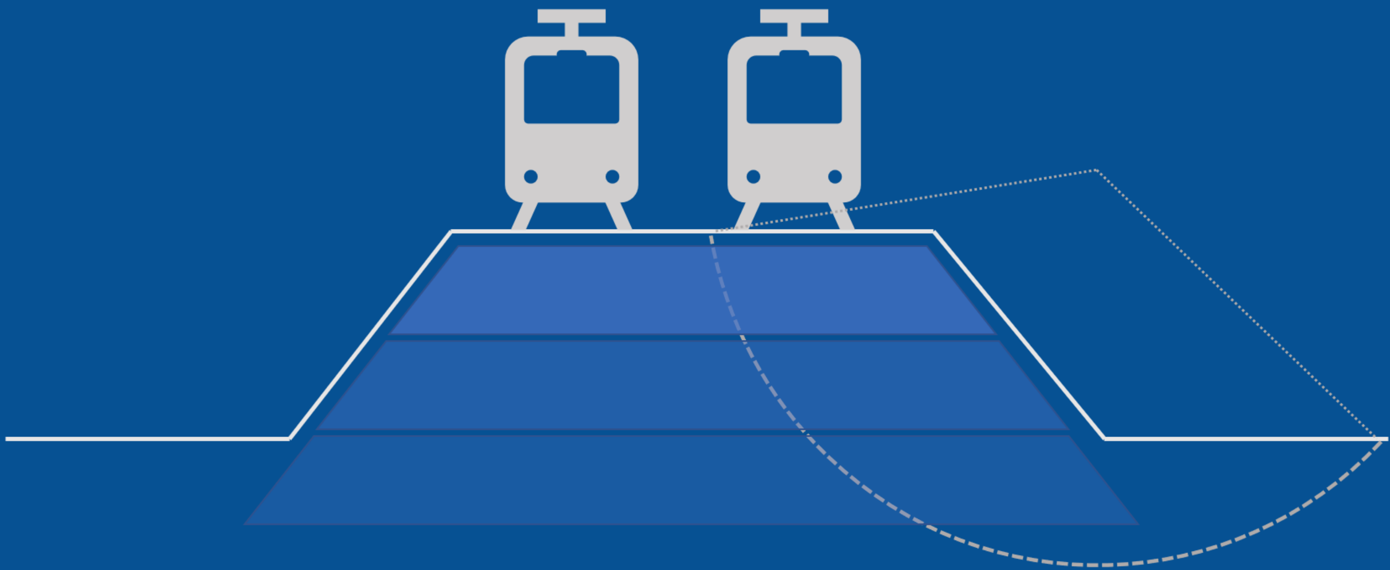
Sustainable Soft Soil Stabilization

A Comprehensive Analysis and Multi-Criteria Assessment for Ensuring Stable and Sustainable Foundations for the Railway Embankment Expansion between Leiden and Utrecht, the Netherlands



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In association with ARCADIS

COLOFON

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PREFACE

As a bachelor civil engineering student at the HZ University of Applied Sciences, I had the invaluable opportunity to undertake my graduation internship with Arcadis, a renowned engineering firm specializing in infrastructure projects. During my time at Arcadis, I was provided with the tools, connections, and support necessary to embark on an exciting and challenging research endeavor. I would like to express my sincere gratitude to Arcadis for their guidance and encouragement throughout this journey.

The motivation behind this research stems from the recognition of the significance of stable and sustainable railway infrastructure. By identifying the most suitable soil stabilization method for the design of a railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk, I aimed to contribute to the field of civil engineering and promote the development of resilient transportation networks.

Throughout this study, I adopted a bachelor student's perspective, utilizing the resources and expertise available to me. While my experience and knowledge may be limited compared to seasoned professionals, I approached the research with enthusiasm and a willingness to learn. I embraced the challenges and utilized both qualitative and quantitative methods to explore the research question.

I would like to extend my appreciation to Arcadis and especially my supervisor Harm Loonstra for providing me with this internship opportunity and supporting me throughout the research process. Furthermore, I would like to express my gratitude to Lelie Shemirani for her invaluable support and guidance throughout this research. Her expertise and mentorship have been instrumental in equipping me with the necessary skills and knowledge to undertake this study.

I would like to express my gratitude to Rik Bisschop, Jeroen Bonnes, Sebastiaan Jongen, Onno van der Wal, and Jan Ruigrok for their invaluable expert judgment and generous sharing of knowledge throughout this project. Their insights and expertise have greatly contributed to the depth and quality of this research. Additionally, I would like to extend my thanks to the entire ProRail project team for granting me the opportunity to be a part of this project and for providing me with valuable firsthand experience that goes beyond mere information.

Lastly, I thank my mentor Christophe Egyed whose commitment to practical education has empowered me to apply the theoretical concepts learned in the classroom to a real-world engineering scenario.

With this preface, I invite you to delve into the subsequent chapters of this research report, which document my findings, analysis, and conclusions. I hope that this study contributes to the existing body of knowledge in the field of soil stabilization for railway embankments, while also highlighting the valuable experience gained as both an intern at Arcadis and a bachelor civil engineering student at HZ University of Applied Sciences.

SUMMARY

This research study aims to determine the most suitable soil stabilization method for ensuring a stable and sustainable foundation for the design of a railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk. The research question is addressed through a comprehensive analysis using both qualitative and quantitative methods.

The importance of this research lies in the need for a reliable and durable foundation for the railway embankment expansion, considering factors such as stability (examined using D-Geo Stability), sustainability, costs, risks, and maintenance. By identifying the most effective soil stabilization method, the study aims to contribute to the design and construction practices in the field of railway infrastructure.

To answer the research question, a systematic approach is adopted, including a Multi-Criteria Analysis (MCA) as the quantitative method. The MCA involves evaluating different criteria and considering three selected variants: the conventional pile mattress, method of preloading, and geotextile encased columns. The qualitative methods involve assessing assumptions, limitations, and available data to inform the analysis.

The result of the MCA indicates that the geotextile encased columns emerge as the most suitable soil stabilization method based on the evaluated criteria. These columns demonstrate high stability and sustainability. While the method has not yet been used for the stabilization of railway embankments in the Netherlands, the long-term cost-effectiveness and low maintenance requirements makes them a preferred choice.

In conclusion, the research establishes that implementing geotextile encased columns would ensure a stable and sustainable foundation for the railway embankment expansion. The study highlights the limitations, assumptions, and areas for further research, such as the inclusion of rolling stock characteristics, (critical) train speed effects, subsidence from peat oxidation, and obtaining more comprehensive and accurate data.

Recommendations for follow-up research include conducting field studies to collect accurate data, monitoring the long-term performance of geotextile encased columns, assessing economic feasibility in more detail, investigating the environmental impact, and exploring emerging soil stabilization methods. These recommendations aim to enhance knowledge, improve design practices, and contribute to the development of sustainable and resilient railway infrastructure.

Overall, this research provides valuable insights into soil stabilization methods for railway embankments, offering a foundation for informed decision-making and promoting the long-term stability and sustainability of railway infrastructure.

SAMENVATTING

Dit onderzoek heeft tot doel de meest geschikte methode voor bodemstabilisatie te bepalen om een stabiele en duurzame fundering te waarborgen voor het ontwerp van de uitbreiding van een spoorwegverhoging tussen Zoeterwoude Oost en Hazerswoude-Rijndijk. De onderzoeksvraag wordt beantwoord door middel van een uitgebreide analyse met zowel kwalitatieve als kwantitatieve methoden.

De relevantie van dit onderzoek ligt in de behoefte aan een betrouwbare en duurzame fundering voor de uitbreiding van de spoorwegverhoging, waarbij factoren zoals stabiliteit (getoets in D-Geo Stability), duurzaamheid, kosten, risico's en onderhoud in overweging worden genomen. Door de meest effectieve methode voor baanstabilisatie te identificeren, beoogt het onderzoek bij te dragen aan ontwerp- en constructiepraktijken op het gebied van spoorweginfrastructuur.

Om de onderzoeksvraag te beantwoorden, wordt een systematische aanpak gehanteerd, waaronder een Multi-Criteria Analyse (MCA) als kwantitatieve methode. De MCA omvat de evaluatie van verschillende criteria en de beoordeling van drie geselecteerde varianten: de conventionele paalmatras, methode van voorbelasting en geotextielomhulde kolommen. De kwalitatieve methoden omvatten het beoordelen van aannames, beperkingen en beschikbare gegevens om de analyse te informeren.

Het resultaat van de MCA geeft aan dat de geotextielomhulde kolommen naar voren komen als de meest geschikte methode voor baanstabilisatie op basis van de geëvalueerde criteria. Deze kolommen vertonen een hoge stabiliteit en duurzaamheid. Hoewel de methode nog niet is toegepast voor de stabilisatie van spoorwegverhogingen in Nederland, maken de kosteneffectiviteit op lange termijn en lage onderhoudsvereisten ze tot een voorkeurvariant.

Concluderend stelt het onderzoek vast dat het implementeren van geotextielomhulde kolommen een stabiele en duurzame fundering zou waarborgen voor de uitbreiding van de spoorwegverhoging. Het onderzoek benadrukt de beperkingen, aannames en gebieden voor verder onderzoek, zoals het opnemen van kenmerken van trein materieel, effecten van de (kritische) treinsnelheid, bodemdaling door veenoxidatie en het verkrijgen van meer uitgebreide en actuele gegevens.

Aanbevelingen voor vervolgonderzoek omvatten het uitvoeren van veldstudies om nauwkeurige gegevens te verzamelen, het monitoren van de langetermijnprestaties van geotextielomhulde kolommen, het gedetailleerder beoordelen van economische haalbaarheid, het onderzoeken van de milieueffecten en het verkennen van opkomende methoden voor bodemstabilisatie. Deze aanbevelingen beogen kennis te vergroten, ontwerppraktijken te verbeteren en bij te dragen aan de ontwikkeling van duurzame spoorweginfrastructuur.

Al met al biedt dit onderzoek waardevolle inzichten in methoden voor bodemstabilisatie bij spoorwegverbredingen, waarmee een basis wordt gelegd voor weloverwogen besluitvorming en het bevorderen van langetermijnstabiliteit en duurzaamheid van de spoorweginfrastructuur.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AHN	Actueel Hoogtebestand Nederland (Current Height Database of the Netherlands)
APPM	Advies- en Project management bureau (Advice and Project Management Firm)
BS	Bovenkant Spoorstaaf (Top of Rail)
C	Cohesion
CBS	Centraal Bureau voor de Statistiek (Central Bureau for Statistics)
Ch.	Chapter
CPT	Cone Penetration Test
CROW	Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek
CRS	Customer Requirement Specification
EN	European Norm
EPS	Expanded Polystyrene
FS	Factor of Safety
GEC	Geotextile Encased Columns
I&W	Ministry of Infrastructure and Water management
IFCO	Intensief Forceren Consolidatie Ondergrond (Intensive Consolidation of Subsoil)
ILT	Inspectie Leefomgeving en Transport
ISO	International Standardization Organization
KLIC	Kabels and Leidingen Informatie Centrum (Database Cables and Pipes)
km	Kilometer
kN	Kilonewton
LCC	Life Cycle Costing
m	Meter
MCA	Multi-Criteria Analysis
mm	Millimeter
MPa	Megapascal
NAP	Normaal Amsterdams Peil (Normal Amsterdam Level)
NEN	Nederlands Normalisatie-instituut
NS	Nederlandse Spoorwegen (Dutch Railways)
OVS	Ontwerp Voorschrift Spoor
PBL	Planbureau voor de Leefomgeving
PDOK	Publieke Dienstverlening Op de Kaart (Dutch Geodatabase)
PET	Polyethylene terephthalate, form of polyester
PM	Pile Mattress
qc	Cone Resistance
Rf	Friction Number
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
RLN	Richtlijn Lichte Railvoertuigen en Tramlijnen
RWS	Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management)
SLT	Sprinter Light Train
SNG	Sprinter Nieuwe Generatie
TRL	Technology Readiness Level

INTRODUCTION

The first chapter sets the stage for the project by introducing the research and addressing the global challenges associated with soft soil stabilization. The significance of the research topic and the growing importance of finding effective solutions for stabilizing soft soils is discussed. Additionally, the chapter introduces the organization involved in the project and provide insights into its structure and background. Since the research is part of an ongoing exploration phase, certain assumptions are necessary to establish the boundaries of the report and clarify its scope. These assumptions are made either due to limited information available or to ensure a clear focus for the research. The chapter concludes by stating the research question that guides the investigation and outlines the approach that is followed to carry out the research effectively.

1

1.1 Background Information

The world of infrastructure has always faced challenges regarding building on weaker subsoil. Construction on such soils require deeper understanding of the soil mechanics and introduces greater costs. Thus, villages and towns were constructed on the strong and stable gravel and sandy soils. However, the need for constructing on less strong soils began to increase, as cities continued to grow. Alongside this trend of increasing urbanization, comes the challenge of better understanding weak subsoils and implementing methods to stabilize such soils.

The increasing urbanization rate causes the growing importance of smart, widely applicable methods to stabilize a variety of these long-avoided substrates to meet the demands of urbanization. One of these demands includes the ability to move fast, efficiently, and above all sustainably, from one place to another: the mobility transition. This transition is having been set in motion to spread the urbanization over a greater area. This combination of the increasing importance of high-quality infrastructure, while the urbanization rates grow, is challenging countries around the world. Both aspects are discussed in greater detail in this subchapter.

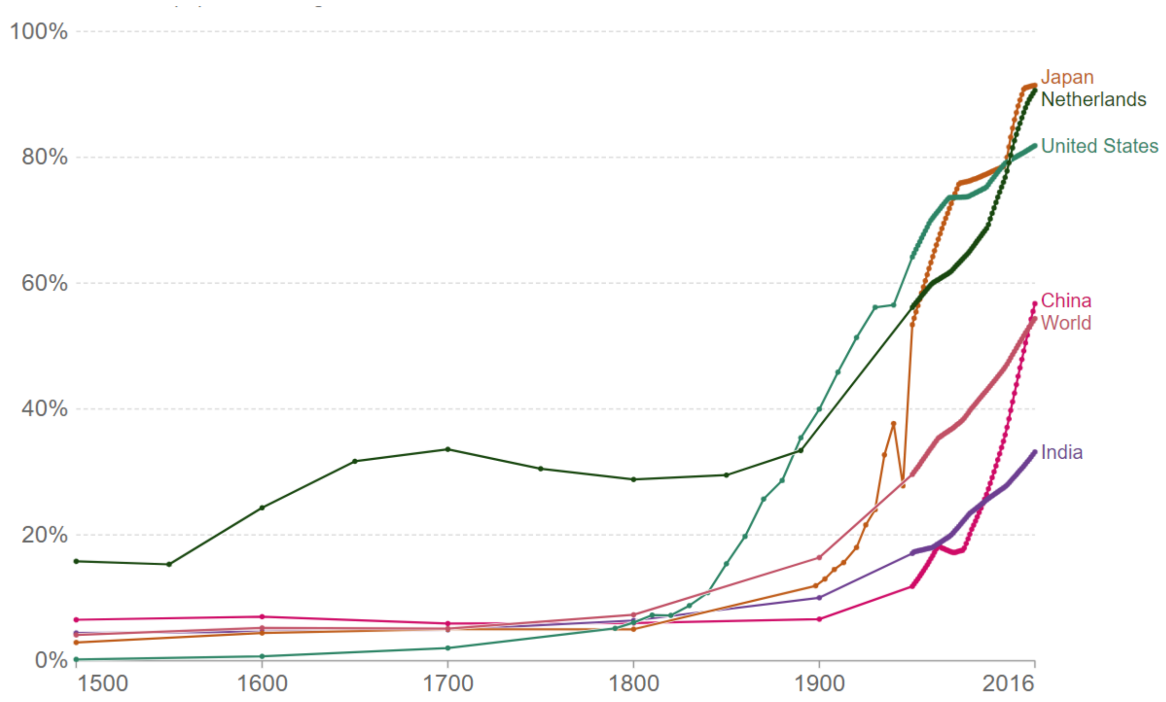


Figure 1 Share of the total population living in urban areas (OWID, 2018)

1.1.1 Building on Weak Soils

Weak soils are a global phenomenon and addressing the stabilization of these soils is becoming increasingly important. The expansion of urban areas often requires construction on substrates that are not ideal, such as soft clay and loose sand. These weaker soils have limited bearing capacity, making them unable to adequately support the load of superstructures. Consequently, implementing solutions is crucial to enhance the bearing capacity of weak soils before commencing construction on them.

The Earth's surface is comprised of diverse soil layers, each with its own distinct properties, and these layers collectively influence the bearing capacity of the soil within a specific project area. **Figure 2** provides an overview of the various soil types found worldwide. The map clearly demonstrates the prevalence of weaker soils in the topsoil. Although the method of soil stabilization may vary depending on the thickness of these weaker layers, the figure underscores the global relevance of addressing soft soil stabilization. By recognizing the significance of weak soils and their impact on construction, the implementation of effective soil stabilization techniques becomes crucial for sustainable and safe infrastructure development worldwide.

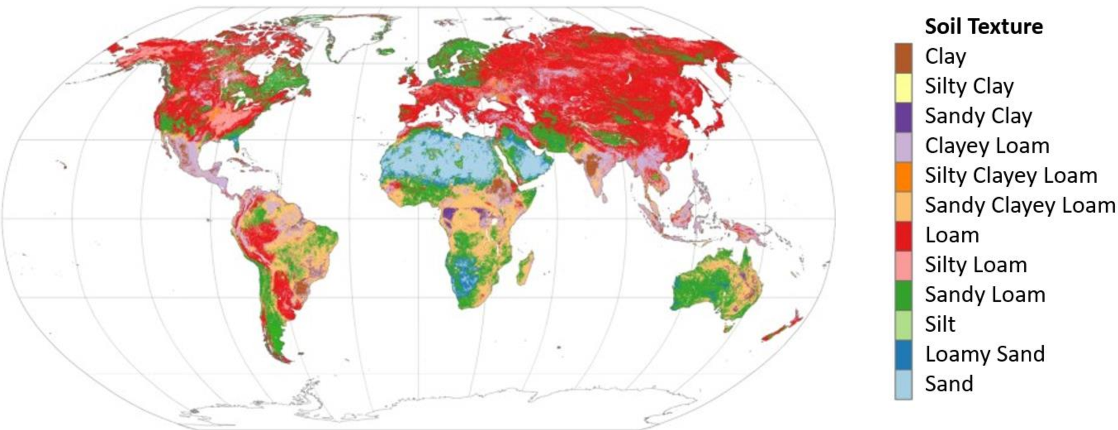


Figure 2 Map of soil texture classes in the soil surface (0 cm) (Wade Ross, 2019)

Soil Stabilization

Soil stabilization involves enhancing the shear strength parameters of unbound material to enhance its bearing capacity. This process becomes necessary when the existing soil composition is unsuitable for supporting structural loads, such as organic particles or soils containing notable amounts of peat, silt, or clay. Generally, soils possess unfavourable engineering properties unless they undergo treatment to improve their physical characteristics, see **Chapter 2.6 – Fundamentals of Soft Soil Stabilization**. Stabilization enhances soil shear strength and manages shrink-swell properties, ultimately improving the load-bearing capacity of sub-grades for pavement and foundation support. Soil stabilization methods encompass two main categories: mechanical stabilization, which modifies soil gradation, and chemical stabilization, which involves incorporating synthetic substances into the soil (T.S. Amhadi, 2018).

Soft Subsoils in The Netherlands

Examining the Netherlands in more detail reveals significant variations in subsoil types within this relatively small country. Urban areas predominantly occupy clayey and sandy substrates. However, with urbanization and the shift towards sustainable mobility, there is a growing need to extend development onto weaker subsoils, such as peat.

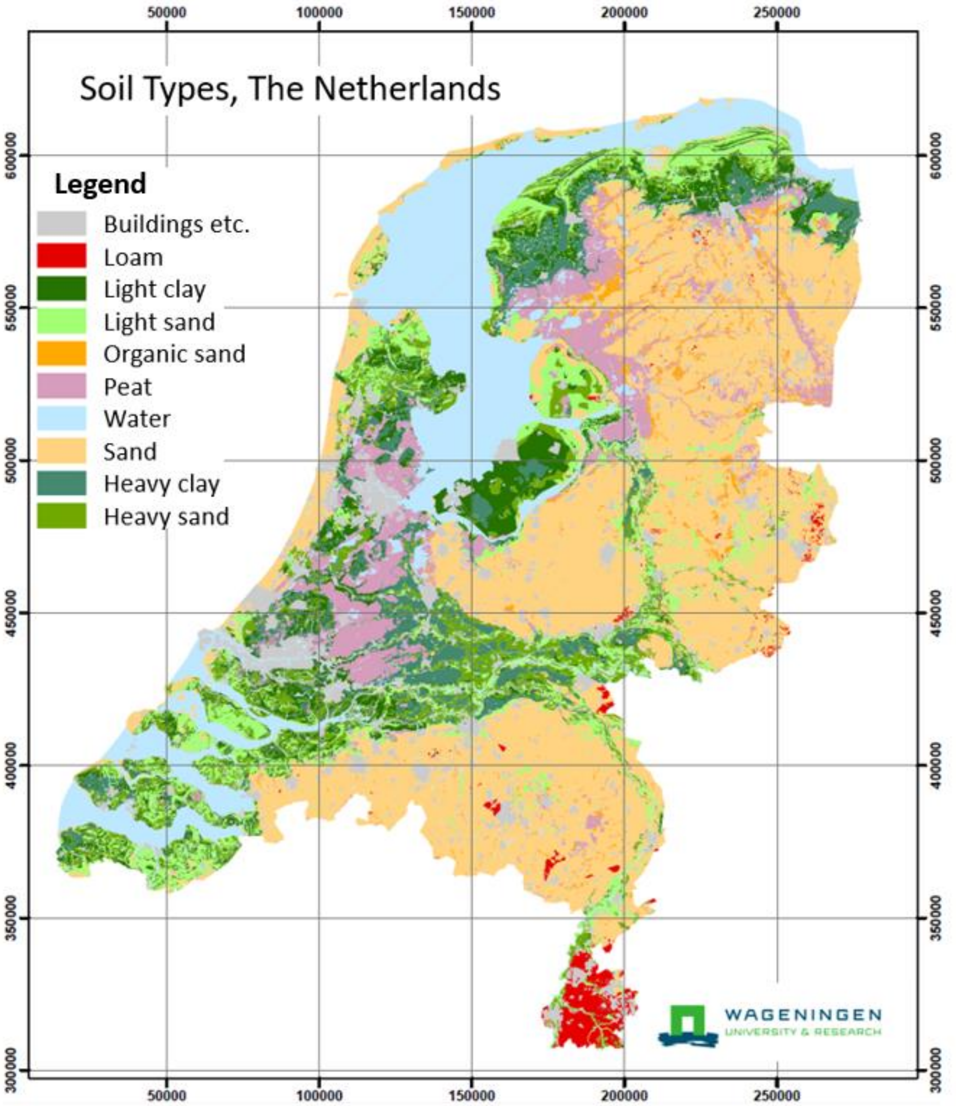


Figure 3 Map of different soil types in The Netherlands (WUR, 2020)

Traditional soft soil stabilization methods, like using a sand body (cunet) or installing concrete foundation piles beneath a reinforced slab, have been historically effective in the Netherlands. Nevertheless, these approaches are costly and have substantial negative environmental impacts in terms of resource extraction, implementation, and their effects on ecosystems. Therefore, exploring more innovative and sustainable soil stabilization techniques, like geotextile encased columns and deep soil mixing, is crucial (Zane Vincevica-Gaile et al., 2021).

As sustainability is becoming of increasing importance in almost every sector including the transportation and construction sector, so does the significance of sustainable construction methods, including soil stabilization. The Dutch government invests in innovative construction methods that are cost-effective and sustainable. The latter is defined as 'meeting the needs of the present without compromising the ability of future generations to meet their own needs' (United Nations, 1987). Soil stabilization methods should therefore not only improve the physical properties in favor of engineering purposes but should use durable materials and should not negatively impact its surroundings. Driven by the desire to improve the sustainability of construction processes, more opportunity is given to investigating the applicability of innovative soil stabilization methods. The latter is frequently conducted in combination with the so-called mobility transition that is arising in the Netherlands.

1.1.2 The Mobility Transition

As recent technologies change the way people work, travel and transport goods, there is an increasing need for transitions to more sustainable ways of living. As mentioned before, the world is changing rapidly, both stimulated and driven by the mobility transition. Mobility must be optimized, better connected and more sustainable to best meet people's current and future needs.

For this reason, the Dutch Ministry of Infrastructure and Water management has drawn up a program, named ''*Toekomstbeeld* OV 2040'' (I&W, ProRail, MRA, MRDH, 2019), to envision the mobility transition by 2040. The aim is to significantly improve the product 'rail' throughout the Netherlands. Many connecting railway lines benefit from the improvements on the railway and its attraction to the surrounding area (Rijn, 2020).

One of the affected railway lines is the connecting railway Leiden-Utrecht. The provinces of South Holland and Utrecht, Ministry of I&W, municipalities of Leiden and Utrecht, the national railway operation Nederlandse Spoorwegen (NS) and rail operator ProRail are working together to improve the Leiden-Utrecht rail link. This project, called *Leiden-Utrecht Beter Bereikbaar* ('*Leiden-Utrecht Better Connected*'), aims to improve the region's accessibility, strengthen development opportunities along the line, and increase the robustness of the broader rail system (ProRail, 2020).

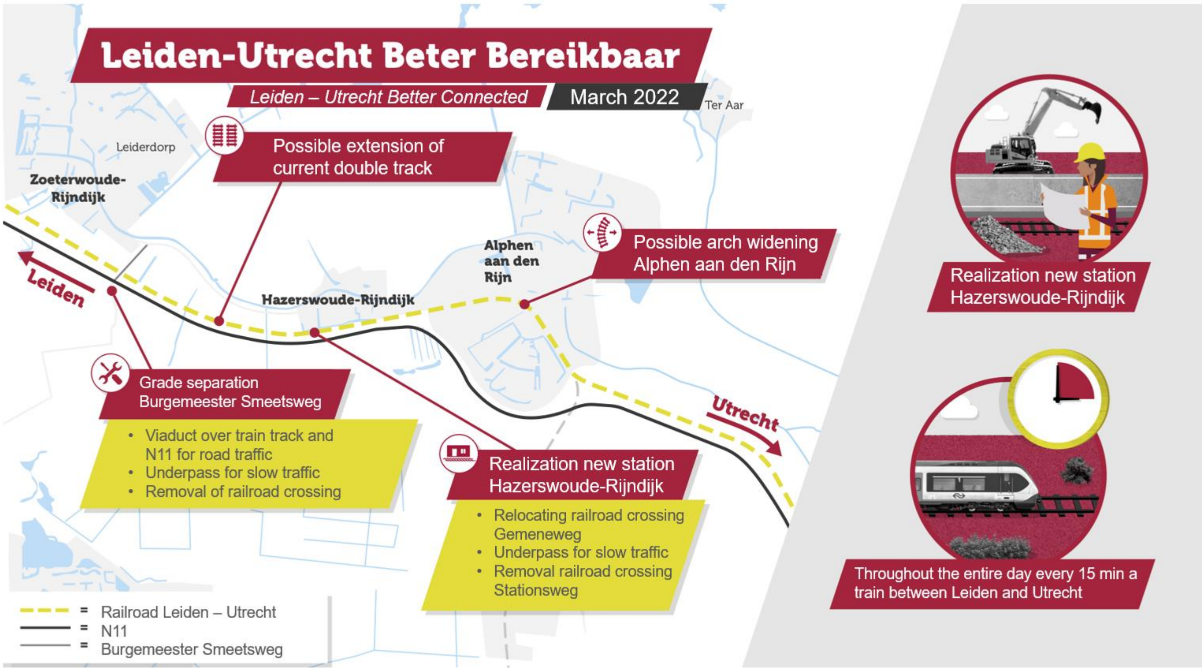


Figure 4 Project Overview Leiden-Utrecht Better Connected (ProRail, 2021)

1.1.3 Hazerswoude-Rijndijk

The village of Hazerswoude-Rijndijk confronts the dual challenge of urbanization, necessitating construction on weak soils, and the ongoing mobility transition. Situated within the Leiden-Utrecht connection, a vital part of the Netherlands' main rail network, Hazerswoude-Rijndijk plays a crucial role in the public transportation infrastructure. However, the area is also located within the renowned "Green Heart" (Dutch: Het Groene Hart), a vast expanse of open peat meadows nestled in the heart of the Randstad region. Designated as a national landscape, these wetlands along the old Rhine River historically served agricultural and peat production purposes due to the difficulties posed by the soft soils (CBS, 2013). Today, the primary functions of the Green Heart encompass agriculture, nature preservation, and recreational activities. With its protective status, striking a balance between development benefits and safeguarding this area presents an ongoing challenge.

Within the project *Leiden-Utrecht Beter Bereikbaar*, this constant trade-off is one of the key parts of the project. The project therefore includes a variety of activities and possible design concepts. Corresponding to **Figure 4**, the realization of new station Hazerswoude-Rijndijk is part of project HOV Leiden-Utrecht. In addition, a train halts twice an hour in each direction at the new Hazerswoude-Rijndijk halt in the future. The scope of the project includes the realization of a new halt on the north side of the track, which should be expandable in the future to account for possible future double track expansion and a grade-separated transfer opportunity (Arcadis, 2016).

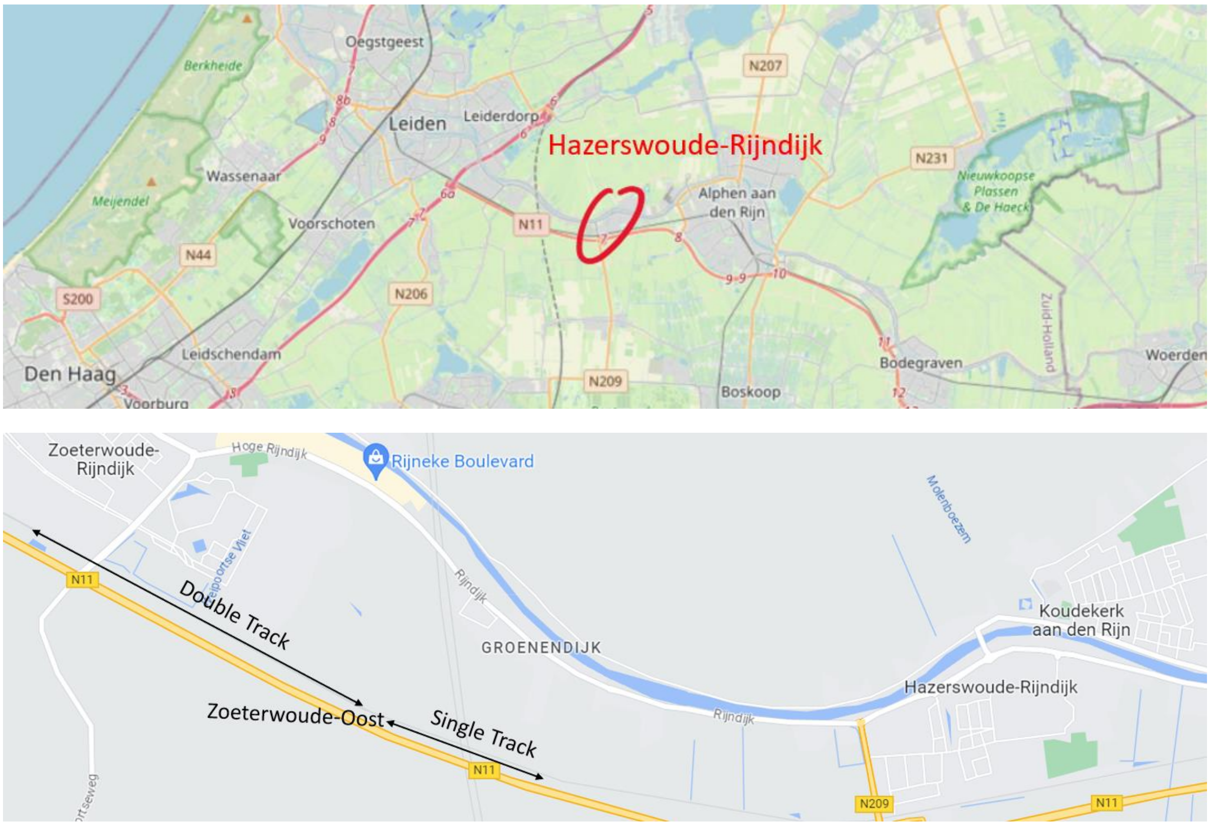


Figure 5 Location of Hazerswoude-Rijndijk (OpenRailwayMap, 2023)

These developments play an increasingly significant role in future endeavours for both Leiden, Alphen aan den Rijn and the region. Engineering and design consultancy office Arcadis has been awarded a contract by rail operator ProRail to work on the *Leiden-Utrecht Beter Bereikbaar* project. Thus, Arcadis works on the design for the Hazerswoude-Rijndijk station. As part of the possible infrastructural changes, the extension of the current double track at Zoeterwoude-Oost is to be investigated see **Figure 5**.

1.1.4 Arcadis

With their motto of "Improving Quality of Life," Arcadis is a global leader in providing sustainable design, engineering, and consultancy solutions for both natural and built assets. Their mission revolves around creating livable and thriving environments where people and communities flourish. A key focus for Arcadis is enhancing mobility by enabling sustainable transportation of people and goods within and between cities. They are dedicated to tackling the world's greatest challenges by offering innovative and sustainable solutions that have a positive impact on people's lives. Arcadis operates through three main divisions: Mobility, Resilience, and Places. Their extensive reach spans over 70 countries, with more than 36,000 employees working across 250 offices worldwide (Arcadis, 2022).

The graduation internship is conducted within the Mobility department of Arcadis. **Appendix A – Organizational Chart, Mobility Department** provides an overview of the subdivisions within the division, showcasing the diverse range of expertise and focus areas within the department.

Figure 6 Organizational Chart Arcadis Nederland B.V. (Arcadis, 2022)

1.2 Problem Statement

The project area is located along the banks of the old Rhine River and is characterized by predominantly peat and clay soils. Historically, these soil types have been considered challenging for construction due to the time-consuming and expensive site preparation required. **Figure 3** provides an overview of the different soil layers present in the area, highlighting the prevalence of peat and clay. Additionally, **Figure 7** illustrates the pattern of urban development, with cities predominantly expanding on more stable soil (cohesion>100 MPa) types while areas with weaker soils (cohesion< 25MPa) remain relatively undeveloped.

Figure 7 Rail track along Hazerswoude-Rijndijk (OpenRailwayMap, 2023)

The weak subsoils (C< 25 MPa) in the project area have been found to have a negative impact on the current train track. Research indicates that the track does not meet the required performance level specified by the NEN8700 standards (APPM, 2019). The NEN8700 sets a specific level of performance that the track structure must meet to ensure its functionality and safety (NEN, 2017). However, ProRail, the rail operator, considers the track to be "safely usable in accordance with the current timetable" (SpoorPro, 2019). According to ProRail, the track has been consistently used in recent years without any incidents of track instability. Therefore, the current scope of the *Leiden-Utrecht Beter Bereikbaar* project does not include an investigation into improving the geotechnical performance of the existing track.

Moreover, the project includes an increase in train frequency to four trains per hour in each direction, outside rush hour as of 2026. In addition, two of the four trains stop at the extra halt at Hazerswoude-Rijndijk (Arcadis, 2023). The latter would result in a timetabling shift, as a result of lost traveling time by stopping at the new halt Hazerswoude-Rijndijk. This lost travel time is problematic, as this delays arrival in Leiden and Alphen aan den Rijn, which in turn results in a loss of connection to other train services. In addition, this railway line consists mostly of a single track with specific double track passing points in order for trains in opposite directions to pass each other. Due to the lost travel time, these passing points are not at the right location anymore, causing further delays.

During the research conducted in 2016, the solution to the issue of lost travel time was found to be an increase in train speed. Therefore, the current rail network would provide ample leeway when implementing the increase in train speeds to continue running while ensuring smooth transfers between the transfer stations Leiden and Alphen aan den Rijn along the line (ProRail, 2023). However, since the project was restarted in 2023, the introduction of new regulations has necessitated a larger minimum clearance time for train operations. This means that additional time is now required between the arrival and departure of trains at sections of the line where only a single track is present and parts of the line where two tracks are present.

On top of the regulatory changes, recent experiences with speed increases on the railway lines that have poorer geotechnical performance are negative (ProRail, 2021). Due to these recent experiences and the geotechnical performance of the Utrecht-Leiden railway line, ProRail is hesitant to increase the speed on the Utrecht-Leiden railway line. This, along with a lengthened halting time at Hazerswoude-Rijndijk, would in fact require a partial extension of the existing double-track line between Hazerswoude and Zoeterwoude-East (ProRail, 2023).

In contrast to the current track, newly built tracks are in fact part of the scope for the investigation into improvement of the geotechnical performance. Therefore, gaining more insight in cost-effective ways of soil stabilization for the construction of a second track, while minimizing the impact on the existing track, is of valuable importance. Research on suitable stabilization methods on clay and peat soils is not only interesting for the success of this project as building on weak soils has become not only a national but also a global challenge.

1.2.1 Subsidence of the Railway Embankment

The stability of the track body causes changes in the geometry of the track body. One of the causes is subsidence due to peat degradation. Soil movement in the Netherlands is caused by a series of causal mechanisms, with soil subsidence occurring in addition to heave. Soil movement occurs over different time scales. In shorter time frames, such as hours to days, factors like heavy precipitation or the dewatering of construction pits play a significant role. Over longer periods of several years to decades, the effects of mining activities and irreversible peat degradation become apparent. Within the project area, subsidence is mainly influenced by the latter factor (PBL, 2015).

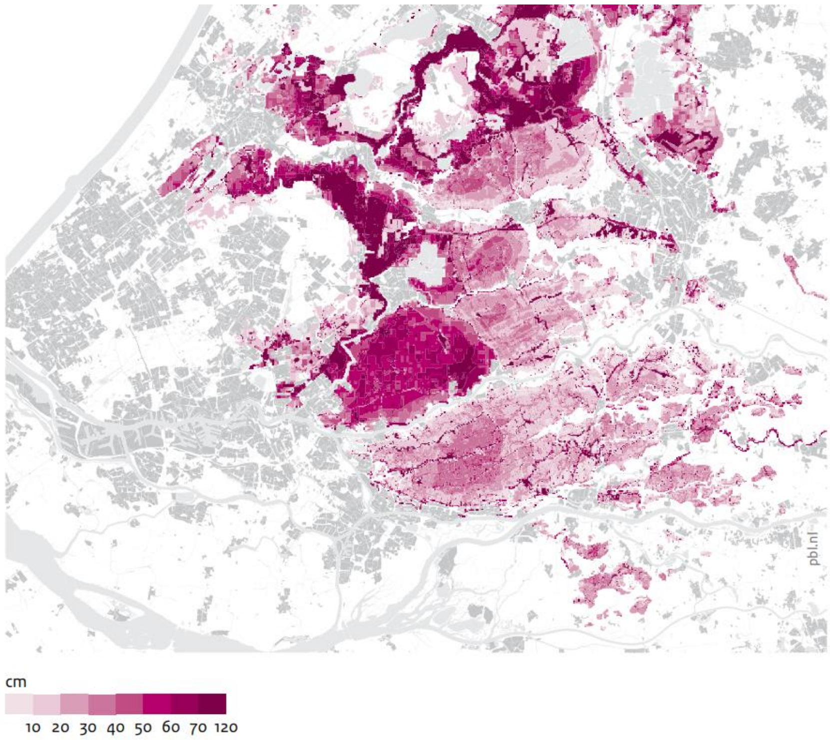


Figure 8 Expected Subsidence as a result of Peat Oxidation, 2010-2050 (PBL, 2015)

The peat soil is subsiding, not only due to the high loads on top of the subsoil, but also because of drainage within the area. Pumping out water results in subsidence due to oxidation in the soil (Heide, 2015). The result of both causes is shown in SkyGeo's subsidence map, see **Figure 9** (SkyGeo, 2020). A soil movement map was produced by processing complex radar data from satellites through the InSAR measurement points. InSAR (Interferometric Synthetic Aperture Radar) is a proven technique for measuring ground motion. Satellites take images of the earth, which are combined to calculate ground surface movements. The InSAR data in the subsidence map are estimates of displacements.

Figure 9 illustrates the estimated annual subsidence in millimeters, indicating the average displacement rate of -7.5 mm/year over a four-year period. This subsidence plays a significant role in the instability of the track under its current conditions.

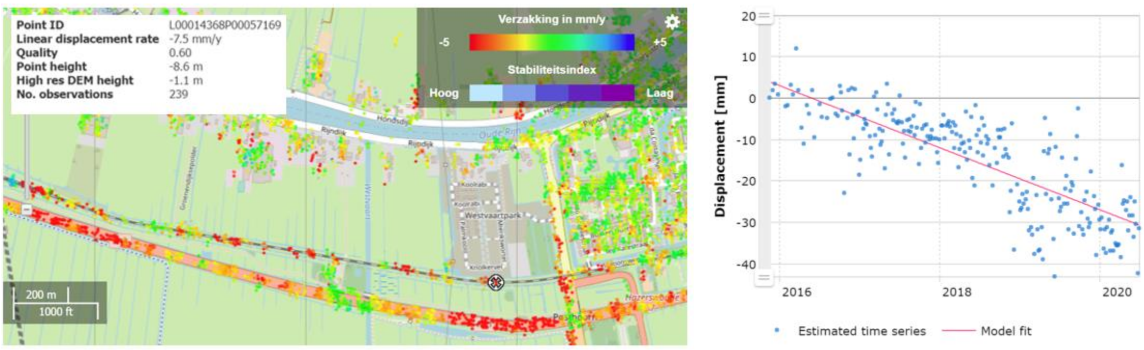


Figure 9 Soil Movement Map and the Estimated Subsidence in mm/year (SkyGeo, 2020)

1.3 Goals and Objectives

The aim of this study is to examine sustainable and cost-effective methods of soil stabilization for the weak subsoils of the train track between Leiden-Utrecht in The Netherlands. The study involves simulating and evaluating different soil stabilization methods using a representative soil sample. The objective is to assess the feasibility of implementing these methods for the extension of the double track between Hazerswoude and Zoeterwoude-East. The focus is on developing a stable and sustainable solution, and further details regarding the criteria are discussed in subsequent chapters. Assumptions are made to define the research's scope and narrow down the focus before formulating the research question and sub-questions.

This study aims to investigate sustainable and cost-effective methods of soil stabilization for the weak subsoils of the train track between Leiden-Utrecht in The Netherlands. The goals of this study are to evaluate different soil stabilization methods through simulation and analysis, assess their feasibility for the extension of the railway embankment between Hazerswoude and Zoeterwoude-East, and develop a stable and sustainable solution that meets the specific requirements of the project. The objectives include conducting a literature review, evaluating, and selecting different methods, analyzing based on a multi-criteria analysis and comparing the results, and presenting the findings and recommendations. By achieving these goals and objectives, this study aims to provide valuable insights into soil stabilization for the railway embankment expansion while ensuring stability and sustainability.

1.4 Assumptions

Given the complexity and broad scope of the project area, which includes the construction of a new station, overall design considerations, and various stakeholders with evolving requirements, this research report establishes certain assumptions to define the scope of the study. These assumptions are necessary to focus the research and address specific aspects, such as the construction of a double track and the integration of the neighborhood with the highway. As stakeholders and clients have not yet finalized their preferences, these assumptions provide a framework for analysis and decision-making within the project's current context.

1.4.1 Design Option: Single or Double Track

Project *Leiden-Utrecht Beter Bereikbaar* is still in its exploration phase. Therefore, little has been decided on the various design options. The two most far-reaching decisions involve connecting the N209 on either side of the tracks, and whether to incorporate a double track. The latter is still being investigated and explored. However, little research is published regarding the options of expanding the double track to Hazerswoude-Rijndijk as these plans are not definite yet.

ProRail has conducted a comprehensive timetable simulation to assess the feasibility of integrating a new Hazerswoude-Rijndijk station into the existing timetable without the need for an additional track. The section between Leiden and Woerden primarily consists of single tracks with limited junctions. Currently, train crossings occur at Bodegraven, Alphen aan den Rijn, between Zoeterwoude East and Zoeterwoude West, and just before Leiden as per the established timetable. The introduction of the new Hazerswoude-Rijndijk halt would result in increased travel time for sprinter trains between Alphen aan den Rijn and Zoeterwoude East. This examination specifically considers the single-tracked timetable and assumes that the new station is not served by Intercity trains. ProRail's research findings indicate that scheduling two sprinter trains per hour on the single-tracked connecting line within a 30-minute interval is not feasible given the existing operational constraints (ProRail, 2023).

To solve the shortfall in time, two possible solutions are proposed by ProRail:

- Extending the double track on the east side of Zoeterwoude East (towards Hazerswoude). Initial estimate is that to solve the time deficit, the double track would have to be extended by approximately 1 km;
- Additional measures (on top of speed increase west of Alphen aan den Rijn) to allow trains between Bodegraven and Zoeterwoude East to increase their speed.

Incorporating the new Hazerswoude-Rijndijk station has implications for the transfer to Gouda in Alphen aan den Rijn. Limiting the extra travel time resulting from the new station is of importance to ensure sufficient transfer times at the stations. Both solutions aim to address the time deficit and maintain adequate transfer times. However, the possibility of increasing train speed is uncertain due to the measured poorer geotechnical performance of the current track. On the other hand, extending the double track offers more opportunities for innovation and long-term improvement of the rail network. Therefore, the assumption is made that extending the double track is part of the project scope.

1.4.2 Design Option: Underpass or Level Crossing

The second high-impact design decision is the consideration of either an underpass or level crossing. The new timetable increases the number of trains passing Hazerswoude-Rijndijk. As a result, the current level crossing is closed to cars, cyclists, and pedestrians several times per hour. The current junction between road and rail traffic is therefore not favorable in combination with the increasing train traffic. For this reason, various structures are being considered to permanently separate both networks to guarantee smooth traffic flows.

Figure 10 Aerial View of the Infrastructure around Hazerswoude-Rijndijk (Google Maps, 2022)

The N209 (Gemeneweg) currently crosses the railway at ground level. The increasing number of passing trains is not the only factor affecting the current intersection between rail and road. In fact, west of Hazerswoude, houses are being built, see **Figure 11**. This therefore results in an increase in car traffic on the Gemeneweg (BGSV, 2016). For reasons of safety and effectiveness, the crossing between rail and road would ideally be permanently grade-separated. Possibilities such as an overpass or underpass are being discussed, which require different construction methods and thus have different influences on the structure. The developments within the project area, including the construction of the new neighborhood and a grade-separated railroad crossing is not considered in this research. This decision has been made as the effects of the grade-separated railroad crossing on the rail embankment require deeper understanding and include more design challenges.

Figure 11 Developments within the Westvaartpark area. Current situation top left, future situation top right and bottom (BGSV, 2016)

1.4.3 Change in Rolling Stock

One assumption pertains to the change in rolling stock usage. Currently, the route is served by Intercity trains, which are equipped for Intercity services. However, ProRail plans to replace these with "lightweight" rolling stock typically used for Sprinter services. This transition aims to maintain track stability, especially when running four trains per hour in each direction throughout the day. Therefore, the Intercity rolling stock is to be substituted with Sprinter rolling stock, specifically the SLT (Sprinter Light Train) and SNG (Sprinter New Generation) models. **Table 1** provides an overview of the various rolling stock types, showcasing the average weight and speed for each model. Despite the increased number of trains, the use of lightweight rolling stock helps maintain a similar load on the track body and a consistent risk profile (Ministry of I&W, 2023). However, the change in rolling stock is not considered in the variant study on soft soil stabilization for the railway embankment expansion. Instead, the embankment's load from the train is based on the standard load specified in the Eurocode, as explained in **Chapter 2.4 – Boundary Conditions and Limitations**.

Table 1 Overview Rolling Stock Types (NS, 2023)

Train Type	Description
Intercity	Intercity trains are designed for long-distance travel, connecting major cities, and providing a faster and more comfortable journey compared to regional trains. These trains typically have higher speeds and fewer stops, allowing passengers to reach their destinations quickly. The weight of intercity trains varies depending on the specific model and configuration. On average, an intercity train weighs between 200 and 300 metric tons.

	In terms of speed, intercity trains are designed to operate at higher speeds compared to regional or commuter trains. The average speed of intercity trains typically ranges from 120 to 160 kilometers per hour.
SLT	the Sprinter Light Train (SLT) is a type of rolling stock used for regional and suburban services. The weight of a Sprinter Light Train in the Netherlands varies depending on the specific configuration. On average, an SLT trainset weighs around 180 to 200 metric tons. The average operating speed of an SLT train in the Netherlands is typically around 100 to 130 kilometers per hour.
SNG	The Sprinter New Generation (SNG) is another type of rolling stock used for regional and suburban services in the Netherlands. The weight of a Sprinter New Generation trainset in the Netherlands varies depending on the specific configuration. On average, an SNG trainset weighs around 150 to 170 metric tons. The average operating speed of an SNG train in the Netherlands is typically around 120 to 140 kilometers per hour.

1.4.4 Speed

Currently, the maximum speed on the track along Hazerswoude-Rijndijk is set at 130 km/h, as indicated in **Figure 12**. While the maximum speed remains unchanged in the upcoming years, the average speed is affected by the new Hazerswoude-Rijndijk halt (Arcadis, 2016). When determining the geotechnical soil stabilization methods for new infrastructure design, the maximum allowed speed is typically considered. Although there may be a significant difference between the maximum speed and the recorded average speeds, this research focuses solely on the maximum speed as a guideline and does not consider the variance between the two.

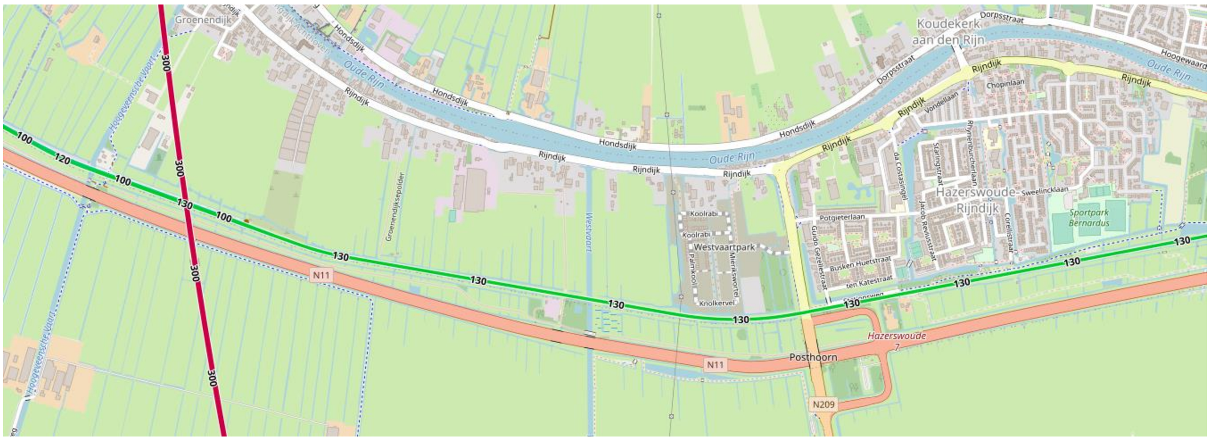


Figure 12 Overview of Maximum Speeds in km/h (OpenRailwayMap, 2023)

1.4.5 Subsidence as result of the Peat Oxidation

The stability of the track body causes changes in the geometry of the track body. One of the causes is subsidence due to peat degradation, see **Chapter 1.2.1 – Subsidence of the Railway Embankment**. **Figure 9** shows the estimated subsidence in millimeters per year. The average displacement rate over the course of four years is estimated to be -7,5 mm/year. This displacement contributes to the instability of the track in its current as well as future situation. As depicted in **Figure 9**, the highway south of the railway embankment is measured to be prone to subsidence despite being constructed on a pile mattress (RWS, 2023). The subsidence as a result of the peat oxidation is not considered in this variant study as finding a solution that is not impacted by this phenomenon is challenging.

1.4.6 Limitations of the Scope

The project scope outlined by ProRail is extensive, but certain limitations have been established based on assumptions and starting points from feasibility studies and exploration documents, in collaboration with relevant stakeholders. ProRail has requested an investigation into the expansion of a double track to accommodate the construction of a new halt at Hazerswoude-Rijndijk. However, there are no specific plans regarding the length of the extension beyond the current endpoint at Zoeterwoude East (km 24.6), as shown in **Figure 13** and **Appendix B – Technical Drawings Train Track k 23.4 – 25.2**. Therefore, the starting point for the newly constructed double track to be at km 24.6. The precise design elements such as level crossings or underpasses have not been decided, so the area surrounding the new station are not included in this research report. The different road structures have a significant impact on soil stabilization parameters. Hence, the extension of the double track "ends" at km 23.5. This choice allows for the delineation of potential influences from track structures, leading to a more accurate assessment of the final design.

To summarize, the following assumptions have been made to confine the research scope:

- The scope is outlined by assuming the expansion to a double track between 23.5-24.6 km;
- The scope is limited vertically and horizontally by only considering influences within the slip plane of the railway embankment, assuming only rotational slope failure;
- Developments within the area, including the restructuring of the Gemeneweg are not considered;
- Preferably, the current track remains in its current state and is not/minimally influenced by the construction of a second track (ProRail, 2023);
- Assuming the double track to be leveled at an elevation similar to that of the existing single track.

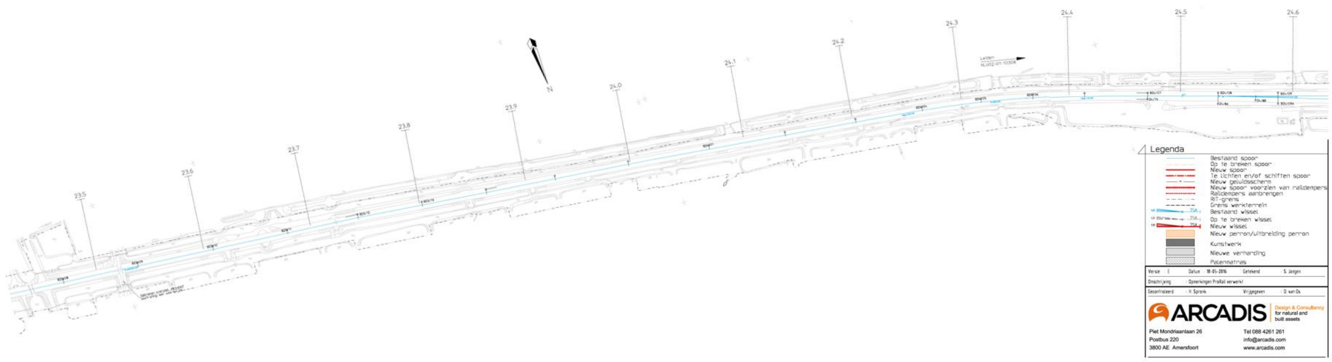


Figure 13 Technical Drawing Track km 23.5 – 24.6 (Arcadis, 2016)

1.5 Research Question

This bachelor thesis answers the main research question:

What soil stabilization method is best implemented to ensure a stable and sustainable foundation for the design of the railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk?

Additionally, the following sub-questions are formulated:

- **What is the current (geotechnical) state of the train track between Zoeterwoude East and Hazerswoude-Rijndijk?**
- **What is the desired situation for the expansion of the train track?**
- **Who are the stakeholders and what are their desires regarding the expansion of the track?**
- **What subsoils are found along the train track?**
- **What methods are proposed to stabilize the subsoil at Hazerswoude-Rijndijk?**
- **What methods are promising and worthwhile to simulate and evaluate the soil stabilization?**
- **What software is proposed to measure geotechnical stability?**
- **What recommendations are to be made based on the obtained results?**

1.6 Research Approach

The research approach adopted for this project has been shaped by the collaborative efforts between Arcadis and ProRail during the collaboration days. These sessions provided valuable insights and inputs from both parties, allowing for a comprehensive understanding of the project requirements and objectives. With a focus on delivering a geotechnical report that meets the necessary standards, the research approach incorporates a systematic and thorough investigation of the soil stabilization methods, considering the specific needs and challenges of the project area. By adhering to established guidelines and requirements, the research aims to provide practical and effective solutions for the expansion of the railway infrastructure while ensuring long-term stability and sustainability.

1.6.1 Collaboration Days Arcadis - ProRail

The extension of the railway embankment between Zoeterwoude-East and Hazerswoude is part of the project *Leiden-Utrecht Beter Bereikbaar*. The companies work closely together and meet physically once a fortnight at the ProRail office in Utrecht. Attending these collaborative days has been important in the process of formulating the research report and obtaining input regarding assumptions, guidelines and wishes stated by ProRail. The collaboration days give greater insight into the why's and how's of the project and the decisions that have been made. Given the exploratory phase of the project, few decisions have yet been documented and/or made public. For this reason, the decision is made to refer to information that comes from one of these biweekly collaboration days as expert judgement, with a general source:

ProRail, Team Memebers. (2023, February-June). Part of project team *Leiden-Utrecht Beter Bereikbaar*. (S.Paulides, Interviewer), refered to as (ProRail, 2023).

1.6.2 Research Approach Geotechnical Report

The approach of this graduation research is based on the requirements of a geotechnical report as stated by NEN 1997-1 (Art. 2.8) (NEN, 2017). The report concerns a variants study in the exploratory phase of a project. For this reason, the assumptions, data, calculation methods and the results of the testing of the safety and usability of the various soil stabilization methods are recorded according to a geotechnical design report. Given the exploratory investigation, the level of detail is limited, but increases over the course of the design process. The geotechnical design report sets certain standards, this research report is arranged accordingly, including the following components:

- A description of the construction site and its surroundings – Chapter 2.1;
- A description of the proposed construction – Chapter 2.2;
- Mention of the standards and guidelines used – Chapter 2.4;
- A statement on the suitability of the site – Chapter 2.5;
- A description of the soil properties – Chapter 2.5;
- Geotechnical design calculations and drawings – Chapter 4.1;
- Recommendation for the design of the foundation – Chapter 4.3.

1.7 Content of the Report

The introduction of a research report provides an overview of the topic under investigation and identifies the purpose, objectives, and significance of the study. In the following chapter, the theoretical framework of the study is presented, which outlines the key concepts of soil stabilization and the variables that guide the research process and analysis. The current and desired situation are described in Chapters 2.1 and 2.2 respectively. The stakeholder analysis follows after which the boundary conditions and limitations are drawn up in Chapter 2.4. These analyses lead to the starting points of the project, including the analysis of the geometry of the embankment as well as the groundwater level and subsoil analysis in Chapter 2.5. Based on the obtained soil profile, the fundamentals of soft soil stabilization are included in the theoretical framework. Chapter 2 – Theoretical Framework, concludes with the program of requirements, distinguishing both functional as well as technical and stakeholder requirements. The analyses, starting points, regulations and assumptions gathered in Chapter 2 form the basis for the methodology described in Chapter 3.

Chapter 3 – Methodology, starts with specifying the methods of desk and interactive research that is conducted to obtain an overview of seven viable soil stabilization methods in Chapter 3.2. Based on expert judgement, a selection of three ground improvement techniques is acquired in the subsequent subchapter. With the aim getting a comprehensive understanding of the preceding and following design processes, the design thinking methodology is drawn up in Chapter 3.4. Here, the software that is used to simulate and test the three soil stabilization methods is introduced as well. The chapter concludes with the detailed design of the variants.

Starting with the stability calculations of the three variants, Chapter 4 – Results, focuses on the comparison of three soil stabilization methods through a multi-criteria analysis. The chapter introduces the concept of the analysis and provides detailed explanations of each criterion, along with the assigned weighting factors. By evaluating the performance of each method based on these criteria, a comprehensive analysis is conducted. The chapter concludes with the identification of the preferred design in Chapter 4.2.

Subsequently, Chapter 5 – Conclusion, addresses and answers the main research question, as well as the sub-research questions, based on the findings and analyses. The chapter aims to provide a clear and concise summary of the research outcomes.

Chapter 6 of the research report, titled "Discussion," delves into a detailed examination of the limitations and validity of the conducted research. This chapter aims to critically analyze the constraints and potential shortcomings that may have influenced the study's outcomes. By thoroughly evaluating these factors, the discussion ensures a balanced and comprehensive assessment of the research results. The chapter provides a comprehensive and insightful discussion of the limitations and validity of the research. Therefore, ensuring that readers gain a clear understanding of the boundaries and potential weaknesses of the study, allowing for a more nuanced interpretation of the results and facilitating future improvements in similar research endeavors.

Finally, Chapter 7 concludes the research report by offering recommendations for further exploration and continuation of the research on soft soil stabilization methods for the expansion of the railway embankment. These recommendations aim to guide future endeavors in this field, considering the insights gained from the study and addressing areas that require further attention and investigation.

THEORETICAL FRAMEWORK

The research approach undertaken in this study involves a thorough investigation of both the current situation and the desired future state, encompassing a detailed analysis of the perspectives and interests of the various stakeholders involved in the project. By considering their diverse needs, the research aims to develop a comprehensive understanding of the requirements and constraints that shape the soil stabilization methods for the extension of the double train track. This includes setting boundaries and limitations to define the scope of the research. Additionally, a schedule of requirements is established to outline the necessary standards that must be met to ensure the safe, and successful implementation of the project.

2

2.1 Current Situation

Prior to investigation of the current situation of the already existing track, gaining a better understanding of the history and construction of the railway embankment is prudent. First, the history of the train track between Leiden and Woerden are to be explored, after which the track in the current state is investigated.

2.1.1 The Current Train Track: Then

In the early days of the railway's existence between Leiden and Woerden, Hazerswoude enjoyed a time of having a train station. After the construction of the connecting line in 1887, two tracks and station Hazerswoude-Koudekerk connected the village to the surrounding cities. However, due to excessive settlement of the structure, the station closed in 1934. Due to the remediation of the station and one of the tracks, both were demolished (Bethlehem, 2018). The remained track, constructed in 1878, has continued to be in use ever since (Stationsweb, 2021).

Figure 14 Station Hazerswoude-Koudekerk and the double track in 1900 (Stationsweb, 2021)

Technical drawings obtained from the Utrecht's Archives (Het Utrechts Archief, 2022) provide more insight into the structure of the track body. Due to poor documentation, limited information is available about the construction or its process. Conversations with rail operator ProRail point out that little groundwork or construction has been conducted on the train track ever since (ProRail, 2023). Therefore, the analysis of the current situation is based on information gained from archival structural drawings.

The archival drawings, enclosed in **Appendix C – Historical Technical Drawings**, show the cross-sectional view of the double train track as constructed in 1877. The cross-section cuts through the station and the track body and extends to the ditches on the north and south sides of the structure. The technical drawing of the emplacement in Bodegraven more clearly illustrates that both tracks were constructed on the same sand body, functioning as a foundation. According to the figures, the assumption that the railway track was built with little to no measures regarding the foundation of the earthwork is plausible. The track was most likely built on a body of sand, which was constructed from ground level up.

2.1.2 The Current Train Track: Now

After remediation of the second track and the station in 1934, the single track has continued to stay in service, see **Figure 15**. Yet, most of the double catenary gantries are still present on the east side of the N209 and could therefore be used again to serve a double track in the future. West of the N209 however, only single catenary poles are present.

Figure 15 Current Situation Track over N209 facing West and Double Overhead Line East of the N209 (Google Maps, 2022)

Due to lack of documentation regarding the maintenance of this track, the assumption is drawn that little has changed in the track structure since its construction in the nineteenth century (ProRail, 2023). However, the geometry of the embankment has changed in consequence of subsidence and settlements within the sand body. These phenomena contribute to the instability of the track (SpoorPro, 2019) and has been further worked out in the subsidence analysis of **Chapter 1.2.1 – Subsidence of the Railway Embankment**. The annual displacement contributes to the instability of the track in its current state, however the impact on the sand body is unknown.

With the rail operator working from a performance-based approach (ProRail, 2023), little is known so far about the condition of the rail embankment. As the track has proved sufficient stability yet, further research has not been conducted. However, due to the introduction of the more frequent travel schedule, the need arose to examine the current route. In the study conducted by management consultancy firm APPM (Advice and Project Management Firm) the current state of the embankment was not adequately investigated, which led to the assumption of a 1-metre-thick sand layer under the rail embankment (APPM, 2019). After global examination, the embankment was found to be not sufficiently stable to build another track in addition to the current railway. Due to lack of information, assumptions are made in this study regarding the state and thickness of the sand layer under the current track. These and other design criteria are discussed in **Chapter 2.5 – Design Criteria**.

The geometry of the current situation is established based on knowledge obtained from historical data (**Appendix C – Historical Technical Drawings**) and recent elevation measurements (AHN, 2023). The cross-sections are drawn by Arcadis' design engineers and show the profile of the current situation every 50 meter between 23.5 – 24.6 km, see **Appendix D – Current Situation: Cross-Sections Trajectory 23.5 – 24.6 km** for a complete overview of the cross-sections. These profiles clearly show the differences in elevation along the trajectory, indicating that the settlement varies along the track.

Figure 16 shows one of the cross-sections and shows the simple and irregular rail embankment in the current state. Compared to the embankment as enclosed in **Appendix C – Historical Technical Drawings**, the slopes have drastically changed and incline irregularly on either side. Since little is known about the height and/or depth of the sand body as applied in 1877, little is ascertained about the current condition of the sand layer beneath the track body nor the changes over time.

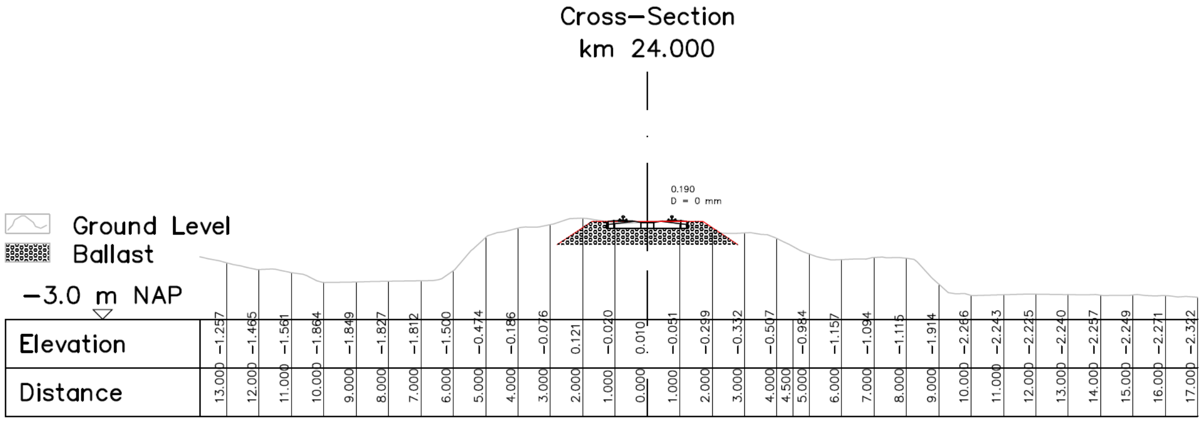


Figure 16 Cross-Section at Km 24.0

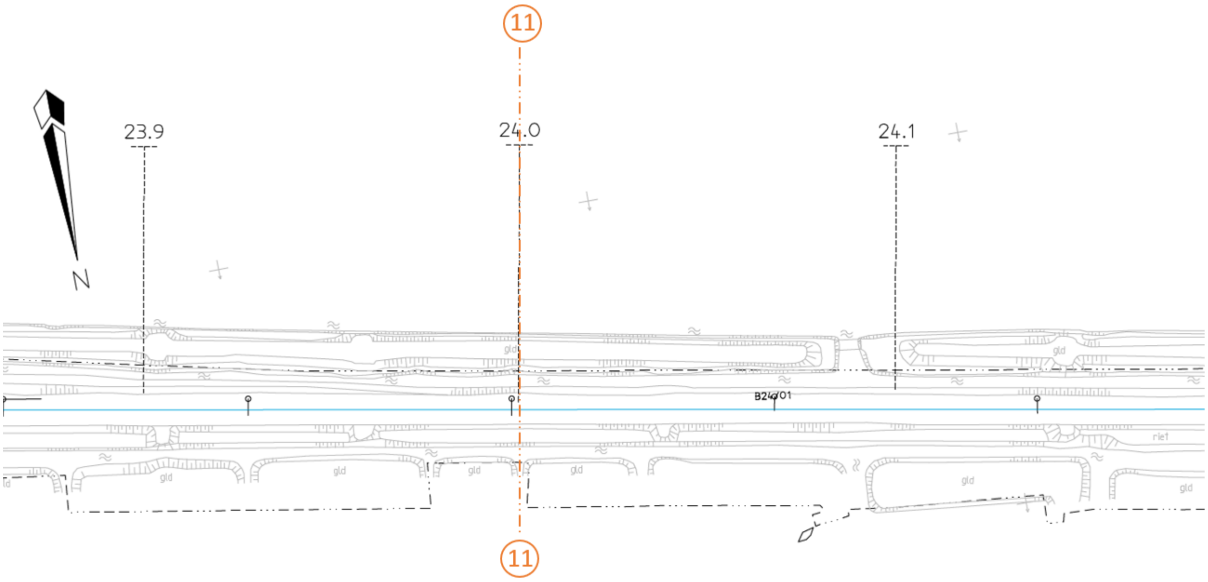


Figure 17 Top View at km 24.0

2.2 Desired Situation

The desired situation, as outlined in **Chapter 1.4 - Assumptions**, serves as a guiding framework for the HOV Leiden-Utrecht project, despite the presence of certain design uncertainties. The project's scope includes the construction of a new halt on the north side of the track, with provisions for future expansion to accommodate double tracks and a grade-separated transfer opportunity, as depicted in **Figure 18**.

