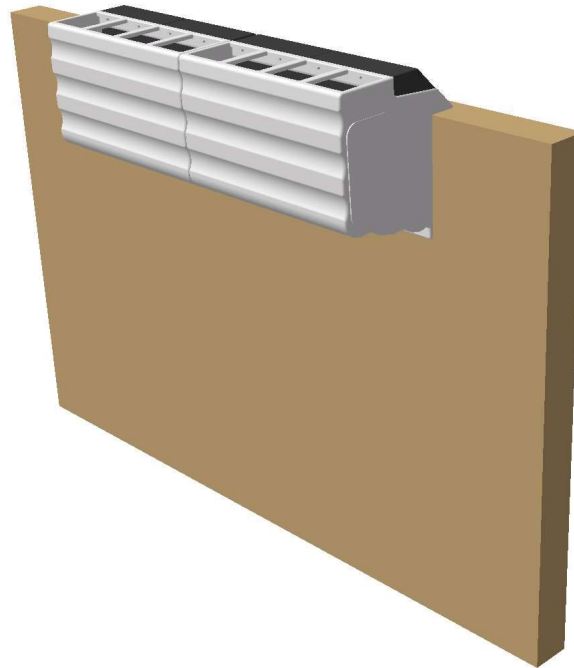




CHALMERS
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Environmental assessment through LCA of Wavebreaker's noise cancelling technology

Potential environmental benefits and drawbacks

Master's thesis in life cycle analysis

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Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

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Environmental assessment through LCA of Wavebreaker's noise cancelling technology

Potential environmental benefits and drawbacks

Master's thesis in the master's program Industrial ecology

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Department of architecture and civil engineering
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Computer rendering of a Wavebreaker module on top of a wall, supplied from Tony Johansson
founder and CEO of Wavebreaker AB.
Department of Architecture and Civil Engineering
Gothenburg, Sweden, 2021

Environmental assessment through LCA of Wavebreaker's noise cancelling technology
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Master's thesis in the master's program *Industrial ecology*

LINUS LEJDFELT

Department of Architecture and Civil Engineering

Division Building Technology

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Abstract

Wavebreaker AB wanted to evaluate their new noise mitigation product for railway infrastructure from an environmental perspective. An environmental performance comparison through a Life Cycle Analysis (LCA) in OpenLCA with an attributional approach of the product in two use cases was chosen.

Based on one Swedish wooden absorptive noise barrier system (Bsk-14F) and a representative conventional reflective reinforced concrete noise barrier (CNB), one worst case, one base case and one best case of soil conditions for the Norwegian concrete foundations Mofix was chosen to provide an adequate spread of possible use cases seen on the European market. This combination was chosen in an attempt to help future stakeholders assess what environmental performance benefits and drawbacks the choice of implementing Wavebreaker's noise mitigation system over installing higher noise barriers could potentially entail.

The comparison was performed between a lower wooden noise barrier utilizing Wavebreaker's new product against a higher wooden noise barrier from the same material, designed for an insertion loss of 19dB, and then repeated for a noise barrier made from reinforced concrete. In order to assess the foundation requirements contribution, a simple variation analysis of the impact of soil conditions was also performed on both comparisons.

The Life Cycle Inventory Analysis results for the wooden use case indicated an overall improvement in Wavebreaker's favour of 17%, and an overall improvement in Wavebreaker's favour of 14% for the reinforced concrete alternative (in normal soil conditions) in 17 out of the 18 impact categories covered in this LCA. This in comparison to the 20-25% material reduction by lowering the height of the wall 0,7-1 m. The only drawback that was identified, was that both material alternatives proved to perform between 2-10% worse in the fossil fuel scarcity impact category, when implementing Wavebreaker's noise mitigation system over installing higher noise barriers (depending on material choice and soil conditions).

One of the largest contributing factors to this result was identified as the high amount of virgin HD-PE plastics, required to produce the Wavebreaker product, and by doing a breakeven point analysis a reduction of HD-PE production of approximately 20% was deemed adequate to assure a performance better or equal to the higher barrier alternative for both materials in a majority of soil conditions.

Key words: Noise mitigation, LCA analysis, Bsk-14F, CNB, Wavebreaker, Mofix, HD-PE

Miljöutredning genom livscykelanalys av Wavebreaker ABs nya ljuddämpande produkt
Potentiella fördelar och nackdelar

Examensarbete inom mastersprogrammet Industriell ekologi

LINUS LEJDFELT

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Sammanfattning

Wavebreaker AB ville utvärdera sin nya bullerreducerande produkt för järnvägsinfrastruktur ur ett miljöperspektiv. En miljöanalytisk jämförelse i form av en livscykelanalys (LCA) i OpenLCA med en attributmetod för produkten i två användningsfall valdes.

