyk to Tjerkgaast and Sloten, and on the east side, the N354 crosses the N927 to St. Nicolaasga.

The intensity of the traffic that passes through the bridge is around 7500 vehicles per day (Wegenwiki, 2022). Moreover, next to the aqueduct is a water purification company (Vitens) where the biggest quantity (25 billion liters per year) with best quality in the Netherlands (Vitens, 2022). The design of the aqueduct should be performed in a way that the Lemmer-Delfzijl canal is attainable for vessels of CEMT-class Va which means that the minimum amount of water for this type of ships is 3.5m (Schouwstra, 2019) . In the case of Spannenburg, the water level on top of the aqueduct must be at least 4.9m since international large ships as well pass through the canal.

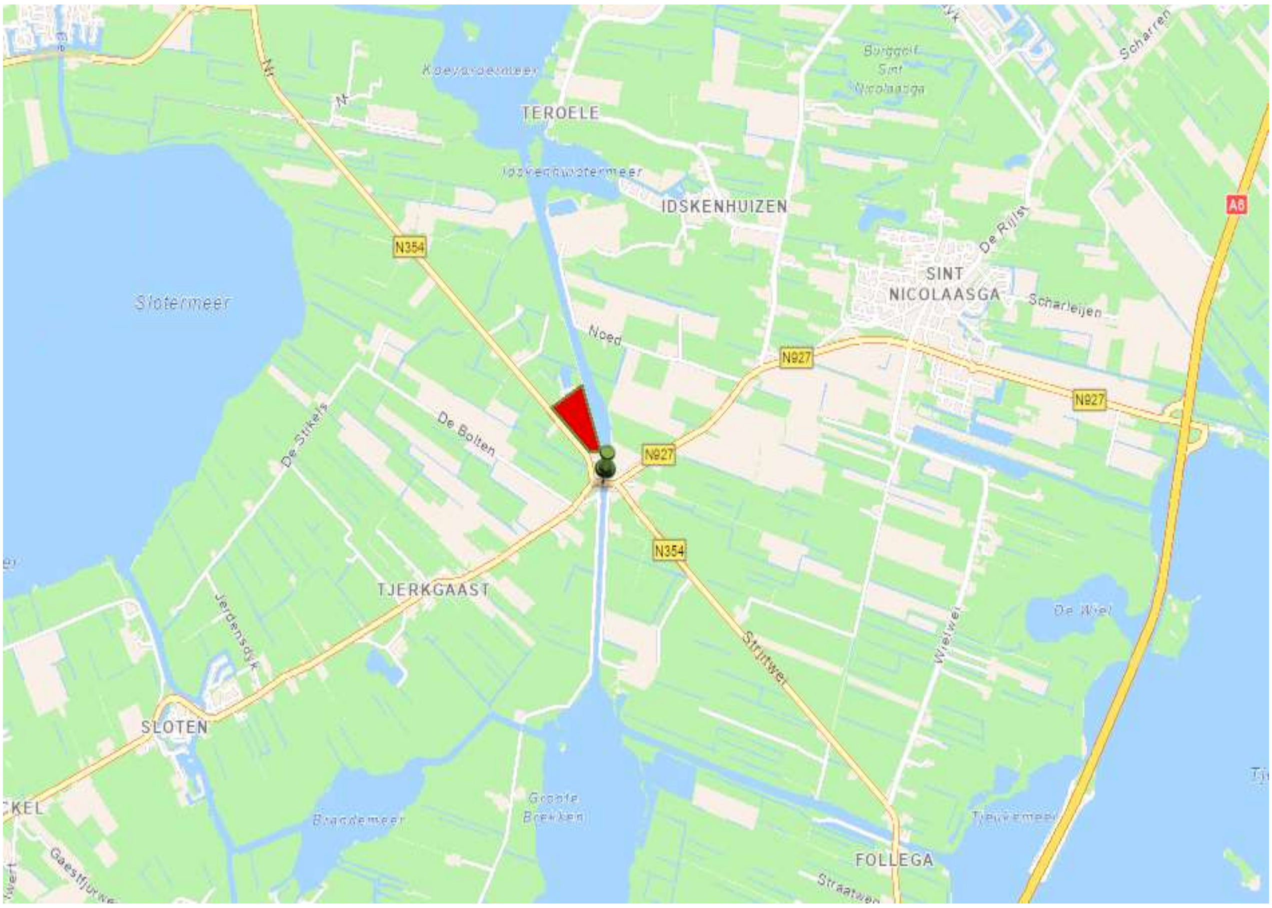


Figure 3-Project area

3.1. Soil profile

Cone Penetration Test (CPTU) is used to identify the soil type; during the test, the cone is put into the ground, and data are collected at regular intervals during penetration (M.Elsami, 2022). This test is the most versatile method of soil exploration; it can identify stratigraphy and materials with their parameters in the ground (R.F.Craig, 2012). The points DKM003, DKM001 and DKM006 shown in figure 4 represent most of the soil characteristics where the closed tunnel is constructed.

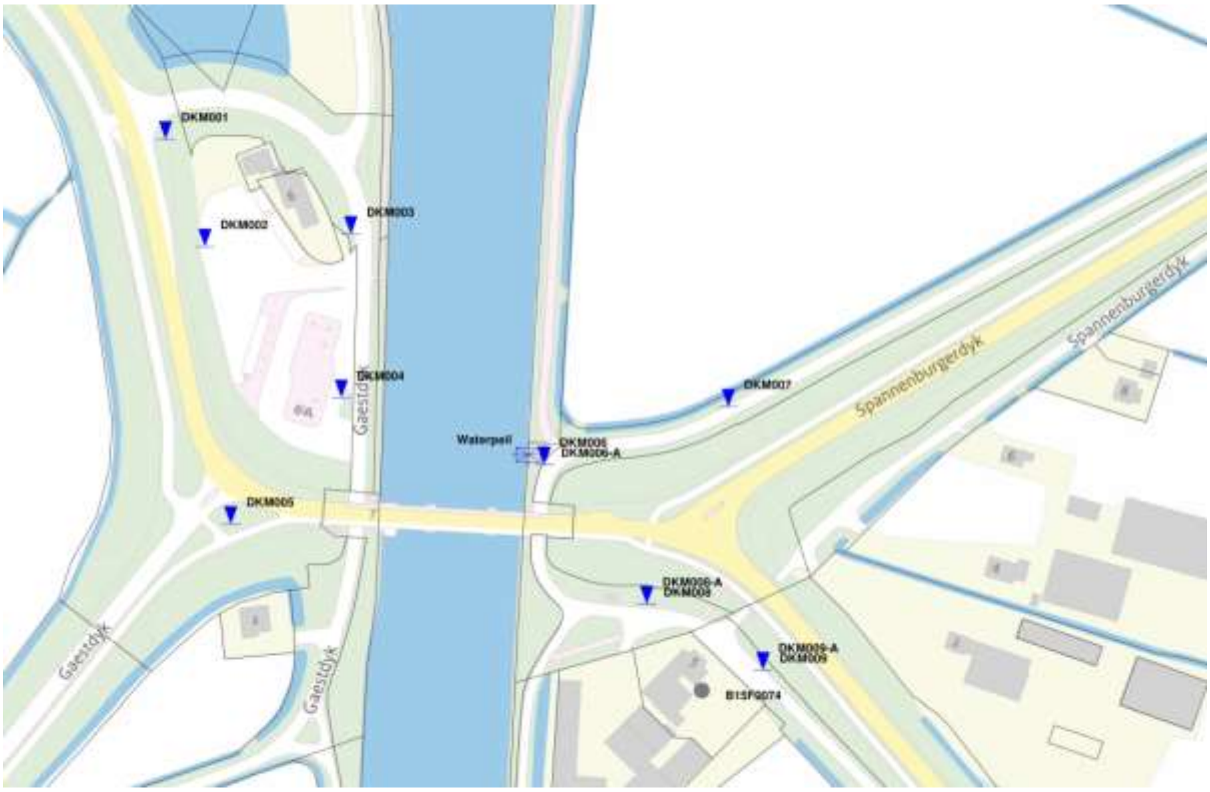


Figure 4-Soil investigated point (Wiertsema & Partners, 2022)

Table 1 shows the results of an investigation about the soil composition in the project location.

Table 1-Soil test results for the project location((Wiertsema & Partners, 2022)

Depth [mNAP]	**Composition of Soil**	**Unit weight [kN/m3]**	**Point**
Ground to - 20,2	Sand	18	DKM001
from -20,2 to -22	clay, silty/lime	16,5	
from -22 to -23,8	clay, little to moderate silt	16	
Ground to -18,8	Sand	18	DKM006
from -18,8 to -21,2	clay, silty/lime	16,5	
from -21,2 to -24	clay, little to moderate silt	16	
Ground to -17,2	Sand	18	DKM003
from -17,2 to -20,2	clay, silty/lime	16,5	
from -20,2 to -23,3	clay, little to moderate silt	16	

More details about the soil parameters of study area are in appendix 12.1.

3.2. Site Limitation

3.2.1. Upward water pressure by aquifer

The aquifer below -19m NAP has been used by the water production company which has been established already and it has been strictly prohibited to damage the confining clay layer where penetration through clay layer can cause contamination of ground water.

In the Spannenburg project, the pressure of aquifer can be challenging during construction stage as it would be a critical issue to be considered in planning stage. It has been identified that negative upward pressure from aquifer at -24m NAP at DKM003, is 211kN/m^2 (Wiertsema & Partners, 2022). Negative pressure has been counterweighted by the overlaying soil layers, where resulting pressure gradient will be downward with an amount of 155kN/m^2. But with excavation for construction works, downward earth pressure will be gradually removed decreased depending on the depth of excavation. Furthermore, it has been uncovered that maximum depth of excavation without exposing the confined aquifer by rupturing the confined layer and contaminating the ground water is -10.2m NAP (Wiertsema & Partners, 2022).

Deeper the structure goes,extra measurements to be taken to achieve necessary stabilization of soil otherwise it will not be feasible to excavate deeper than -10.2m NAP without extra measurements to be taken. Therefore, adhering to the issue with technically and environmentally feasible solution is one of major challenge that the project requires to be faced from planning stage.

How to prevent the clay layer bursting ?

Grouting involves injection of a liquid or suspension under pressure in to the voids of soil layers underground. The injection material eventually solidifies and fills the voids of the soil or rock, improving bearing capacity of soil as well as greatly reducing the permeability of layer, preventing ground water seeping upward. For the improvement of soil including aquitard clay layer, cement/chemical grouting methods are suggested as those methods are proven useful in improving permeable and alluvial soils for tunnelling (GDI, 2021). Particulate grouts such as cement based grouts, chemical grouts such as water glass, compaction grouts such as low slump concretes are commonly utilized for the purpose of enhancing soil properties. By grouting the subsoil, it is expected to achieve (Monsees, 2004);

- Strengthen loose or weak soil and prevent cave-ins due to disturbance of loose, sensitive, or weak soils by the tunnelling operation
- Decrease permeability and groundwater flow
- Subsidence effects of dewatering or to prevent the loss of fines from the soil
- Stabilize sandy soils that have a tendency to run in a dry state or to flow when below the water table.

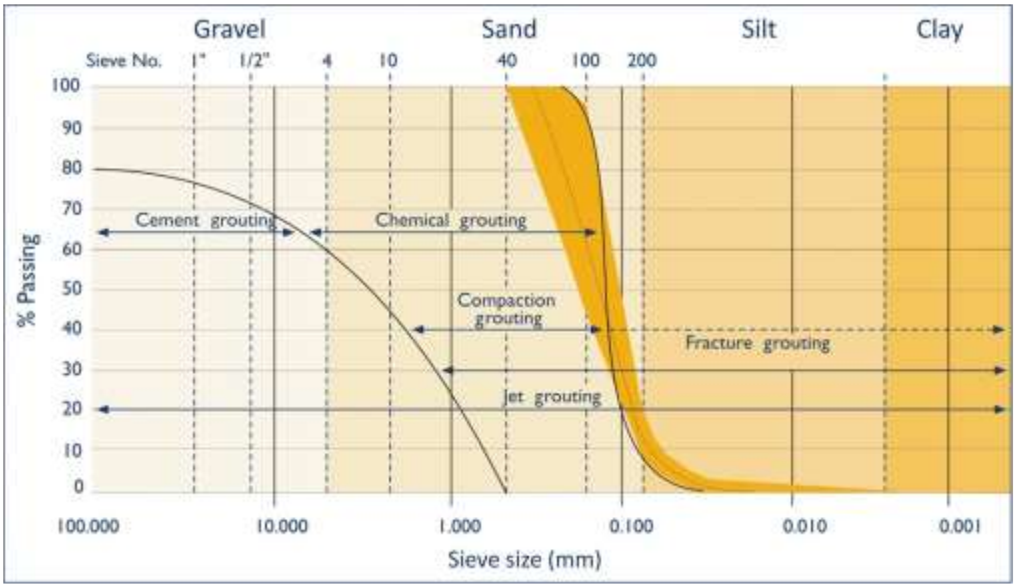


Figure 5-Soil gradation applicable for different grouting methods (Nicholson, 2015)

From above mentioned type of grouts, a suitable type of grout has to be used to improve the sub soil under the excavation area in order to prevent burst opening of ground due to artesian pressure.

It is already known that soil strata underneath the tunnel section is sandy soil (3.1) therefore according to above figure 5, chemical grouting method should be utilized for the project to enhance the properties of sand. Chemical grouting will use permeation action to fill the voids of sand soil and it hardened through chemical reactions, creating a 3D dense structure. There are no particulate solids in suspension. As such, chemical grouts may be able to permeate into finer soil gradations (medium to fine sands and silty sands) and that is an advantage based on the soil type in Spannenburg. Sodium silicates and acrylate gels are some of the most utilized chemical grouts materials for hydraulic barriers, and provide "modest performance at modest cost" (Nicholson, 2015). Use of chemical grouting to prevent artesian pressure has been used several times as there are several evident case studies; it has been stated by (Nicholson, 2015) that In Dearborn, MI, chemical grouting was used to prevent artesian inflow into two sewer shafts. Acrylamide permeation grouting was used in the contact soils, while a combination of acrylamide and traditional cement grout was used in the underlying bedrock. Furthermore, in Dworshak Dam, Idaho where increased seepage flows of groundwater encountered in foundation excavation (19000 L/min) was prevented by creating a grout curtain, which eventually stabilized the ground water seepage issue.

Choice of material and method has to be decided up on soil permeability amongst many other parameters such as percentage of fine particles and particle size distribution of soil (Monsees, 2004). Therefore, in order to reduce permeability of soil below -10.2NAP, this report suggests usage of chemical grouting due to sandy soil, while using grouting agent of sodium silicates. However further geotechnical investigations have to be carried out to decide the grouting parameters such as depths. Since this report covers pre-design stage where feasibility of the methods is assessed, this report does not cover the detailed design of grouting. With proper parameters, the geotechnical design for grouting to improve water tightness of the soil below -10.2NAP can be achieved.

3.2.2. Clay layer at -19m NAP

As outlined in the problem statement section, the construction of any deep structures within the vicinity of Spannenburg is prohibited, unless a compelling justification can be provided to demonstrate that the proposed structure will not negatively impact the groundwater resources in the area or penetrate the clay layer (-19m NAP) to a depth greater than one meter. This is illustrated in Figure 6, which depicts the depth of the sealing layer. Each circle in the figure represents a survey point, with the location of the top of the sealing layer indicated in meters relative to the Normal Amsterdam Peil (NAP).

Figure 6-Sealing layer depth (Wiertsema & Partners, 2022)

Figure 7 shows the thickness of the sealing layer in the location of Spannenburg. Each circle represents a survey point, for which the thickness of the top of the sealing layer is indicated in metres.

Figure 7-Sealing layer thickness (Wiertsema & Partners, 2022)

The second site limitation is approached by introducing different construction methods for the aqueduct and that is depicted in chapter 5.

4. Characteristics of the aqueduct

As mentioned in the scope section, this research aims not to design an aqueduct but to find an approach to construct the aqueduct considering the site constraints. Therefore, the dimensions of the aqueduct are estimated based on similar aqueducts with similar requirements, such as the number of lanes. Thus, firstly the aqueduct will have two lanes, cycle path ,sidewalk and gutter with the following dimensions.

- Two step barrier = 2× 1.35=2.7m
- Two lanes =3.1 × 2
- Bike lane and Side walk =4.25m
- Median (vehicle lane-to-vehicle lane)=1.2 m
- Median (vehicle lane-to-bike lane)= 0.4m
- Tunnel length =60m

Figure 8 shows the cross-sectional dimensions of the required aqueduct.

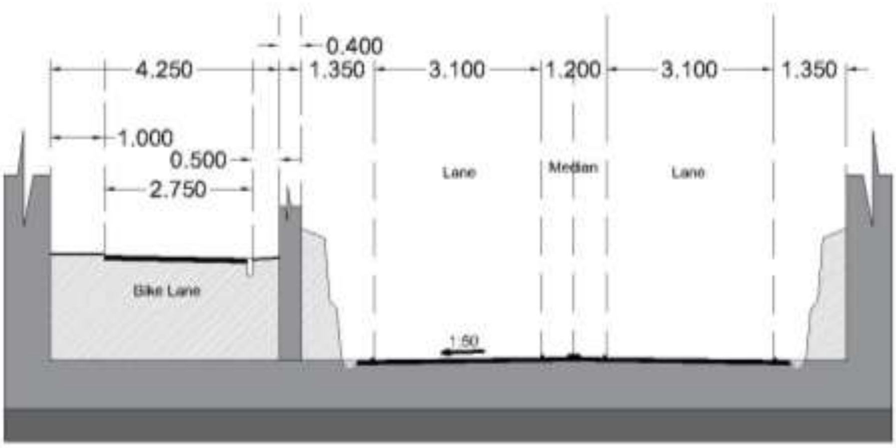


Figure 8-Aqueduct cross section

5. Construction Methods

This sections gives an illustration about the application of three construction methods in Spannenburg inspired by previously constructed aqueducts in the area. Moreover, it gives a brief overview about loads, characteristics and properties of the aqueduct in each method. MATLAB software is used for dimension optimisation. In this chapter the design for the tunnel is investigated and the construction site preparation for each method is discussed in the next chapter.

Notes : The units used in the figures are in meters and the third dimension is always 1m in all calculations.

5.1. Eared(cut and cover) construction method

In-situ construction of the tunnel where the design includes ear-like structural extensions from sections, which are designated to add favourable loading to the structure to overcompensate the buoyancy forces. The process is a derivative of conventional cut and cover tunnelling. The processes included in these methods are, dewatering where necessary at the initial stage, install ground support system, excavate the subgrade to desired level and transportation to disposal, Construction of structure, waterproofing, back filling and finalizing the finishes (Wilton, 1996). Applying this method to the Spannenburg situation has pros and cons as it is explained in the following chapters. This sections demonstrates an application of this type of tunnels in Spannenburg is conducted.

5.1.1. Eared aqueduct optimisation

The dimensions of the tunnel including length of the ears are estimated and optimised based on the uplifting buoyancy force resulted from the water pressure. Figure 9 the optimised dimension of cross section of the tunnel and the five major forces acting on the tunnel namely ; hydrostatic force, soil force , water weight and aqueduct material weight respectively.

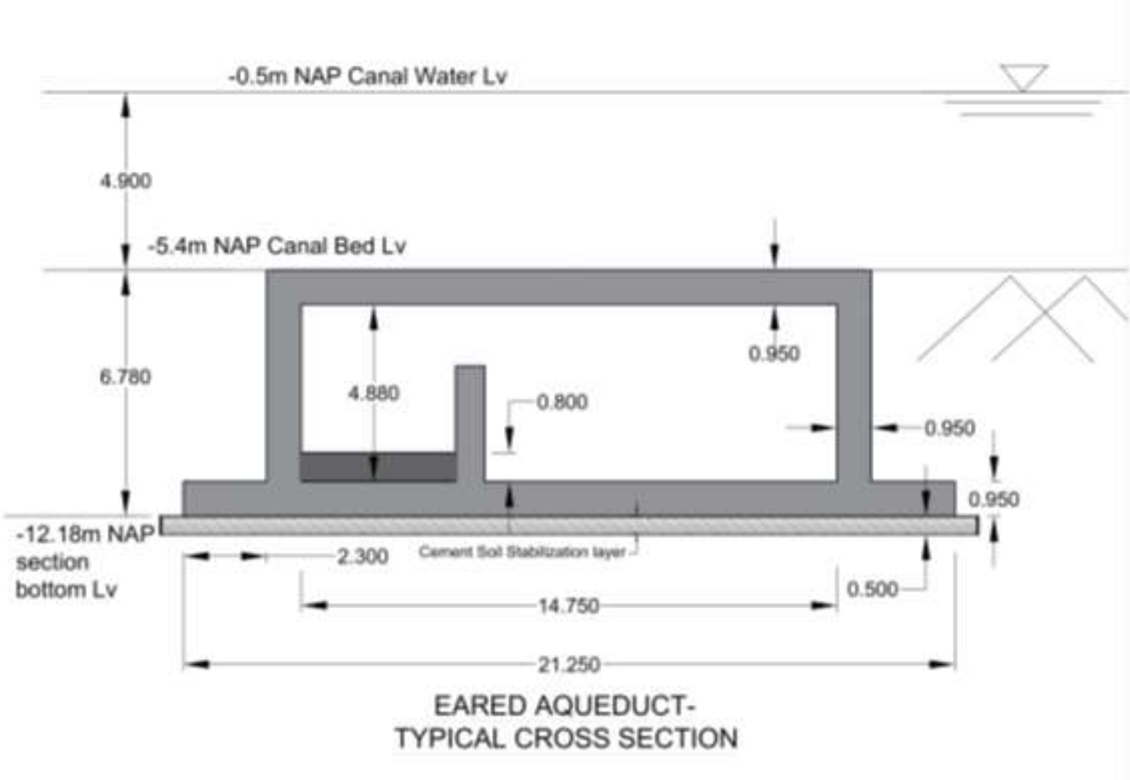


Figure 9-Optimised eared tunnel

5.1.2. Equilibrium Forces and characteristics of aqueduct

The uplifting buoyancy force of water with load factor of 1.1 as unfavourable load

$F_b = 2756kN/m$

Force of concrete including ballast with Safety factor of 0.95 for favourable loads

$F_{cocnrete} = F_{material} + F_{asphalt} + F_{ballast} = 1324kN/m$

$F_{w(down)} = 989.2kN/m$

$F_s = 458.6\ kN/m\ for\ both\ ears$

$F_{sum} = 2771.9 - 2756 = 15.9\text{kN/m downwards}$

Figure 10 depicts the free body diagram of the eared method.

The step-by-step calculation and the values of each parameter is done by MATLAB in *appendix12.2*.