The location of the halt is planned to be at the level of the current Gemeneweg, necessitating a diversion of the Gemeneweg approximately 100 meters to the west. Furthermore, an inter-neighborhood connection is to be established at the western end of the track. The primary station facilities are to be situated on the north side of the tracks and is integrated with the ongoing developments surrounding Westvaart Park. These design choices and infrastructure arrangements aim to enhance the efficiency and accessibility of the HOV Leiden-Utrecht project. By providing a new halt with expandability options, improving interconnectivity between neighborhoods, and strategically locating station functions, the project seeks to optimize public transportation services and support the surrounding urban developments (Arcadis, 2016).

Figure 18 Design Station Hazerswoude-Rijndijk (Studio Alphen, 2020)

The achievement of the desired situation is contingent upon two possibilities: either a railway curve widening in Alphen aan den Rijn or an extension of the double track from Zoeterwoude-Oost, as illustrated in **Figure 4**. This report focuses on the latter option, which holds significant importance and carries far-reaching implications for the project. The construction of the double track plays a vital role in realizing the desired situation at Hazerswoude-Rijndijk.

In relation to the double track, the construction should be as close to the existing track as feasible to minimize the need for land expropriation and contain costs. **Chapter 2.4 - Boundary Conditions and Limitations** provides a comprehensive overview of these constraints and considerations.

Drawing upon the historical analysis presented in **Chapter 2.1 - Current Situation**, the most favorable location for the second train track is determined to be on the north side of the current track. This preference is primarily driven by the presence of double tracked overhead lines that facilitate the expansion north of the existing line. **Figure 19** illustrates the desired solution proposed by ProRail, showcasing the track's proximity to the existing line. The minimum center-to-center distance of 4.5 meters, as discussed with ProRail and in accordance with OVS 00056-7.1 art. 3.2 (see **Chapter 2.4 – Boundary Conditions and Limitations**), is adhered to. For an overview of the cross-sections depicting excavations and elevations related to the desired situation at intervals of 50 meters, please refer to **Appendix E - Desired Situation: Cross-Sections Trajectory 23.5 - 24.6 km**.

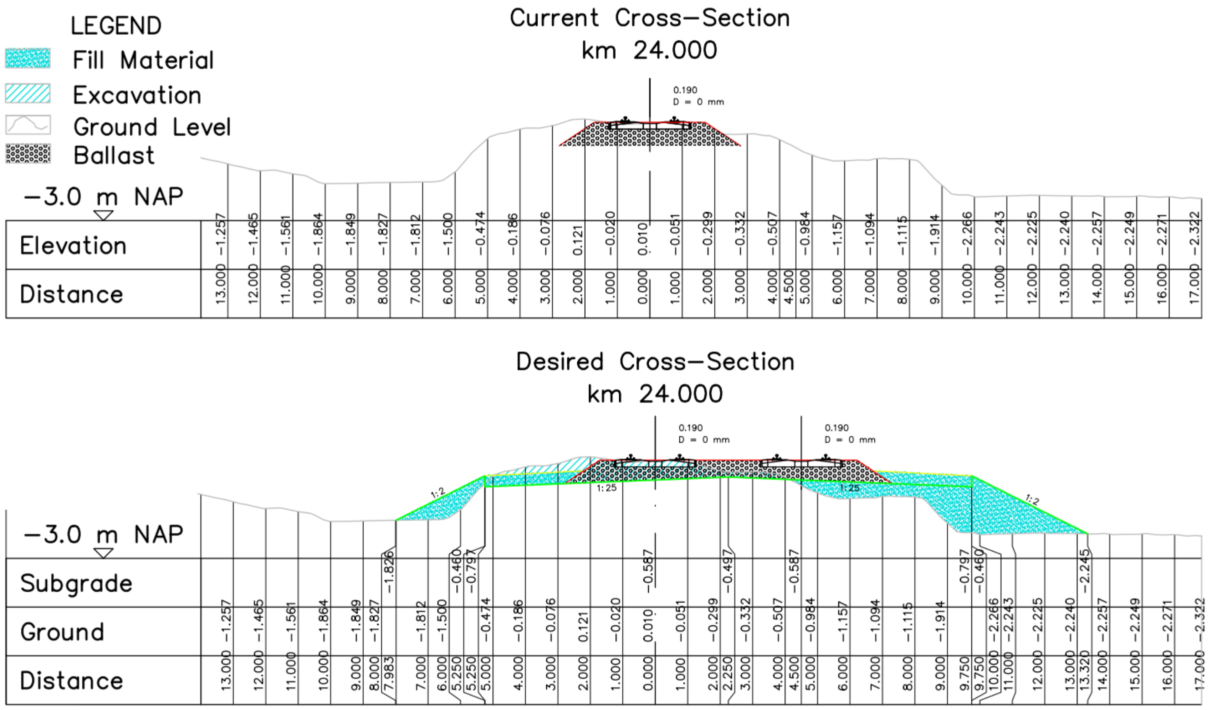


Figure 19 Cross-Sections of the Current and Desired Situation at km 24.0

These design considerations, encompassing the location of the double track and compliance with specific criteria and regulations, are crucial for realizing the desired situation and ensuring the successful implementation of the HOV Leiden-Utrecht project. By meticulously addressing these factors, the project aims to optimize efficiency, minimize disruptions, and meet the expectations of stakeholders involved.

2.3 Stakeholder Analysis

The desired situation for the railway embankment expansion project between Zoeterwoude East and Hazerswoude-Rijndijk is shaped by the requirements, wishes, and ambitions expressed by various stakeholders. This subchapter aims to introduce the most important stakeholders and establish a stakeholder map to develop a strategy for each stakeholder category. Analyzing the stakeholders is crucial as their diverse perspectives, wishes, and requirements provide valuable insight. Given the project's significant impact, the stakeholders extend beyond the client and Hazerswoude's residents to include commuters traveling between Leiden and Utrecht, among others.

2.3.1 Introduction of the different Stakeholders

The analyses of the current and desired situation indicate the large area of impact and interest of the project. On a national scale is the interest of the Dutch Government that wants to strengthen the polycentric structure of the Netherlands. The network provides strong economic connectivity, great regional diversity and supports a high quality of life. This is essential for the attraction of both international and national knowledge, labor, and capital. The government aims to strengthen this quality by building on the existing urban (infra)structure (Rijn, 2020).

On a regional scale the railway line Leiden-Utrecht fulfils various functions, such as connecting multiple smaller villages to the respective university cities. Additionally, the connecting line provides an alternative rail connection between The Hague/Schiphol/Utrecht and thus relieves some of the pressure off the connecting line to Schiphol Airport. Moreover, the railway is a faster and cheaper alternative to the car for residents of the surroundings towns within the area. This in turn results in a reduction of car traffic to the centre of the municipalities, thus contributing to a better accessibility and overall healthier living environment within the city centres on either side of Hazerswoude-Rijndijk.

The stakeholders of local interest encompass the municipality of Alphen aan den Rijn. Situated at the crossroads of the Randstad and the Green Heart, this municipality holds a strategic position and is committed to remaining at the forefront of regional developments by investing in its infrastructure. Both the municipalities of Leiden and Alphen aan den Rijn share the goal of becoming well-connected cities with strong links to the surrounding areas. Through investments in stations and transfer hubs located on the outskirts of city centres, the aim is to redirect car traffic to these hubs, thereby freeing up space within the city centres for new functions. The development of the Hazerswoude-Rijndijk station serves to enhance connectivity between Alphen aan den Rijn, Leiden, and the surrounding regions, integrating them into the daily urban system of the Randstad. This interconnectedness facilitates efficient and seamless transportation for residents and commuters within the region (Rijn, 2020).

2.3.2 Identification of the Stakeholders

The findings of the investigation into the key stakeholders involved in the project are shown in **Table 2**. Each stakeholder is briefly described, providing an understanding of their impact, influence, and/or interest in the project. Based on this assessment, a detailed analysis is conducted to ascertain their level of interest and power. Furthermore, a comprehensive strategy is developed for the relevant stakeholders, considering their specific interests and influence. These strategies are further elaborated upon in **Chapter 2.3.3**, where a stakeholder map and individual strategies per category are presented.

Table 2 Identification of the Stakeholders

Stakeholder	**Role, Responsibilities, and Interests**
1. LOCOV	The LOCOV (Landelijk Overleg Consumentenbelangen Openbaar Vervoer) as a consumer organization represents the interests of train passengers. They do so by consulting with and advising the Dutch Railways (NS), rail manager ProRail and the Ministry of Infrastructure and Water Management (I&W). The main point of interest of the LOCOV is public rail transport at both national and international level on the main rail network. This involves concrete implementation measures of importance to rail passengers, like changes regarding the timetable, and the accessibility of the trains (LOCOV, 2023). **Role**: Collaborate, advise, and consult on behalf of the train passengers. **Strategy**: Keep informed and keep satisfied during the project by monitoring the stakeholder as their interest and power are limited to a certain extent.
2. Municipalities Leiden, Zoeterwoude, Alphen aan den Rijn, Woerden and Utrecht	The responsibilities of the municipalities include providing relevant data and informing both the internal organisation as well as their citizens. All municipalities are to some degree affected by the construction of/along the train track and should therefore be managed closely and kept satisfied. **Role**: In their responsibility of providing data and informing their citizens, they all have a role through their competent authority for permits such as the planning permits. **Strategy**: Managed closely as both their power and interest are high. By organizing regular meetings, these stakeholders stay closely invested in the project.

3. NS — Delivering reliable train product in accordance with the agreement framework, is one of NS' responsibilities. Being able to prepare and manage the transport equipment and provide data for the purpose of transport analyses are also among its responsibilities. As a stakeholder, NS should collaborate in adjusting the timetable during the expansion of the double train track, and possibly should introduce replacement transport like NS Buses in the case of temporary decommissioning of the existing track.
Role: NS is a stakeholder as advisor as they are the passenger carrier on the Utrecht-Leiden line. In accordance with the agreement framework, NS represents the interest including the NS Maintenance Company.
Strategy: The NS should be kept informed throughout the project to adjust their train product in time while collaborating as they are impacted largely during the construction phases.

4. NS Stations — Interest in functionality and safety of the infrastructure, commercial exploitation as well as services and revenues. However, since the track extension does not directly impact the station, this stakeholder must be monitored carefully. However, when due to the double track extension, trains run more frequently, the impact on the stations is to be far-reaching. With an eye on a future possible track extension reaching station Hazerswoude-Rijndijk, their interests may be included in these preliminary stages to better meet the future needs of the infrastructure and its surroundings.
Role: Owner of the station buildings, and therefore collaborates, advises, and consults in case of a double tracked train station at Hazerswoude-Rijndijk.
Strategy: Stakeholder should be monitored as their power and interest in the double track extension is small.

5. Rail Contractors — Conduct rail infrastructure maintenance and construction on behalf of ProRail. Depending on the chosen soil stabilization method, the current track might require additional monitoring and support conducted by the assigned rail contractors. Furthermore, depending on the application of ground stabilization on one or both tracks, the maintenance required should be adjusted. This also applies to the transition zones between the existing and newly stabilized tracks near Zoeterwoude East.
Role: Maintenance operator that provides input and advice within the project and should be flexible in their maintenance and monitoring.
Strategy: Keep informed.

6. Ministry of I&W — Their responsibilities lie in political and administrative decision-making and are important for issuing decisions and grants. Their interests are that the project during all phases fit within scope, budget, regulations, and policy development.
Role: I&W is financier of the project.
Strategy: As the main financier, the ministry of I&W has both power and a high degree of interest and should therefore be managed closely.

7. Province of South-Holland — The main interest of the province is the accessibility of the public transportation within the region. Their interest is higher than their power,

		however they contribute to the project by communicating desires and demands with the relevant municipalities. **Role**: Giving advice based on its own visions and desires, usually in discussion with the municipalities. **Strategy:** To manage them closely as both interest and power are large.
8.	Province of Utrecht	Is a stakeholder concerning the improved accessibility and transfer between Utrecht to Gouda and are therefore stakeholders of the double track extension as this impacts the transfer between the two cities. **Role**: The Province of Utrecht is mainly indirectly affected by the changes in and around Hazerswoude-Rijndijk. **Strategy:** Both power and interest are limited. The strategy is therefore to monitor and keep them updated on the progress of the project.
9.	ProRail	The responsibilities as the main rail operator include the service of safe and efficient passenger and freight transport. One of the interests is increasing the capacity of the rail network by expanding the network and making optimal use of the existing infrastructure. ProRail is responsible for investigation of the transport specification. They guarantee the functionality, safety, and accessibility of the rail infrastructure, and are responsible for the project management as well as the execution of the project assignment within the given scope. **Roles**: Managing the railways, assisting, participating, and advising, managing, and maintaining the rail infrastructure, and specifying requirements. **Strategy**: Manage closely as they are the client, combined with the Ministry of I&W.
10.	Citizens	The citizens in and around Hazerswoude-Rijndijk require to being able to go about their daily business with as little inconvenience as possible. Being well-informed during the entire process. They share their interest through (social) media, politics, and public procedure. **Role**: Despite having little power, the citizens are largely affected by the changes within the area. Their wishes should be listened to, and the citizens should feel included in the project, while the disturbance should be limited as much as possible. **Strategy**: Ensure residents are informed properly and in a timely manner through information letters. Keep these stakeholders informed via the municipality and workshops that anyone may attend.
11.	Train Passengers	The train passengers' interest is to get from Leiden to Utrecht and vice versa as much as possible according to the current timetable. As minor delay as possible during the construction phase. More frequent running trains after implementation of the new timetable between Leiden and Utrecht. This must not compromise on the efficiency of transfers between different transport modes. **Role**: Affected by the change in timetable and temporary (partly) closure of the track leading to inconvenience and larger travel times. **Strategy**: Being well-informed, through the travel planner and the informative signs at the stations. Influence through (social) media and politics.

12. Parcel Owners — Owners of parcels HZW00-H-887, HZW00-H-458 and possibly other surrounding parcels (Kadastrale Kaart, 2023). Acquisition of land from the owners to realize the second track might be required. The assumption is made that the owners of these parcels is ProRail itself, thus limiting the required expropriation of the agricultural lands. However, depending on the soil stabilization method, more land might be purchased to ensure a safe and stable embankment. Despite the limited data accessible, these stakeholders are important to mention as their interest is high but power limited.
Role: Owners of the adjacent land on which the track extension would take place.
Strategy: These stakeholders should be kept satisfied as their power is large but their interest in the project limited.

13. ILT — The Human Environment and Transport Inspectorate (ILT) is the supervisor of the Ministry of Infrastructure and Water Management (ILT, 2023). They ensure safety, trust and sustainability in transport, infrastructure, environment, and housing. Taking one track out of service while train traffic is managed on the other track is no longer preferred by the ILT, as this would be too dangerous for railway workers (Kruyt, 2022).
Role: Their interest is that railways are safely returned to operation.
As a stakeholder with power but little interest in the project, they should be kept satisfied.
Strategy: Monitoring is sufficient as they mainly supervise I&W. Their power and interest in the project are limited.

14. Owner Cables and Pipes — Based on the cables & pipes analysis, there are mainly cables from ProRail, the municipality, grid operators and a large gas pipeline. Due to limited data regarding the owners of these cables and pipes, they are considered as one stakeholder. Depending on the chosen soil stabilization method, the cables and pipes in the project area might need to be relocated, monitored carefully and/or adjusted based on the requirements of the double track.
Role: Transporting gas, electricity etc. through pipes and cables in the soil.
Strategy: Interest and power are limited and should therefore be monitored carefully.

2.3.3 Stakeholder Map and Strategy per Category

Figure 20 depicts the stakeholder map, which serves as a visual representation of the key stakeholders identified through the investigation. The stakeholder map enables a clear and concise overview of the important parties involved in the project, showcasing both their influence on and impact from the project. By visually arranging the stakeholders, their connections and interdependencies are highlighted, providing valuable insights into the network of stakeholders associated with the project. The stakeholder map serves as a valuable tool for project management and decision-making, ensuring that the interests and concerns of all relevant stakeholders are appropriately addressed throughout the project lifecycle.

Figure 20 Stakeholder Map

Four categories are to be distinguished based on their degree of interest and power within the project. The division of the stakeholders in the map is an estimation and is based on literature research (ProRail, 2021). However, the evaluation gives insight into the optimal strategies per category.

- Keep Satisfied: The stakeholders with high power but little interest in the project. The strategy is focused on meeting the stakeholders' needs by engaging and consulting in their area of interest.
- Manage Closely: The stakeholders with both large power and interest in the project. These are the key players on which the efforts must be focused. They involve in governance and decision-making bodies and should therefore be engaged and consulted on a regular basis to keep them both satisfied and informed.
- Monitor: The stakeholders in this category have little interest and power and are therefore considered 'less' important. Information nor collaboration is required, and informing via general communication is sufficient to keep them satisfied and up to date.
- Keep Informed: This group should be kept informed and consulted on their area of interest. Through involvement in low-risk areas, like surveys and/or informative evenings among the citizens and train passengers, their attitude of interest is used wisely. In addition, this group may include potential supporters and should therefore be valued.

2.4 Boundary Conditions and Limitations

The boundary conditions of the project encompass the requirements set forth by laws and other relevant stakeholders. These conditions serve to define the project's scope and establish the rules and regulations that must be adhered to. The scope is determined by both practical and theoretical boundary conditions. The theoretical conditions arise from the calculation approach and limitations within the software used to compare different soil stabilization methods. **Chapter 3.5 – Geotechnical Software D-Geo Stability,** elaborates on these conditions as they are integral to the research methodology.

Furthermore, this subchapter outlines the practical boundary conditions derived from legally applicable documents. In the Netherlands, four key regulatory documents are recognized regarding the construction and stability of a rail embankment: the NEN, CROW, OVS, and RLN. NEN stands for "Nederlands Normalisatie-instituut," which holds responsibility for the development and maintenance of standards in various industries in the Netherlands. CROW stands for "Kennisplatform voor infrastructuur, verkeer, vervoer en openbare ruimte," which is a Dutch organization that focuses on knowledge exchange, research, and innovation in the field of transportation and infrastructure. OVS stands for "Ontwerp Voorschrift Spoor," which includes a set of design regulations specifically for railway infrastructure in the Netherlands. OVS provides guidelines and requirements for the construction, maintenance, and safety aspects of railways. RLN stands for "Richtlijn Lichte Railvoertuigen en Tramlijnen," which is a guideline that provides specific regulations and requirements for the design, construction, and operation of light rail vehicles and tram lines in the Netherlands.

Before listing the specifics of these regulations, the design's purpose is stated, significantly narrowing down the relevant regulations and auxiliary boundary conditions that apply to the construction of a railway embankment.

The purpose of the railway embankment, according to OVS00056-7.1 (ProRail, 2016), includes:

1. Supporting the superstructure by ensuring both sufficient load-bearing capacity and stability;
2. Fixing the superstructure (limiting both deformations and deformation differences);
3. Drainage of the superstructure (water management);
4. Ensuring passenger comfort (dynamic behavior);
5. Fitting into the environment (think of the urban development or landscape plan, noise barriers, etc.);
6. Facilitating possibility of crossing the railway (Including enabling crossings of traffic, animals, cables, and pipes).

This design requirement document focuses mainly on the first function: carrying the superstructure with respect to stability. Specific design guidelines apply to the design and testing of railway embankments, supplementing the Eurocodes (NEN) and CROW guidelines. For construction of new track body and engineering structures, ProRails various design regulations (OVS) apply. In addition, for assessment of the structural safety of existing track bodies, a specific guideline (RLN) is available. ProRails design regulations (OVS) are often derived from the RLN specifications and serve as complementary design regulations on top of the RLN design guidelines. In this project a new construction and the existing situation are combined, which requires the necessary expertise to make responsible choices for the applicability of regulations and guidelines. These choices are essential for an optimal project result, both on the side of ProRail and on the contractor's side.

2.4.1 The Eurocode and NEN

Agreements that different parties jointly agree on, or broadly supported agreements, enable international trade, innovation, safety, efficiency, and sustainability. At NEN, Nederlands Normalisatie-instituut, parties and stakeholders are connected by ensuring that they reach agreements that are laid down in standards and guidelines. This is done in national and/or international standards committees. The standards and guidelines are the international (ISO, International Organization for Standardization), European (EN) and national (NEN) standards accepted in the Netherlands (NEN, 2022).

NEN is an independent, autonomous foundation, and as such is not a government body. Standards are therefore not laws, but 'best practices'. In business agreements, standards have an important function. Standards offer market parties clarity about and confidence in products, services or organizations and challenge society to innovate. In addition, the government often refers to these standards. For this reason, the guidelines as drawn up in the NEN are starting points for design.

The NEN 1997-1 sets out the principles and requirements for safety and serviceability, describes the foundations of design and provides guidance on related aspects of the structural reliability. The regulation is applied to geotechnical aspects of the design of both buildings and civil engineering works. NEN 1997 deals with requirements for strength, stability, serviceability, and durability of structures.

2.4.2 CROW

CROW (Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek) is a Dutch foundation that acts as a knowledge institute for infrastructure, public space, traffic and transport, and construction and safety. CROW focusses on regulations and research in both civil and traffic engineering and draws up recommendations and guidelines on design and sizing of infrastructure. These guidelines are largely published in CROW publications and are used as advisory documents in the design of a variety of infrastructures (CROW, 2023).

2.4.3 OVS

The OVS (Ontwerp Voorschrift Spoor) covers ProRail's operating design regulations and are intended for contractors and engineering firms. They specify how new construction and maintenance should be conducted. Specifically, for the design of new runway bodies, the OVS00056-7.1 "Design Regulations for Runway Body and Geotechnical Engineering" applies and is consistent with NEN-9997-1 (Eurocode 7) for geotechnical structures. This design regulation specifies the scope, requirements, methods of determination, loads and required soil investigations. This applies to the stability in use phase, settlements and settlement differences, static and dynamic bearing capacity (e.g., testing of critical train speed), water management and material requirements for the track. (ProRail, 2016).

The OVS00056-7.1 specifies the minimum requirements and assessment criteria for the design and assessment of new railway lines and modifications of existing railway lines. The regulation is applicable to railway lines that are or may be managed by ProRail, which is the case for trajectory Leiden-Utrecht.

ProRail aims to achieve the best possible result when constructing and maintaining its infrastructure. Where the OVS deviates from other Dutch and European standards, the OVS prevails. As important preconditions for the design and construction of railway lines, the following applies in succession:

1. Dutch legislation;
2. The Dutch European standards;
3. ProRail policy, the purport of which is incorporated in the OVS regulation;
4. Other ProRail regulations, including the RLN Guidelines.

2.4.4 RLN

Drawn up by ProRail, the RLN00414-1 is intended as a means of unambiguously testing existing runway bodies, so that these railway embankments demonstrably comply with the specified requirements. The target group of this RLN (Richtlijn Lichte Railvoertuigen en Tramlijnen) are the engineering firms, which conduct the assessment. This RLN (ProRail, 2016) concerns the mathematical test to be performed to establish the safety level of the runway body. Any measures to be taken to increase safety if necessary are outside the scope of this RLN. According to the legal framework, the RLN00414-1 applies, if:

a. There are indications that the existing track body may not meet rejection level;
b. A project is being conducted in, on or adjacent to the track body; that affects structural safety;
c. A superstructure renewal also involves modification of the top of the runway body;
d. The use of the infra is aggravated by increasing track section speed and/or increasing axle loads.

The NEN8700 standard defines two safety levels: the reconstruction level and the rejection level. The reconstruction level represents the minimum legal requirement for structural safety when evaluating designs for the reconstruction of an existing embankment (Article 1.5.1.13). On the other hand, the rejection level represents the minimum legal requirement for structural safety, irrespective of any adjustments, and applies to the current state of the track (Article 1.5.1.0a).

In accordance with the Strength and Stability Assessment Framework outlined in the RLN (Railway Construction Guidelines), assessment of whether the safety level meets the required standards is crucial. The desired safety levels are detailed in **Table 3**, providing a clear reference for evaluating and ensuring the adequacy of the safety measures in place.

Table 3 Safety Requirement RLN00414-1 (ProRail, 2016)

RLN- Number	Requirement
RLN00414-1-001	The safety of the existing rail track should reach a minimum rejection level. The minimum value for the factor of safety is 1.0 in the ultimate limit state.
RLN00414-1-002	The safety of the existing rail track before rebuilding should achieve minimum rebuild level. The minimum value for the factor of safety is 1.0 in ULS.

As examined by Arcadis (APPM, 2019), the single track does not meet the RLN requirements. According to RLN00414-1, an existing structure must have a minimum factor of safety of 1.0 in the ultimate limit state before a conversion or extension may take place. A lower calculated value than 1.0 means that an improvement of the track body must first take place before starting any modification to the track. Despite the criterion not being met in this project, neither the RLN nor the OVS are legal rules. ProRail is therefore allowed to derogate from their regulations and guidelines.

ProRail has made the decision to allow for this regulation not to be met for the extension of the double track between Zoeterwoude East and Hazerswoude-Rijndijk, which indicates the rather rudimentary research approach. The scope is therefore not limited by the wishes nor rules which state that either the entire (re)construction of a double tracked railway, nor the solely construction of a second track. The soil stabilization method could possibly be applied to both tracks simultaneously, successively, and to the new track exclusively.

2.4.5 Limitations

To ensure a focused and manageable research scope, several assumptions have been made to delineate the project area. These predetermined boundaries serve to narrow down the research area, establish the limits of the theoretical framework, and provide clear guidelines for the research methodology. By defining these boundary conditions, the project scope is effectively delimited, allowing for a more targeted investigation. Furthermore, these assumptions aim to minimize the influence of various developments within the area, enabling a more accurate and focused analysis. The specific limitations outlining the project area are detailed in **Chapter 1.4 - Assumptions**, providing a transparent framework for the research undertaken in this study, and include:

- The scope is outlined by assuming the expansion to a double track between 23.5-24.6 km;
- The scope is limited by only considering influences within the slip plane of the rail body;
- Developments within the area, including restructuring of the Gemeneweg are not considered;
- Preferably, the current track remains in its current state and is not (negatively) influenced by the construction of a second track;
- Assuming the double track to be leveled at a similar elevation to existing single track;
- The minimal center-to-center distance between both tracks is 4.5 meter.

2.5 Design Criteria

To establish the parameters and conditions within the project area, defining the starting points becomes essential. These starting points are derived from a combination of online data and research conducted in collaboration with Arcadis, yielding valuable insights into the characteristics of the project area. Additionally, certain assumptions have been made to enhance understanding of influential factors, such as the ground water level. This subchapter delves into a thorough examination of various aspects, including elevations, soil characteristics, and the presence of cables, among others. Through the study of these factors, a comprehensive understanding of the project area is achieved, laying the groundwork for subsequent analysis and design processes.

2.5.1 Geometry and Elevation

The geometry of the existing rail embankment is obtained from data collected by the AHN Viewer. The Actueel Hoogtebestand Nederland (AHN, 2023) collects detailed height data of the Netherlands. The latest version, AHN3, contains detailed and precise elevation data measured between 2014 and 2019, with an average of eight height measurements per square meter, see **Figure 21**. AHN is a collaboration of the provinces, the government, and the Dutch water boards. The height of each patch of land measuring half a meter by half a meter is known in relation to NAP. All altitudes in the Netherlands are measured relative to the same level, the Normal Amsterdam Level. An NAP height of 0 m is roughly equivalent to the mean sea level of the North Sea (RIVM, 2023).

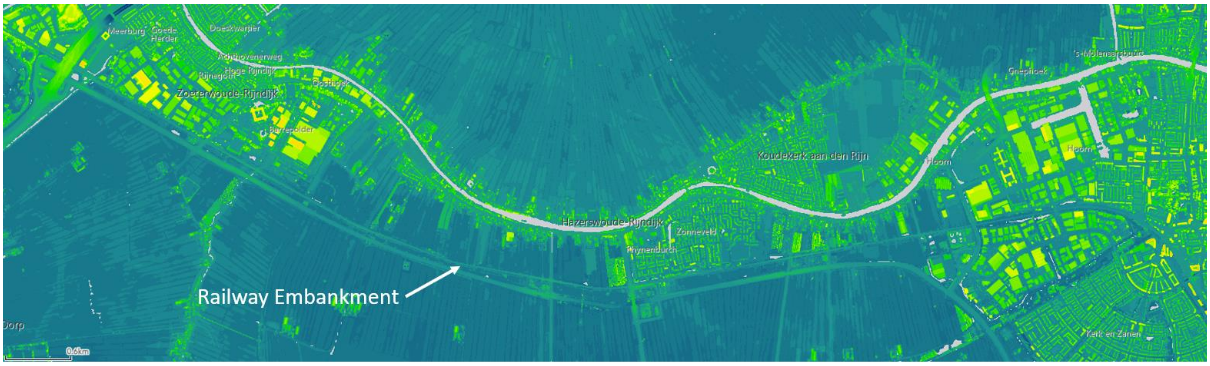


Figure 21 Elevations as shown in the AHN Viewer (AHN, 2023)

The AHN Viewer allows to user to create a cross-section of the embankment at any randomly chosen location along the track between Zoeterwoude and Hazerswoude, see **Appendix G – Geometry & Elevation Investigation**. However, to obtain a more accurate geometry of the railway, the AHN data was processed, measuring the elevation per every meter width for every 50 meters of track. The elevation of the railway is determined by measuring the height of the upper side of the rail (Dutch: *BS – "Bovenkant Spoorstaaf"*) with respect to NAP, see **Figure 22**. The figure shows the method of measuring the railway elevation at km 23.5, the train track is roughly situated at 1.66 m+NAP.

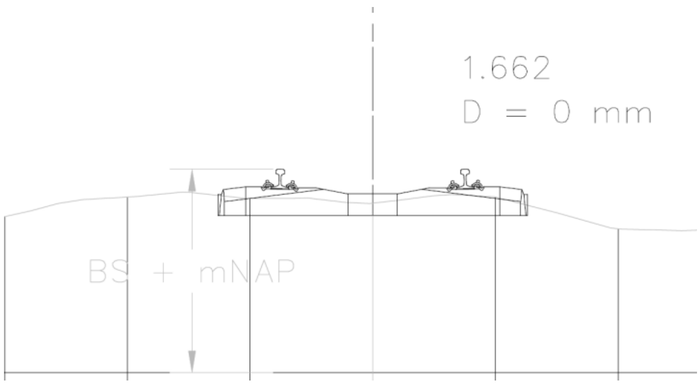


Figure 22 Measured Railway Elevation in BS + m NAP at km 24.0 is 1.662 m + NAP.

A clear overview of the geometry and elevation data between km 23.5 – 24.6 is enclosed in **Appendix D – Current Situation: Cross-Sections Trajectory 23.5 – 24.6 km**, where the elevation with respect to m+NAP is referred to as '*Existing (Elevation)'*. From the obtained and analyzed geometry, the conclusion is drawn that the elevation of the railway varies between 1.66 m + NAP down to nearly 0 m + NAP over a trajectory of 1.1 km.

In the process of track doubling, some excavation or soil removal may be necessary, depending on the original profile of the site. **Appendix E – Desired Situation: Cross-Sections Trajectory 23.5 – 24.6 km** provides illustrations of potential changes in the soil layers resulting from the track doubling project. However, the specific earthwork required in the topsoil is one of the starting points that may be subject to modification based on the selected soil stabilization method. Nonetheless, this information offers an initial overview of the anticipated alterations to the embankment's profile, serving as a reference point for understanding the expected adjustments and assisting in the planning and implementation of the railway embankment expansion.

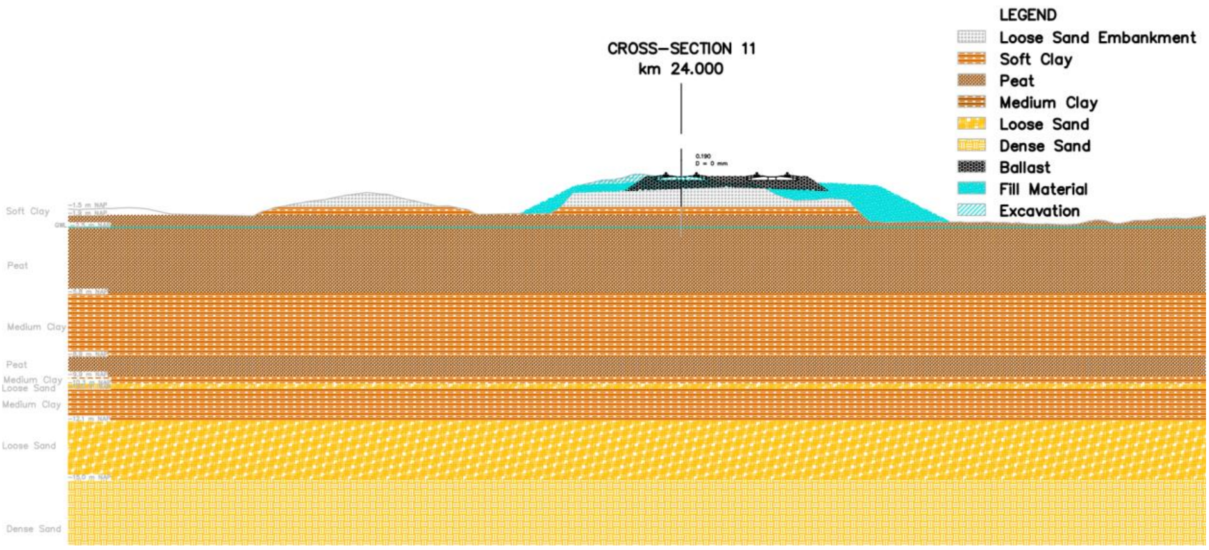


Figure 23 Desired Geometry including the Elevations and Soil Layers at km 24.0.

2.5.2 Groundwater Level

Groundwater is the water that fills the spaces between solid particles in the subsoil, such as sand, clay, silt, peat, and loam. In the Netherlands, groundwater plays a crucial role as a source of potable water and is essential for maintaining natural areas and a healthy ecosystem (RIVM, 2023). The level of groundwater, known as the groundwater level, has significant impacts on the soil. Insufficient or contaminated groundwater has detrimental effects on both natural and residential areas, including issues like acidification, settlement of peat soils, and the drying out of sensitive plant species.

While up-to-date groundwater level data is lacking in the DINOLoket database, historical data provides insights into the trend (DINOloket, 2023). **Appendix H – Groundwater Level Investigation** presents historical data, indicating a general increase in the groundwater level over the past few decades, see **Figure 24**. This trend is expected to continue in the future, as supported by literature research conducted by Studio Alphen in 2019 (Studio Alphen, 2019). Based on the available data and the trendline, the assumption is made that the groundwater level is approximately -2.5 meters NAP (Normaal Amsterdams Peil), which serves as a reference point for further analysis and considerations regarding soil stabilization methods and their impact on groundwater conditions.

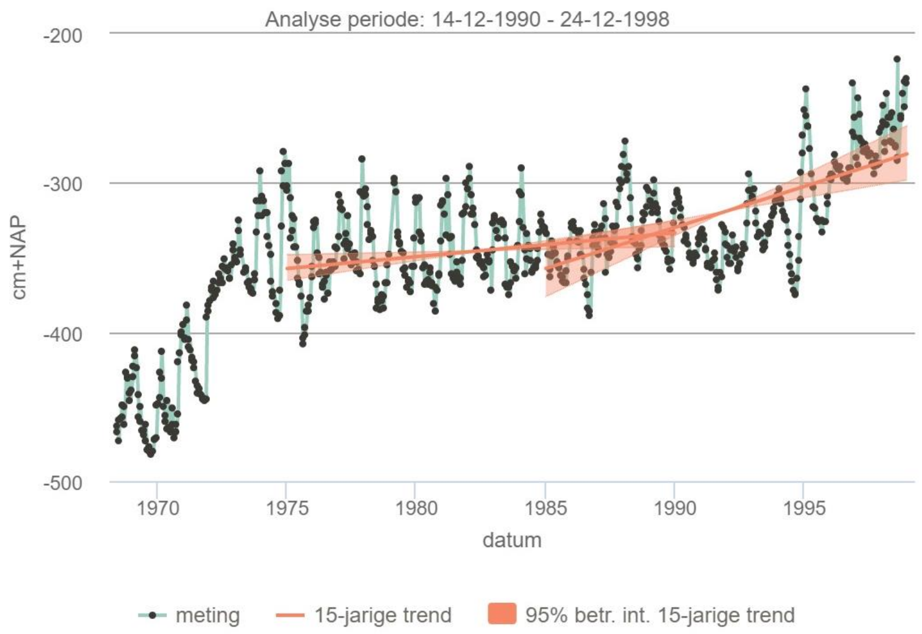


Figure 24 Groundwater Level Measurements and corresponding Trends (Grondwatertools, 2020)

In peatlands like Het Groene Hart, the groundwater level has been intentionally maintained at a low level to facilitate agricultural activities for farmers and cattle breeders. This practice has facilitated land cultivation and management. However, keeping the groundwater level low in peat soils has adverse consequences. As water evaporates from the pores, the peat soils dry out, resulting in increased greenhouse gas emissions. Moreover, the low water levels have detrimental effects on the stability of buildings and infrastructure in urban areas, leading to damages. Considering these significant impacts, the upward trend of rising groundwater levels continue in the foreseeable future, necessitating careful consideration of soil stabilization methods and their implications on groundwater management (Hulsbeek, 2023).

2.5.3 Soils and Subsoils

In addition to the embankment's elevation and the groundwater level, the subsoils play a crucial role in the variant study on soft soil stabilization. Specifically, the stability assessment of the railway embankment relies on data related to the soil layers directly beneath the track to ensure a thorough examination. Information pertaining to the subsoils is obtained from DINOLoket, as depicted in **Figure 2**5. This database serves as a valuable resource, offering a compilation of geoscientific data on both the deep and shallow subsurface of the Netherlands (TNO, 2023).

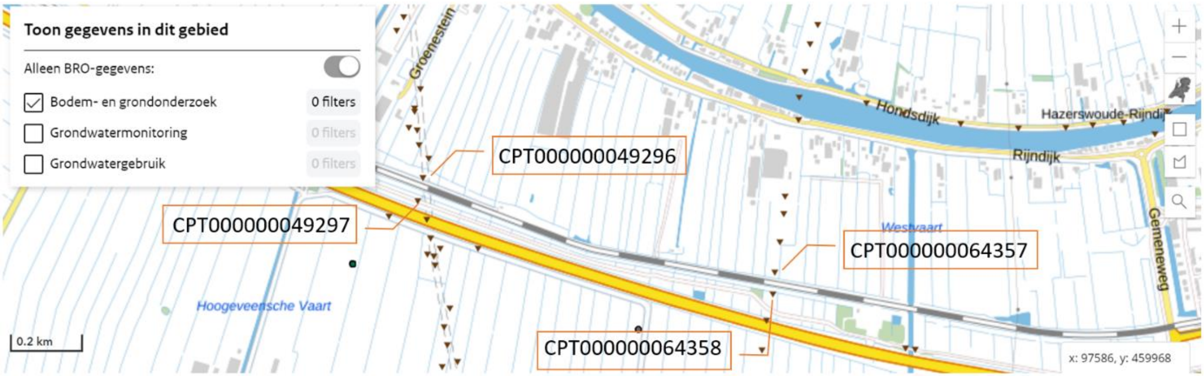


Figure 25 Cone Penetration Tests taken along the Train Track west of Hazerswoude-Rijndijk (TNO, 2023)

For accurate soil analysis, cone penetration tests (CPT) are preferably conducted within the railway embankment. These tests aim to assess the load-bearing capacity of the soil. A cone-shaped bar is gradually pushed into the ground at a constant speed, as illustrated in **Figure 26**. The resistance encountered during this process is referred to as the cone resistance, which is measured in megapascals (MPa). Clay or peat layers typically exhibit lower cone resistance values, indicating less resistance to the cone penetration. Conversely, sandy layers display higher cone resistance values, suggesting greater resistance. The measurement data obtained from the CPT is presented in CPT diagrams, showcasing the cone resistance (qc) in MPa and the friction number (Rf) in percentage, as provided in **Appendix I – Soil Investigation**.

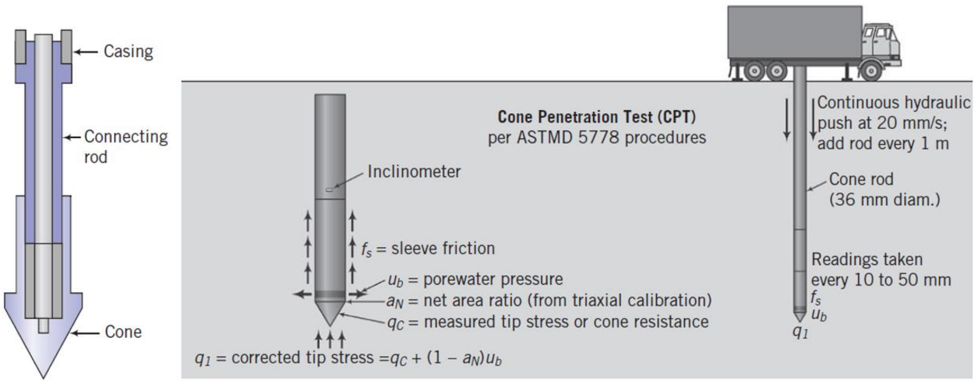


Figure 26 A Cone Penetration Test (CPT) (Budhu, Soil Mechanics Fundamentals, 2015)

As depicted in **Figure 25**, no available soil data exists regarding the specific embankment supporting the train track. Due to limited data concerning the subsoils of the embankment, CPT's taken closely along the railway were analyzed instead. To justify that the soil sample is representative of the expected subsoil composition under the track, the four CPTs closest to the track are analyzed, see **Appendix I – Soil Investigation**. In addition, comparing the different soil samples provides more insight into the variations in subsurface layers along the track. The assumption that the available CPTs are representative of the soil texture under the track body results in the assumption that the soil consists of a similar structure, see **Figure 27**.

Figure 25 illustrates the absence of available soil data specifically for the embankment supporting the train track. Consequently, the analysis focuses on the cone penetration tests (CPTs) conducted in close proximity to the railway. To ensure the representativeness of the soil samples in relation to the expected subsoil composition beneath the track, four CPTs closest to the track are examined (see **Appendix I – Soil Investigation**). By comparing these soil samples, a deeper understanding of the variations in subsurface layers along the track is obtained. Assuming that the available CPTs adequately represent the soil texture beneath the track, results in the soil investigation shown in **Figure 27**.

In discussion with geotechnical experts, the decision is made to use the soil sample with the least favorable characteristics as starting point for the soil analysis. This approach leads to the premise that the expected soil composition of the railway embankment is similar to **Figure 27**. For the remainder of the study, a single soil sample is assumed for the entirety of the track extension. Variations in soil layers and differentiation in properties are most likely and should not be excluded in the interpretation of the result, as they affect the stability of the trajectory.

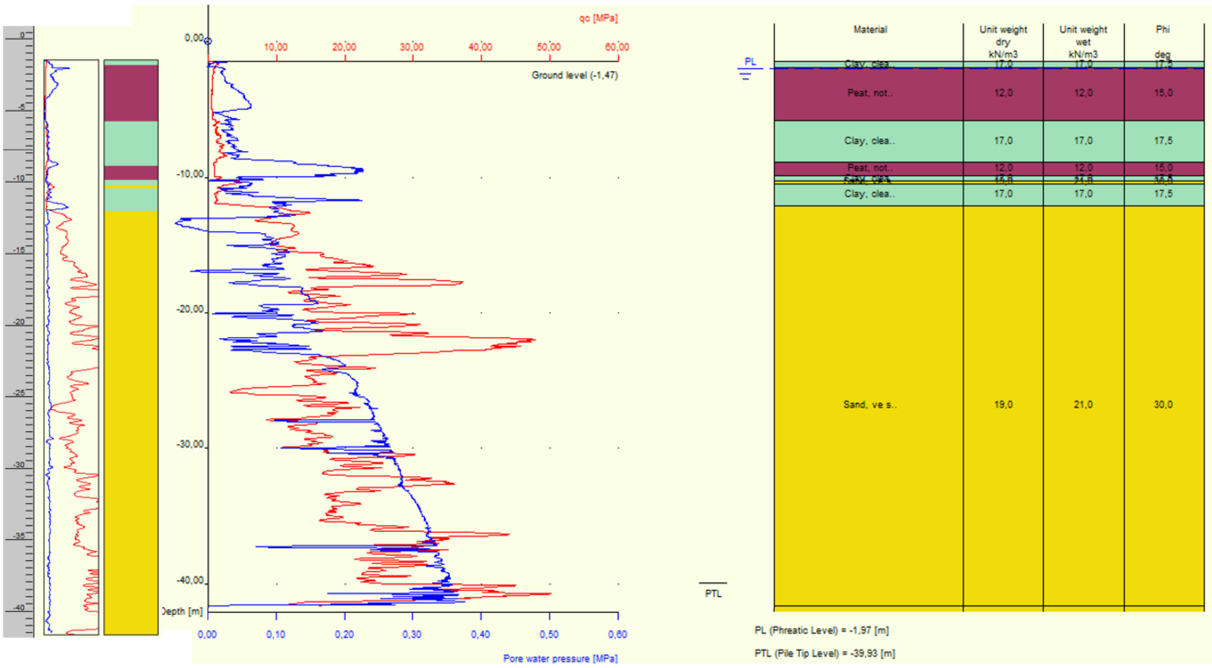


Figure 27 Composition of the Soil Layers based on CPT 49296 (D-Foundations , 2023)

Figure 27 presents the soil investigation conducted with BRO-ID CPT 49296, displaying the conus resistance (qc), pore water pressure, and friction in graphical form. This data facilitates the classification of the soils according to the characteristic soil properties outlined in NEN 9997-1. The determination of soil types is guided by several fundamental principles (Budhu, Soil Mechanics Fundamentals, 2015):

- Sands and gravels are coarse-grained soils, with a texture that is gritty and hard;
- Coarse-grained soils are indicated by a large cone resistance;
- Coarse-grained soils generate more friction and resistance compared to fine-grained soils;
- Fine-grained soils are clays and silts, characterized by a smooth texture;
- Fine-grained soils are characterized by a small cone resistance.

The unit weight may differ depending on whether the particles are situated above or below the phreatic level. Coarse-grained soils are characterized by their high load-bearing capacity, drainage qualities and their strength. The properties of these soil types are mainly controlled by the grain size of the particles and their structural arrangement. Coarse-grained soils like sands allow free passage of water in a relatively short time. In contrast, fine-grained soils have a poor load-bearing capacity and are practically impermeable. The degree of (im)permeability affects the unit weight of each layer with respect to the phreatic level. Where clays and peats naturally adsorb water, sandy soils are either unsaturated (above the phreatic level) or saturated (below the groundwater level). For saturated sands, a unit weight γ_{sat} of approximately 19 kN/m^3 is considered, and 17 kN/m^3 for sand found above the phreatic level γ_d.

In addition to the unit weight, the friction angle ϕ in degree is obtained from the table 'Characteristic Values Soil Properties' (NEN, 2017) in **Appendix F – Characteristic Values Soil Properties**. Similarly, the cohesion C' for each layer is determined based on the NEN 9997-1. The unit weight, conus resistance q_c, angle of internal friction ϕ, and cohesion c' are determined for each distinctive soil layer. The characteristic values that are considered for each soil type are based on NEN 9997-1 art. 2.4 (NEN, 2017). The composition of the subsoil and geotechnical starting points are shown in **Table 4**. These values are considered for the continuation regarding the stability calculations.

Table 4 Composition of the soil layers and their respective characteristics according to CPT 49296

Layer #	Top level (m)	Soil	Unit Weight (kN/m3)	q_c (Mpa)	ϕ (deg.)	C'
1	-1.5	Clay, clean, weak	14	0.5	17.5	0
2	-1.9	Peat, not pl, weak	12	0.1-0.2	15	2-5
3	-5.8	Clay, clean, weak	17	1.0	17.5	10
4	-8.9	Peat, not pl, weak	12	0.1-0.2	15	2-5
5	-9,9	Clay, clean, weak	17	1.0	17.5	10
6	-10,3	Sand, ve sil, loose	17/19	5>10	30	n/a
7	-10,5	Clay, clean, weak	17	1.0	17.5	10
8	-12,1	Sand, ve sil, loose	17/19	5>10	30	n/a
9	-15,0	Sand, ve sil, dense	19/21	5>15	32.5	n/a

The investigation of the geometry, and analysis of the respective elevations, combined with the soil investigation, result in the analysis of the current situation as shown in **Figure 28.** The assumption is drawn that the top layer of the rail embankment mainly consists of a sand body based on the historical analysis in **Chapter 2.1 – Current Situation**. The subsoils consist of soft clays, peats, medium clays, and loose and dense sands respectively. However, the track has been in use since 1887 (Bethlehem, 2018), assuming that the subsoils have been subject to consolidation over the course of the years. The CPT's on which the subsoil composition is based, are conducted in 1997 (DINOloket, 2023). Despite the low hydraulic conductivity of clayey and peaty soils, the conclusion is drawn that after steady static and dynamic loading, most of the consolidation has occurred (Geo Engineer, 2023). The assumption that the soil composition is uniform along the width as well as length of the embankment, as shown in **Figure 28**, is a starting point for the continuation of this variant study on soft soil stabilization methods.

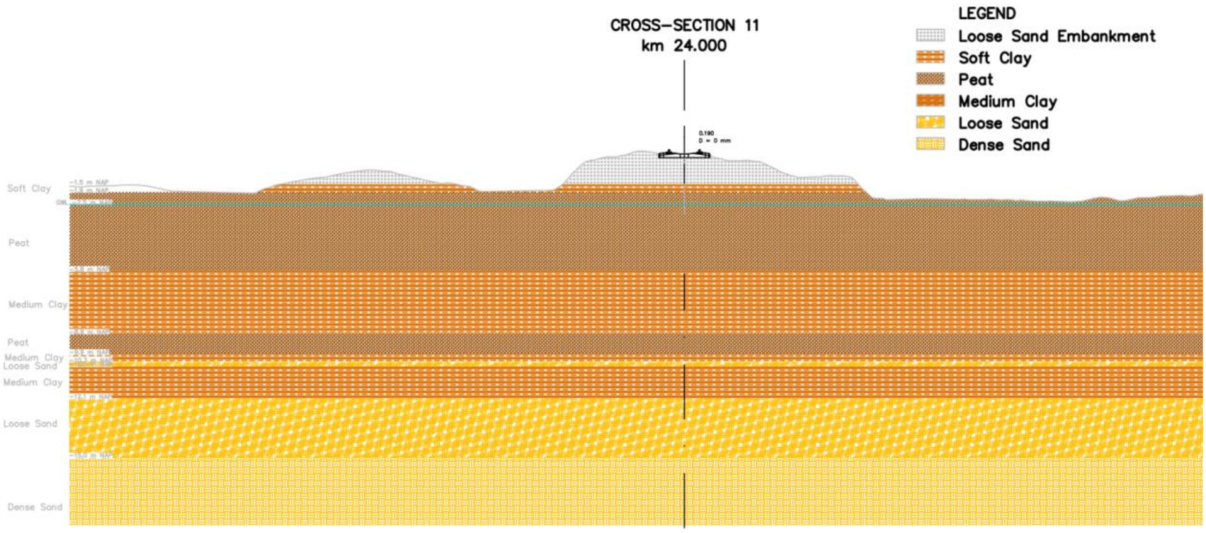


Figure 28 Current Geometry including the Elevations and Soil Layers at km 24.0.

The soil classification and the respective characteristic values are determined by geotechnical parameters and were obtained from NEN 9997-1, art. 2.4.5. Possible differences between the soil properties and geotechnical parameters obtained from test results on the one hand and the properties that determine the behavior of the geotechnical structure on the other must be considered. These differences may be due to the stress level in the soil, deformations of the layers by dynamic loads, but also the effect of construction activities on the soils may result from differences in standard and actual geotechnical parameters.

2.5.4 Material, Capacity and Exploitation

With regard to adjusting the train schedule, in agreement with ProRail, the decision has been taken to change the train type on the Leiden-Utrecht railway line. At times when trains are running four times an hour per direction, only so-called 'light' types of rolling stock may be used. This includes both the SLT (sprinter light train) and SNG (sprinter new generation) vehicles, see **Figure 29**. By using only light weight rolling stock, the load on the track body and thus the risk profile, despite the larger number of trains, remains similar to the current situation.

Figure 29 Sprinter Light Train (left (Vulpen, 2022)) and Sprinter New Generation (right) (NVBS, 2023)

Research into the expected required capacity is important regarding the exploitation of the trajectory between Leiden and Alphen aan den Rijn. Based on the spatial programme and distance classes, an estimate of the transport value is worked out by ProRail (ProRail, 2020). This includes the following starting points:

- The number of passengers hopping on/off at nearby stations decreases. Currently, part of the future Hazerswoude-Rijndijk travellers use the station in Alphen aan den Rijn. These board and exit at their own station in the future.
- The amount of through travelers decreases. The travel time between Leiden-Utrecht is approximately 2 minutes longer due to the extra halt. This makes the train less attractive, resulting in fewer passengers using the train.

Based on these assumptions, the transport value is lower than the number of passengers entering and exiting at station Hazerswoude Rijndijk. Transport value is the expected transport volume, the number of passengers, in any given region based on population, employment and other amenities. ProRail has drawn up a prognosis based on 10,000 inhabitants in and around Hazerswoude-Rijndijk in 2020, see **Table 5**.

Table 5 Prognosis Transport Value Hazerswoude-Rijndijk (ProRail, 2020)

	Number of Passengers
Passengers hopping on/off	1,418
Passengers shifting from station Alphen aan den Rijn to Hazerswoude-Rijndijk	-/- 646
Decrease due to travel time increase	-/- 183
Expected Transport Value	**589**

The expected transport value changes depending on the developments within the area. As described in **Chapter 1.4.2 – Underpass or Level Crossing**, the village of Hazerswoude-Rijndijk is expanding, leading to an increase in population and employment. This trend of the increasing number of inhabitants in and around Hazerswoude is depicted in **Figure 30**. The number of inhabitants is obtained from data gathered by the municipality of Alphen aan den Rijn (CBS, 2023) and is estimated to be 12,000 for both Hazerswoude-Dorp and Hazerswoude-Rijndijk combined. Both graphs exhibit a gradual and consistent growth in population over the recent years. This trend suggests a plausible scenario where the number of residents in and around Hazerswoude continue to rise in the foreseeable future. Consequently, the transportation demand and requirements are expected to evolve accordingly.

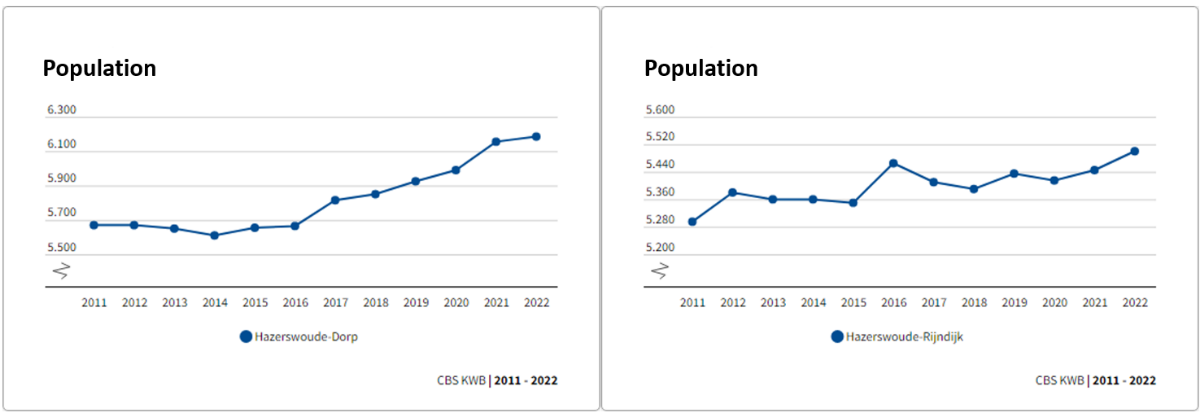


Figure 30 Population of Hazerswoude between 2011 and 2022 (CBS, 2023)

The increasing transport value potentially results in adjustments to the number of trains that run on the trajectory Leiden-Utrecht, or the weight or length of the train. Therefore, constructing the track doubling with a mind to the future and the many developments taking place in the area and its surroundings is reasonable. The change in material, capacity, and exploitation are starting points for the project, which impact the durability of the design.

Anticipating trends in transportation is crucial for ensuring the long-term sustainability and viability of railway systems. This becomes especially important in track doubling projects like the Leiden-Utrecht trajectory, where factors such as adjustments in train weight or length, as well as the growing transport demand in the surrounding area, must be considered. Therefore, incorporating these considerations into the initial design phases of such projects is of importance. By doing so, not only is the present operational efficiency ensured, but also the future sustainability and durability of the railway system.

2.5.5 Loads

The determination of loads on the railway embankment is a crucial aspect that adheres to the guidelines specified in OVS00056-7.1 (ProRail, 2016). These loads are broadly classified into two categories: permanent loads and dynamic loads. Permanent loads encompass the static or constant forces acting on the embankment over time, including the weight of track components such as rails, sleepers, ballast, as well as fixed structures like bridges and tunnels. On the other hand, dynamic loads involve transient forces resulting from the movement of trains and other vehicles, considering factors such as train speed, axle loads, and configurations. Accurate determination and consideration of these loads are essential for evaluating the embankment's structural capacity, ensuring its ability to withstand the applied forces, and maintaining safe and reliable operation throughout its intended lifespan.

Permanent Loads

The permanent load includes the soils own weight and the weight of the superstructure, see **Figure 31**. The latter consists of the substructure, ballast, sleepers, track rods and their fixings. The characteristic value for the weight of the superstructure $Q_{k;rep}$ is considered to be 12.5 kN/m^2, in accordance with OVS 00056-7.1.

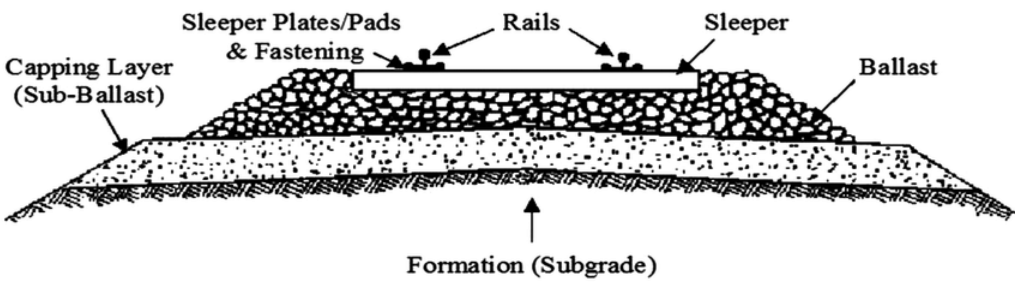


Figure 31 Cross-Section of a typical Railway Track (Elkhoury, 2018)

Train Loads

The track loads to be considered for the design of the embankment are derived from the load model in accordance with NEN-EN1991-2. These track loads schematized in **Figure 32**, note that the safety factor α = 1.21, stated by NEN-EN1991-2 is discounted.

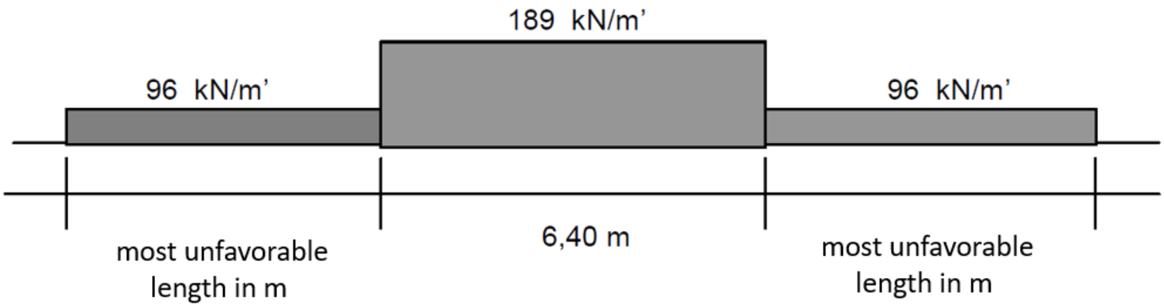


Figure 32 Equivalent Dynamic Load per meter track including safety factor α =1.21 (ProRail, 2016)

The loads shown in **Figure 32** are simplified to an equivalent representative dynamic load in accordance with OVS00056-7.1. Therefore, the dynamic loads $Q_{mob;rep}$ are simplified to be either:

- 76 kN/m^2 on underside of sleeper over a sleeper width of 2.5 m for load capacity testing and soil retaining structures, or
- 63 kN/m^2 over a width of 3.0 m (underside of ballast bed, 0.7 m -BS) for determining the overall stability of ground structures.

For the continuation of the report, a value of 63 kN/m^2 over a width of 3.0 m applies as dynamic load, with a maximal degree of distribution of 30 degrees, to determine the overall stability of the embankment. By using standard values in accordance with the rules, representative calculations are obtained.

2.5.6 Cables and Pipes

The Dutch railway are a complex system, in which safety and serviceability is ensured by protecting the network through a variety of security systems. To provide a safe rail network, all required equipment is connected by cables. Not only NS services have cables under the tracks, internet providers and data companies also use them. Glass fiber cables are usually installed at a depth of about 60 cm. However, power supply cables for trains and substations need more ground coverage and are laid 90 cm deep. In addition to the electricity, TV and telephone cables, there are also gas pipes and water pipes under or next to the track, making the investigation of their presence of great importance for the research on subsoil stabilization (Rijksoverheid, 2023).

The KLIC (Cables and Pipelines Information Centre) is a national foundation of the participating cable and pipeline operators. They provide overviews of the cable network to prevent excavation damage to underground cables and pipelines and promote safety during excavation work (Rijksoverheid, 2023).

Figure 33 KLIC Hazerswoude-Rijndijk (Kadaster, 2023)

Figure 33 and **Appendix J - Cables and Pipes** (Kadaster, 2023) provide a comprehensive overview of the cables and pipelines that exist in the future location of Station Hazerswoude-Rijndijk. Alongside the train track, there are data transport and low to medium power supply cables that have been installed. Exercising caution within the precaution area, indicated in pink, signifying the presence of these infrastructure elements, is important. While a significant gas pipeline is known to be located on the southern side of the railway embankment, further investigations are necessary to accurately identify this pipeline and other pipelines in the vicinity. Historically, the land south of the track has been primarily utilized for the installation of cables and pipes due to the former double track being situated north of the current track. Expert consultations suggest that the track extension area is expected to have minimal cable and pipe presence, but a thorough assessment is still required.

2.5.7 Nature Preservation

The Nature Network Netherlands is the Dutch network of existing and newly created nature areas. The network aims to better connect nature areas with each other and with the surrounding agricultural area. In doing so, so-called preserved nature exists, including ecological connections, nature preservations and Natura 2000 areas.

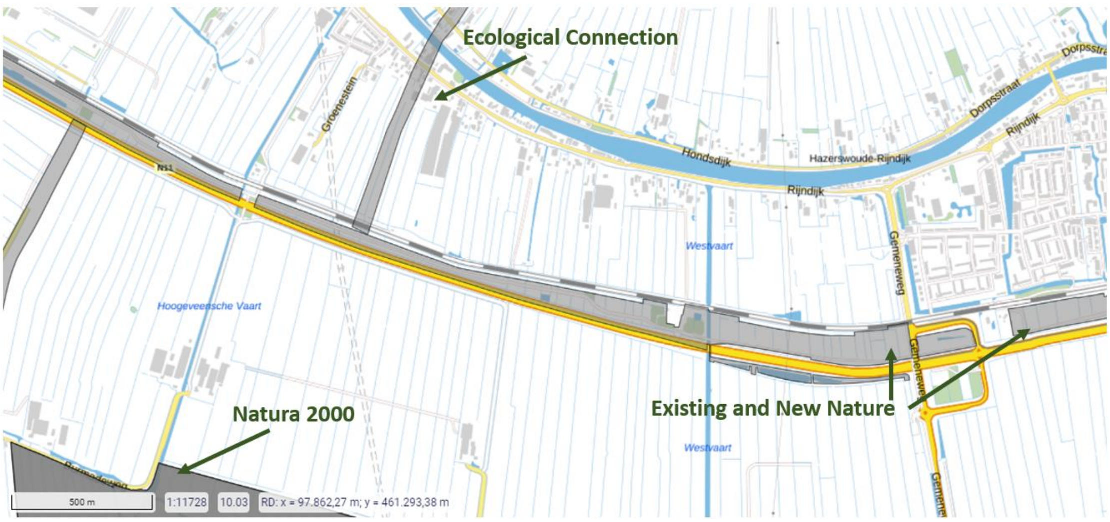


Figure 34 Nature Preservation (PDOK, 2023)

Ecological Connection

In **Figure 34,** an overview of the protected nature areas is presented. Of particular note is the ecological connection to the Braassemermeer located north of the train track. This connection serves as a vital route for bird protection, and therefore, the impact of the track extension on this area is minimal. The establishment of a connection between various natural areas is crucial to promote the dynamics and migration of birds and small animals. Enhancing the quality of the ecological connection zone is achieved by integrating green and water structures in the surrounding area, further contributing to the preservation and enhancement of biodiversity (Urban Green Blue Grids, 2023). Awareness of the protected flight path is important depending on the installation equipment needed. In addition, consideration should be given to limiting negative impacts on birds in the vicinity, depending on the season of installation. However, as there is minor change in the environment regarding the ecological connection, the impact of the track extension is minimal.

Nature Preservation

The southern part alongside the train track between Leiden and Alphen aan den Rijn is however allocated to nature preservation. This implies limiting nitrogen as well as carbon dioxide emissions and protecting the overall flora and fauna in the area. The protected Braassemermeer impacts the design choices related to the track as emissions must stay limited during all construction stages. However, according to the law Nature Preservation (Afdeling advisering van de Raad van State, 2023), compensating the nature area in case not all requirements are met during a project is allowed. This law gives more leeway regarding constructing in or near a protected nature area. However, efforts should be made to always protect nature as much as possible. Looking for opportunities to enrich nature in the variants study is of importance.

Natura 2000

In addition, a Natura 2000 area (a European network of protected nature areas) is located south of the project site. Plant and animal species threatened in Europe and their natural habitats are protected to preserve biodiversity. Because of the ecological importance, building in these protected areas is forbidden (Broekmeyer & Kistenkas, 2006). This area, however located more distant, majorly impacts the design and execution phase of the project. General measures to improve nature in nitrogen-sensitive areas apply to a Natura 2000 area. These include the increase of management fees and forest compensation for example. This not only contributes to nature and biodiversity, but also to achieving climate goals. With an increase in management fees, the land management organizations Staatsbosbeheer, Natuurmonumenten and LandschappenNL conduct the management needed to maintain or improve the quality of nature (Rijksoverheid, 2023).

The presence of these nature areas underscores the significance of carefully considering the opportunities and requirements of the project area, considering both the current and future natural surroundings. Conducting further research to determine the specific needs of these areas and explore how the new infrastructure effectively contributes to the preservation and enhancement of flora and fauna is valuable. By aligning the project with the ecological requirements, the sustainable coexistence of the railway and the natural environment is ensured, promoting the well-being of the local ecosystem for years to come.

2.5.8 Archaeology and National Monuments

One crucial aspect of preliminary investigation that is often overlooked is the assessment of archaeology within the project area. Considering the potential presence of archaeological artifacts before undertaking significant excavation for soil improvement techniques is essential. By conducting this assessment, the excavation method is adjusted accordingly, ensuring the preservation and protection of historical monuments and artifacts that may be discovered during the construction process. This proactive approach not only safeguards valuable cultural heritage but also allows for the proper documentation and study of any archaeological finds.

Archaeological Sites

For this reason, the Cultural Heritage Agency created an archaeological monument map, see **Figure 35** (Cultural Heritage Agency, 2014). The map is intended as a tool for spatial planning and for managing and protecting archaeological information preserved in the soil. Using this map, the archeological value within the area is considered during various planning decisions, containing information about known archaeological sites, including protected monuments as well as the likelihood of archaeological findings. However, since 2014, the AMK is no longer maintained by the National Cultural Heritage Agency. For this study, the assumption is drawn that the archaeological monuments map provides sufficient insight into the archaeological value of the area.