Baserat på ett svenskt träbaserat bullerbarriärsystem (Bsk-14F) och en representativ konventionell reflekterande armerad betong bullerskärm (CNB) valdes ett värsta fall, ett neutralt fall och ett bästa fall av markförhållanden för de norska betongfundamenten Mofix i försök att tillhandahålla en adekvat spridning av möjliga användningsfall på den europeiska marknaden. Denna kombination valdes i ett försök att hjälpa framtida intressenter att bedöma vilka fördelar och nackdelar ur ett miljöperspektiv som valet av att implementera Wavebreakers bullerreduceringssystem över installation av högre bullerbarriärer potentiellt skulle kunna innebära.

Jämförelsen utfördes mellan en lägre bullerbarriär av trä med Wavebreakers nya produkt mot en högre bullerbarriär i samma material, utformad för en inkopplingsförlust på 19 dB, och upprepades sedan för en bullerbarriär av armerad betong. För att uppskatta bidraget från variation av grundläggningsbehov genomfördes också en enkel variationsanalys av markförhållandets påverkan på båda jämförelserna.

Resultaten från inventeringsanalysen tyder på en övergripande förbättring i fördel för Wavebreaker med 17% i fallet med bullerbarriär i trä och en total förbättring av 14% i fördel för Wavebreaker i alternativ fallet med armerad betong (under normala markförhållanden) i 17 av de 18 påverkan kategorier som omfattas av denna LCA. Detta jämfört med den 20–25% materialreduktion som uppnås genom att sänka väggens höjd 0,7–1 m. Den enda nackdelen som identifierades var att båda materialalternativen visade sig prestera mellan 2–10% sämre i kategorin fossilbränsleförbrukning vid implementering av Wavebreakers bullerreduceringssystem i stället för installation av högre bullerbarriärer (beroende på materialval och markförhållanden).

En av de största bidragande faktorerna till detta negativa resultat identifierades som den höga mängden jungfru HD-PE-plast, som krävs för att producera Wavebreaker-produkten, och genom att göra en breakeven-point-analysis ansågs en minskning av HD-PE-produktionen på cirka 20% vara adekvat för att säkerställa en prestanda som är bättre eller lika med det högre barriäralternativet för båda materialen under de flesta jordförhållanden.

Nyckelord: bullerskyddsåtgärder, LCA analys, Bsk-14F, CNB, Wavebreaker, Mofix, HD-PE

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Preface

This LCA comparison study of two test cases for Wavebreaker's new noise mitigation solution was performed in OpenLCA between January and June 2021. This research falls under the discipline of material science and sustainable building and was developed in collaboration between "Miljöbro Väst" and Wavebreaker AB and actualized in the form of a thesis work at Chalmers university of technology Sweden, under the department of architecture and civil engineering.

The study has been performed under the guidance of Prof. Holger Wallbaum to whom I am extremely grateful to have had the opportunity to have worked with in the role of both supervisor as well as examiner, and with tremendous help and support from the founder of Wavebreaker AB, Tony Johansson. The software tools for this thesis have been OpenLCA with the database Ecoinvent version 3.2 supplied from the department of Architecture and Civil Engineering at Chalmers University of Technology. Other software that has been extremely helpful has been the Freeware POLEFDN.xls version 2.3 developed by Alex Tomanovich. Valuable help in form of consultation have been graciously provided by the following people: Joosef Leppänen at Chalmers university. Monica Waaranperä at Trafikverket and Gustav Grundfelt at Trafikförvaltningen. Thanks also goes out to Elin Ekström project coordinator at "Miljöbron Väst" who helped facilitate the contact with Wavebreaker AB and who kept in constant contact throughout the project, as well as to Heidi Wåxberg at Chalmers university for helping to navigate and utilise available tools and support at the university.

Göteborg June 2021.

Linus Lejdfelt.

List of abbreviations

Bsk-14F:	Stands for Noise Barrier 14 experimental, which is the English translation of the original Swedish name “Bullerskärm 14 Försök”.
CML:	Institute of Environmental Sciences.
CNB:	Conventional Noise Barrier.
dB:	Decibel, relative unit of measurement corresponding to one tenth of a bel (B).
EEA:	European Environmental Agency.
END:	Environmental Noise Directive.
EOL:	End-of-life.
EPD:	Environmental product declaration.
ERRAC:	European Rail Research Advisory Council.
EU:	European Union.
EURO-06:	Vehicles produced after 2014 for light passenger and commercial vehicles.
GaBi:	A life-cycle assessment modelling program produced by thinkstep.
HD-PE:	High-density polyethylene or polyethylene high-density is a thermoplastic polymer Plastic produced from the monomer ethylene.
HEA140:	H Steel beams HEA are a very commonly used type of steel profile.
IEA:	International Energy Agency.
IL:	Insertion loss.
ISO:	International Organization for Standardization.
KTH:	Royal Institute of Technology.
LCA:	Life Cycle Assessment.
LCIA:	Life cycle impact assessment.
PVC:	A synthetic plastic polymer.
ReCiPe:	A method to perform LCIA in LCA.
RIVM:	National Institute for Public Health and the Environment.
RÖK:	Above rail top.
Wall 1A:	A wooden wall of 2 m in height with Wavebreaker installed.
Wall 1B:	A wooden wall of 2,7 m in height without Wavebreaker installed.
Wall 2A:	A Concrete wall of 3 m in height with Wavebreaker installed.
Wall 2B:	A Concrete wall of 4 m in height without Wavebreaker installed.
WHO:	World Health Organization.