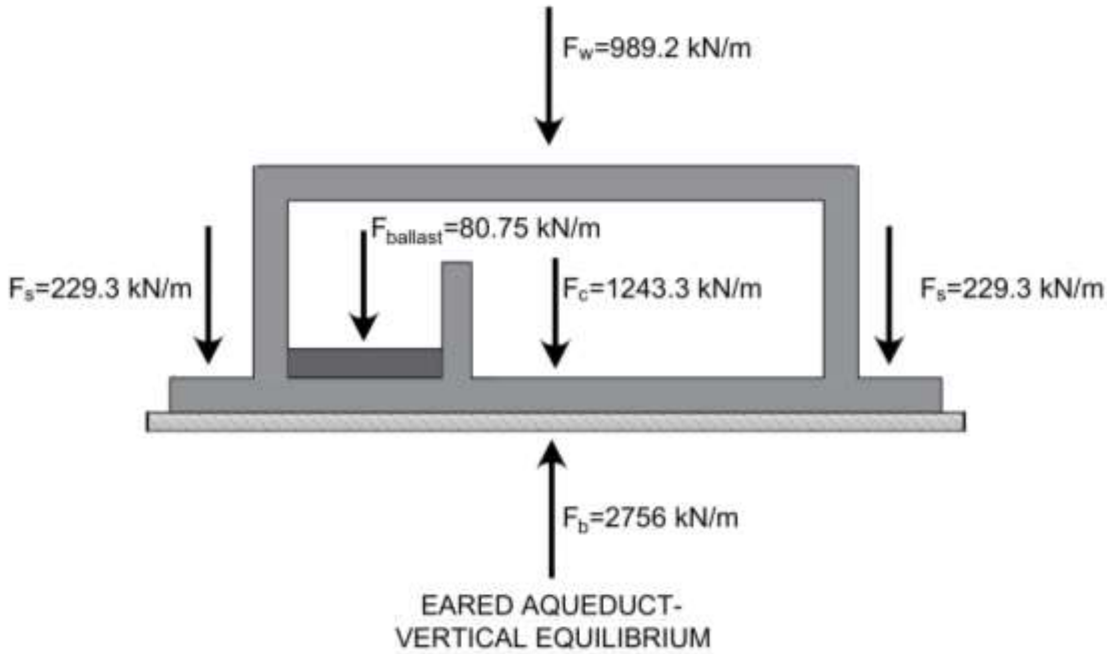


Figure 10-FBD for the eared tunnel

Table 2 shows the characteristics of the aqueduct.

Table 2-Characteristics of the Spannenburg eared aqueduct (Updated)

Characteristics	Value
Amount of concrete area material per meter	51.17m^3
Ballast concrete (only asphalt layer 0.08m)	1.18 m^3
Depth of the structure	-12.18m NAP
Ear length and thickness in m	2.3m *0.95m
Soil Removal width for tunnel	21.25m
Soil removal for working space	2.5m
Soil backfilling area for both ears	5.83m*2.3*2
Cemented Sand layer backfilling under the tunnel	0.5m
Safe for the clay layer	Yes

5.2. Immersed construction method

Immersed tunnels have become one of the main methods for constructing long tunnels across rivers or seas(Zhou *et al.*, 2022). In this method the tunnel is constructed in a dry dock area and then being floated to the right place in the canal using 'Ballast water system ' to control the total weight of immersed tunnel elements in the processes of sinking(Zhou *et al.*, 2022). The elements of the tunnel are prefabricated on shore and then brought to the tunnel trench. In the case of long tunnels, the elements are brought one by one and connected together. The elements can be constructed nearby the project location in a dry dock as seen in figure 11. Moreover, selecting a location to establish worksite will pose several challenges to designers as;

- The dry dock should be accessible to tunnel's location with deep enough waterways where the sections can be submerged, floated and dragged to required location. Obstacles such as bridges where piers can be obstructive to transporting the sections, narrower sections where the flow is too turbulent and man-made structures such as weirs should be avoided.
- Dry dock should have access to easy transporting of material, machinery, equipment and all the other requirement for the special construction project.
- Mechanisms for draining and pumping out water from the dry dock basin, pumping back water in to the basin at required flow rates and retaining the water for required time periods where the sections are floated and transported out should be installed. In order to secure the basin walls, sheet piles can be utilized as in shoring works, where active earth will be retained while effect on nearby high-water table also repelled by preventing seepages.

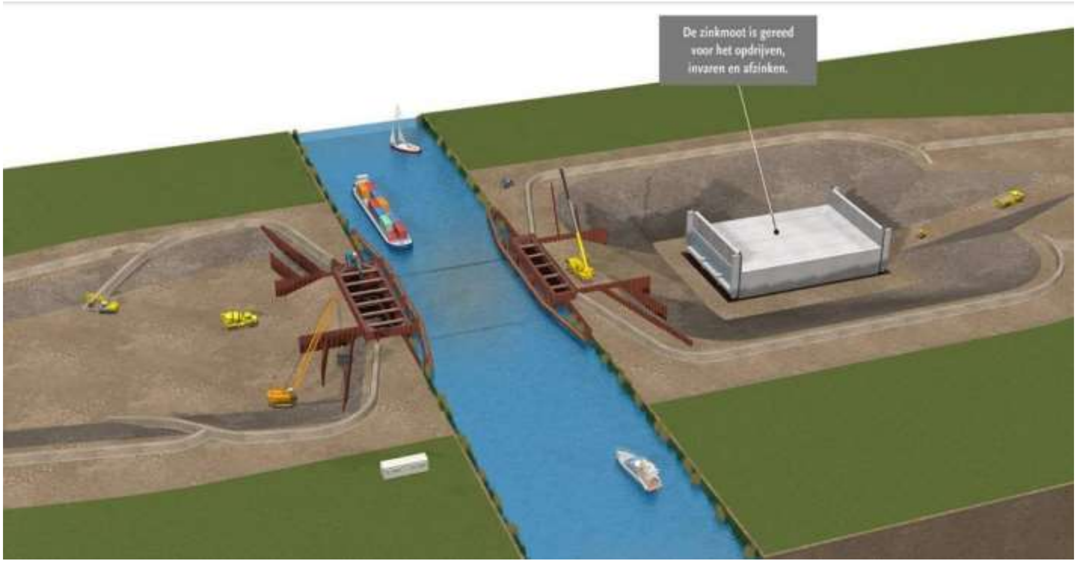


Figure 11-Immersed tunnel ((Boskalis, 2014)

Once the aqueduct elements are constructed, then the dry dock is filled with water as shown in figure 12 so the aqueduct is then floating up to be transported to the right place.

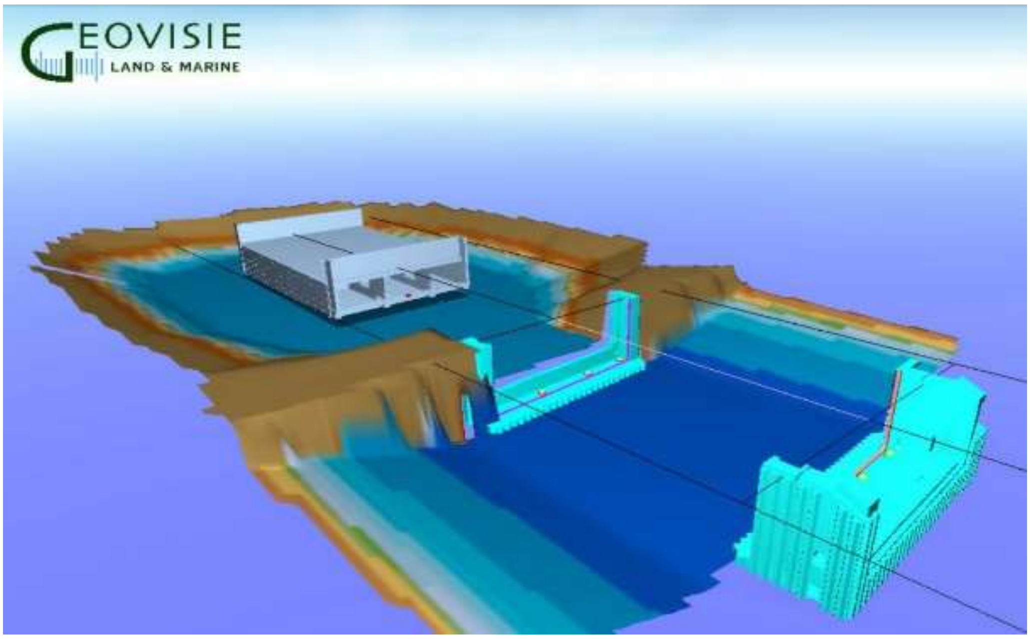


Figure 12-Sinking the tunnel (Geovisie, 2014)

In this method, the ballast water system helps the aqueduct to sink and overcome the uplifting forces to prevent floating. Once the tunnel is moored, it is connected to the side columns built on the river's edge. Ballast tanks are symmetrically distributed alongside the aqueduct and get supplied with water and discharged using pipelines and a remote control system to receive and send information during the immersing process*(Zhou et al., 2022).*

The steps of immersing the tunnel are briefly explained as follows:

- First, the aqueduct structure elements are completed in the trench in one side of the canal where the aqueduct is then positioned .
- Floating up the aqueduct by filling the construction site with water.
- Floating the aqueduct to the right place in the canal. Suspension wires are used to control the lowering speed and the attitude of the aqueduct and the winch anchoring controls the position of the aqueduct.
- To make the aqueduct heavier and sink it to the bottom, the tube tanks are filled with water.
- The water weight is compensated with concrete weight so the aqueduct has sufficient negative buoyancy force ,knowing that 1 cubic meter of concrete is 2500 kg and one cubic meter of water is 1000 kg thus each 2.4 cubic meter of water is replaced with one cubic metre of ballast concrete.
- Once the sufficient water is provided synchronously , the aqueduct is connected to the foundation on the dry area in both sides of the canal. Then, Removing the water tubes after casting the concrete.
- Lastly , the sand flow operation starts to construct the foundation bed of the aqueduct as shown in figure 13. After completion of the sand flow operation, the jacks were released and the element was set down on the created sand bed, after which locking fill and back fill to the sides of the element within the dredged trench could start

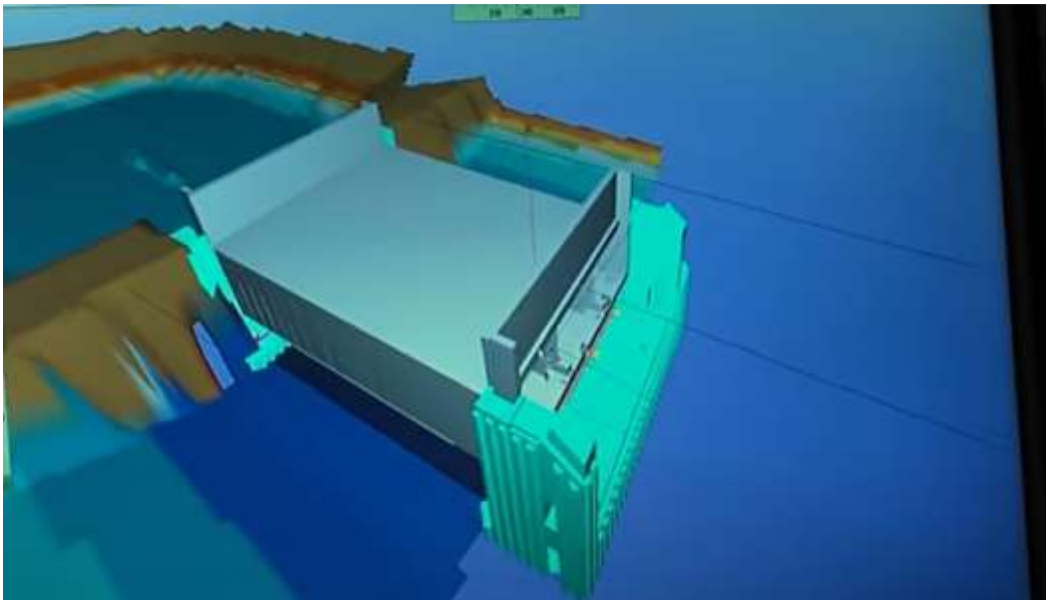


Figure 13-Positioning the tunnel (Geovisie, 2014)

5.2.1. Immersed aqueduct optimisation

Figure 14 shows the final optimised tunnel dimensions of the cross section and the forces acting on the tunnel respectively. There are vertical forces acting on the aqueduct namely; materials weight , ballast concrete and the buoyancy force.

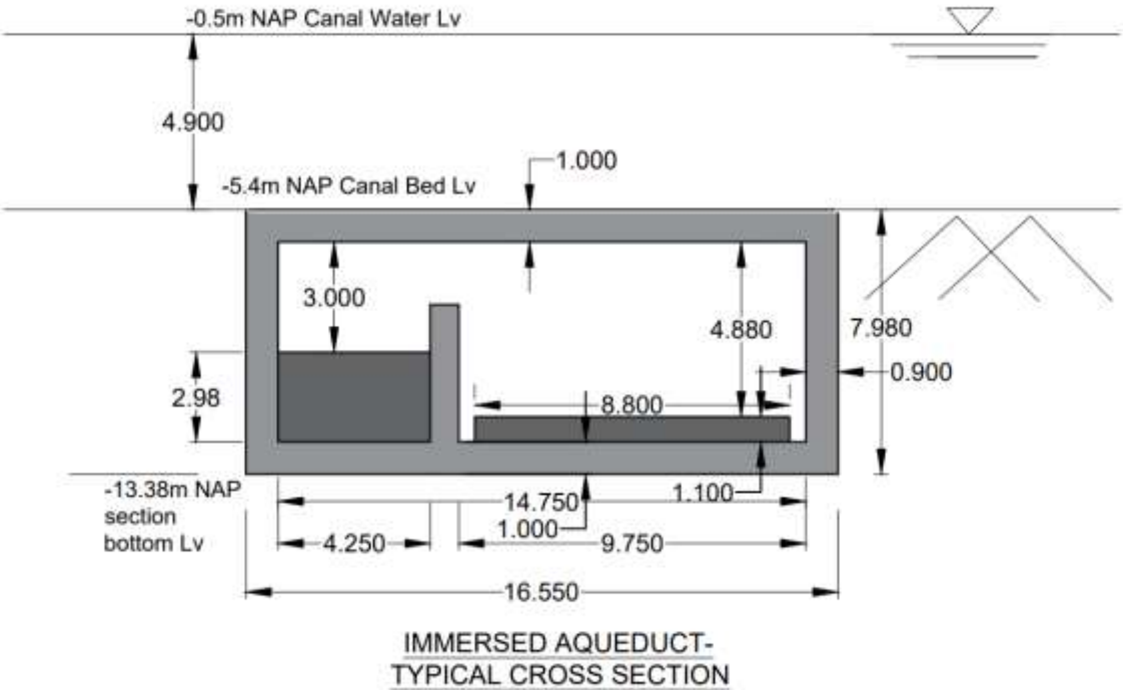


Figure 14- Optimised immersed tunnel

5.2.2. Equilibrium of forces and characteristics of

Using Safety factor (0.95)

$F_{down} = 2407kN/m$

Using Load factor (1.1)

$F_{w(uplift)} = 2345KN/m\ Upwards$

$F_{sum} = 2407 - 2345 = 62KN/m\ downwards$

Figure 15 shows the Free body diagram of the tunnel and table 3 shows the characteristics of the immersed tunnel. More details about the calculations and values of each parameter are in appendix 12.3.

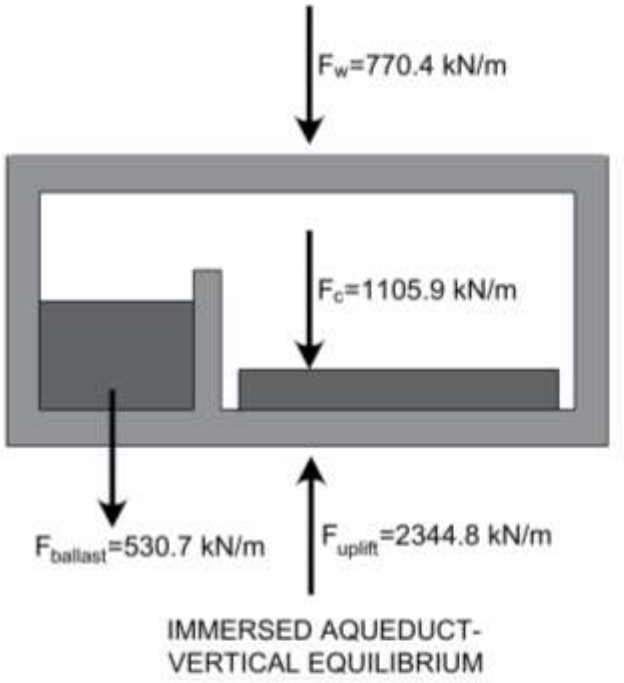


Figure 15-FBD immersed tunnel

Table 3-Characteristics of the Spannenburg immersed aqueduct

Characteristics	***Value***
Amount of concrete material per meter including Asphalt	*46.56m^3*
Ballast concrete	*22.4m^3*
Soil dredging width for sinking the tunnel	*16.55m*
Structure height	*7.98m*
Structure Depth	*-12.78m NAP*
Safe for the clay layer	*Yes*

5.3. Piled-Raft construction method

Pile foundations are commonly used solution for buildings constructed in areas with weak soil conditions or hight groundwater levels which can result in differential settlement and cause the structural raptures (Basilen, 2013). Piles are cylindrical structural elements in the ground to transfer the load of a building to deeper and stronger soil layer or rock stratum. Piles are usually made of steel or concrete and are designed to resist both compressive and uplift forces generated by water pressure. When designing pile foundations to resist water pressure, engineers consider factors such as the water table level, soil type, and load capacity of the piles(El-Reedy, 2015). To further enhance the resistance of pile foundations to water pressure, engineers may use grouting techniques to fill the annular space between the pile and soil with a flowable material such as concrete. The design of pile foundations must consider various factors such as soil type, water table level, and load capacity to ensure that the piles can resist the forces generated by water pressure. Grouting techniques can further enhance the resistance of pile foundations to water pressure (Meyerhof, 1976).

Moreover , In the case of Spannenburg, to design the piles , first the location soil type is defined (Section 1.3) then considering the Dutch soil Standards (NEN2012) to define other parameters of the soil such as the undrained shear strength $C_u=100kPa$.

Raft foundation

In Spannenburg there is a high water levels thus the piled-raft foundation system is needed. A study by (Venkatraman, et al., 2021) found that the use of a raft foundation increased the stability and longevity of pile foundations in areas with high water tables. A raft foundation is a type of shallow foundation that spreads the load of a structure over a large area. By connecting the superstructure to the piles through a raft foundation as shown in figure 16, the settlement and water pressure are distributed over a larger area, reducing the load on individual piles and increasing the stability of the overall foundation system. Moreover, there have been several studies and research papers that have investigated the effectiveness of raft foundations in resisting settlement and water pressure. For example, a study by (Gamage *et al.*, no date) found that raft foundations significantly reduced the settlement and water pressure on piles compared to when piles were used alone. Figure shows the combination of the piled-raft foundation system.

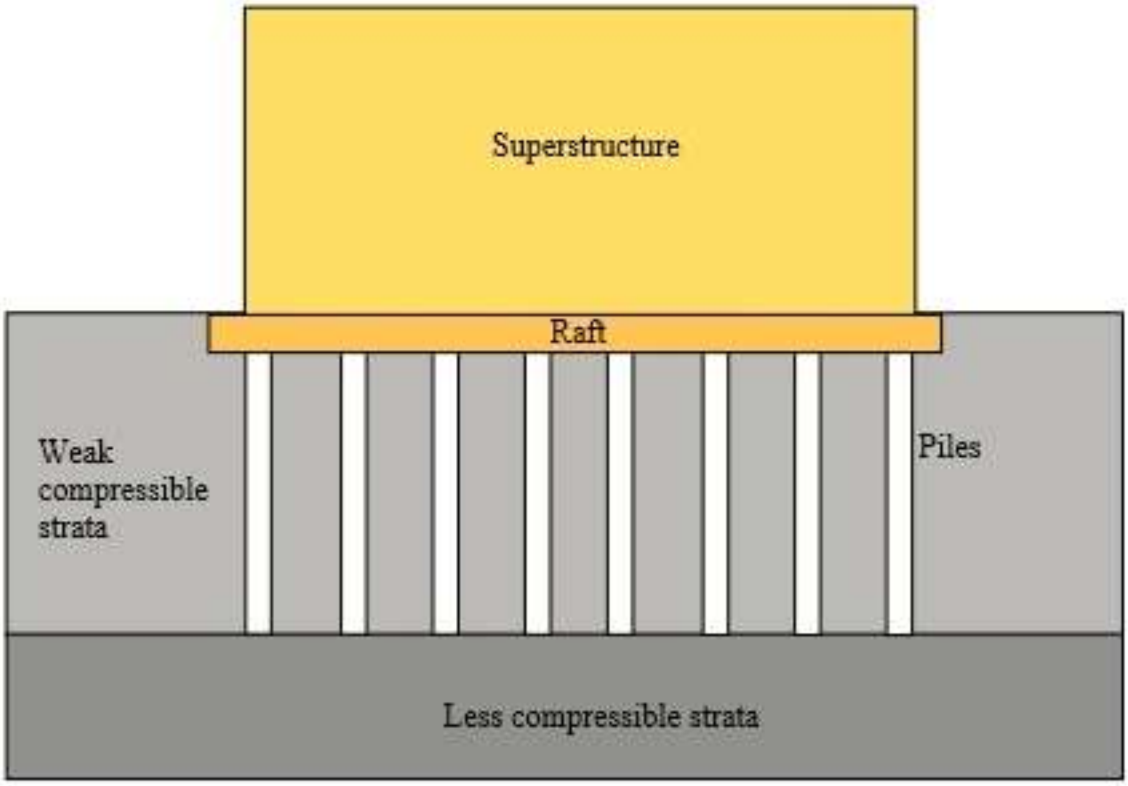


Figure 16-Piled-raft foundation system (The construction wiki, 2022)

Grouting or Replacing

The Spannenburg project geotechnical data states (Section 1.3) that the soil strata available is sandy, where it will act weaker in bearing impacts. Following two methods are proposed as piled foundation design in order to bear upward pressure;

1. Constructing grout piles where sub soil is improved using appropriate grout to enhance the friction interactions of the pile surface (figure 17).
2. Excavating and removing the soil in subjected area, to replace with soils having angle of friction which is adequate for providing required skin friction.

Due to preservation of -19NAP clay layer, excavation of larger areas will not be feasible as the reduction of overburden pressure can cause burst opening of clay layer due to upward pressure by confined aquifer. However, grouted piles, which are widely used for construction of underwater structure foundations, specially in offshore areas has been proven very useful for scenarios as like this (Ehlers & Ulrich, 1977). In the method, large area excavations are not conducted, only required positions are bored using a drilling rig to a diameter which is larger than the steel pile diameter. Usually the difference between the pile to bored diameter is kept at 75mm to ensure proper bonding between ground and soil, also grout and pile (Kraft & Lyons, 1974).