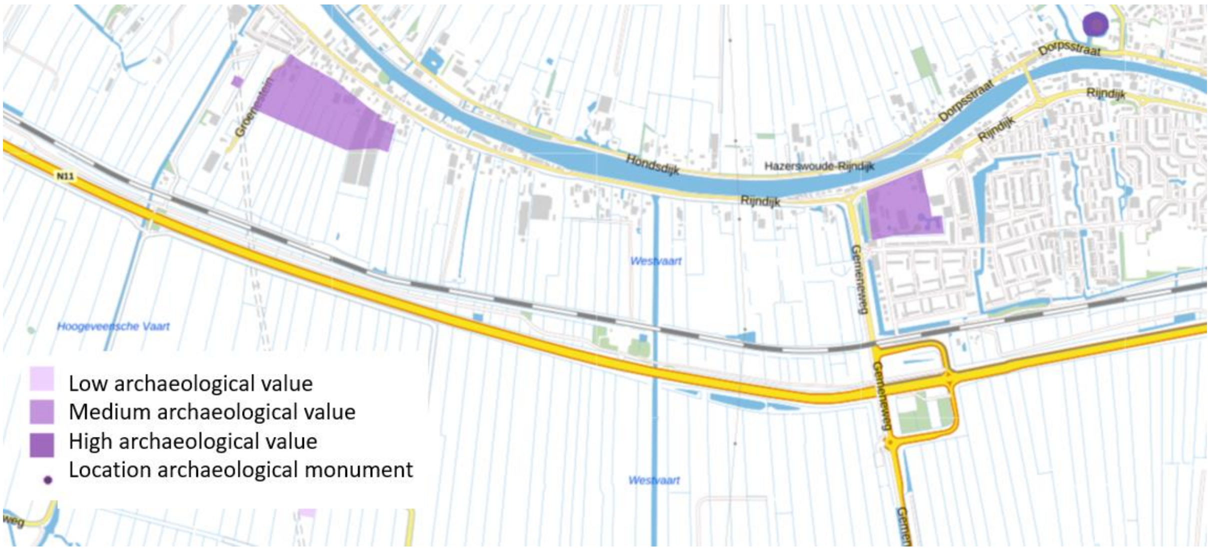


Figure 35 Archaeological Sites between Zoeterwoude and Hazerswoude-Rijndijk (Cultural Heritage Agency, 2014)

The following archaeological sites are found, and therefore might increase the likelihood of archaeological findings near the project area:

- Polder Groenedijk, Roman Settlement with high archaeological value: Site with traces of habitation from the Roman period. Traces of a native settlement were found here in 1951. This site has a high value because of the high probability of finding reasonably rare, reasonably intact Roman occupation traces and because of the present landscape context with the Rhine and a Roman road.
- Rijnenburg, Medieval castle with high archaeological value: Site with remains of Rijnenburg Castle from the Late Middle Ages and the later mansion Rijnenburg from the Middle Ages. This site has a high value because of the high probability of finding and because of the quality and the high information value of the remains of the castle.

National Monuments

In addition to archaeological sites, some national monuments are present in the area. A historical building may be of national importance because of its great cultural-historical or scientific value (Het Nationaal Restauratiefonds, 2023). The overview of the monuments in the Netherlands is depicted in **Figure 36**, where each monument is marked with a blue dot.

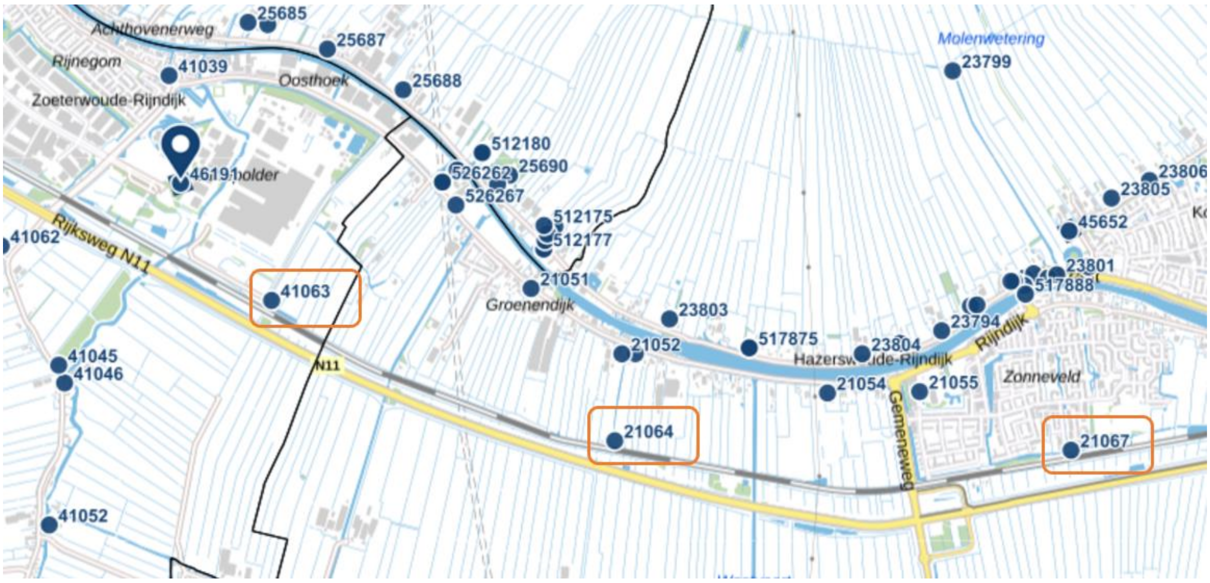


Figure 36 Map of National Monuments (Cultural Heritage Agency, 2023)

Along the train track, three relevant national monuments are found, see **Table 6**. The State protects national monuments with general rules that prohibit damaging, destroying, and neglecting national monuments. Furthermore, activities related to or in the surroundings of a national monument are only possible with a permit. The municipality is responsible for the permit application in most cases (IPLO, 2023). Timely investigating with the municipality of Alphen aan den Rijn if and how the track extension affects the national monuments and whether additional measures are needed to guarantee the stability and preservation of the monuments is of importance.

Table 6 Description of the monument (Molendatabase, 2023) and their number (Cultural Heritage Agency, 2023)

Monument number	Description of the monument
41063	The Barremolen is a polder mill on the Burgemeester Smeetsweg near Zoeterwoude-Rijndijk and is located north of the railway line. The mill dates from 1652 and was built for the purpose of pumping the Oude Groenendijksche or Barrepolder.
21064	The red seesaw mill dates from the 17th century and served as a pumping station. Nowadays, the mill has no function in water management, but still grinds.
21067	The Rijnenburger in the village of Hazerswoude-Rijndijk is a polder mill built in 1722 to replace a burnt-out seesaw mill. The mill pumped the Rijnenburger polder and was in full operation until 1965. There is a small house in the mill itself, but a house was also built next to it.

2.5.9 Expropriation of Land

A starting point that limits the total expected costs related to the expansion of the railway between Zoeterwoude-East and Hazerswoude-Rijndijk, is whether the land north of the railway is owned by the farmers, municipality or ProRail. As mentioned in **Chapter 2.3 – Stakeholder Analysis**, the expropriation of land must be limited as much as possible to limit the costs associated with preparing the land for the construction works. Using the property map provided by ProRail (ProRail, 2023), more insight is gained in the expected magnitude of the costs related to land expropriation. In addition, the ownership results in a better understanding of the possibilities within the project area.

The cadastral map gives an overview of the different plots and their borders (ProRail, 2023), depicted in **Figure 37**. The investigation of the parcels north of the existing rail embankment indicate a small variety of owners.

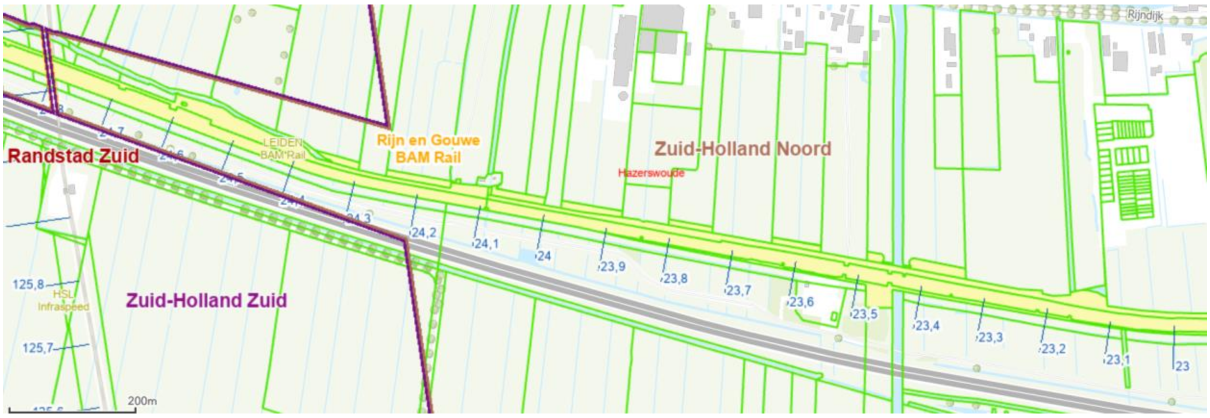


Figure 37 Overview of Parcels along Train Track between Zoeterwoude and Hazerswoude-Rijndijk

First, ProRail owns the parcels marked yellow in **Figure 38**. Parcels 813 and 815 are shown to belong to Railinfratrust B.V. Railinfratrust B.V. is the legal owner of the public railway infrastructure in the Netherlands (Port of Amsterdam, 2023). The organization bears responsibility for maintenance, operation, and expansion of the railway network. To carry this out, Railinfratrust engages its subsidiary ProRail. This organization economically owns the railway network and regulates rail traffic control and the distribution of railway capacity among the various carriers, such as NS. Railinfratrust is an independent company owned by the Dutch state.

Parcels 771 and 363 for example are owned by the municipality of Alphen aan den Rijn. Since they are major stakeholders within the project, these parcels are easily repurchased to ensure more space for the embankment construction. Parcels 125, 814 and 816 however, belong to third parties (ProRail, 2023).

Figure 38 Investigation of Land Expropriation (ProRail, 2023)

Based on the available information, anticipated is that the strip of land encompassing parcels 125, 813, 771, and 363, among others, is likely necessary for the extension of the double track. However, further investigation is needed to gather detailed information about the ownership of these parcels and identify the third-party owners involved. For the purposes of this report, the assumption is drawn that ProRail is actively engaged in communication with these landowners. Furthermore, the presumption is made that the required land has been successfully acquired and is under the ownership and management of ProRail prior to commencing the construction preparations. This assumption serves as the starting point for the subsequent phases of the project.

2.5.10 Climate in the Netherlands

Embarking on infrastructure projects such as embankment construction requires an understanding of the impact that extreme weather conditions might have on them. The vulnerable nature of embankments to breaches during high-intensity weather events is a challenge that must be addressed in the construction process. Moreover, weathering also poses challenges related to changes in permeability of slopes and embankments.

The Netherlands has a temperate maritime climate, with relatively mild winters, mild summers, and precipitation throughout the year, see **Figure 39**. The Netherlands owes this climate to the influence of the North Sea. Annual rainfall in the Netherlands averages around 800 millimeters, although dry years (around 500 millimeters of precipitation per year) as well as very wet years (up to almost 1,000 millimeter) occur (Royal Dutch Meteorological Institute, 2023). In addition, windy conditions are found along the coast. The west of the Netherlands is more vulnerable to depressions coming from the North Sea. These deep depressions cause strong winds and should be considered during construction.

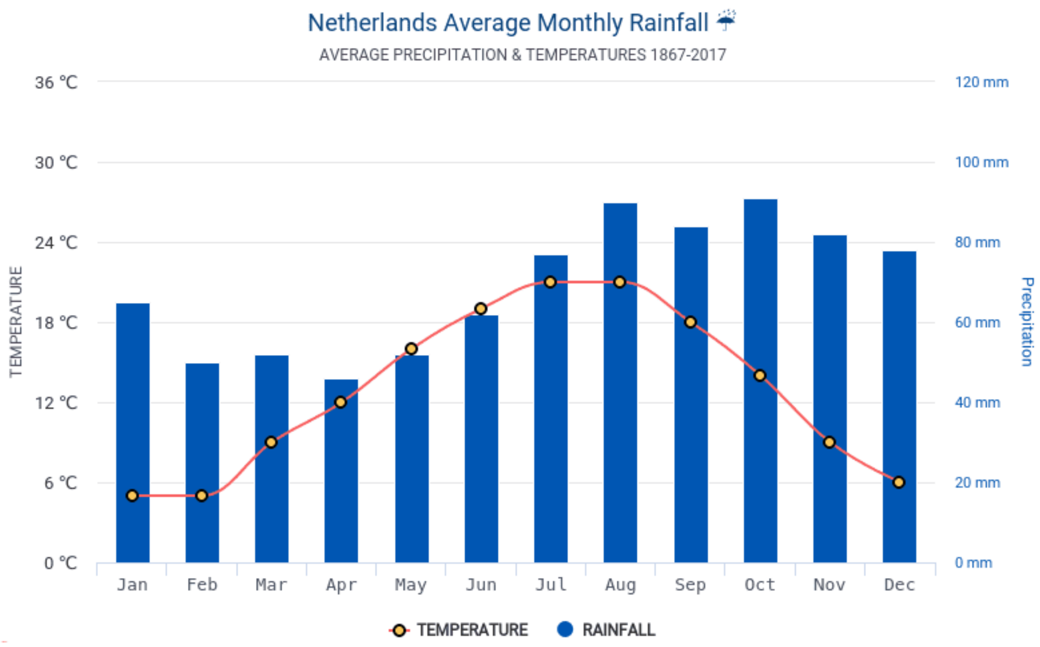


Figure 39 Average Precipitation & Temperatures 1867-2017, The Netherlands (Hikersbay, 2023)

Dutch summers are generally changeable and unpredictable. Temperatures and weather patterns are erratic within one season. Winters are almost as unpredictable as summers. In this season, temperatures easily rise to well above 10 degrees, just as likely as freezing may occur. However, winters are becoming slightly milder on average and the likelihood of lengthy periods of frost is decreasing (Royal Dutch Meteorological Institute, 2023). The main causes are its location by the sea, the lack of mountains and the fact that its often subject to a dividing line between warm and colder weather. These factors all contribute to the unpredictability of the weather. The influence of the unpredictability of the weather in the Netherlands, leads to a comprehensive construction planning. However, since the project is still in its proposal phase, considering the weather conditions during all construction phases is important. The construction of embankments primarily involves the use of soil material, which needs careful management and monitoring during the construction process since several factors, including weather conditions, significantly impact their performance. Weather plays a crucial role in determining the success of soft soil embankment construction. To ensure a successful embankment construction, considering the expected weather conditions, the construction planning should include the following factors:

- Firstly, understanding the impact of weather patterns on embankment fills should play a crucial role in designing sustainable infrastructure that performs well over its service life despite unpredictable environmental factors such as rainfall patterns and temperature fluctuations, which may vary over time.
- Secondly, the soft soils are prone to failure in case of heavy rainfall, especially during the construction phase. Therefore, the site-specific weather forecasts should be regularly monitored to schedule operations during periods of low precipitation or temperature.
- During the structure's lifetime, weather conditions must be taken into consideration and should influence the maintenance plan. Weather conditions and its fluctuations have a significant impact on the mechanical behaviour of embankment fills, which ultimately affects its service life and stability. Additionally, the rail embankment constructed on soft soil requires special attention from geotechnical engineers due to the potential for failure, excessive settlement, and stability issues during seasonal changes.

Finally, construction planning must consider unpredictable changes in weather patterns during all phases of the project's execution. This should include contingency plans designed specifically around key potential risks as identified through careful risk assessment analysis. In conclusion, understanding how changing weather conditions impact different types of embankment materials is crucial in ensuring the success and longevity of infrastructure project.

2.6 Fundamentals of Soft Soil Stabilization

The soil investigation in **Chapter 2.5 – Design Criteria** identified the soil layers on which the rail embankment is constructed. The embankment is measured to be unstable, not meeting the requirements for the expansion to a double tracked railway embankment. This results in the need for ground improvement, to ensure sufficient stability of the embankment. Before researching the possible soil stabilization methods that are proposed to be implemented, a better understanding of the different soil layers and their characteristics is required.

Soil is a mixture of solids, liquids, and gases. The solid component is made up of minerals, organic matter, or a combination of both. Within the soil, there are spaces between the solid particles known as voids, as depicted in **Figure 40**. The liquid component in the voids is primarily water, referred to as porewater, while the gas component is mainly air. The presence and behavior of porewater are significant factors in how soils respond to applied loads. When all the voids in the soil are completely filled with water, the soil is considered saturated. If the voids are not entirely filled with water, the soil is classified as unsaturated. A soil is considered dry when all the voids are filled with air and no water is present.

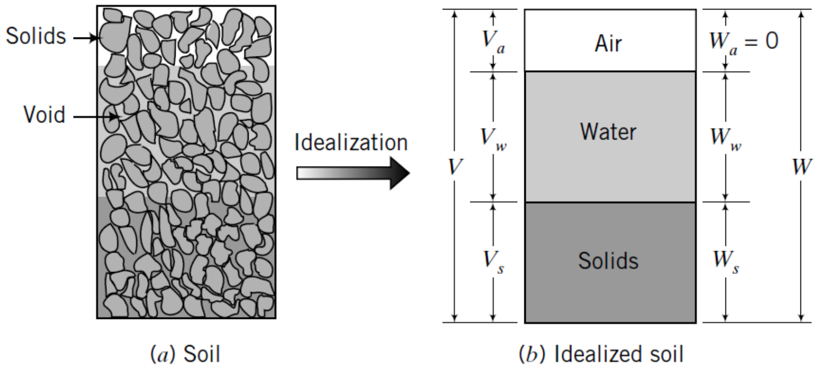


Figure 40 Soil Phase (Budhu, Soil Mechanics and Foundations, 2011)

Water content ($w = \frac{W_w}{W_s} \times 100\%$) is the ration of weight of water to the weight of the solids since the weight of air is negligible. Depending on the water content of a soil, the physical and mechanical behavior of the soil changes. When the water content reduces, the volume changes accordingly, see **Figure 41.** Consequently, the decrease in voids between the particles result in an increased cohesion, causing the soil to be stronger. The soil improvement technique that is based on the reduction of voids in a soil is called compaction. Densification of the particles is achieved through mechanical compaction (reducing the gases) or drainage (reducing the water content). Based on the composition of the soil layers and the purpose of the structure, a soil improvement method is chosen to stabilize the soil.

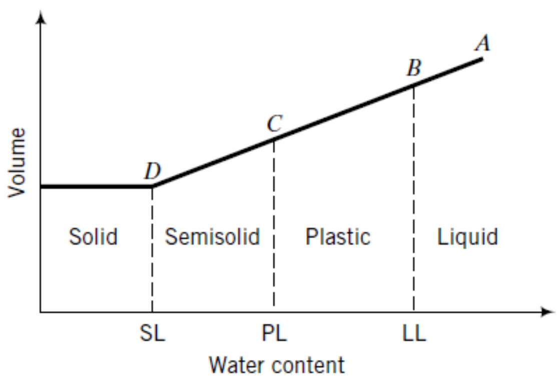


Figure 41 Changes in soil states as a function of volume and water content (Budhu, Soil Mechanics and Foundations, 2011)

Based on the soil investigation described in **Chapter 2.5 – Design Criteria**, the conclusion is drawn that the soil layers up to -12 m NAP consist of mainly clays and peats. The characteristics of these soil types determine the suitability of possible soil improvement methods.

The particles that give clay its characteristic properties are clay minerals. These have a plate-like shape, clogging the pores between the solid particles, resulting in the impermeability characteristic of clay. As a result, clay is always bound to water (Budhu, Soil Mechanics and Foundations, 2011). In addition, peat layers are found in the project area. Peat is highly heterogeneous formed due to the decomposition of organic matter such as plant remains – leaves, trunks, roots and so on. The organic particles are arranged horizontally, which results in relative impermeability to water. The high moisture content and water-holding capacity result in the low shear strength and bearing capacity of the soil.

Because of the characteristic properties of clayey and peaty soils, improving the soil by reduction of the water content through drainage or compaction is difficult. Therefore, more advanced methods of soil stabilization are required to ensure a safe and stable embankment. These include extensive techniques like transferring loads to the solid sandy soils (-12mNAP), or a combination of successive less intrusive soil improvement methods.

2.7 Fundamentals of Slope Stability

The stability of railway embankments is of great importance for the longevity and durability of the structure as well as the overall safety of the commuters. Geotechnical engineering pays particular attention to geology, surface drainage, groundwater and the shear strength of soil when assessing the stability of an embankment. The analyses of slope stability are based on simplifying assumptions; the design of a stable railway embankment relies on experience and careful site investigation.

Slope failures are a result of slope instability, influenced by soil types, stratification, groundwater, seepage as well as the overall embankment geometry. Various slope failures are to be distinguished, of which the rotational slide is most common (Budhu, Soil Mechanics and Foundations, 2011). Here, the point of rotation is situated on an imaginary axis parallel to the slope, resulting in the failure surface to pass through the base, toe, or slope of the embankment, see **Figure 42**.

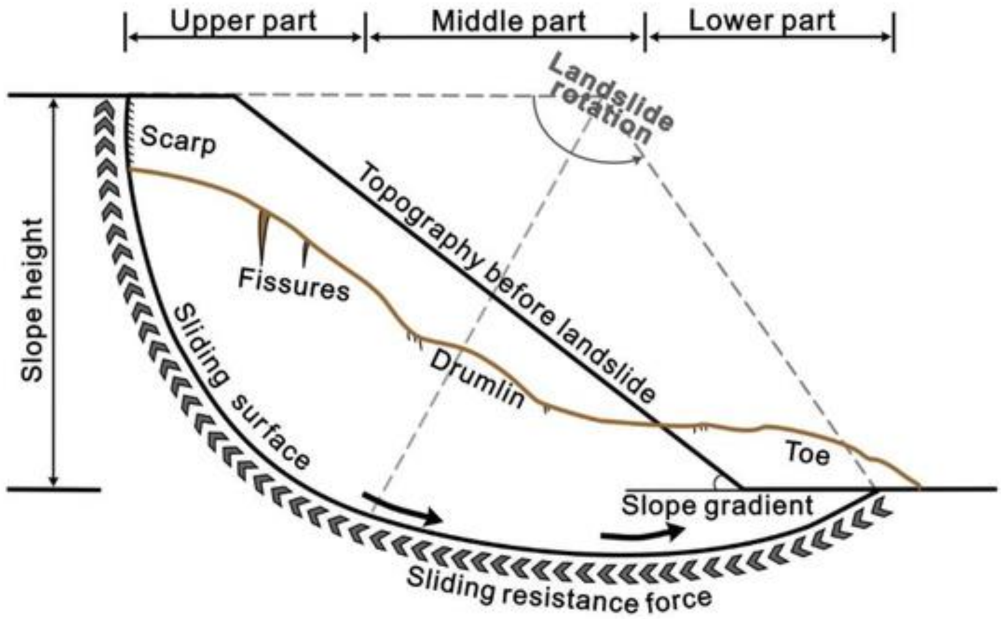


Figure 42 Schematization Rotational Slope Failure (Ma & Qiu, 2023)

Generally, slope failures are caused by natural forces, human activities and misjudgment and burrowing animals. Some of the factors that provoke slope failure include rainfall, external loading, and construction activities. The first saturates and soften soils when long periods of precipitation occur. The weakening of the underlying soil layers result in sliding slopes. External loading on the crest of an embankment adds to the gravitational load and may cause slope failure (Budhu, Soil Mechanics and Foundations, 2011). Lastly, construction activities near the toe of an existing embankment increase the chance of failure due to decreasing lateral resistance.

To understand the degree of stability of a structure, the factor of safety (FS) is determined. This factor is defined as the relationship between the capacity (C, strength or resisting force) and the demand (D, stress, or disturbing force). The factor of safety is dependent on a variety of factors, including the geological conditions, the duration and frequency of temporary surcharge, reliability of soil parameters, ground water and environmental conditions. The railway embankment is considered as stable when the capacity is 1,3 times larger than the demand i.e., FS > 1,3 (Budhu, Soil Mechanics and Foundations, 2011).

$$FS = \frac{C}{D}$$

2.7.1 Method of Bishop

Bishop's limit equilibrium method is commonly used to analyze slope stability. This approach assumes a circular slip plane and focuses on moment equilibrium, with the sliding soil as a rigid body that rotates around a center point on the circular slip surface. The slip surface is divided into vertical rectangular strips of equal width. The method involves calculating the sliding forces and anti-sliding forces for each strip, considering both vertical equilibrium and shear resistance. The factor of safety of the slope is determined through iterative calculations, aiming to find a stable condition where the forces are balanced.

The equilibrium of moment applies to the center of the circular slip plane, following that for a stable slope, the stabilizing moment M_{stab} must be greater than or at least equal to the driving moment M_{dr}:

$$\frac{M_{stab}}{M_{dr}} = FS \geq 1{,}3$$

The driving moment in the slope stability analysis is determined with respect to the center of rotation of the slide circle. Any soil or forces positioned on the higher side of the vertical line passing through the center of rotation are considered unfavorable and contribute to the driving moment in the stability calculation. Conversely, elements or forces located on the lower side of the vertical line act favorably and counteract the driving moment. The stabilizing moment is provided by the shear stresses along the sliding surface. By summing these shear stresses over the length of the section at the slip plane, the total shear force is calculated, see **Figure 43** for a visual representation of this process.

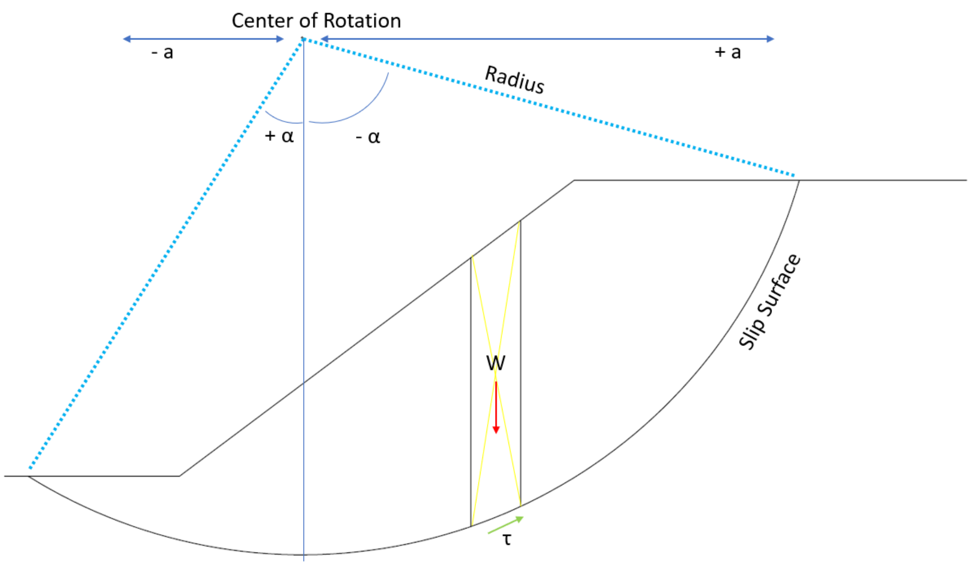


Figure 43 Schematization Method of Bishop (courtesy of author)

The stabilizing moment and the driving moment for the calculation of one slice, are defined as:

$$M_{stab} = R \times \sum(\tau \times l)$$
$$M_{dr} = \sum(W \times a)$$

- R, the radius of the slip plane
- τ, the shear stresses
- l, the length of the slice
- W, the weight of slice
- a, the distance from the center of the slice to vertical axis of the slip plane

Shear stresses are determined at the center of the sliding surface of the slat. A radius is drawn between the center of rotation and the center of the section. The angle between that radius and the vertical through the center of rotation, is the angle α. This angle is positive when situated on the side of the vertical where the toe of the embankment is located. The angle on the other side of the vertical axis is negative. The cohesion and angle of internal friction are known and defined in the NEN, see **Chapter 2.4 – Boundary Conditions and Limitations**.

The shear stress per slide is formulated as:

$$\tau = \frac{sin\varphi' \times \cos\alpha}{\cos(\varphi' + \alpha)} (\sigma' + c' \times cot\varphi')$$

- φ', angle of internal friction in degrees
- c', cohesion of the slide in kN/m^2
- σ', effective pressure in kN/m^2
- α , angle between horizontal and vertical axis of slip circle

To determine the stability of embankments and compare various soil stabilization methods, the software program D-Geo Stability is utilized. This program is specifically designed for analyzing slope stability and enables the calculation of the lowest stability factor. The details of the methodology, including the use of D-Geo Stability, are outlined in **Chapter 3 - Methodology** of the report.

2.8 Program of Requirements

The Program of Requirements plays a crucial role in the project, specifying both functional and technical requirements beyond those defined by the stakeholders. These requirements guide the project to ensure that the design of the railway embankment meets all necessary conditions, including legal obligations, regulations, and design standards, as well as the specific requirements and expectations of the stakeholders involved. By clearly outlining the project's goals, objectives, and constraints, the Program of Requirements ensures the development of a safe and satisfactory rail embankment that meets the needs of all stakeholders.

2.8.1 Functional Requirements

Given that the rail widening variant is still in a very primitive phase, there are few technical and functional requirements for the design yet. However, the following requirements are linked to the design regarding Hazerswoude-Rijndijk Station (ProRail, 2022).

Regarding line and track use, the following requirement has been drawn up:

- The infrastructure on the Leiden-Utrecht trajectory must enable line operation four times per hour both in peak and off-peak hours and two times an hour service of the new Hazerswoude-Rijndijk station.

The functional requirements with respect to nuisance both during construction and after commissioning are as follows:

- During the construction phase, an optimum must be found between track work and train traffic in accordance with the timetable. Consider here the divisibility of the work to be conducted for the purpose of transport nuisance limitation.
- In the completed final situation, an optimum must be found between the scheduled track maintenance and train timetable.
- Objects should be placed in such a way that maintenance does not require total decommissioning of the track.
- Work zones should be arranged in such a way that planned track maintenance is performed safely with minimum disruption to adjacent tracks.

2.8.2 Technical Requirements

The construction of the embankment provides the foundation for the superstructure. In order to meet the necessary standards, the substructure and subgrade must adhere to specific requirements. These requirements are pre-defined in a general schedule of requirements, as outlined by (CROW, 2023) . The schedule serves as a guideline to ensure that the substructure and subgrade are built to the required specifications, guaranteeing the stability and durability of the embankment. By following these guidelines, the construction process is proceeded in a systematic and quality-controlled manner. These requirements include the following:

General Technical Requirements

- The substructure must be sufficiently strong to transfer its own weight and the loads exerted on the rail tracks to the solid sandy soil layers.
- No damage should occur to the structure due to settlements and settlement differences from the subsoils.
- The embankment must have sufficient rigidity to keep deformations (indentation, wave formation) caused by rail traffic within certain values.
- Settlement of the existing embankment, occurring during construction of the extension, must remain within set limits.
- The settlement over time must be within predetermined limits, which controls maintenance costs after commissioning for a considerable number of years.
- The settlement behaviour of the railway widening should not deviate from the existing track, to limit the settlement differences.
- The widening should be resistant to erosion, frost, moisture, mechanical forces during execution and chemical influences.
- The method of execution must be manageable.
- Construction time and space requirements must be within the specified limits.
- The construction must meet durability requirements.
- The impact of the structure on its surroundings must be acceptable: requirements regarding vibrations and deformations of adjacent structures, underground infrastructure and water management must be met.

Geotechnical Specific Requirements

The technical specifications and requirements for the rail embankment and subsoil layers are derived from OVS00056-7.5, which outlines the design regulations for the rail embankment, as specified by (ProRail, 2016). These geotechnical requirements cover various aspects related to the design, construction, and performance of the embankment and its underlying soil layers. Additionally, these requirements align with the standards defined in NEN9997, as discussed in **Chapter 2.4 – Boundary Conditions and Limitations**. By adhering to these regulations and standards, the project ensures that the rail embankment meets the necessary geotechnical criteria for stability, safety, and long-term performance. The following (geo)technical requirements apply to the design of the railway embankment:

- The design life of a structure like a railway embankment is in accordance with NEN-EN 1990+A1 determined, the infrastructure should be designed accordingly. Permanent rail embankments are classified in design life class 4 with a design life of at least 100 years; the structures are classified in consequence class 3 (CC3) with reliability class 3 (RC3) according to OVS00056-7.1 art. 2.2 (ProRail, 2016) .

Regarding the stability and allowed settlement, the following technical requirements have been drawn up by ProRail according to OVS00056-7.5 art. 6, compliant with NEN9997 (ProRail, 2016):

- If calculations are based on representative soil parameters and characteristic loads according to NEN 9997, the minimum stability factor for track in operation is 1.3 (ProRail, 2016).
- The residual settlement of the track body after 100 years (36500 days) from start of operation may not exceed 0.15 meters (ProRail, 2016).
- The annual settlement of the embankment from the start of operation shall not exceed the following values:
    - First year from start of operation: 0.04 meters
    - Second year from start of operation: 0.03 meters
    - Third and subsequent years from start of operation: 0.01 meters
- At the locations where a new runway (widening) is realized next to the existing runway a maximum (additional) settlement of 0.03 meters applies at the location of the nearest rail on the existing runway over a period of 10,000 days. The annual residual settlement of the closest rail on the existing track may not exceed 0.01 meters.
- If a settlement-free or settlement-limiting structure is needed to meet the settlement requirements, the following steps should be followed, in accordance with OVS00056-7.1 art. 6.5 (ProRail, 2016):
    - The entire procedure of the project is in consultation with ProRail, Asset Management, Architecture and Engineering.
    - The properties (over the lifetime) of the materials to be applied and of the entire building system must be unambiguously determined based on available testing standards (preferably from European regulations).
    - In the absence of standardized testing and inspection standards, a pilot or trial project must be defined in advance with a monitoring program for approval by ProRail.
    - Current environmental and groundwater legislation applies.
    - The possible locations for crossing underground infrastructure should be determined in consultation with the manager/permitting authority.
    - Future (regular) track maintenance and future track extensions must be possible without restrictions on rail traffic and must be coordinated with the manager.

- Changes in the geohydrological situation do not cause any negative effects on both the railway infrastructure and the surroundings of the track.

Critical Train Speed Requirements

The critical train speed ($C_{crit, min}$) is the speed at which the train travels at approximately the same speed as the ground vibration waves generated by the train itself. As a train approaches the critical train speed, the interaction of the vibration waves causes the deformation of the track body and track structure to increase rapidly. The permissible deformation of the rack and its embankment is limited to a maximum for safety and comfort reasons. Evaluation at what speed this phenomenon occurs is important and whether the deformations are within the set limits, in accordance with OVS00056-7.5 art. 7.3 (ProRail, 2016).

- The critical train speed aspect should be considered at speeds higher than 100 km/h. The diagram in **Figure 44** shows the steps to be followed to demonstrate whether a critical train speed problem occurs.
- The design speed (V_d) of the train should be less than 0.6 times the critical train speed ($C_{crit, min}$). If not, the dynamic indentation should be smaller than 2.5 mm, in order for the track to be sufficiently resilient against the deformations caused by the critical train speed.

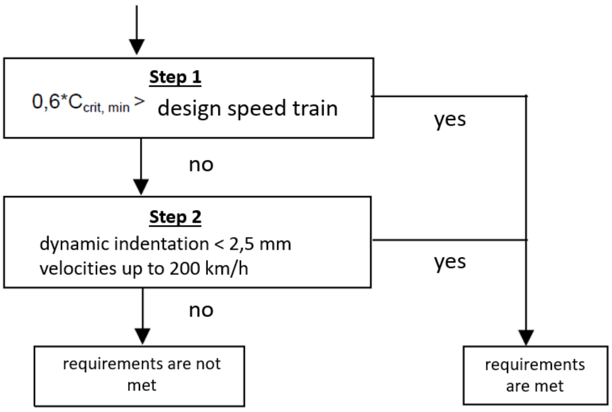


Figure 44 Technical Requirements Dynamic Compression due to Critical Velocity (ProRail, 2016)

2.8.3 Stakeholder Requirements

The customer requirements specification, provided by the most influential stakeholder, plays a significant role in shaping the project. The extension of the double-track is a specific requirement driven by the developments in and around Hazerswoude-Rijndijk. While ensuring compliance with the technical requirements takes precedence in the design process, some flexibility is allowed to address the wishes and needs of various stakeholders. Through interviews with the client (ProRail, 2023) , several requirements have been identified that influence the design of the track doubling to varying degrees. These requirements form important considerations for the project and contribute to the overall success and satisfaction of the stakeholders involved.

- The location of the station square functions of the Hazerswoude-Rijndijk halt is situated to the north of the railway, aligning with the current Gemeneweg. The primary objective is to establish the main reception area and access to the halt on the northern side of the railway, as this area is anticipated to have the highest passenger traffic. Consequently, the track extension should be constructed at the same elevation as the existing railway, ensuring a seamless connection and convenience for passengers accessing the station.

- The construction of the railway extension should aim to minimize the required shutdown of the connecting line between Leiden and Alphen aan den Rijn.
- The design of the new stop should prioritize the safety of waiting passengers by ensuring that a person on the platform has a clear view of all other individuals on the platform.
- In consideration of a potential future track doubling on the north side of the current track, no additional functions should be implemented directly north of the railway track, apart from the platform.
- As a government organization, ProRail is accountable for its choices and expenditures. To mitigate risks, traditional and well-established methods are preferred for the construction of the rail network, with a focus on limiting both costs and risks.
- ProRail utilizes the TRL Scale to assess the maturity of different techniques applicable in railway projects. Given the high costs and risks associated with track stabilization, ProRail prefers methods with a high Technology Readiness Level (TRL) as they provide greater predictability in terms of costs and risks.

METHODOLOGY

The methodology chapter serves as a crucial framework for this research study, guiding the process of exploring and evaluating soil stabilization methods for the extension of a railway embankment on challenging clay and peat subsoils. The chapter begins by identifying and analyzing the specific challenges associated with this type of project. Through a combination of desk research and interactive investigations, a comprehensive understanding of various ground improvement techniques is acquired. These initial investigations lay the foundation for the development of a methodology that effectively addresses the predetermined requirements and objectives of the study. Expert judgement is employed to select the three most promising soil stabilization methods, which is further examined and developed in subsequent stages. By following this methodology, the study aims to provide valuable insights and recommendations for achieving a stable and sustainable railway embankment expansion.

3

3.1 Research Methodology

The research methodology explains and discusses the collection of data and analysis methods that are used in this research report. Generally, two types of research are to be distinguished: desk research and interactive research. Both methods are used alternately to explore the various soil stabilization methods. First, an overview of the possible methods is obtained through a qualitative research approach. The set of possible solutions is described in **Chapter 3.2 – Overview of Soil Stabilization Techniques**. The selection of the different soil stabilization techniques follows. Based on interactive research, three promising variants are selected in **Chapter 3.3 – Selection of Soil Stabilization Techniques**. These variants are further worked out in detail based on both qualitative and quantitative research.

3.1.1 Desk Research

The overview of the possible soil stabilization techniques is obtained through desk research. This form of research uses pre-existing data. To answer the sub-research questions, information and insight are obtained from secondary data. By studying the available internal company data, **Chapter 2 -Theoretical Framework** is drawn up. Desk research focuses on creating the first selection of possible solutions based on literature review. The aim is to obtain theoretical and scientific knowledge on the subject of soft soil stabilization. Available information has been carefully evaluated ensuring that the most relevant and recent data has been obtained. Sources are based both on research reports, comparable projects (enclosed in **Appendix K – Reference projects Soil Stabilization Method**), and knowledge from specialized geotechnical engineering companies. The overview of possible soil stabilization methods, based on desk research, is a preparation and complement to the subsequent field research, also called interactive research.

3.1.2 Interactive Research

In the initial design stages of a project, the selection of possible soil stabilization methods is often accomplished based on expert judgment and experience, the same contemplative approach is used to achieve a selection of soil stabilization methods. Based on interviews and brainstorm session with different geotechnical experts within Arcadis, the suitability of each soil stabilization method is ranked by experience. By basing the selection of the different soil stabilization methods on the judgement of geotechnical experts, a rather quick and reliable evaluation is obtained. The qualitative approach of evaluation is chosen as expert judgement is a method to establish a preliminary selection based on experience. The evaluation of seven methods leads to the selection of the three best variants that are further worked out and analyzed based on both qualitative and quantitative analyses.

3.2 Overview of Soil Stabilization Techniques

Extensive desk research forms the basis for exploring the soil improvement methods deemed promising for stabilizing the railway embankment in the variant study. These methods are classified into two main categories: those that have been successfully employed in similar environments and for similar purposes, and techniques that have been implemented in projects that are not directly comparable but hold potential based on research or similar conditions. Both categories are thoroughly investigated to ensure a comprehensive and diverse understanding of the viable soil stabilization methods applicable to the double track extension between Zoeterwoude and Hazerswoude-Rijndijk. The research aims to identify effective and suitable techniques that meet the specific requirements and challenges posed by the project.

3.2.1 Pile Mattress

Weak subsoils are common in the Netherlands; therefore, several methods have already been used to support the extensive railway network. A method that is often used in road construction, is increasingly used in the stabilization of railway embankments as well, is the pile mattress construction, see **Appendix K.1 – Pile Mattress Construction in Houten, The Netherlands**.

The Method

The principle of a pile mattress is to create a settlement-free platform on top of soft compressible soil. An embankment on soft compressible soil is constructed with extremely limited residual settlement in a brief period of time (Cofra, 2023). The mattress on which the embankment is constructed, is supported by piles. These concrete piles transfer the loads directly to the steady sandy soils. The weak subsoils are therefore not subject to the loads of the superstructure, leading to negligible settlements.

Pile mattresses are typically used to reduce residual settlement after construction. This improves the transition zone between the different structures. The system is also used when the construction period is too short to use the commonly used consolidation solutions. The pile mattress system is very suitable for projects in locations adjacent to existing infrastructure that is vulnerable to vibrations or settlement damage. Furthermore, due to the high production rates that are achieved, large areas are made residual settlement-free in a short period of time.

The Installation

In case of very weak soils, the piles are installed by static compression without vibration, often using a permanent casing that protects the concrete piles from aggressive acids of peat soils. The piles are installed in a predetermined pattern from ground level and are installed using a modified vertical drain stitcher. A round steel tube and base plate are pushed into the ground. The tube is inserted at a regular speed, minimizing disturbance to the subsoil. When the desired resistance is reached, the pressure is maintained, and a casing is inserted into the tube. This casing is filled with mortar and concrete. After the concrete has cured sufficiently, the space between the pile heads is filled with sand or peat and the geogrid is placed on the piles, as depicted in **Figure 45**.

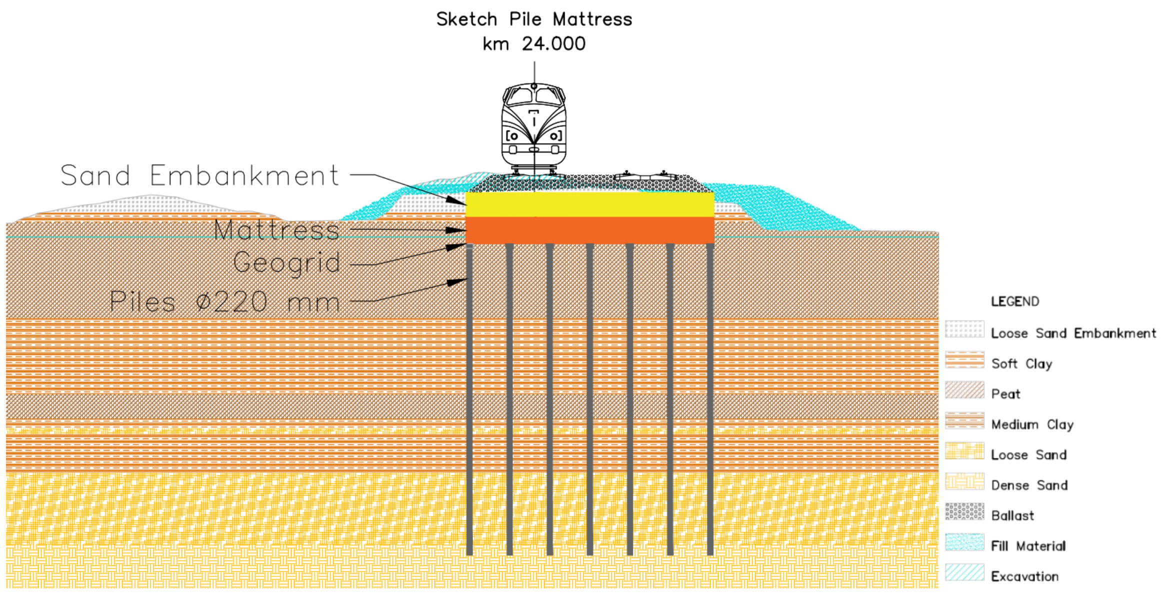


Figure 45 Sketch of Pile Mattress Stabilization Method at km 24.0 (not to scale)

3.2.2 Cunet

In addition to the widely used pile mattress method, the cunet method is used often for the stabilization of soft subsoils. Cunets are frequently used for the widening of the road infrastructure as well as the expansion of the rail network, see **Appendix K.2 – Cunet Construction for road widening in The Netherlands**.

The Method

The gap method, or cunet, is a method often used in embankment widening and includes the excavation of the weak subsoils. Traditionally, compacted sand is used to replace the soil to form a solid foundation, see **Figure 46** for a schematic overview. Sand is hardly subject to settlement, making the raw material an ideal soil improvement. Sand bodies are widely used since excavation is relatively easy; even in extreme weather conditions such as rain or slight frost (P.Geertsma, 2014). The cunet method is often used in combination with another stabilization method, such as vertical drains, over height or air pressure consolidation, to regulate the consolidation process (Rijkswaterstaat, n.d.).

The Installation

The stabilization of the soil by constructing a cunet is carried out by deploying several excavators. Depending on the type and depth of the soil layers, vertical drains may be installed first to ensure evenly settlement after application of the sand body. The method of installation of a cunet consists of three steps:

1. The excavation of a certain amount of weak subsoil. The thickness of the sand layer in a cunet varies, depending on the required bearing capacity.
2. The next step includes evenly dumping the sand body into the cunet.
3. Lastly, after application and spreading, the sand body is compacted with a vibrating plate. The air from the pores is pushed out, causing direct primary settlement. Depending on the choice regarding drainage, a period of rest follows. By regulating the settlement process prior to loading the embankment, the consolidation over time is limited.

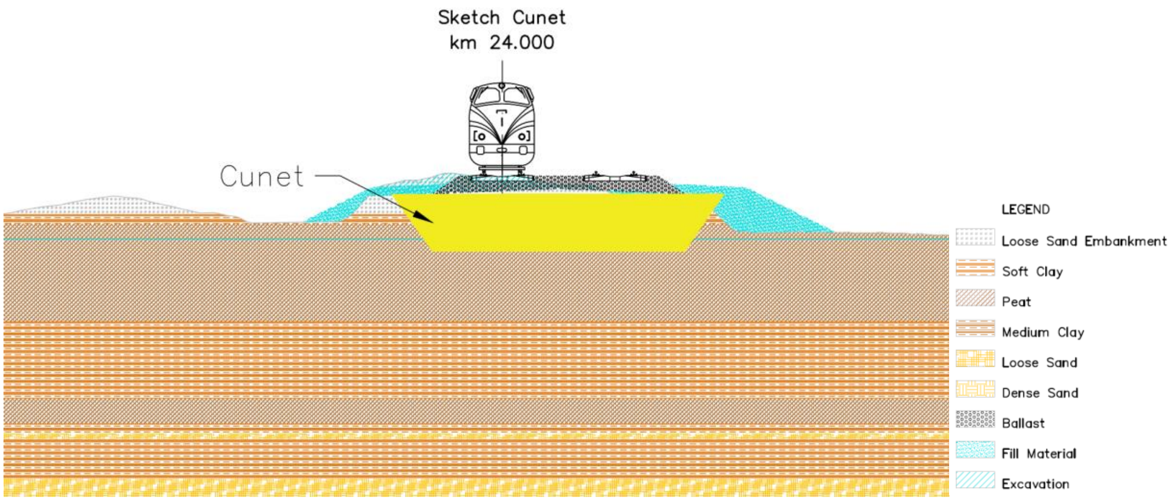


Figure 46 Sketch of Cunet Stabilization Method at km 24.0 (not to scale)

3.2.3 Deep Soil Mixing with Cement

To investigate suitable soil stabilization methods, not only proven solutions within the Netherlands are explored. Indonesia is a country with a comparable soil composition and faces similar challenges considering the stabilization of the subsoil. One method that offers a solution is mixing the soft soils with cement, see **Appendix K.3 – Cement Injection Double Railway Track in Kroya, Indonesia.**

The Method

Deep Soil Mixing – the intermixing of in-situ soil with binder to increase the strength and stiffness of the improved soil – is generally split into dry and wet mixing methods (Gastager, 2022). For the dry mixing method, the binder (e.g., cement) is filled in without water as powder into the ground and directly mixed with the soil and pore water. As no additional water is added into the ground, this method is usually applied in very wet and soft clays and peat, see **Figure 47.**

The Installation

Cement injection through deep soil mixing is a ground improvement technique that improves soft, high moisture clays, peat, and other weak soils by mechanically mixing them with a cementitious binder (Keller, 2023). Furthermore, injection of cement is applicable in high ground water conditions. The chemical reaction between the soil, groundwater and the stabilizing dry binders is called dry mixing. Both approaches, with or without added water, result in a higher bearing capacity and overall decrease in settlement. Furthermore, the application of the cement injection stabilization method is conducted quietly and free of vibrations.

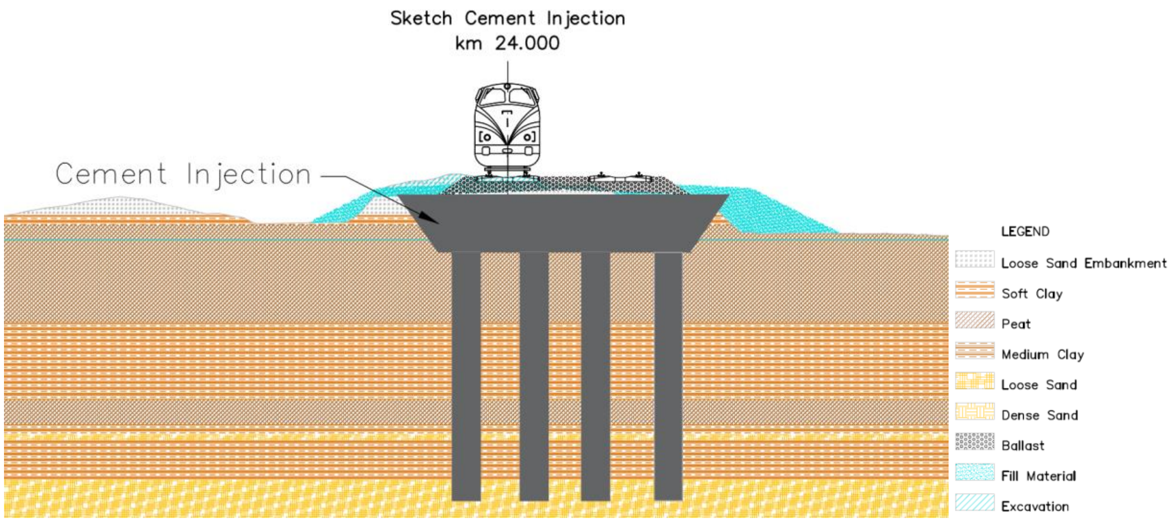


Figure 47 Sketch of Cement Injection Stabilization Method at km 24.0 (not to scale)

3.2.4 Preloading combined with lightweight filling material

In contrast to the previously mentioned ground improvement methods, preloading combined with lightweight filling material has not yet been used in the construction of a railway embankment. Glass foam is a lightweight fill material, that is able to withstand pressure and retains its shape. Because of these favorable properties, the method is increasingly used in road construction. A reference project is enclosed in Appendix **K.4 – Preload with Glass Foam for Road Construction in Purmerend, The Netherlands**, and may be promising for the rail infrastructure.

The Method

The rather traditional method of preloading, combined with glass foam is another feasible and promising method. Pre-loading is an economical and effective soil improvement method that reduces settlement and increase the bearing capacity of soft soil, see **Figure 48**. Preloading accelerates the settlement of soil before construction of the structure. Pre-loading is done by placing a large volume of sand or similar soil on the construction site, resulting in high pressure on the subsoil layers. The preloading soil is compressed and compacted, ensuring the largest soil settlements to have taken place before the start of the construction phase, resulting in less subsidence occurs after construction of the structure (Technischwerken, 2014).

The Installation

The method of preloading starts by applying a temporary load on the embankment. During preloading, drainage is required as the pore water pressure increases as a result of the surcharge load. After the predetermined consolidation has occurred, the sand body is replaced by lightweight fill material. An example is the use of glass foam. Glass foam consists of chunks foamed-up recycled glass. The material is light and durable with thermal insulating properties, barely absorbs water and is not moisture-sensitive, as a layer of glass foam has a relative high permeability. Due to the rough surface, the chunks hook together with a high hook resistance. This resistance prevents shifting in an embankment, for example. Due to the economical and effective characteristics of preloading, this method is promising in the stabilization of a railway embankment.

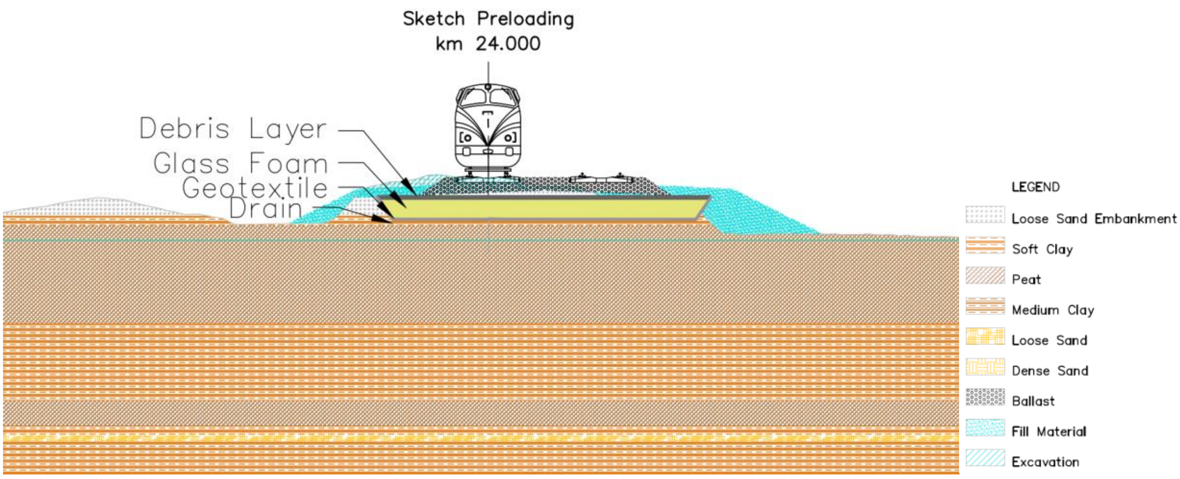


Figure 48 Sketch of Preload & Lightweight Fill Material Stabilization Method at km 24.0 (not to scale)

3.2.5 IFCO-Method

Another method that relies on allowing much of the consolidation to take place in advance in a controlled manner is the IFCO method. Although the method is still relatively unknown in railway construction, the techniques may be a promising one, due to its fast and effective results, see **Appendix K.5 – Accelerated site preparation using the IFCO Method in Assendelft, The Netherlands** for a reference project.

The Method

The IFCO (intensive forcing of subsoil consolidation) method is based on reducing the voids between the solid particles. This is obtained by lowering the groundwater level combined with applying negative pressure on the subsoils. This way both the voids filled with liquids and gases are reduced, see **Figure 49**. Controlled acceleration of the consolidation limits the settlement over time. By applying sheet pile walls right next to the existing infrastructure, settlements are limited during construction. The method has not previously been used for railways in the Netherlands but offers opportunities due to the controllability of the consolidation and relatively easy installation method.

The Installation

Using a deep-draining machine, parallel vertical trenches are made in the soil. A horizontal drain is laid at the bottom of the trench, after which the trench is filled with sand. The large surfaces of the sandy trenches contribute to the drainage of the soil. The trenches extend as far as possible to the deepest soft soil layer to obtain maximum consolidation of the subsoil layers. The method of draining however, is limited depending on the drains used (Movares, 2015). Digging the trench, laying the drain, and filling the gap with sand is done in one operation. The maximal depth is therefore limited by the equipment that is used to dig the trenches.

Subsequently, the installation of special pumps at the bottom of each trench is used to firstly extract the groundwater, resulting in about 80% settlement in a relatively brief period of time. During the IFCO process, a fill material may be used at the surface of the embankment to increase the pressure and compensate for the subsidence. Over time, the drains not only extract groundwater but also extract gases from the soil's pores, creating negative pressure in the sandy trenches. When the desirable pressure is achieved, any top load is applied to the soil's surface without danger of instability (IFCO Methode, 2019). As major subsidence is reached after about nine months, maintenance required due to subsidence in the following years is minimal. The latter is advantageous as the method could potentially be implemented alongside existing infrastructure that is affected as little as possible.

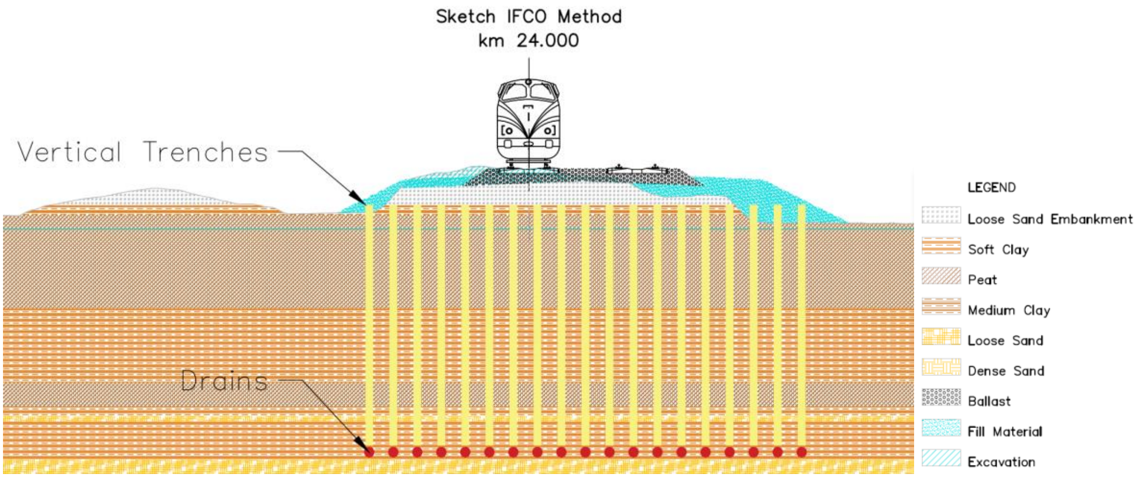


Figure 49 Sketch of IFCO Stabilization Method at km 24.0 (not to scale)

3.2.6 Geotextile Encased Column

A rather new method of soil stabilization is the so-called Geotextile Encased Column (GEC) method. These columns are made of granular materials like sands. The granular piles are encased with a high strength geotextile (Cofra, 2022). The method is increasingly implemented in a variety of projects, due to its efficiency and sustainability advantages, see **Appendix K.6 – Geotextile Encased Columns for the stabilization of soft soils in Hamburg, Germany** for reference project.

The Method

The main component of the GEColumn is the encasement of the pile by the usage of a geotextile. This geotextile provides support for the filled material and forms a rigid, though flexible shell that is tightened by outward horizontal stresses. These forces are the result of compaction through vibration of the granular column during the installation process. The system acts as both a drain and a pile. Due to the sleeve, the column function as a filtration drains, speeding up the settlement and consolidation process. In addition, the pile transfers most of the load to the bearing layers. This results in a reduction of the load on the soft material and thus minimizes both the direct and residual settlements. The system is often used in combination with ground reinforcement on top of the piles to improve load distribution, which is achieved using a geotextile layer, see **Figure 50**.

The Installation

The Installation process starts with the installation of the casings through vibration. After the pipe has reached the firm sandy soil foundation, the geotextile is placed within the case. The filling of the sock is followed up by pulling the casing up under vibration, ensuring a compact encased column. After successful installation of the piles, a geotextile layer is applied to reinforce the topsoil and distribute the loads evenly over the piles.

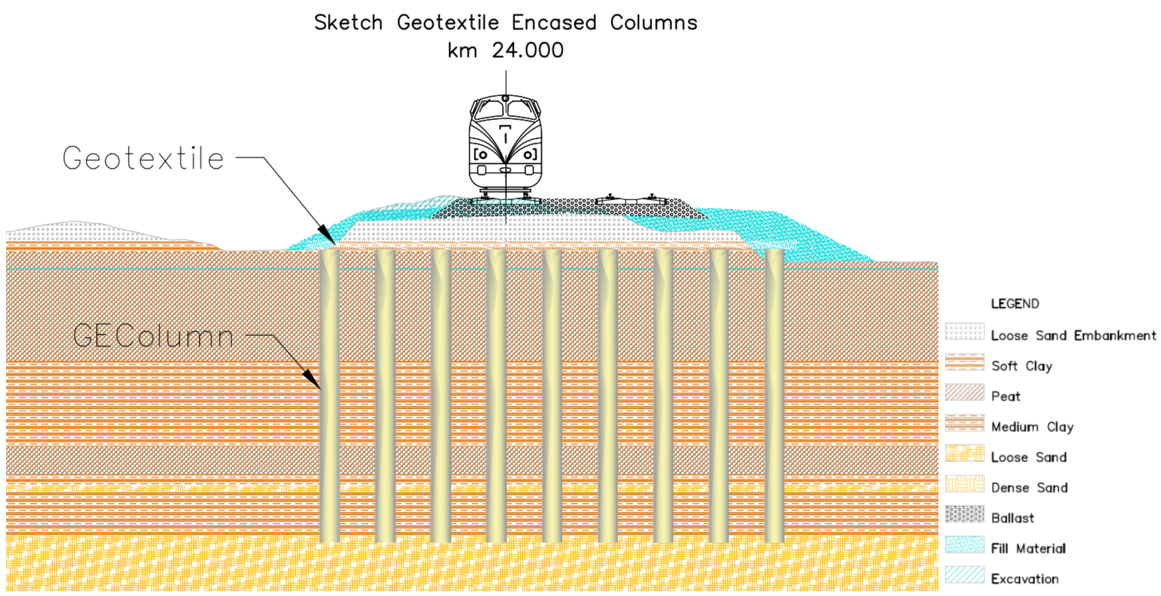


Figure 50 Sketch of the Geotextile Encased Column Stabilization Method at km 24.0 (not to scale)

3.2.7 Gravel Columns

A method similar to the Geotextile Encased Columns is the implementation of gravel columns. Even though vibro replacement is an accepted method for subsoil improvement, whereby large columns of coarse backfill material are installed in the ground, the method is rarely used for the stabilization of a railway embankment in the Netherlands. However, this method has proven to successfully stabilize soft soils for a variety of international projects. Using the method of vibro replacement ensured the successful expansion of a railway line in Malaysia, see **Appendix K.7 – Electrified Double Track for the Gemas-Bahru Rail Project in Malaysia** for the reference project.

The Method

The so-called vibro stone column technique densifies the granular soil and reinforces a variety of subsoils. This soil stabilization method is rather new in the Netherlands, especially its application for railway embankments. However, the method has proven to successfully improve the soil permeability by lowering the pore pressure, as well as reducing the settlements of future structures (Keller , 2022). The soil stabilization method involves the improvement of weak soils by the installation of densely compacted columns, made from gravel or similar material using a vibrator to install, see **Figure 51.** Improvement of the characteristics of soil layers is achieved by inserting gravel with lateral displacement. The process of displacement reinforces all soils in the treatment zone, resulting in a densification of the surrounding granular soils.

The Installation

The method of installation starts by a vibrator penetrating to the predetermined depth using its own weight as well as air jets that are located in the tip of the machine. When the depth is reached, gravel is added, filling the voids created as the machine is lifted a few hundred millimeters at a time. The vibro replacement process is repeated and continues by systematically raising the pipe while simultaneously applying and compacting the required amount of gravel until a dense stone column is constructed to the ground surface (Keller, 2023).

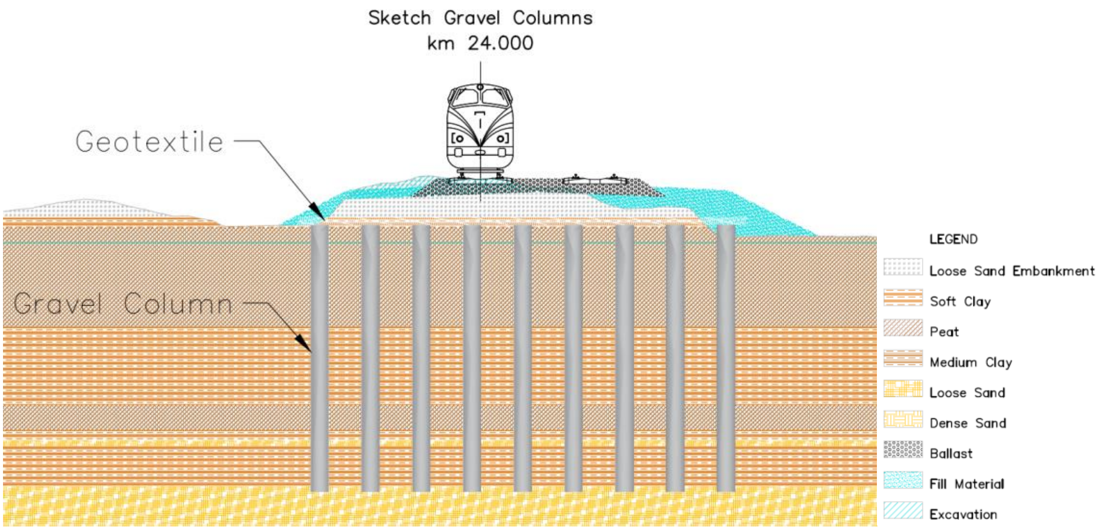


Figure 51 Sketch of the Gravel Column Stabilization Method at km 24.0 (not to scale)

After investigation of the different soil types within the project area, and consideration of their respective properties, various possible soil stabilization methods are to be explored, based on comparable projects, proven successes, and in-depth research. This subchapter concludes with seven different methods that, based on expert judgment in **Chapter 3.3 – Selection of Soil Stabilization Techniques**, are selected, and considered as possible stabilization methods at the given project site.

3.3 Selection of Soil Stabilization Techniques

In the initial design stages of a project, the selection of possible soil stabilization methods is often accomplished based on expert judgment and experience, the same contemplative approach is used to achieve a selection of soil stabilization methods. Based on interviews and brainstorm session with different geotechnical experts within Arcadis, the suitability of each soil stabilization method is ranked by experience. Consequently, the three methods that are ranked the best based on a number of criteria are further worked out as alternative designs in **Chapter 3.4 – Design Methodology**.

By basing the selection of the different soil stabilization methods on the judgement of geotechnical experts, a rather quick and reliable evaluation is obtained. The classification of the methods is conducted using a rudimental multi-criteria analysis. The criteria on which each method is ranked through expert judgement, in accordance with the program of requirements drawn up in **Chapter 2.6 – Fundamentals of Soft Soil Stabilization**.

The program of requirements includes the importance of costs, risks, and shutdown as well as the Technology Readiness Level as maturity indicator of a soil stabilization method. The various factors identified as important by the client, contractor and other parties of interest have been narrowed down into seven criteria. The criteria are the starting points in the evaluation and ranking of the different soil stabilization methods, see **Table 7**.

Table 7 Rudimental Multi-Criteria Analysis

Criterion	Description
Costs	• Estimated based on expected required materials, machinery, and services during installation of the construction; • Variant with the lowest costs is awarded the highest Cost Grade;
Risks	• Evaluated based on severity of harm and likelihood of occurrence; • Variant with the lowest risks is awarded the highest Risk Grade;
Settlement and Stability	• Evaluated based on degree of stability and expected settlement over a period of time; • Variant with the lowest settlement during the operational lifetime is awarded the highest Settlement Grade;
Technology Readiness Level	• Evaluated with TRL Scale based on expert judgement and literature research; • Variant with the highest TRL is awarded the highest TRL Grade;
Maintainability	• Evaluated based on the estimated lifespan and expected maintenance costs; • Variant with the highest maintainability is awarded the highest Maintainability Grade;
Sustainability	• Evaluated based on the type and quantity of materials used; • Variant with the highest sustainability is awarded the highest Sustainability Grade;
Shutdown	• Evaluated based on the estimated number of shutdown days and their respective costs; • Variant with the lowest shutdown is awarded the highest Shutdown Grade;

In the orientation phase, the selection of variants is made based on expert judgement. Therefore, no weighting factors have yet been assigned to each criterion. For each criterion, the variants are ranked from 'best' to 'least good' and are thus assessed with a rating between 1-7; 1 being awarded to the method that best meets the criterion. The ranking of the variants is established through a rough estimate, see **Appendix L – Ranking based on Expert Judgement**. Based on experience of Arcadis' geotechnical experts, the result of the selection of the soil stabilization methods as depicted in **Table 8.**

Table 8 Evaluation of the Methods based on rudimental Multi-Criteria Analysis

	Method	Settlement	Sustainability	TRL	Costs	Risks	Maintenance	Shutdown	Points	Ranking
1	Pile Mattress	1	1	1	4	1	1	1	10	1
2	Cunet	5	7	5	7	7	5	3	39	7
3	Cement Injection	7	2	6	5	3	7	2	32	5
4	Preload + Glass Foam	2	5	2	6	6	3	5	29	3
5	IFCO method	4	6	4	3	4	4	4	29	4
6	Geotextile Encased Column	3	4	3	2	2	2	6	22	2
7	Gravel Columns	6	3	8	1	5	6	7	36	6

The qualitative approach of evaluation is chosen as expert judgement is an excellent method to establish a preliminary selection based on experience. However, the different methods are ranked in comparison to each other. This creates an order of methods based on how well they score on a given criteria. One of the starting points include the approach that one method is simply better or worse than another method. This is much less unequivocal in practice. Methods can, possibly through adjustments in design or method of execution, be improved. However, this has not been considered in the evaluation. The standard, most commonly used design and implementation of each method has been assumed.