Grout shall consist of a stable colloidal suspension of cement, bentonite or other additives in water. In special cases where enhancing the frictional resistance further, fine sand particles also added to the grout (Nicholson, 2015). The soil-pile interface is to be enhanced with higher frictional resistance by grouting the soil with pile together. However, the grout utilized should have special properties to successfully achieve the desired level of frictional resistance increment. Moreover, in order to prevent shrinkages of grout due to hardening and losing the contacts between pile-grout interface and grout-soil interface, suitable shrinkage resistant or expansive agent should be used in cement suspension, in order to make the grout expand while hardening.

Type of Pile

For the Spannenburg construction project, steel piles with circular cross sections are used in the to bear the uplifting water pressure, moreover the piles are expected to develop adequate skin friction in order to achieve that. Conventional impact driven piles will damage the existing soil strata specially the clay layer situated in -19NAP and due to existence of sandy soil throughout the length of the pile, conventional cast in situ piles will not generate adequate skin friction to resist uplift forces. Figure 18 shows a typical grouted pile.

Therefore, it is proposed to go for grouted piles where special cementitious grout is used to enhance the cohesion and shear strength of sandy soil near the pile by applying pressurized grout in order to penetrate the cavities and pores in the sandy soil to strengthen the interaction capacity of soil-pile interface. Installation process will be as following (Kraft & Lyons, 1974);

- A hollow pile, which has a larger diameter than the insert pile is driven to ground and soil within the hollow pile is removed by airlifting, drilling or any suitable method.
- Insert pile, which will be used to bear the loading from structure is lowered to the hollow pile, centring and levelling is kept at accurate level.
- The casing will be removed as the grout is placed inside of the annulus between insert pile and bore hole.

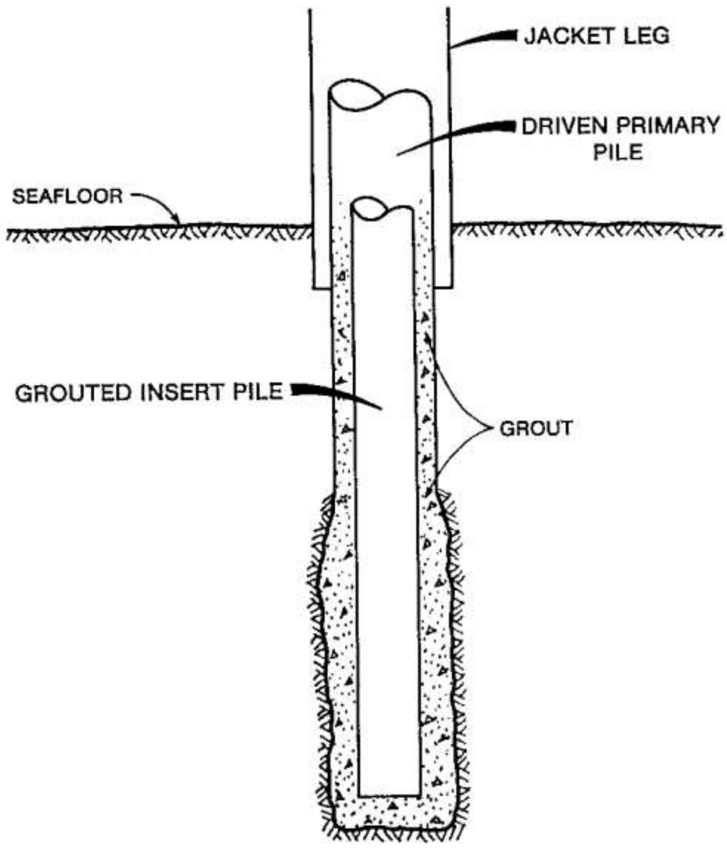


Figure 17-Typical offshore grouted pile (Kraft & Lyons, 1974)

5.3.1. Optimised piled-raft aqueduct

Figure 18 shows the final product of the piled-raft construction method for the case of Spannenburg.

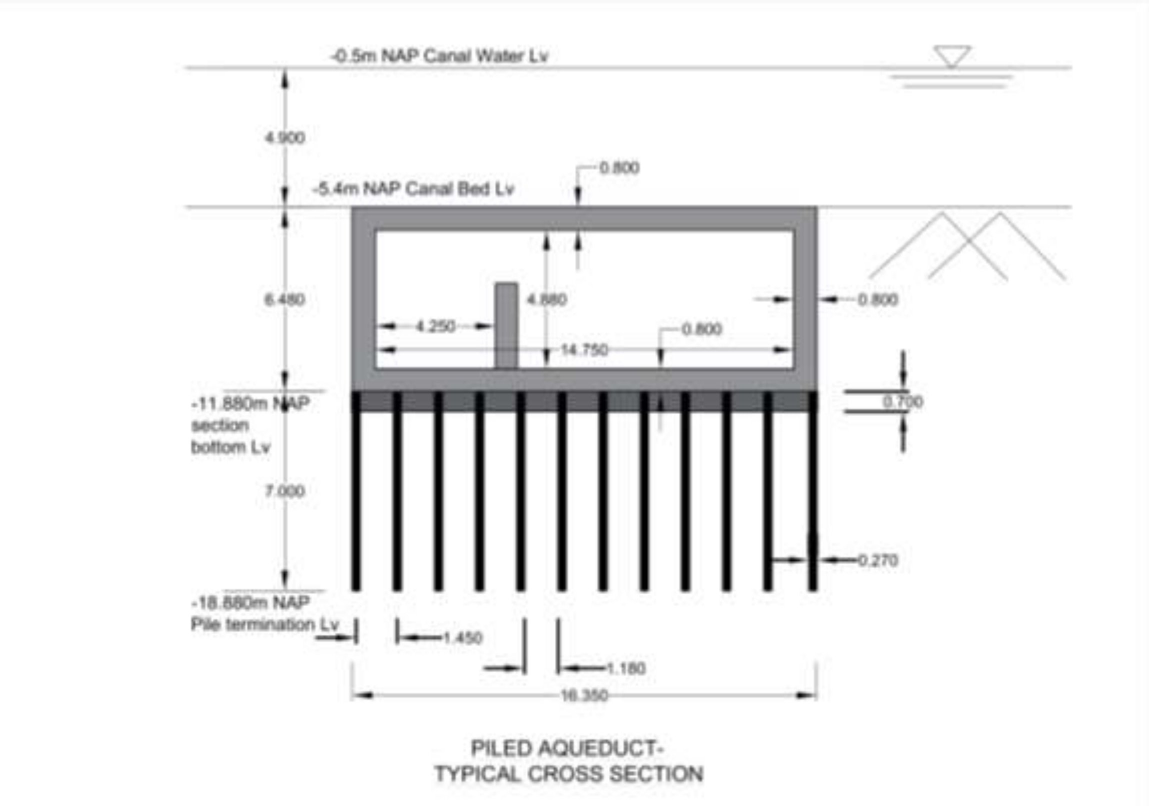


Figure 18-Optimised piled-raft tunnel

5.3.2. Equilibrium forces

Upon initial analysis utilizing MATLAB to determine the forces without incorporating the use of piles, it was determined that the resultant force exerted was 268.1kN/m in an upward direction. As a result of this finding, it was necessary to introduce the use of piles in order to mitigate this difference. Figure 19 shows the free body diagram of the aqueduct.

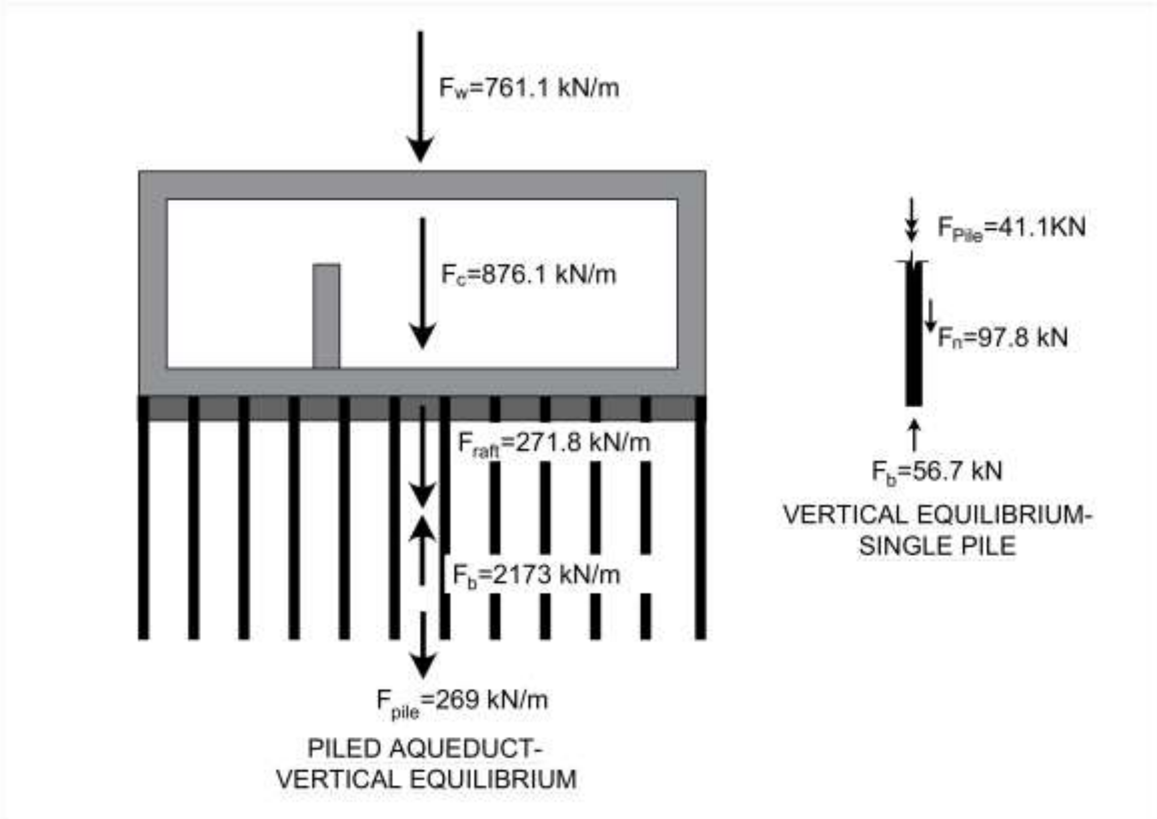


Figure 19-FBD for the piled-raft method

Downward forces using safety factor (0.95)

$F_{downward\ total} = 1904.5\ kN/m\ downwards$

Upward forces using load factor (1.1)

$F_{upward} = 2172.6\ kN/m\ upwards$

$F_{sum} = 1904.5 - 2172.6 = 268.1\ kN/m\ Upwards$

Appendix 12.4 gives more details about the calculation of forces.

Pile forces and required number of piles

$F_{upward} \; = \; 268.1 \; kN/m \; upwards$

The value (0.95) is used as load factor for calculating the negative skin friction (*Fn*) and 1.1 as load factor for the end bearing capacity (*Fb*)

$F_{pile} = Fn - \; F_b = 97.8 - 56.7 = 41.1 \; kN/$m as shown in figure 19.

More details about the calculations of forces is in appendix 12.4.1.

$$Total \; uplift \; force \; on \; aqueduct \; = 2155 - 1933 = 268.1 \; kN/m \; upwards$$

$$Total \; length \; of closed \; aqueduct = 60 \; m$$

$$Total \; uplift \; force \; on \; whole \; aqueduct \; = 60 * 268.1 = 16086 \; kN$$

$$Downward \; force \; from \; single \; pile = 41.1 KN/pile$$

$$Required \; number \; of \; piles = \frac{Total \; uplift \; force \; on \; whole \; aqueduct}{Downward \; force \; from \; single \; pile} = \frac{16086}{41.1} \approx 392 piles$$

When we consider the 12 pile group (12 piles in 16.35m width)

$$Distance \; between \; center \; \; of \; piles \; = \frac{16.35 - 0.27}{12 - 1} \; \approx 1.45m$$

$$Required \; number \; of \; pile \; groups = \frac{392}{12} \approx 33$$

$$Distance \; between \; center \; of \; the \; pile \; groups = \frac{60 - 0.27}{33 - 1} \; m \approx 1.86m$$

As depicted in Figure 19, it is clear that the introduction of piles has effectively balanced the forces of uplift and downward compression, as they are relatively similar in magnitude. This outcome can be attributed to the fact that the design of the piles is based on the difference between the upward and downward forces, thus the two forces are not vastly disparate. Pile characteristics are shown in table 4.

Table 4-Piled aqueduct characteristics

Characteristics	***Value***
Amount of concrete material for tunnel per meter(asphalt included)	*49.32m^3/m*
Ballast concrete	*0m^2*
Raft foundation thickness	*0.7 (Rule of thumb)*
Soil excavation width for structure	*16.35m*
Soil excavation height for tunnel	*6.48m*
Soil excavation width for shoring work	*2.5m*
Structure depth	*18.88*
Clay layer clearance from structure	*0.12m*

Safety for the clay layer	*Very low*
Pile diameter	*0.27m*
Pile length	*7m*
Type of piles	*Grouted steel piles*
Number of piles	*392*
Piles in one group (cross-section)	*12*
Distance between pile centres	*1.45m*
Distance between pile groups	*1.87m*

6. Construction Site Preparation (shoring works)

In order to facilitate dry working conditions for commencing the construction processes for eared aqueduct construction method and piled aqueduct construction method, a shoring system will be required. Furthermore, the dry dock basin on immersed aqueduct construction method also requires shoring. A shoring system is a temporarily lateral earth support system, which allows excavation of a neat area without failure of earth. Therefore, it ensures the safety of equipment, workers and machinery from sudden failures of earth. In the case of Spannenburg project, the excavations are needed to be done under the canal, therefore dry spacing should be provided to facilitate excavation, which can be achieved by shoring the required area. There are several techniques in shoring construction;

- Solder piles and lagging
- Steel sheet piles figure(20)
- Diaphragm walls
- Soil-cement mixing walls

Many of above-mentioned shoring constructions are related to in-situ casting or treating soil. But for the case of shoring under water at the initiation of construction stage, soil under the canal is inaccessible. Therefore, most suitable shoring method will be using steel sheet piles. Steel sheet piles can be transported to location and driven to desired depth, creating a shoring around the required perimeter. Special interlocking mechanism of sheet piles allows it to be interconnected with abysmal seepages through joints, which can be sealed off. Moreover, sheet pile shoring would be very advantages to the project as driving it to directly to clay layer will significantly reduce water seepages by lowering the water table inside of shoring from the canal in to working area as it cuts off the water seepage paths when touched the clay layer.

Figure 20-sheet pile used in Galamadammen aqueduct ((Wiki, 2022)

6.1. Shoring system for eared tunnel

Once the soil is improved and grouted to prevent bursting of the clay layer as mentioned in (section 3.2.1), eared aqueduct requires a shoring system that would be providing adequate clearance of area for constructing the tunnel. For the Spannenburg project, proposed eared aqueduct section has a width of 21.25m alone for the structure, furthermore in providing workspace for construction works require at least 1.25m of clear space each side, makes a requirement of shoring a 23.750 m width along the proposed alignment. Steel sheet piles can be used for the project, but with higher water table and lateral water pressure by surrounding area poses a risk of failure of shoring system, therefore proper anchorage has to be provided using grouted anchors or any suitable method. Furthermore, necessary safety precautions has to be taken deciding up on the freeboard of shoring, considering expected maximum flood levels of canal. Sheet piles must be driven up to clay layer, to prevent seepages towards working space.

Moreover, stabilization of top layer of sandy soil in the excavation pit prior to initiation of aqueduct section construction works has to be done. Sandy soil is commonly stabilized using cement based compounds. Cement is mixed with the sandy soil, then compacted, then let it to be hardened via hydration reaction of cement, absorbing required moisture from soil and creating a hardened and levelled surface for construction works(Makusa, 2012). Cement requirement is highly depending on availability of fine particles in sand and required final compacted density. To prevent the entry of water into the stabilized sand, a waterproof membrane can be placed below the sand layer. Additionally, proper grading and drainage measures should be taken to ensure that water does not collect near the stabilized area. This will prevent the stabilization layer from being undermined and potentially washing away(Makusa, 2012).

6.2. Shoring system for piled tunnel

The method requires almost same shoring works as eared aqueduct construction method, as deep excavation and grouting works will require cutting off seepages and lowering water table inside the working space otherwise lateral water seepages may tend to collapse the walls of excavated bore.

The objective of cutting off seepages can be achieved by as mentioned above, driving the sheet piles up to clay layer and capping it, significantly preventing seepages in to workspace. However, water table may require to reduced further by a dewatering well system prior to deep excavating for piles to ensure bore will not collapse due to seepages. For Spannenburg project, piled aqueducts require shoring of (16.35+2.5)m of width in order to provide necessary working space.Figure 21 shows the shoring work depths for the eared and piled aqueducts.

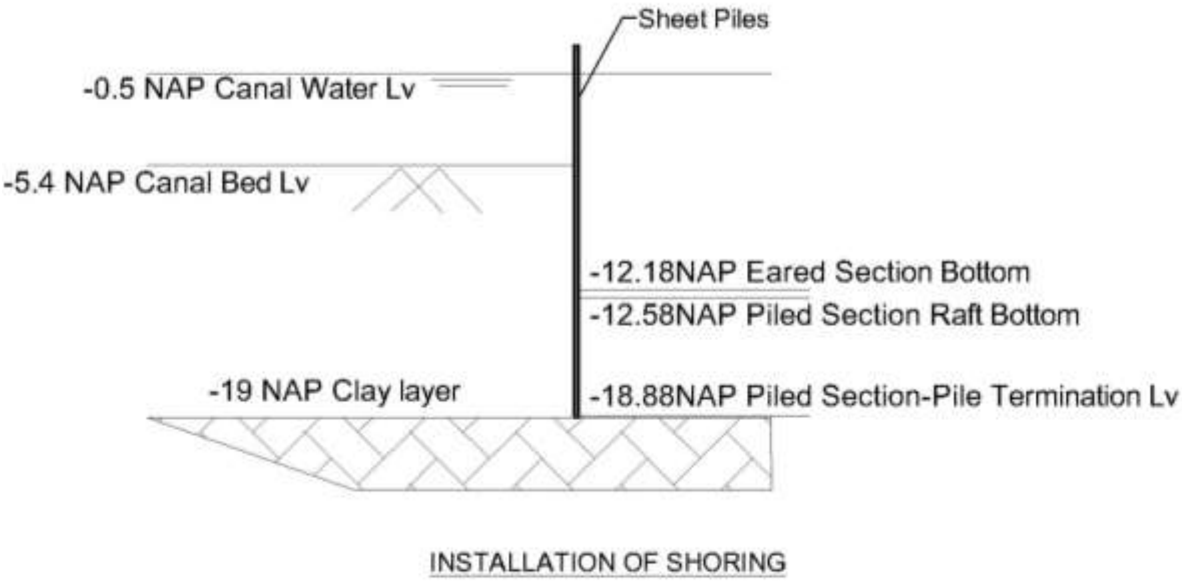


Figure 21-Shoring depth for eared and piled methods

6.3. Drydock and shoring works for immersed tunnel

Dry dock is the construction yard that fabrication of immersed tunnel sections will take place. A dry dock consists if plants, machinery and fabrication yards with construction yard which can be flooded when necessary (Christian, 2004) as explained in (Section 5.2.1).

Water basin has to be designed as it will reach the water level of the canal after filling, which it should facilitate transporting the section with proper freeboards top and bottom as (Christian, 2004) from Hogeschool van Utrecht suggests; 500mm bottom and 100mm top minimum. Therefore, the ground has to be excavated and held to create the water basin, for that case, sheet piles will be used to create a perimeter where the dry dock basin is created. Excess material will be excavated out to create the basin. Sheet piles will act as a basin walls and they should be driven up to the clay layer to prevent unnecessary seepages of water through perimeter of water basin.

The estimated size for the dry dock is width of the tunnel +10m and length of the tunnel +10m with the same depth around 8m. To construct the dry dock adjacent to proposed alignment would be the best possible solution but due to existence of Vitens water company on the left bank and N394 and N354 road networks on the right bank, both adjacent areas to alignment are blocked. Therefore it is proposed to move and locate the dry dock on the right bank of the canal, little further from the alignment where it is currently used as farmlands as shown in figure 22. The proposed location may require additional transportation of section but it still is the best feasible location.

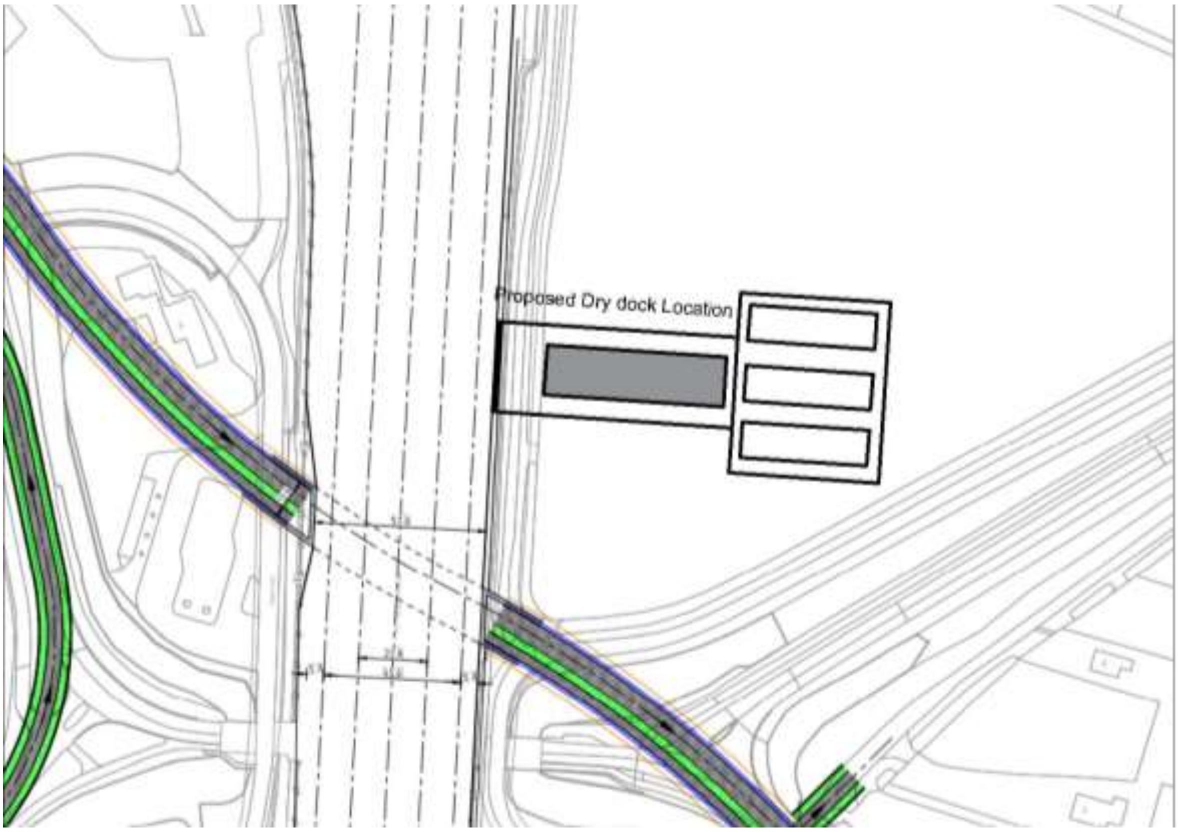


Figure 22-Dry dock location (Wiertsema & Partners, 2022)

.