The conclusion is drawn that the pile mattress and geotextile encased columns were ranked as the two most suitable soil stabilization methods for the extension of the double track at the project location. The IFCO method and preloading combined with glass foam, methods 4 and 5, both obtained a similar score based on the evaluation of the different criteria.

Since this research report focuses on the overall stability and sustainability of different soil stabilization methods, the selection of the third variant is justified based on these criteria. Therefore, the three methods that are to be further worked out as variants based on the qualitative research analysis, are:

1. The Pile Mattress
2. Geotextile Encased Columns
3. Preloading combined with Glass Foam

3.4 Design Methodology

Prior to discussing the design methodology of the different variants, prudent is to discuss the chosen framework and the associated scenarios to provide a nuanced understanding of the different variants in relation to the variables as assumed or investigated in **Chapter 2 – Theoretical Framework**.

A scenario is defined as the effect of a changed variable, while a variant is the effect of another elaborated solution within a project. To establish the soil stabilization variants, one of the many possible scenarios was chosen as a starting point. Therefore, the design methodology leading to the chosen scenario is explained. In addition, the other possible scenarios are discussed. The chosen scenario that is based on extensive research, influences the design process of the different variants in this study. The design methodology of the variants follows. The iterative process is described after which the criteria for comparing the different variants are to be defined.

3.4.1 Designing Scenarios

Prior to working out the different variants, explaining why a specific scenario has been chosen is important. The framework influences the design and even selection of the soil stabilization variants. The scenario decided on as the baseline and framework within which the research is conducted, derives from a variety of assumptions and starting points based on collected data in the previous chapters. However, important is to be aware that changes in variables and assumptions may lead to different scenarios and thus affect the different variants in this research report.

However, changes in these starting points and assumptions, result in different scenarios. Roughly, four scenarios are to be distinguished:

1. The embankment is stable, no additional stabilization techniques are required when expanding the double tracked railway.
2. The embankment is stable, but soil stabilization is required to ensure sufficient stability for the railway embankment extension.
3. The embankment is unstable; therefore, soil improvement methods are required.
4. The embankment is (un)stable, however the railway embankment is not expanded, leaving no need to support the embankment by soil stabilization. This is the so-called zero scenario.

Scenario's result from both design-, as well as starting point-based assumptions, see **Chapters 1.4 – Assumptions and 2.5 – Design Criteria**, respectively. The chosen scenario includes the data indicating a subsidence rate of 7,5 mm annually, the location of the track extension between km 23.5 up to km 24.6, and overall proneness to instability based on the subsoil analysis of the railway embankment among others. Scenario three is validated and based on a variety of factors substantiated by research or data collection or as a starting point supported by expert judgement.

3.4.2 Designing Variants

The methodology of the variants' design process is the result of the iterative design thinking approach, see **Figure 52**. The process starts by understanding the problem and the stakeholders. Based on these analyses, variants are generated through both desk and interactive research. The creation of the variants is based on research and by iterative adjustments along the process. The variants are tested to ensure the refining of the variants and the final product. Geotechnical software, called D-Geo-Stability, is used to simulate, and adjust each soil stabilization method to best meet the criteria and optimize the design.

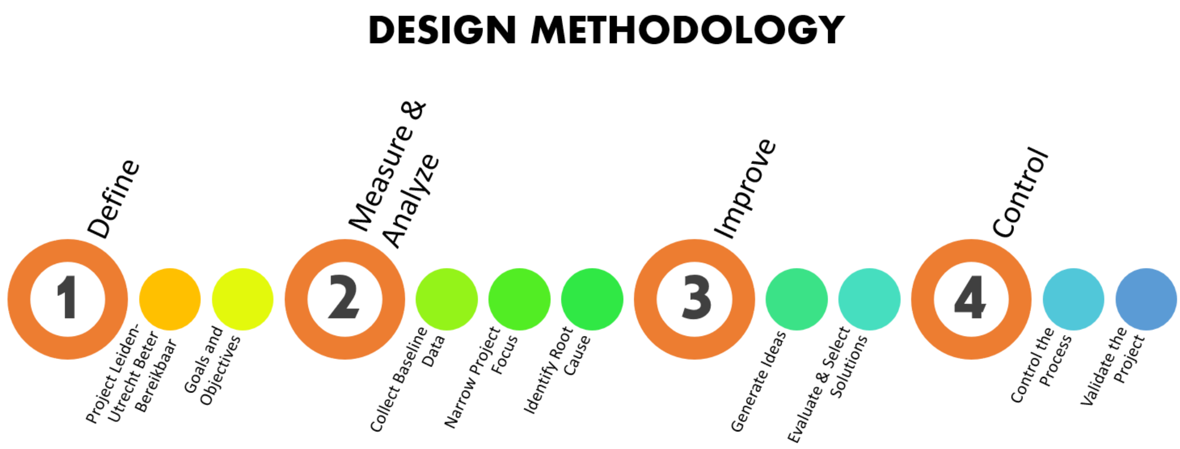


Figure 52 Method of Defining, Measuring, Analyzing, Improving and Controlling the Research Process

The different soil stabilization methods are first collected based on the obtained and analyzed data. Seven possible ground improvement techniques are explored. Out of these seven methods, three most promising techniques are selected through expert judgement, guided by the evaluation of each criterion. The second selection results from further elaboration and application of the variants. By assessing each technique using a multi-criteria analysis, a comprehensive comparison is be obtained. Therefrom, one method is selected and is recommended for the expansion of the railway embankment. The overview of this iterative design thinking process is shown in **Figure 53.** Generally, the following methodology describes the steps taken to design the different soil stabilization variants:

1. Improve – Based on the defined scope and investigation on the desired situation, improvement of the current situation is required to ensure that the necessary adjustments are made on and surrounding the railway to meet the projects requirements. One of the improvements includes the stabilization of the expanded railway embankment to support the double track extension.
2. Generate Ideas – Possible solutions are explored through desk research. Both research papers on innovative soil stabilization methods as well as comparable projects have been investigated. The different methods have been refined to meet the project's criteria, resulting in seven soil improvement methods that are promising techniques for the stabilization of the railway embankment.
3. Evaluate – The possible solutions are evaluated and selected based on expert judgement through interactive research methods like brainstorm sessions. Each soil stabilization method is evaluated based on seven criteria: stability, sustainability, maturity (Technology Readiness Level), cost, risks, maintenance, and shutdown. The three variants that score best based on these criteria are further worked out.
4. Test – All three variants are to be tested, to allow for a more extensive comparison. The possible solutions are evaluated through a comprehensive multi-criteria analysis. The criteria are the same as in the previous selection: stability, sustainability, TRL, cost, risks, maintenance, and shutdown. However, this analysis also includes the different weighting factors for each criterion. In this way, a comparison is made between the different methods, after which one technique emerges as the best, and thus answering the main question as the most stable and sustainable soil stabilization method.
5. Improve – The design methodology concludes by further improving the methods to achieve optimal design and implementation.

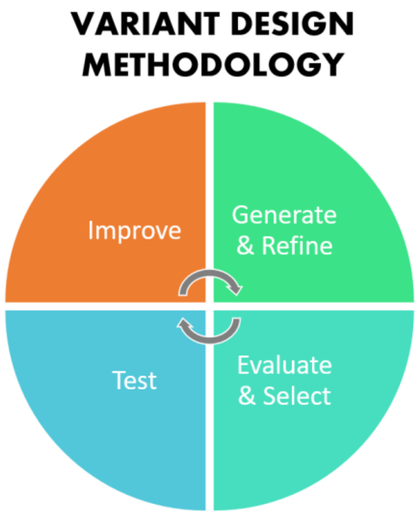


Figure 53 Methodology of Designing the Variants

3.5 Geotechnical Software D-Geo Stability

The stability of the embankment expansion using different soil stabilization methods, is examined using Deltares' slope stability software for soft soil engineering, called D-Geo Stability (Deltares, 2020). Deltares is a Dutch knowledge institute and works on innovative solutions in the field of water and subsoil engineering. D-Geo Stability, version 18.2, is used to analyze slope stability of soft soils in a two-dimensional geometry. The three variants are simulated in the software to gain deeper understanding on the stability of each of the soil improvement methods.

3.5.1 Main Features

D-Geo-Stability allows for the soil structure to be composed of several soil layers with an arbitrary shape and orientation. The deep soil layer is assumed to be infinitely thick. The soil modeling includes that each layer is connected to a certain soil type, allowing drain as well as undrained parameters to be defined.

In addition, various options are provided regarding the modeling of the loads in and on the soil. Piezometric level lines are specified to determine the hydrostatic pore pressure distribution as well as the phreatic level in each layer. Porewater pressures are defined with piezometric level lines or with a degree of consolidation. Surcharges are included as well in the program, both point and distributed loads. The latter is positioned as permanent or temporary loads on the surface of the soil structure. An angle of dispersion is to be defined, while allowing the specification of a degree of consolidation.

The method of Bishop is a limit equilibrium which determines the safety factor along a given slip plane. Since an infinite amount of slip planes occur in a geometry, an algorithm is used to find the representative slip plane. D-Geo Stability uses the grid method to determine the slip plane. By defining a square with center points and a number of tangent lines, all combinations of possible slip planes are explored. The results of the analysis are presented in both a tabular and graphical form, containing the calculated slip surfaces

3.5.2 Limitations

D-Geo Stability automatically determines the position of a critical slip circle. The algorithm is accurate as long as the distribution of center points and tangent lines is reasonable, the location of the grid yields a slip circle at the right slope, and the shape of the true slip surface does not deviate significantly from the assumed shape. Furthermore, the following limitations apply:

- The software discards the friction as a result of the horizontal stress component at the vertical slice interfaces and therefore assumes that the orientation of a slip surface is predominantly horizontally;
- The software assumes values for the total vertical stress that are estimated from the composed weight of a vertical column of soil and from the additional surcharge loads. The influence of load spread by a non-horizontal soil surface is therefore not considered;
- The software only assumes two-dimensional plane-strain.

3.5.3 Geotextiles

As described in **Chapter 2.7 – Fundamentals of Slope Stability**, shear stresses and normal effective stresses act along the slip circle. The shear stresses prevent the soil mass from sliding along the slip surface. The stabilizing moment M_{stab}, or resisting moment, is defined as the moment caused by the shear stresses that occur along the slip plane. Geotextiles are used to reinforce and improve the overall stability of embankments, see **Figure 54**.

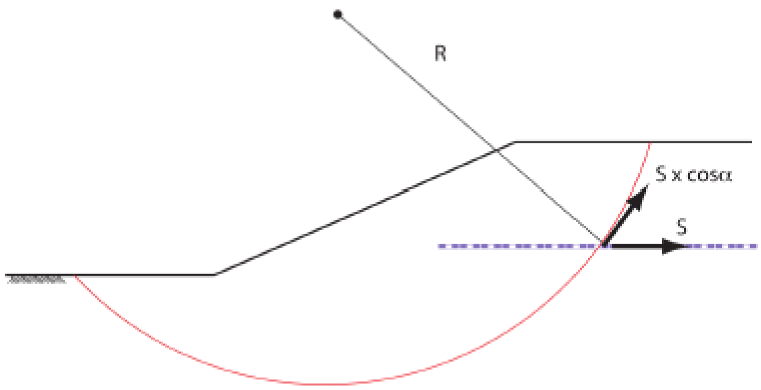


Figure 54 Resisting contribution by Geotextiles (Deltares, 2020)

In D-Geo Stability, the geotextile introduces a force that acts at the boundary of a slip circle. In case geotextiles are used, the software calculates the safety factor by including an additional resisting moment:

$$M_{stab;geotextile} = R \times S \times cos\alpha$$

- R, the radius of the slip circle;
- S, the mobilized tensile strength in kN;
- α, the angle between the geotextile and the tangent line along the circle where the geotextile intersects the slip circle in degrees.

The contribution of the geotextile depends on the distance between the center of the slip circle and the geotextile. Therefore, in order to acquire a larger safety factor, the distance should increase. Furthermore, only geotextiles that intersect a slip circle contribute to the resisting moment.

3.6 Alternative Designs

Prior to working out and investigating the different stabilization methods, establishing the so-called zero variant is of importance. This is the variant including embankment widening but excluding soil stabilization methods. A simplified representation of the desired geometry is modelled, see **Figure 55**. The following parameters are included in the geometry and design of the embankment:

- Temporary train load of 63 kN/m^2, in accordance with RLN 00414-1 (ProRail, 2016);
- Permanent ballast and superstructure load of 12,5 kN/m^2, in accordance with RLN 00414-1;
- Based on expert judgement, a value of 25 degrees of load distribution is chosen, in accordance with RLN 00414-1;
- In accordance with RLN00414-1, the minimum required distance of 4,5 between two tracks;
- A gradient of 1:2 on either side of the slope, in accordance with OVS00056-5.1 (ProRail, 2016);
- The top of the embankment at -0.46 m+NAP.

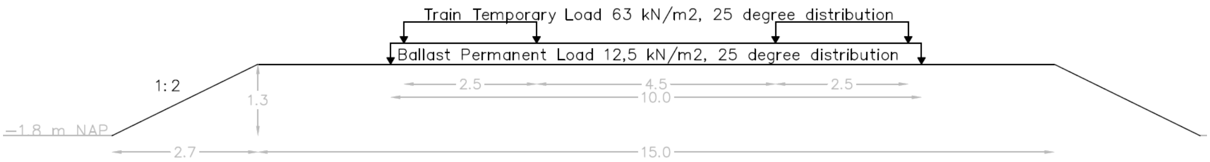


Figure 55 Representation of the desired Geometry

Using the software D-Geo Stability, the model shown in **Figure 56** is designed. The various design criteria as well as the soil composition and its characteristics are included in the design. The permanent load, indicated by P1, as well as the temporary train loads T2 and T3 are applied to the model.

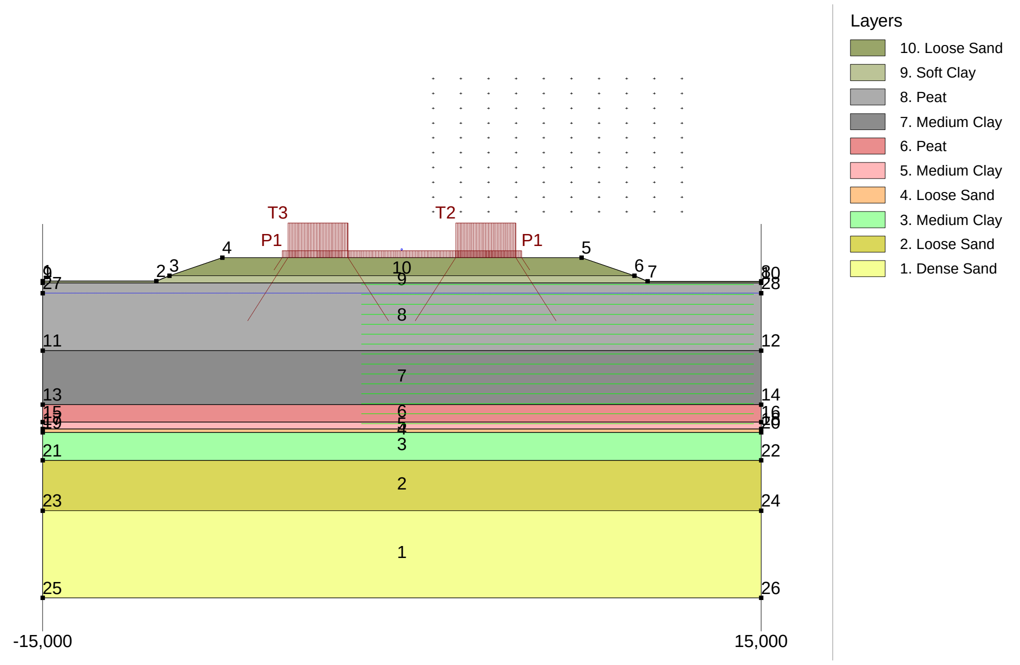


Figure 56 D-Geo Stability Model Embankment Expansion, Zero Variant

Using Bishop's method, the factor of safety (FS) is determined. Important to note is that an embankment is stable when the FS is greater than or equal to 1.3. Moreover, a stress analysis is obtained as well as a safety overview. Bishop's critical circle of the embankment expansion is shown in **Figure 57**. The safety overview and report are enclosed in **Appendix N – Stability Analysis Zero Variant**.

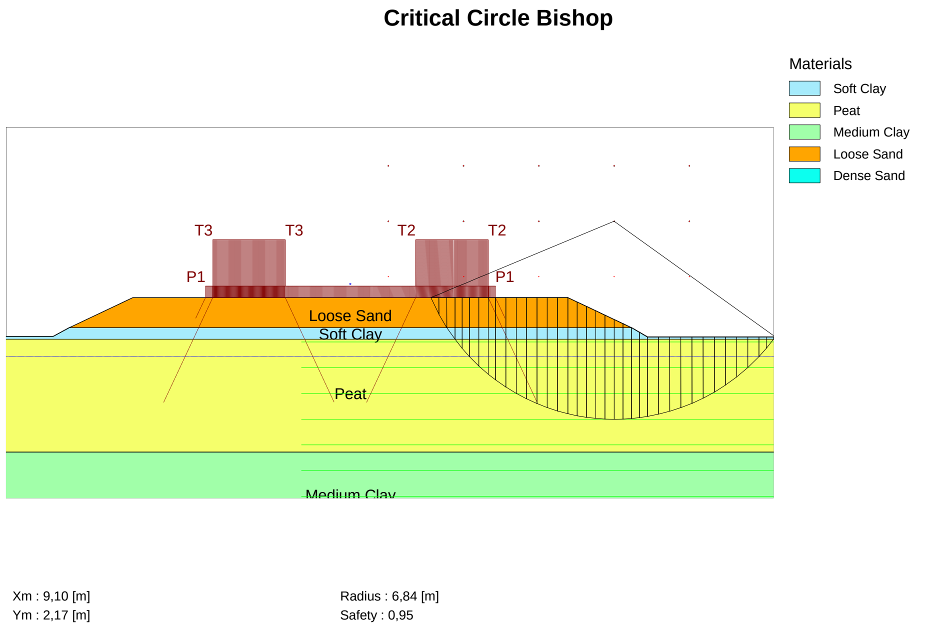


Figure 57 Bishop's Critical Circle, Zero Variant

The analysis of the critical slip circle shows that the safety factor is 0.95 in the case of embankment expansion without added soil improvement techniques. The stability investigation supports the need for implementation of soil stabilization methods in order to support the embankment expansion.

3.6.1 Alternative 1 – Pile Mattress

Pile mattress systems are widely used for the construction of roads, railway embankments and structures on soft soils. This soil stabilization method combines a foundation of piles with a reinforced granular layer. The load from the embankment and top load are transmitted through the soft soil to the load-bearing subsoil via the piles. In order to bridge the space between the piles, the embankment is supported by one or more layers of horizontally placed geotextile as reinforcement. Generally, on top of the geogrid, a layer of granular material is applied to evenly transfer the loads via the mattress to the piles. Using this technique, a subsidence-free, or a settlement-limited foundation is created. Therefore, the pile mattress method is used for the construction of railway embankments where strict requirements are set for residual settlement, or a very fast construction method is required.

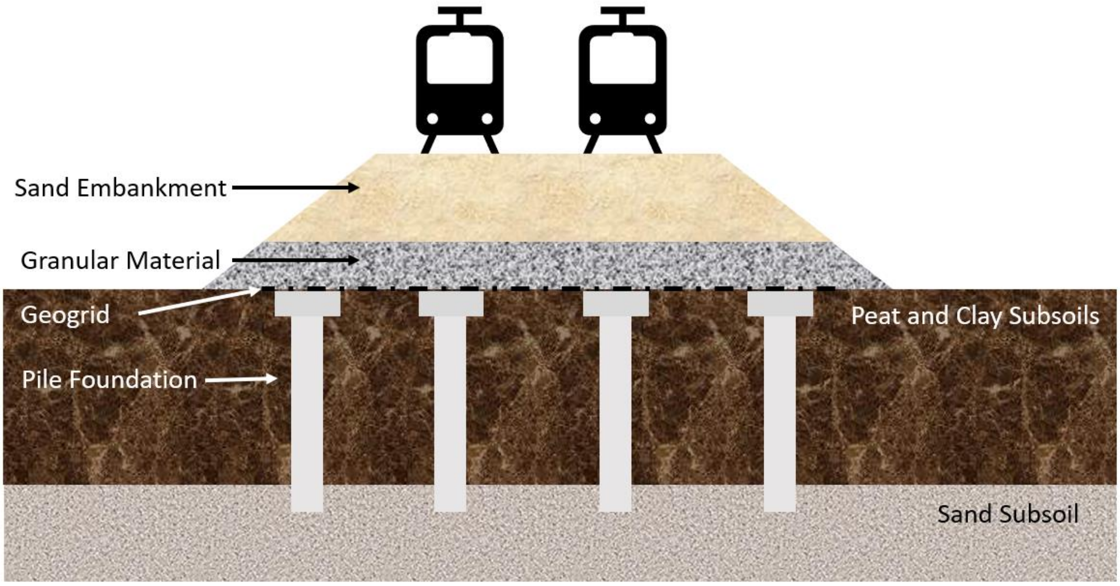


Figure 58 Schematical Overview Pile Mattress System

Materials

To design the piles, standard concrete pile foundations are used, in accordance with CUR 2007-2 (CUR Bouw & Infra, 2007), CUR is part of knowledge platform CROW (CROW, 2023), see **Chapter 2.4. – Boundary Conditions and Limitations**. The concrete piles are often prefabricated and extend to the sand layer. The piles are placed at a center-to-center distance between 0.8 and 3.0 meters and are arranged depending on the pile type and load in a triangle or square grid (Fugro). Given the large number of piles required to support the railway embankment, piles that are installed quickly and easily are considered. The Cofra's AuGeo pile type is often chosen because of its slim design, with a minimum diameter of 150 millimeters. The AuGeo pile is a pile installed by static compression force without vibration, often using a permanent casing that protects the concrete from aggressive acids of the peat. Since all load is transferred, the soft compressible soil in which the piles are installed remains unaffected. The use of static push force makes the AuGeo system very suitable for projects on sites where there is existing infrastructure that should not be exposed to vibration and settlement damage.

Due to the high production rates that is achieved, large areas are made residual settlement-free in a short period of time (Cofra, 2023).

Specific requirements are imposed on the materials for the mattress. The different materials are roughly divided into three groups: granular material, sand, and residues (Delft Cluster Blijvend Vlakke Wegen, 2007). In CUR 2002-7, requirements are set for the mattress material (CUR Bouw & Infra, 2007). Generally, a coarse-grained granular material of decent quality is preferred. The material must be able to withstand the peak stresses that occur above the pile caps. Fine-grained material, such as sand, may be prone to leaching and disruption of the interaction with the geogrid reinforcement during dynamic loads, therefore sands are never entirely used as mattress material. Moreover, the embankment material should prevent water spans in the mattress. Thus, the mattress material must be sufficiently draining. Therefore, concrete debris granular material is chosen as material for the mattress system.

Regarding the geotextiles, a variety of materials is used. A type of geotextile that is often used in pile mattress systems are the geogrids. Functioning as both a stabilizer, reinforcement, and separation layer between the granular fill material on the top and the soft soils on the bottom, geogrids successfully support the load transfer from the embankment to the piles. One of the few geogrids proven to work combined with vertical piles is Huësker's Fortrac geogrid (Delft Cluster Blijvend Vlakke Wegen, 2007). Fortrac geogrids provide for the formation of long-term stabilization of a soil arch above the piles to ensure low-settlement transmission of loads to the deeper foundation. In addition, this type of geogrid is able to withstand biaxial loads, making the use of inclined piles redundant (Huësker, 2019). Fortrac geogrid made from recycled bottles ensure the sustainable use of materials. The Fortrac T Eco geogrid is made from high modulus polyester yarns, produced from recycled PET bottles. Huësker's sustainable ecoLine product variant is proven to have the same performance and properties as the classic Fortrac geogrid. Using this material is a sustainable option of the reinforcement using the pile mattress method (Huësker, 2023).

Table 9 Material Properties of Huësker's Fortrac Geogrid (Huesker, 2017)

	Geogrid Fortrac
Material	PET (recycled)
Tensile Strength	Up to 120 kN/m
Coating	Polymer
Function	Reinforcement

Stability

The pile mattress is to be designed in two different ways: settlement-free and settlement-reducing. In the first case, the system is designed so that virtually no settlement occurs. The piles are capable of bearing the full load. However, due to subsidence of the soil, a gap may develop under the mattress (CUR Bouw & Infra, 2007). Often, the gap is applied in advance to allow for the deformation of the geogrid prior to completion of the construction. Deformation as a result of this gap below the geogrid does not result in long-term settlement. In addition, if the piles stand on a sand layer that is still subject to settlement, the construction is considered to be a settlement-free system.

In a settlement-reducing system, the piles carry only part of the total load. The piles only reduce the load on the weak soil layers, thereby reducing the overall settlement. Larger deformation is accepted in this type of pile mattress system. The design of a railway embankment must limit the allowed settlement to a few centimeters per year, see **Chapter 2.7 – Fundamentals of Slope Stability**. Therefore, a settlement-free design is chosen for the stabilization of the railway embankment.

Sustainability

The overall sustainability regarding the pile mattress system is positively influenced by the fact that this traditional method is frequently used on infrastructure projects. Due to the experience of both installing and maintaining the system, the social sustainability dimension is high. The workers are familiar with the different components of the pile mattress system, resulting in the knowledge of operating in safe ways. In a similar way, the economic sustainability dimension benefits from the knowledge gained from similar projects. This allows costs to be determined in advance with high accuracy. In addition, the durability of the structure is high because the piles in the system are treated to be protected against degradation by the peat acids (Boekhorst, 2007).

To promote design sustainability, decisions regarding material use may be made. For example, AuGeo piles are installed nearly vibration-free, and Fortrac Eco is made of recycled materials. By making sustainable choices regarding material use and machinery, the traditional pile mattress system is built to reduce negative impacts on the environment and promote recycling and reuse of materials (Huësker, 2023).

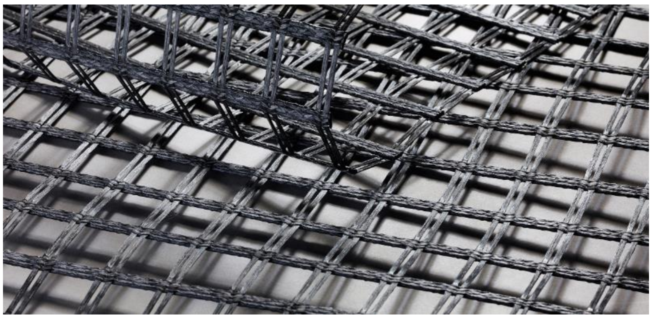


Figure 59 The Fortrac T Eco Geogrid is a sustainable type of geogrid (Huësker, 2023)

Technology Readiness Level

The method of stabilization through a pile mattress system is widely used in road construction in the Netherlands. Huësker's Fortrac geogrid pile mattress system has successfully been implemented in several infrastructural stabilization projects. A reference project is included in **Appendix M.1 – Huësker's Pile Mattress for the N210 Design in the Netherlands** (Huësker, 2019). This national road in the Netherlands crosses soft organic subsoils, which are up to 15 meters thick. The road is therefore carried on a geosynthetic reinforced embankment built on driven precast concrete piles with pile caps. The project includes a monitoring system, used to verify the design, and confirm the safety standard of the pile mattress system. Despite the regular use of this soil stabilization method in road construction, the implementation in railway embankments is limited and requires careful monitoring (see **Appendix K.1 – Pile Mattress Construction in Houten, The Netherlands**, for a reference project using the pile mattress system for railway embankment stabilization). In addition, limited knowledge concerning the specific material implementation in railway embankments is available. For this reason, Huesker's pile mattress system, applied in road construction, is being monitored and analyzed to gain more knowledge regarding the performance of the materials.

Costs

The indicative costs for the materials and construction of the pile mattress system are based on a comparable variant study (Boekhorst, 2007) and the estimated construction costs according to an experienced engineering firm (Fugro). The costing includes the following material and execution costs:

- Procurement of prefab concrete piles;
- Installation costs of driving the piles;

- Purchase and installation of the geogrids, price obtained from (Van Walraven, 2023);
- Purchase of the sand for the embankment;
- Transport costs for delivering the sand.

Costs for excavating the peat and costs for compacting the sand and granulate package are not included in the cost estimate. In addition, monitoring costs and costs related to land acquisition and site preparation are not included in the cost estimate.

Table 10 Estimated Costs for the Pile Mattress System

	Price per unit
<u>Purchase Materials</u>	
Concrete piles	€ 17,50 / meter pile
Geogrids	€ 8, -/ m^2
Sand body	€ 10, -/m^3
<u>Installation Costs</u>	
Concrete piles	€ 30, -/m
Transport sand	€ 7, -/ m^3

Risks

Despite the frequent use of pile mattress systems in infrastructural constructions, risks remain due to the various variables that affect the performance of the stabilization system, including the composition of the subsoil and the load on the embankment. Regarding the preliminary design of the pile mattress system, several risks are to be identified based on similar projects and literature research. The potential risks are summarized in the **Table 11**.

Table 11 Evaluation of the Risks associated with the Pile Mattress

Description and Evaluation
Insufficient bearing capacity of the pile foundations is one of the risks of the system. Causes vary but are generally the result of too small a pile diameter, too short a length of pile or a damaged pile due to transport. The result is the collapse of the pile foundation, causing the entire pile mattress system to fail in its function **(Fugro)**. Another risk is the formation of gaps in the design of the mattress. This is caused by uncertain load paths to the pile foundation. The result is impermissible settlements in the mattress and failure of the geogrids. This risk causes overall instability and may eventually lead to overall failure of the pile mattress in its function **(Fugro)**.
A risk related to the adjacent track is the vibrations created during the driving of the piles into the ground. This may increase the instability of the single track to such an extent that the track may (temporarily) not be used and may require measurements to restore the embankment's stability **(Fugro)**.
Lack of experience with the construction method due to unfamiliarity with pile mattress systems for railway embankments is a risk that may mainly entail additional costs. Moreover, the construction time may be longer compared to implementing pile mattress systems elsewhere, as the adjacent track may not be adversely affected as a result of railway embankment extensions. This may require additional expertise and measures to achieve successful design and installation of the pile mattress system **(Fugro)**.
Discrepancy between the model and reality is a risk that affects the integrity of the design. The model, which considers only two dimensions, is a simplified version of reality. The load path from

the embankment to the pile foundation may be different, and horizontal loads may have a greater influence on the overall stability **(Boekhorst, 2007)**.

The risks are to be controlled by taking effective measures in time. Accurate monitoring of the pile mattress system ensures timely and sustainable maintenance, which minimizes cost, material, and disturbances to the surrounding area. Periodic measurements of the strain in the geogrids are valuable to tackle settlements due to uneven load distribution in time. In addition, the risk of damage to the environment is reduced by regular visual inspection and monitoring of sensitive transition points in and around the railway embankment.

Maintainability

The required maintenance of the pile mattress system depends on its technical lifetime. Regarding Cofra's AuGeo piles, the lifespan is expected to be unlimited (Fugro). In a settlement-free pile mattress system, only the top layers of the railway embankment require periodic maintenance. However, at the location of the transition structures to the sections that are prone to larger settlements, frequent monitoring is required during the first years after completion of construction. If during monitoring the piles and load spreading layer are found to function as expected, the embankment does not undergo settlement in the operational stage. No special measures are to be then required as part of management and maintenance (Fugro).

The technical lifetime of the pile mattress system is mainly dependent on the technical lifetime of the geogrids. Factors influencing the technical service life of the geosynthetics are production uncertainties, load and change thereof, creep, mechanical deterioration, and environmental degradation. With regard to possible chemical attack, based on the groundwater quality, a geosynthetic product with sufficient resistance is selected. Suppliers of geosynthetic reinforcement quote an average lifespan of 80 years (CUR Bouw & Infra, 2007).

Degree of Shutdown

The degree of shutdown depends on the method of execution and its different construction phases. Although some phases are completed adjacent to the single track that remains in use, space is required adjacent to the embankment for machinery and materials. For this reason, the decision is made to keep the adjacent track out of service in order to complete the embankment widening from the single track, if possible.

The implementation phase of the pile mattress system consists of three phases, starting with preparing the work floor. The existing embankment has to be prepared for the track widening. Next, the piles are installed by pressure force. Steel-encased plastic tubes are pushed into the ground, after which the plastic tube is cut at the desired height and fitted with a plastic pile head. The tube is filled with concrete. Production averages 20 piles per hour (Fugro). After placing the piles, the application of the geogrids and granulate follows. Lastly, the sand embankment and superstructure are placed. The sand for the embankment is generally brought in and spread by trucks. The advantage of using dump trucks and bulldozers is the method of driving in such a way so the sand is compacted. If sand is delivered via the adjacent track, a vibratory roller must be used to meet the compaction requirements of the sand embankment.

The extent of decommissioning is difficult to estimate as this is dependent on a variety of factors. Moreover, further research is required to determine the extent to which the adjacent track remains in use during the embankment expansion. However, based on similar literature studies, an indication of the extent of downtime is given. Since the pile mattress system relies on transferring the loads of the embankment directly to the loadbearing layers in the subsoil, the embankment is commissioned immediately, and residual settlements are negligible. The time required to complete the railway embankment widening using the pile mattress method has been estimated at 30 days (Unidek Group B.V., 2005).

Design

The design of the pile mattress system is established based on the information mentioned above, combined with the trial-and-error approach to arrive at a stable design in the software D-Geo-Stability. However, the two-dimensional model does not consider horizontal loads in other directions. The result is an incomplete picture of load propagation via the geogrids to the piles. Due to the discrepancy between the model and reality, larger forces act on the geotextile than is considered in the model. The geosynthetic reinforcement sags slightly between the pile heads, see **Figure 60**. The formation of this gap depends on the degree and speed at which the subsoil compresses. Therefore, a lacune is created between the pile caps during construction, resulting in the deformation of the geogrid to have occurred prior to completion of the structure. This way, the deformation of the pile mattress system is almost entirely determined by the subsidence of the pile heads. After the construction phase, only creep occurs in the geogrids, which, with correct design and execution, does not lead to significant settlement.

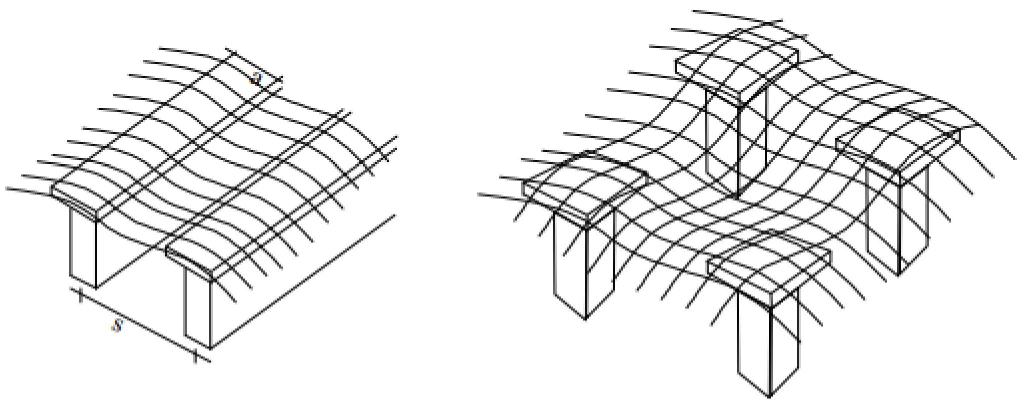


Figure 60 The Difference between the two- and three-dimensional approach (CUR Bouw & Infra, 2007)

3.6.2 Alternative 2 – Geotextile Encased Columns

Geotextile encased columns, or GEC in short, are relatively strong and rigid elements applied in weak cohesive soils to accelerate settlement and increase the stability of embankments. Geotextile encased columns are granular columns, usually consisting of sand, encased in a high-strength geotextile. The purpose of this geotextile is to ensure the integrity of the column and provide confinement in very weak soil layers up to an undrained shear strength of 15 kPa. During installation, the geotextile sleeve is stretched and filled with sand, resulting in horizontal stresses, leading to high strength and stiffness of the column. Similar to the pile mattress systems, the geotextile encased columns transfer the loads from the embankment to the load-bearing layer (Fugro).

The most important component in the column is the enclosure of the column with the geotextile. This geotextile provides support for the backfill material, creating a rigid flexible casing that is stretched by the outward horizontal stresses of the backfill. The system acts as both a drain and a column. The column shifts most of the load to the lower bearing layer and creates equilibrium with the surrounding soil through deformation of the column, reducing the load on the soft material and reducing settlement. The system is often used in combination with a mattress construction on top of the piles to improve load distribution (Cofra, 2023).

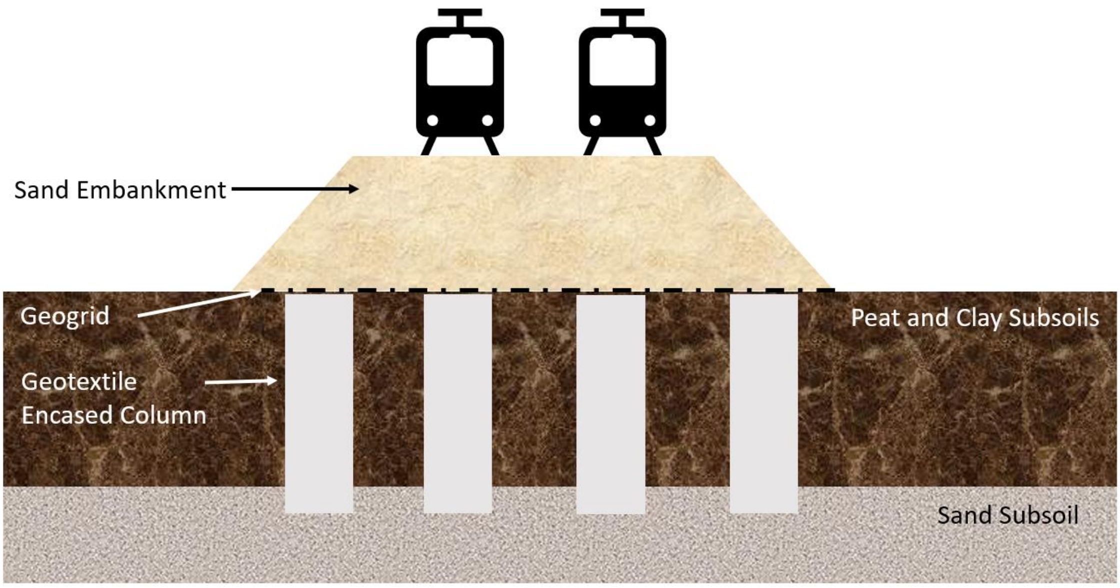


Figure 61 Schematical Overview Geotextile Encased Columns

Materials

Construction of the GE columns starts with preparing the ground and possibly applying sand for work traffic. Steel tubes are then vibrated into the ground. The geotextile sleeve is lowered into the casing and filled with sand. The casing is filled while vibrating to ensure sufficient strength. A load-spreading layer of geogrid is then applied. Application of the sand embankment follows.

The column diameter varies between 0.6 and 1.5 meters. The sand piles are usually placed in a triangular pattern at a center-to-center distance varying between 1.0 to 3.0 meters. The bearing capacity of the column is partly derived from the tensile strength of the geotextile encasement and the horizontal soil pressure in the weak layer. In this soil displacement method, relatively small column diameters are used. Combined with the fact that no soil needs to be removed, this method has a fast construction time. The piles are driven through into the load-bearing sand layer. The piles also act as vertical drains, speeding up the consolidation process (Fugro).

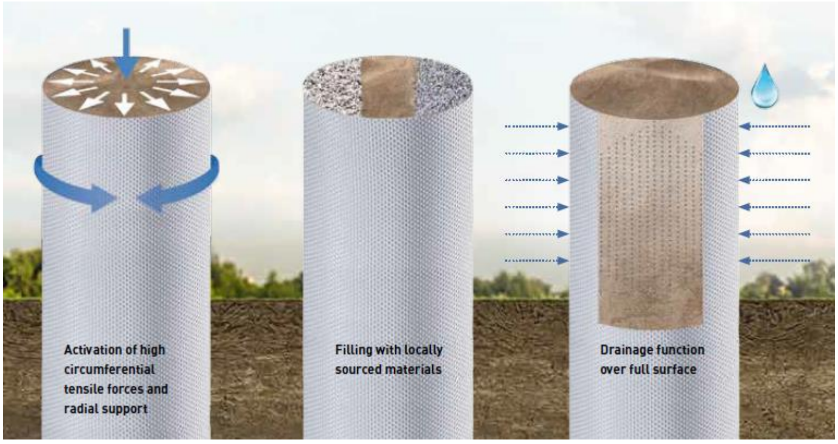


Figure 62 The benefits of Huësker's Ringtrac geotextile encased columns (Huësker, 2019)

The geotextile encasement distinguishes this soil stabilization method from similar vertical pile foundations like the pile mattress system. A geotextile that is increasingly used and has proven to ensure strength and stability of weak subsoils, is Huësker's Ringtrac system (Delft Cluster Blijvend Vlakke Wegen, 2007). The Ringtrac foundation system combines Huësker's Stabilenka geogrid with Ringtrac geotextile encased sand columns. The GEC Ringtrac system offers high ductility and adaptability to variable subsoil conditions. In addition, the full-surface drainage capability of the woven geotextile and fill material vastly speed up the consolidation time, with 90% of the settlement occurring during the construction phase (Huësker, 2019).

Table 12 Material Properties of Huësker's GEC system (Huesker, 2017)

	Geogrid Stabilenka	Ringtrac Geotextile Encased Columns
Material	PET	PET
Tensile Strength	Biaxial up to 200 kN/m	Up to 600 kN/m
Function	Reinforcement, separation, filtration	Reinforcement, separation, filtration, drainage
Dimensions		Diameter ranging between 600-1500 millimeters, lengths up to 30 meters

Stability

The Ringtrac foundation system is developed for construction on extremely soft soils (shear strengths smaller than 0,5 kN/m^2) successfully contributes to subsoil improvement. Uniformly arranged columns of non-cohesive material with an encasement of geotextile form the core of the system. An additional horizontal reinforcement of Stabilenka geotextile ensures load transfer from the embankment to the piles. Geotextile encased columns (GEC) are a development of conventional ballast columns. The statically effective geosynthetic shell forms the supporting element with a filling of granular mixtures.

Locally available mixtures are used as fill material, saving additional time and costs. With the Ringtrac foundation system of geotextile encased columns and horizontal reinforcement, not only sustainable soil reinforcement and subgrade improvement are obtained, but also a reduction in construction time through shorter a consolidation period. Due to the full surface draining effect of the geotextile and the filler material, 90 % of the settlements occur during the construction phase. This makes the GEC system a virtually settlement-free method (Huesker, 2021).

Sustainability

The sustainability of the geotextile encased column system is influenced by its reliance on specialized companies. The method has had very limited application in similar projects, leaving much to be gained in terms of sustainability of the production and installation process. However, because the GEC system is only installed and designed by specialized construction firms, results-oriented advice ensures safety and social sustainability of the workers and its environment (Huesker, 2021). The latter results in a high level of certainty in costing and construction process, contributing to the economic sustainability of the project. In addition, the geotextile encased column system is able to accommodate dynamic loads without damage to the surroundings, leaving adjacent infrastructure unaffected by settlements. Environmental sustainability is ensured through the geotextile that maintains the permeability of the weak subsoils. Preserving the integrity of the soil's properties upholds the ecosystem in and around the embankment.

Lastly, economical sustainability is ensured as locally sourced soils are used as column fill, limiting the transportation costs while stimulating the sustainable use of materials. In addition, the method does not require the disposal of water or contaminated soil.

Technology Readiness Level

The geotextile encased column system has not yet been used for the stabilization of a railway embankment in the Netherlands yet. However, the Huësker's soil stabilization method has proven to be successful for the reinforcement of embankments on soft soils. A reference project is included in **Appendix M.2 – Huësker's Geotextile Encased Columns for the Steigereiland in Amsterdam, the Netherlands** (Huësker, 2023). For the construction of the new district IJburg in Amsterdam, eight newly constructed islands were constructed in the IJmeer. An acceptable bearing capacity was found at a depth of 10 meters. Geotextile encased columns, using Stabilenka geogrid and Ringtrac geotextile, were successfully placed along the edge of an island. After placing the columns, the area was enclosed by small dykes and brought up to level using hydraulic fill. However, due to the limited use of this method in the stabilization of a railway embankment, careful monitoring is required to limit the risks and gain deeper understanding on the performance of the system under large dynamic loading.

Costs

The indicative costs for the materials and construction of the GEC system are based on the estimated construction costs according to an experienced engineering firm (Fugro). The costing includes the following material and execution costs:

- Purchase of the sand for the embankment and drainage layer;
- Purchase and installation of the column, including Huësker's Ringtrac geotextile;
- Purchase and installation of Huësker's Stabilenka Geogrid (Van Walraven, 2023).

Table 13 Estimated Costs of the geotextile encased column system

	Price per unit
<u>Purchase Materials</u>	
GEColumn	€ 12,-/ m^3
Geogrids	€ 4,5 / m^2
Sand body	€ 10, -/m^3
<u>Installation Costs</u>	
Transport sand	€ 7, -/ m^3

The price estimate does not include the costs related to facilities to make the site accessible. In addition, the installation costs of the columns and geogrids are included in the acquisition price. To date, outside specialized contractors conducted the installation of the system, as limited experience with GEC systems is available in the Netherlands. For this reason, the price of the GEColumn includes both delivery and installation of the pile system by a specialized company. The cost of the geotextile casing accounts for about a third of the cost of the column. Therefore, in case of more frequent and larger-scale application, the price of the sand piles decreases (Fugro).

Risks

In ground stabilization using the geotextile encased column system, several risk factors are to be identified, of which an overview is depicted in **Table 14**.

Table 14 Evaluation of the Risks associated with Geotextile Encased Columns

Description and Evaluation
Insufficient knowledge to predict and simulate in advance the deformation of the adjacent embankment. Monitoring is required to act appropriately and mitigate the influences around the adjacent embankment **(Fugro)**. This includes damage to adjacent track due to vibration during construction and horizontal deformation due to the soil displacement method. The risk is low and is to be mitigated, for example, by pre-drilling before installing the piles **(Fugro)**.
Uncertainty of the properties of the weak soil layers in terms of compression characteristics, permeability, strength, and stiffness. Further soil investigation is required to limit this risk of uncertainty **(Fugro)**.
Lack of experience with the construction method due to unfamiliarity with geotextile encased columns for railway embankments in the Netherlands is a risk that may mainly entail additional costs **(Fugro)**.
Discrepancy between the model and reality is a risk that affects the integrity of the design. The model, which considers only two dimensions, is a simplified version of reality. The load path from the embankment to the geotextile encased columns may be different, and horizontal loads may have a greater influence on the overall stability **(Boekhorst, 2007)**.

The aforementioned risks are controlled and limited through careful monitoring. During the installation of the geotextile encased columns, the following measurements are taken to control the risk of unfavorable effects, (Fugro):

- General control measurement and analysis of casing penetration data during the installation process;
- Excessive settlement in the operational phase is controlled by measuring the strain in the geosynthetic encasement and measurements of the diameter of the case. These measurements are of paramount importance during pilot projects, to gain deeper understanding about the performance of the system over the course of time;
- Damage to the adjacent track and embankment are monitored by visual inspection and measuring vibrations during installation.

Maintainability
The maintainability of the GEC soil stabilization method depends on the technical lifespan of each of the components of the structure. The technical lifetime of the sand piles is mainly determined by the technical lifetime of the geosynthetic encasement and geogrid. Factors that influence the technical service life of the geotextile are production uncertainties, change in load, the occurrence of creep and degradation by environmental influences, such as the acidity of the peat. Depending on the desired service life, a strong and durable geotextile is chosen. Ringtrac is designed as a cylindrical seamless reinforcement sleeve for uniform tensile strength and axial stiffness, ensuring the longevity of the geotextile and result in an unlimited lifespan. In addition, the Stabilenka geogrid ensures a proven resistance of up to 120 years. Therefore, the service life of the overall system is unlimited and requires little maintenance (Fugro). The main concern for the operator is the occurrence of settlement and horizontal deformations in the operational phase. If the system functions as expected, the embankment undergoes virtually no subsidence. As part of management and maintenance, no special measures are then required.

Degree of Shutdown
The degree of shutdown depends on the method of execution and its different construction phases. Although some phases are completed adjacent to the single track, space is required to the embankment for machinery and materials. For this reason, the adjacent track is kept out of service in order to complete the embankment widening from the single track, if possible.

The sand piles are installed using a vibrating block and a steel casing. The installation starts by vibrating the steel casing into the bearing layer. On average, the casing has a diameter of between 0.6 and 0.8 meters. The geosynthetic sleeving is then lowered into the casing. The encasement is seamless and consists of a high-strength geotextile, fulfilling both a reinforcement and filter function. The sock is then filled with sand. The steel casing is pulled out of the ground while vibrating. The vibrations compact the sand in the geotextile encasement, which contributes to the overall strength of the column (Fugro). After completion of the sand piles and application of a load-spreading geogrid, the sand is applied in layers. As the sand piles also act as vertical drains, the soil between the sand piles is given the opportunity to consolidate, enabling the soil to provide the required bearing pressure. After constructing the embankment, the stabilized soil is put to use immediately as there is virtually no settlement after completion (Huesker, 2021).

The extent of decommissioning is difficult to estimate as this is dependent on a variety of factors. Moreover, further research is required to determine the extent to which the adjacent track remains in use during the embankment expansion. However, based on similar literature studies, an indication of the extent of downtime is given. Since the geotextile encased columns method relies on transferring the loads of the embankment directly to the loadbearing layers in the subsoil, the embankment is commissioned immediately, and residual settlements are small. The time required to complete the embankment widening using the GEC method is estimated at 60 days (Unidek Group B.V., 2005).

Design
It is important to mention that the discrepancy between the design and reality results in an incomplete design as three-dimensional influences are not considered in the software. Moreover, the design is created based on limited knowledge and through trial and error. An attempt is made to design as realistic a simulation of a GEC system as possible to arrive at a design that guarantees stability of the embankment expansion.

When designing a sand embankment on geotextile encased columns, the geometry of the sand piles is determined iteratively. This involves both the center-to-center distance and the column diameter.

3.6.3 Alternative 3 – Preloading combined with Glass Foam

In the pre-loading method, the subsoil is first pre-loaded with a sand embankment for some time, after which the sand is partially replaced with a very light fill material. Vertical plastic drains are installed to accelerate the consolidation of the subsoil. The purpose of the pre-loading with sand is to pre-load the ground in such a way that during the utilization phase virtually no settlement occurs under the weight of the remaining sand embankment, light embankment material and superstructure.

The overall execution sequence starts with preparing the project site. Next, the plastic drains are installed. The sand embankment is applied as pre-loading. After a certain settling time, excavation is carried out to the desired level. The lightweight embankment material is applied on a geotextile layer, after which the sand embankment is constructed. The finished embankment is in principle settlement-free. The advantage of this method is that no deep excavation is required next to the existing track. This eliminates the need for measures to prevent the instability of the adjacent track (Fugro).

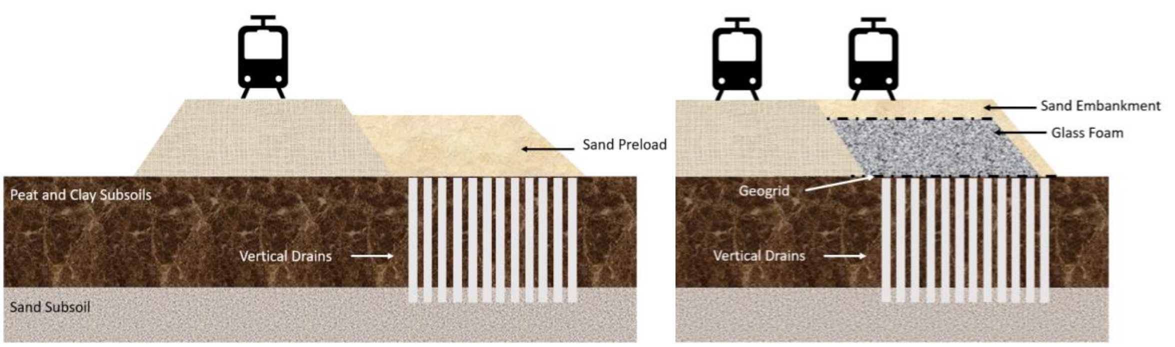


Figure 63 Schematical Overview Preload + Glass foam

Materials

Depending on the properties of the chosen embankment material, the pre-loading method consists of a sand body, light fill material and plastic drains. Vertical drains are mainly used in sand embankments to quickly drain the pore water in the compressible layers to speed up the settlement process and increase stability during construction. A temporary additional over height may be applied to reduce the residual settlement to a predetermined value within an acceptable time.

Using a light embankment material is a suitable solution if a balance is achieved where the road and foundation together are as high in weight as the excavated soil package. The road floats more or less and moves with the adjacent ground level. Traditionally, EPS (expanded polystyrene foam) is used as a light embankment material (Fugro). The volumetric mass of EPS is smaller than that of a peat layer (about 1,000 kg per cubic meter) and has therefore been widely used as a material in infrastructure projects on soft substrates. However, EPS requires additional measures to prevent degradation by oil and rodents. Moreover, EPS is not permeable to water, so an additional drainage system must be applied for water drainage (Glasschuim, 2023).

A rather new material is glass foam. The low weight, load-bearing capacity, and water permeability of a layer of glass foam make the material an ideal solution for stabilizing settlement-prone peatlands. Glass foam weighs 300 kg/ cubic meter, increasing to a maximum of 450 kg/m3 under water absorption. The fill material has a significantly smaller volumetric weight compared to peat, so less excavation is required to achieve the required weight reduction for a balanced foundation. An environmental advantage is that the glass foam is a recycled material, thus contributing to the sustainability of the system (Glasschuim, 2023).

Figure 64 Glass foam as lightweight fill material after preloading (Glasschuim, 2023)

To preserve the compacted fill material layer, a geotextile is applied at the bottom of the glass foam. The ROMFIX R'Cel geocell is a 3-dimensional foundation reinforcement that causes the foundation to be divided into interconnected cells to form a large mattress of the fill material layer. The geocell consists of plastic strips in a honeycomb structure ensuring optimal pressure distribution and is often used in combination with the lightweight and sustainable recycled glass foam material (Romfix, 2023).

Stability

The effect of the embankment extension on the adjacent track affects the overall stability and expected settlement. The construction of the embankment causes horizontal and vertical deformations in the existing embankment. These lead to instability during the construction phase. By applying vertical drains, settlement of the embankment expansion accelerates. In this project, no vertical drainage is present under the adjacent track, which should be considered in the design. Much of the deformations of the existing embankment occurs during the construction of the railway embankment extension. Due to the lack of vertical drainage, the existing embankment may consolidate differently than the widening where vertical drains have been applied (Fugro).

The installation of the glass foam requires excavation of part of the sand embankment. Measures may be required to ensure the stability of the existing embankment during that phase, such as a temporary earth retaining structure. For this reason, the adjacent track would be temporarily taken out of service.

Sustainability

The sustainability of the preloading method depends on the materials used, and the degree of reusability of the materials used in different phases. The latter applies especially to the possibility of reusing the vertical drains. In practice, recovering and reusing the drains has proven to be impossible, as they lie below the embankment (Fugro).

Unlike the plastic drains, the lightweight fill material is an innovative material that offers many advantages, both in terms of environmental and economic sustainability. The glass foam is a highly sustainable and circular aggregate which is made from foamed recycled glass, giving the glass waste a new purpose. The air bubbles in the glass foam result in its purpose of both a lightweight foundation material and an insulating material. Due to the closed pores, the glass foam absorbs virtually no water, allowing rainwater to easily wash through, improving the overall environmental sustainability dimension (Romfix, 2023). The economic sustainability is influenced by the limited maintenance required and the high durability of each of the materials and the stabilization system as a whole. In addition, the method of preloading is not unknown in the Netherlands, resulting in experience that increases the knowledge of working safely and efficiently while stabilizing the embankment expansion.

Technology Readiness Level

Stabilizing an embankment, or any other subsoil, by means of preloading is not new in the Netherlands. The method is mostly used in infrastructure projects and residential areas where there is no time pressure, and the relatively long time of pre-loading is allowable. However, innovative elements are increasingly applied to achieve a more sustainable system. Experiments are mostly carried out using more environmentally friendly and recycled materials, such as glass foam.

A reference example in the immediate vicinity of Hazerswoude-Rijndijk, is the use of glass foam in the stabilization of a road in Hazerswoude-Dorp, see **Appendix M.3 – Preload and Glass Foam for the stabilization of the Montfoortlane in Hazerswoude-Dorp** for a reference project using the method of preloading combined with glass foam (Van der Werff Groep, 2017). Foam glass was used for the embankment of a lane in Hazerswoude-Dorp. Hazerswoude suffers from excessive settlement, which reaches to about 80 centimeters locally due to the underground peat soil. By first preloading the road and then raising using a 50-centimeter-thick layer of lightweight foam glass, the settling was limited to about 7 centimeters over a 30-year span.

Costs

The indicative costs for the materials and construction of the preloading system are based on the estimated construction costs according to an experienced engineering firm (Fugro). The costing includes the following material and execution costs:

- Purchase of the sand for the embankment as well as preloading material;
- Removal of the preload material (Unidek Group B.V., 2005);
- Purchase and installation of vertical drains;
- Purchase and installation glass foam (Romfix, 2023);
- Purchase and installation Romfix Geocell (Romfix, 2023).

Table 15 Estimated Costs for the Preloading Method

	Price per unit
Purchase Materials	
Vertical drains	€ 0,65 /m
Glass foam	€ 135,- / m²
Sand body	€ 10, -/m³
Sand Preload	€ 10, -/m³
Geotextile	€ 20,- / m²
Installation Costs	
Removal Preload	€ 4, -/ m³
Transport Sand	€ 7, -/ m³

The excavation of sand is usually done in a cost-neutral manner. The cost of water control, including measures to drain the water released from the drains, is not included in the cost estimate. Facilities to make the site accessible are also not included. Moreover, to be mentioned is that the vertical plastic drains are a mass item, and therefore relatively cheap. The cost depends on the installation speed, which depends on the drain length, soil structure and accessibility (Fugro).

Risks

Despite the frequent use of the preloading method in infrastructural constructions, risks remain due to the various variables that affect the performance of the stabilization system, including the composition of the subsoil and the load on the embankment. Regarding the preliminary design of the preloading system, several risks are to be identified based on literature research. The potential risks are summarized in **Table 16**.

Table 16 Evaluation of the Risks associated with the method of Preloading

Description and Evaluation
Despite the structure being virtually settlement-free in the use phase, a changed groundwater level and surcharge load negatively affect the stability of the embankment. Fluctuation in groundwater level and load must therefore be prevented to ensure stability **(Fugro)**.
Uncertainty regarding the horizontal permeability and consolidation coefficient of the soil. This risk, although very small, is limited by conducting extensive soil investigations before designing the preload system **(Fugro)**. A much determining risk factor is the uncertainties in the determination of the compressive properties, permeability, strength, and stiffness parameters of the weak layers. These risks are also limited by conducting soil testing.
Risk of damage to adjacent track during pre-loading with sand. Although the damage is moderate and regulable, further investigation should reveal whether and what measures should be taken to ensure the stability of the adjacent track **(Fugro)**.
Discrepancy between the model and reality is a risk that affects the integrity of the design. The model is a simplified version of reality. Horizontal loads may have a greater influence on the overall stability of the embankment expansion **(Boekhorst, 2007)**

The aforementioned risks are controlled and limited through careful monitoring. During the installation of the preloading system, the following measurements are taken to control the risk of unfavorable effects, (Fugro):

- Excessive settlement in the operational phase is limited by monitoring the time-settlement curve;
- By performing visual inspection, horizontal deformation is to be monitored to limit the risk of instability of the existing embankment.

Maintainability

The requested lifetime of vertical plastic drains is generally less than two years and is shorter than the technical lifetime. The effective life of the drain depends on clogging of the drain with fine particles and buckling due to settlement. However, sufficient drainage capacity always remains during the usage phase (Fugro).

In general, the technical lifetime of glass foam is unlimited. Low temperatures and exposure to freeze-thaw cycles do not negatively affect the mechanical behavior of the material (Glasschuim, 2023). Therefore, the embankment does not require frequent maintenance. However, monitoring is required to identify in time possible deformations during the operational phase of the embankment (Fugro). The main concern for the operator is the occurrence of settlement and horizontal deformations in the operational phase. If the system functions as expected, the embankment undergoes virtually no subsidence. As part of management and maintenance, no special measures are then required.

Degree of Shutdown

Since the different phases influence the adjacent single track, the decision is made to keep the adjacent track out of service in order to complete the embankment widening.

The working floor must be sufficiently permeable to drain the water released from the vertical drains. Installation of plastic drains is done by crane. The drainage and fill sand are generally brought in by trucks, after which the sand is spread by a bulldozer in thin layers of half a meter. In doing so, the vehicles should drive in such a way that the sand is compacted simultaneously. Application of the glass foam embankment starts with the installation of temporary earth-retaining structures, if any. The existing soil is then excavated to a predetermined depth. After depositing and compacting the glass foam layer, a cover plate is placed after which the rest of the embankment is constructed (Fugro).

The extent of decommissioning is difficult to estimate as this is dependent on a variety of factors. Moreover, further research is required to determine the extent to which the adjacent track remains in use during the embankment expansion. However, based on similar literature studies, an indication of the extent of downtime is given.

Since the method of preloading relies on temporarily increasing the loads on the subsoil, a considerable amount of time is required before the embankment is actually built. The pre-loading phase takes place along the entire length of the embankment at the same time, as a result, the embankment extension cannot be worked on in stages. However, after the pre-loading period, the embankment is commissioned immediately, and residual settlements are virtually negligible. The time required to complete the railway embankment widening has been estimated at 250 days (Unidek Group B.V., 2005).

Design

It is important to mention that the discrepancy between the design and reality results in an incomplete design as three-dimensional influences are not considered in the software. Moreover, the design is created based on limited knowledge and through trial and error. An attempt is made to design as realistic a simulation of a preloading system as possible to arrive at a design that guarantees stability of the embankment expansion.

RESULTS

The Methodology chapter concludes the investigation into various soft soil stabilization methods by selecting three of the most promising options through expert judgment. These three variants, namely the pile mattress, geotextile encased columns, and the method of preloading, are then subjected to a comprehensive comparison using a multi-criteria analysis. The analysis considers multiple factors, including sustainability, technology readiness level, and cost estimation. The chapter begins by conducting stability calculations using D-Geo Stability models, followed by evaluating the seven predefined criteria and scoring each variant accordingly. The subsequent comparison of the three methods allows for the selection of the most suitable soil stabilization technique that ensures the stability of the railway embankment expansion. The chapter's ultimate goal is to determine the optimal solution based on a thorough and systematic analysis.

4

4.1 Alternative Design Calculations

The testing of the stability of each alternative design is conducted using the software D-Geo Stability. This subchapter includes the design calculations of the different soil stabilization methods. The methodology used to design the three variants is described in **Chapter 3.5 – Geotechnical Software D-Geo Stability.**

4.1.1 Pile Mattress Design Calculations

Examination of the stability of the pile mattress design is conducted using the D-Geo Stability software. A simplified representation of the design is modelled, see **Figure 65**. The material properties of the geotextile are obtained from Huësker's Fortrac product overview (Huësker, 2023). The tensile strength of Fortrac geotextile is 120 kN/m. The geotextile extends over the total width of the embankment, with a total length of 24 meters. In addition, to ensure optimal transition between the weak layers and the sand embankment, the choice is made to apply the geotextile at a depth of -1.9 m+NAP.

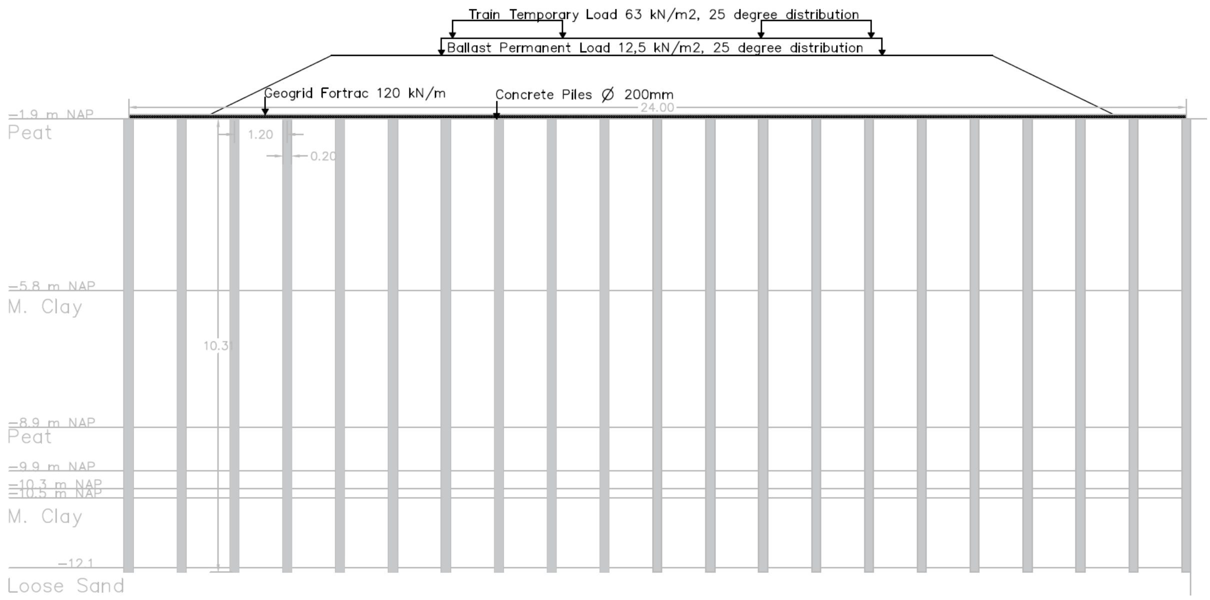


Figure 65 Design of the Pile Mattress

The properties of foundation piles are based on literature research. The total unit weight and friction angle of concrete piles are 22.0 kN/m^3 and 30.0 degrees respectively (Alexandridis & Gardner, 2003). To achieve an optimal and stable design for the pile foundation, a center-to-center distance of 1.2 meters is chosen. The slender piles have a diameter of 200 millimeters. By selecting a slim diameter, vibrations during installation are reduced, as well as allowing the piles to be installed relatively quickly (Skanska, 2021). The piles, including pile caps, have a total length of 10.3 meters and reach the sand layer at -12.2 m+NAP.

The following parameters are included in the design of the pile mattress system, see **Figure 66** for the D-Geo Stability model:

- Temporary train load of 63 kN/m^2 (ProRail, 2016);
- Permanent ballast and superstructure load of 12,5 kN/m^2;
- Based on expert judgement, a value of 25 degrees of load distribution is chosen;
- A minimum required distance of 4,5 between two tracks;
- The minimum required factor of safety (FS) is 1,35 (ProRail, 2016);
- A gradient of 1:2 on either side of the slope (ProRail, 2016);
- The top of the embankment at -0.46 m+NAP;

- Total of 22 concrete piles ϕ200 mm, center to center distance of 1,2 meter;
- Piles from -1,9 m+NAP to a depth of -12,2 m+NAP, a length of 10,3 meters including pile caps;
- Fortrac Geotextiles with effective tensile strength of 120 kN/m (Huësker, 2023);
- Geotextile at a depth of -1,9 m+NAP, with a total width of 24 meters.

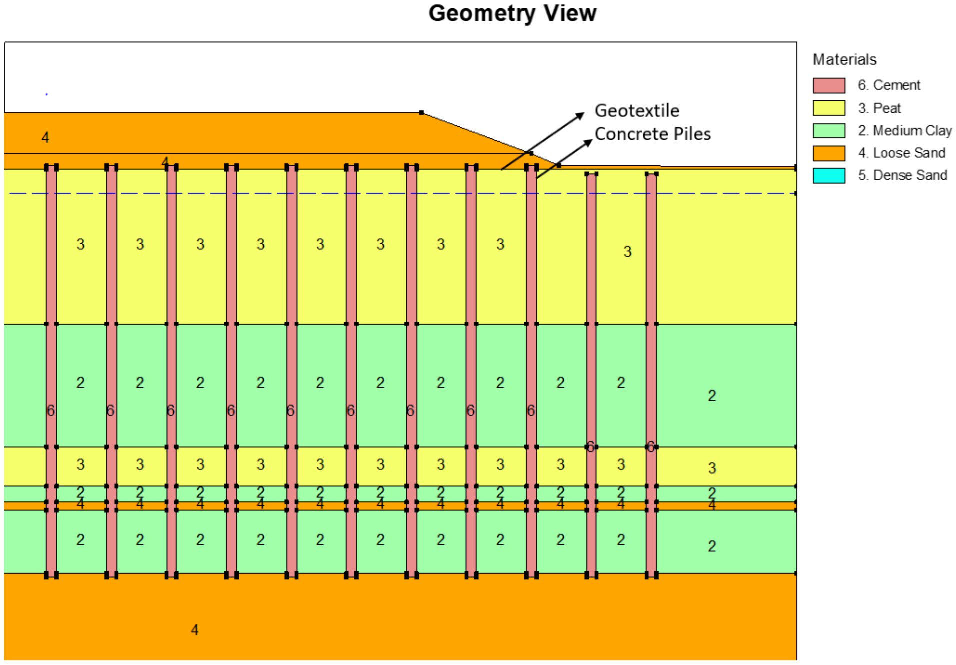


Figure 66 D-Geo Stability Model Embankment Expansion, Pile Mattress Variant

Using Bishop's method, the factor of safety (FS) is determined. In addition, the stress analysis is obtained as well as a safety overview. Bishop's critical circle of the embankment expansion is shown in **Figure 67**. The safety overview and report are enclosed in **Appendix O – Stability Analysis Pile Mattress Variant**.

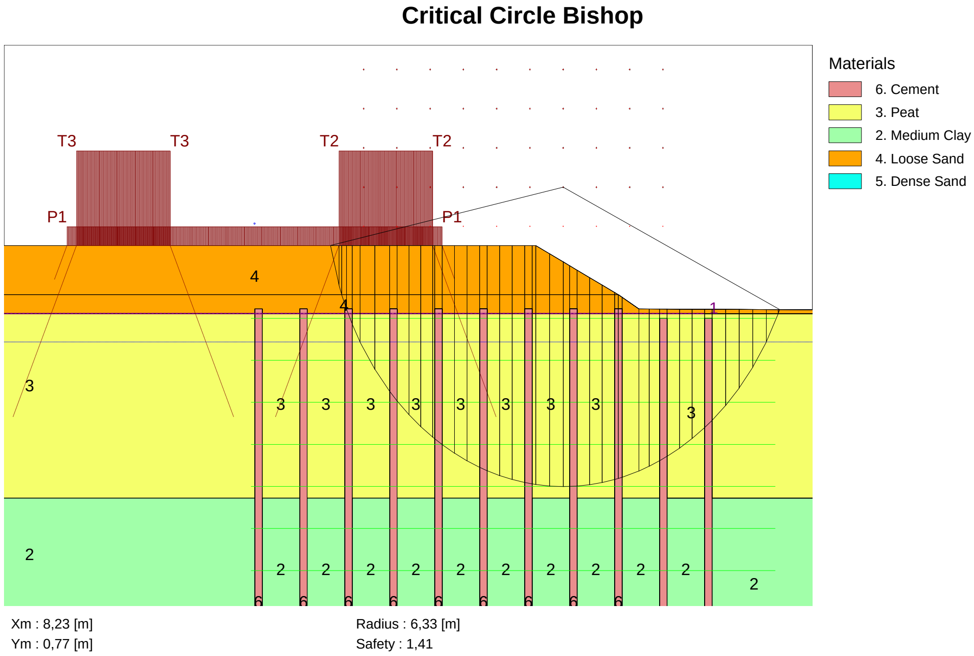


Figure 67 Bishop's Critical Circle, Pile Mattress Variant

The analysis of the critical slip circle shows that the safety factor is 1,41 in the case of embankment expansion using the pile mattress stabilization method. Therefore, the safety factor exceeds the minimum required safety factor of 1,35 stated by the regulations (ProRail, 2016). The stability investigation proves that the design of the pile mattress system meets the design criteria and requirements and is therefore stable.

4.1.2 Geotextile Encased Columns Calculations

Examination of the stability of the geotextile encased column (GEC) design is conducted using the D-Geo Stability software. A simplified representation of the design is modelled, see **Figure 68**. The material properties of the encased columns are obtained from Huësker's Ringtrac product overview (Huësker, 2005). The system is characterized by a total unit weight of 9 kN/m^3 and a friction angle of 30 degrees. In addition, the Huësker's Stabilenka Geogrid has a tensile strength of 200 kN/m. The geogrid extends over a total width of 22 meters. In addition, to ensure optimal load transfer between the geogrid and the geotextile encased columns, Huësker's geogrid is applied at a depth of -1,9 m+NAP.

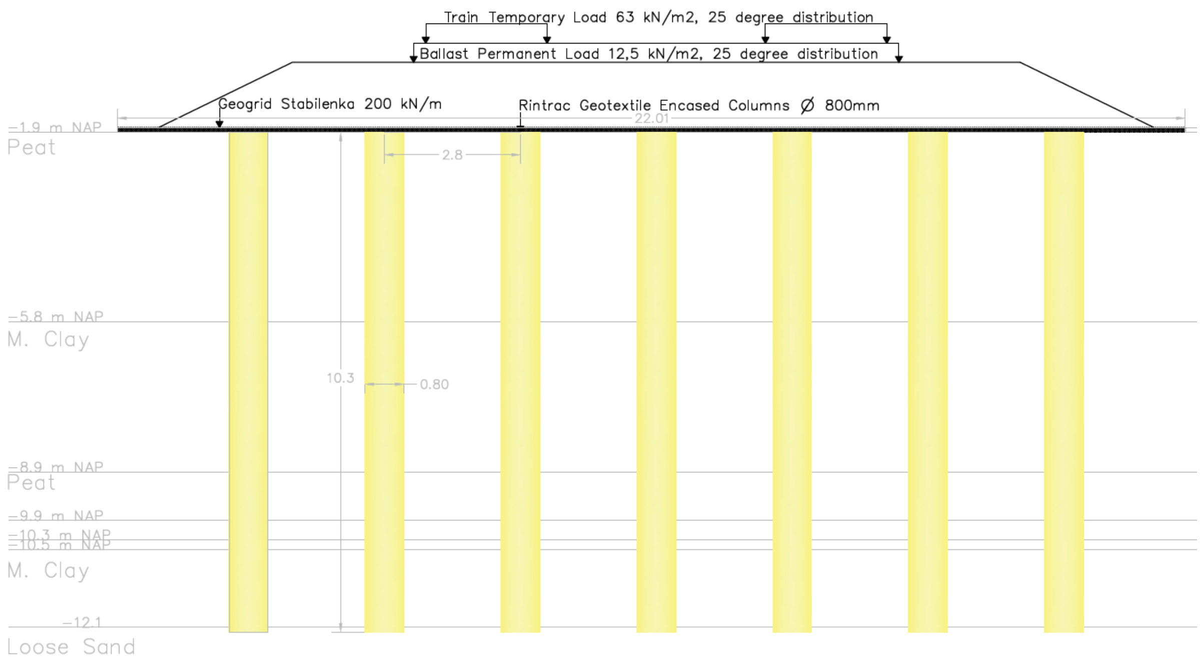


Figure 68 Design of the Geotextile Encased Columns

In order to obtain an optimal and stable design for the GEC stabilization method, a center-to-center distance of 2.8 meters is chosen. The columns have a diameter of 800 millimeters and have a total length of 10.3 meters, reaching the sand layer at -12.2 m+NAP.

The following parameters are included in the geotextile encased column design, see **Figure 69** for the D-Geo Stability model:

- Temporary train load of 63 kN/m^2 (ProRail, 2016);
- Permanent ballast and superstructure load of 12,5 kN/m^2;
- Based on expert judgement, a value of 25 degrees of load distribution is chosen;
- A minimum required distance of 4,5 between two tracks;
- The minimum required factor of safety (FS) is 1,35 (ProRail, 2016);
- A gradient of 1:2 on either side of the slope (ProRail, 2016);
- The top of the embankment at -0.46 m+NAP;
- Total of 7 geotextile encased columns with ϕ800 mm, center to center distance of 2,8 meters;

- Columns from -1,9 m+NAP to a depth of -12,2 m+NAP, a length of 10,3 meters;
- Stabilenka Geogrid with effective tensile strength of 200 kN/m (Huesker, 2017);
- Geogrid at a depth of -1,9 m+NAP, with a total width of 22 meters.

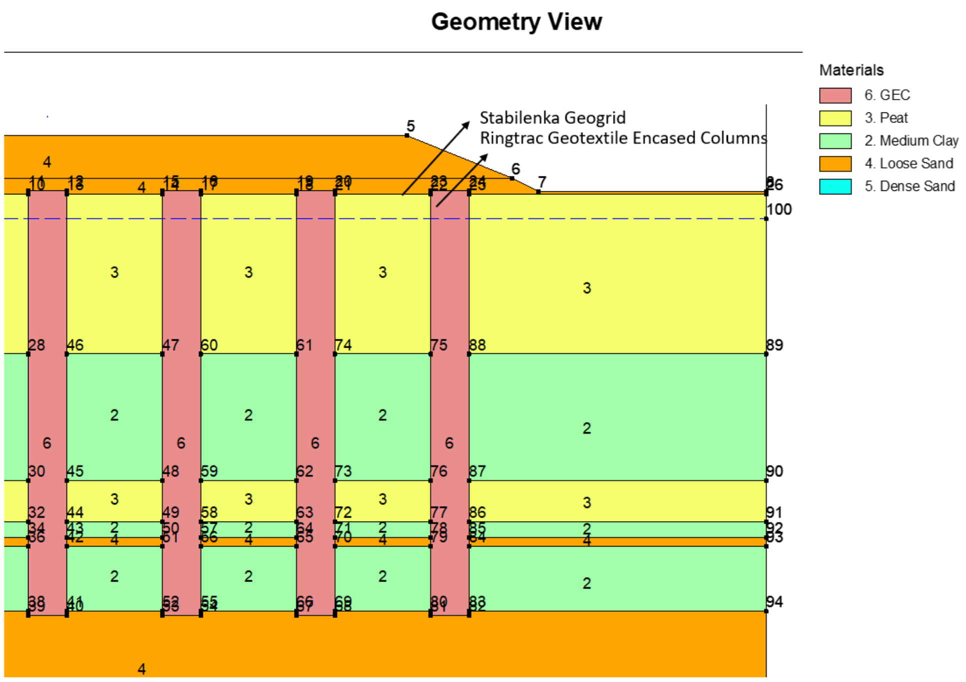


Figure 69 D-Geo Stability Model Embankment Expansion, Geotextile Encased Column Variant

Using Bishop's method, the factor of safety (FS) is determined. In addition, the stress analysis is obtained as well as a safety overview. Bishop's critical circle of the embankment expansion is shown in **Figure 70**. The safety overview and report are enclosed in **Appendix P – Stability Analysis Geotextile Encased Column Variant**.

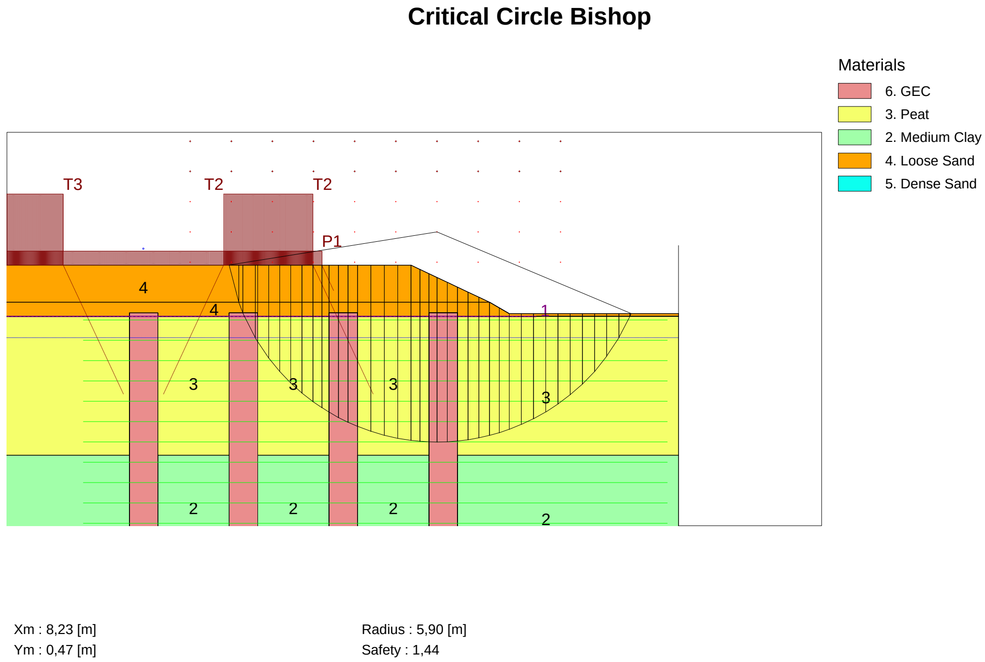


Figure 70 Bishop's Critical Circle, Geotextile Encased Column Variant

The analysis of the critical slip circle shows that the safety factor is 1,44 in the case of embankment expansion using the geotextile encased column method. Therefore, the safety factor exceeds the minimum required safety factor of 1,35 stated by the regulations (ProRail, 2016). The stability investigation proves that the design of the GEC system meets the design criteria and requirements and is therefore stable.

4.1.3 Preloading combined with Glass Foam

Examination of the stability of the preload combined with glass foam design is conducted using the D-Geo Stability software. A simplified representation of the design is modelled, see **Figure 71**. The material properties of the glass foam are obtained from literature research (Teymur & Tuncel, 2013), pointing out a total unit weight of 3 kN/m^3 when drained and a saturated unit weight of 4,5 kN/m^3. In addition, the material is characterized by a friction angle of 45 degrees. The lightweight fill material covers over a total width of 16 meters, with a thickness of 0,90 meters, applied at a depth of -1,0 m+NAP.

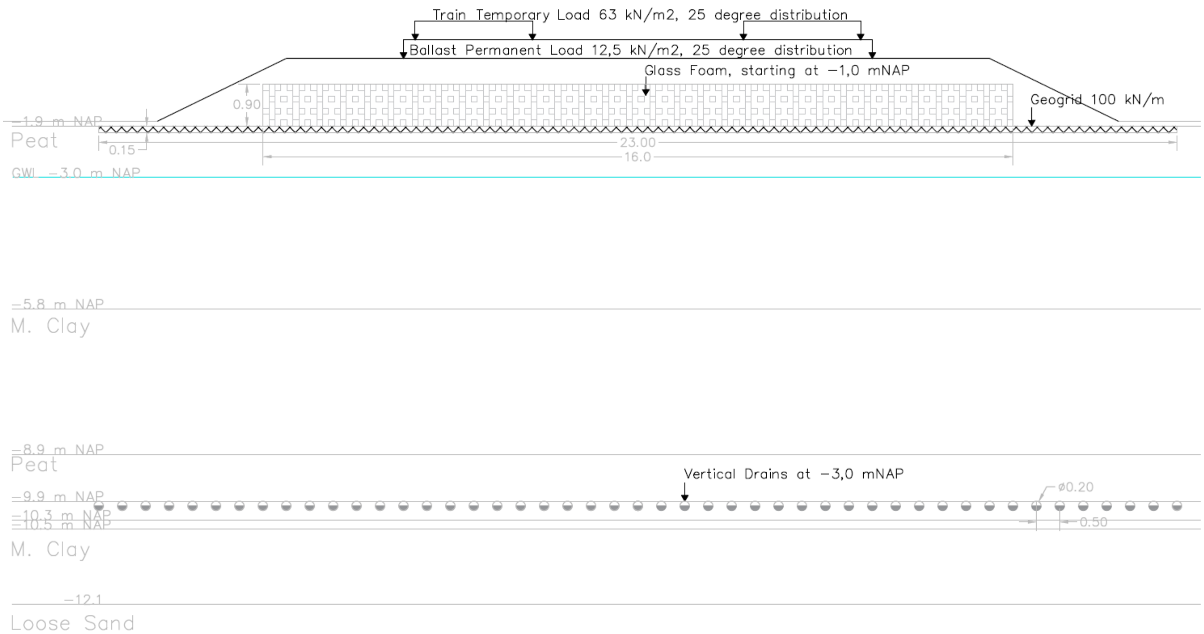


Figure 71 Design of the Preload combined with Glass Foam

In order to increase the consolidation process of the preloading stabilization method, vertical drains are implemented to lower the ground water level to a depth of -3,0 m+NAP, with a center-to-center distance of 0,5 meter. The drains have a diameter of 200 millimeters and cover the entire width of the embankment. To obtain an optimal and stable design, a geotextile is implemented at the bottom of the compacted glass foam layer. The geotextile is characterized by an effective tensile strength of 100 kN/m (Romfix, 2023).

The following parameters are included in the preloading design, see **Figure 72** for the D-Geo Stability model:

- Temporary train load of 63 kN/m^2 (ProRail, 2016);
- Permanent ballast and superstructure load of 12,5 kN/m^2;
- Based on expert judgement, a value of 25 degrees of load distribution is chosen;
- A minimum required distance of 4,5 between two tracks;
- The minimum required factor of safety (FS) is 1,35 (ProRail, 2016);
- A gradient of 1:2 on either side of the slope (ProRail, 2016);

- The top of the embankment at -0.46 m+NAP;
- Glass foam layer from -1,0 m+NAP to a depth of -1,9 m+NAP
- The lightweight fill material covers the 16 meters width of the embankment;
- Glass foam properties including total dry unit weight of 3 kN/m^3 and a 45-degree friction angle;
- Vertical drains lowering the ground water level from -2,5 m+NAP to -3,0 m+NAP;
- Romfix geotextile are applied at the t bottom of the glass foam layer (Romfix, 2023);
- Geotextile with an effective tensile strength of 100 kN/m (Romfix, 2023);
- Bottom geotextile installed at a depth of -1,9 m+NAP, covering a total width of 23 meters.

Geometry View

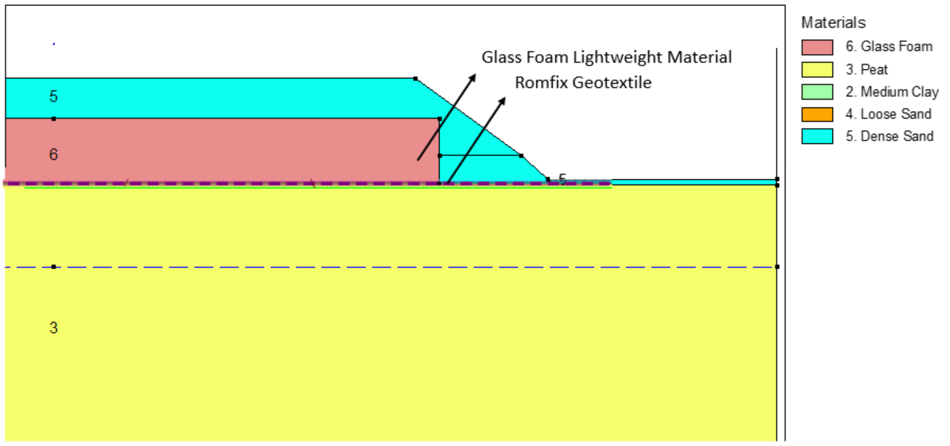
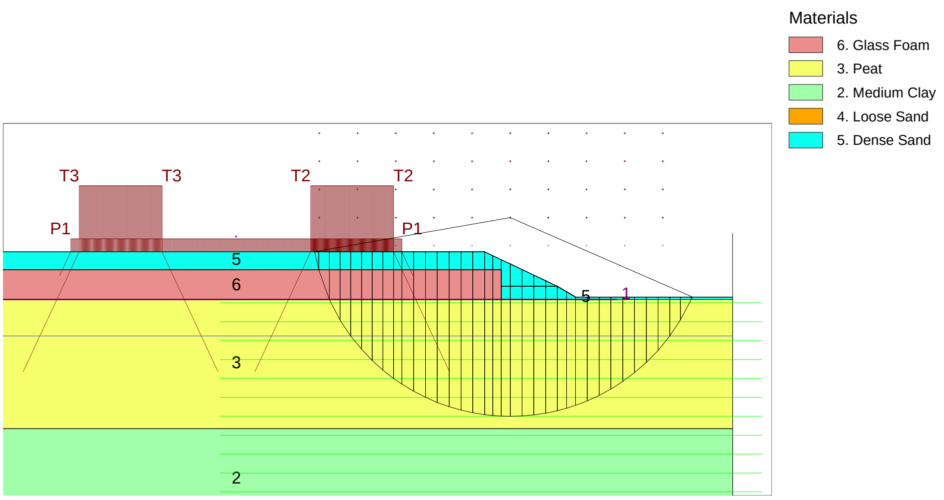


Figure 72 D-Geo Stability Model Embankment Expansion, Preloading Variant

Using Bishop's method, the factor of safety (FS) is determined. In addition, the stress analysis is obtained as well as a safety overview. Bishop's critical circle of the embankment expansion is shown in **Figure 73**. The safety overview and report are enclosed in **Appendix Q – Stability Analysis Preloading Variant**.

Critical Circle Bishop



Xm : 8,28 [m]
Ym : 0,57 [m]
Radius : 6,00 [m]
Safety : 1,37

Figure 73 Bishop's Critical Circle, Preloading Variant

The analysis of the critical slip circle shows that the safety factor is 1,37 in the case of embankment expansion using the preloading method combined with glass foam and geotextiles. Therefore, the safety factor exceeds the minimum required safety factor of 1,35 stated by the regulations (ProRail, 2016). The stability investigation proves that the design of the preloading system meets the design criteria and requirements and is therefore stable.

4.2 Multi-Criteria Analysis

The multi-criteria analysis (MCA) is a systematic approach to ranking possible solutions to a given problem based on different criteria and priorities. Using this type of analysis has several advantages, offering the opportunity to compare different qualitative and quantitative factors and thus providing insight into the effect of different value judgments. In addition, performance measures are outsourced to experts, allowing representative value judgments to be factored into the analysis of different variants.

For the examination and evaluation of the different soil stabilization methods, an MCA consisting of seven criteria is used. The most important requirements and factors as communicated by the client have been incorporated into the matrix. These are made up from both consultations, and matrices from similar studies and projects. In addition, Arcadis' requirements, such as the relevance of sustainability, have also been included. In doing so, the tradeoff-matrix analyzes a variety of requirements drawn up by the different stakeholders:

1. **Settlement & Stability** – Estimated settlement and degree of stability based on expert judgement as well as calculations using D-Geo Stability software;
2. **Sustainability** – Estimated grading various sustainability key performance indicators (KPI's), based on expert judgement of the sustainability advisor as well as literature research;
3. **Technology Readiness Level** (TRL) – Guided by the TRL scale, based on literature research;
4. **Costs** – Estimated costs per meter construction, based on literature research;
5. **Risks** – Estimated risks during installation and maintenance, based on expert judgement as well as literature research;
6. **Maintainability** – Estimated required maintenance over the expected lifetime of the structure, based on literature research and expert judgement;
7. **Degree of Shutdown** – Measured in estimated number of days.

4.2.1 Criteria

The description and weighting factor for each criterion are discussed and worked out in detail. Examples of grading forms are drawn up to support the way of analyzing and evaluating the different soil stabilization methods.

Stability

The stability of the railway embankment expansion is dependent and therefore evaluated by both the expected secondary settlement as well as the factor of safety of the structure. The first is a result of the constant load applied on the soil resulting in vertical movements of the embankment. The latter is calculated using the software of D-Geo Stability.

The soil's vertical movements are a result of immediate settlement, consolidation settlement and creep settlement, also referred to as secondary settlement. The first occurs in the soil body upon load application, resulting in a reduction of void spaces. Primary or consolidation settlement is caused by volumetric change and is induced by the reduction of voids as a result of the gradual squeezing of water between soil particles. Lastly, due to the constant load applied on the soil, creep settlement occurs (Geo Engineer, 2020).

The total settlement of the soil is to be carefully calculated and must comply with the schedule of requirements as described in **Chapter 2.8 – Program of Requirements**. The different variants limit these settlement components in a different way or use the characteristics to their benefit. Despite all methods aiming to minimize the long-term effects, the degree of settlements varies. Since the settlement rate is predicted with an increasing accuracy, vertical movements are often considered during the design phase. However, due to the expected increase in groundwater level, **Chapter 2.5 – Design Criteria**, the secondary settlements and possibly the overall stability, changes as a result over time. Controlling secondary settlements limits potential risks regarding the overall stability as well as the maintenance costs and is therefore of great importance in the evaluation of the different soil stabilization variants. The extent to which settlements occur in an uncontrolled manner are estimated and evaluated based on literature research and expert judgment.

In addition, to understand the degree of stability of a structure, the factor of safety (FS) is determined. This factor is defined as the relationship between the capacity (C, resisting force) and the demand (D, disturbing force). The railway embankment is considered as stable when the capacity is 1,3 times larger than the demand i.e., FS > 1,3 (Budhu, Soil Mechanics and Foundations, 2011). The variants as described in **Chapter 3 – Methodology**, are modelled in the geotechnical software D- Geo Stability to calculate the factor of safety based on the method of Bishop as described in **Chapter 2.7 – Fundamentals of Slope Stability**.

As both the secondary settlement and the factor of safety are important parameters in the examination of the overall stability of the variants, the two are to be investigated. Secondary settlements are explored qualitatively, based on literature research and reference projects, while the factor of safety (FS) is quantitatively determined. As a result of the different analysis approaches, the factor of safety contributes for $^{2}/_{3}$ to the overall stability analysis, while the expected secondary settlement accounts for $^{1}/_{3}$, see **Table 17**.

Table 17 Stability Evaluation Form

Variant	Settlement	Settlement Grade Settlement * $^{1}/_{3}$	Safety	Safety Grade Safety * $^{2}/_{3}$	**Stability Grade** Settlement Grade + Safety Grade
A	1	0,33	3	2,00	**2,33**
B	2	0,67	2	1,33	**2,00**
C	3	1,00	1	0,67	**1,67**

For the secondary settlements, the variant with the lowest expected settlements gets 1 point, and the design with the most settlement comes third. The *Settlement Grade* is therefore calculated as the awarded points multiplied by $^{1}/_{3}$. The same ranking system applies to the factor of safety, where the highest factor of safety is awarded first place i.e., 1 point. The *Safety Grade* is calculated by multiplying the points by $^{2}/_{3}$. The settlement grade and safety grade of each variant combined result in the *Stability Grade*, where the smallest grade indicates the soil stabilization variant with the highest overall stability.

- **Stability evaluated based on secondary settlement and factor of safety;**
- **Settlement examined based on literature research, safety calculated using D-Geo Stability;**
- **Variant with the lowest *Stability Grade* awarded to the most stable variant;**
- **Stability weighting factor is 22% of the MCA.**

Sustainability

The increasing interest to measure the sustainability of infrastructure projects has attracted the attention of both researchers and government organizations such as ProRail. Infrastructure projects are typically characterized by major expansions of the network and has a significant impact on the sustainable construction environment. The combination of these features makes infrastructure projects have a major impact on urban and general project management, especially because of the large impact spheres. The construction sector is estimated to account for about 40% of global energy consumption, 20% of water consumption and 40% of global carbon emissions (Ricardo Prata Fernandes Ferrarez et al., 2020). In the civil construction sector, infrastructure projects account for a significant portion of this impact. For these reasons, evaluating an infrastructure's contribution to sustainable goals and ambitions is of great importance.

In accordance with the three pillars of sustainability (Ben Purvis et al., 2018), the evaluation of contribution to sustainability is subdivided into three dimensions: environmental, economic, and social, see **Figure 74**. The first focuses on a variety of aspects including environmental preservation, pollution management and control and sustainable practices like sustainable drainage systems, soil restoration and material source. The economic pillar focuses on ecosystem rehabilitation costs, the durability of the structure and the economic benefits generated by the project. Lastly, the social dimension focusses on both public and worker health and safety and social responsibility. The latter includes a careful investigation of the social and cultural impact as a result of the project.

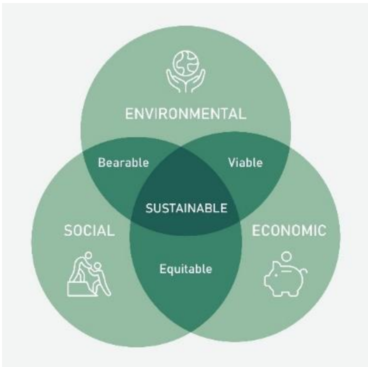


Figure 74 Three Pillars of Sustainability (SNC Lavalin, 2022)

As sustainability has a wide variety of interpretation, the concept is measured in different ways. However, certain indicators are to be checked to examine the three sustainability pillars, see **Table 18**. Moreover, these indicators provide valuable insight into a project's level of sustainability, allowing for informed comparisons between different methods. The degree of contribution to the sustainability goals are based on expert judgement by both geotechnical and sustainability experts within the company.

Table 18 Infrastructure Sustainability Indicators (Ricardo Viana Vargas et al., 2020)

Dimension	Indicator	Focus
Environmental	1. Biodiversity preservation	Environmental preservation
	2. Preservation of historical and archaeological sites	
	3. Soil conservation	
	4. Water preservation	
	5. Air pollution	Pollution management and control
	6. CO2 emission	
	7. Greenhouse gas emissions	
	8. Long-term ground/soil contamination	
	9. Long-term water pollution	
	10. Noise pollution	
	11. Impact on the natural environment	Environmental (risk) management
	12. Climate change risks and resilience	
	13. Risk of landslides, erosion, and sedimentation	
	14. Drainage systems	Sustainable practices
	15. Soil restoration	
	16. Sustainable material source	
Economic	17. Ecosystem rehabilitation costs	Economic benefits
	18. Durability of structures	
	19. Economic benefits	
Social	20. Public health and safety	Social responsibility
	21. Worker health and safety	
	22. Social and cultural impact due to the project	

The sustainability of a variant is evaluated based on a grading form, see **Table 19**. Since every aspect contributes to the overall sustainability of the design, each indicator equally adds to the *Total Sustainability Grade* of a soil stabilization method. Each aspect is graded based on the Indicator Grading Form, depicted in **Figure 75**. The degree of applicability is calculated based on this scheme. Sustainability indicators with a strong negative impact receive a -2, while a +2 is assigned to the indicators with a strong positive sustainable impact. By using a five-level grading form, the degree of sustainability is examined on various criteria while a distinction is made on the degree of its applicability.

Indicator Grading Form

-2	Highly negative impact
-1	Small negative impact
0	No (noticeable/measurable) impact
1	Small positive impact
2	Large positive impact

Figure 75 Grading of a Sustainability Indicator

The grading of each sustainability indicator is conducted based on expert judgement. The sum of the grades results in the *Sustainability Grade*. Finally, the highest *Sustainability Grade* indicates the soil stabilization method with the highest predicted sustainability.

Table 19 Sustainability Evaluation Form

Dimension	Indicator	Grade
Environmental	1. Biodiversity preservation	
	2. Preservation of historical and archaeological sites	
	3. Soil conservation	
	4. Water preservation	
	5. Air pollution	
	6. CO2 emission	
	7. Greenhouse gas emissions	
	8. Long-term ground/soil contamination	
	9. Long-term water pollution	
	10. Noise pollution	
	11. Impact on the natural environment	
	12. Climate change risks and resilience	
	13. Risk of landslides, erosion, and sedimentation	
	14. Drainage systems	
	15. Soil restoration	
Economic	16. Ecosystem rehabilitation costs	
	17. Durability of structures	
	18. Economic benefits	
Social	19. Public health and safety	
	20. Worker health and safety	
	21. Social and cultural impact due to the project	
	Sustainability Grade	

- **Evaluated based on the grading of sustainability indicators;**
- **The degree of sustainability based on expert judgement;**
- **Variant with the highest sustainability is awarded the highest Sustainability Grade;**
- **Sustainability weighting factor is 22% of the MCA.**

Technology Readiness Level

The Technology Readiness Level (TRL) is a method of understanding the so-called technical maturity of a technological method during the procurement phase. Nine levels are distinguished, in which the highest level equals the greatest degree of readiness for implementation. The nine levels are categorized into four overarching phases, namely *Discovery*, *Development*, *Demonstration* and *Deployment*, see **Figure 76**.

Figure 76 TRL Scale and its phases (SNN Kennisbank, 2022)

The State has determined that ProRail is responsible for the construction, management, and maintenance of the railways in the Netherlands (Rijksoverheid, 2023). As such, ProRail is a government organization and must account for its choices and expenditures. Risks are avoided and limited by relying on traditional and well-known methods for the construction of the rail network. Innovative methods involve unknown risks and potentially expenses. For this reason, the choice of method of soil stabilization, for example, almost always remains within the well-known methods, whose risks and costs are determined accurately in advance based on experience.

ProRail uses the TRL Scale to make distinctions and trade-offs between different methods of ground stabilization. The high costs and risks involved in ground track stabilization result in a preference for methods with a high Technology Readiness Level, see **Figure 77**. The methods that score high, fall in the demonstration and deployment rate. The methods are proven to work in similar operational conditions. Experience thus limits unforeseen costs and limits risks.

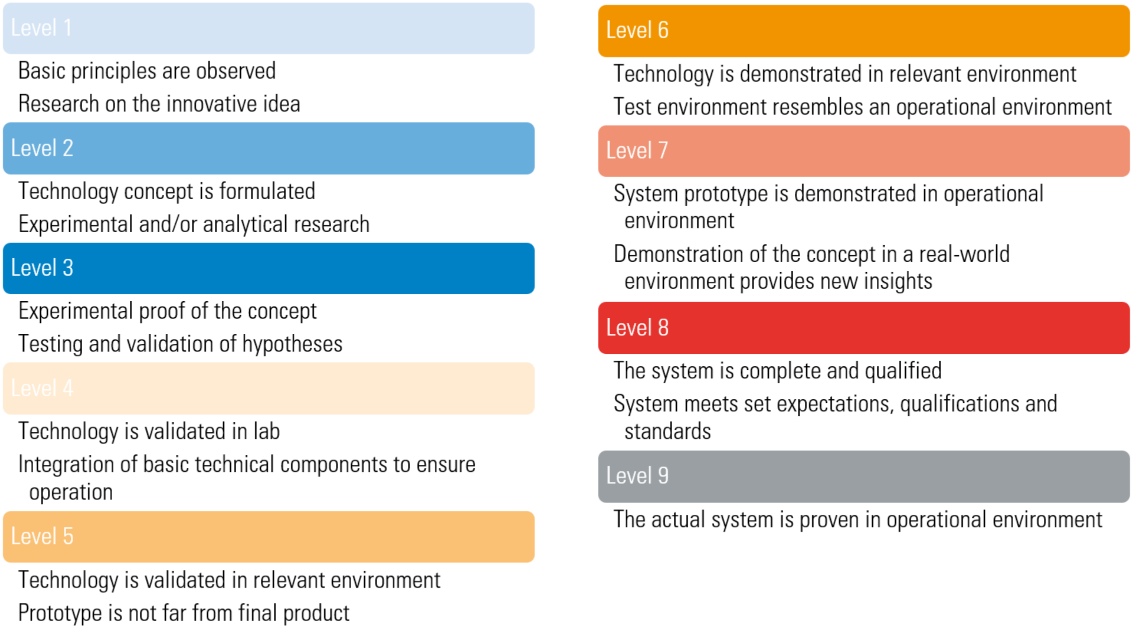


Figure 77 Nine Levels of Technology Readiness based on (TWI, 2023)

The TRL is closely related to the expected costs and risks. Still, implementing methods in the development phase is a valuable investment. By applying innovative ground stabilization methods, deeper knowledge and understanding of these methods and stabilization in general is gained. These contribute to ambitions such as being progressively advanced and investing in sustainability. The level of technology readiness is determined based on reference projects, research, and expert judgement.

The grading of each method's Technology Readiness Level is based on the description of each level, see **Figure 77**. Since the levels six up to nine indicate the demonstration of the technology in the relevant environment, these levels are graded the highest accordingly, see **Table 20**.

Table 20 Example of Grading based on the Technology Readiness Level

Variant	TRL-Scale
A	9
B	6
C	7

After analyzing the Technology Readiness Level of each variant, the methods are arranged accordingly. The highest *TRL-Scale* indicate the variant with the highest likelihood of implementation and thus is graded the highest compared to other variants. The TRL scale divides the soil stabilization methods based on their maturity. The method provides insight into which approaches offer room for improvement and thus potentially lead to reductions in costs and risks in the future. The TRL scale thus transcends expected costs and risks and provides a broader, more nuanced, picture of a particular soil stabilization method.

- **Evaluated with TRL Scale based on expert judgement and literature research;**
- **Variant with the highest TRL indicates the most mature design variant;**
- **Technology Readiness Level weighting factor is 16% of the MCA.**

Costs

Ideally the cost of implementation of the project should be kept as low as possible while ensuring a high quality of the structure. This parameter is of interest to most stakeholders. The investment in the track body may not be directly visible, but accounts for the success, safety, and longevity of the second track as well as the Hazerswoude-Rijndijk station.

Although the costs are estimated and calculated to a certain extent during the construction phases, the task is complex. The accuracy of the estimated costs depends on the degree of accuracy of the current and desired situation, as well as a deeper understanding of the soil stabilization method and its implementation. Therefore, the costs are estimated based on the expected required materials and services, see **Table 21**. The price per unit is determined based on expert judgement and literature research. The analysis aims to evaluate the different methods in comparable levels of detail. In this way, a well-considered ranking of the soil stabilization methods is obtained. The variant with the lowest costs is be awarded the highest *Costs Grade*.

Table 21 Example of a cost analysis of one soil stabilization method

Costs = Dimensions X Price per Unit

Material	Width	Length	Duration in days	Price per unit €/m3 or €/m2	Costs
Sand body	8	2	none	8,77	16
Excavation	7	5	none	4,5	35
Traffic Measures	none	none	5	10	50
Drainage	none	none	10	15	150 +
				Estimated price per meter stabilized soil	**251**

- **Estimated based on expected required materials and services;**
- **Prices based on expert judgement and literature research;**
- **Variant with the lowest costs is awarded the highest Cost Grade;**
- **Costs weighting factor is 10% of the MCA.**

Risks

This criterion evaluates the extent to which controlled and uncontrolled risks may occur during both construction and maintenance of the structure. These are investigated based on literature research as well as discussions with geotechnical experts. Risks may result from ignorance or inaccurate surveying of the project area. The risks as a result of lack of clarity, however, are similar for all variants. Therefore, the risks during construction and maintenance are considered in more detail. As one variant is to a greater or lesser extent implemented in similar project circumstances, the predictability of the associated risks varies. Different stabilization methods involve different risks as method of installation and impact on its surroundings does vary for each approach.

Based on expert judgement, risks are drawn up and graded based on the severity of harm, see **Table 22**. The listed risks are arranged from largest to smallest and graded accordingly so that the risk with the largest severity of harm is graded with the lowest number. After investigation, the risks per soil stabilization method are to be evaluated and graded, based on the *likelihood of occurrence*, combined with the severity grade, see **Table 23**. The likelihood of occurrence is graded for each method separately, as the proposed soil stabilization method influences the likelihood of occurrence of a specific risk. The degree of occurrence is estimated based on expert judgement, and in such a way that the risk with the largest likelihood of occurrence is graded with the lowest number.

Table 22 Example of the Risk Assessment Form

Arranged based on expert judgement →

Risk Number	Risk Description	Severity of harm
1	...	2
2	...	1
3, etc.	...	3

To obtain representative and distinctive values of the risk assessment, the *Product Value* is established by multiplying the severity by the likelihood. The *Final Score* is the sum of all Product Values, and thus the expected risks of a soil stabilization method. The smallest *Final Score* indicates the variant with the highest likelihood and severity of risks and thus is graded the lowest compared to other variants. Therefore, the highest *Final Score* is awarded to the soil stabilization method with the lowest predicted risks.

Table 23 Example of the Risk Assessment Form

Variant	Risk Number	Risk Assessment					Final Score	Risk Grade
		Severity	*	Likelihood	=	Product Value		
Pile Mattress	1	1	*	3	=	3	3	
	2	2	*	2	=	4	4	
	3	3	*	1	=	3	3 + 10	3
GEC	2	2		1		2		
	6	5		2		10	12	2
Preloading	1	1		2		2		
	3	3		3		9		
	4	7		1		7		
	6	5		4		20	38	1

- **Evaluated based on severity of harm and likelihood of occurrence;**
- **Degree of occurrence is estimated based on expert judgement;**
- **Variant with the lowest risks is awarded the highest Risk Grade;**
- **Risks weighting factor is 10% of the MCA.**

Maintainability

Maintainability is considered inseparable from the design of a building system, ensuring ease, accuracy, safety, and economy of maintenance tasks. The goal of maintainability is to improve the effectiveness and efficiency of maintenance. In the multi-criteria analysis, a clear distinction is made between investment costs and management and maintenance costs. One reason for the distinction is the fact that ProRail outsources track maintenance to multiple track contractors (ProRail, 2023). Separating these costs give greater insight in the costs allocated in different phases of the structure.

The lifecycle costing (LCC) gives an overview of the costs involved in different stages of the structure (LCC, see **Figure 78**). This tool emphasizes the importance of distinguishing the costs made during the entire lifetime cycle of the structure. The LCC differentiates roughly three phases: costs made during the design phase, the purchase price and all associated costs during the construction and installation of the structure, and the operating and maintenance costs over the course of the structure's lifetime. The latter is estimated to take up between 50-80% of the total life cycle cost. The costs as a result of the maintainability of the structure are therefore evaluated separately.

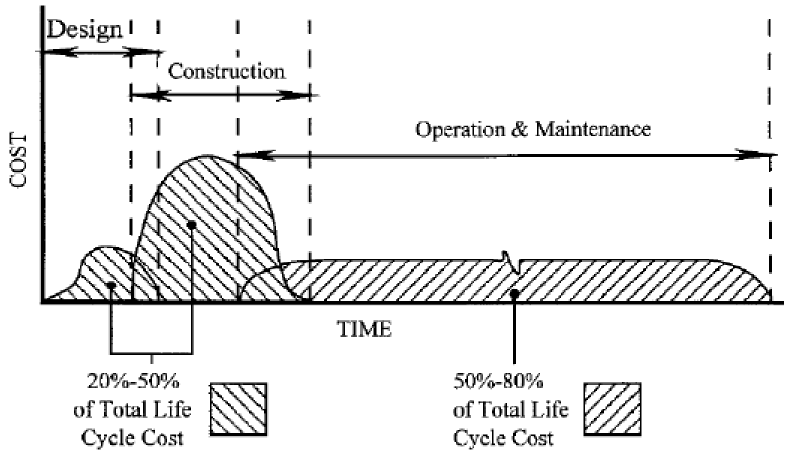


Figure 78 Life Cycle Costing profile (Eric Too et al., 2011)

However, due to limited information regarding the costs related to the required maintenance of the different stabilization methods and embankment, comparison of the estimated maintenance is investigated instead. The periodic maintenance over the predetermined design lifetime is to be evaluated to assess the maintainability of different soil stabilization methods. The evaluation is based on both literature research and expert judgement, see **Chapter 3.6 – Alternative Designs**.

The analysis of the maintainability of each variant is established by drawing up an overview of the required maintenance. Based on expert judgement, the three designs are ranked, preferring little maintenance over frequent periodic maintenance. The investigated characteristic features contribute either negatively (-) or positively (+) to the overall foreseeable maintenance and hence the costs associated. The highest *Maintainability Grade* is awarded to the design that is awarded most positive and is estimated to be low maintenance, provided that the construction is stable meets the design requirements.

- **Degree of maintainability based on literature research and expert judgement;**
- **The low maintenance design is awarded the highest Maintainability Grade;**
- **Maintainability weighting factor is 10% of the MCA.**

Degree of Shutdown

The degree of shutdown criterion holds significant importance when considering methods for railway embankment expansion, measuring the extent of disruption or temporary closure required for construction activities. Two options arise regarding shutdown: total or partial closure of the adjacent railway. While some designs allow for the use of soil retaining structures, enabling adjacent tracks to remain operational during expansion, ProRail, the Dutch railway infrastructure manager, does not support partial shutdown due to safety concerns.

To assess the degree of shutdown, the level of disruption is evaluated, which directly influences the duration of railway line closure and associated inconveniences. The level of disruption directly impacts the project timeline, cost, and overall feasibility. Shutting down train traffic between Zoeterwoude Oost and Alphen aan den Rijn has a major impact on a large group of passengers on the Leiden-Utrecht route. Evaluating construction time and immediate serviceability post-completion aids in determining the optimal method while minimizing disruptions to railway operations.

The degree of shutdown is estimated by the number of days that is required for the construction of the embankment expansion, while requiring the main line to be shut down, and whether or not the design allows to be put into service immediately after completion, see **Table 24**. The degree of required shutdown is evaluated in discussion with geotechnical experts and comparing to similar projects based on literature research.

Table 24 Example Degree of Required Shutdown per Soil Stabilization Method

	Shutdown days	**Immediate serviceability**
Pile Mattress		
Geotextile Encased Columns		
Preloading		

The analysis of the degree of shutdown of each variant is followed by the ranking based on the estimated number of days, with a preference for a small number of required shutdown days and immediate serviceability. The highest *Shutdown Grade* is awarded to the soil stabilization method with the lowest predicted shutdown.

- **Evaluated based on the estimated number of shutdown days;**
- **The degree of shutdown based on expert judgement and literature research;**
- **Variant with the lowest shutdown is awarded the highest Shutdown Grade;**
- **Degree of Shutdown weighting factor is 10% of the MCA.**

4.2.2 Weighting Factors

This research report focuses on the investigation of soil stabilization methods that are both stable and sustainable. The importance of these criteria is reflected in the MCA, as most logical is to count the stability and durability with the highest weighting factor. The other criteria, except for the technology readiness level (TRL) criterion, are equally important. The TRL was found to be more important than risk, cost, maintenance, and shutdown. This criterion, requested by ProRail, gives an indication of the level of predictability and indirectly the associated costs and risks. However, the ratio between the different weighting factors is the same in this trade-off matrix with four criteria being awarded the same weighting factor. By choosing this approach, the choice remains free to the party of interest or stakeholder to decide which criteria they themselves consider more important. The importance of sustainability and stability remains, but room exists for one of the criteria to contribute more to the consideration and analysis of the multicriteria analysis.

Table 25 Weighting Factors per Criterion

CRITERIA AND EVALUATION	WEIGHTING FACTOR
STABILITY • Secondary settlement based on literature research • Factor of safety based on D-Geo Stability calculations	22%
SUSTAINABILITY • Measured based on sustainable Key Performance Indicators • Based on expert judgement	22%
TRL • Measured according to the TRL scale • Based on expert judgement and/or literature research	16%
COSTS • Measured in € per meter construction • Based on expert judgement and rough calculations	10%
RISKS • Based on risk analysis (severity and likelihood) • Based on expert judgement	10%
MAINTENANCE • Measured over the expected lifecycle • Based on expert judgement and literature research	10%
SHUTDOWN • Measured in number of days • Based on expert judgement	10%
TOTAL	**100%**

4.2.3 Scoring and Explanation

In the previous subsections, the three different variants have been described, elaborated, designed, and calculated. To obtain a comparison, the methods are analyzed and ranked based on the multi-criteria analysis. Starting with a brief explanation, the three soil stabilization methods are graded and compared.

Stability

The stability of the railway embankment expansion is evaluated by both the expected secondary settlement as well as the factor of safety of the structure. The first is a result of the constant load applied on the soil resulting in vertical movements of the embankment, and is evaluated based on literature research, see **Chapter 3.6 – Alternative Designs**. The investigation on expected secondary settlement results in the following comparison:

Table 26 Settlement Evaluation

Soil Stabilization Variant	Description
Pile Mattress	The settlement-free system is designed so that virtually no settlement occurs. The piles are capable of bearing the full surcharge and embankment load. However, due to subsidence of the soil, a gap may develop under the mattress (CUR Bouw & Infra, 2007). Often, the gap is applied in advance to allow for the deformation of the geogrid prior to completion of the construction. Deformation as a result of this gap below the geogrid does not result in secondary settlements.
Geotextile Encased Columns	The system not only offers sustainable soil reinforcement and improvement, but also a reduction in construction time through shorter a consolidation period. Due to the full surface draining effect of the geotextile and the filler material, 90 % of the settlements occur during the construction phase. This makes the GEC system a virtually settlement-free method (Huesker, 2021).
Preloading Glass Foam	The construction of the embankment causes horizontal and vertical deformations in the existing embankment. These lead to instability during the construction phase. By applying vertical drains, settlement of the embankment expansion accelerates. In this project, no vertical drainage is present under the adjacent track, which should be considered in the design. Much of the deformations of the existing embankment occur during the construction of the railway embankment extension. Due to the lack of vertical drainage, the existing embankment may consolidate differently than the widening where vertical drains have been applied (Fugro).

Based on the comprehensive comparison conducted, the pile mattress system demonstrates superior performance in limiting settlements. The design characteristics of the pile mattress, such as its ability to distribute loads evenly and provide enhanced support, contribute to its effectiveness in minimizing settlement potential. The geotextile encased columns (GEC) system also shows favorable settlement characteristics, albeit slightly higher than the pile mattress. On the other hand, the preload system exhibits more complexity in terms of estimating secondary settlements. While the system is an effective technique for long-term settlement control, accurately predicting the magnitude and duration of secondary settlements is challenging. This uncertainty leads to a lower score in the settlement limitation category compared to the other two methods. Overall, considering the settlement grade and the associated safety implications, the pile mattress system is deemed the most favorable option, followed by the geotextile encased columns system. The preload method, while still capable of achieving acceptable stability, requires careful consideration and ongoing monitoring to effectively manage settlements.

In addition to assessing the stability of each design, the factor of safety (FS) is determined as a measure of stability. The factor of safety represents the ratio between the capacity (C), which is the resisting force, and the demand (D), which is the disturbing force. A railway embankment is considered stable when the capacity is at least 1.3 times larger than the demand, meaning FS > 1.3 (Budhu, Soil Mechanics and Foundations, 2011). In order to calculate the factor of safety, the variants described in **Chapter 3 – Methodology** are modeled in the geotechnical software D-Geo Stability, using the Bishop's method explained in **Chapter 2.7 – Fundamentals of Slope Stability**. The detailed calculation model and design are discussed in **Chapter 4.1 – Alternative Design Calculations**. While all soil stabilization variants are designed to be sufficiently stable, the actual values of the factor of safety may vary among the different methods. The comparison of the factor of safety calculations for each variant yields the results depicted in **Table 27**.

Table 27 Factor of Safety Evaluation

Soil Stabilization Variant	**Factor of Safety**
Pile Mattress	1,41
Geotextile Encased Columns	1,44
Preloading Glass Foam	1,37

The analyses of the expected settlement and factor of safety result in the scoring of the three soil stabilization methods shown in **Table 28**. For the secondary settlements, the variant with the lowest expected settlements gets 1 point, and the design with the most settlement comes third. The *Settlement Grade* is therefore calculated as the awarded points multiplied by $^1/_3$. The same ranking system applies to the factor of safety, where the highest factor of safety is awarded first place i.e., 1 point. The *Safety Grade* is calculated by multiplying the points by $^2/_3$.

Table 28 Scoring Stability Criterion

	Settlement	Settlement Grade	Safety	Safety Grade	**Stability Grade**
Pile Mattress	1	0,33	2	1,33	**1,67**
Geotextile Encased Columns	2	0,67	1	0,67	**1,33**
Preloading	3	1,00	3	2,00	**3,00**

After considering the settlement grade and safety grade of each variant, their combined evaluation results in the *Stability Grade*. The *Stability Grade* allows for the comparison of the soil stabilization variants based on their overall stability, with a smaller grade indicating a higher level of stability. Based on this evaluation, the geotextile encased columns method achieves the highest *Stability Grade*, followed by the pile mattress method, and finally the preloading method.

Sustainability

The sustainability of each variant is evaluated by means of the Sustainability Evaluation Form, see **Table 29**. The degree of applicability of each sustainability indicator, is graded based on the Indicator Grading Form, see **Figure 79**. Sustainability indicators with a strong negative impact receive a -2, while a +2 is assigned to the indicators with a strong positive sustainable impact as a result of the soil stabilization method. The grading of each sustainability indicator is conducted based on expert judgement as well as literature research, see **Chapter 3.6 – Alternative Designs**. Finally, the highest *Sustainability Grade* indicates the soil stabilization method with the highest estimated sustainability.

Indicator Grading Form

-2 (--)	Highly negative impact
-1 (-)	Small negative impact
0	No (noticeable/measurable) impact
1 (+)	Small positive impact
2 (++)	Large positive impact

Figure 79 Grading of a Sustainability Indicator

The overall sustainability regarding the pile mattress (PM) system is positively influenced by the fact that this traditional method is frequently used on infrastructure projects. Due to the experience of both installing and maintaining the system, the social sustainability dimension is high. The workers are familiar with the different components of the pile mattress system, resulting in the knowledge of operating in safe ways. In a similar way, the economic sustainability dimension benefits from the knowledge gained from similar projects. This allows costs to be determined in advance with high accuracy.

The sustainability of the geotextile encased column (GEC) system is influenced by its reliance on specialized companies. The method has had very limited application in similar projects, leaving much to be gained in terms of sustainability of the production and installation process. However, because the GEC system is only installed and designed by specialized construction firms, results-oriented advice ensures safety and social sustainability of the workers and its environment, contributing to the economic sustainability dimension. In addition, the system preserves the integrity of the soil's properties, upholding the ecosystem in and around the embankment expansion.

The sustainability of the preloading method depends on the materials used, and the degree of reusability of the materials used in different phases. The lightweight glass foam is an innovative material that offers many advantages, both in terms of environmental and economic sustainability. The glass foam is a highly sustainable and circular aggregate which is made from foamed recycled glass, giving the glass waste a new purpose. The economic sustainability is influenced by the limited maintenance required and the high durability of the materials of the stabilization system.

Table 29 Scoring Sustainability Criterion

Dimension	Indicator	PM	GEC	Preload
Environmental	1. Biodiversity preservation	0	0	+
	2. Preservation of historical and archaeological sites	--	-	+
	3. Soil conservation	-	++	-
	4. Water preservation	+	+	+
	5. Air pollution	0	+	+
	6. CO2 emission	-	-	-
	7. Greenhouse gas emissions	-	-	-
	8. Long-term ground/soil contamination	+	++	++
	9. Long-term water pollution	0	+	+
	10. Noise pollution	-	-	+
	11. Impact on the natural environment	0	0	0
	12. Climate change risks and resilience	+	+	-
	13. Risk of landslides, erosion, and sedimentation	++	+	-
	14. Drainage systems	0	++	+
	15. Soil restoration	0	+	-
Economic	16. Ecosystem rehabilitation	0	0	0
	17. Durability of structures	++	++	+
	18. Economic benefits	+	+	+
Social	19. Public health and safety	+	+	+
	20. Worker health and safety	++	++	+
	21. Social and cultural impact due to the project	0	0	0
	Sustainability Grade	**+5**	**+14**	**+7**

The degree of sustainability of each soil stabilization variant is assessed based on multiple criteria using a five-level grading form, considering the level of applicability. The *Sustainability Grade* is obtained by summing up the grades for each criterion, reflecting the overall sustainability of each variant. According to the assessment, the geotextile encased columns receive the highest grade, indicating the highest level of overall sustainability among the designs. The preloading method follows closely behind in terms of sustainability, while the pile mattress system ranks third in the assessment.

Technology Readiness Level

The Technology Readiness Level (TRL) serves as a valuable tool to assess the technical maturity of a technological method during the procurement phase. With nine distinct levels, ranging from low to high, the TRL provides insights into the readiness of a method for practical implementation. In the context of railway embankment stabilization, where significant costs and risks are involved, methods with a higher TRL are preferred. To evaluate the TRL of each method, the description of the different levels, as illustrated in **Figure 80**, is utilized, enabling a comprehensive understanding of their respective technological readiness.

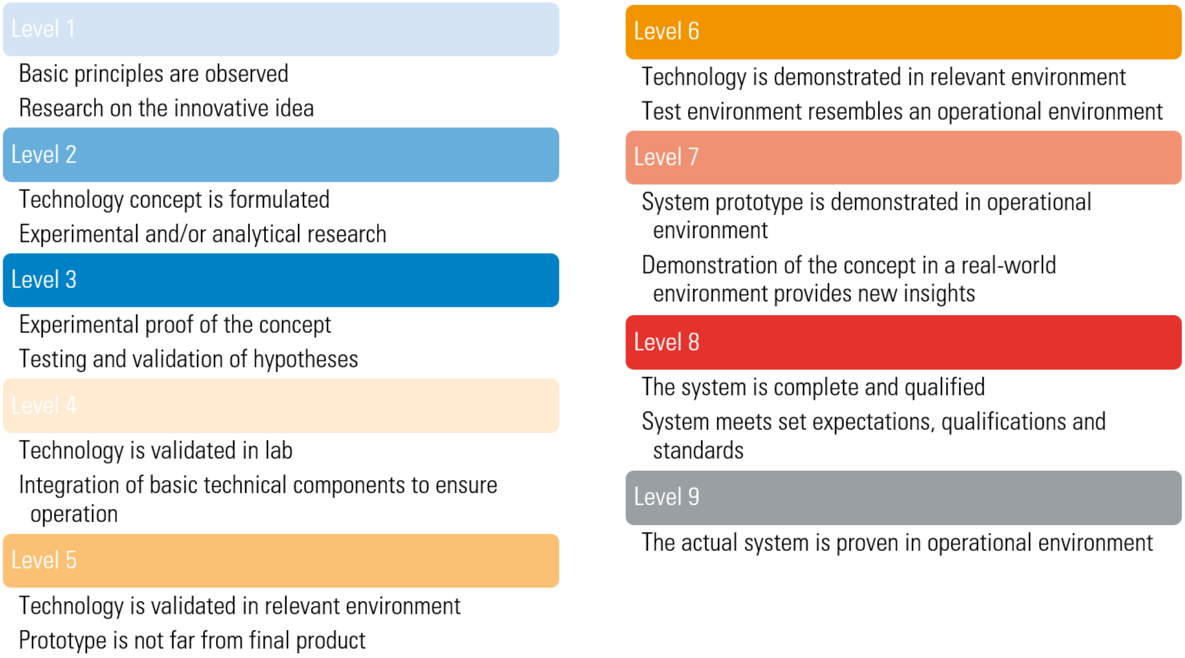


Figure 80 Nine Levels of Technology Readiness based on (TWI, 2023)

The TRL scale serves as a valuable framework for assessing the maturity of soil stabilization methods, offering insights into their potential for improvement and subsequent reductions in costs and risks. By considering reference projects and conducting thorough literature research, the maturity of each variant is thoroughly investigated in **Chapter 3.6 – Alternative Designs**. This comprehensive analysis considers not only the expected costs and risks but also factors such as technological advancements, innovation potential, and the availability of supporting evidence from previous projects. By utilizing the TRL scale, a broader and more nuanced understanding of each soil stabilization method is achieved, enabling informed decision-making, and identifying areas for further development and optimization.

Table 30 Scoring Technology Readiness Level Criterion

Soil Stabilization Variant	**Explanation and TRL-Scale**
Pile Mattress	The Technology Readiness Level of the pile mattress system as stabilization method for railway embankments in the Netherlands is influenced by the regular and successful implementation in road construction on similar subsoils on one hand, and the limited knowledge of the system and its materials in railway embankments on the other hand. Therefore, the maturity of pile mattresses in railway embankments is **graded a Technology Readiness Level 8**, indicating that the system is complete and qualified through a few pilot projects, and meets set expectations, qualifications, and standards.
Geotextile Encased Columns	The Technology Readiness Level of the geotextile encased column system as stabilization method for railway embankments in the Netherlands is influenced by the limited but successful implementation in construction on similar subsoils on one hand, and the limited knowledge of the system and its materials in railway embankments on the other hand. The technology is demonstrated in a relevant environment and comparable subsoils, indicating a technology readiness level 6. Through increasing implementation of GEC systems in a variety of projects, new insights are gained, indicating level 7 on the TRL scale. However, due to very limited implementation of the method in railway embankments, the maturity of the geotextile encased columns is **graded a Technology Readiness Level 6**, indicating that pilot projects in comparable operational environments is required to ensure the system meets the set expectations in the stabilization of a railway embankment.
Preloading	The preloading method combined with the glass foam lightweight fill material is successfully demonstrated in an operation environment and provided new insights into the performance over the course of time. However, the particular system has not yet been implemented for the construction of a railway embankment. Therefore, pilot projects are valuable to better understand the influence of large dynamic loads on the preloaded embankment. For this reason, the maturity of the system is on **level 7 of the Technology Readiness Level**, indicating that the method has proven to work in relevant and comparable environments, but has not yet been implemented in the stabilization for a railway embankment.

The analysis of the Technology Readiness Level results in the ranking of the methods based on the maturity of the system as soil improvement for a railway embankment expansion. The highest *TRL-Scale* indicates the variant with the highest likelihood of implementation and thus is graded the highest compared to other variants. Therefore, the pile mattress is considered the most mature system, followed by the method of preloading and lastly the geotextile encased columns.

Cost

The cost analysis aims to evaluate the different methods in comparable levels of detail. The investment in the embankment extension may not be directly visible, but accounts for the success, safety, and longevity of the development around the new Hazerswoude-Rijndijk station. The costs per variant is estimated based on the expected required materials and services. The price per unit is determined based on expert judgement and literature research, see **Chapter 3.6 – Alternative Designs**.

The indicative costs for the materials and construction of the pile mattress system are based on a comparable variant study (Boekhorst, 2007) and the estimated construction costs according to an experienced engineering firm (Fugro). Costs for excavating the peat and costs for compacting the sand and granulate package are not included in the cost estimate. In addition, monitoring costs and costs related to land acquisition and site preparation are not considered in the cost estimate.

Table 31 Cost Evaluation Pile Mattress

Material	Length (m)	Width (m)	Height (m)	Volume (m3)	Number of Units	Price per Unit	Costs
Purchase Materials							
Concrete Piles			10,3		22	€ 17,50	€ 3.965,50
Geogrids	1	24				€ 8,00	€ 192,00
Sand Body				23		€ 10,00	€ 230,00
Installation Costs							
Concrete Piles			10,3		22	€ 30,00	€ 6.798,00
Transport Sand				23		€ 7,00	€ 161,00
Estimated Costs per meter Pile Mattress Construction							€ 11.346,50

The indicative costs for the materials and construction of the geotextile encased column system are based on the estimated construction costs according to an experienced engineering firm (Fugro). The price estimate does not include the costs related to facilities to make the site accessible. In addition, the installation costs of the columns and geogrids are included in the acquisition price. To date, outside specialized contractors conducted the installation of the system, as limited experience with GEC systems is available in the Netherlands. For this reason, the price of the geotextile encased column system includes both delivery and installation of the pile system by a specialized company.

Table 32 Cost Evaluation Geotextile Encased Columns

Material	Length (m)	Width (m)	Height (m)	Volume (m3)	Number of Units	Price per Unit	Costs
Purchase Materials							
GEColumn			10,3		7	€ 12,00	€ 865,20
Geogrids	1	22				€ 4,50	€ 99,00
Sand Body				23		€ 10,00	€ 230,00
Installation Costs							
Transport Sand				23		€ 7,00	€ 161,00
Estimated Costs per meter GEC Construction							€ 1.355,20

The indicative costs for the materials and construction of the preloading system are based on the estimated construction costs according to an experienced engineering firm (Fugro). The excavation of sand is usually done in a cost-neutral manner. The cost of water control, including measures to drain the water released from the drains, is not included in the cost estimate.

Table 33 Cost Evaluation Preloading Method

Material	Length (m)	Width (m)	Height (m)	Volume (m3)	Number of Units	Price per Unit	Costs
Purchase Materials							
Vertical Drains					50	€ 0,65	€ 32,50
Glass Foam	1	16	0,9			€ 135,00	€ 1.944,00
Sand Body				8,6		€ 10,00	€ 86,00
Sand Preload				23		€ 10,00	€ 230,00
Geotextile	1	23				€ 20,00	€ 460,00
Installation Costs							
Transport Sand				(8,6+23)		€ 7,00	€ 221,20
Removal Preload				23		€ 4,00	€ 92,00
Estimated Costs per meter Preloading Construction							€ 2.973,70

The cost estimation per meter width of the soil improvement methods for the railway embankment expansion plays a crucial role in determining their economic viability. The analysis reveals the relative cost effectiveness of each variant, with the lowest estimated costs indicating the most economically favorable option. Based on this assessment, the geotextile encased columns emerge as the most cost-effective method, offering potential cost savings in comparison to the other alternatives. The preloading method follows closely behind in terms of economic feasibility, while the pile mattress ranks as the least cost-effective option. These findings provide valuable insights for decision-making, allowing for the selection of a soil stabilization method that not only meets the technical requirements but also optimizes cost efficiency for the railway embankment expansion project.

Risks

The evaluation of risks associated with the railway embankment expansion project takes into consideration both the severity of potential harm and the likelihood of occurrence. This criterion assesses the magnitude of controlled and uncontrolled risks that may arise during the construction and maintenance phases of the structure. To identify and evaluate these risks, a comprehensive overview is compiled based on a combination of literature research and expert judgment, as detailed in **Chapter 3.6 - Alternative Designs**. Each risk is carefully analyzed and assigned a grade based on the severity of potential harm, with the highest-risk scenario receiving the lowest numerical grade. The risks drawn up and graded based on the severity of harm are depicted in **Table 34.** This systematic approach enables a thorough understanding of the risks associated with each soil stabilization method, aiding in the selection of the safest option for the railway embankment expansion project.

Table 34 Risk Evaluation

Risk Number	Description	Severity of harm
1	Damage to the design of the system, caused by uncertain transfer of loads or insufficient bearing capacity of the soil stabilization method. The result is impermissible settlements, causing overall instability or even failure of the system in its function.	1
2	Insufficient knowledge to predict and simulate in advance the deformation of the adjacent embankment. A risk related to the adjacent track is the vibrations created during the construction phase. This may increase the instability of the single track to such an extent that the track may (temporarily) not be used and may require measurements to restore the embankment's stability.	2

3	Lack of experience with the construction method due to unfamiliarity with the systems for railway embankments is a risk that may mainly entail additional costs.	3
4	Discrepancy between the model and reality is a risk that affects the integrity of the design. The model, which considers only two dimensions, is a simplified version of reality. The model does not encompass the complex components and interactions between the different components.	6
5	Uncertainty of the properties of the weak soil layers in terms of compression characteristics, permeability, strength, and stiffness. Further soil investigation is required to limit this risk of uncertainty (Fugro).	5
6	Embankment prone to fluctuations such as a changed groundwater level and surcharge load, that negatively affect the stability of the embankment.	4

After assessing the risks associated with the stabilization of soft soils and the railway embankment expansion, the next step is to evaluate the likelihood of occurrence for each variant. The likelihood of occurrence is estimated through expert judgment, allowing the risks to be ranked in order of frequency, with the most common risk assigned a score of 1 point, as presented in **Table 35**. This systematic approach enables a comprehensive understanding of the potential risks and their likelihood of occurrence for each soil stabilization method. By considering both the severity of harm and the likelihood of occurrence, stakeholders are able to make informed decisions and prioritize risk management strategies during the implementation of the railway embankment expansion project.

Table 35 Scoring Risk Criterion

	Risk Number	**Risk Assessment**			**Final Score**	**Risk Grade**
		Severity	**Likelihood**	**Product Value**		
Pile Mattress	1	1	1	1		
	2	2	2	4		
	3	3	3	9	**38**	3
	4	6	4	24		
GEC	2	2	1	2		
	5	5	3	15	**47**	1
	3	3	2	6		
	4	6	4	24		
Preloading	6	4	1	4		
	5	5	2	10		
	2	2	3	6		
	4	6	4	24	**44**	2

To obtain representative and distinctive values of the risk assessment, the *Product Value* is established by multiplying the severity by the likelihood. The *Final Score* is the sum of all Product Values, and thus the expected risks of a soil stabilization method. The smallest *Final Score* indicates the variant with the highest likelihood and severity of risks and thus is graded the lowest compared to other variants. Therefore, the geotextile encased columns are considered to be the least high-risk method, followed by preloading and lastly the pile mattress.

Maintainability

The periodic maintenance over the predetermined design lifetime of each design is evaluated to assess the maintainability of different soil stabilization methods. The evaluation is based on both literature research and expert judgement, see **Chapter 3.6 – Alternative Designs**.