7. Criteria for the best construction method (Comparison)

7.1. Safety (-19 NAP clay layer)

Table 5 shows the safety to the clay layer achieved by each construction method.

Table 5-Distance between the clay layer and bottom of the structure

Structure Depth	Depth of the structure
Eared	-12.18m NAP
Immersed	-13.38m NAP
Piled	-18.88m NAP

7.2. Environmental impacts

Energy activities, such as the extraction, production, and use of fossil fuels, can have significant environmental effects. These effects can include air and water pollution, habitat destruction, and greenhouse gas emissions, which contribute to climate change(Lüthi *et al.*, 2008). Additionally, the disposal of waste products and materials associated with energy production can also have negative impacts on the environment (Chandrasekar *et al.*, 2018). It's important to consider these effects and work towards sustainable energy solutions that minimize harm to the environment. In the

Spannenburg condition, the construction methods have different types of impacts on environment thus the following sections considered this impact qualitatively and quantitatively for each construction method.

7.2.1. Life Cycle Assessment (LCA)

This section focuses on calculating the amount of emissions result from concrete amount used in the structure, transportation of the structure elements to the construction site and other energy-based activities applied in each method such as sinking in the immersed method. **GaBi** software is used to conduct this process.

Energy activities for each method

The energy activities considered for the eared ,piled and immersed methods are shown in tables 6, 7 and 8 respectively. Some parameters are roughly estimated based on similar processes in other projects for instance ,in the immersed tunnel, the speed of water pumping to sink the tunnel was assumed be the same as in the Harlingen immersed aqueduct(G.de Rooij and A.Luttikholt, 2018). The concrete impact is also included in the process.

Table 6-Eared method energy activities

Characteristics	*Value*
Soil Excavation Volume including the ears and the workspace	*60*(21.25+2.5)*6.78=9661.5m^3 Soil excavation width for the tunnel = 21.25m with height 6.78m and that is added to the excavation for workspace (2.5m).Considering the length of aqueduct =60m.*
Sand Soil backfilling (workspace and soil above ears)	*Soil above ears =6.78-0.95=5.83, the widht of ears =2.3 thus V=2.3*5.83*60*2=1609m^3 For the workspace :2.5*6.78*60=1017m^3*
Soil Disposal amount	*9661.5m3*
Soil Disposal Distance	*40km (Afzetbak company)-Westellingwerf*
Concrete Company Distance	*25km(Friesland Beton Hierenveen BV)*
Electricity needed for 1 m^3 of concrete	568.6 MJ (Vázquez-Calle, et al., 2022)
Dewatering for construction pit and shoring work.	*(4.9*21.25*60)+(2.5*4.9*60)=6938m3* The 4.9 is the water depth in the canal and the width of the structure is 21.25 with 2.5m of working space. The seepage is not calculated here because it is hard to be estimated in this stage since it depends also number of working days.

Table 7-Energy activities for Piled method

Characteristics	*Value*
Sand Soil Excavation including workspace(2.5m)	*(16.35+2.5)*6.48*60=7329m3*
Soil backfiliing (workspace)	*2.5*6.48*60=972m3*
Soil Disposal amount	*7329m3*
Soil Disposal Distance	*40km (Afzetbak company)-Westellingwerf*
Concrete Company Dsitance	*25km (Friesland Beton Hierenveen BV)*
Amount of steel needed for piles	*392 *volume of one pile =*

	$392*\pi*r^2*h=392*3.14*0.135^2*7=1163.2m^3$
Dewatering for sheet piles	(4.9*16.35*60)+(2.5*4.9*60)=5542m3 Seepage not included

Table 8-Energy activities for immersed method

Characteristics	Value
Soil dredging volume	7924.14m3 Considering the depth =7.98m with width 16.55m and length of 60m.
Soil Disposal Distance	40km (Afzetbak company)-Westellingwerf
Concrete Company Dsitance	25km(Friesland Beton Hierenveen BV)
Drydock size	14868m3 As an estimation the drydock size= (60+10) m, (16.55+10)m and depth of 8m. This includes additional space for the construction and maintenance of the tunnel.
Drydock water to float the tunnel	Size-Volume=14868-(60*7.98*16.55)=6924m3
Average Speed Used for Dewatering the drydock (construction site).	400km/hr
Time needed to dewater the dry dock	6924m3/400km/h=17.30h. Incase of 6pumps then 17.3/6=2.9h
Type and number of pumps for water	6pumps with capcity of 75000 J/s The strengh of one pump is 75kW. Number of pumps =6 *75kW=450kW=450*10^3 jouls/s as a whole capcity for all pumps
Amount of ballast concrete needed to stable the tunnel	V=22.4m3/m*60m=1344m3
Ballast cocnrete injecting machinery type	HBT90-22-199R with 38.21 kg/hour of Diesel consumption
Time needed to inject the ballast concrete	1344/200≈ 7h (V/speed) ,the speed is assumed to be less than average (de Rooij & Luttikho, 2018) because of the seneistivity of the process (200m3/h).
Amount of water needed to sink the tunnel	2.4*22.4*60=3225.6m3 of water needed to sink the tunnel. 2.4*amount of ballast concrete (as one cubic meter of concrete =2.4 cubic meters of water)
Sludge to be disposed after dredging the trench	7924.1m3 -the same as the volume of the tunnel.
Sand flow under the tunnel (bed)	0.5m
Number of winches used in transporting the tunnel and the capacity	4 winches with load of 66 tons
The time of transporting the tunnel	10 hours (assumption)

Results of Life Cycle Assessment (LCA)

The results of the Life Cycle Assessment (LCA) are divided into two sections. The initial results, as depicted in Figures 23 to 26, reveal that the pile method exhibits a superior performance in terms of CO2 emissions, human toxicity, natural land transformation, and water depletion. This can be attributed to the minimal excavation and backfilling required during the construction process, as well as the limited usage of concrete. In contrast, the immersed method appears to be the least favourable option among the environmental factors considered.

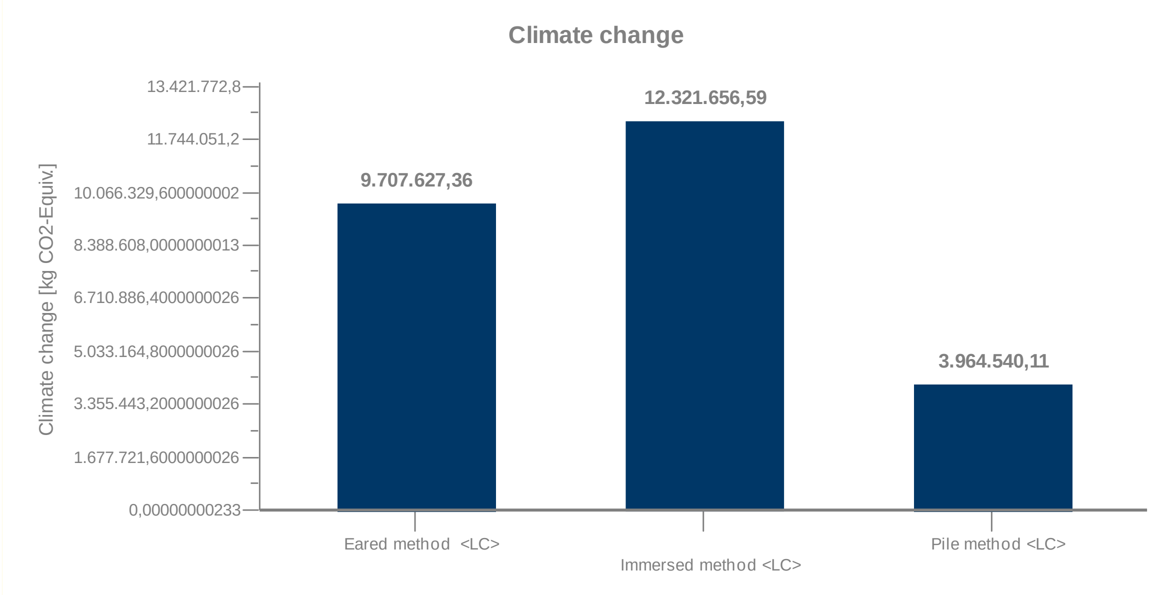


Figure 23-CO2 emissions for the three construction methods

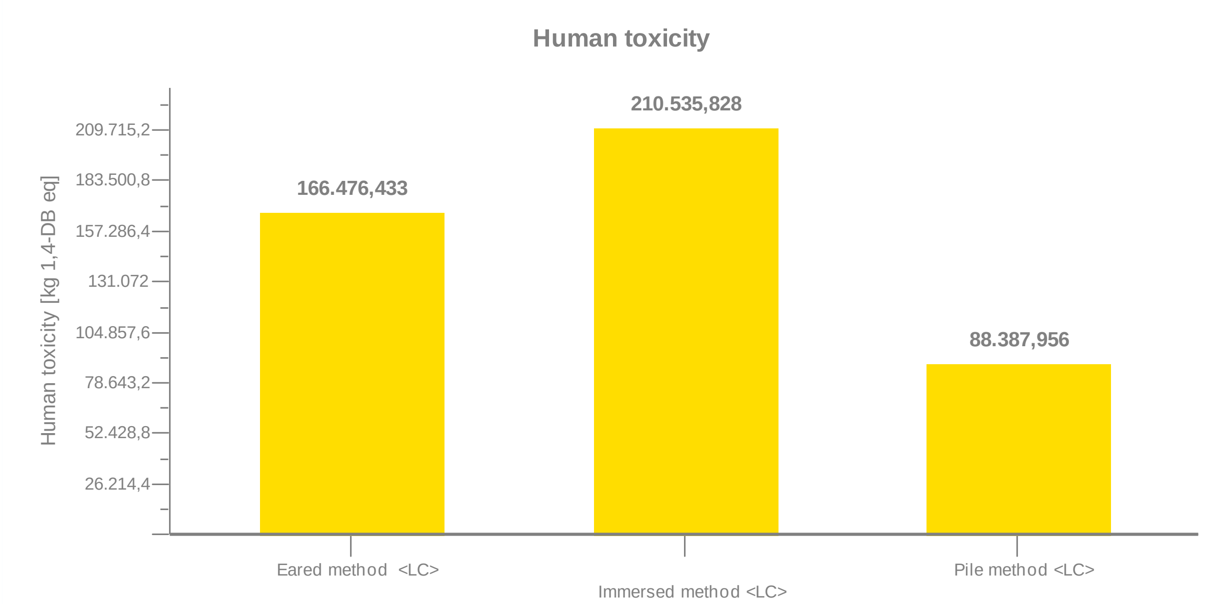


Figure 24-Human toxicity in kg for the three methods

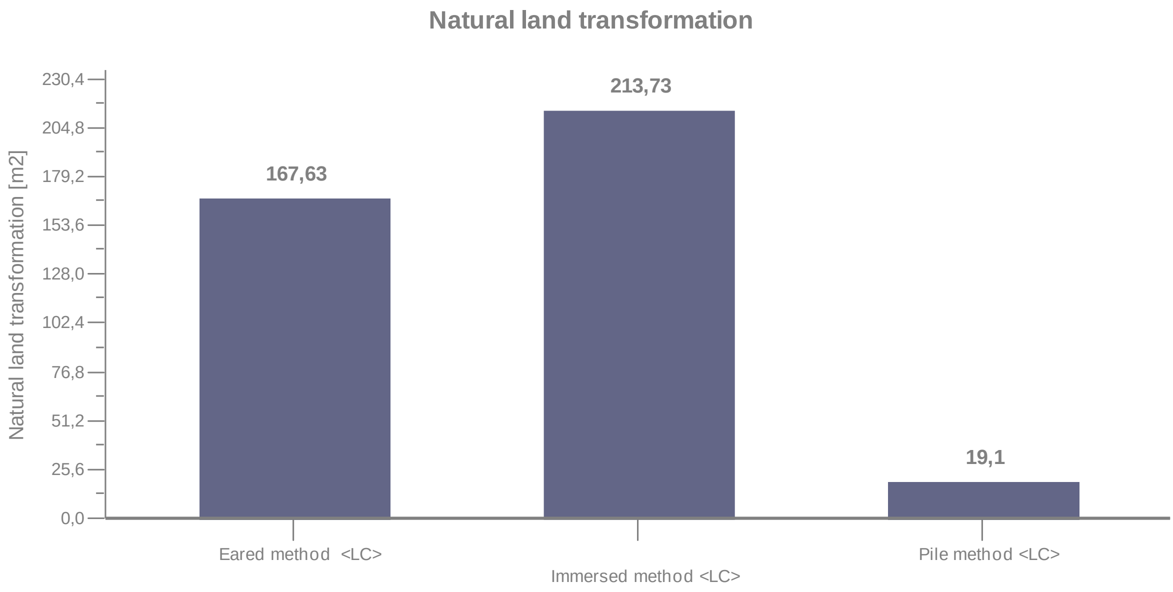


Figure 25-Impact of the three construction methods on natural land transformation

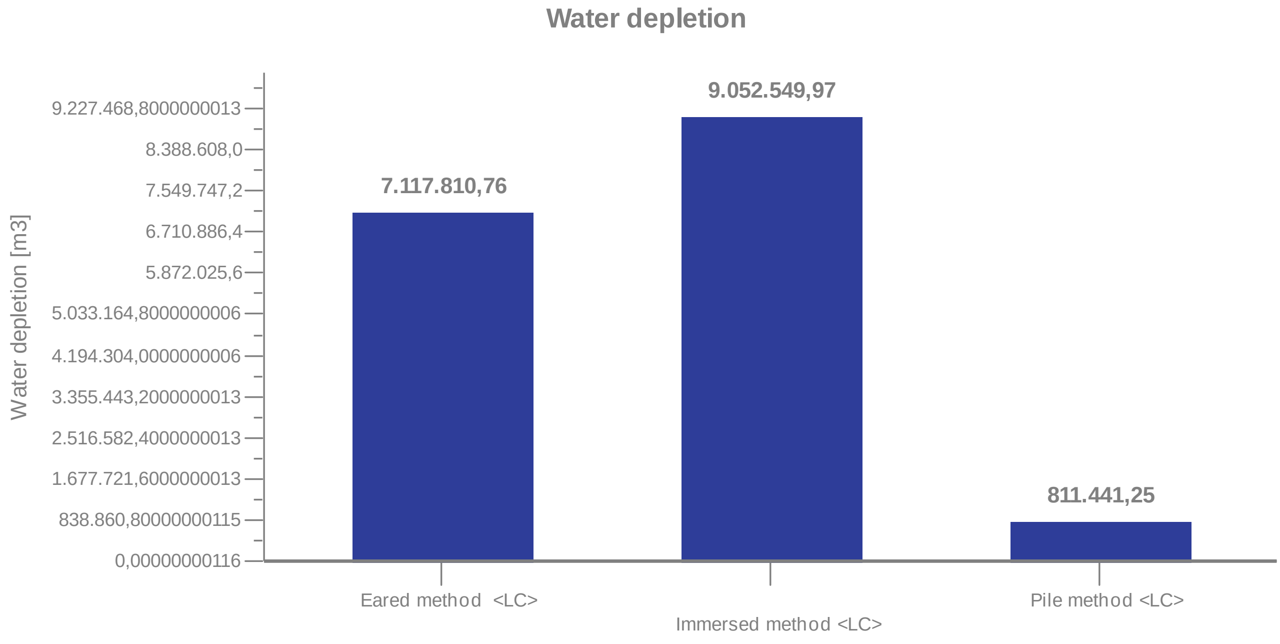


Figure 26-Impact of the three construction methods on water depletion

The latter portion of the findings demonstrates a suboptimal outcome for the piled method with regards to freshwater ecotoxicity and metal depletion, as depicted in Figures 27 and 28, respectively. This can be attributed to the substantial usage of steel in the piling process. On the other hand, the eared method emerges as the most favourable among the three methods in terms of these factors. Despite this, the immersed method remains the most unfavourable from an environmental standpoint.

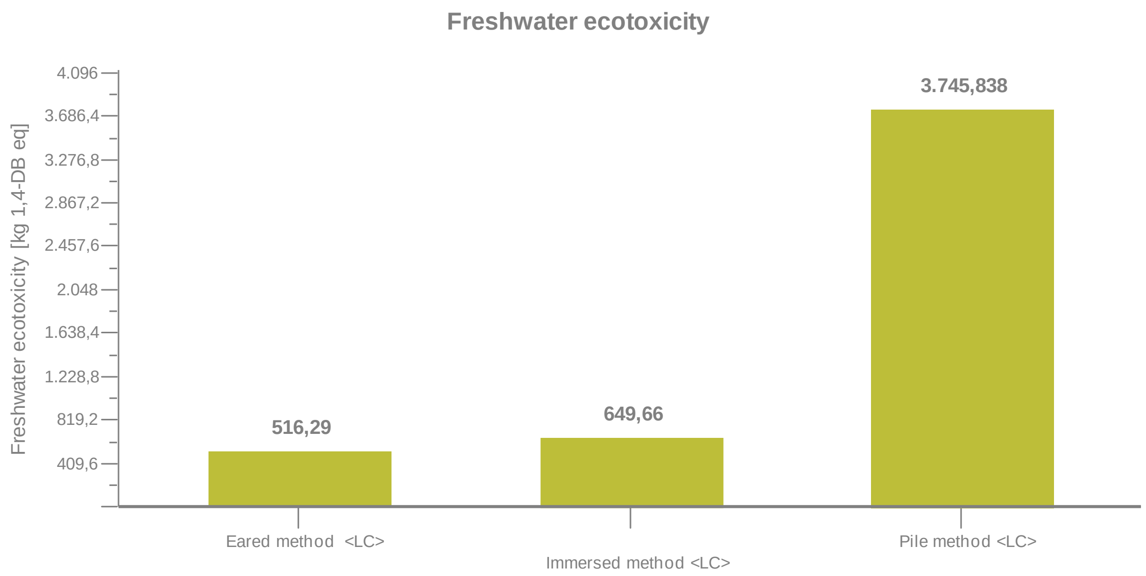


Figure 27-Impact of the three methods on freshwater ecotoxicity

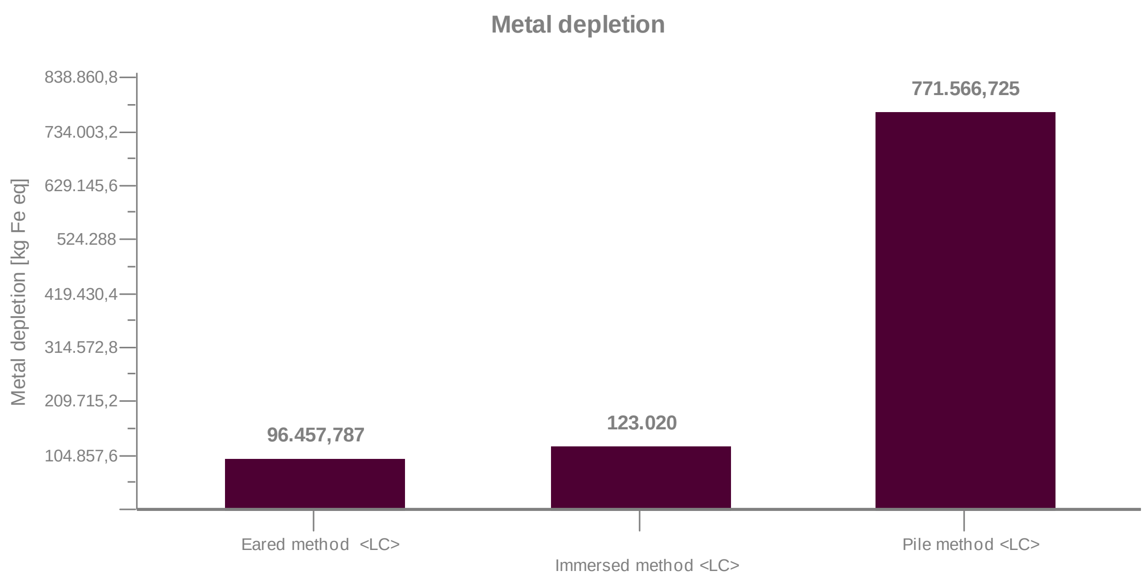


Figure 28-Impacts of the construction methods on marine ecotoxicity

Based on the analysis of the environmental factors discussed, it can be concluded that the pile method represents the most favourable choice in terms of its environmental impact, followed by the eared construction method. On the other hand, the immersed method emerges as the least environmentally favourable option among the three methods.

7.3. Convenience

Ultimate goal of the project is to provide better transit across Prinses Margarietkanaal where the motorway and waterborne transport can be facilitated with each not interrupting the other. However, during the construction phase, there can be several impacts to regular life in the vicinity directly or indirectly caused by construction works. The impacts can be positive or negative, ultimately affect the lifestyles of the people in the vicinity. Positive impacts are generally common for all three methods and identified as following :

- Employment opportunities, business opportunities for suppliers of material and machinery will be available, which will beneficial for the people in vicinity.
- Infrastructure such as connection road etc will be included in the project therefore overall area will be developed along with the project

In this report, for de decision making, negative impacts are considered as the objective to minimize and mitigate negative impacts to regular life due to the project. Each construction method has unique negative impacts and in following section it will be presented:

7.3.1. Immersed tunnel

- Construction related traffic may cause traffic congestion, however for immersed aqueduct construction method, most of the construction works will be carried out in a selected dry dock, where most of the traffic is diverted to there. So, with careful traffic plan, the impact on routine traffic can be minimized. Therefore, the immersed aqueduct method will have the least impact om traffic congestion.
- The method will require closure of the canal and stabilizing its tidal waves for certain period of time, preventing any transportation or other purposes that canal occupied for, however the floating, transportation and immersion process will only last for few weeks therefore this method will have least impact on canal closure (de Rooij & Luttikho, 2018).

7.3.2. Eared tunnel

- Eared/winged aqueduct construction method requires long term shoring for provisioning workspace for in-situ construction works. As the canal is occupied with transportation and recreational purposes, closure of canal will affect adversely day-to-day life. Yet the impact can be minimized by commencing the project in two stages, closing only half of canal span per stage.
- To provide workspace, the canal bed has to be excavated up to 6.78m from ground level, for a width of 23.75m (structure width plus working space of 2.5m including shoring). Which will result for an excavation of approximately 9661.5m3 of soil. The excavated material has to be removed from site therefore there will be constant transporting of excavated soil using dump trucks, which will induce significant traffic congestions in the vicinity or there is the option of utilizing a barge to transport the excavated material via canal however it would badly.

7.3.3. Piled tunnel

- Piled aqueduct construction method requires long term shoring for provisioning workspace for piling works as well as in-situ construction works. This will cause closure of the canal even for a half of the canal, for extensive periods to construct piles, pile caps and structure.
- To provide workspace, the canal bed has to be excavated up to 6.48m from canal ground level, for a width of 18.85m (structure width plus working space of 2.5m including shoring). Which will result for an excavation of approximately 7329m^3 of soil. The excavated material has to be removed from site therefore there will be constant transporting of excavated soil using dump trucks or ships, which will induce significant traffic congestions in the vicinity.

From the above description, it can be inferred that the eared and piled methods exhibit similar impacts on daily activities, whereas the immersed method presents a superior performance in terms of this aspect.

7.4. Feasibility of Construction

7.4.1. Eared tunnel

When it comes to the construction feasibility, this construction method may not be easy to carry out as it would need the canal to be blocked partially by shoring, constant dewatering will be required also for provision of space including extended ears, the excavation volume will be higher. Advantages and disadvantages of the method is as following;

Advantages

- The method is conventional as it simply requires shoring, excavation and in situ casting of sections where it does not require specially designed machinery or highly trained staff.
- Construction processes are conventional and risks and consequences of quality management is relatively lower as a correction or adjustment can be done due to in in-situ constructions.
- The method allows engineers to adopt simpler and more robust breakdown of structural steps to construct the aqueduct as the structure is constructed on the site.

Disadvantages

- Total construction area requires shoring to provide adequate works space. Since the waterbody is a canal accommodating transportation of ships, total width cannot be blocked by shoring at once therefore whole construction project may carried out in two phases, one per each side of the canal.
- Backfilling will be required after construction of the structure, facilitating suitable filling material for backfill. Material may require to be transported from outsource since excavated materials are highly unlikely to be used in a backfill due lack of compaction which can compromise the stability and integrity of the backfill material. Additionally, the excavation process often causes soil disturbance, leading to soil particle size segregation and loss of soil cohesion(Hale *et al.*, 2021).

7.4.2. Immersed tunnel

As stated in previous sections, the immersed tunnelling method consists of constructing the segments of tunnel in nearby trench area or dry dock which can be filled and drained, and transport the segments using specially designed transportation system. However, construction of immersed tunnel will provide several challenges toward the contractor as the work will include immersion engineering, transportation engineering, construction engineering, guidance for transporting and immersion of the aqueduct and backfilling of the dredged trenches under the tunnel (de Rooij &

Luttikho, 2018). Thus there are aadvantages and disadvantages of immersed tunnels in aspects of ease of construction can be stated as (Gursoy, 1996);

Advantages

- In situ construction works are greatly reduced as the sections are constructed in a separate construction yard or dry dock, therefore after sections are completed, only placing and connecting the sections will be required.
- Since the construction is carried out in a dry working space, there will be no constant seepages to workspaces, hence no dewatering requirements moreover better quality of construction can be achieved compared to in-situ construction.
- Progress will less likely to be affected by natural causes such as weather, rising of flood level in canal or man-made causes since the construction works of sections carried out in a separate dry workspace.

Disadvantages

- Requires special machinery for construction, floating up, transportation and immersion process with specially trained workers to transport, align and immerse the segments.
- A Dredged trench having a length of 60 and bottom width of 16.55 will be required to place the tunnel sections in desirable depth of -12.78NAP, which is 7.38m deep from canal bed, hence dredging will require extensive care to prevent excessive sludge and removal of excess material will be challenging.
- Foundation or bedding such as sand bed, for sections may needed to be constructed prior to placing sections and after placing sections (de Rooij & Luttikho, 2018).
- Whole process has to be carried out with extra quality control, quality assurance with special consultant's supervision, therefore it will affect ease of construction adversely.

7.4.3. Piled tunnel

The piled construction method has advantages and disadvantages and they are as follows:

Advantages

- The construction will not be affected by very soft and settling clayey soil availability in canal bed, in most of cases it is common to identify very soft clay layers which will result uneven settlement in few years, inducing unfavourable stresses to the structure.
- The construction techniques used for the method will not be extensively demanding specialized machinery or skilled workforce apart from a conventional construction crew for a structure with deep excavations.
- Due to simplicity the quality assurance and quality management works will be less complex, therefore can lead to better job quality.

Disadvantages

- High risk of penetration of impermeable clay layer as the pile termination level is -17.88NAP and clay layer level is -19NAP, which overlays the ground aquifers, therefore extra care has to be taken during deep excavation processes.
- Construction works may interrupt by adverse weather conditions, floodings, storms etc where the concerns of safety will arise when working in confined spaces on the canal.
- In-situ piled aqueducts typically take longer to construct. This is because the aqueduct must be built on-site, which requires more time and resources. Additionally, the construction process for in-situ piled aqueducts is often more complex and time-consuming, as the piles must be carefully installed and the aqueduct itself must be built to exacting standards.

It can be concluded that the in-situ piled and eared methods are more straightforward in terms of construction feasibility. The construction of these methods is simple and does not require complicated type of machinery. Moreover, the immersed tunnel is more complex as it requires the construction of a drydock, the transportation of the tunnel sections, and the installation of the tunnel in the ground.

7.5. Health and safety

The health and safety can be divided into two parts ;

7.5.1. Human health and safety

Construction works are inherited of significant risks to the employees and visitors to the construction site. Health and safety, which is commonly considered as paramount and good practices which are not only technically viable, also ethically acceptable will be always in advantage of project manager in successfully completing the project (Harrin, 2015). The hazardous activities can cause minor injuries to catastrophic tragedies to employees and assets, costing lives and money for stakeholders. It has been identified that there can be several critical safety hazards for all three construction methods despite their selection, which are listed out as following;

- Working in elevated levels
- Slip, trip and fall hazards.
- Falling in to water and drowning.
- Exposure to excess noise and vibration.
- Collapse of loose materials.
- Electricity.
- Exposure to toxic material.

The occurrence of these events and severity will change due to selection of construction method among available, which incorporates different construction activities and, can be calculated from previous experiences and available data, after that a probability value for occurrence and severity can be calculated (Smith, et al., 2006).

All of above-mentioned hazards are common for the project despite the selection of construction method however it can be stated that risk of failing and drowning of workers is significantly higher in immersed tunnel construction method as it would require workers to work on the water, where both other methods use shoring to provide work space.

Furthermore, excavation induced noises and vibration levels are highest in piled aqueduct construction as it would require deep excavation. Eared aqueduct construction also will induce significant amount of noise and vibration due to excavation and transportation of materials. However, the severity of noise and vibration is lower than drowning therefore both methods possess lower health and safety concerns than immersed aqueduct construction method.

7.5.2. Human toxicity caused by harmful emissions

Construction related emissions has been known as a significant contributor to air pollution and water pollution specially. In the context of Spannenburg aqueduct project, Emissions caused by plants, machinery, vehicles and materials used for construction works and Dust or sludge generation by demolition or excavation works are prominent polluters that can pose severe health and safety hazards to workers as well as residents in the vicinity. These emissions can cause toxicity, causing

Coughs, wheezing and shortness of breath, Cardiovascular and respiratory diseases, Lung cancer, Strokes, or Exacerbation of asthma. Frequent exposure to dusts, fumes and gases emitted by machinery lead to higher rate of lung cancer among construction workers (Guzder, 2019).

In the context of this project, it has been already established by LCA that human toxicity in aspects of 1,4-dichlorobenzene is lowest by the piled construction method, comparing with immersed method which ranked highest and eared method, which ranked second in human toxicity generation. Generation of toxicity can be caused by above mentioned activities; therefore, it is accurate to assume with lesser amount of work done, there will be lesser toxicity. Generation of toxicity of each method can be discussed as;

Eared Aqueduct

Eared method high excavation amount comparing to the other two methods which will require excessive machine working hours, leading to high emissions, thus high toxicity exposure.

Immersed Aqueduct

Immersed method has ranked as highest toxicity as it would be using several special machineries with special activities, which can cause severe emissions. Pumping water to drydock, draining water from ballasts, pumping ballast concrete, transporting sections etc. will generate high emissions by machinery and equipment, furthermore, sludge generation due to dredging more than 7m of river bed will cause significant water pollution.

Piled Aqueduct

The method promises least toxic emissions as indicated in LCA also, as it would emit lesser amount of CO_2 too, mainly due to the requirement of least machine hours between all three methods. Furthermore, there will be minimum amount of sludge due to shoring and dry excavation, which will prevent creating water toxicity

7.5.3. Noise and Vibration generation

Machine and equipment induced vibrations will be a significant environmental concern that was not included in the LCA analysis ,as the area around Spannenburg has several constructions and houses as well and that an pose risks of damages to the existing bridge as the aqueduct passes closer to the existing bridge Vibrations can cause movement if building floors, rattling of windows, cracking of glass panels, cracking of masonry walls, and for some extreme cases, there are structural damages also reported (Mahmud, 2022). The main causes for the project to create extensive vibrations is construction activities such as excavation deep excavation.

Immersed tunnel construction method being the method having least environmental impacts in terms of high vibrations and noises as there are minimal excavation works are to be done. On the contrary, piled aqueduct and eared aqueduct construction methods requires significantly high quantities of soil excavation, backfilling with suitable soil and compacting to reach desired degree of compaction, which all above mentioned activities emit high vibrations. Furthermore, construction induced traffic such as transporter dump trucks, barges, in situ machinery such as compressors, loaders and rollers, rammers etc will generate altogether a higher noise level, which will be unpleasing to the residents in the vicinity. As per immersed tunnelling method, noise and vibrations will not be an issue as at planning stage, the impact can be minimized by planning ahead and selecting a casting yard at an unpopulated area, where the other method does not possess that luxury.

To conclude, each method has its own advantages and disadvantages, and the trade-off between these benefits and drawbacks must be carefully evaluated when making a decision. Thus they are considered to have an equal impact when making the decision in this research.

8. Balancing the alternatives (MCDM)

In practical construction projects are complex systems are usually quite difficult to be designed because the structure analysis is influenced by different parameters. Therefore ,making a choice of one alterative over another needs balancing of conflicting objectives and the multicriteria decision making (MCDM) using Additive Ratio Assessment (ARAS) to choose the best alternative based on defined criteria of actors and stakeholders. The multiple-criteria decision-making model allows the analysis of several preference criteria simultaneously. As the economic, environmental, social and technological actors must be considered (Zavadski, et al., 2010).

Since the project is affecting several stakeholders, for deciding the construction method, it has been decided to include significance of each criterion to the decision-making process by all the stakeholders. Based on a meeting between me and my supervisor Mr. Dirk and discussing the importance of each criterion, I came up with that the most important criteria is the safety to clay layer followed by the environmental impact of each construction method then comes the ease of construction.

In this method, a score is given to each criterion based on the importance with 10 means the most important criteria and 1 is the least significant criteria. Table 9 shows the criteria. The weight is calculated by dividing the value of each criteria by the sum.

Table 9-Significance index matrix

Set of Criteria	Notation	Optimal solution	Significance	Weight (w)
Feasibility of Construction	x1	Max	8	0.21
Convenience of the project	x2	Max	5	0.13
Health and safety	x3	Max	7	0.18
Environmental Feasibility in aspect of LCA	x4	Max	9	0.23
Safety to the clay layer	x5	Max	10	0.26
Sum			39	1.01

For the initial decision making matrix , the values was given by looking at each criteria for each method. For instance, in feasibility of construction, the immersed method based on the explanation in the previous criteria chapter is the most unfeasible and complex process (‘immersed tunnels’, 1978) thus it has the lowest score of 6. The eared method is given a score of 8 as the best option. When it comes to safety to clay layer(x5), the distance between the bottom of the tunnel and the clay layer (-19m NAP) is used as a score for each method as shown in the last column of table 10.

Table 10-Initial decision making matrix

Alternative	Criteria				
	x1*	**x2***	**x3***	**x4***	**x5***
Optimum direction	max	max	max	max	max
Weights of criteria	**0.17**	**0.13**	**0.18**	**0.23**	**0.26**
A0-Optimal value	8	8	7	9	6.82
A1-Immersed aqueduct	6	8	7	5	5.62
A2-Eared aqueduct	8	7	7	9	6.82
A3-Piled aqueduct	7	7	7	7	0.12
Sum	21	22	21	20	12.56

Since we used direct values not score in the safety to clay layer criteria, the initial decision making matrix must be normalized by dividing the sum of each criteria on the performance of each method in each criteria as shown in table 11. For instance the immersed method in the initial decision making matrix took a score of 6 in criteria x1 thus the normalized value is 6/21=0.29.

Table 11-Normalised decision making matrix

	$\overline{X_1}$	$\overline{X_2}$	$\overline{X_3}$	$\overline{X_4}$	$\overline{X_5}$
W(weight)	**0.21**	**0.13**	**0.18**	**0.23**	**0.26**
A0-Optimal value	0.38	0.36	0.33	0.43	0.54
A1-Immersed aqueduct	0.29	0.36	0.33	0.24	0.45
A2-Eared aqueduct	0.38	0.32	0.33	0.43	0.54
A3-Piled aqueduct	0.33	0.32	0.33	0.33	0.01

The final decision making matrix in table 12 is constructed by multiplying the weight with the value of each criterion in each construction method.

Table 12-Final decision making matrix

	X1	**X2**	**X3**	**X4**	**X5**	**S**	**Mark**	**Rank**
A0-Optimal value	0.0798	0.0468	0.0594	0.0989	0.1404	0.4253	1	
A1-Immersed aqueduct	0.0609	0.0468	0.0594	0.0552	0.0117	0.339	0.798	2
A2-Eared aqueduct	0.0798	0.0416	0.0594	0.0989	0.1404	0.420	0.988	1
A3-Piled aqueduct	0.0693	0.0416	0.0594	0.0759	0.0026	0.249	0.585	3

All three methods are compared with optimal solution available; the calculation process suggests that eared aqueduct method is the most feasible construction method as it reached 0.988 mark followed by the immersed tunnel with 0.798 where optimal solution is 1.

9. Retaining wall design

Since the results of the MCDM analysis concludes that the eared construction method is more promising than the other two methods, the retaining walls are designed accordingly. The same problem discussed in designing the aqueduct, the retaining walls needs to be heavy enough to resist different failures could occur to the structure namely; sliding, overturning and uplifting. There are two promising types of retaining walls that could be considered in the project of Spannenburg. Firstly, gravity retaining walls which are usually constructed by masonry or mass concrete as shown in figure 29. As the name implies, the gravity retaining walls depends on self-weight to achieve stability and can be constructed up to maximum of 2m height (Venkatramaiah, 1993).

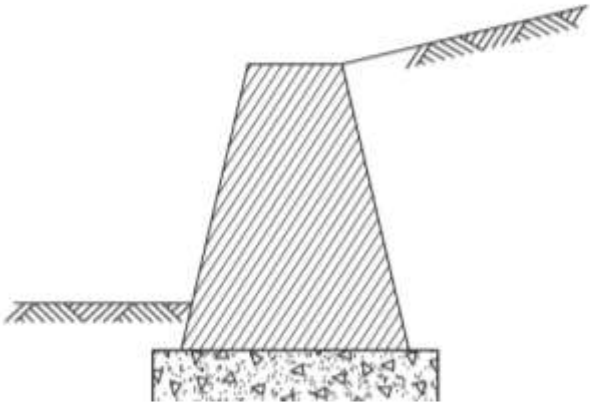


Figure 29-Gravity wall

The second type is ccantilever walls as shown in figure 30 which are usually constructed with reinforced concrete where a horizontal base and vertical stem are monolithically casted in place to withstand rotations and horizontal forces. They can be constructed to greater heights as cantilever walls depends on soil loaded on the wall as in heel and toe for stability (Venkatramaiah, 1993). Thus, the second option is more suitable to the aqueduct of Spannenburg

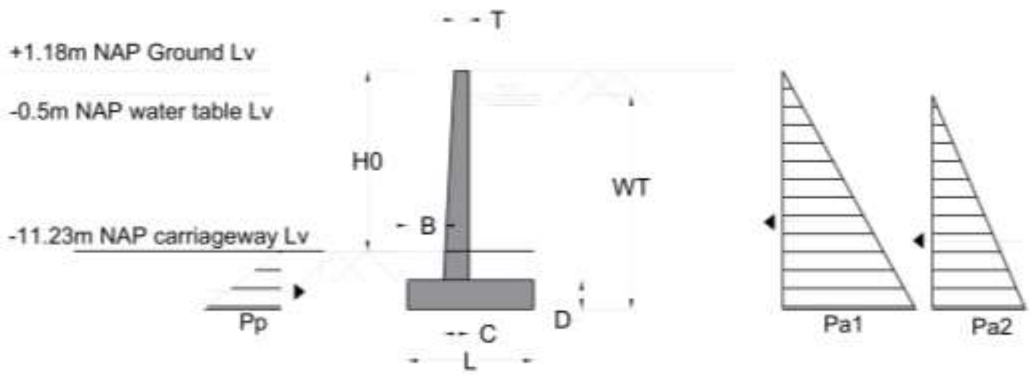


Figure 30-Cantilever wall

9.1. Optimization of the wall

The retaining wall is first calculated at a point right next to the closed tunnel where the ground level is taken to be 1.18m NAP (DKM003). Figure 31 shows the final dimensions of the retaining wall. The distance from the road inside the tunnel and the bottom of the wall base is 4m. The appearing height of the wall is 10.36m while the total height from the ground to the bottom of the wall base is 16.36m. More detailed calculations are in appendix 12.5.

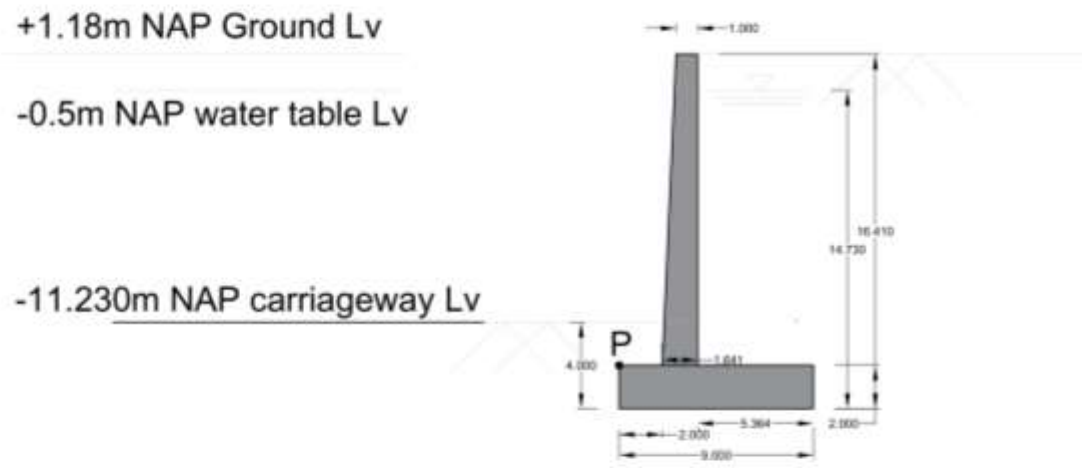


Figure 31-Optimised dimensions of the retaining wall

9.2. Equilibrium of the wall

The forces acting on the wall are the self-weight of the structure elements, the upward force due water, the active horizontal forces due water and soil and the passive horizontal force due the soil in the side of the road. Three tests are applied to ensure the stability of the retaining wall namely; sliding, overturning and uplifting test. Figure 32 shows the free body of the retaining wall and table 13 shows the forces and moments acting on the retaining wall.

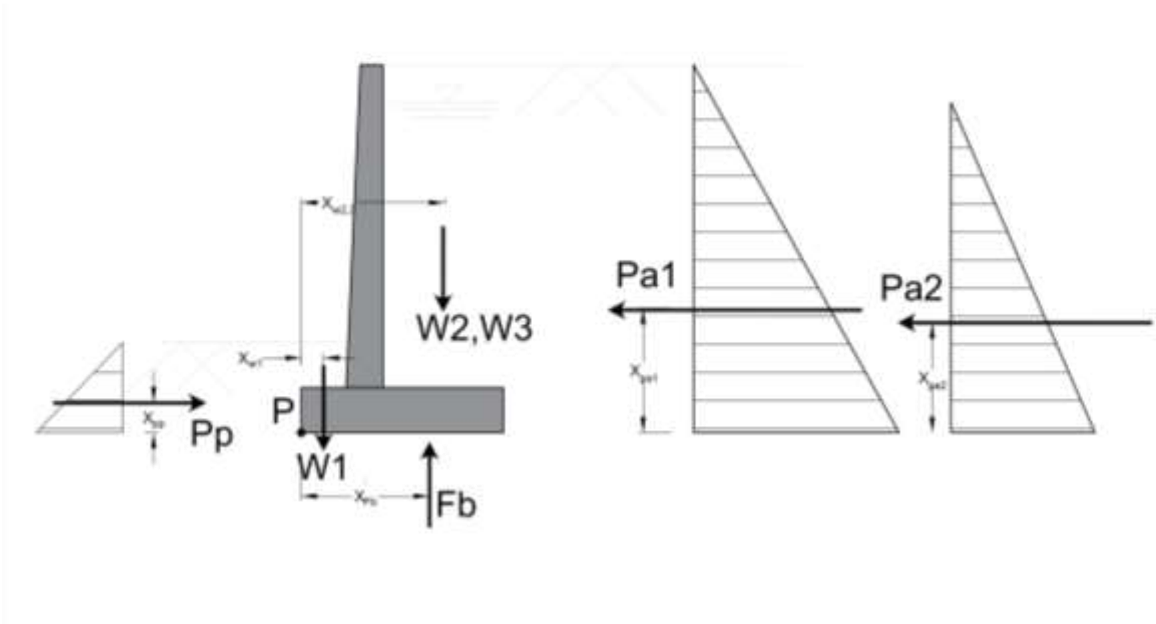


Figure 32-FBD of the retaining wall

Table 13-Structural analysis of the retaining wall

Weights	**Forces (kN/m)**	**Equation**	**Distances from P for moments(m)**	**Moments of each force in kNm/m**	**Moment Direction**
Pa1 (soil active pressure	1255.5	=H/3	5.53	M_Pa1=6942.7	
Pa2 (water in the wing)	1064.3	=WT/3	4.91	M_Pa2=5225.5	Left side Moment
Fb (Buoyancy force)	877.8	=2L/3	6	M_buoyancy =5249.19	
W1 (soil weight in passive side	72	=B/2	1	M1=72	
W2 (soil in active side)	1402	=L-(L-(B+C))/2	6.33	M2=8878.0	Right side moment
W3(water active side)	667	=L-(L-(B+C))/2	6.33	M3=4221.7	
W4 (base weight)	450	=L/2	4.5	M4=2025.0	
W5 (weight of wall)	484..9	=L/2	4.5	M5=2182.2	
Pp (passive earth pressure)	383.55	=Hp/3	1.3	Mp_p=511.4	

More details about calculation of forces and values of each parameter used in the calculating process are in the appendix12.5.