The analysis of the maintainability of each variant is established by an overview of the required maintenance, see **Table 36**. Based on expert judgement, the three designs are ranked, preferring little maintenance over frequent periodic maintenance. The investigated characteristic features contribute either negatively (-) or positively (+) to the overall foreseeable maintenance and hence the costs associated.

Table 36 Scoring Maintainability Criterion

	Required Maintenance	Scoring	Grade
Pile Mattress	Piles characterized by unlimited lifespan	+	
	Transition structures require frequent monitoring and maintenance accordingly	-	+
	Fortrac geogrid proven lifespan up to 80 years	+	
GEC	Ringtrac characterized by unlimited lifespan	+	++
	Stabilenka geogrid proven resistance up to 120 years	+	
Preloading	Glass foam characterized by unlimited lifespan without maintenance	+	0
	Embankment requires frequent monitoring and maintenance in case of deformations	-	

Based on the evaluation of maintainability, the design that requires the least amount of maintenance is awarded the highest *Maintainability Grade*. In this case, the geotextile encased columns receive the highest grade, indicating that they are estimated to be low maintenance when the construction is stable and meets the design requirements. The pile mattress system is ranked second in terms of maintainability, followed by the method of preloading, which is projected to require a relatively higher level of maintenance. By considering the maintainability aspect, stakeholders assess the long-term costs and efforts associated with the maintenance of each soil stabilization method for the railway embankment expansion.

Degree of Shutdown

To assess the degree of shutdown, the level of disruption is evaluated, which directly influences the duration of railway line closure and associated inconveniences. The level of disruption directly impacts the project timeline, cost, and overall feasibility. The degree of shutdown is estimated by the number of days that is required for the construction of the embankment expansion, while requiring the main line to be shut down, and whether or not the design allows to be put into service immediately after completion, see **Table 37**. The degree of required shutdown is evaluated in discussion with geotechnical experts and comparing to similar projects based on literature research.

The evaluation of the degree of shutdown for the pile mattress variant is based on similar projects and literature studies, indicating the degree of expected downtime. Since the pile mattress system relies on transferring the loads of the embankment directly to the loadbearing layers in the subsoil, the embankment is commissioned immediately, and residual settlements are negligible. The time required to complete the railway embankment widening using the pile mattress method has been estimated at 30 days (Unidek Group B.V., 2005).

The geotextile encased columns method relies on transferring the loads of the embankment directly to the loadbearing layers in the subsoil. Therefore, the embankment is commissioned immediately, and residual settlements are small. The time required to complete the railway embankment widening using the GEC method has been estimated at 60 days (Unidek Group B.V., 2005).

Since the method of preloading relies on temporarily increasing the loads on the subsoil, a considerable amount of time is required before the embankment is actually built. The pre-loading phase takes place along the entire length of the embankment simultaneously, as a result, the embankment extension cannot be worked on in stages. However, after the pre-loading period, the embankment is commissioned immediately, and residual settlements are virtually negligible. The time required to complete the railway embankment widening has been estimated at 250 days (Unidek Group B.V., 2005).

Table 37 Scoring Degree of Shutdown Criterion

	Shutdown days	Immediate serviceability
Pile Mattress	30	+
Geotextile Encased Columns	60	+
Preloading	250	+

Based on the analysis of the expected shutdown per variant, the designs are to be ranked, with a preference for a small number of required shutdown days and immediate serviceability. The evaluation shows that all three variants allow immediate commissioning. However, the time required to complete construction varies. Based on the preference for rapid implementation and thus minimal disruption to the surroundings, the pile mattress is considered the most advantageous design, followed by the geotextile encased columns and lastly the method of preloading.

4.3 Preferred Design

The selection of the preferred variant among the three designs (pile mattress, geotextile encased columns, and preloading) is based on their evaluation across seven criteria: stability, sustainability, technology readiness level (TRL), costs, risks, maintenance, and shutdown, see **Chapter 4.2 – Multi-Criteria Analysis**. A summary of the rankings for each design per criterion provides insights into their comparative performance.

In terms of stability, the geotextile encased columns (GEC) demonstrate the highest ranking, followed by the pile mattress, with the method of preloading ranked last. The GEC method proves to be particularly effective in providing stability by combining effective transfer of loads to the load bearing layers with the drainage characteristics of the encased columns. Similarly, in terms of sustainability, the GEC secures the top position, while preloading is ranked second as a result of both their use of local and recycled materials.

When considering the technology readiness level, the conventional pile mattress method receives the highest ranking, as the technique is widely used in the Netherlands for various infrastructural projects, including railway embankment stabilization. Preloading follows in terms of TRL, as the method is commonly employed in other infrastructural projects. In terms of costs, the geotextile encased columns take the first place, excluding the outsourced specialists involved in cost estimation. The preloading method is next, involving a relatively simple execution process and material usage but requires a significant amount of time. The pile mattress is ranked as the least cost-effective option; however, its proven track record and reference projects make the costs more predictable based on past experiences.

Considering the risks involved, the geotextile encased columns exhibit minor risks with lower severity, followed by the method of preloading. In terms of maintenance requirements, the GEC method requires the least amount of maintenance as a result of the system's long lifespan, closely followed by the pile mattress, while the method of preloading necessitates frequent monitoring and maintenance accordingly. In terms of the degree of shutdown required for implementation, the pile mattress is installed within a relatively short period. The geotextile encased columns require more time for installation, and the preloading method takes the longest to complete due to the nature of the preloading process.

The multi-criteria analysis (MCA) concludes by combining the ranking of the variants per criterion and weighing each factor according to its degree of importance. **Chapter 4.2.2 – Weighting Factors** describes the allocation of appropriate weighting factors to each criterion. In this research report, particular emphasis is placed on stability and sustainability of the design, which both account for 22% of the total MCA. Another significant factor is the technology readiness level, which holds a weightage of 16%. Additionally, criteria such as costs, risks, maintenance, and shutdown are considered, with each contributing 10% to the multi-criteria analysis. By placing the rankings of the three different designs into the matrix, a comprehensive evaluation is achieved that determines the winning design based on a rigorous and systematic assessment of multiple factors, see **Table 38**.

Table 38 Multi-Criteria Analysis

Criterion		**Pile Mattress**	**Geotextile Encased Columns**	**Preloading**
Stability	ranking	2	1	3
	22%	**0,44**	**0,22**	**0,66**
Sustainability	ranking	3	1	2
	22%	**0,66**	**0,22**	**0,44**
TRL	ranking	1	3	2
	16%	**0,16**	**0,48**	**0,32**
Costs	ranking	3	1	2
	10%	**0,3**	**0,1**	**0,2**
Risks	ranking	3	1	2
	10%	**0,3**	**0,1**	**0,2**
Maintenance	ranking	2	1	3
	10%	**0,2**	**0,1**	**0,3**
Shutdown	ranking	1	2	3
	10%	**0,1**	**0,2**	**0,3**
Final Grade		**2,16**	**1,42**	**2,42**

Based on the comprehensive evaluation of the rankings across all criteria, the geotextile encased columns emerge as the preferred variant for the design of the railway embankment expansion. The GEC method exhibits favorable rankings in terms of stability, sustainability, technology readiness, costs, risks, maintenance, and shutdown. Its combination of stability, cost-effectiveness, low maintenance requirements, and manageable risks results in the optimal choice for ensuring a stable and sustainable foundation for the railway embankment.

CONCLUSION

The conclusion chapter serves as the culmination of the research conducted in this study, building upon the results presented in Chapter 4 – Results. In this chapter, the evaluations and multi-criteria analysis (MCA) are carefully examined to draw meaningful conclusions regarding the optimal soil stabilization method for the railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk. The sub-research questions posed throughout the study are addressed, providing insights into the various aspects of each soil stabilization variant. Ultimately, the main research question is answered, revealing the most suitable method that ensures both stability and sustainability for the design of the railway embankment.

5

This thesis report has successfully addressed the main research question, which aimed to determine the most suitable soil stabilization method for ensuring a stable and sustainable foundation for the design of the railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk. The comprehensive research conducted in this study has been guided by the sub research questions, which provided a structured approach to gathering relevant information and analyzing key factors. The sub research questions as stated in **Chapter 1.5 – Research Question**, have been elaborated upon in the subsequent sections.

- **What is the current (geotechnical) state of the train track between Zoeterwoude East and Hazerswoude-Rijndijk?**

The current geotechnical state of the train track between Zoeterwoude East and Hazerswoude-Rijndijk is explored through an analysis of historical records and recent measurements, see **Chapter 2.1 – Current Situation**. The track was originally constructed in the late 19th century, with limited documentation on its construction process. The archival drawings suggest that the track was built on a sand body without extensive measures for foundation stability. Over time, the track has experienced subsidence and settlements, leading to changes in the embankment geometry. The exact condition and thickness of the sand layer beneath the track are unknown, and assumptions have been made in previous studies. Recent elevation measurements and cross-section profiles indicate variations in settlement along the track. The irregular slopes and lack of information about the sand layer highlight the need for further investigation into the current state of the track and its geotechnical stability.

- **What is the desired situation for the expansion of the train track?**

The desired situation for the expansion of the train track includes the realization of a new halt on the north side of the track, which may be expanded in the future to accommodate a double track and a grade-separated transfer opportunity. The halt is to be located at the level of the current Gemeneweg, requiring a diversion of the road. The primary station functions are to be developed on the north side of the tracks, connected to the developments around Westvaart Park. The success of the desired situation depends on either a railway curve widening in Alphen aan den Rijn or an extension of the double track from Zoeterwoude-Oost. The double track should be constructed as close as possible to the existing track to minimize land acquisition and costs. The preferred location for the second track is on the north side, supported by existing double tracked overhead lines. The desired solution is illustrated in **Chapter 2.2 – Desired Situation**, with specific measurements and details provided in the cross-sections.

- **Who are the stakeholders and what are their desires regarding the expansion of the track?**

The stakeholders involved in the track expansion project include LOCOV (consumer organization), municipalities (Leiden, Zoeterwoude, Alphen aan den Rijn, Woerden and Utrecht), NS (passenger carrier) and NS Stations, rail contractors, Ministry of Infrastructure and Water Management, Province of South-Holland, and Utrecht, ProRail (main rail operator), citizens, train passengers and the ILT (Human Environment and Transport Inspectorate). Each stakeholder has specific desires and interests, ranging from improved rail transport and infrastructure to safety and reliable services, **see Chapter 2.3 – Stakeholder Analysis**. They are categorized into "Keep Satisfied," "Manage Closely," "Monitor," and "Keep Informed" groups, with strategies tailored to their power and interest levels.

- **What subsoils are found along the train track?**

The subsoils found along the train track consist of various soil types, including clay, peat, sand, and medium clay. The specific composition of the subsoils was analysed through cone penetration tests (CPT) conducted closely along the railway embankment, see **Chapter 2.5 – Design Criteria**. The CPT data provided information on the cone resistance (qc) and friction number (Rf), which were used to classify the soils according to their characteristic properties. The soil layers were characterized based on their unit weight, cone resistance, angle of internal friction, and cohesion. The subsoil composition assumed for the railway embankment consists of soft clays, peats, medium clays, and loose and dense sands. The subsoil composition along the track may vary, but for the purpose of the study, a uniform composition is assumed. In addition, the geotechnical parameters and soil properties obtained from the CPTs, and classification are based on standard values, which may differ from the actual conditions due to factors such as stress level, dynamic loads, and construction activities.

- **What methods are proposed to stabilize the subsoil at Hazerswoude-Rijndijk?**

Various methods are to be employed to stabilize the subsoil at Hazerswoude-Rijndijk. These methods include pile mattress construction, cunet excavation and replacement, deep soil mixing with cement, preloading combined with lightweight filling material, the IFCO method, geotextile encased columns, and gravel columns. Each method offers its own advantages and has been successfully applied in similar projects or environments, see **Chapter 3.2 – Overview of Soil Stabilization Techniques**. Pile mattress construction involves creating a settlement-free platform supported by piles, while cunet excavation replaces weak subsoil with compacted sand. Deep soil mixing with cement improves soil strength and stiffness, while preloading with lightweight filling material reduces settlement. The IFCO method allows controlled consolidation by lowering groundwater levels, and geotextile encased columns provide support and drainage. Lastly, gravel columns densify the subsoil through vibro replacement. These methods offer potential solutions for stabilizing the subsoil at Hazerswoude-Rijndijk.

- **What methods are promising and worthwhile to simulate and evaluate the soil stabilization?**

To simulate and evaluate the soil stabilization methods at Hazerswoude-Rijndijk, a selection of promising techniques was made based on expert judgment and experience. Through interviews and brainstorming sessions with geotechnical experts, the suitability of each method was ranked using a rudimentary multi-criteria analysis, see **Chapter 3.3 – Selection of Soil Stabilization Techniques**. The criteria included factors such as stability, sustainability, technology readiness level, costs, risks, maintainability, and shutdown. Based on these evaluations, the pile mattress, geotextile encased columns, and preloading combined with glass foam were identified as the three most promising methods for further analysis. These methods are thoroughly examined and compared using both qualitative and quantitative assessments to determine the best option for the project's overall stability and sustainability.

- **What software is proposed to measure geotechnical stability?**

To measure geotechnical stability, the software called D-Geo-Stability is utilized. This software, developed by Deltares, is specifically designed for slope stability analysis in soft soil engineering. The software allows for the modelling of soil layers with different properties and includes options for defining loads, porewater pressures, and surcharges, see **Chapter 3.5 – Geotechnical Software D-Geo Stability**. The software employs the Bishop method for limit equilibrium analysis, determining the safety factor along a slip plane and providing results in tabular and graphical forms, presenting calculated slip surfaces.

- **What recommendations are to be made based on the obtained results?**

Based on the obtained results, the recommendation that are to be made is to adopt the geotextile encased columns (GEC) as the preferred soil stabilization method for the railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk. The extensive Multi-Criteria Analysis (MCA) demonstrated that the GEC system outperformed the other variants in terms of stability, sustainability, technology readiness level, costs, risks, maintenance, and shutdown, see **Chapter 4.3 – Preferred Design**. The GEC method showcased high stability and sustainability, effectively distributing loads, and minimizing environmental impact. Although the method has a relatively lower Technology Readiness Level locally, the GEC system's success in similar applications and its cost-effectiveness in the long run make the technique a worthwhile approach to consider and implement for this project. The analysis also highlighted its lower risks and the reduced need for maintenance, further supporting the recommendation for the geotextile encased columns as the most suitable soil stabilization method for the railway embankment expansion.

In conclusion, this thesis report has provided a clear and definitive answer to the main research question:

What soil stabilization method is best implemented to ensure a stable and sustainable foundation for the design of the railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk?

The extensive analysis and evaluation conducted throughout the study have demonstrated that the geotextile encased columns offer the most suitable solution for achieving a stable and sustainable foundation. By selecting the geotextile encased columns as the preferred soil stabilization method, this research report provides practical and actionable recommendations for the successful implementation of the railway embankment expansion project. The geotextile encased columns excel in terms of stability, sustainability, cost-effectiveness, and risk reduction, making them the optimal choice for ensuring the long-term integrity and functionality of the railway infrastructure.

DISCUSSION

The Discussion chapter critically examines the research findings and delves into the limitations encountered throughout the study. These limitations encompass various aspects, including design constraints, parameters considered (such as peat oxidation), limited information and data availability, as well as the utilization of basic software. By addressing these limitations, the chapter aims to provide a comprehensive understanding of the boundaries and constraints within which the research was conducted. Additionally, the chapter explores the validity of the research, assessing the reliability and credibility of the findings, and considering the implications of any potential biases or shortcomings. Through this reflective analysis, the Discussion chapter contributes to a nuanced and well-rounded interpretation of the study's outcomes and provides valuable insights for future research and application.

6

The discussion chapter presents an analysis and interpretation of the results obtained from the evaluation of different soil stabilization methods for the railway embankment extension project. The findings shed light on the performance of various techniques and provide valuable insights, despite the limitations of the research. In terms of expectations, initially anticipated was that the Pile Mattress (PM) variant, being a widely used method, would score high across all criteria. However, advancements in the geotechnical field have led to the emergence of improved techniques. This prompted an investigation into the relatively new Geotextile Encased Columns (GEC) system and its potential worthiness in railway embankment stabilization. The results not only offer a comparative assessment between PM and GEC but also highlight the overall advancements and innovations in the geotechnical field. These new insights contribute to a better understanding of the most suitable soil stabilization method for the project, considering factors such as stability, sustainability, technology readiness level, cost, risks, maintenance, and shutdown. Despite the research's imperfections and limitations, the gained insights hold significant value for informing decision-making processes in similar projects.

6.1 Limitation of the Research

The research conducted in this study is subject to certain limitations, which should be acknowledged to provide a comprehensive understanding of the research scope and potential areas for improvement. These limitations include:

1. Assumptions in design: The research made certain assumptions that may have influenced the findings. Firstly, the assumption is made that there would be no change in rolling stock, and as a result, the calculations did not consider any potential impacts that changes in rolling stock characteristics may have on the stability of the embankment. Similarly, the assumption of no change in speed posed limitations, as the software program used, D-Geo Stability, does not directly consider speed in its calculations. Therefore, the potential effects of speed variations on embankment stability remain to be examined, highlighting a limitation in the research.
2. Subsidence from peat oxidation: One key factor not included in the stability evaluation was the potential subsidence resulting from peat oxidation. Peat oxidation significantly impacts the stability of the embankment over time. However, this aspect was not considered in the research, indicating a limitation in the evaluation of long-term stability.
3. Limited information on the current single track: The availability of information regarding the current single track was limited, which led to the formulation of assumptions about the embankment foundations. These assumptions served as starting points for the selection and design of different soil stabilization methods. However, the reliance on assumptions due to limited data introduces a level of uncertainty to the findings.
4. Evaluation based on limited available data: The evaluation of the three soil stabilization methods was based on the limited data available online. The lack of comprehensive and detailed information may have affected the accuracy and reliability of the evaluation. A more extensive and thorough data collection process would have provided a more robust foundation for the evaluation.
5. Limitation of knowledge and software: The research faced limitations due to the researcher's limited knowledge, time constraints, and the need to learn a new software program within a limited timeframe. While the chosen software, D-Geo Stability, was suitable for the research objectives, the software may not offer the same level of sophistication and insight into soil behaviour as more advanced software. One of the limitations of the software includes assuming a predominantly horizontal orientation of slip surfaces and considering two-dimensional plane-strain conditions. Additionally, the critical train speed, although relevant to the embankment, was not included in the analysis due to software limitations. Utilizing a more

sophisticated software program could provide a deeper understanding of soil behaviour but would require additional expertise, time, and resources.

The identified limitations may have some impact on the research results. The specific geographical focus may limit the generalizability of the findings to other regions. The reliance on data and assumptions may introduce uncertainties that could affect the accuracy of the evaluation. The subjectivity in evaluating sustainability factors may influence the relative importance and ranking of different criteria in the multi-criteria analysis. Recognizing these limitations is important as they provide avenues for future research and improvement. Overcoming these limitations enhances the accuracy, reliability, and comprehensiveness of future studies in this field.

Based on the limitations and further areas of exploration, several recommendations for follow-up research are to be made, see **Chapter 7 - Recommendations**. These include conducting field studies and experiments to validate the performance of geotextile encased columns in the local context and assessing the long-term durability and maintenance requirements of the selected method.

6.2 Validity of the Research

The validity of this research study should be considered in light of several factors. Firstly, the research methodology employed a systematic approach, including extensive Multi-Criteria Analysis (MCA) to evaluate and compare different soil stabilization methods. The MCA process involved the consideration of various criteria, such as stability, sustainability, technology readiness level, costs, risks, maintenance, and shutdown. This systematic and structured methodology enhances the validity of the research findings, as the approach ensures a comprehensive evaluation of the alternatives.

Moreover, the research made use of available data and information to support the analysis and decision-making process. Although there were limitations regarding the limited information available online and the assumptions made, the research took a rigorous approach by acknowledging these limitations and discussing their potential impact on the findings. By transparently addressing these limitations, the study demonstrates a commitment to maintaining the validity of the research and providing a balanced and informed analysis.

Additionally, the selection of the geotextile encased columns as the preferred variant based on the MCA results contributes to the validity of the research. The MCA is a widely recognized and accepted method for decision-making, providing a robust framework for evaluating and comparing multiple alternatives. By following this established methodology and considering multiple criteria, the research findings are strengthened and are seen as valid and reliable.

However, noting that the validity of the research is also influenced by the availability and accuracy of the data used in the analysis, is of importance. While efforts were made to gather relevant information, the reliance on limited online data introduces a potential source of uncertainty. Future studies could benefit from accessing more comprehensive and reliable data sources to further enhance the validity of the research findings.

Follow-up research greatly influences the validation of the results obtained in this study. Field studies and experiments would provide empirical data to validate the performance and effectiveness of the geotextile encased columns in the specific project area. This would help confirm the reliability of the current findings and provide additional evidence for their implementation. The prioritization of future research should focus on addressing the identified limitations, further exploring the sustainability aspects, and evaluating the long-term performance of the selected soil stabilization method.

Overall, considering the systematic approach, transparency in addressing limitations, and adherence to recognized decision-making methodologies, this research is deemed valid. However, continuous efforts to improve data collection, explore alternative methods, and validate the findings through field observations or further investigations would contribute to strengthening the validity and reliability of the research outcomes.

RECOMMENDATIONS

The final chapter of this research study presents valuable recommendations based on the comprehensive analysis and evaluation conducted throughout the study. These recommendations are aimed at guiding decision-makers and stakeholders involved in the design and implementation of the railway embankment expansion between Zoeterwoude East and Hazerswoude-Rijndijk. Drawing upon the conclusions and findings from previous chapters, this chapter provides practical and actionable recommendations that address the main research question: What soil stabilization method is best implemented to ensure a stable and sustainable foundation for the design of the railway embankment expansion? The recommendations encompass various aspects, including design considerations, risk management strategies, cost-effectiveness, and sustainability measures. By following these recommendations, project stakeholders make informed decisions and implement the most suitable soil stabilization method, ultimately ensuring a successful and enduring railway infrastructure project.

7

Based on the findings and limitations of this study, several recommendations are to be made for future research in the field of soil stabilization for railway embankments. Firstly, conducting a comprehensive field study is recommended to collect more accurate and detailed data about the current single track and embankment foundations. This would provide a solid foundation for subsequent research and reduce the reliance on assumptions. Additionally, future studies should consider incorporating the effects of rolling stock characteristics and train speed into stability evaluations. This could be achieved by either utilizing more advanced software programs capable of simulating dynamic loading conditions or conducting physical testing to assess the impact of these variables on embankment stability.

To further enhance the understanding of soil stabilization for railway embankments, the recommendation is made to explore the long-term performance and durability of the chosen stabilization method, specifically the geotextile encased columns. Conducting field monitoring and assessments of existing geotextile encased column installations in similar geotechnical conditions would provide valuable data on their performance over time. This information could help validate the findings of this study and provide insights into the effectiveness and longevity of the chosen method.

Furthermore, investigating the economic aspects in more detail is beneficial and recommended. While this study considered costs as one of the criteria in the MCA, a more comprehensive cost analysis could be conducted to assess the long-term economic feasibility of the geotextile encased columns compared to other methods. This analysis should include not only the initial construction costs, but also long-term maintenance, repair, and potential risks associated with each method. A life cycle cost analysis would provide a holistic perspective on the economic viability of the chosen stabilization method.

Another avenue for future research could involve investigating the environmental impact of the different soil stabilization methods. This study touched upon sustainability as one of the criteria in the MCA; however, a more in-depth assessment of the environmental implications, such as carbon footprint, energy consumption, and material utilization, would contribute to a more comprehensive understanding of the sustainability aspect. Such an analysis would help decision-makers and designers make informed choices that align with environmental objectives.

Considering the evaluation and comparison of soil stabilization methods, the chosen method for the railway embankment extension project holds significant implications for the stability of the existing train track. The recommendation is made that further research be conducted to assess the potential impacts of the selected soil stabilization method on the stability of the existing track. This follow-up research should include detailed geotechnical analyses, such as slope stability assessments and geotechnical monitoring, to understand the behaviour of the track under the influence of the chosen method. By examining factors such as settlement, lateral movement, and overall stability, this research provides insights into the long-term performance and safety of the railway infrastructure. Additionally, field measurements and performance data collected over an extended period should be incorporated to validate and refine the findings. The outcomes of this follow-up research serve as a valuable resource for infrastructure managers, engineers, and decision-makers involved in the project, enabling them to make informed decisions and implement appropriate measures to ensure the continued stability and functionality of the existing train track.

Lastly, considering the rapid advancements in technology and innovative solutions in the field of soil stabilization, future research could explore emerging methods or materials that have shown promise in other geotechnical applications. This could involve investigating the feasibility and effectiveness of these alternative methods for railway embankment stabilization. By embracing innovative technologies and materials, the industry continually improves and optimizes the design and construction practices for more sustainable and stable railway embankments.

Overall, these recommendations aim to further advance the knowledge and understanding of soil stabilization methods for railway embankments. By addressing these areas in future research, engineers and designers make informed decisions, enhance the performance of railway embankments, and contribute to the development of sustainable and resilient transportation infrastructure.

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APPENDICES

Appendix A – Organizational Chart, Mobility Department

Figure 81 Organizational Chart, Business Area Mobility (Arcadis, 2022)

Appendix B – Technical Drawings Train Track km 23.4 – 25.2

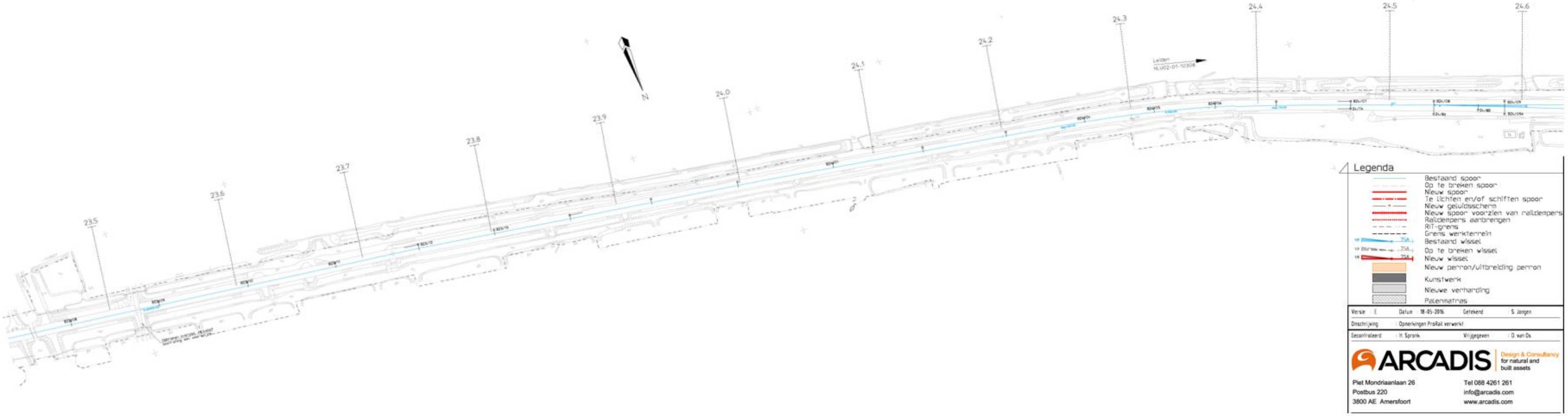


Figure 82 Top View Railway Embankment between Hazerswoude-Rijndijk and Zoeterwoude East (Arcadis, 2016)

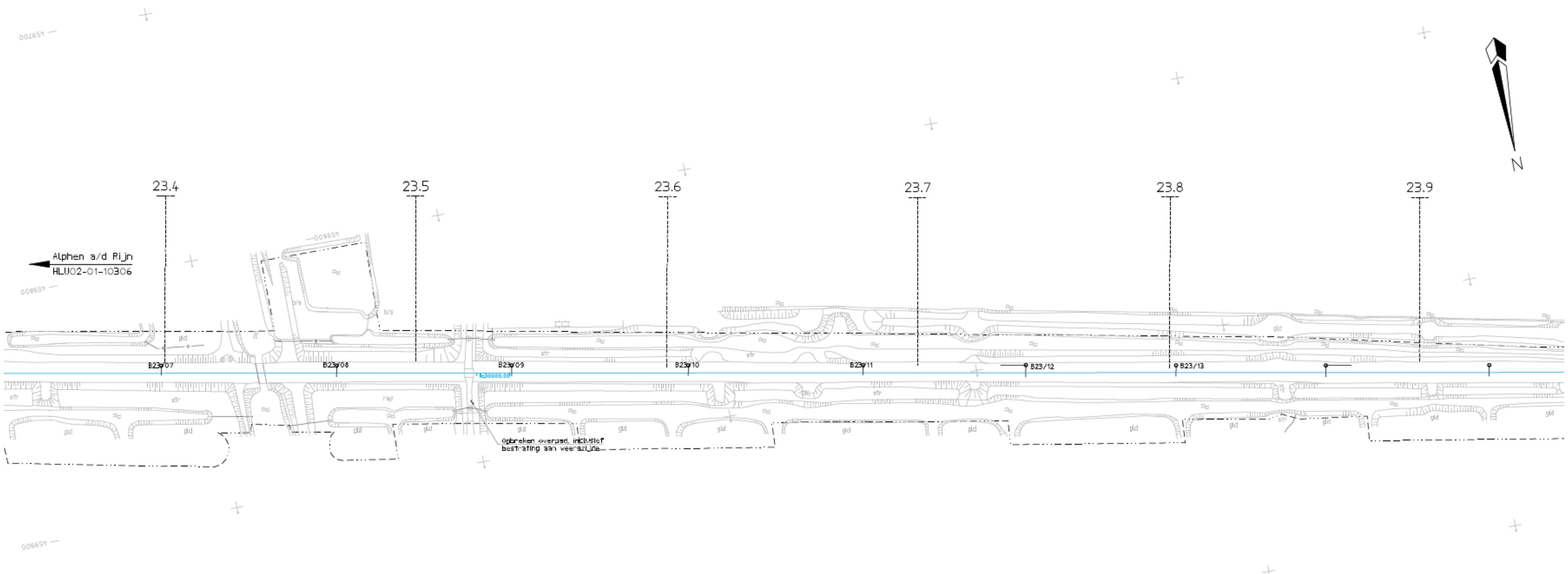
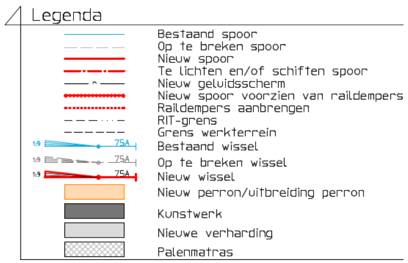


Figure 83 Top View Railway Embankment between km 23.4 – 23.9 (Arcadis, 2016)



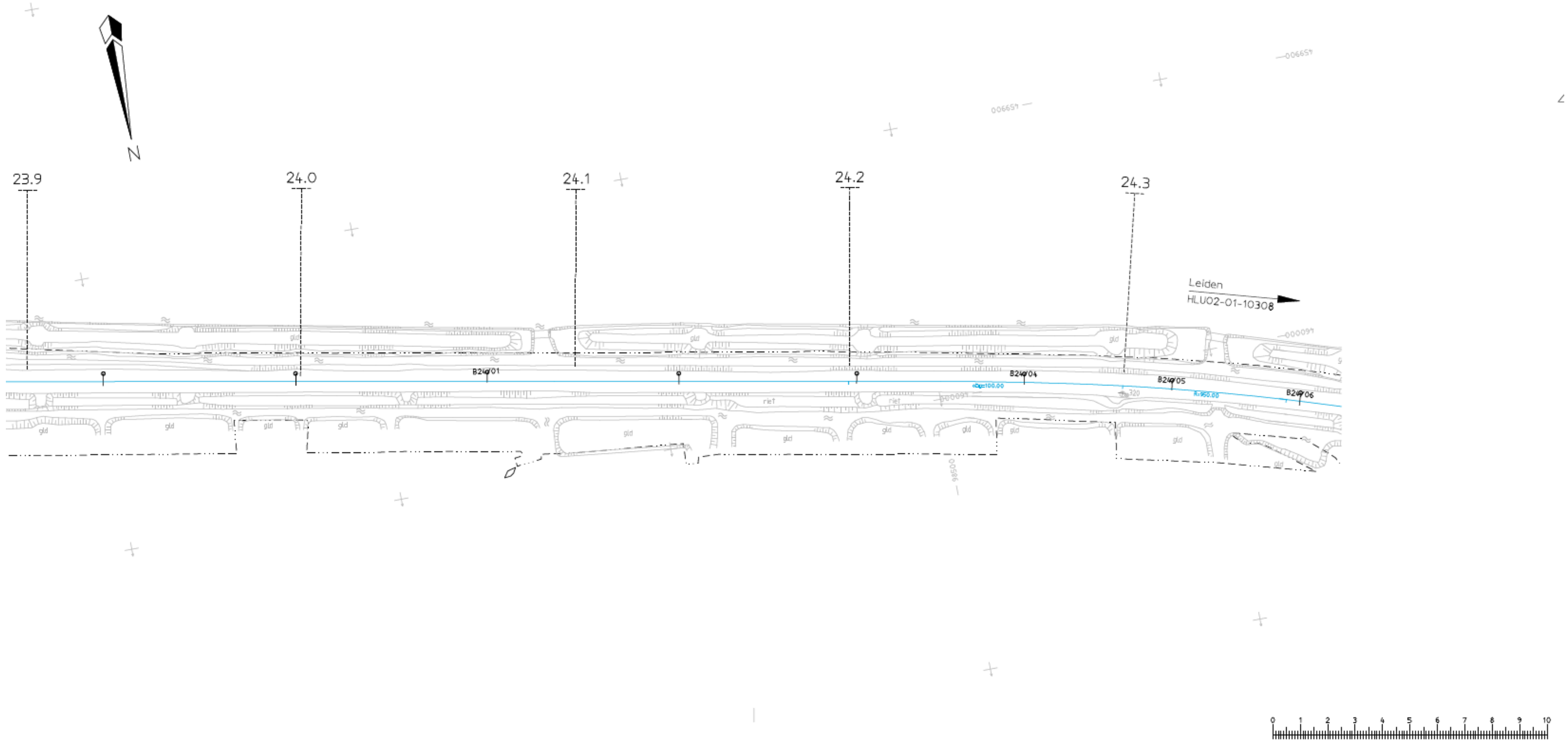


Figure 84 Top View Railway Embankment between km 23.9 – 24.3 (Arcadis, 2016)

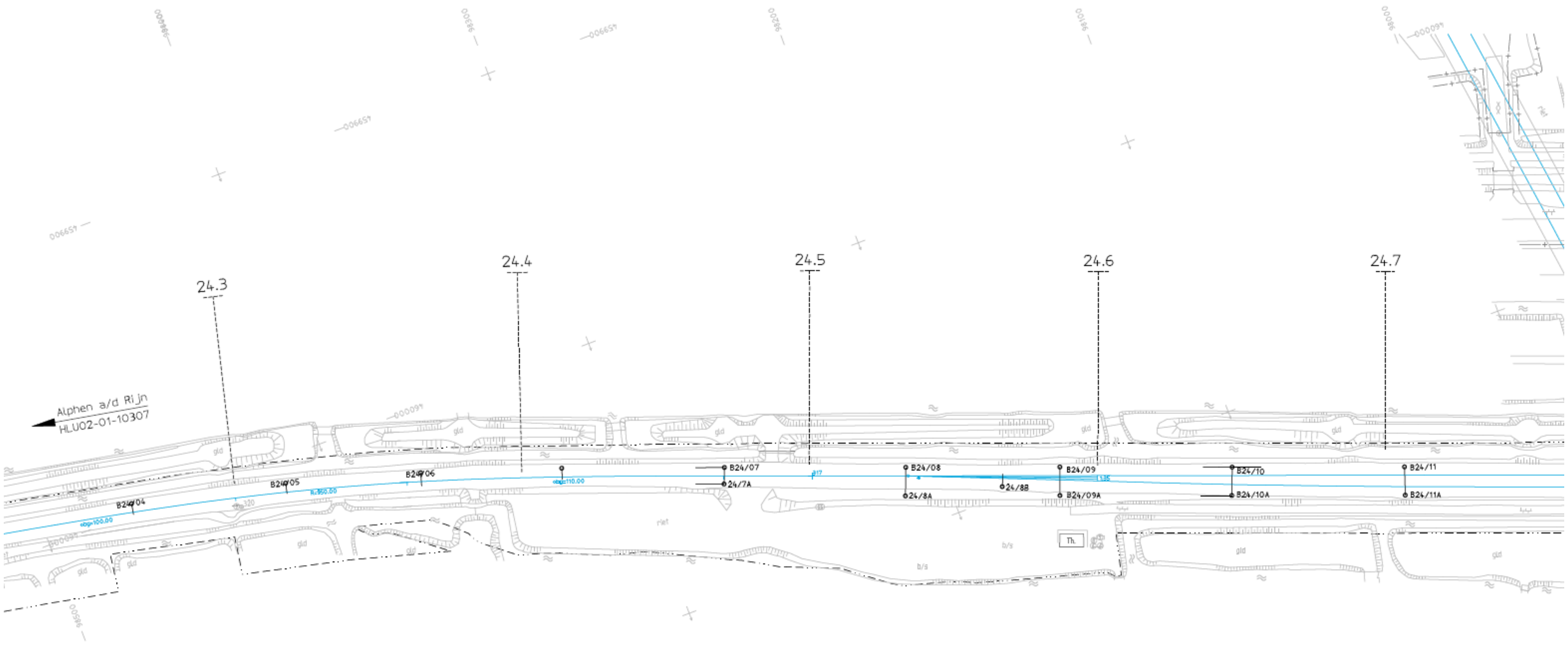


Figure 85 Top View Railway Embankment between km 24.3 – 24.7 (Arcadis, 2016)

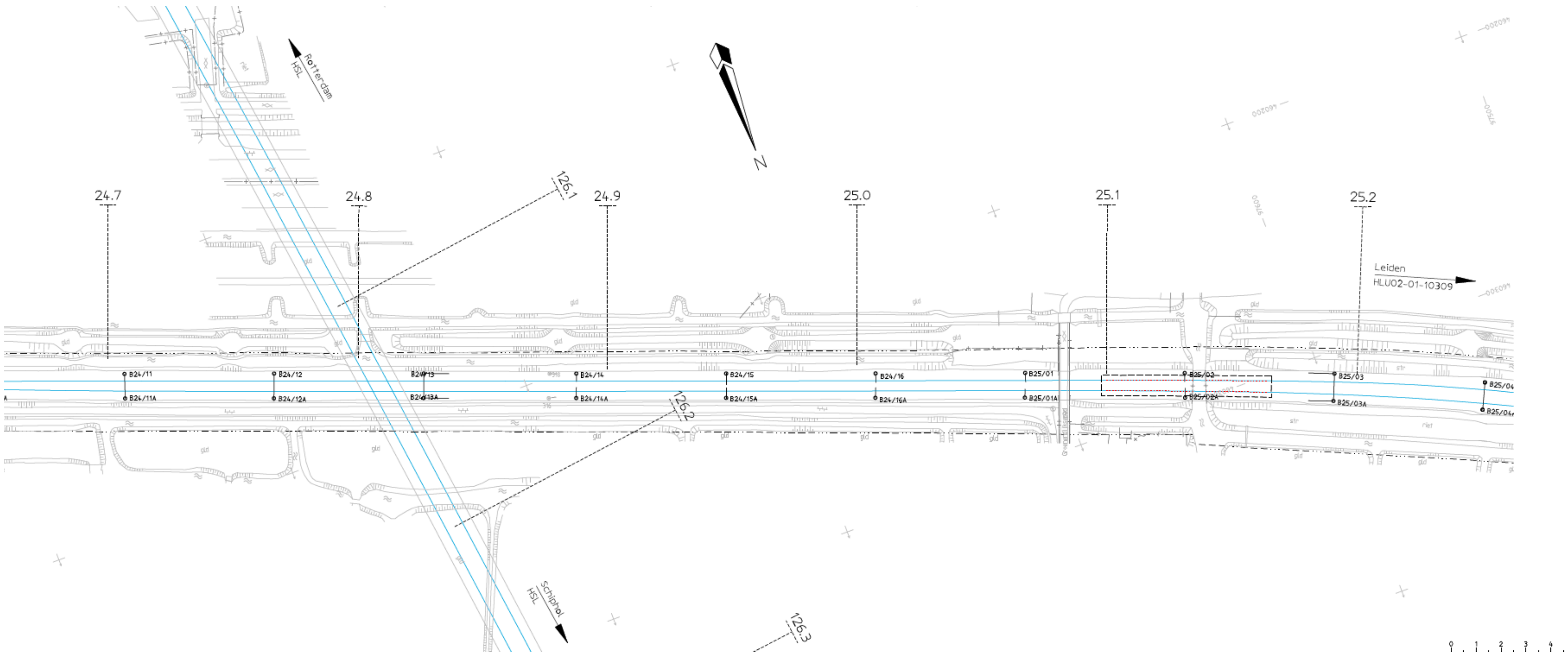
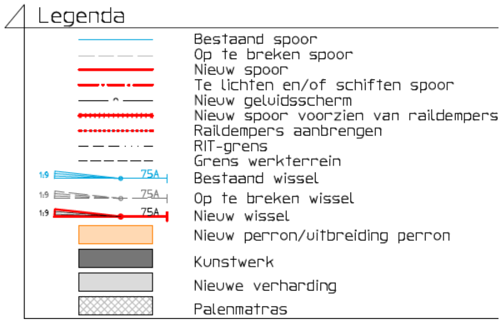


Figure 86 Top View Railway Embankment between km 24.7 – 25.2 (Arcadis, 2016)



Appendix C – Historical Technical Drawings

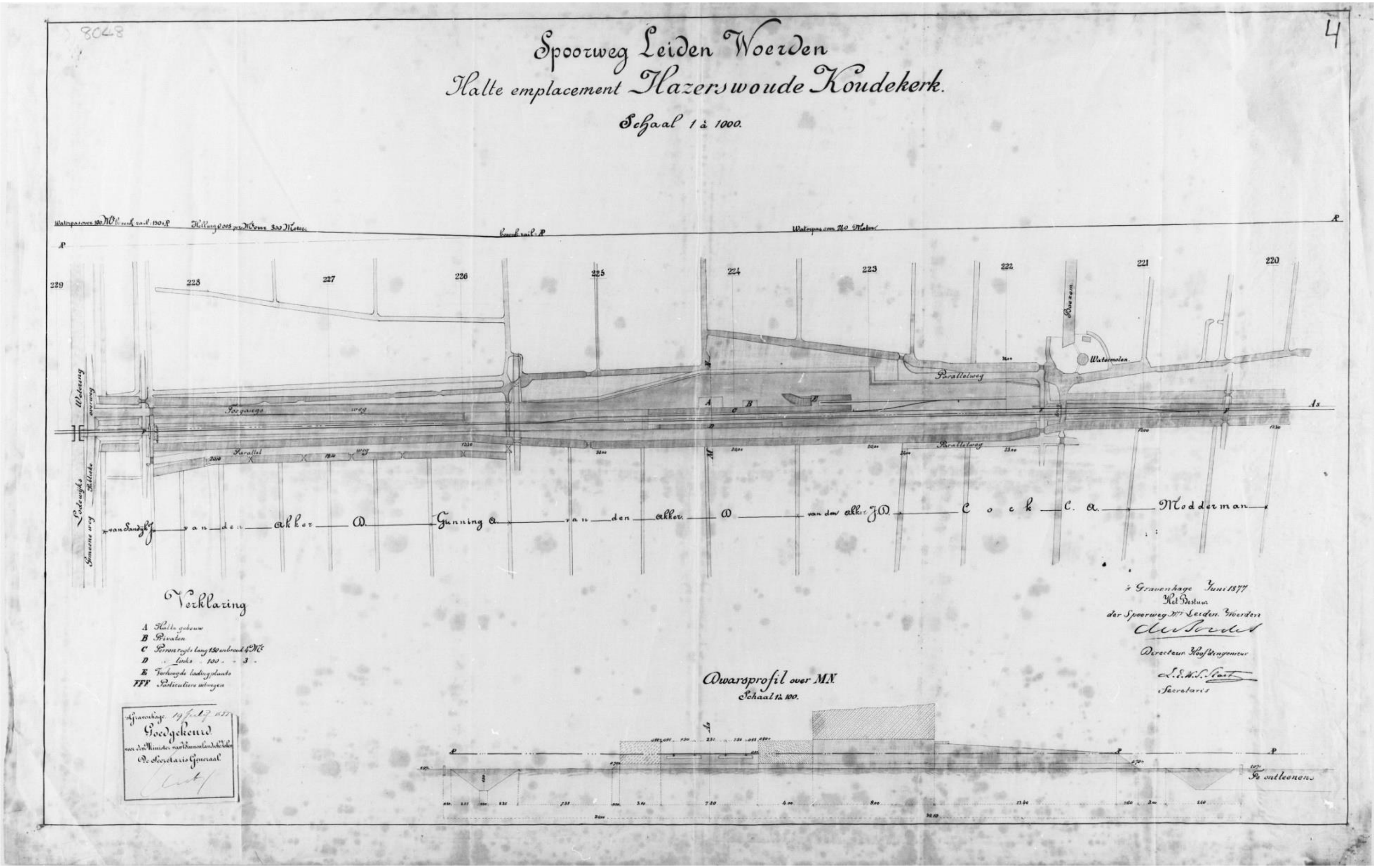


Figure 87 Halt Emplacement Hazerswoude-Koudekerk, 1877 (Het Utrechts Archief, 2022)

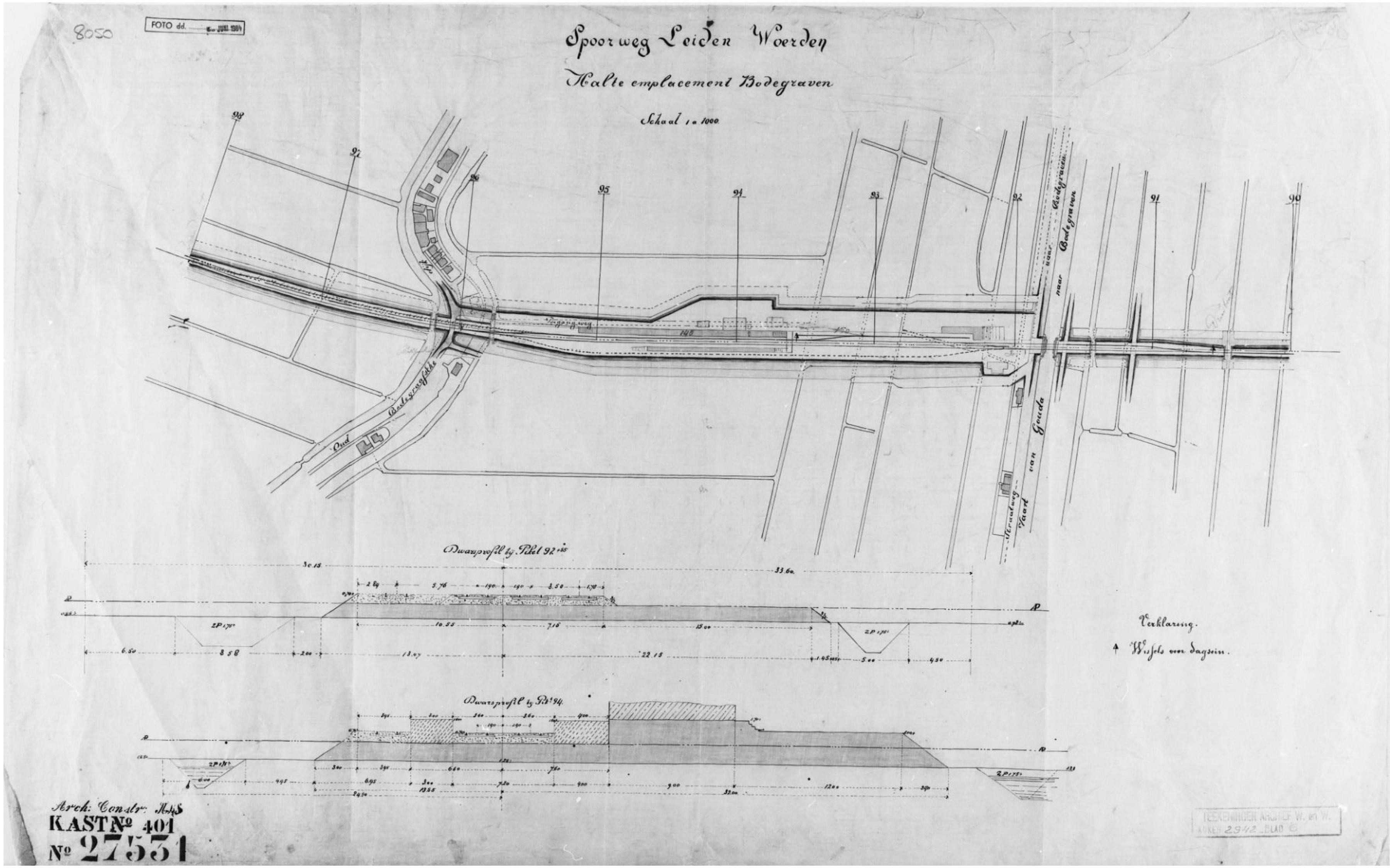
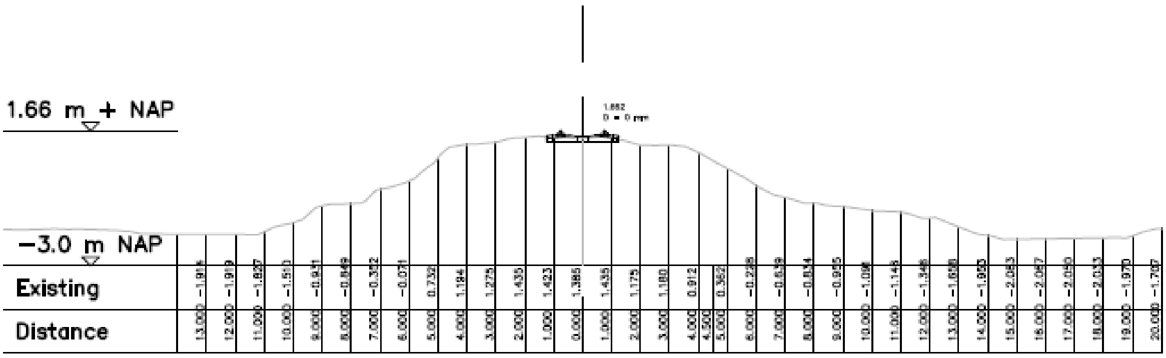


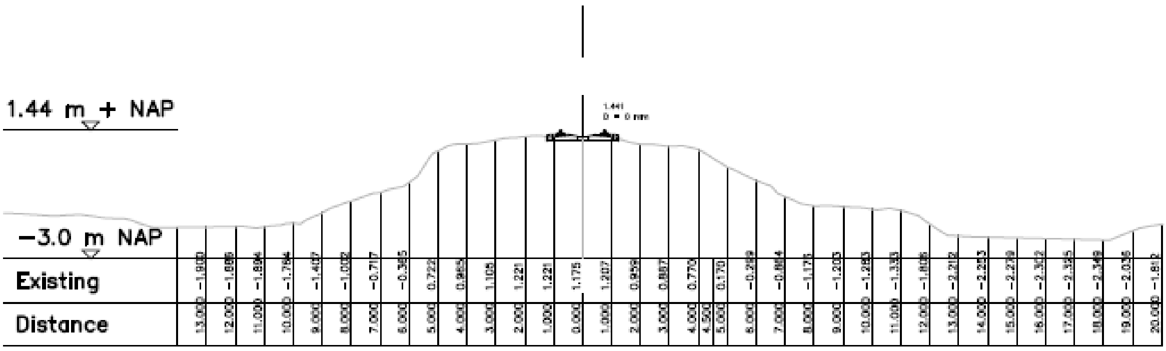
Figure 88 Halt Emplacement Bodegraven, 1877 (Het Utrechts Archief, 2022)

Appendix D – Current Situation: Cross-Sections Trajectory 23.5 – 24.6 km

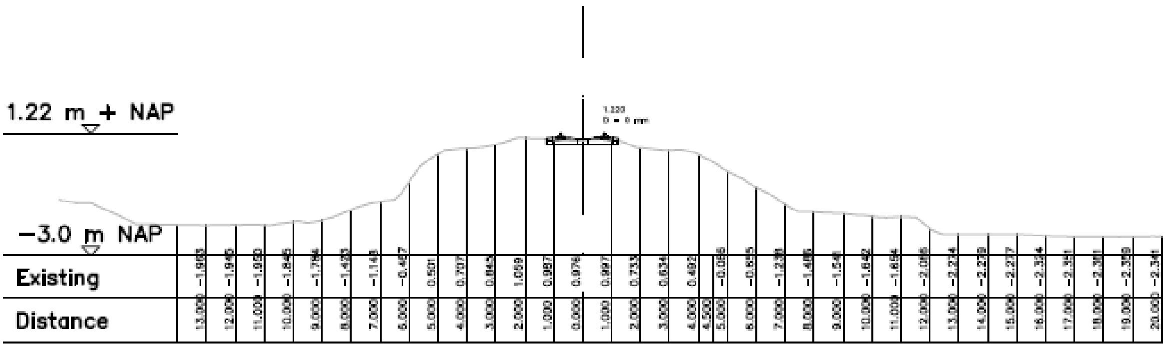
Dwarsprofiel 1
km 23.500



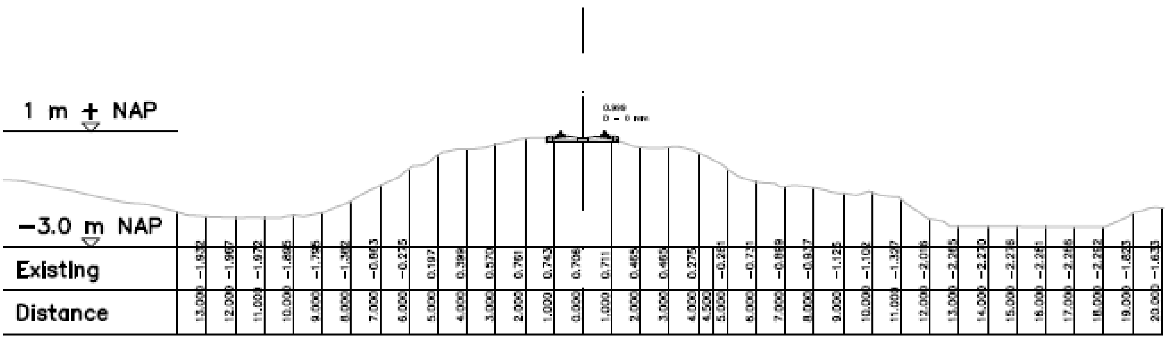
Dwarsprofiel 2
km 23.550



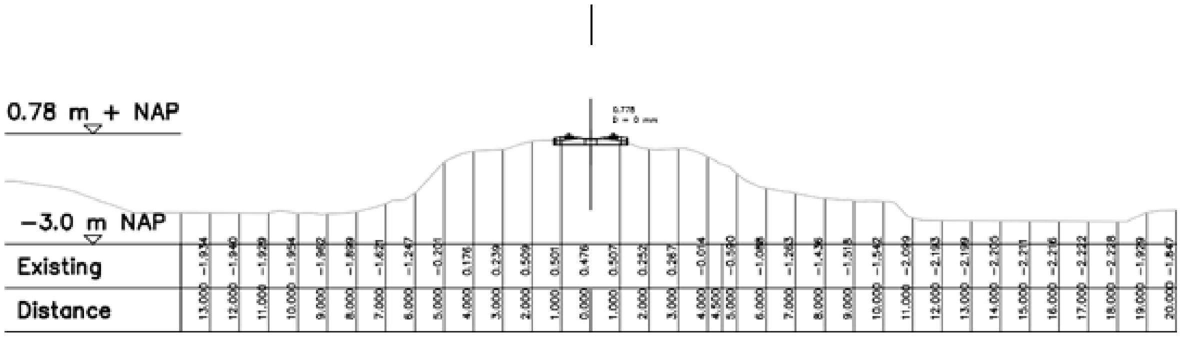
Dwarsprofiel 3
km 23.600



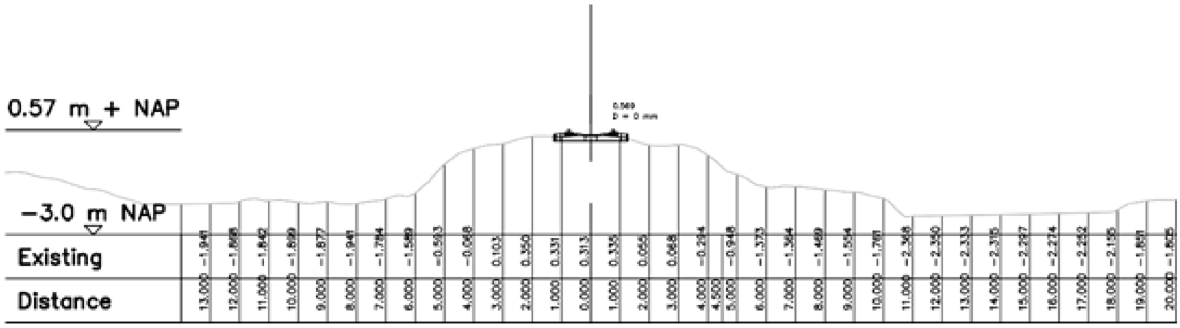
Dwarsprofiel 4
km 23.650



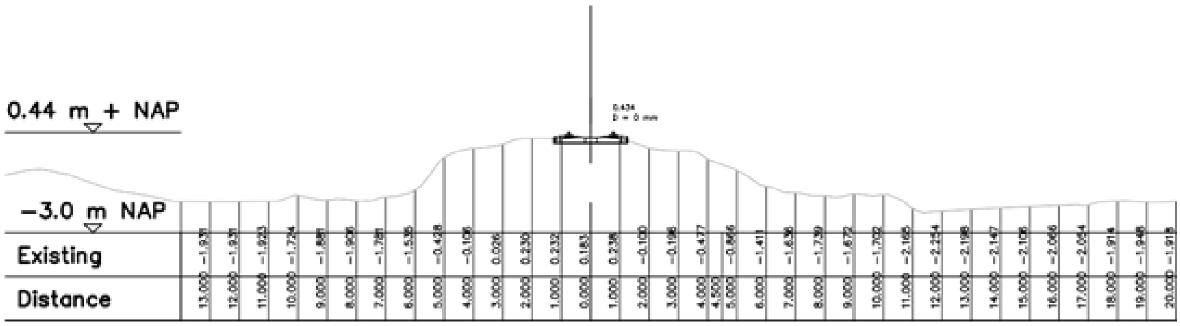
Dwarsprofiel 5
km 23.700



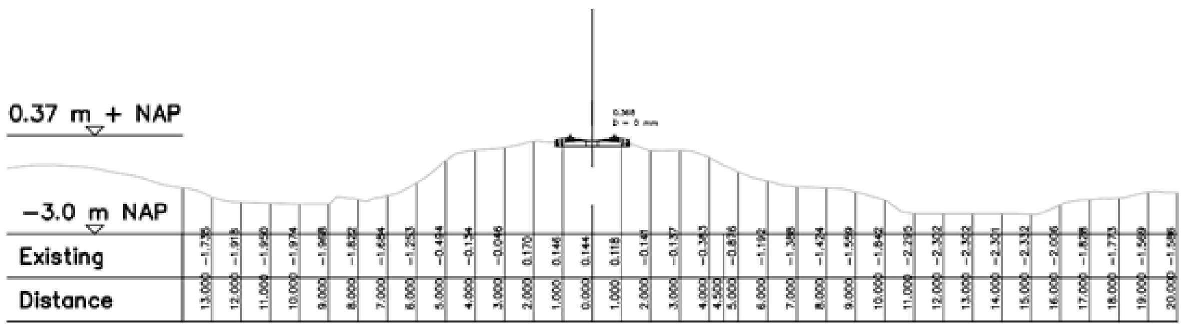
Dwarsprofiel 6
km 23.750



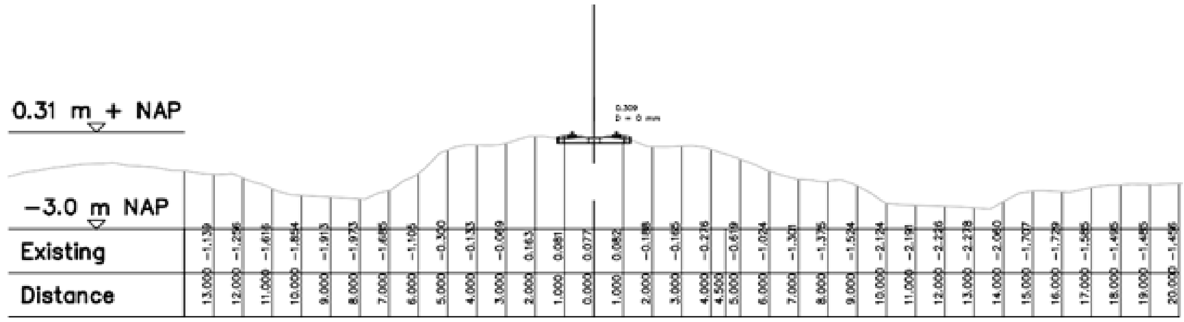
Dwarsprofiel 7
km 23.800



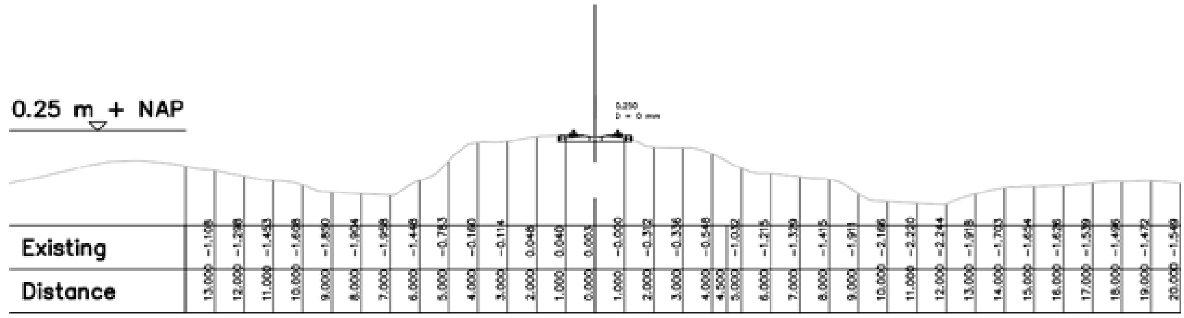
Dwarsprofiel 8
km 23.850



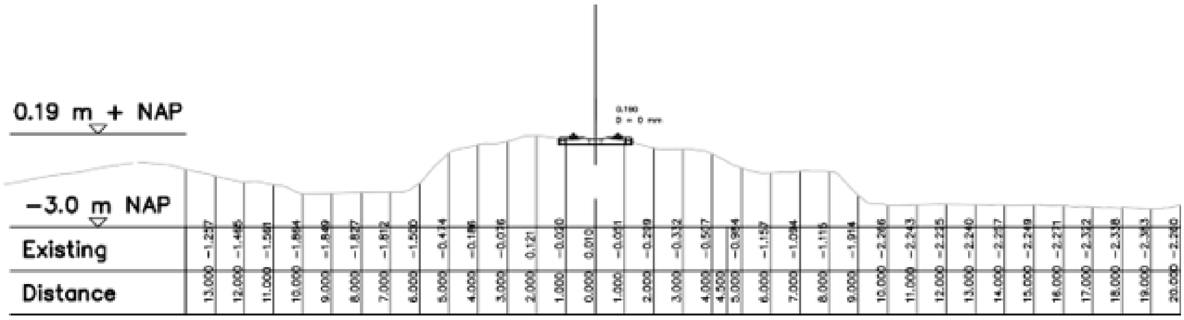
Dwarsprofiel 9
km 23.900



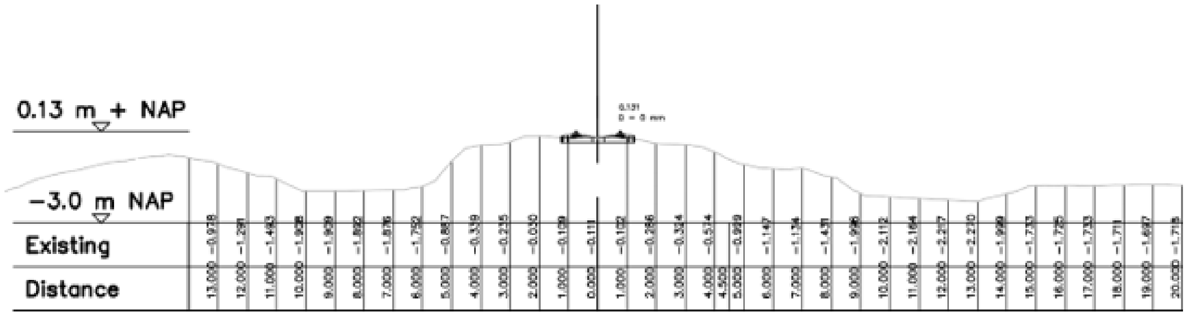
Dwarsprofiel 10
km 23.950



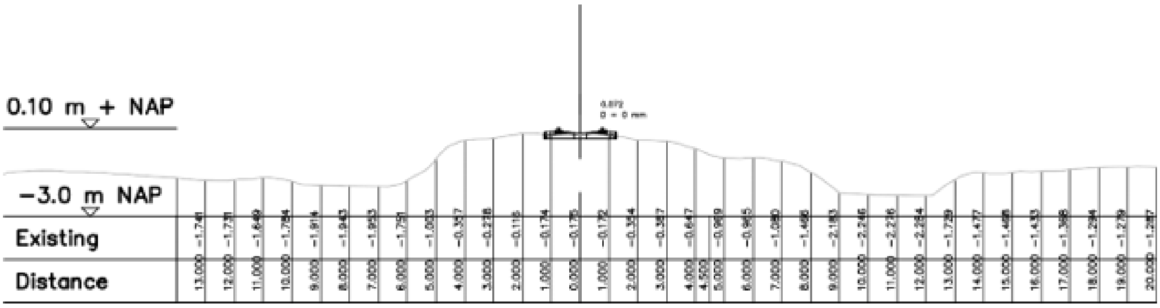
Dwarsprofiel 11
km 24.000



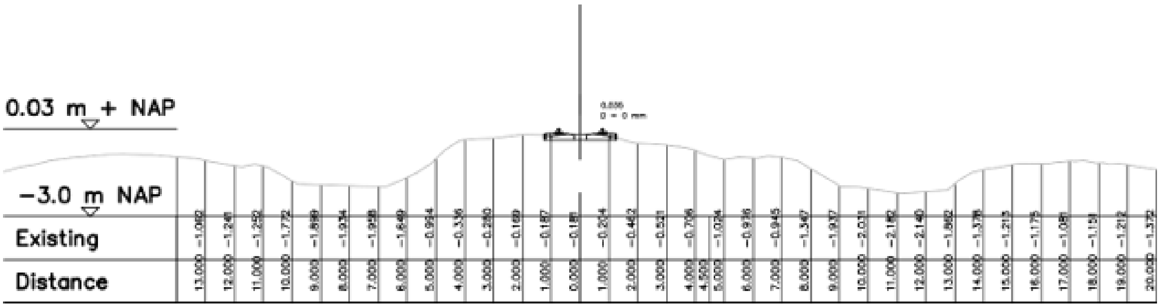
Dwarsprofiel 12
km 24.050



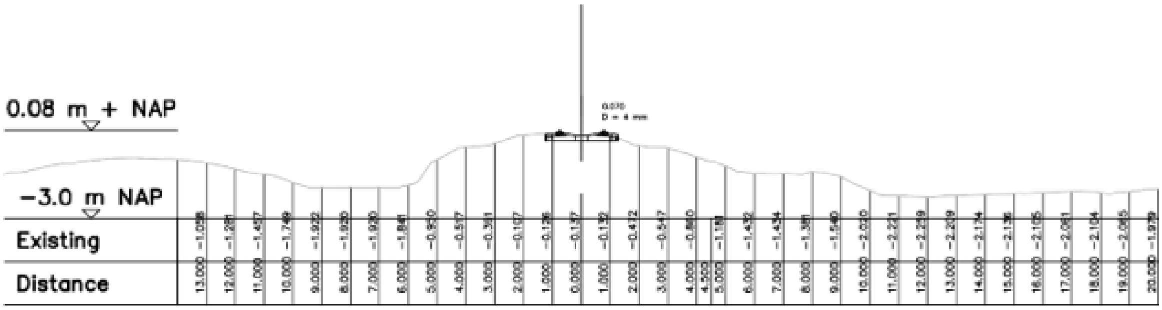
Dwarsprofiel 13
km 24.100



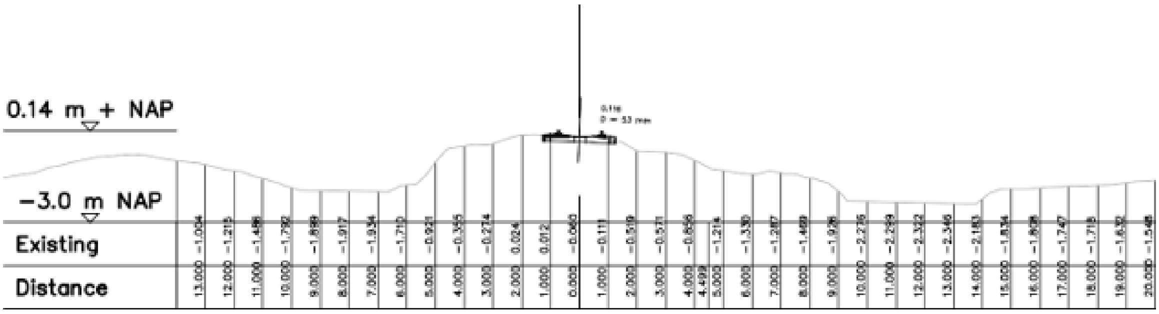
Dwarsprofiel 14
km 24.150



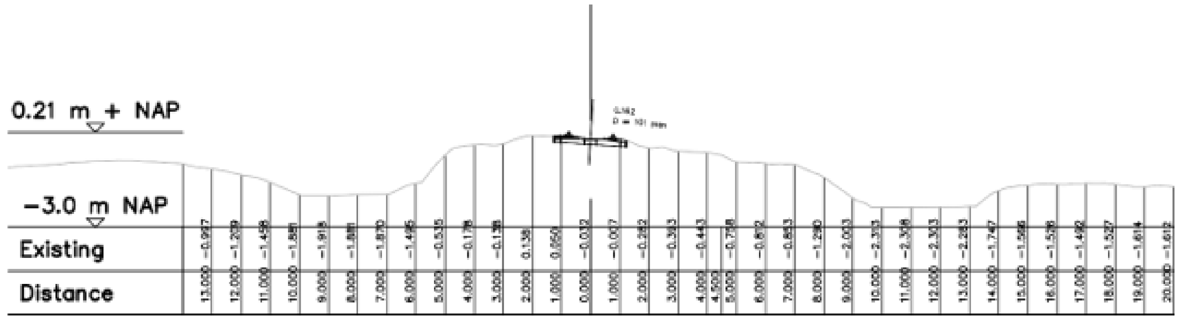
Dwarsprofiel 15
km 24.200



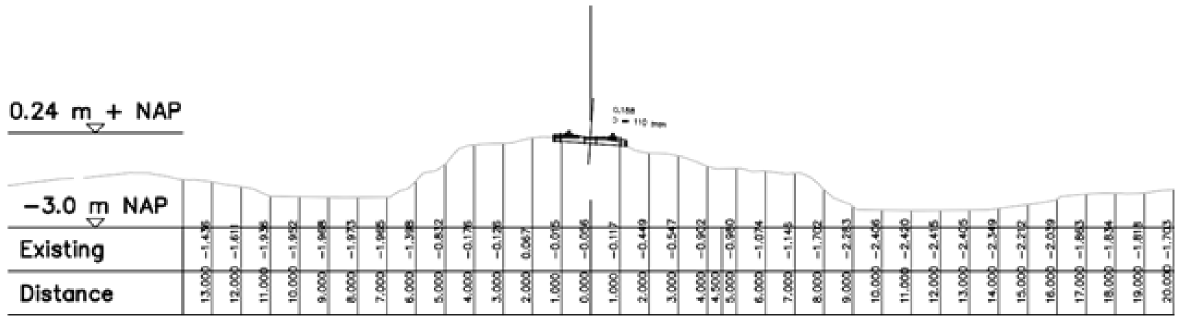
Dwarsprofiel 16
km 24.250



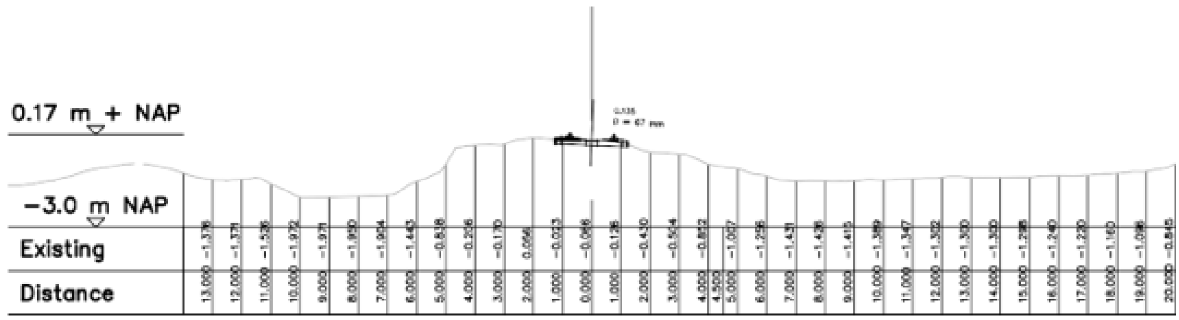
Dwarsprofiel 17
km 24.300



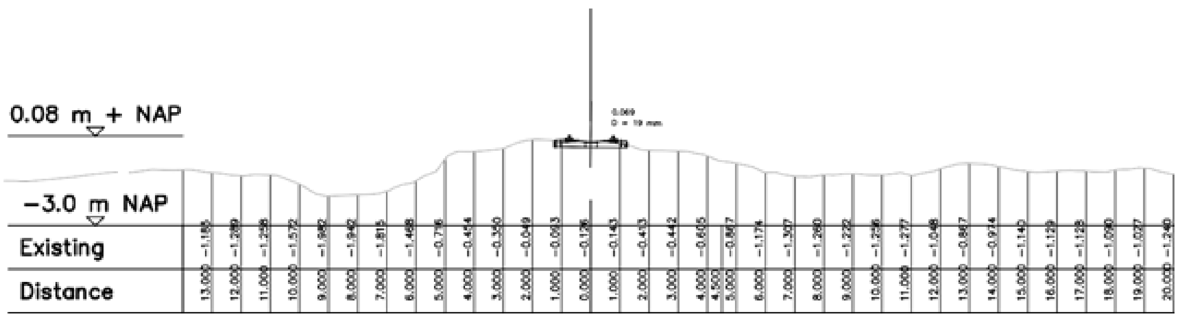
Dwarsprofiel 18
km 24.350



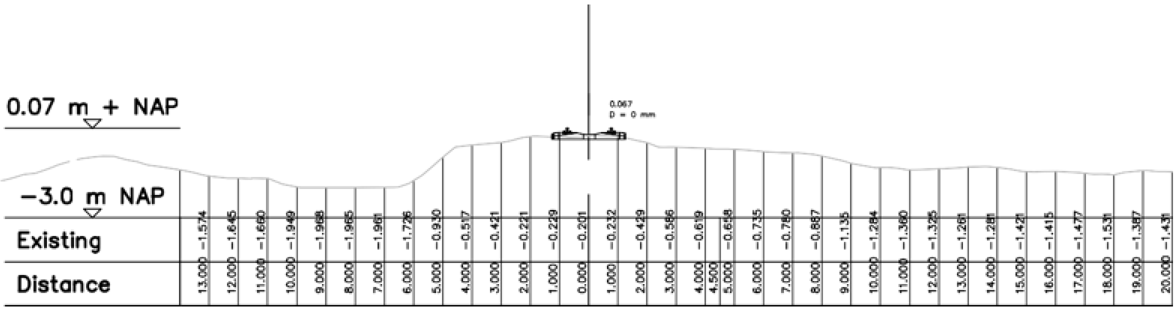
Dwarsprofiel 19
km 24.400



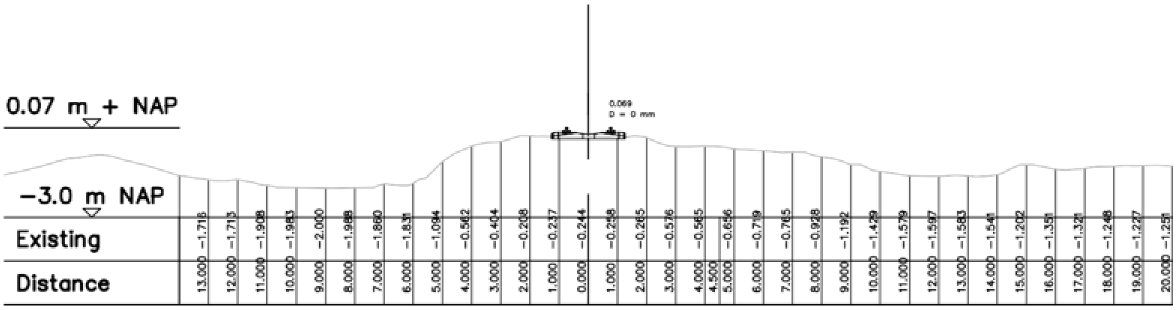
Dwarsprofiel 20
km 24.450



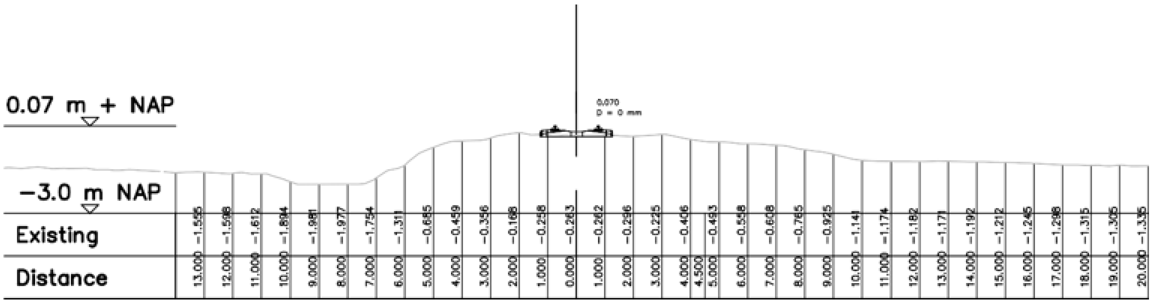
Dwarsprofiel 21
km 24.500



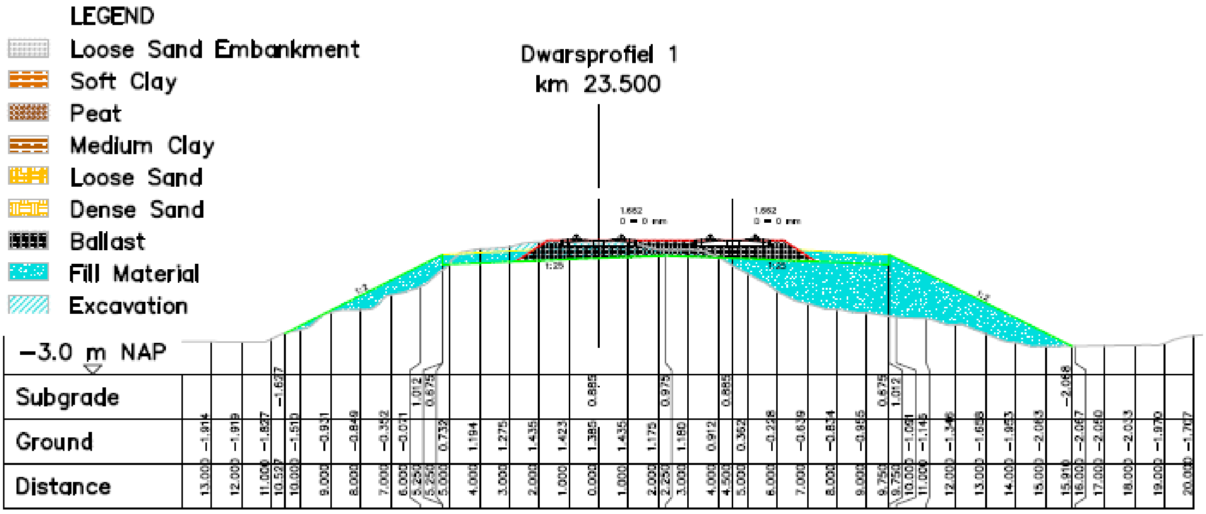
Dwarsprofiel 22
km 24.550

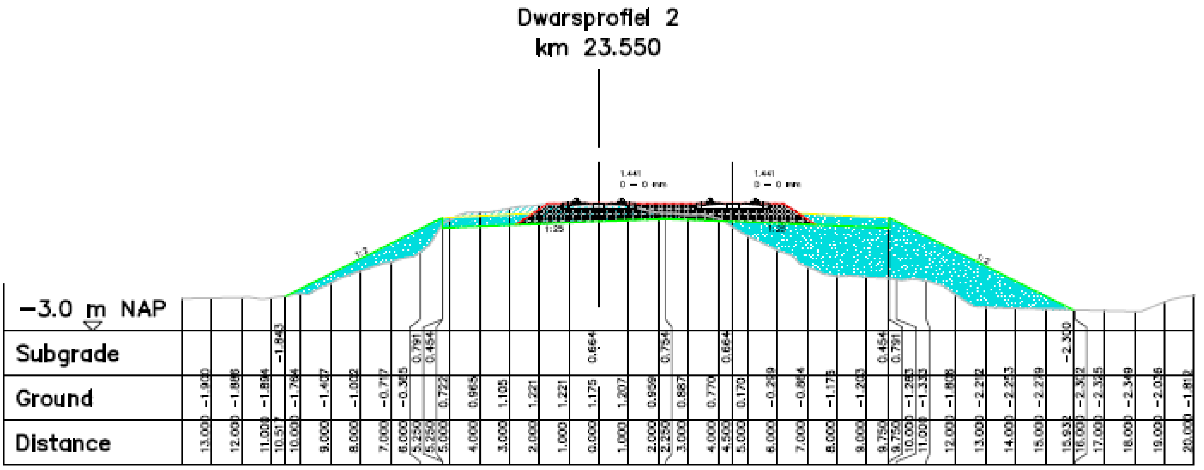


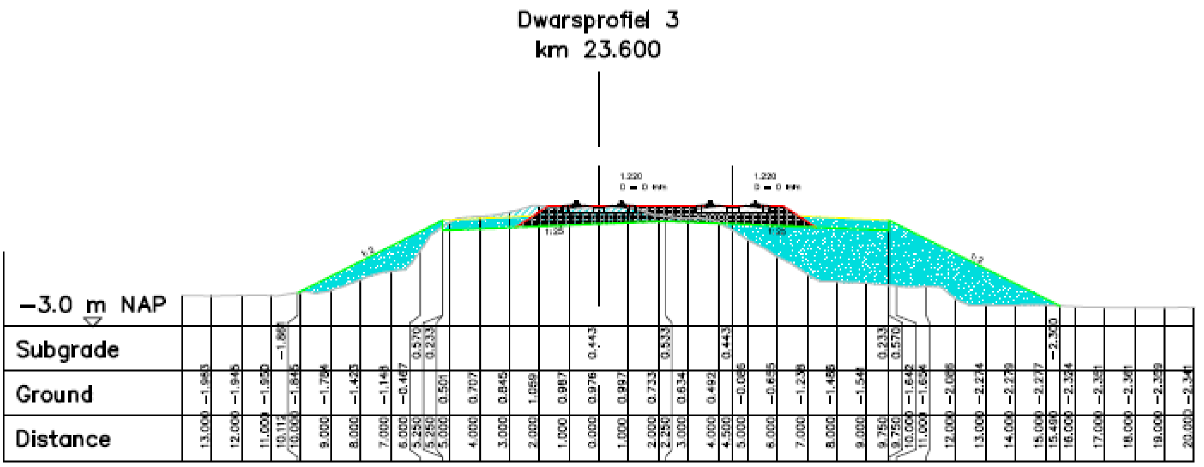
Dwarsprofiel 23
km 24.600



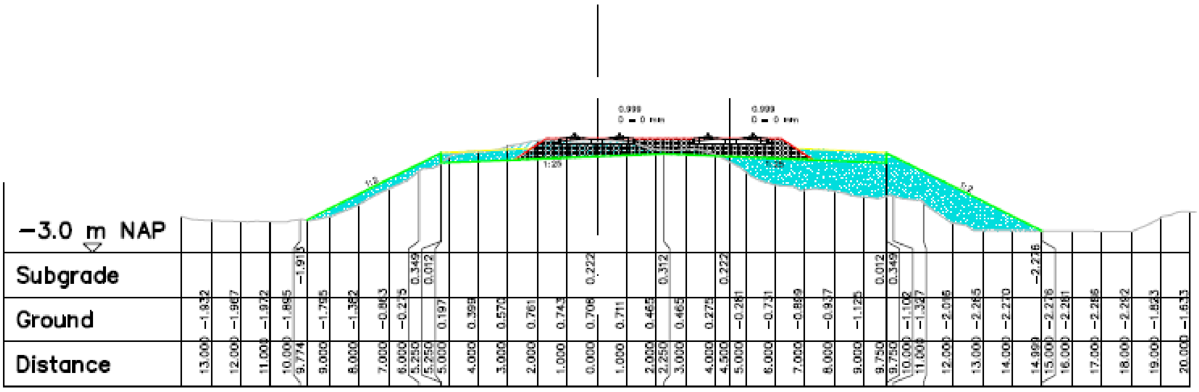
Appendix E – Desired Situation: Cross-Sections Trajectory 23.5 – 24.6 km



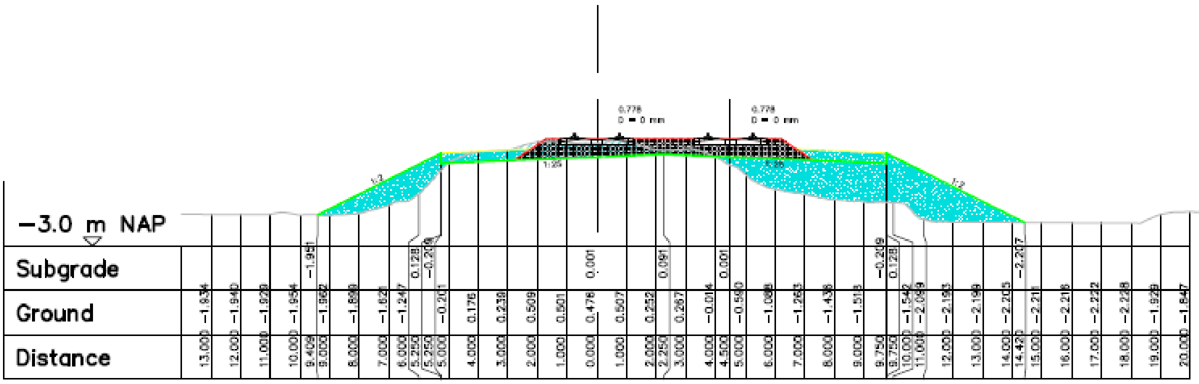




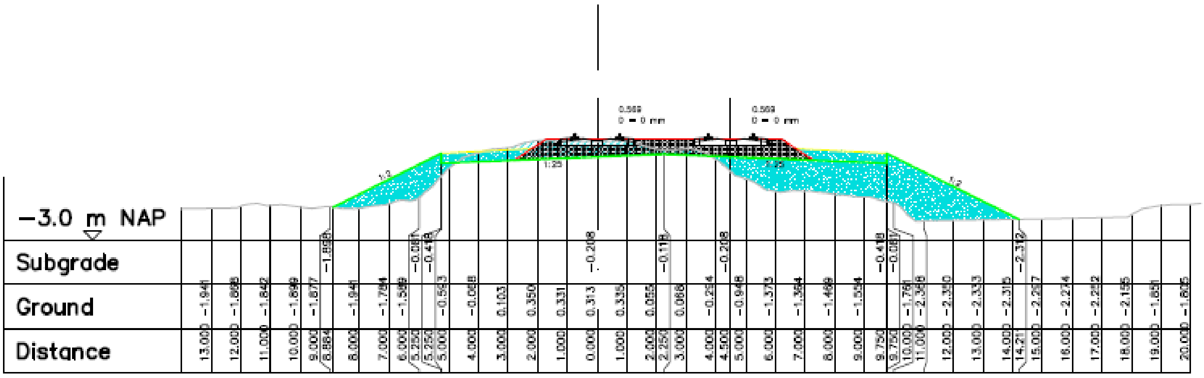
Dwarsprofiel 4
km 23.650



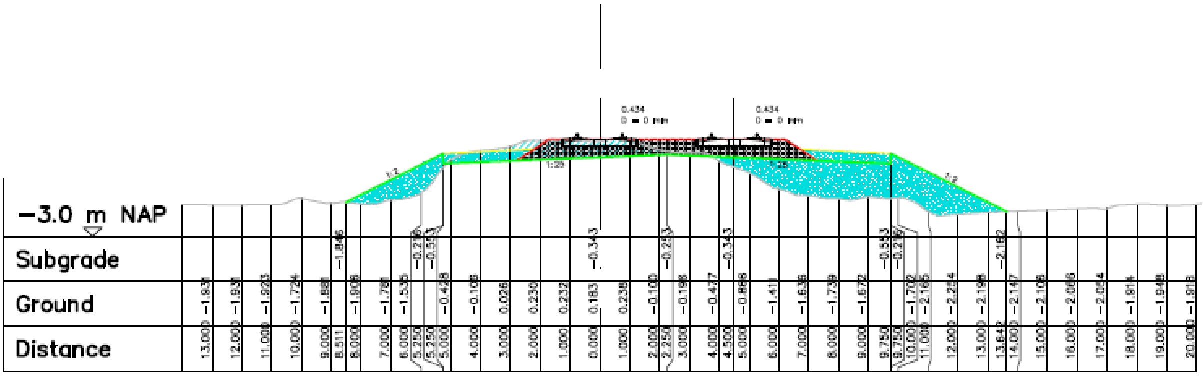
Dwarsprofiel 5
km 23.700



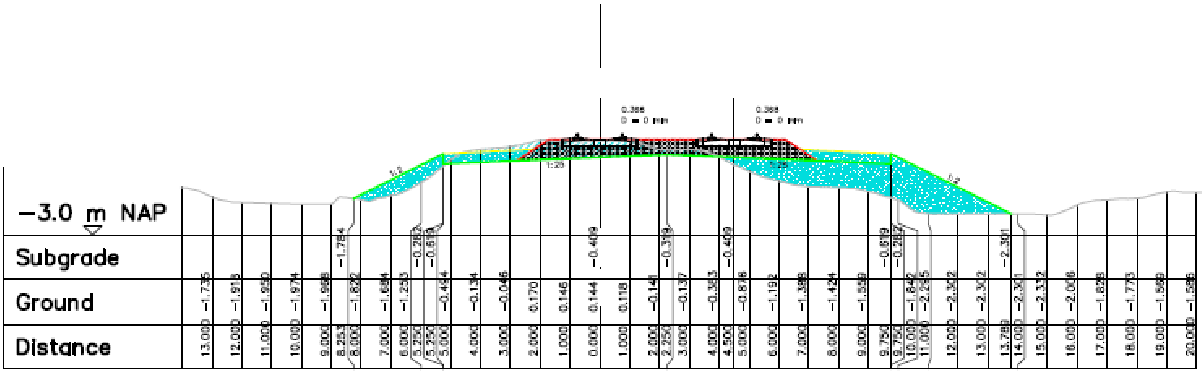
Dwarsprofiel 6
km 23.750



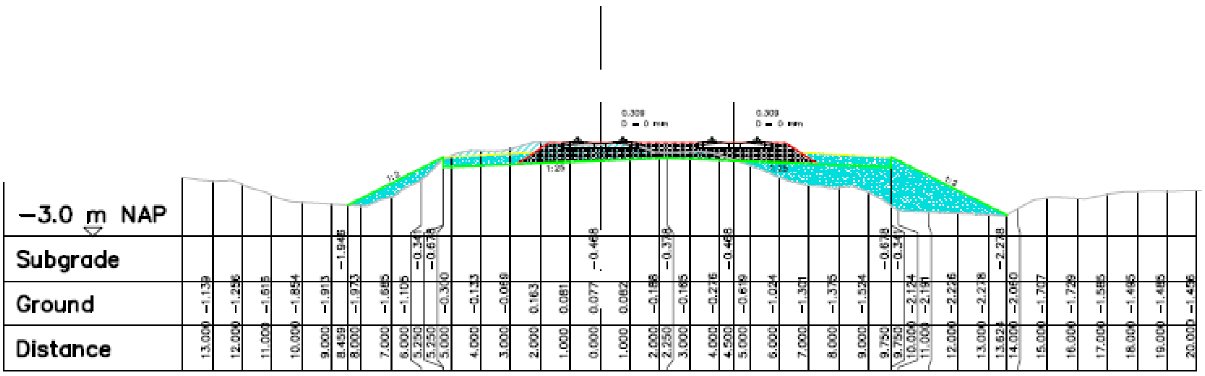
Dwarsprofiel 7
km 23.800



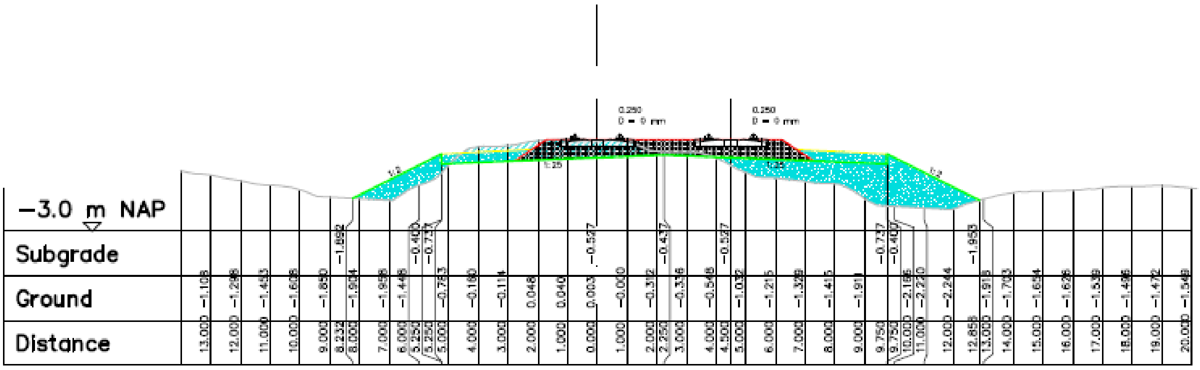
Dwarsprofiel 8
km 23.850



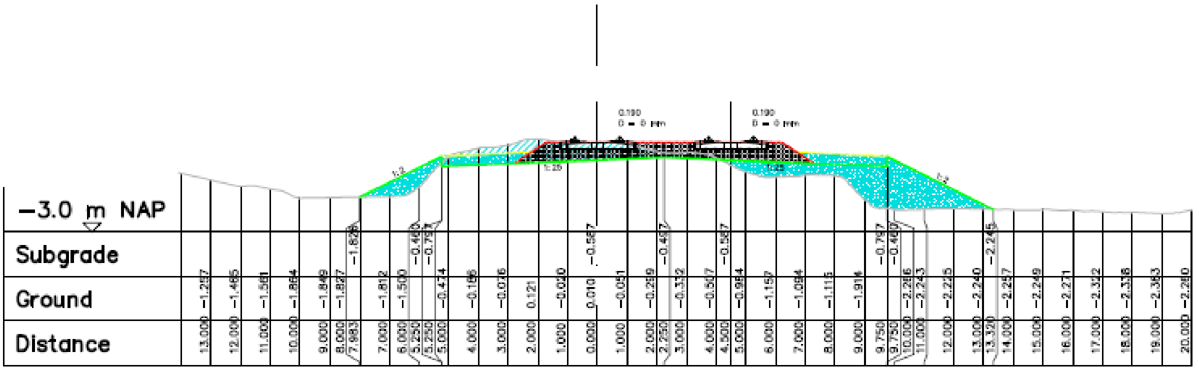
Dwarsprofiel 9
km 23.900



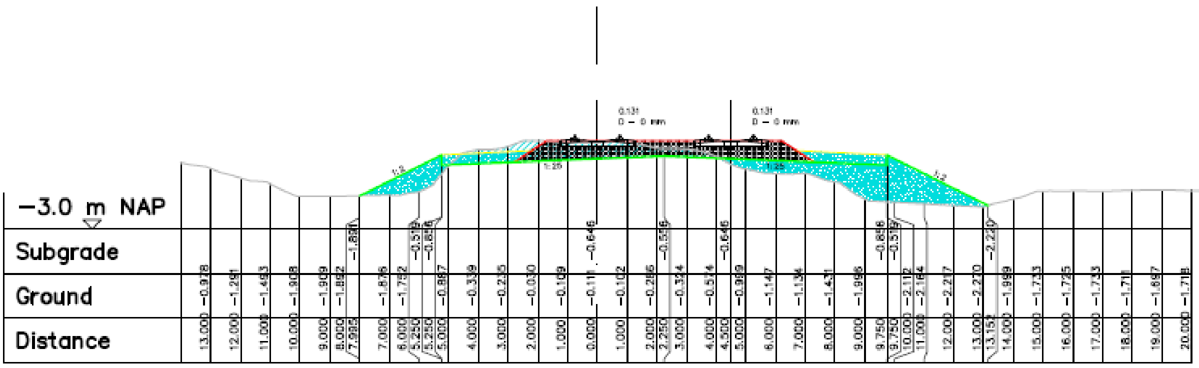
Dwarsprofiel 10
km 23.950



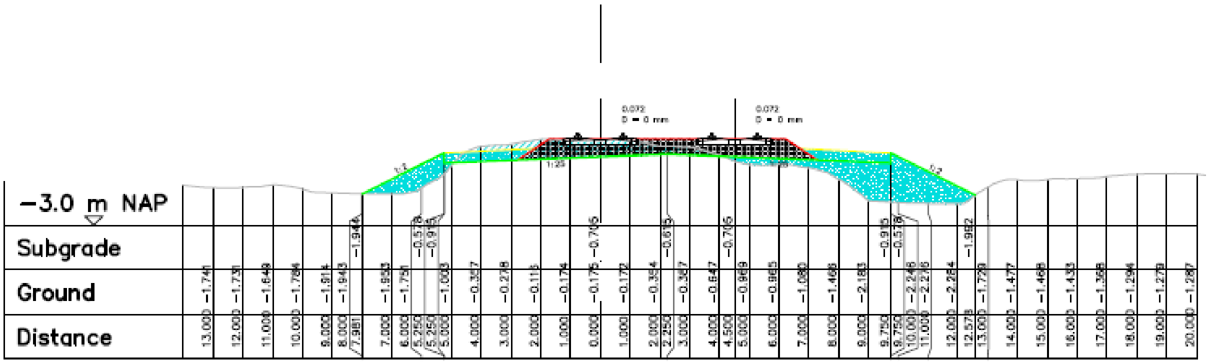
Dwarsprofiel 11
km 24.000



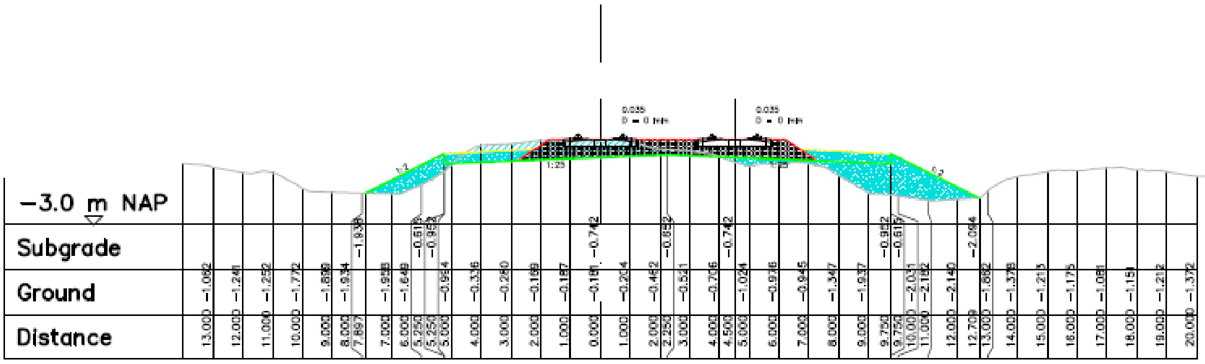
Dwarsprofiel 12
km 24.050



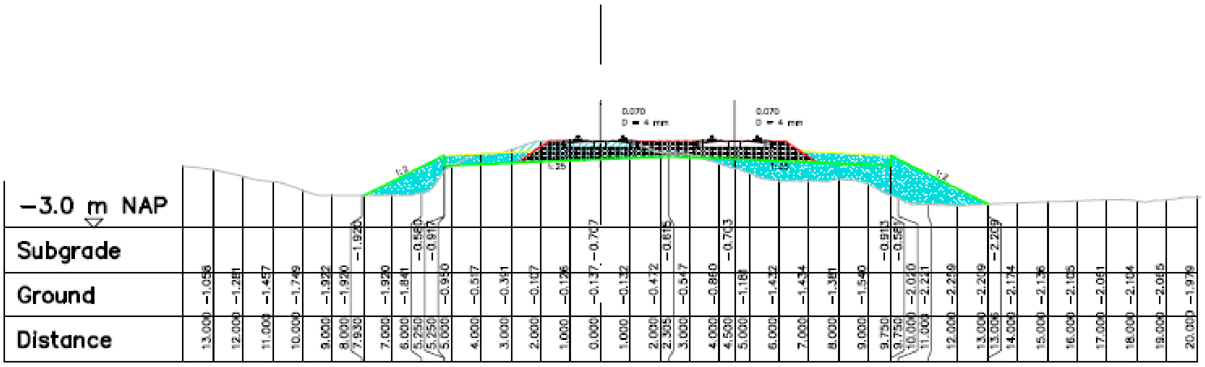
Dwarsprofiel 13
km 24.100



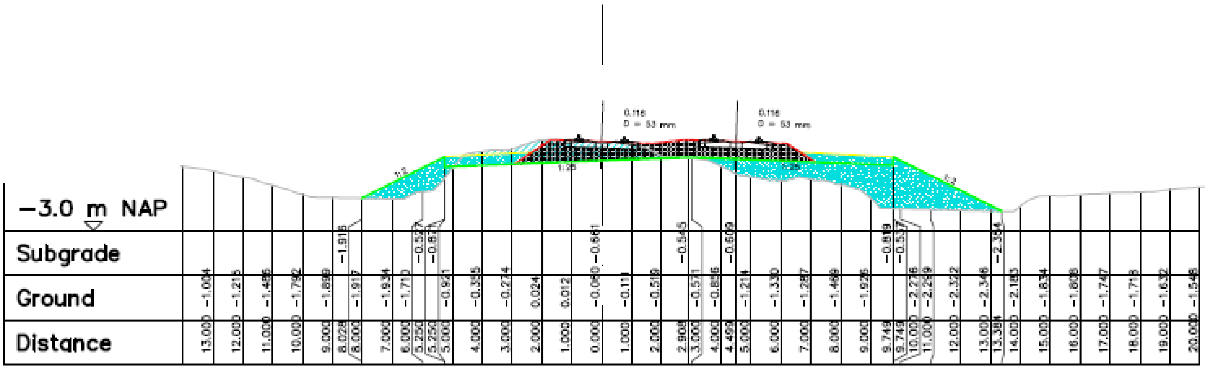
Dwarsprofiel 14
km 24.150



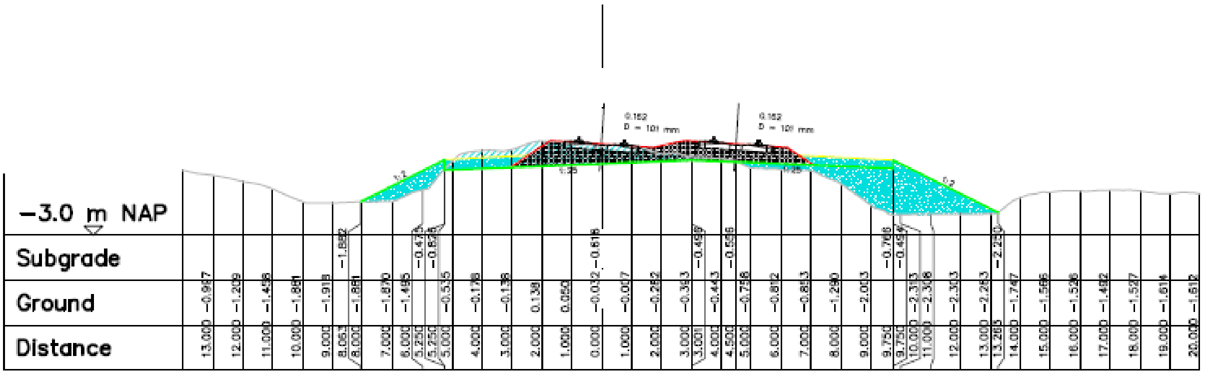
Dwarsprofiel 15
km 24.200



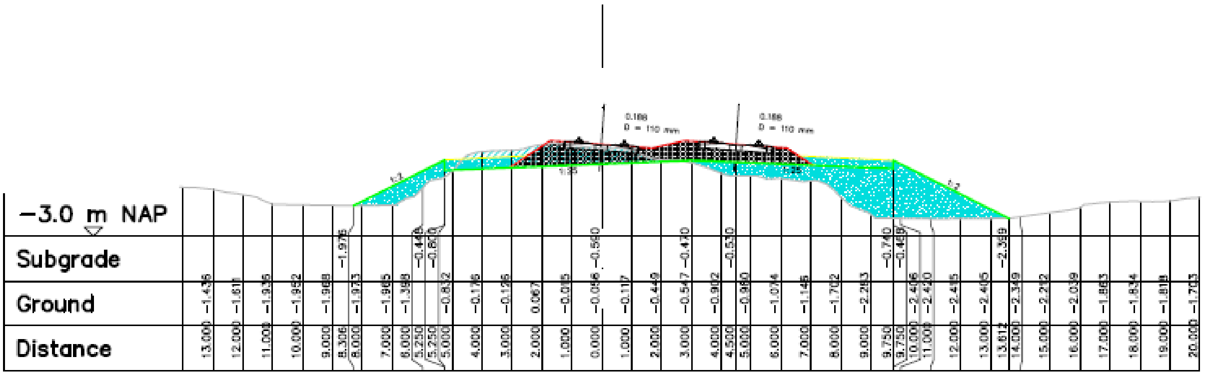
Dwarsprofiel 16
km 24.250



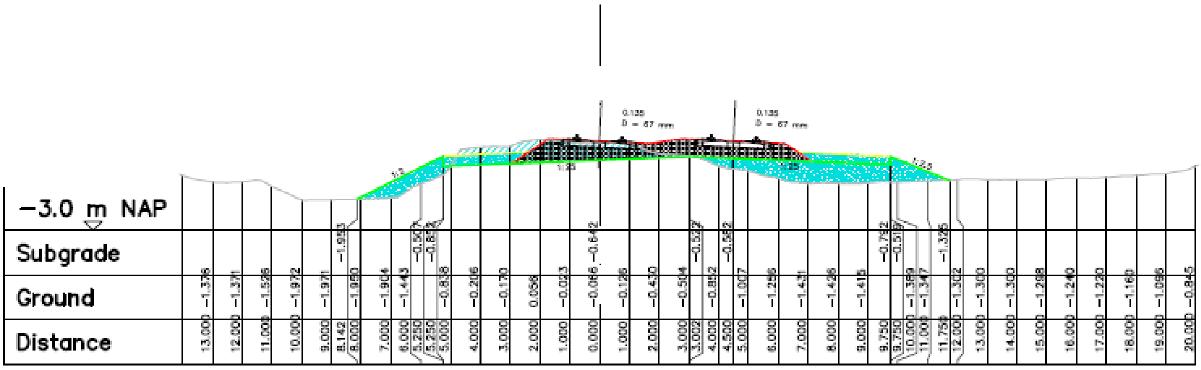
Dwarsprofiel 17
km 24.300



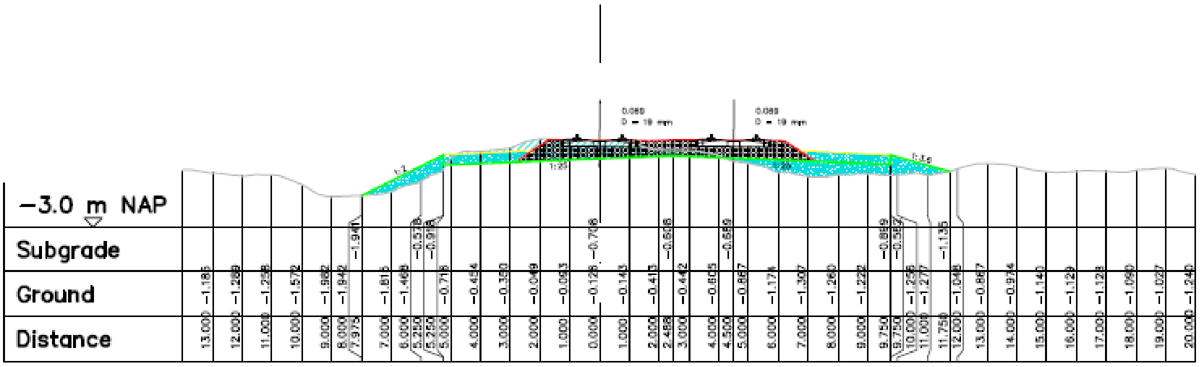
Dwarsprofiel 18
km 24.350



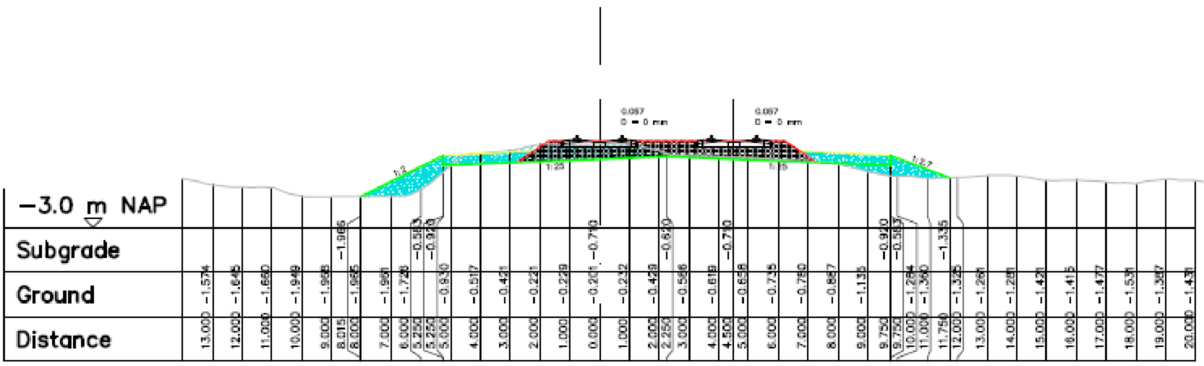
Dwarsprofiel 19
km 24.400



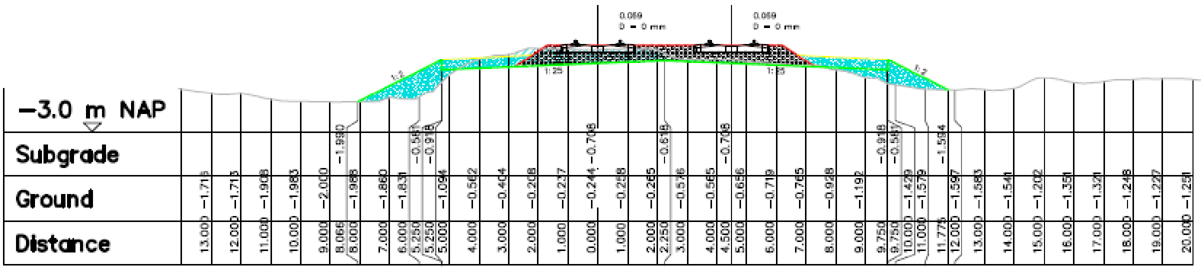
Dwarsprofiel 20
km 24.450



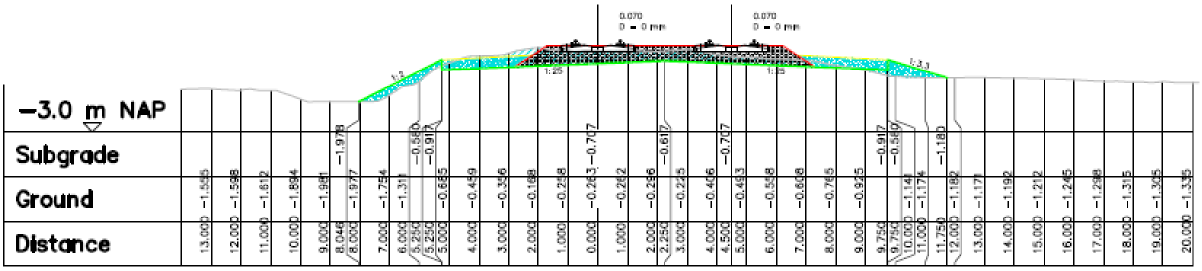
Dwarsprofiel 21
km 24.500



Dwarsprofiel 22
km 24.550



Dwarsprofiel 23
km 24.600



Appendix F – Characteristic Values Soil Properties

Table 39 Table of Characteristic Values Soil Properties (NEN, 2017)

Soil type		Representative average value of the soil properties												
Main name	Additional Info	Consistency 1)	*Y 2)* kN/M3	*Ysat* kN/m3	*qc* 3)6) MPA	*C' p*	*C's*	*Cc*	*Ca*5)	*Csw*	*E6* MPa	*Ø'*	*C'*	*fundr* kPa
Gravel	Slightly silty	Loose Moderate Fixed	17 18 19 or 20	19 20 21 or 22	15 25 30	500 1000 1200 or 1400	- - -	0.008 0.004 0.003 or 0.002	0 0 0	0.003 0.002 0.001 or 0	75 125 150 or 200	32.5 35 37.5 or 40	n/a	n/a
	Very silty	Loose Moderate Fixed	18 19 20 or 21	20 21 22 or 22.5	10 15 25	400 600 1000 or 1500	- - -	0.009 0.006 0.003 or 0.002	0 0 0	0.003 0.002 0.001 or 0	50 75 125 or 150	30 32.5 35 or 40	n/a	n/a
Sand	Clean	Loose Moderate Fixed	17 18 19 or 20	19 20 21 or 22	5 15 25	200 600 1000 or 1500	- - -	0.021 0.006 0.003 or 0.002	0 0 0	0.007 0.003 0.001 or 0	25 75 125 or 150	30 32.5 35 or 40	n/a	n/a
	Slightly silty		18 or 19	20 of 21	12	450 or 650	-	0.008 or 0.005	0	0.003 or 0.001	25 or 35	27 or 32.5	n/a	n/a
	Clay-like													
	Very silty		18 or 19	20 or 21	8	200 or 400	-	0.019 or 0.009	0	0.006 or 0.001	20 or 30	25 or 30		
	Clay-like													
Loam 4)	Slightly sandy	Soft Moderate Fixed	19 20 21 or 22	19 20 21 or 22	1 2 3	25 45 70 or 100	650 1300 1900 or 2500	0.168 0.084 0.049 or 0.030	0.004 0.002 0.001	0.056 0.028 0.017 or 0.005	2 5 10 or 20	27.5 or 30 27.5 or 32.5 27.5 or 35	0 2 5 or 7.5	50 100 200 or 300
	Very sandy		19 or 20	19 or 20	2	45 or 70	1300 or 2000	0.092 or 0.055	0.002	0.031 or 0.005	5 or 10	27.5 or 35	0 or 2	50 or 100
Clay	Clean	Soft Moderate Fixed	14 17 19 or 20	14 17 19 or 20	0.5 1.0 2.0	7 15 25 or 30	80 160 320 or 500	1.357 0.362 0.168 or 0.126	0.013 0.006 0.004	0.452 0.121 0.056 or 0.042	1 2 4 of 10	17.5 17.5 17.5 or 25	0 10 25 or 30	25 50 100 or 200
	Slightly sandy	Soft Moderate Fixed	15 18 20 or 21	15 18 20 or 21	0.7 1.5 2.5	10 20 30 or 50	110 240 400 or 600	0.759 0.237 0.126 or 0.069	0.009 0.005 0.003	0.253 0.079 0.042 or 0.014	1.5 3 5 or 10	22.5 22.5 22.5 or 27 5	0 10 25 or 30	40 80 120 or 170
	Very sandy		18 or 20	18 or 20	1.0	25 or 140	320 or 1680	0.190 or 0.027	0.004	0.063 or 0.025	2 or 5	27.5 or 32.5	0 or 2	0 or 10
	Organic	Soft Moderate	13 15 or 16	13 15 or 16	0.2 0.5	7.5 10 or 15	30 40 or 60	1.690 0.760 or 0.420	0.015 0.012	0.550 0.250 or 0.140	0.5 1.0 or 2.0	15 15	0 or 2 0 or 2	10 25 or 30
Peat	Not preloaded	Soft	10 or 12	10 or 12	0.1	5 or 7.5	20 or 30	7.590 or 1.810	0.023	2.530 or 0.600	0.2 or 0.5	15	2 or 5	10 or 20
	Moderately preloaded	Moderate	12 or 13	12 or 13	0.2	7.5 or 10	30 or 40	1.810 or 0.900	0.016	0.600 or 0.300	0.5 or 1.0	15	5 or 10	20 or 30
Variety Coefficient			0.05		-	0.25						0.10	0.20	

Appendix G – Geometry & Elevation Investigation

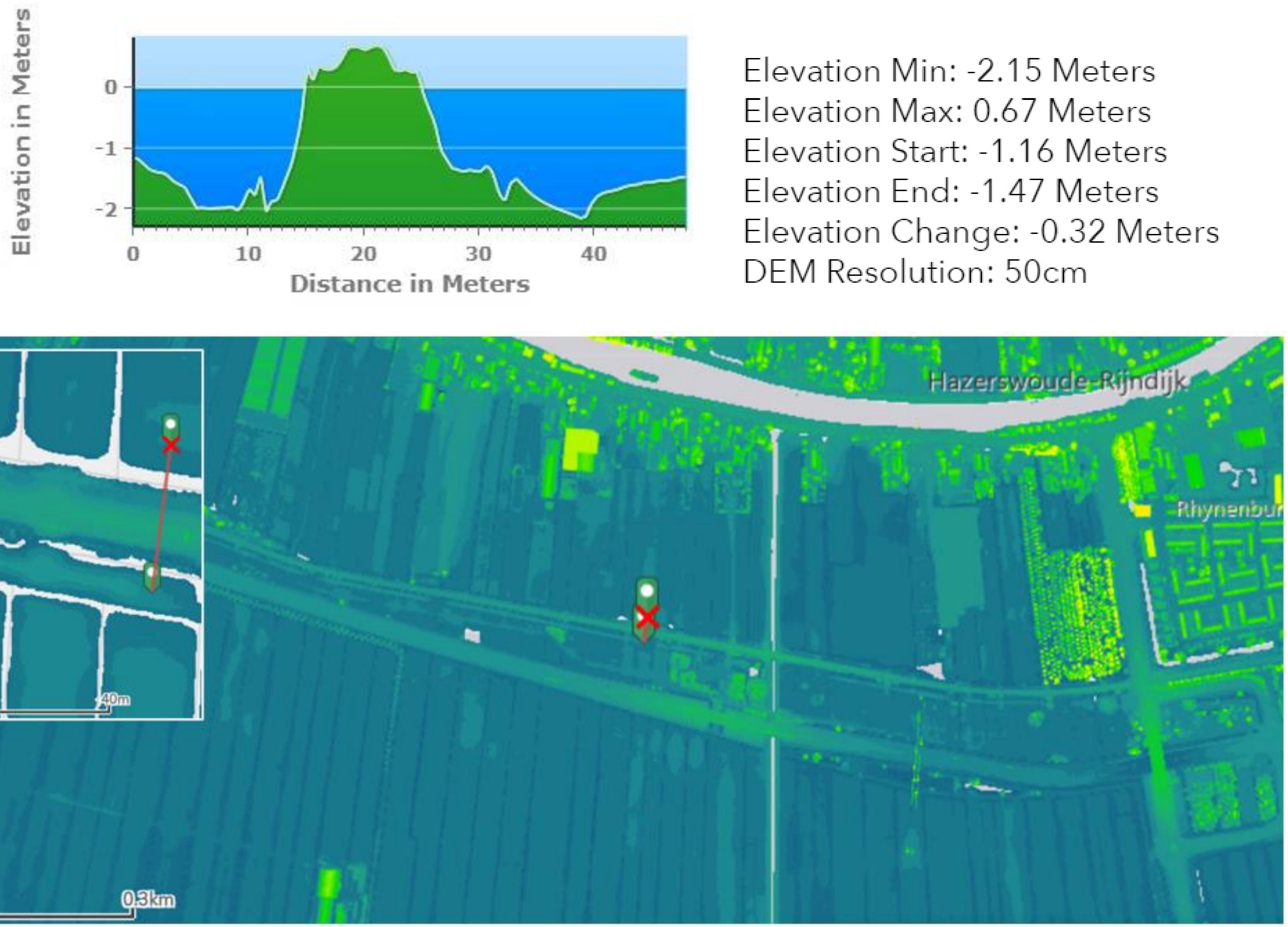


Figure 89 Geometry and Elevation Investigation (AHN, 2023)

Elevation Min: -1.16 Meters
Elevation Max: 1.20 Meters
Elevation Start: -1.10 Meters
Elevation End: -1.16 Meters
Elevation Change: -0.06 Meters
DEM Resolution: 50cm

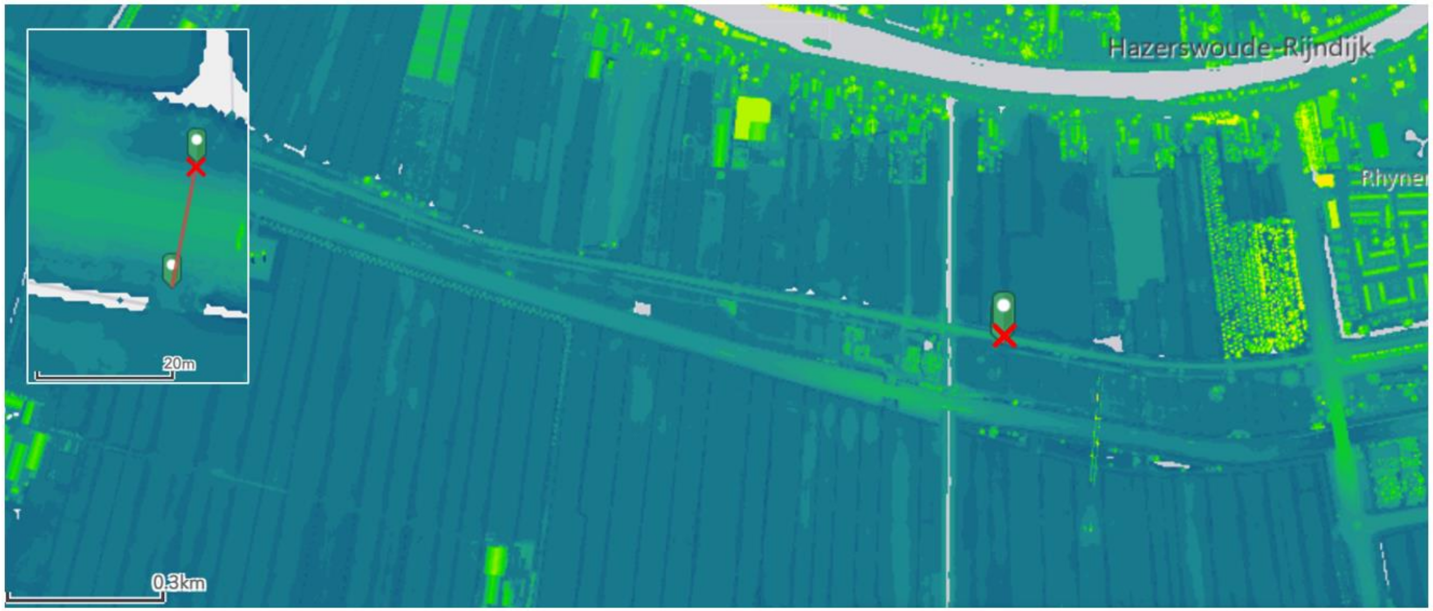


Figure 90 Geometry and Elevation Investigation (AHN, 2023)

Appendix H – Groundwater Level Investigation

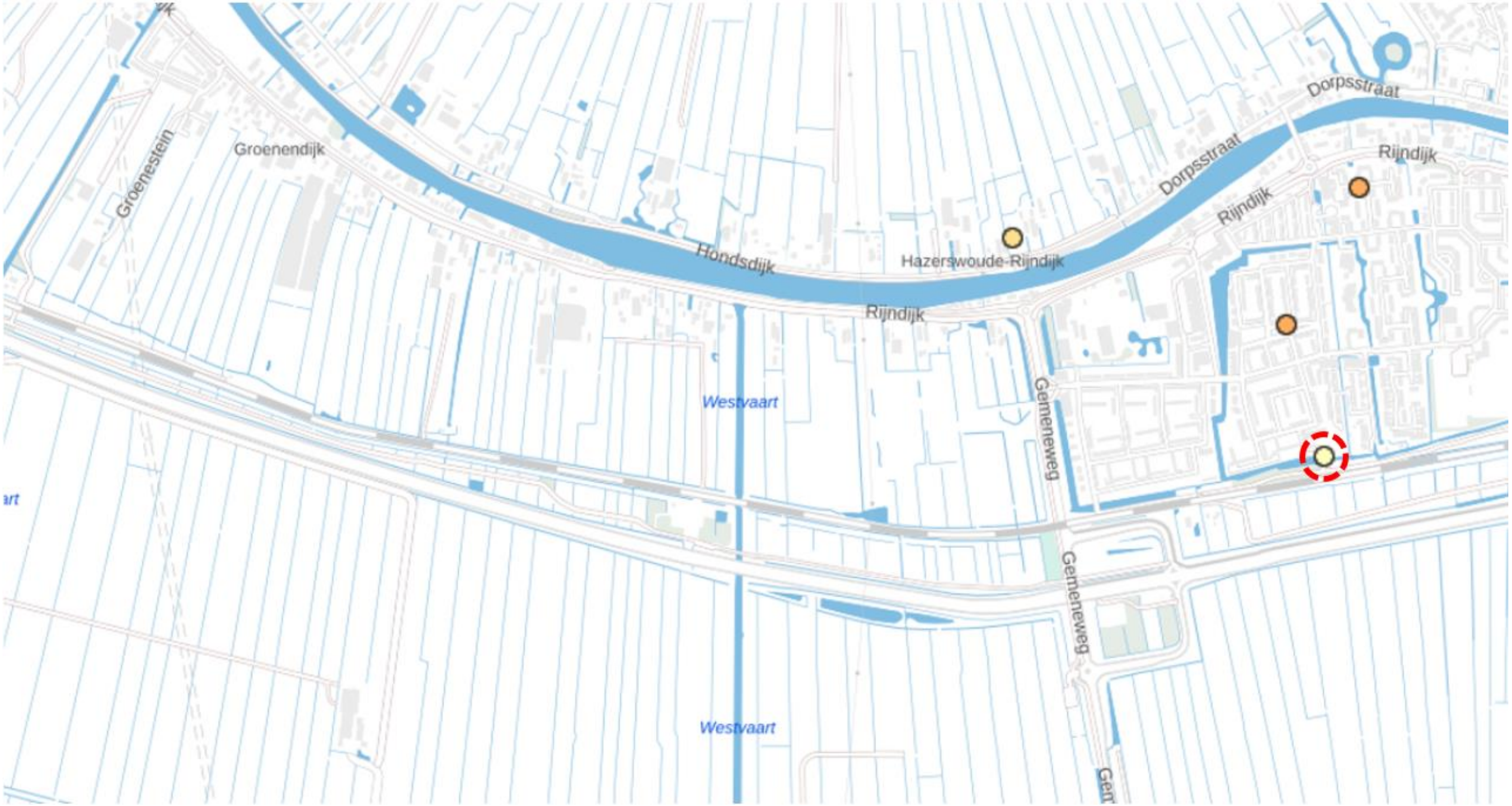


Figure 91 Location of the Groundwater Analysis (Grondwatertools, 2020)

Identificatie buis:	B31C0147-001
Coördinaten:	100565, 459951 (RD)
Maaiveld:	-1.46 m t.o.v. NAP
Hoogte bovenkant filter t.o.v. NAP:	-13.46 m
Hoogte onderkant filter t.o.v. NAP:	-14.46 m
Diepte bovenkant filter t.o.v. maaiveld:	12 m
Diepte onderkant filter t.o.v. maaiveld:	13 m
Drukopnemer aanwezig:	nee
Begindatum:	07-06-1968
Einddatum:	30-11-1998
Aantal metingen:	710

Grondwaterstanden

Identificatie:	B31C0147
Identificatie buis:	B31C0147-001
Coördinaten:	100565, 459951 (RD)
Maaiveld:	-1.46 m t.o.v. NAP

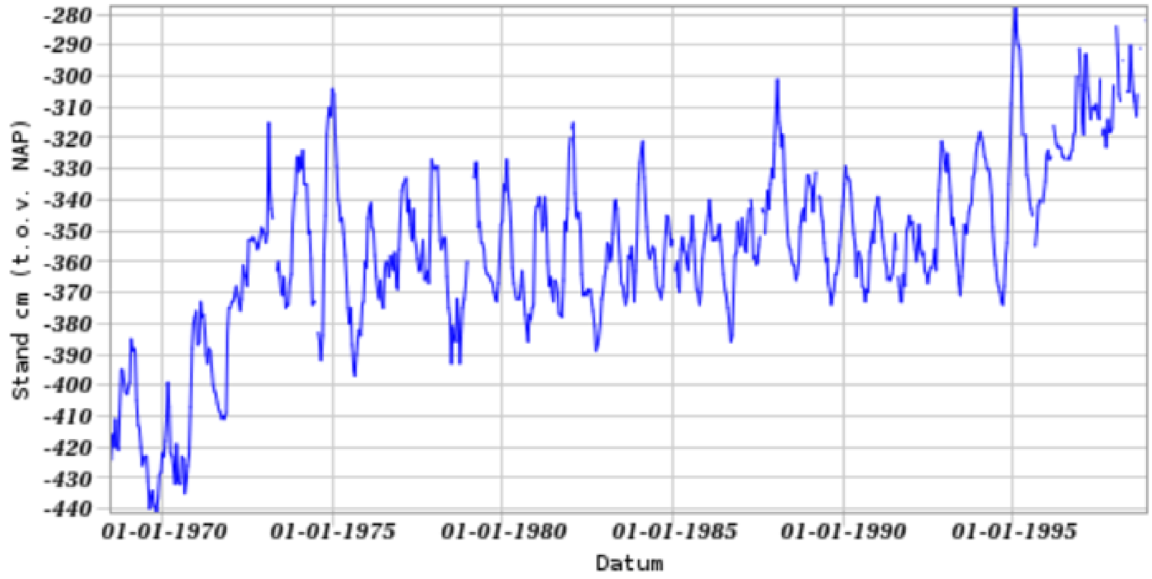


Figure 92 Obtained GWL Data from tube B31C0147 (DINOloket, 2023)

Appendix I – Soil Investigation

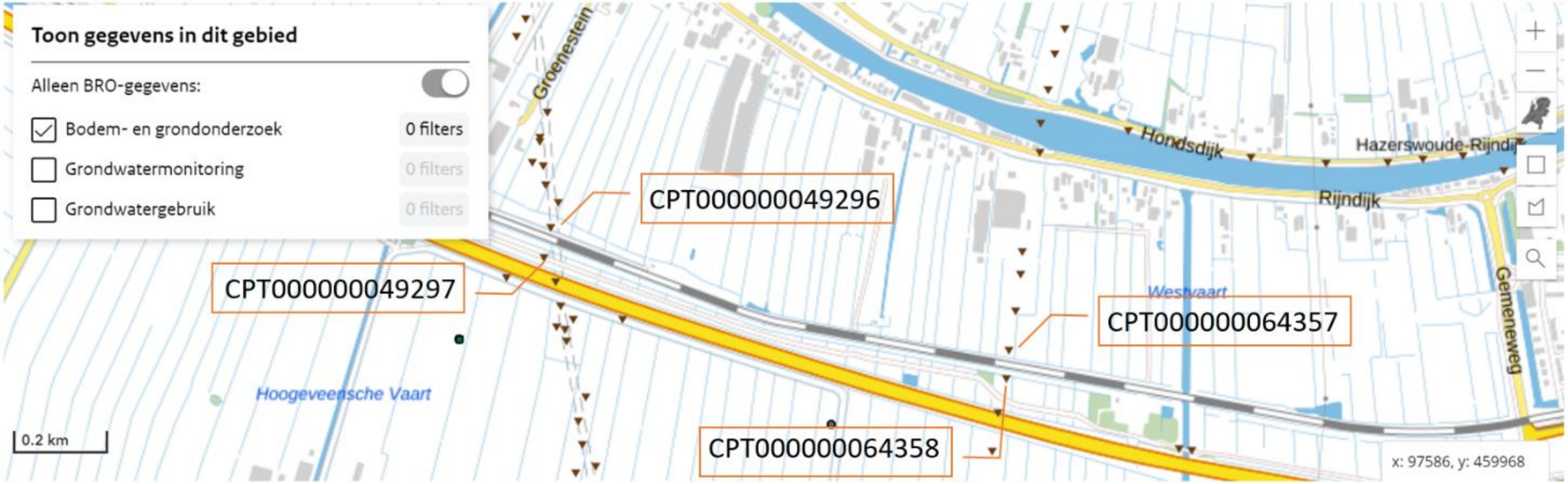


Figure 93 Location of the CPT's along the Railway Embankment (TNO, 2023)

CPT 49296

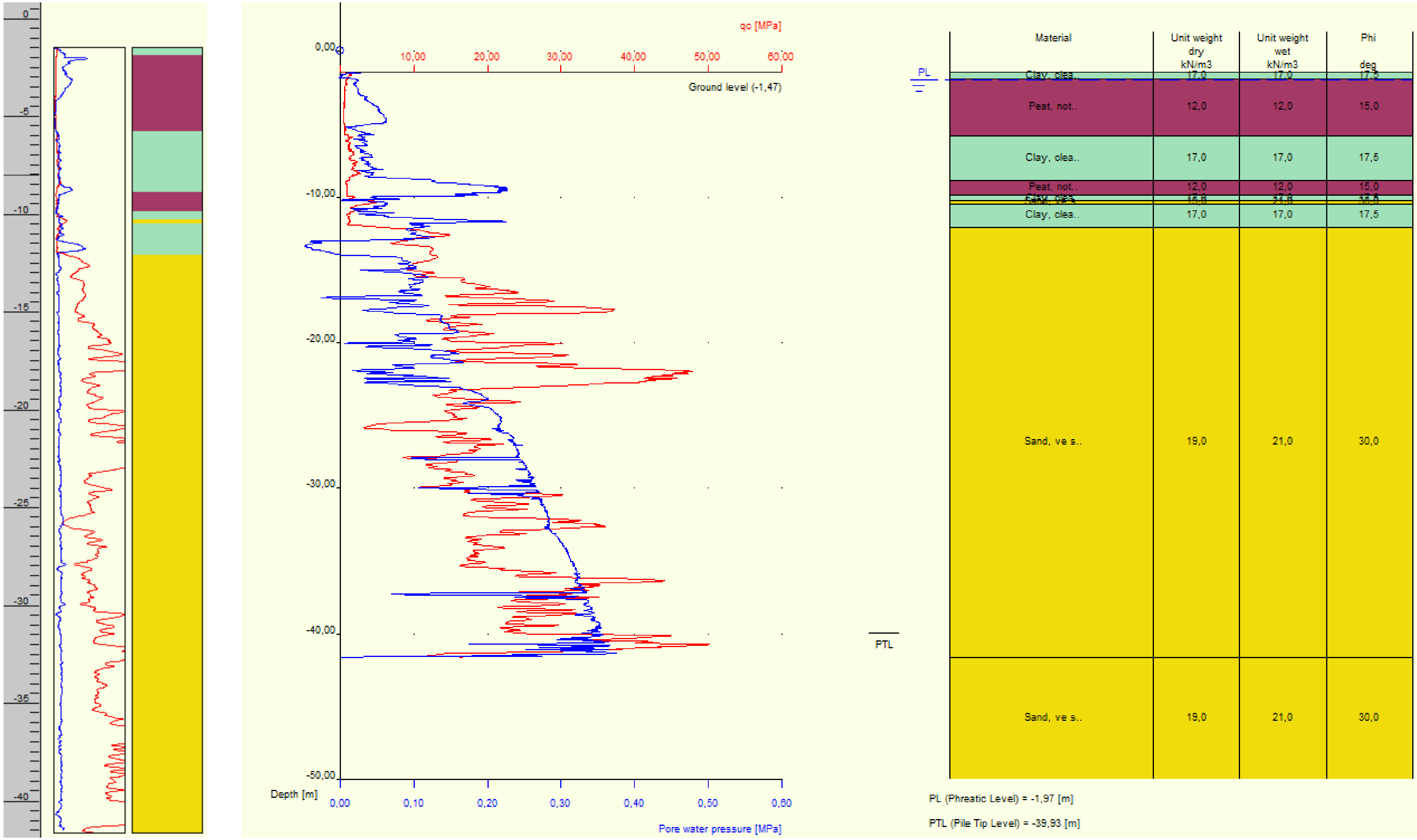


Figure 94 Soil Investigation CPT 49296 (D-Foundations , 2023)