Overturning stability

$$Overturning\ safety\ = \frac{\text{Total right side moment}}{\text{Total left side moment}} = 1.026 > 1 \text{ Safe against overturning}$$

Uplifting stability

Unfavourable safety factor =1.35

Friction coefficient =Tan(Ø)=Tan((32.5))=0.637; (NEN2012)

$$Uplifting\ safety\ = (W1 + \cdots + W5) * 0.637 - (1.35) * F_b$$
$$= 1060 kN/m\ downwards\ \text{ Safe against uplifting}$$

Sliding stability

$$Sliding\ \ safety\ = \frac{\text{Friction Forces (vertical)}}{\text{Total Sliding Forces}} = \frac{(W1 + \cdots W5\ ) * Firction\ coefficient}{Pa1 + Pa2 - P_p} =$$
$$= 1.0123 > 1 \text{ Safe against sliding}$$

To conclude the retaining wall is stable against all the aforementioned failure mechanisms.

Figure 33 shows the result of combining the aqueduct with retaining walls assuming that the walls on top of the edges of the tunnel (parallel to the tunnel) have height of 4.9+1=5.9m.

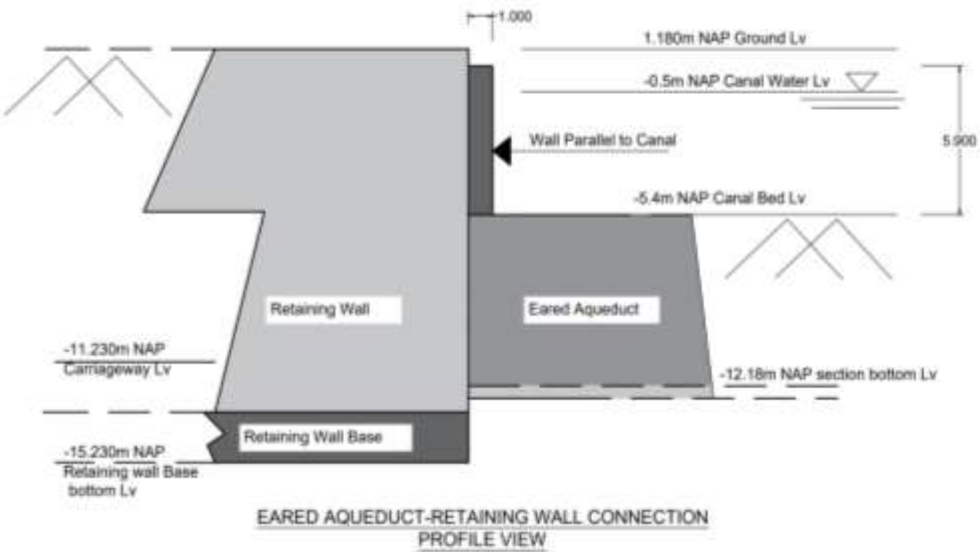


Figure 33-Eared aqueduct connected to the retaining wall

10. Conclusion

The construction of an aqueduct in Spannenburg, Friesland is a critical project that demands a meticulous evaluation of various factors to ensure the safety, efficiency, and effectiveness of the infrastructure. The current study aimed to compare three construction methods, namely eared, immersed, and piled aqueducts, during the construction phase based on five criteria, including safety to the groundwater, environmental impact, feasibility, health and safety, and impact on regular life. The results of the Multi-Criteria Decision Making (MCDM) analysis showed that the eared method demonstrated the best performance.

The importance of these results cannot be overemphasized, as they provide valuable guidance to decision-makers in the province of Friesland as they strive to select the best approach to improve the transportation infrastructure and guarantee the efficient and safe movement of boats and ships versus vehicles. The study offers a preliminary indication of the most promising construction methods for the construction of an aqueduct to replace the Spannenburg bridge.

However, it is imperative to acknowledge the limitations and assumptions of the study, which require further investigation. It is therefore recommended that a more comprehensive investigation be carried out to fully evaluate the potential of each construction method, taking into account a wider range of criteria, such as long-term maintenance, flexibility and timeframe.

In conclusion, while the present study provides useful insights into the most likely construction method to be considered in future research, it should be considered as a preliminary investigation rather than a comprehensive evaluation of the construction options. Further studies are necessary to gain a complete understanding of the potential of each construction method and make informed decisions about the best approach.

11. References

Alexandria, V., 1961. *Foundations and Earth Science,* Washington : Naval Facilities Engineering Command.

Basilen, F., 2013. Effects oftunnellingonpilefoundations. *Soils andFoundations,* 1(2013), pp. 1-16.

Bleijenberg, A., 2021. *Renewal of civil infrastructure. Dutch National Forecast for Replacement and Renovation,* Delft: TNO.

Bond, A. J. & Schuppener, B., 2013. Retaining structures. In: S. Dimova, B. Nikolova & A. V. Pinto, eds. *Eurocode7: Geotechnical Design.* Dublin: EC, pp. 43-56.

Boskalis, G., 2014. [Online]
Available at: https://cob.nl/magazines-brochures-en-nieuws/verdieping/verdieping-jan2015/geslaagde-afzinkoperatie-aquaduct-leeuwarden/

Business.gov.nl, 2022. *Health and safety at work.* [Online]
Available at: https://business.gov.nl/regulation/health-safety-work/
[Accessed 29 January 2023].

Choudhary, A. K., Mondel, S. & Metaya, S., 2020. *Advances in Geo-science and Deo-strucutures,* Jamshedpur: Department of Civil Engineering ,NIT.

Christian, P., 2004. *Phase in Immersed Tunnel Design,* s.l.: Hogeschool van UtrechtUniversity.

de Rooij, G. & Luttikho, A., 2018. *Proceedings of the Transport and Immersion Operations of the N31 Aqueduct in Harlingen, The Netherlands,* Dubai: TEC.

Edgar, H. & Richard, W., 2018. The growing importance of scope 3 greenhouse gas emissions from industry..

Ehlers, J. & Ulrich, E. J., 1977. *Design criteria for grouted piles in sand.* Houston, Offshore Technology Conference.

GDI, 2021. *Grouting principles and methods.* [Online]
Available at: https://geotechnicaldesign.info/en12715-2000/g7-3.html
[Accessed 25 Janury 2023].

Geovisie, 2014. [Online]
Available at: https://cob.nl/magazines-brochures-en-nieuws/verdieping/verdieping-jan2015/geslaagde-afzinkoperatie-aquaduct-leeuwarden/

Gursoy, A., 1996. Immersed Tube Tunnels. In: J. O. Bickel, T. R. Kuesel & E. H. King, eds. *Tunnel Engineering Handbook.* Boston: KLUWER ACADEMIC PUBLISHERS, pp. 268-289.

Guzder, K., 2019. *Pollution from Construction: What Are the Types & How Can We Prevent It?.* [Online]
Available at: https://www.highspeedtraining.co.uk/hub/pollution-from-construction/#:~:text=Frequent%20exposure%20to%20dusts%20and,particularly%20common%20amongst%20construction%20workers.
[Accessed 29 January 2023].

Harrin, E., 2015. *15 Top Skills Project Managers Need.* [Online]
Available at: https://www.strategyex.co.uk/blog/pmoperspectives/15-skills-project-managers-will-

need-2015/
[Accessed 17 January 2023].

Ingason, H., Li, Y. Z. & Lönnermark, A., 2015. *Tunnel fire dynamics.,* New York:: Springer.

Jenny, R. J., 2004. Safety Provisions. In: J. O. Bickel, R. K. Thomas & H. E. King, eds. *Tunnel Engineering Handbook.* KLUWER ACADEMIC PUBLISHERS: Boston, pp. 360-368.

Kahvita, S. & Nayana , A. Y., 2017. EVALUATION OF C02 EMISSIONS FOR GREEN CONCRETE WITH HIGH VOLUME SLAG,RECYCLED AGGREGATE, RECYCLED WATER TO BUILD ECO ENVIRONMENT. May.

Korff, M., 2017. Learning from case studies and monitoring of Dutch tunnel projects. *Proceedings of the Institution of Civil Engineers - Forensic Engineering (online),* 170(3), pp. 134-143.

Kraft, L. M. & Lyons, C. G., 1974. *State of the art: Ultimate Axial capacity of Grouted Piles.* Texas, Offshore Technology Conference.

M.Elsami, A. E. a. S. M. a. H. M. a. M., 2022. *Piezocone and Cone Penetration Test in Foundation Engineering.* Matthew Deans ed. s.l.:Matthew Deans.

Mahmud, A. R., 2022. Review on Tunnel Construction Method and Environmental Impact. *International Journal of Advanced Research in Technology and Innovation ,* 4(1), pp. 97-105.

Meyerhof, 1976. *Pile Foundations in Engineering Practice.* s.l.:s.n.

Monsees, J. E., 2004. Soft Ground Tunneling. In: J. O. Bickel, T. R. Kuesel & E. H. King, eds. *Tunnel Engineering Handbook.* Boston: Kluwer Academic Publishers, pp. 97-121.

Nicholson, P. G., 2015. *Soil improvement and ground modification methods.* first ed. Oxford: Butterworth Heinemann.

Proske, D., Panagiotis, S. & Lukas, H., 2019. *Comparison of tunnel failure frequencies and failure probabilities.* Edinburgh, s.n.

R.F.Craig, 2012. *CRAIG'S SOIL MECHANICS.* New York &London: Spon Press.

Schouwstra, G., 2019. *Trends voor klasse IV in Fryslan,* Sneek: AA-Planadvies.

Smith, N. J., Merna, T. & Jobling, P., 2006. Quantitative Methods for Risk Analysis. In: N. J. Smith, ed. *Managing risk in construction projects.* Leeds: Wiley-Blackwell, pp. 78-102.

The construction wiki, .., 2022. *Construction Wiki.* [Online]
Available at: https://www.designingbuildings.co.uk/wiki/Piled_raft_foundation
[Accessed 04 02 2023].

TNO, 2013. *the Working Conditions Act,* s.l.: Netherlands Focal Point for Safety and Health at Work.

Vázquez-Calle, K., Guillén-Mena, V. & Quesada-Molina, F., 2022. Analysis of the Embodied Energy and CO2 Emissions of Ready-Mixed Concrete. 14 May, p. 1.

Venkatramaiah, C., 1993. *Geotechnical Engineering.* 8th ed. Tirupati: New Age International.

Venkatraman, B., Jayasiri, N. S. & Oh, E., 2021. Piled Raft on Sandy Soil - An Observational Study. September .

Wiertsema & Partners, 2022. s.l.: s.n.

Wiertsema & Partners, 2022. *Opdrijfcontrole ontgravingsvlak aquaduct Spannenburg,* Tolbert: Raadgevend Ingenieursbureau Wiertsema & Partners B.V..

Wiki, 2022. [Online].

Wilton, J. L., 1996. Cut-and-Cover Tunnel Structures. In: J. O. Bickel, T. R. Kuesel & E. H. King, eds. *Tunnel Engineering Handbook.* Boston: Kluwer Academic Publishers, pp. 320-359.

Zavadski, E., Turskis, Z. & Vilutiene, T., 2010. *Multiple criteria analysis of foundation instalment alternatives by applying Additive Ratio Assessment (ARAS) method,* Vilnius: s.n.

Brolsma, J. U. and Roelse, K. (2011) 'Waterway guidelines 2011', *ISBN 9789036900690*, p. 186. Available at: https://repository.tudelft.nl/islandora/object/uuid%3A966c55b0-1d49-4a59-b46b-b9ce5b4ee936 (Accessed: 11 November 2022).

Chandrasekar, M. *et al.* (2018) 'Experimental investigation on a solar dryer integrated with condenser unit of split air conditioner (A/C) for enhancing drying rate', *Renewable Energy*, 122, pp. 375–381. doi: 10.1016/J.RENENE.2018.01.109.

El-Reedy, M. A. (2015) 'Geotechnical data and piles design', *Marine Structural Design Calculations*, pp. 217–280. doi: 10.1016/B978-0-08-099987-6.00006-4.

De Feo, G. *et al.* (2013) 'Historical and Technical Notes on Aqueducts from Prehistoric to Medieval Times', *Water 2013, Vol. 5, Pages 1996-2025*, 5(4), pp. 1996–2025. doi: 10.3390/W5041996.

G.de Rooij and A.Luttikholt (2018) 'Proceedings of the Transport and Immersion Operations of the N31 Aqueduct in Harlingen The Netherlands', *TEC*, p. 13. Available at: https://tec-tunnel.com/wp-content/uploads/2018/05/Proceedings-of-the-Transport-and-Immersion-Operations-of-the-N31-Aqueduct-in-Harlingen-The-Netherlands.pdf (Accessed: 27 December 2022).

Gamage, B. G. S. T. *et al.* (no date) 'Piled Raft Foundation System for Tall Buildings'. doi: 10.1007/978-981-15-7222-7_30.

Hale, S. E. *et al.* (2021) 'The reuse of excavated soils from construction and demolition projects: Limitations and possibilities', *Sustainability (Switzerland)*, 13(11), p. 6083. doi: 10.3390/SU13116083/S1.

'immersed tunnels' (no date).

Kamal, M. A. and Khan, M. A. (2022) 'Appraisal of Aqueduct as an Ancient Water Supply Control System View project Priyanka Pahuja'. Available at: https://www.researchgate.net/publication/364517366 (Accessed: 10 November 2022).

Lüthi, D. *et al.* (2008) 'High-resolution carbon dioxide concentration record 650,000-800,000 years before present', *Nature*, 453(7193), pp. 379–382. doi: 10.1038/NATURE06949.

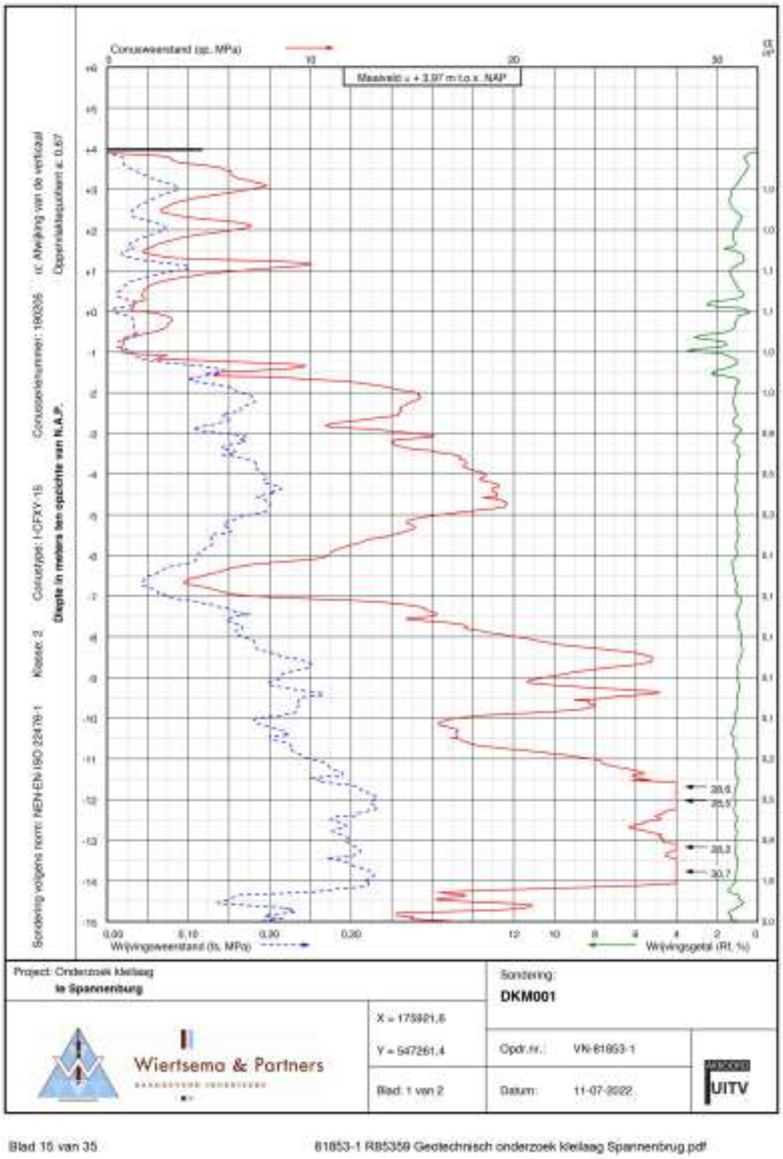
Makusa, G. P. (no date) 'STATE OF THE ART REVIEW SOIL STABILIZATION METHODS AND MATERIALS IN ENGINEERING PRACTICE'.

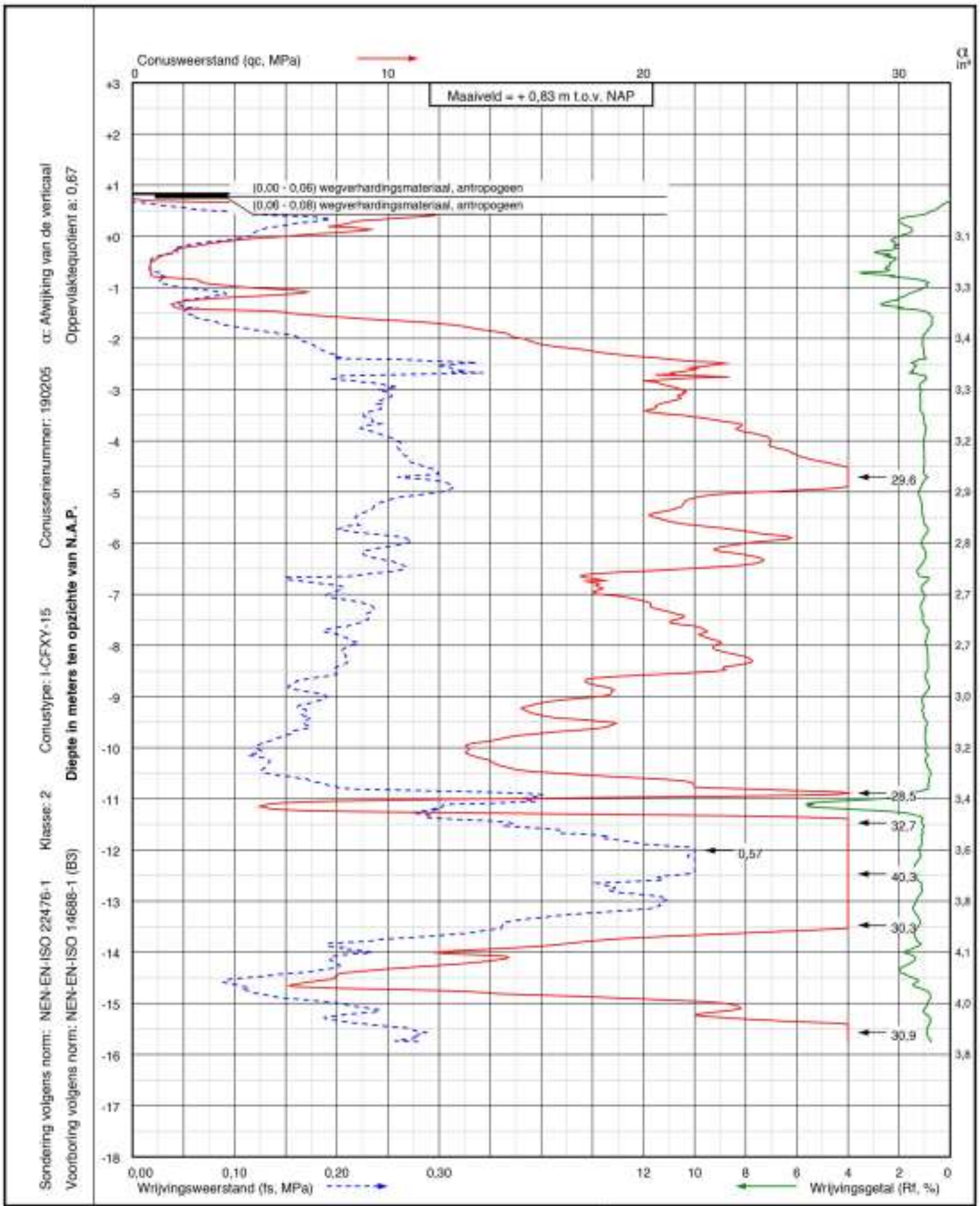
Waterman, R. E. and Brouwer, J. (no date) 'AQUAPUNCTURE©: SUSTAINABLE FUTURE OF INLAND WATERWAYS'.

Zhou, X. *et al.* (2022) 'Development and application of a new ballast water system for immersed tunnel installation: A case study of the Yuliangzhou tunnel in Xiangyang, China', *Tunnelling and Underground Space Technology*, 119. doi: 10.1016/J.TUST.2021.104261.