CPT 49297

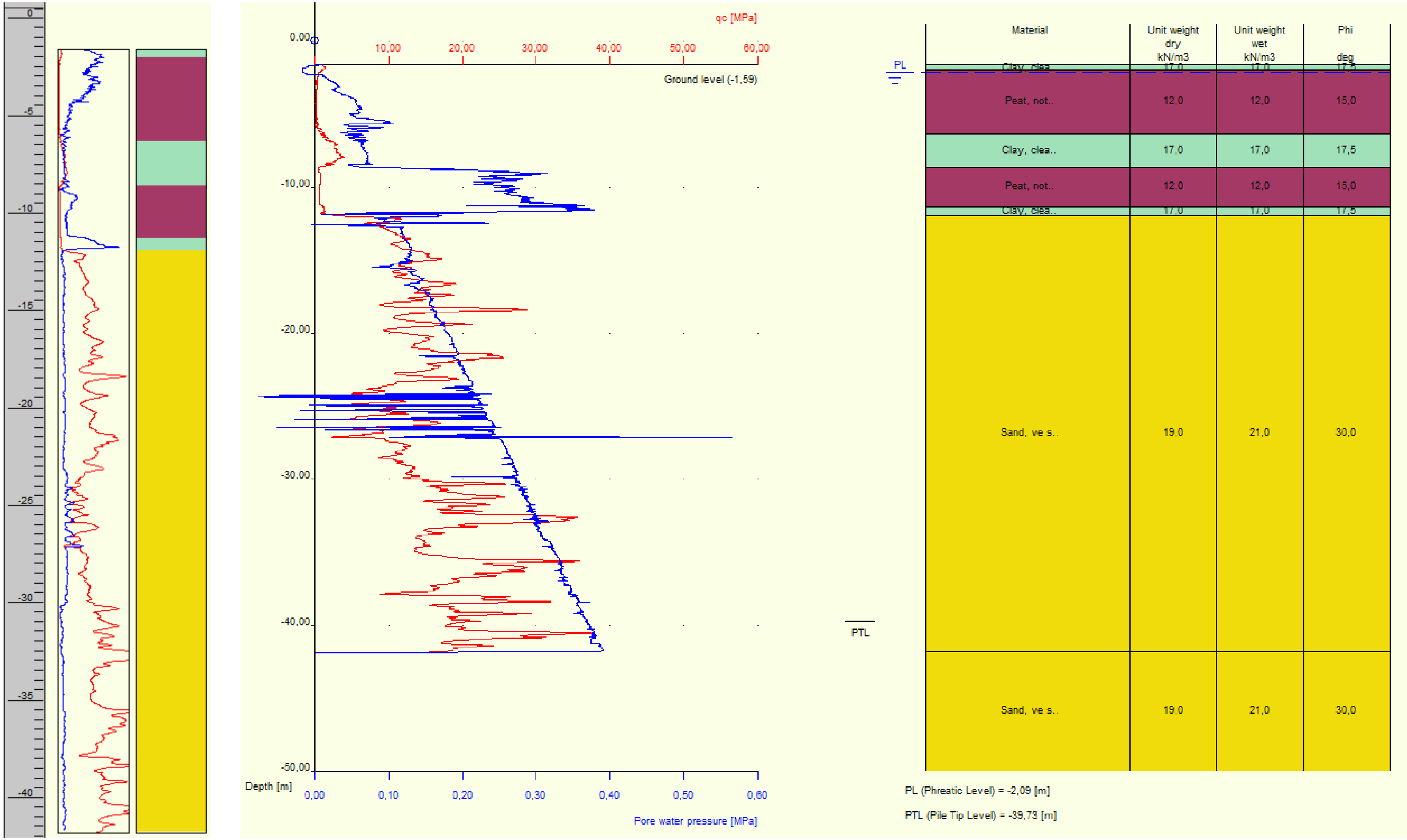


Figure 95 Soil Investigation CPT 49297 (D-Foundations , 2023)

CPT 64357

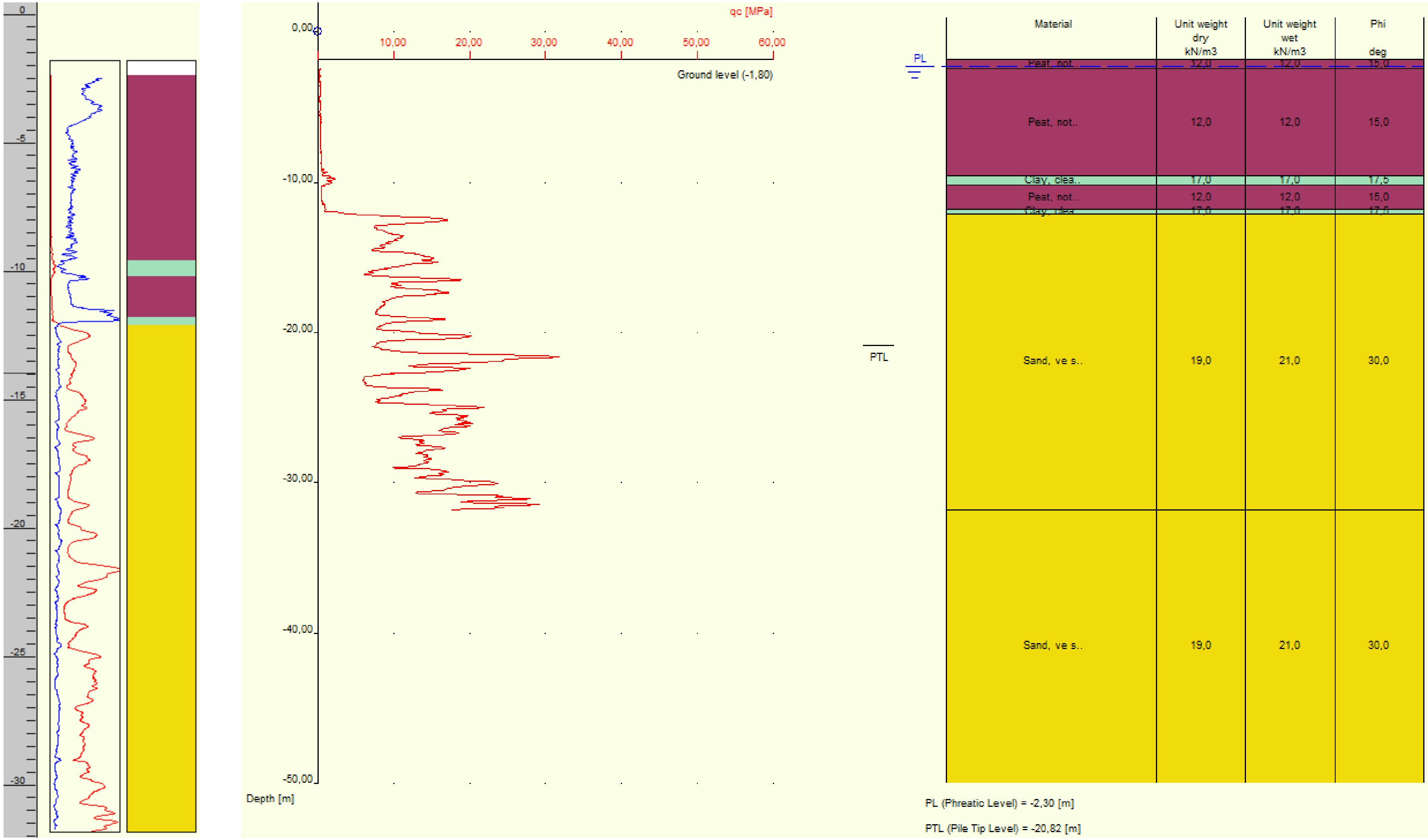


Figure 96 Soil Investigation CPT 64357 (D-Foundations , 2023)

CPT 64358

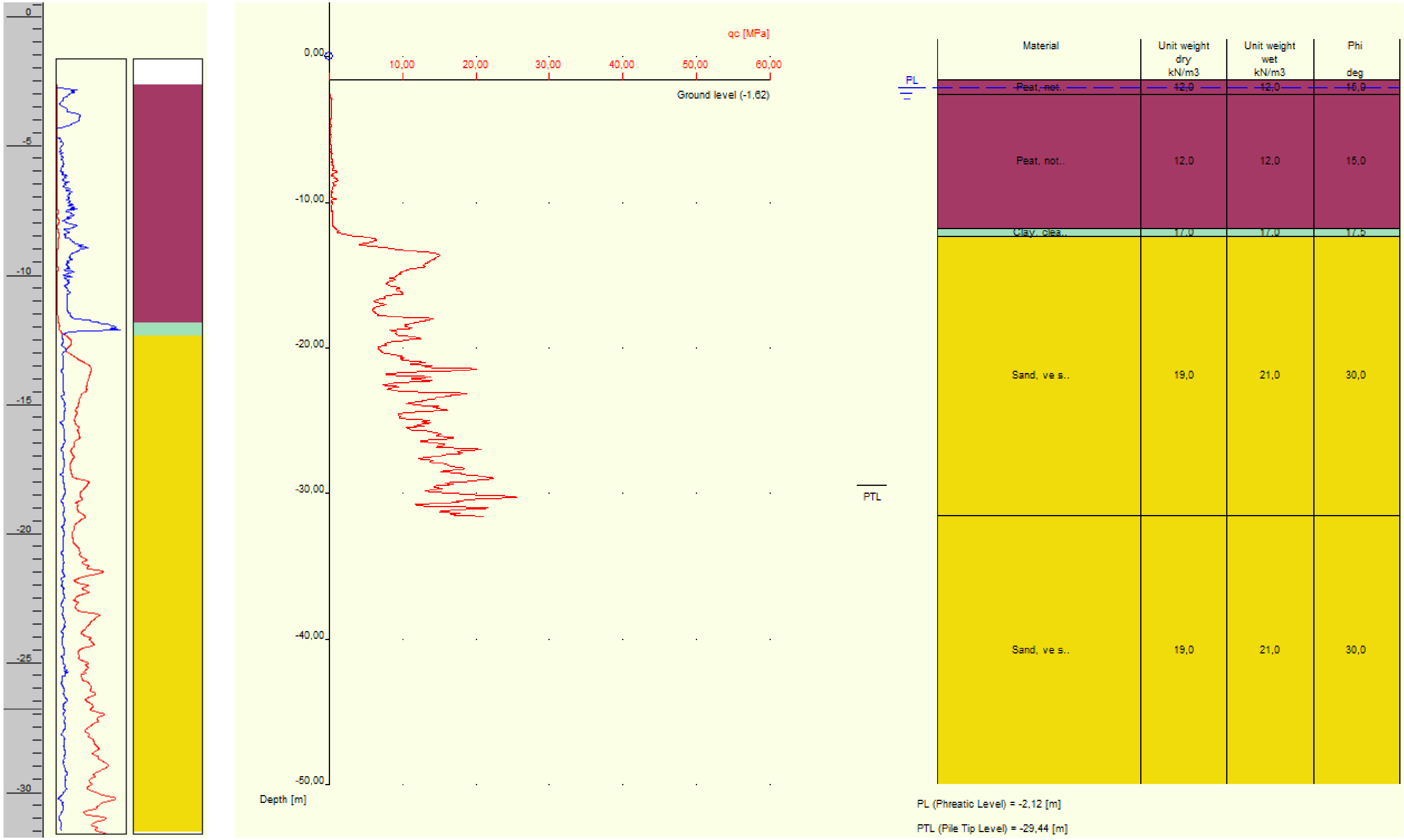


Figure 97 Soil Investigation CPT 64358 (D-Foundations , 2023)

Table 40 Investigation of the Soil Layers

BRO-ID	CPT 49296		CPT 49297		CPT 64357		CPT 64358	
VERSCHUIVING MAAIVELD T.O.V. NAP	-1.47 m		-1.59 m		-1.8 m		-1.62 m	
EINDDIEPTE T.O.V. MAAIVELD	40.16 m		40.23 m		30.01 m		29.98 m	
	Top level (m)	**Soil**	**Top level (m)**	**Soil**	**Top level (m)**	**Soil**	**Top level (m)**	**Soil**
	-1.47	Clay, clean, weak	-1,59	Clay, clean, weak	-1,8	Peat, not pl, weak	-1,62	Peat, not pl, weak
	-1.87	Peat, not pl, weak	-1,99	Peat, not pl, weak	-2,4	Peat, not pl, weak	-2,62	Peat, not pl, weak
	-5.77	Clay, clean, weak	-6,31	Clay, clean, weak	-9,6	Clay, clean, weak	-11,82	Clay, clean, weak
	-8.87	Peat, not pl, weak	-8,61	Peat, not pl, weak	-10,2	Peat, not pl, weak	-12,32	Sand, ve sil, loose
	-9,87	Clay, clean, weak	-11,31	Clay, clean, weak	-11,8	Clay, clean, weak	-31,52	Sand, ve sil, loose
	-10,27	Sand, ve sil, loose	-11,91	Sand, ve sil, loose	-12,1	Sand, ve sil, loose		
	-10,47	Clay, clean, weak	-41,75	Sand, ve sil, loose	-31,8	Sand, ve sil, loose		
	-12,07	Sand, ve sil, loose						
	-41,61	Sand, ve sil, loose						

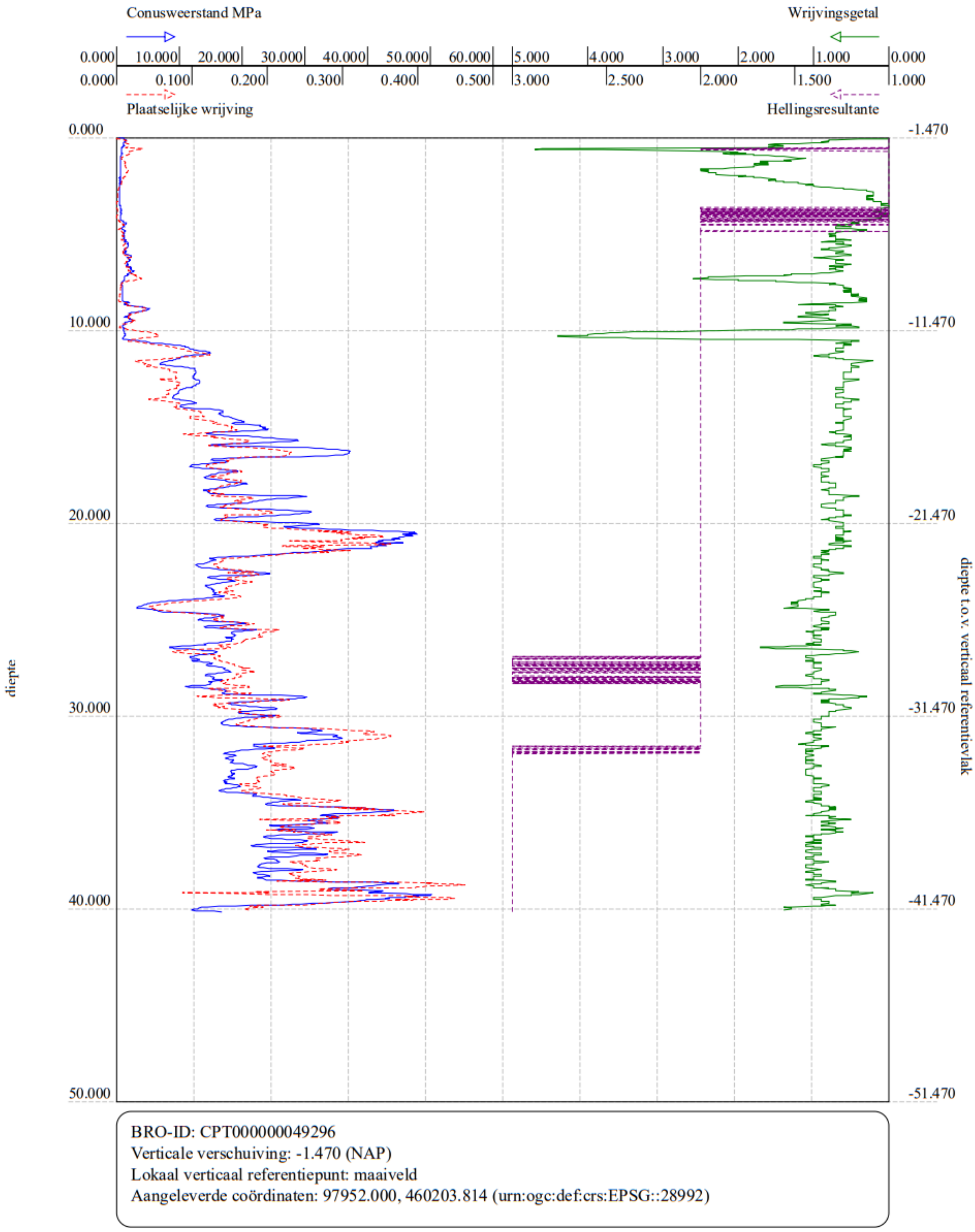


Figure 98 CPT 49296 (TNO, 2023)

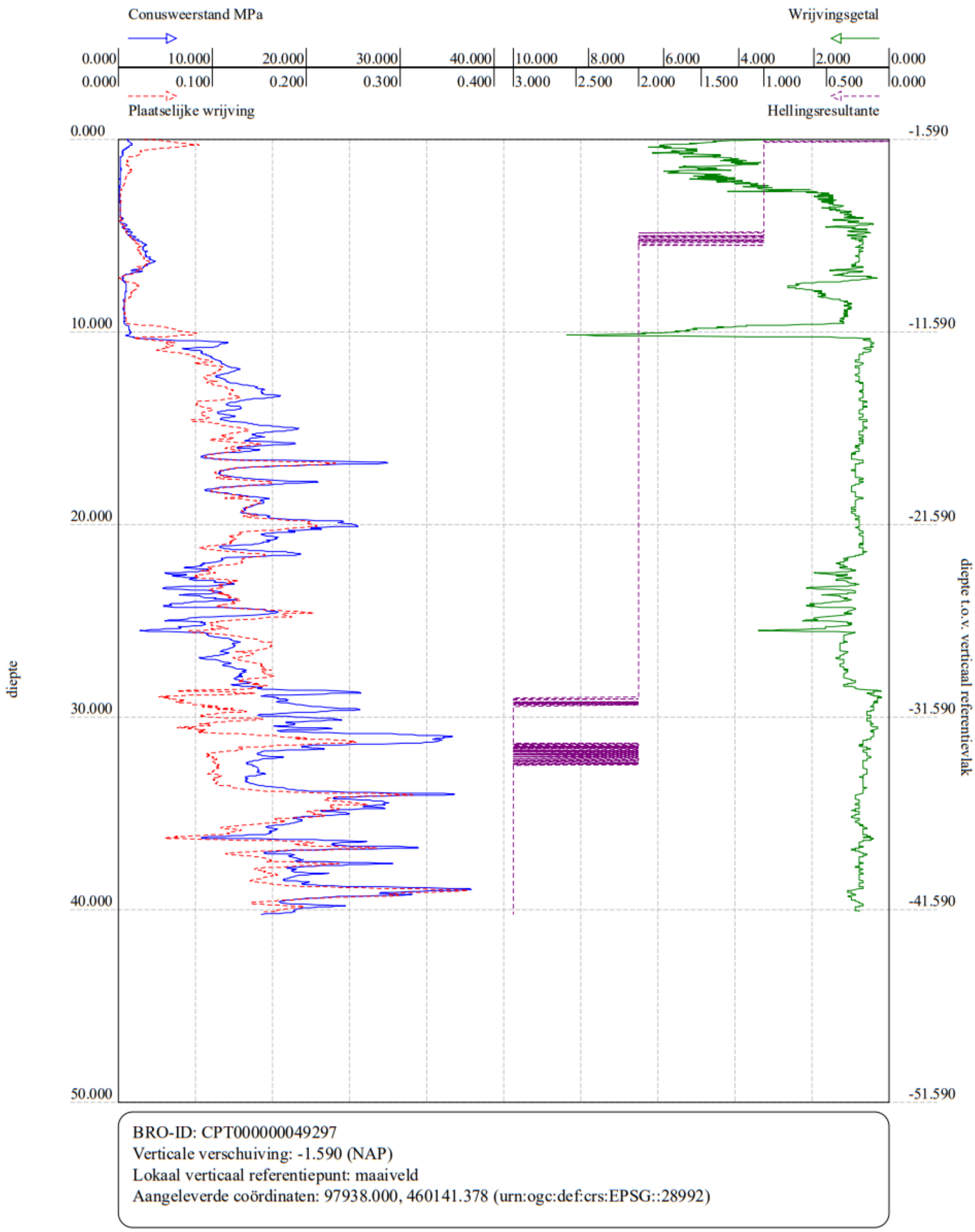


Figure 99 CPT 49297 (TNO, 2023)

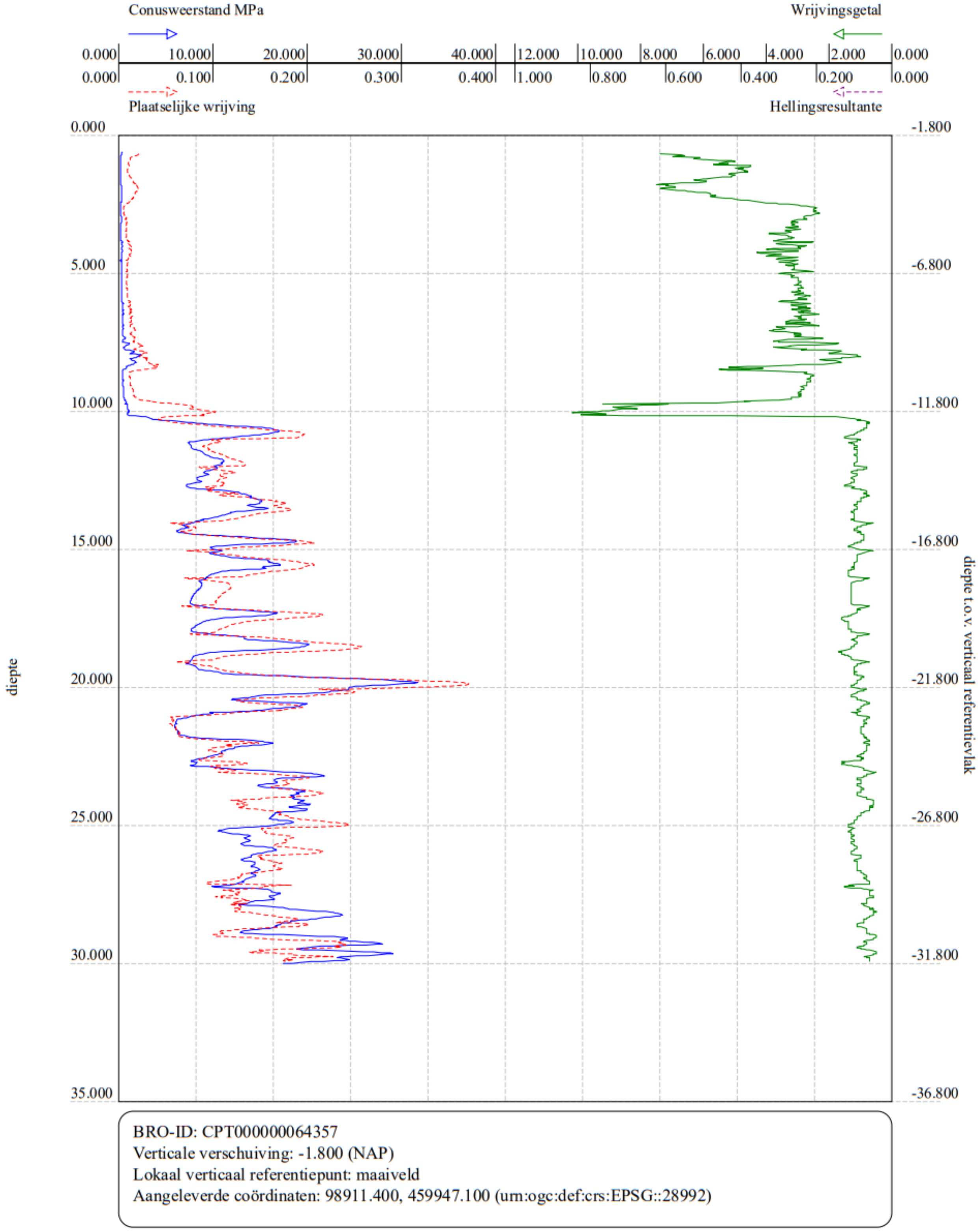


Figure 100 CPT 64357 (TNO, 2023)

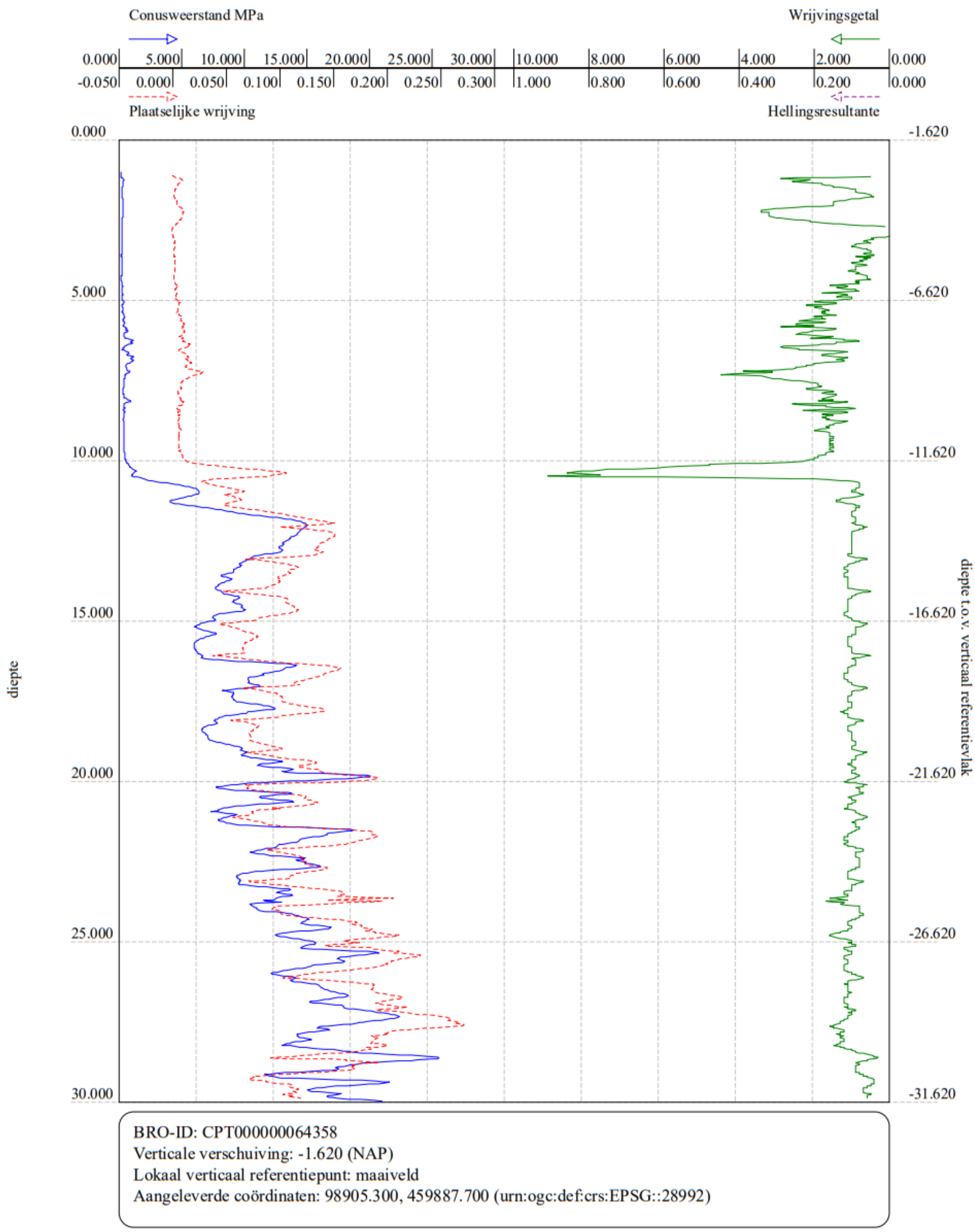


Figure 101 CPT 64358 (TNO, 2023)

Appendix J – Cables and Pipes

Figure 102 Cables and Pipes Investigation (Kadaster, 2023)

Appendix K – Reference Projects Soil Stabilization Methods

This appendix includes the reference projects, obtained through desk research. The soil improvement methods that are promising for the stabilization of the railway embankment are explored in **Chapter 3 – Methodology**. The various methods are broadly divided into two categories: soil stabilization methods that have been applied in a similar environment for a similar purpose, and techniques that have been applied in a non-comparable project but are promising methods.

K.1 – Pile Mattress Construction in Houten, The Netherlands

Problem Need for extra train track next to existing track near station Houten on soft soils.

Situation ProRail chose a pile mattress for the construction of a new train track alongside an existing one because there was no opportunity to pre-load the subgrade (time aspect) and a parking garage had to be built right along this track (space constraint).

Solution **Pile mattress construction**. The mattress lies between a structure founded on piles (the station) and a conventional earth track (Voton HSP, 2008). The pile mattress forms the gradual transition between the cast-in-place rails on the structure (0 cm. residual settlement) and the track in ballast on a conventional earth track (15 cm. settlement in 30 years).

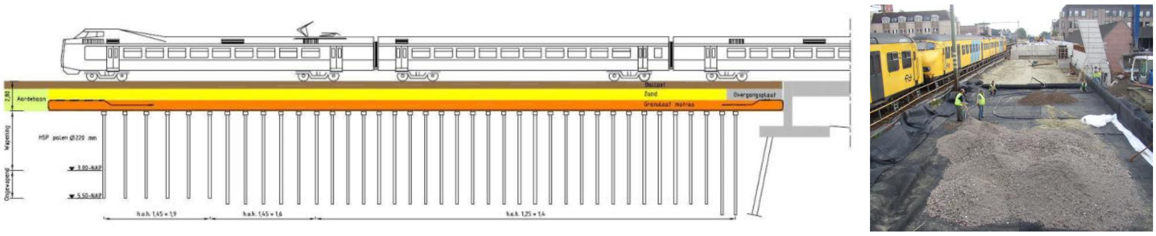


Figure 103 Pile Mattress System, implemented in Houten, The Netherlands (Voton HSP, 2008)

K.2 – Cunet Construction for road widening in The Netherlands

Problem Need for road widening next to existing highway water on soft soils.

Situation Often, the cunet method is chosen to expand the existing road infrastructure in the Netherlands, depending on the depth of the soft soil layers. The cunet has proven to work for the construction of a new road alongside an existing one (P.Geertsma, 2014).

Solution **Cunet construction**. a method often used in road widening and includes the excavation of the weak subsoils. Traditionally, compacted sand is used to replace the soil to form a solid foundation. Sand is hardly subject to settlement, making sand an ideal raw material for soil improvement. Sand bodies are widely used since excavation is relatively easy; even in extreme weather conditions such as rain or slight frost.

Figure 104 Examples of road widening by creating a cunet (Drenth Groep, 2023)

K.3 – Cement Injection Double Railway Track in Kroya, Indonesia

Problem Need for a double railway track on soft saturated clayey soil.

Situation Project includes double tracking the Java railway network. Designed to expand the line capacity for the future traffic demand in Central Java by constructing railway double track (Bauer, 2017).

Solution Treatment of underlying soft saturated clays by means of **Deep-Soil-Mixing method** in order to improve its bearing capacity and limit settlements under the proposed double railway track. A total of 2,903 soil cement columns with diameter of 1 m and variable lengths were constructed.

Figure 105 Cement Injection as Soil Stabilization Method in Train Track Construction (Bauer, 2017)

K.4 – Preload with Glass Foam for Road Construction in Purmerend, The Netherlands

Problem New road infrastructure on weak subsoils.

Situation As a result of the construction of a residential area along a canal, expansion of the road infrastructure is required to connect with the surrounding area. The design had to meet minimum maintenance, disruption, and settlement requirements. Because of the very weak subsoil, glass foam was chosen as a lightweight foundation material (L.J.Oostlander, 2020).

Solution Raising by using **glass foam after preloading** the weak soils was chosen in order to improve the bearing capacity and limit settlements under the new road infrastructure.

Figure 106 Preloading combined with lightweight Glass Foam in Road Construction (L.J.Oostlander, 2020)

K.5 – Accelerated site preparation using the IFCO Method in Assendelft, The Netherlands

Problem In times of housing shortage, there is a need to be able to construct residential areas in a short period of time.

Situation Due to the housing shortage, a weak subsoil had to be made ready for building and living in the Kreekrijk in Assendelft in a short time. The client wanted maximum flexibility in its choice of sequence for building the approximately 600 houses. To speed up the preparation of the public areas for construction, the IFCO method was used. This made 70,000 square meters ready for building within half a year. The rest of the construction process could be started quickly (Gebr. Van Kessel, 2022).

Solution Using the **IFCO method**, weak subsoils are made ready for building in an accelerated manner. The construction process is shortened by several months. This not only saves time but also considerably cuts down costs.

Figure 107 IFCO-Method used to prepare the soft subsoil for project Kreekrijk in Assendelft (IFCO, 2023)

K.6 – Geotextile Encased Columns for the stabilization of soft soils in Hamburg, Germany

Problem Stabilization of soft subsoil conditions of 140 ha reclaimed land in the river Elbe estuary.

Situation A scheme to extend the DASA Airbus plant at the Mühlenberger Loch site in Hamburg involved the reclamation of 140 ha of land in the river Elbe estuary. The extremely soft subsoil conditions necessitated the adoption of a foundation system incorporating 60,000 Ringtrac Geotextile Encased columns. This system offered tremendous advantages over the originally envisaged sheet piling solution: apart from shortening the construction period by over a year, the method eliminated the need for 35,000 tonnes of sheet piling, approx. 1.1 million cubic metres of sand and 8 million litres of fuel (Huesker Inc., 2019).

Solution The Ringtrac foundation system combines Stabilenka horizontal reinforcement with a regular arrangement of columns of non-cohesive material placed inside a geosynthetic casing. **Geotextile-encased columns** are a development of the traditional vibro stone columns. The structural action of the geotextile casing transforms granular columns into efficient load-bearing elements. The system offers high ductility and adaptability to variable subsoil conditions. Given that the full-surface drainage capability of the Ringtrac columns vastly speeds up consolidation times, over 90% of settlement already takes place during the construction period. Creep settlement is also reduced by 50-75% compared to unimproved ground. The fact that locally sourced mineral mixes can be used as fill brings additional savings on time and cost.

Figure 108 GEC-Method used in Germany for the stabilization of soft soils (Huesker Synthetic GmbH, 2014)

K.7 – Electrified Double Track for the Gemas-Bahru Rail Project in Malaysia

Problem The Gemas-Johor Bahru Electrified Double Track Railway project is a Malaysian Government request to complement the existing electrified railway service that connects Padang Besar, in the north of Peninsular Malaysia, to Gemas, in the south (Menard, 2023).

Situation The project starts in Gemas and covers 4 main districts of Johor: Segamat, Kluang, Kulai and Johor Bahru, ending in Johor Bahru Sentral. The line provides Malaysia with electrified tracks that connect to the southern tip of the country. The distance of the track is 192 km and passes through eleven stations with a nominal speed of 160 km/h. The main challenge of this project is that the construction works had to be carried out while the existing railway line was still operational. Thus, Menard had to plan very carefully to ensure that the installation of the stone columns could be carried out safely and without disrupting rail traffic.

Solution Menard was contracted to supply and install 1.0 m diameter **stone columns** using the dry method in 3 of the 5 key sections of the project. More than 200,000 linear meter of stone columns were installed. The stone column technique has been chosen to improve the soil between five and up to 15 m in depth so that the embankment, to support the new railway line, could be built.

Figure 109 Expansion of the railway line using the method of gravel columns in Malaysia (Menard, 2023)

Appendix L – Ranking based on Expert Judgement

Ranking obv expert judgement: grondstabilisatie methoden

Uitgangspunten:

- Alle methoden over dezelfde lengte worden uitgevoerd;
- Grove inschatting, ene methode is 'beter' dan de andere;
- Ranken op zo'n manier dat 1 = beste/goedkoopste/minste zettingen / minste onderhoud/ minste risico's/ minste dagen buitendienststelling nodig en 7=minst goed;
- De grond bestaat tot -12mNAP uit klei en veen. Daaronder ligt zand;
- GWL op ongeveer -2mNAP;

U hoeft enkel pagina 2 in te vullen, bedankt voor uw hulp!

Voorbeeld:

Ranking Zettingen en Stabiliteit

- Zettingen na verloop van tijd .

Methode	Ranking (1-7)
Pile Mattress	1
Cunet & Gap method	4
Cement Injection	5
Preload + Glass foam	2
IFCO methode	6
Geotextile encased column	3
Grind Column	7

Dit voorbeeld geeft aan dat het paalmatras mbt de verwachtte zettingen, het beste is omdat de methoden de minste zettingen zou geven.
De voorbelasting met licht ophoogmateriaal zou ook resulteren in weinig zettingen. De grindkolommen en IFCO methoden zijn in dit voorbeeld als 'slechtste' beoordeeld omdat de zettingen het grootst zullen zijn.

#	Settlement	Risk	Sustainability	Maintainability	Costs	Shutdown	TRL
1	Pile M.	Pile M.	Pile M.	Pile M.	Grind K.	Pile M.	Pile M.
2	Preload	GOZ	Cement	GOZ	GOZ	Cement	Preload
3	GOZ	Cement	Grind K.	Preload	IFCO	Cunet	GOZ
4	IFCO	IFCO	GOZ	IFCO	Pile M.	IFCO	IFCO
5	Cunet	Grind K.	Preload	Cunet	Cement	Preload	Cunet
6	Grind K.	Preload	IFCO	Grind K.	Preload	GOZ	Cement
7	Cement	Cunet	Cunet	Cement	Cunet	Grind K.	Grind K.

Ranking Zettingen en Stabiliteit

- Zettingen na verloop van tijd .

Methode	Ranking (1-7)
Paalmatras	1
Cunet	6
Cement Injectie	7
Voorbelasting + licht ophoog materiaal	2
IFCO methode	4
Geotextiel Ommantelde Palen (GOZ)	3
Grind Kolommen	6

Ranking Risico's

- Gedurende het installeren en onderhoud (ook risico's meegenomen in relatie tot invloed op het bestaande baanlichaam)

Methode	Ranking (1-7)
Paalmatras	1
Cunet	7
Cement Injectie	3
Voorbelasting + licht ophoog materiaal	6
IFCO methode	4
Geotextiel Ommantelde Palen (GOZ)	2
Grind Kolommen	5

Ranking Duurzaamheid

- Materiaal gebruik (hierop beoordeeld);

Methode	Ranking (1-7)
Paalmatras	1
Cunet	7
Cement Injectie	2
Voorbelasting + licht ophoog materiaal	5
IFCO methode	6
Geotextiel Ommantelde Palen (GOZ)	4
Grind Kolommen	3

Ranking Onderhoud

- Gedurende de ontwerp levensduur;
- Voornamelijk de kosten als gevolg van periodiek onderhoud.

Methode	Ranking (1-7)
Paalmatras	1
Cunet	5
Cement Injectie	7
Voorbelasting + licht ophoog materiaal	3
IFCO methode	4
Geotextiel Ommantelde Palen (GOZ)	2
Grind Kolommen	6

Ranking Kosten

- Aanleg/constructie;
- Materiaal/ machines.

Methode	Ranking (1-7)
Paalmatras	4
Cunet	7
Cement Injectie	5
Voorbelasting + licht ophoog materiaal	6
IFCO methode	3
(GOZ)	2
Grind Kolommen	1

Ranking Buitendienststelling

- Voorkeur methode die de aantal dagen/weken buitendienststelling van naastgelegen spoor limiteert.

Methode	Ranking (1-7)
Paalmatras	1
Cunet	3
Cement Injectie	2
Voorbelasting + licht ophoog materiaal	5
IFCO methode	4
Geotextiel Ommantelde Palen (GOZ)	6
Grind Kolommen	7

Appendix M – Reference Projects Design Variants

This appendix includes reference projects for the design of the three viable solutions as described in **Chapter 3 – Methodology**. The three variants are designed based on literature research. Therefore, reference projects and application examples are collected to ensure the combination of materials is viable and has proven to work.

M.1 – Huësker's Pile Mattress for the N210 Design in the Netherlands

The N210 national road in the Netherlands crosses soft organic subsoils, which are up to 15 meters thick. The road is therefore carried on a geosynthetic reinforced embankment built on driven precast concrete piles with pile caps. As part of the contract, a 50 m trial embankment section was constructed and fitted with a monitoring system. The recorded data were used to verity the design and confirm the high safety standard of Huësker's Fortrac geogrid pile mattress system. Under quality assurance regime, data logging continues for at least another 20 years (Huësker, 2019).

Figure 110 Application of Huësker's Fortrac Geogrid on the N210 National Road (Huësker, 2019)

M.2 – Huësker's Geotextile Encased Columns for the Steigereiland in Amsterdam, the Netherlands

The municipality of Amsterdam decided to build the new district IJburg on eight newly made island in the IJmeer east of Amsterdam city. The islands are built up using sand-layers to a total thickness of 4 to 6 meters, placed on the bed of the IJmeer. An acceptable bearing capacity is reached around 10 meters beneath the first sand layer. On the Steigereiland, one of the eight islands, an embankment construction was planned along the edge. A woven polyester with an ultimate tensile strength of 400 kN/m was required. The 5-meter width geotextile was supplied in lengths to minimize installation losses. On site, the geotextile was placed on the first sand layer above water level and then sewn together using portable sewing machines to form large panels. After placing the geotextile, the area has been enclosed by small dykes and brought up to level using hydraulic fill (Huësker, 2023).

Figure 111 Application of Huësker's Geotextile Encased Columns on the Steigereiland in Amsterdam (Huësker, 2023)

M.3 – Preload and Glass Foam for the stabilization of the Montfoortlane in Hazerswoude-Dorp, the Netherlands

Foam glass was used for the embankment of a lane in Hazerswoude-Dorp. Hazerswoude suffers from excessive settlement, which can reach about 80 centimeters locally due to the underground peat soil. By first preloading the road and then raising using the lightweight foam glass, the settling was limited to about 7 centimeters over a 30-year span. Over 6,500 cubic meters of foam chunks were processed under the road; a fill material thickness of 50 centimeters is used (Van der Werff Groep, 2017).

Figure 112 Application of preload combined with Glass Foam on the Montfoortlane (Omroep West, 2017)

Appendix N – Stability Analysis Zero Variant

```
Program      : D-Geo Stability
Version      : 18.2.2.32619
Company      : ARCADIS Infrastructure
Date         : 02/06/2023
Time         : 16:25:18
==========================    BEGINNING OF DATA     ==========================

               ECHO OF THE INPUT
               =================

 Calculation model       : Bishop
 Default shear strength : C phi


               PL-LINES
               ========

 Pl-line no. | Co-ordinates [m]
 ------------|--------------------------------------------------
             |
   1  - X -  | -15.00    15.00
   1  - Y -  |  -2.50    -2.50


 Unit weight of water used for calculation:     9.81 [kN/m3]
 The groundwater level is determined by Pl-line number 1

               SOIL PROPERTIES
               ===============

 Layer no.| Material name
 ---------|-----------------------------
      10  | Loose Sand
       9  | Soft Clay
       8  | Peat
       7  | Medium Clay
       6  | Peat
       5  | Medium Clay
       4  | Loose Sand
       3  | Medium Clay
       2  | Loose Sand
       1  | Dense Sand

  Layer    | Gam usat| Gam sat | Pl-line | Pl-line |
  number   | [kN/m3] | [kN/m3] |   top   | bottom  |
 ---------|---------|---------|---------|---------|
      10  |   17.00 |   19.00 |    1    |    1    |
       9  |   14.00 |   14.00 |    1    |    1    |
       8  |   12.00 |   12.00 |    1    |    1    |
       7  |   17.00 |   17.00 |    1    |    1    |
       6  |   12.00 |   12.00 |    1    |    1    |
       5  |   17.00 |   17.00 |    1    |    1    |
       4  |   17.00 |   19.00 |    1    |    1    |
       3  |   17.00 |   17.00 |    1    |    1    |
       2  |   17.00 |   19.00 |    1    |    1    |
       1  |   19.00 |   21.00 |    1    |    -    |


               UNIFORM LOAD
               ============

   Uniform    |Magnitude| X start |  X end  | Distrib.|   Load    |
 load number  | [kN/m]  |   [m]   |   [m]   | degrees |   Type    |
 ------------|---------|---------|---------|---------|-----------|
     1        |  12.50  |  -5.00  |   5.00  |  25.00  | Permanent |
     2        |  63.00  |   2.25  |   4.75  |  25.00  | Temporary |
     3        |  63.00  |  -4.75  |  -2.25  |  25.00  | Temporary |


****************  The input has been tested, and is correct.  ****************
******************************************************************************
```

```
                 RESULTS OF THE SLOPE STABILITY ANALYSIS
                 =======================================

The center point of the critical circle lies on the edge of the grid.

New grid with  : X minimum =    1.31  [m]
                 X maximum =   11.69  [m]
                 Y minimum =    0.26  [m]
                 Y maximum =    7.91  [m]


Information on the critical circle  : Fmin =       0.953
Calculation method used             : Bishop - C phi
=============================================================================

X co-ordinate center point      :          9.10  [m]
Y co-ordinate center point      :          2.17  [m]
Radius of critical circle       :          6.84  [m]

The center point of the critical circle is enclosed

Total driving moment            :       1193.03  [kNm/m]
Driving moment free water       :          0.00  [kNm/m]
Driving moment external loads   :        804.45  [kNm/m]
Iterated resisting moment       :       1137.10  [kNm/m]
Non-iterated resisting moment   :       1143.79  [kNm/m]

                            END OF D-Geo Stability OUTPUT
                            =============================
```

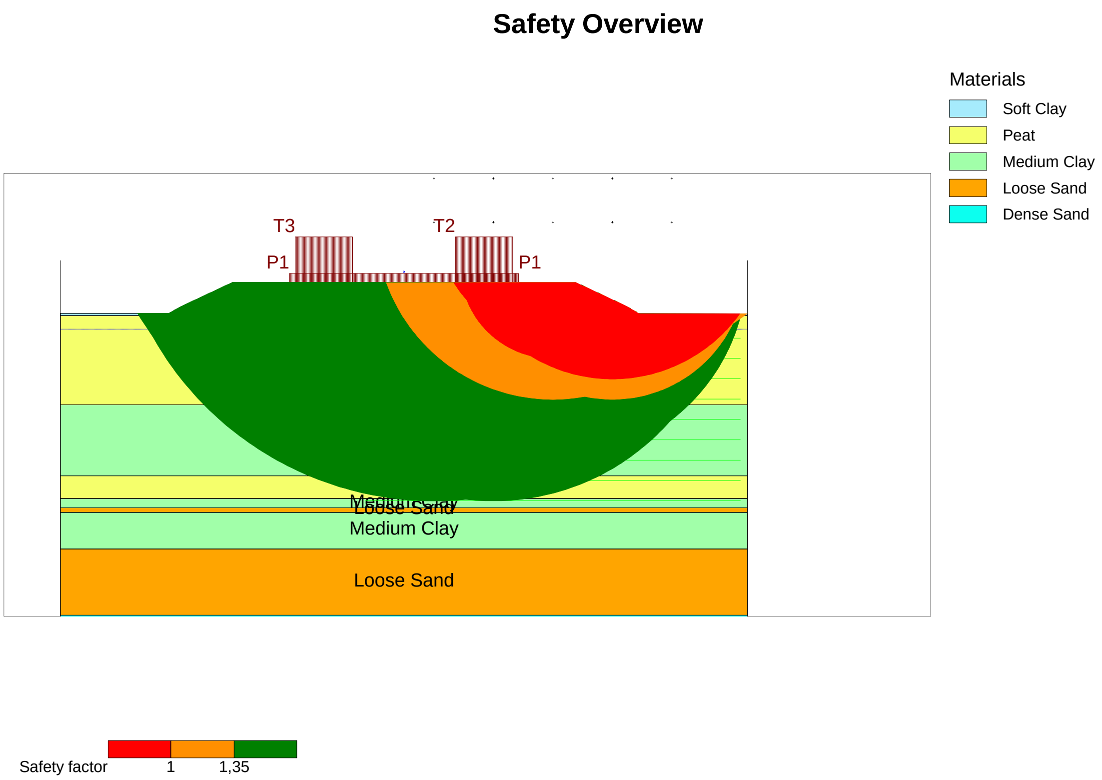


Figure 113 Safety Overview Zero Variant D-Geo Stability

Appendix O – Stability Analysis Pile Mattress Variant

```
Program      : D-Geo Stability
Version      : 18.2.2.32619
Company      : ARCADIS Infrastructure
Date         : 02/06/2023
Time         : 23:31:03

==========================    BEGINNING OF DATA     ==========================


               ECHO OF THE INPUT
               =================

 Calculation model       : Bishop
 Default shear strength : C phi


               PL-LINES
               ========

 Pl-line no. | Co-ordinates [m]
 ------------|---------------------------------------------------
             |
   1  - X -  | -15.00    15.00
   1  - Y -  |  -2.50    -2.50


 Unit weight of water used for calculation:     9.81 [kN/m3]
 The groundwater level is determined by Pl-line number 1


               CENTER POINT GRID AND TANGENT LINES
               ===================================

 X co-ordinate grid left                  :    2.91 [m]
 X co-ordinate grid right                 :   10.89 [m]
 Number of grid points in X - direction   :    10

 Y co-ordinate grid bottom                :    0.77 [m]
 Y co-ordinate grid top                   :    8.23 [m]
 Number of grid points in Y - direction   :    10

 Y co-ordinate tangent smallest circle    :   -2.00 [m]
 Y co-ordinate tangent biggest  circle    :  -10.00 [m]
 Number of circles per grid point         :    10

 No fixed points input.

 Total number of center points in the grid:   100
 Total number of slip circles in the grid :  1000

               UNIFORM LOAD
               ============

   Uniform    |Magnitude| X start |  X end   | Distrib.|    Load    |
 load number  |  [kN/m] |   [m]   |   [m]    | degrees |    Type    |
 ------------|---------|---------|---------|---------|-----------|
     1        |  12.50 |  -5.00 |   5.00 |   25.00 | Permanent |
     2        |  63.00 |   2.25 |   4.75 |   25.00 | Temporary |
     3        |  63.00 |  -4.75 |  -2.25 |   25.00 | Temporary |

               GEOTEXTILES
               ===========

  Geotextile |  E.T.S  | X start |  X end   |     Y    |reduction|
    number   |  [kN/m] |   [m]   |   [m]    |    [m]   | zone [m]|
 ------------|---------|---------|----------|---------|---------|
     1        |  120.00 |  -12.00 |   12.00 |   -1.90 |    0.00 |

  E.T.S. = Effective tensile strength

****************  The input has been tested, and is correct.  ****************
******************************************************************************
```

```
               RESULTS OF THE SLOPE STABILITY ANALYSIS
               =======================================
The center point of the critical circle lies on the edge of the grid.

New grid with  : X minimum =    2.91  [m]
                 X maximum =   10.89  [m]
                 Y minimum =   -0.06  [m]
                 Y maximum =    7.40  [m]


Information on the critical circle  : Fmin =      1.409
Calculation method used             : Bishop - C phi
=============================================================================

X co-ordinate center point      :          8.23  [m]
Y co-ordinate center point      :          0.77  [m]
Radius of critical circle       :          6.33  [m]

The center point of the critical circle is enclosed

Total driving moment            :       1333.71  [kNm/m]
Driving moment free water       :          0.00  [kNm/m]
Driving moment external loads   :        920.66  [kNm/m]
Iterated resisting moment       :       1878.53  [kNm/m]
Non-iterated resisting moment   :       1819.68  [kNm/m]


Information of the geotextile results
=====================================

     | intersection point|  embedding  |mobilized embedd.|  resisting   |
     | X-coord  | Y-coord  | length min.|tensile strength |   moment     |
  nr |   [m]    |   [m]    |    [m]     | [%] |  [kN/m]   |  [kNm/m]     |
-----|----------|----------|------------|-----|-----------|--------------|
   1 |    2.49  |   -1.90  |      9.51  | 100 |    120.00 |    320.76    |
-----|----------|----------|------------|-----|-----------|--------------|
Total resisting moment from geotextiles                    |    320.76    |

                          END OF D-Geo Stability OUTPUT
                          =============================
```

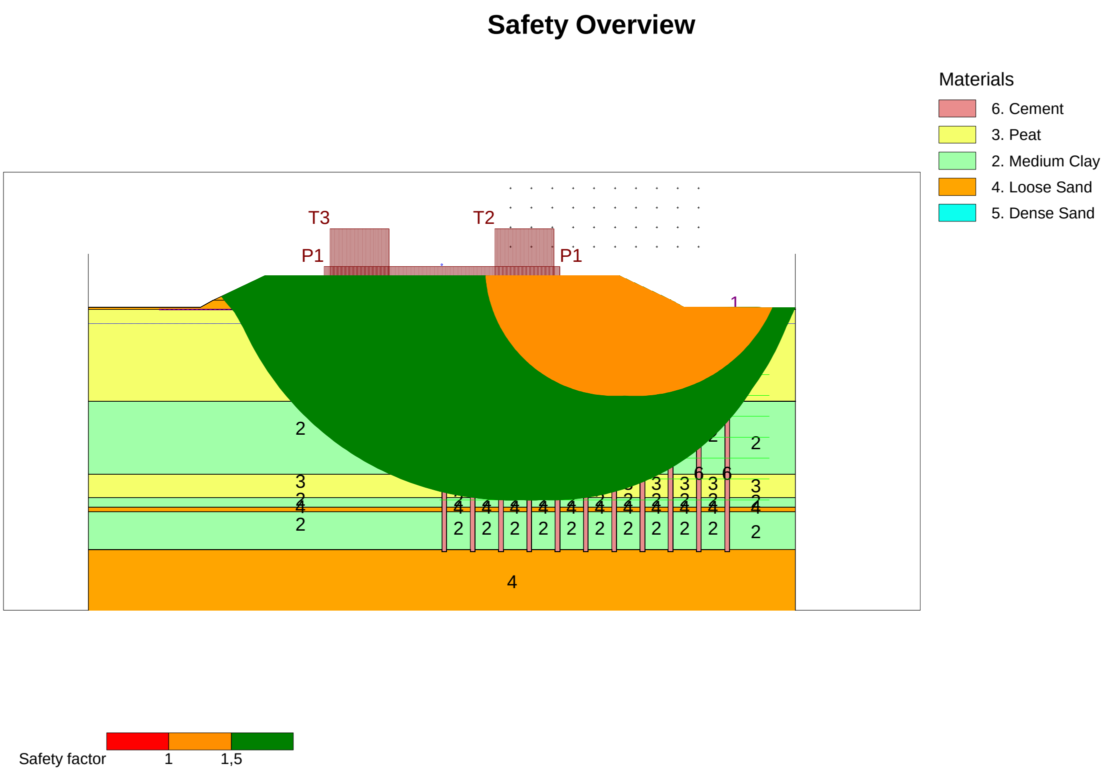


Figure 114 Safety Overview Pile Mattress D-Geo Stability

Appendix P – Stability Analysis Geotextile Encased Column Variant

```
Program      : D-Geo Stability
Version      : 18.2.2.32619
Company      : ARCADIS Infrastructure
Date         : 02/06/2023
Time         : 23:05:58

==========================    BEGINNING OF DATA     ==========================
               ECHO OF THE INPUT
               =================

 Calculation model      : Bishop
 Default shear strength : C phi

               CENTER POINT GRID AND TANGENT LINES
               ===================================

 X co-ordinate grid left                  :    1.31 [m]
 X co-ordinate grid right                 :   11.69 [m]
 Number of grid points in X - direction   :    10

 Y co-ordinate grid bottom                :    2.17 [m]
 Y co-ordinate grid top                   :    9.83 [m]
 Number of grid points in Y - direction   :    10

 Y co-ordinate tangent smallest circle    :   -2.00 [m]
 Y co-ordinate tangent biggest  circle    :  -10.00 [m]
 Number of circles per grid point         :    15

 No fixed points input.

 Total number of center points in the grid:   100
 Total number of slip circles in the grid :  1500

               UNIFORM LOAD
               ============
   Uniform    |Magnitude| X start |  X end  | Distrib.|   Load    |
 load number  |  [kN/m] |   [m]   |   [m]   | degrees |   Type    |
 ------------|---------|---------|---------|---------|-----------|
     1        |   12.50 |   -5.00 |    5.00 |   25.00 | Permanent |
     2        |   63.00 |    2.25 |    4.75 |   25.00 | Temporary |
     3        |   63.00 |   -4.75 |   -2.25 |   25.00 | Temporary |

               GEOTEXTILES
               ===========
  Geotextile |  E.T.S  | X start |  X end  |    Y    |reduction|
    number   |  [kN/m] |   [m]   |   [m]   |   [m]   | zone [m]|
 ------------|---------|---------|---------|---------|---------|
     1       |  200.00 |  -11.00 |   11.00 |   -1.90 |    0.00 |

  E.T.S. = Effective tensile strength

****************  The input has been tested, and is correct.  ****************
******************************************************************************
                RESULTS OF THE SLOPE STABILITY ANALYSIS
                =======================================
 The center point of the critical circle lies on the edge of the grid.
 New grid with  : X minimum =    1.31 [m]
                  X maximum =   11.69 [m]
                  Y minimum =    1.32 [m]
                  Y maximum =    8.98 [m]

 The center point of the critical circle lies on the edge of the grid.
 New grid with  : X minimum =    1.31 [m]
                  X maximum =   11.69 [m]
                  Y minimum =    0.47 [m]
                  Y maximum =    8.13 [m]

 The center point of the critical circle lies on the edge of the grid.
 New grid with  : X minimum =    1.31 [m]
                  X maximum =   11.69 [m]
                  Y minimum =   -0.38 [m]
                  Y maximum =    7.28 [m]
```

```
Information on the critical circle  : Fmin =      1.439
Calculation method used             : Bishop - C phi
=============================================================================

X co-ordinate center point      :         8.23 [m]
Y co-ordinate center point      :         0.47 [m]
Radius of critical circle       :         5.90 [m]

The center point of the critical circle is enclosed

Total driving moment            :      1168.33 [kNm/m]
Driving moment free water       :         0.00 [kNm/m]
Driving moment external loads   :       834.73 [kNm/m]
Iterated resisting moment       :      1681.40 [kNm/m]
Non-iterated resisting moment   :      1618.01 [kNm/m]


Information of the geotextile results
=====================================

     | intersection point|  embedding |mobilized embedd.|  resisting   |
     | X-coord | Y-coord | length min.|tensile strength |    moment    |
  nr |   [m]   |   [m]   |     [m]    | [%] |  [kN/m]   |   [kNm/m]    |
-----|---------|---------|------------|-----|-----------|-------------|
   1 |    2.83 |   -1.90 |       8.17 | 100 |    200.00 |    474.42    |
-----|---------|---------|------------|-----|-----------|-------------|
Total resisting moment from geotextiles                   |    474.42    |

                         END OF D-Geo Stability OUTPUT
                         =============================
```

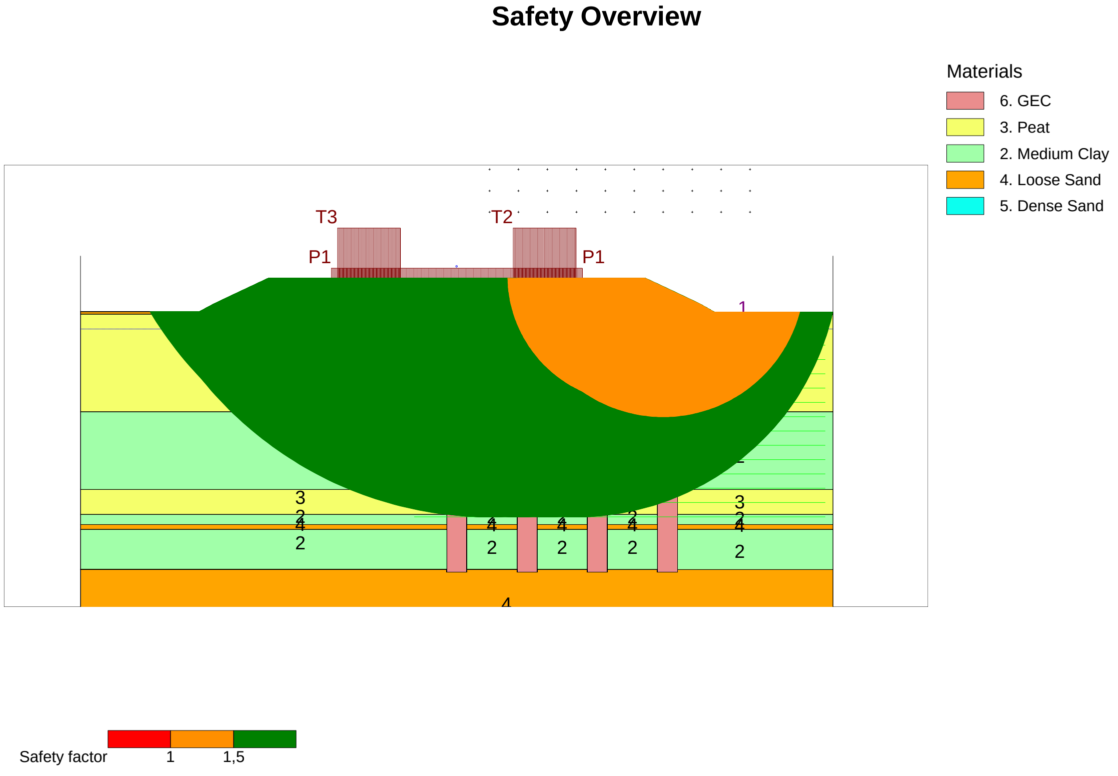


Figure 115 Safety Overview Geotextile Encased Column

Appendix Q – Stability Analysis Preloading Variant

```
Program      : D-Geo Stability
Version      : 18.2.2.32619
Company      : ARCADIS Infrastructure
Date         : 05/06/2023
Time         : 11:43:38

==========================    BEGINNING OF DATA     ==========================

               ECHO OF THE INPUT
               =================
 Calculation model      : Bishop
 Default shear strength : C phi

               PL-LINES
               ========

 Pl-line no. | Co-ordinates [m]
 ------------|----------------------------------------------------
             |
   1  - X -  | -15.00    15.00
   1  - Y -  |  -3.00    -3.00

 Unit weight of water used for calculation:     9.81 [kN/m3]
 The groundwater level is determined by Pl-line number 1

               CENTER POINT GRID AND TANGENT LINES
               ===================================

 X co-ordinate grid left                   :    2.51 [m]
 X co-ordinate grid right                  :   12.89 [m]
 Number of grid points in X - direction    :    10

 Y co-ordinate grid bottom                 :    0.57 [m]
 Y co-ordinate grid top                    :    8.23 [m]
 Number of grid points in Y - direction    :    10

 Y co-ordinate tangent smallest circle     :   -2.00 [m]
 Y co-ordinate tangent biggest  circle     :  -10.00 [m]
 Number of circles per grid point          :    15

 No fixed points input.

 Total number of center points in the grid:   100
 Total number of slip circles in the grid :  1500


               UNIFORM LOAD
               ============

   Uniform    |Magnitude| X start  |  X end   | Distrib.|   Load     |
 load number  |  [kN/m] |   [m]    |   [m]    | degrees |   Type     |
 ------------|---------|----------|----------|---------|-----------|
     1        |   12.50 |   -5.00  |    5.00  |   25.00 | Permanent  |
     2        |   63.00 |    2.25  |    4.75  |   25.00 | Temporary  |
     3        |   63.00 |   -4.75  |   -2.25  |   25.00 | Temporary  |

               GEOTEXTILES
               ===========

  Geotextile |  E.T.S   | X start  |  X end   |    Y    |reduction|
    number   |  [kN/m]  |   [m]    |   [m]    |   [m]   | zone [m]|
 ------------|---------|----------|----------|---------|---------|
     1       |  100.00 |  -11.50  |   11.50  |  -1.90  |    0.00 |

  E.T.S. = Effective tensile strength

****************  The input has been tested, and is correct.  ****************
******************************************************************************

                RESULTS OF THE SLOPE STABILITY ANALYSIS
                =======================================
 The center point of the critical circle lies on the edge of the grid.

 New grid with  : X minimum =    2.51 [m]
```

```
                  X maximum =   12.89 [m]
                  Y minimum =   -0.28 [m]
                  Y maximum =    7.38 [m]

Information on the critical circle  : Fmin =      1.368
Calculation method used             : Bishop - C phi
=============================================================================
X co-ordinate center point      :         8.28 [m]
Y co-ordinate center point      :         0.57 [m]
Radius of critical circle       :         6.00 [m]

The center point of the critical circle is enclosed

Total driving moment            :      1042.65 [kNm/m]
Driving moment free water       :         0.00 [kNm/m]
Driving moment external loads   :       860.49 [kNm/m]
Iterated resisting moment       :      1425.97 [kNm/m]
Non-iterated resisting moment   :      1381.55 [kNm/m]

Information of the geotextile results
=====================================

     | intersection point|  embedding  |mobilized embedd.|  resisting   |
     | X-coord  | Y-coord  | length min.|tensile strength |    moment    |
  nr |   [m]    |   [m]    |     [m]     | [%] |  [kN/m]   |   [kNm/m]    |
-----|----------|----------|-------------|-----|-----------|-------------|
   1 |    2.81  |   -1.90  |       8.69  | 100 |    100.00 |    247.30   |
-----|----------|----------|-------------|-----|-----------|-------------|
Total resisting moment from geotextiles                     |    247.30   |

                        END OF D-Geo Stability OUTPUT
                        =============================
```

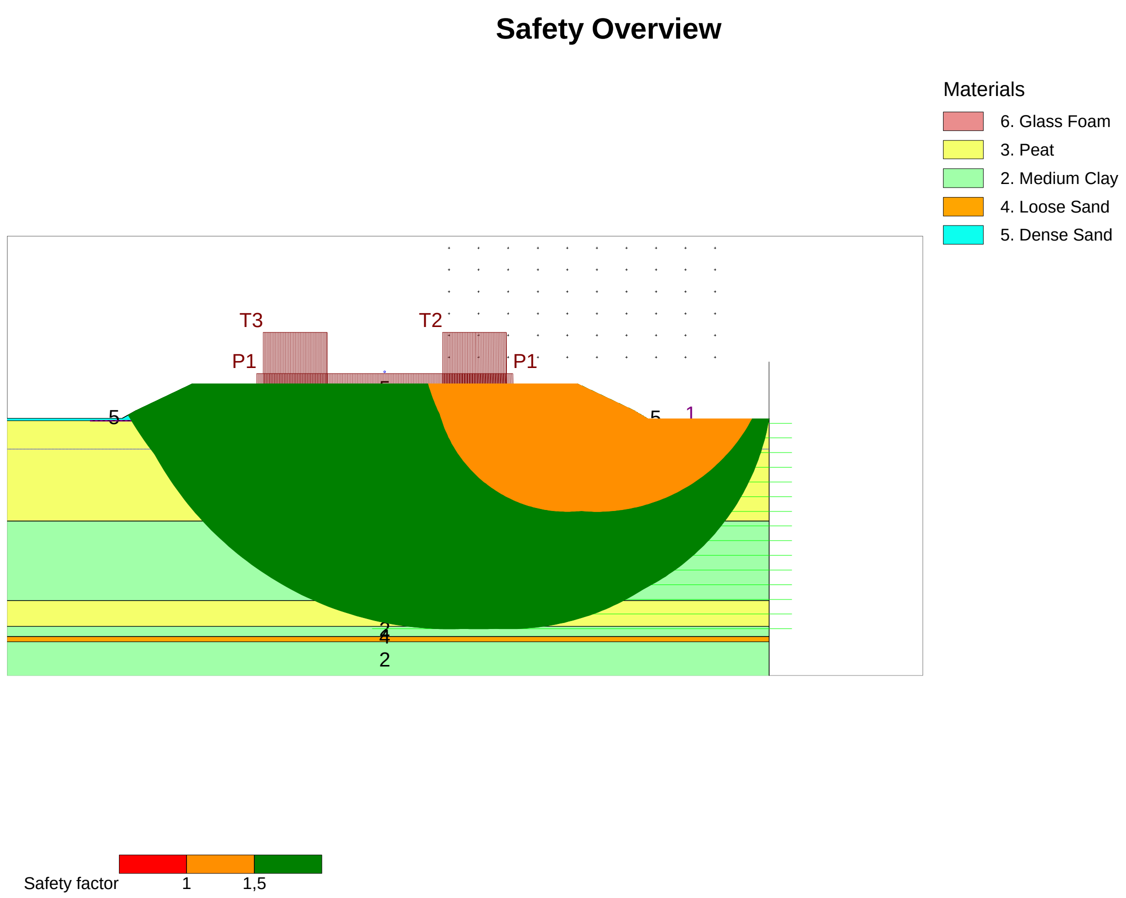


Figure 116 Safety Overview Preloading combined with Glass Foam