12. Appendices

12.1. Soil test results

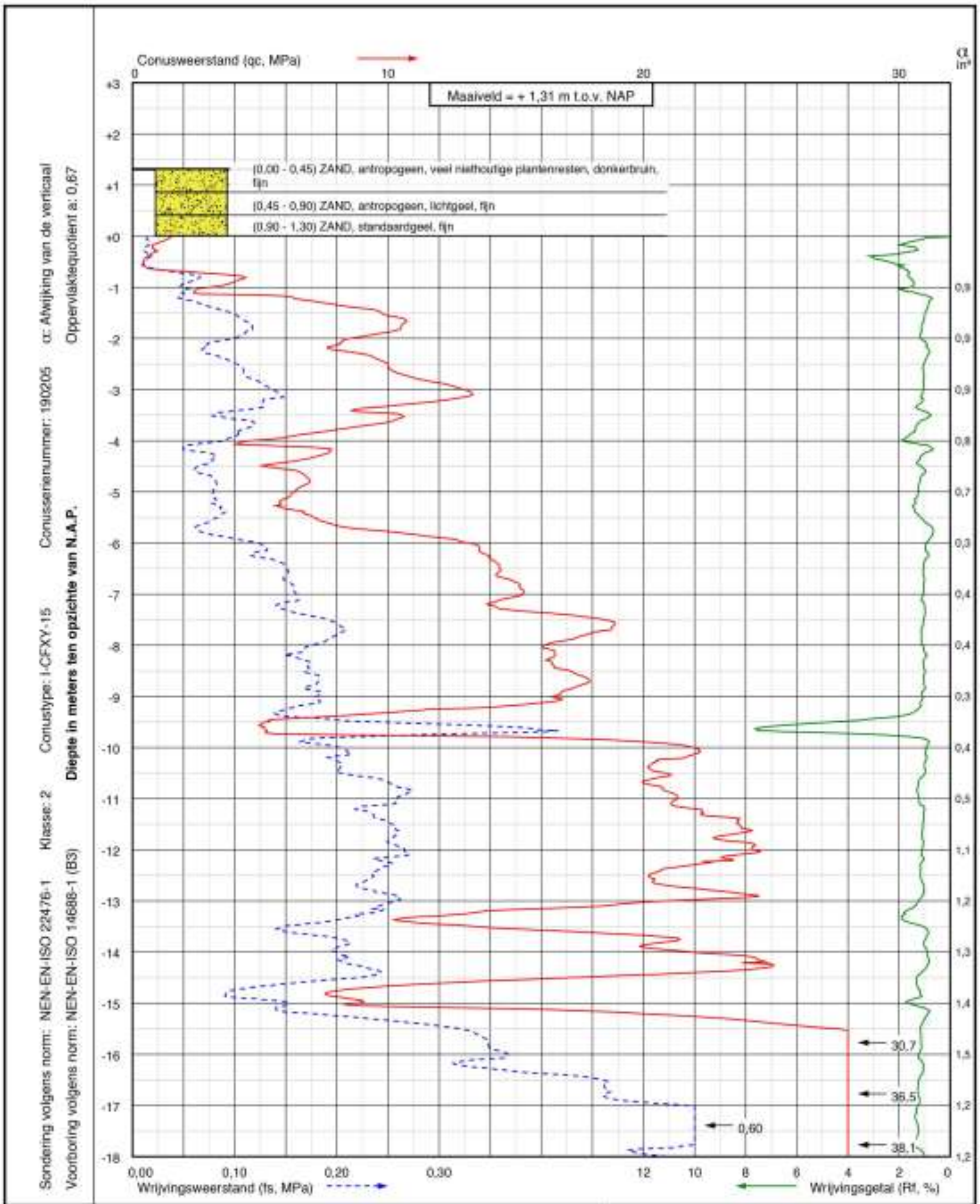




Project: Onderzoek kleilaag **te Spannenburg**		Sondering: **DKM002**
Wiertsema & Partners RAADGEVEND INGENIEURS	X = 175938,3	
	Y = 547215,3	Opdr.nr.: VN-81853-1
	Blad: 1 van 1	Datum: 11-07-2022

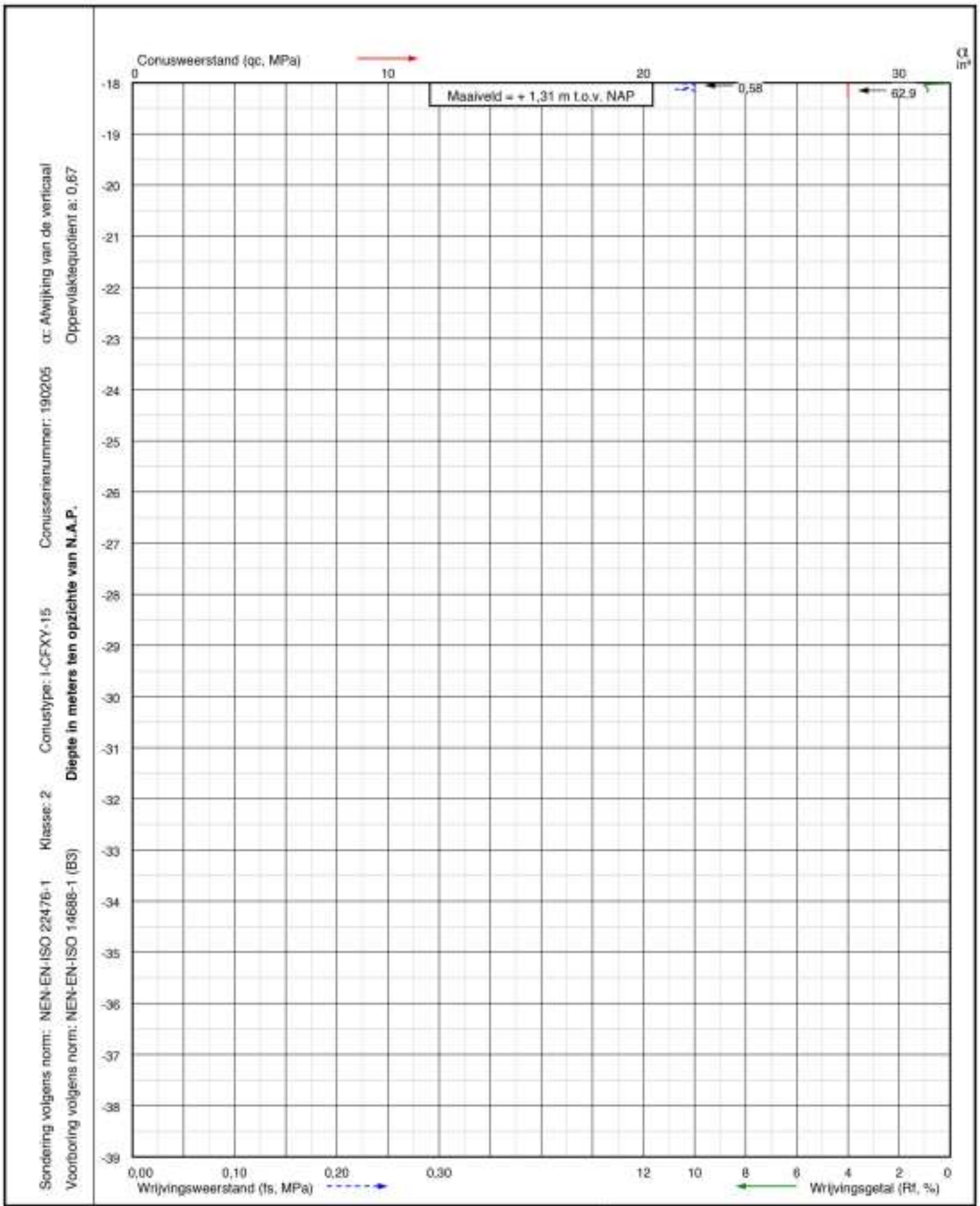
AKKOORD UITV

Blad 17 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf



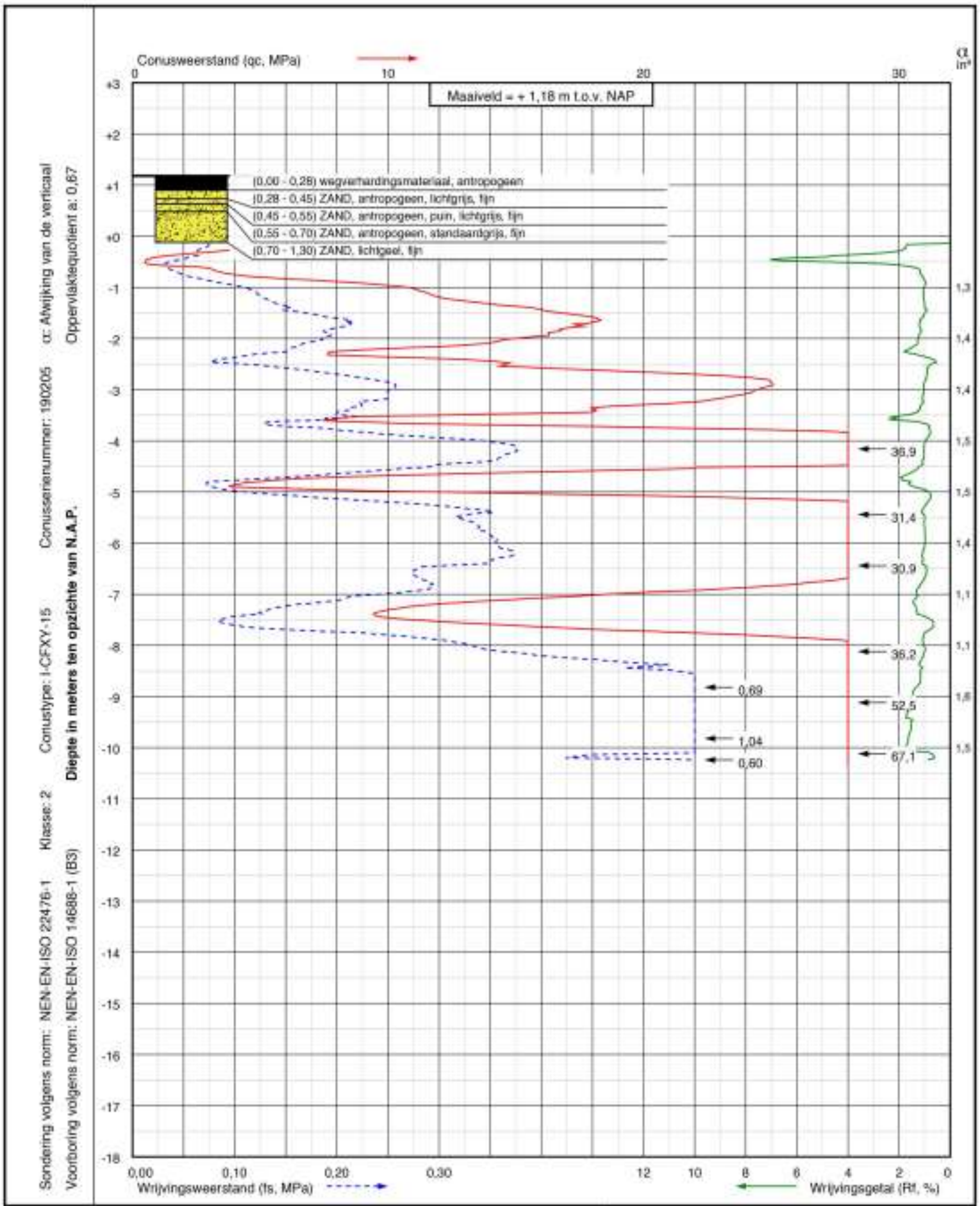
Project: Onderzoek kleilaag **te Spannenburg**		Sondering: **DKM003**	
Wiertsema & Partners RAADGEVEND INGENIEURS	X = 176000,6		
	Y = 547220,7	Opdr.nr.: VN-81853-1	AKKOORD UITV
	Blad: 1 van 2	Datum: 11-07-2022	

Blad 18 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf



Project: Onderzoek kleilaag **te Spannenburg**		Sondering: **DKM003**	
Wiertsema & Partners RAADGEVEND INGENIEURS	X = 176000,6		
	Y = 547220,7	Opdr.nr.: VN-81853-1	AKKOORD UITV
	Blad: 2 van 2	Datum: 11-07-2022	

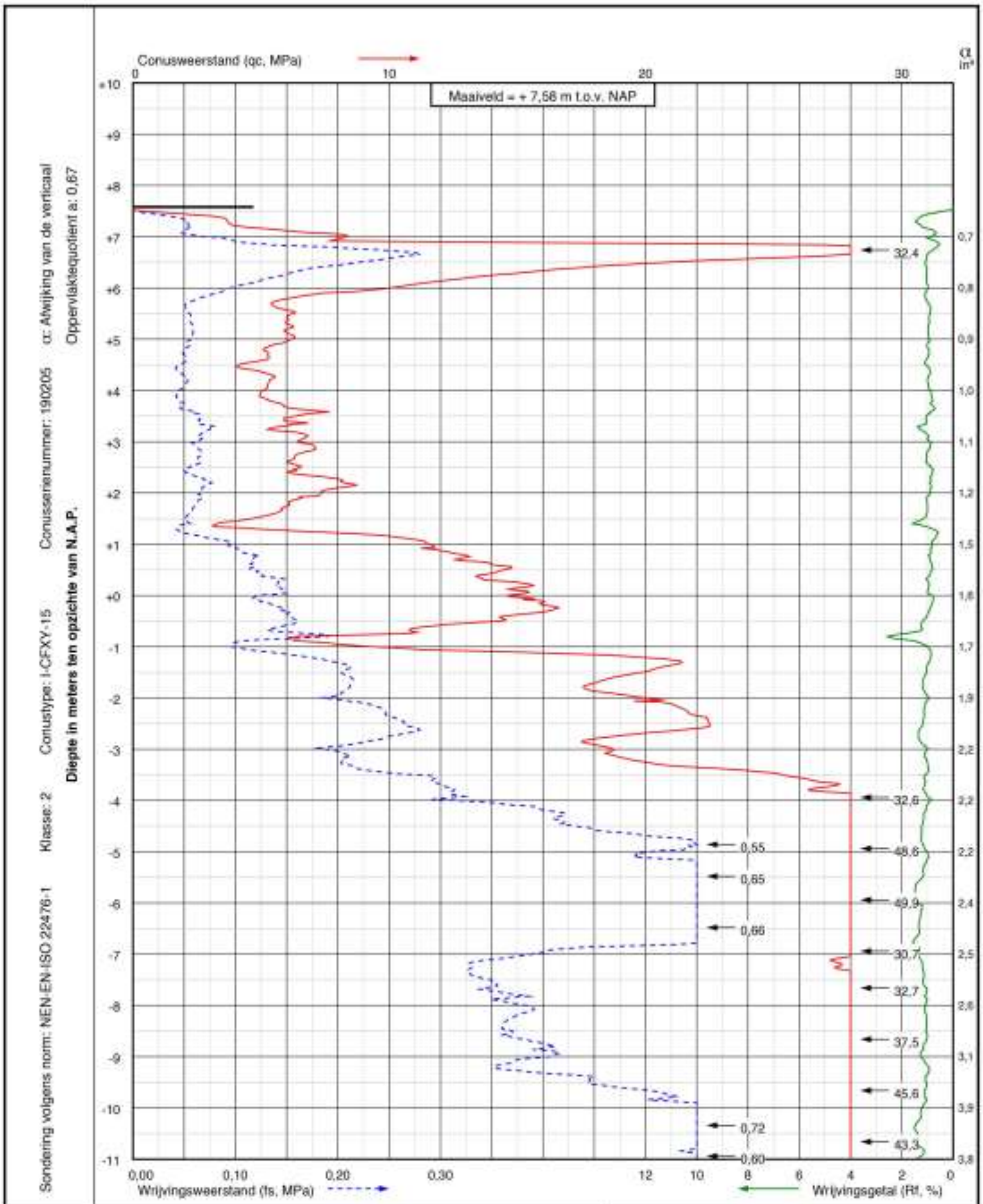
Blad 19 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf



Project: Onderzoek kleilaag **te Spannenburg**		Sondering: **DKM004**
Wiertsema & Partners RAADGEVEND INGENIEURS	X = 175996,4	
	Y = 547150,5	Opdr.nr.: VN-81853-1
	Blad: 1 van 1	Datum: 11-07-2022

AKKOORD UITV

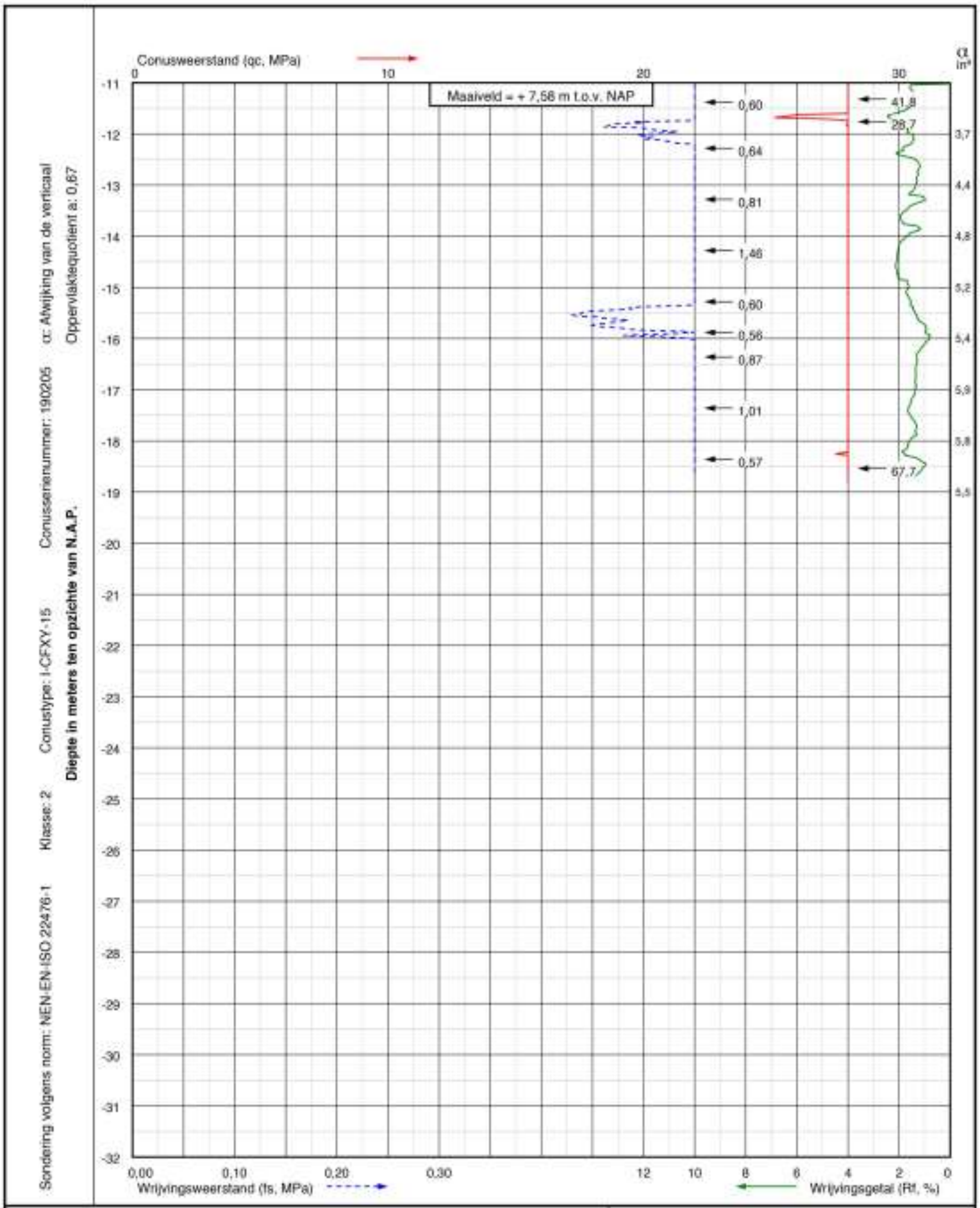
Blad 20 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf



Project: Onderzoek kleilaag **te Spannenburg**		Sondering: **DKM005**
Wiertsema & Partners RAADGEVEND INGENIEURS	X = 175949,4	
	Y = 547096,4	Opdr.nr.: VN-81853-1
	Blad: 1 van 2	Datum: 11-07-2022

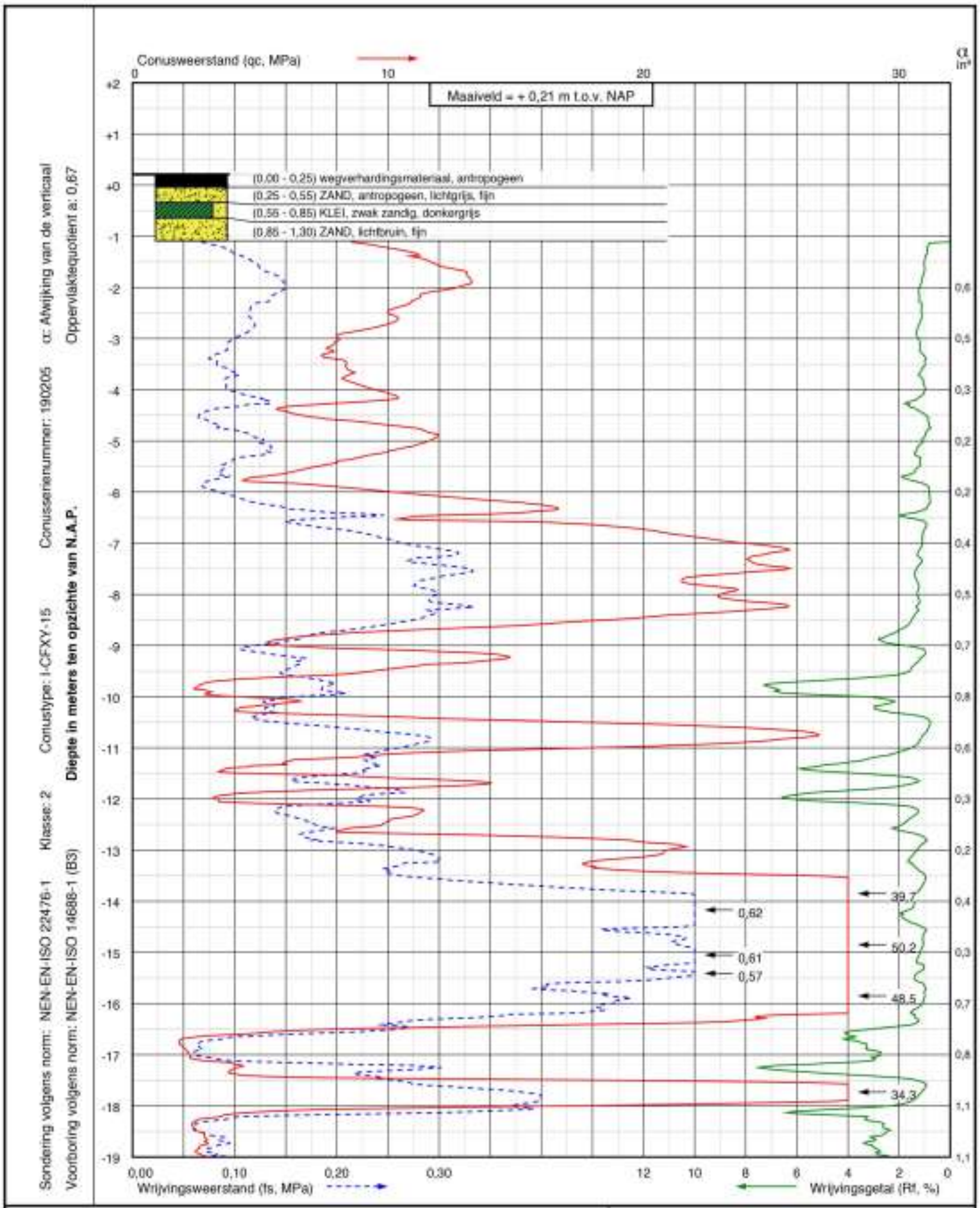
AKKOORD UITV

Blad 21 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf



Project: Onderzoek kleilaag **te Spannenburg**		Sondering: **DKM005**
Wiertsema & Partners	X = 175949,4	
	Y = 547096,4	Opdr.nr.: VN-81853-1
	Blad: 2 van 2	Datum: 11-07-2022

Blad 22 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf



Project: Onderzoek kleilaag
te Spannenburg

Sondering:
DKM007

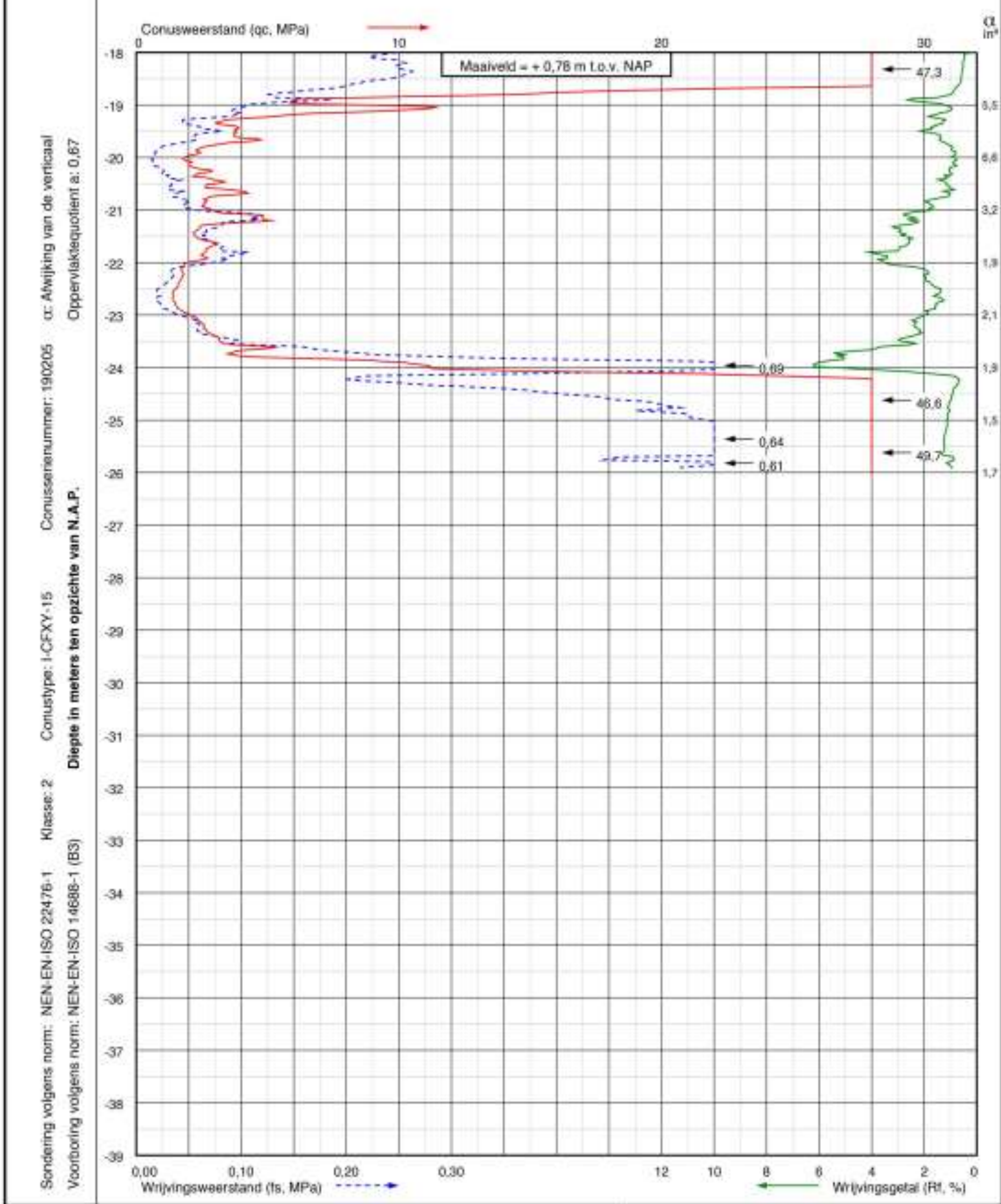
X = 176161,3
Y = 547146,7
Blad: 1 van 2

Opdr.nr.: VN-81853-1
Datum: 11-07-2022

Wiertsema & Partners
RAADGEVEND INGENIEURS

AKKOORD
UITV

Blad 25 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf



Project: Onderzoek kleilaag te Spannenburg		Sondering: **DKM006**	
Wiertsema & Partners	X = 176082,8		
	Y = 547121,9	Opdr.nr.: VN-81853-1	AKKOORD UITV
	Blad: 2 van 2	Datum: 07-07-2022	

Blad 24 van 35 81853-1 R85359 Geotechnisch onderzoek kleilaag Spannenbrug.pdf

12.2. Eared method structural analysis

```
%Unit weights for different materials (Constants)in kN/m3
Y_concrete=25;
Y_w=10;
Y_sat=18;
Y_dry=8
Load_factor=1.1 %for the uplift water pressure
Safety_factor=0.95
%%%%%%SEE Figure for better understanding of calcualtions%%%%%%%%%%%%%%


%Area of cocnrete elements of the aqueduct in m2
Length_ear=2.3   %Length of ears
A_ears=0.95*Length_ear*2   %area of two ears with 2.3 length
A_walls=0.95*4.88*2   % Area of two walls
A_floors=(0.95*21.25)+(0.95*16.65) %Area of two floors
A_b_veh=0    %ballast concrete on vehicle lanes and median b/w lanes
A_b_bike=0.8.*4.25 %ballast cocnrete on bike lane is 1m
A_column=0.40.*3.8   %Concrete column between bike lanes and vehicle lanes

%CONCRETE LOAD
A_mconcrete=A_walls+A_floors+A_ears+A_column %area materials concrete
F_mconcrete=A_mconcrete.*Y_concrete .*Safety_factor  %materials concrete
A_bconcrete =A_b_veh+A_b_bike    %Ballast concrete area
F_bconcrete =A_bconcrete.*Y_concrete.*Safety_factor  %Force from ballast
concrete


%Asphalt load
F_asphalt=0.08*14.75.*Y_concrete .*Safety_factor %asphalt thickness is
0.08m

%LOAD CONCRETE DOWNWARD
F_concrete=(F_bconcrete+F_mconcrete+F_asphalt) %total concrete
force(ballast+material)


%WATER LOAD DOWNWARD ON TOP OF AQUEDUCT
A_submerged= 21.25*1    %width of aqueduct =20.95 including ears
water_level=4.9         %water level on top of structure
F_waterweight=water_level.*A_submerged.*Y_w .*Safety_factor

%SOIL and  WATER LOAD ON EARS

Height_soil=5.83  %height of soil on top of ears
F_soil_ears=(Length_ear.*Height_soil.*2 .*Y_sat ) .*Safety_factor %this
includes water and soil unit weight (10+8)


%WATER UPWARD Force
A_submerged= 21.45*1    % per meter
Structure_height=6.78   %aqueduct height
Water_end_level=water_level+ Structure_height %water level at bottom of
aqueduct
F_water =A_submerged.*Y_w.*Water_end_level   %Boyouncy force at bottom of
aqueduct
```

```
%Total Downward Load of aqueduct elements

F_down=(F_concrete+F_waterweight+F_soil_ears)

%Total Uplifting forces (Boyoyncy)with safet factor (1.1)
F_uplift= F_water*Load_factor  %Water force with the safety factor

%Equilibrium equation
Sum_Forces= F_uplift-F_down   %in kN

Strcuture_Depth=Water_end_level+0.5  %Depth to Nap
Structure_to_clay =19-Strcuture_Depth

if F_uplift <F_down
    disp('Equilibrium achieved')
else
    disp('Equilibrium not achieved')
end
```

Table 14-Results of eared tunnel

Name	Value
A_b_bike	3.4000
A_b_veh	0
A_bconcrete	3.4000
A_column	1.5200
A_ears	4.3700
A_floors	36.0050
A_mconcrete	51.1670
A_submerged	21.4500
A_walls	9.2720
F_asphalt	28.0250
F_bconcrete	80.7500
F_concrete	1.3240e+03
F_down	2.7718e+03
F_mconcrete	1.2152e+03
F_soil_ears	458.5878
F_uplift	2.7559e+03
F_water	2.5054e+03
F_waterweight	989.1875
Height_soil	5.8300
Length_ear	2.3000
Load_factor	1.1000
Safety_factor	0.9500
Strcuture_Depth	12.1800
Structure_height	6.7800
Structure_to_clay	6.8200
Sum_Forces	-15.8705
Water_end_level	11.6800
water_level	4.9000
Y_concrete	25
Y_dry	8
Y_sat	18
Y_w	10

12.3. Immersed method structure analysis

```
%Unit weights for different materials (Constants)in kN/m3
Y_conrete=25;
Y_w=10;
Y_sat=18;
Y_dry=8 ;
Load_factor=1.1 %for the uplift water pressure
Safety_factor=0.95

%Area of cocnrete elements in m2
A_walls=0.9*5.98*2   % Area of two walls
A_floors=1*16.55*2   %Area of two floors
A_b_veh=1.1*8.8    %ballast concrete on vehicle lanes and median b/w lanes
A_b_bike=4.25*2.98 %ballast cocnrete on bike lane
A_column=0.4.*3.8

%CONCRETE LOAD
A_mconcrete=A_walls+A_floors+A_column
F_mconcrete=A_mconcrete.*Y_conrete.* Safety_factor  %materials concrete

A_bconcrete =A_b_veh+A_b_bike   %Ballast concrete area
F_bconcrete =A_bconcrete.*Y_conrete.* Safety_factor  %Force from ballast
concrete



%LOAD CONCRETE DOWNWARD
F_asphalt=0.08*14.75.*Y_conrete .* Safety_factor %asphalt thickness is
0.075m
F_concrete=F_bconcrete+F_mconcrete+F_asphalt  %total concrete
force(ballast+material)


%LOAD WATER  DOWNWARD
A_submerged= 16.55*1
water_level=4.9   %water level on top of structure
F_waterweight=water_level.*A_submerged.*Y_w.* Safety_factor


%WATER UPWARD Force
Structure_height=7.98   %aqueduct height
Water_end_level=water_level+ Structure_height %water level at bottom of
aqueduct

F_water =A_submerged.*Y_w.*Water_end_level   %Boyouncy force at bottom of
aqueduct


%Total  Downward Load of aqueduct
F_down=(F_concrete+F_waterweight)

%Total Uplifting forces (Boyouncy)with safet factor (1.1)
F_uplift= F_water*Load_factor  %Water force with the safety factor
```

```
%Equilibrium equation and Results
Sum_Forces= F_uplift-F_down    %in kN
Strcuture_Depth=Water_end_level+0.5   %Depth to NAP
%the 0.5 stands for the water level
Structure_to_clay =19-Strcuture_Depth

if F_uplift <F_down
    disp('Equilibrium achieved')
else
    disp('Equilibrium not achieved')
end
```

Table 15-Results of immersed tunnel

Name	Value
A_b_bike	12.6650
A_b_veh	9.6800
A_bconcrete	22.3450
A_column	1.5200
A_floors	33.1000
A_mconcrete	45.3840
A_submerged	16.5500
A_walls	10.7640
F_asphalt	28.0250
F_bconcrete	530.6938
F_concrete	1.6366e+03
F_down	2.4070e+03
F_mconcrete	1.0779e+03
F_uplift	2.3448e+03
F_water	2.1316e+03
F_waterweight	770.4025
Load_factor	1.1000
Safety_factor	0.9500
Strcuture_Depth	13.3800
Structure_height	7.9800
Structure_to_clay	5.6200
Sum_Forces	-62.1872
Water_end_level	12.8800
water_level	4.9000
Y_conrete	25
Y_dry	8
Y_sat	18
Y_w	10

12.4. Piled-raft method structure analysis

```
%Unit weights for different materials (Constants)in kN/m3
Y_concrete=25;
Y_w=10;
Y_sat=18;
Y_dry=8
Load_factor=1.1 %for the uplift water pressure
Safety_factor=0.95
%Area of cocnrete elements of the aqueduct in m2
A_walls=0.8*4.88*2   % Area of two walls
A_floors=(0.8*16.35.*2)   %Area of two floors
A_b_veh=0    %ballast concrete on vehicle lanes and median b/w lanes
A_b_bike=0 %ballast cocnrete on bike lane is 1m
A_column=0.4.*3.88  %column b/w bike and vehicle lanes


%CONCRETE LOAD
A_mconcrete=A_walls+A_floors+A_column %area materials concrete
F_mconcrete=A_mconcrete.*Y_concrete.*Safety_factor   %materials concrete
A_bconcrete =A_b_veh+A_b_bike    %Ballast concrete area
F_bconcrete =A_bconcrete.*Y_concrete.*Safety_factor  %Force from ballast
concrete

%Asphalt load
F_asphalt=0.08*14.75.*Y_concrete.*Safety_factor  %asphalt thickness is
0.08m

%LOAD CONCRETE DOWNWARD
F_concrete=F_bconcrete+F_mconcrete  %total concrete force(ballast+material)


%% WATER LOAD DOWNWARD ON TOP OF AQUEDUCT
A_submerged= 16.35*1    %width of aqueduct =20.95
water_level=4.9   %water level on top of structure
F_waterweight=water_level.*A_submerged.*Y_w.*Safety_factor


%% RAFT Foundation Weight
thicknes=0.7   %thickness of the raft foundation
width=16.35    %width of the raft foundation (slab along the aqueduct)
A_Raft=thicknes.*width  %amount of concrete
F_raft=A_Raft.*Y_concrete .*Safety_factor %Weight of the raft foundation


%% %WATER UPWARD Force
A_submerged= 16.35*1    % per meter

Structure_height=6.48   %aqueduct height
Water_end_level=water_level+ Structure_height+thicknes %water level at
bottom of aqueduct
F_water =A_submerged.*Y_w.*Water_end_level   %Boyouncy force at bottom of
aqueduct



%% %%Total Downward Load of aqueduct elements
F_down=(F_concrete+F_waterweight+F_asphalt+F_raft)
```

```
%Total Uplifting forces (Boyouncy)with safet factor (1.1)
F_uplift= F_water*Load_factor  %Water force with the safety factor

%Equilibrium equation
Sum_Forces= F_uplift-F_down   %in kN

if F_uplift <F_down
    disp('Equilibrium achieved')
else
    disp('Equilibrium not achieved')
end
```

Table 16-Results of piled-raft tunnel

C: ▸ Users ▸ nazir

Workspace

Name	Value
A_b_bike	0
A_b_veh	0
A_bconcrete	0
A_column	1.5520
A_floors	26.1600
A_mconcrete	35.5200
A_Raft	11.4450
A_submerged	16.3500
A_walls	7.8080
F_asphalt	29.5000
F_bconcrete	0
F_concrete	888.0000
F_down	1.9045e+03
F_mconcrete	888.0000
F_raft	286.1250
F_uplift	2.1726e+03
F_water	1.9751e+03
F_waterweight	801.1500
Load_factor	1.1000
Safety_factor	0.9500
Structure_height	6.4800
Sum_Forces	268.0518
thicknes	0.7000
Water_end_level	12.0800
water_level	4.9000
width	16.3500
Y_concrete	25
Y_dry	8
Y_sat	18
Y_w	10

12.4.1. Pile design

```
%Unit weights for different materials (Constants)in kN/m3
%% Constants

Y_concrete=25;
Y_w=10;
Y_sat=18;
Y_dry=8 ;
%% Difference between upward and downward forces without piles

%when we considered the dimensions of the aqueduct with 0.9 thickness
F_upward=2173    %upward force due pressure from table (results of piled-
raft tunnel)
F_down =1904 %downward force KN
Resultant=F_upward-F_down
Length =60    %length of the aqueduct


%% Charecteristics of the backfilling soil

%NEN 2012 is used for charecteristic values of the Dutch soil (see figure
in report
%the soil chosen is clay to get higher negative friction
Y_sand=18    %the unit weight of the new soil to treat the location
angle=0.3054  %the internal friction angle of sand soil
Cu=120     %undrained shear strength for sand soil estimated from (NEN2012)

ka=(1-sin(angle))./(1+sin(angle)) %Active rank coefficient
kp=(1+sin(angle))./(1-sin(angle))
Surface_angle= 0.5 .*angle  %surface friction angle of soil
K=(ka+kp)./2    %passive and active factors of soil


%% charecteristics of the piles

L=8           %the length of the piles
D=0.220        %diameter of pile
P =pi.*D      %P :the perimeter of the pile (pi=3.14)

%% Forces generated by each pile
Fn=0.5.*P.*(L.^2).*Y_sand .*K.*tan(Surface_angle) %Negative skin friction
Ap=(pi.*(D.^2))./4   %Base area of the pile
Nc=9     %Ultimate end bearing capacity of soft clay
Fb= Nc *Cu.*Ap  %End bearicing capacity for pile
F_Pile=Fn-Fb    %the generated downward negative skin friction per pile
%% Number of piles and distance between them
Number_of_piles= (Resultant.*Length)./F_Pile
Piles_in_a_group=12  %consider 12 piles in one cross section
Required_pile_groups=Number_of_piles./ Piles_in_a_group
Distance_between_pile_groups=Length./(Required_pile_groups-1)
```

Table 17-Pile design values

C: ▸ Users ▸ nazir ▸ Desktop

Workspace

Name	Value
angle	0.3054
Ap	0.0380
Cu	120
D	0.2200
Distance_between_pile_groups	1.4806
F_down	1904
F_Pile	32.3917
F_upward	2173
Fb	41.0543
Fn	73.4460
K	1.1988
ka	0.5377
kp	1.8599
L	8
Length	60
Nc	9
Number_of_piles	498.2765
P	0.6912
Piles_in_a_group	12
Required_pile_groups	41.5230
Resultant	269
Surface_angle	0.1527
Y_concrete	25
Y_dry	8
Y_sand	18
Y_sat	18
Y_w	10

12.5. Retaining wall design

```
%% Safety factors from Eurocode 07 and Coefficients

%Actions according to (Bond and Schppener ,2013)
DA3=1.35     %unfavorable load safety factor; favorable =1
M=1.25       %Material safety factor
R=1           %Resistance safety factor


%Constants
Y_sat=18   %saturated soil unit weight
Y_w=9.81   %water unit weight
Y_concrete=25  %concrete unit weight


%% Dimensions of the retaingin wall in meters

HA=-12.41      %Height of Aqueduct (eared method as the best one)
GL=1.18    %ground level of DKM003 next to the closed tunnel
L=9        %Width of the base
D=2        %Thickness of the base
d=1     %thickness of the section
B=2       %Width of the toe
WT=14.73   %water table depth
Hp=4       %Passive earth height
angle =0.471343618  %Factored shear angle (32.5 using NEN2012 -Canvas)
%the equation of factoring the angle is angle=atan(tan(32.5)/1.25)=27.006
%then converted to radians

ka=(1-sin(angle))./(1+sin(angle)) %Active rank coefficient
kp=1./ka  %Passive rank coefficient
H0=GL-(HA+d) %Height of ground to tunnel bottom
H=H0+Hp    %Height of RW from road to
C=0.1*H      %Stem thickness of bottom
T=1        %Stem thickness of top


%% Active Pressure (safety factor=1.35)

Pa1=0.5*(1.35*Y_sat.*ka.*H.^2)   %pressure force due to retained soil on
the wing
Pa2=0.5*(Y_w.*WT.^2)  %pressure force due to water retained in the wing
%for water pressure ,no need to use safety factor coefficients Eurocode 07



%% Passive Earth Pressure(safety factor=1)
Pp=0.5*(Y_sat.*kp.*Hp.^2)

%% Buoyouncy Force
F_buoyouncy =(WT.*Y_w.*L./2).*DA3
```

```
%% Dead Load of Retaining wall in kN/m
W1=(Hp-D).*B.*Y_sat  %Weight of the soil in the passive side
W2=Y_sat.*(H-D).*(L-(B+C))  %weight of the soil in the active side
W3=Y_w.*(L-(B+C)).*(WT-D)   %weight of the water in the active side
W4=L.*D.*Y_concrete     %weight of the base
W5=(H-D).*Y_concrete.*(T+C)./2  %wegiht of the wall

%% Moment Calculations around Point P (KNm/m
M1=W1.*(B./2)              %weight of soil moment passive
M2=W2.*(L-(L-(B+C))./2)          %weight of soil moment (active)
M3=W3.*(L-(L-(B+C))./2)          %weight of soil moment (active)
M4= W4.*(L./2)             %Weight of the base moment
M5=W5.*(L./2)              %weight of the walls moment
M_Pp=Pp.*(Hp./3) %weight of the passive earth pressure

Right_Moment=M1+M2+M3+M4+M5+M_Pp  %moment in the right side

M_Pa1=Pa1.*(H./3)
M_Pa2=Pa2.*(WT./3)
M_b=F_buoyouncy.*(2.*L)./3
Left_Moment=M_Pa1+M_Pa2+M_b    %the overturning moment
Overturning_Stability=Right_Moment./Left_Moment     %Rotation equilibrium
checking


%%  Sliding Equilibrium

%the selfweights and the active pressures only contributing to sliding
Coeff=0.63707   %the coeficient of friction between the soil and the
concrete

Resistence_forces=Coeff.*(W1+W2+W3+W4+W5)   %friction resitance to sliding


Sliding_forces=Pa1+Pa2-Pp

Sliding_Stability=Resistence_forces./Sliding_forces

%The sliding safety factor =1.4 which means it is safe against sliding
%% Equilibrium against uplifting

Sum_down_forces=0.63.*(W1+W2+W3+W4+W5)   %downword forces due self-weight

Vertical_stability=Sum_down_forces-F_buoyouncy

if Sliding_Stability | Overturning_Stability |Vertical_stability >1
    disp('Retaining wall is Safe')
else disp('Retaining wall is not Safe')
end
```

Table 18-Retaining wall parameters

Name	Value
angle	0.4713
B	2
C	1.6590
Coeff	0.6371
d	1
D	2
DA3	1.3500
F_buoyouncy	877.8454
GL	1.1800
H	16.5900
H0	12.5900
HA	-12.4100
Hp	4
ka	0.3754
kp	2.6636
L	9
Left_Moment	1.7435e+04
M	1.2500
M1	72
M2	8.8781e+03
M3	4.2217e+03
M4	2025
M5	2.1822e+03
M_b	5.2671e+03
M_Pa1	6.9427e+03
M_Pa2	5.2255e+03
M_Pp	511.4047
Overturning_Stability	1.0261
Pa1	1.2555e+03
Pa2	1.0643e+03
Pp	383.5535
R	1
Resistence_forces	1.9600e+03
Right_Moment	1.7890e+04
Sliding_forces	1.9362e+03
Sliding_Stability	1.0123
Sum_down_forces	1.9382e+03
T	1
Vertical_stability	1.0604e+03
W1	72
W2	1.4027e+03
W3	666.9910
W4	450
W5	484.9351
WT	14.7300