1. Introduction

Wavebreaker AB is a Swedish start-up, aiming to bring the urban environment in Sweden closer to the guidelines set out in the Environmental Noise Directive (END) by improving the effectivity of existing sound barriers and thereby reduce the material needed in future noise barriers for rail traffic infrastructure projects. To do this, Wavebreaker is carving out a market for themselves within the rail traffic industry and pushing the industry forward through new thinking and efficiency improvement. By evaluating Wavebreaker's technology through a life cycle perspective, this thesis hopes to further the adaptation of this new technology and to assess whether the adaptation of this new product can lead to environmental benefits as well as improvement in soundscape at a lower cost than traditional railway sound barriers.

The World Health Organization (WHO) classify environmental noise (or noise pollution) as a highly crucial environmental risk regarding human health. WHO sees a growing concern over noise pollution from both the public as well as from policymakers within the European Union (EU), regarding the detrimental effect on humans' mental and physical health (World Health Organization, 2018).

Noise pollution has historically not received as much attention as research into other environmental impacts, such as pollution of air, soil, and water. But in recent decades the debate on the importance of environmental noise has started to gain momentum (European Commission, 1996, Goines, & Hagler, 2007). So much that traffic noise is now considered one of the largest contributors of adverse health effects in western Europe, only second to fine particulate matter pollution (Peris, 2019).

According to the European Environmental Agency (EEA) around 17 million people are exposed to daytime railway-related noise pollution, and around 15 million are exposed to night-time railway-related noise pollution exceeding the recommended thresholds set out in the WHO Environmental Noise Guidelines for the European Region (2018).

Rail traffic was according to the EEA (2020) considered to be the second-largest contributor to environmental noise pollution, second only to that of car traffic within central Europe. One of the largest fallouts of the Covid-19 pandemic of 2020 was the near-total collapse of the international air traffic industry, furthering the already existing trends and interests in the rapidly expanding European rail infrastructure market (Creel, et. al. 2020). In their 2019 report titled "The Future of Rail", the International Energy Agency (IEA) predicted a 100% increase in passenger and freight activity within the next 30 years, this in conjuncture with the rapid population growth and rapid rate of urbanisation around the world, the number of people exposed to dangerous levels of environmental noise pollution can only be expected to increase.

A large focus is placed on the long-term environmental impact of human activities on the ecosystem and the global climate, causing other aspects to get overlooked. In Life Cycle Assessment (LCA) (which is used to evaluate the negative effects of products and services on the environment) negative effects on the environment are divided into a small set of generalized impact categories where: Global warming, ozone layer depletion, fossil fuel depletion, and acidification are some of the more commonly used, but none of those tries to account for environmental noise effects.

The author of this report hopes that by contributing with LCA research in the highly lacking product category of noise mitigation measures, this will help to further the growing interest of

bridging the gap between noise pollution research and other environmental research areas of interest.

1.1. Aim and research questions

The main aim of this thesis is to assess the potential environmental performance benefits and drawbacks offered by installing the noise mitigation solution Wavebreaker instead of installing higher noise barriers. Wavebreaker claims to offer the same level of noise reduction to lower walls as would be achieved by upgrading existing noise barriers by extending the wall upwards by approximately one meter.

Therefore, two scenarios will be analysed in detail:

- Extension of an existing complex wooden structure representing a Swedish base case.
- Second, the extension of a structure made out of reinforced concrete representing a more common base case for the rest of the world.

The study also aims to contribute to filling in the existing gap of research regarding environmental impact related to the choice of noise mitigation measure.

To achieve this an LCA analysis on Wavebreaker's new product in combination with two barrier alternatives of different materials will be performed. The thesis will compare Wavebreaker's new product to two comparable industry alternatives that achieve the same noise reduction levels at the same distance. The study also hopes to lay the foundation for the development of an environmental product declaration (EPD). An EPD will provide important performance information for Wavebreaker's market communication, and thereby help prospective customers to reach an informed conclusion on to which extent this product fulfils their (environmental) procurement requirements.

The main research question of this thesis is;

- What environmental impact results does implementation of Wavebreaker's new noise mitigation solution have compared to a comparable alternative used on the market today?

In addition to this, the thesis will also look at the effects of changes in soil conditions and how this could contribute to the performance of the product. The thesis then also looks at what product weight reduction would be required in order to outperform the market alternative in all categories covered in the ReCiPe 2016 midpoint lifecycle inventory assessment method. The thesis therefore also considers the following follow up questions.

- What effect do the soil conditions and therefore foundation requirements play in Wavebreakers environmental performance? And
- What weight reduction would be required to outperform the market alternatives covered in this thesis in all 18 categories covered by the ReCiPe 2016 midpoint lifecycle inventory assessment method?

1.2. System boundary

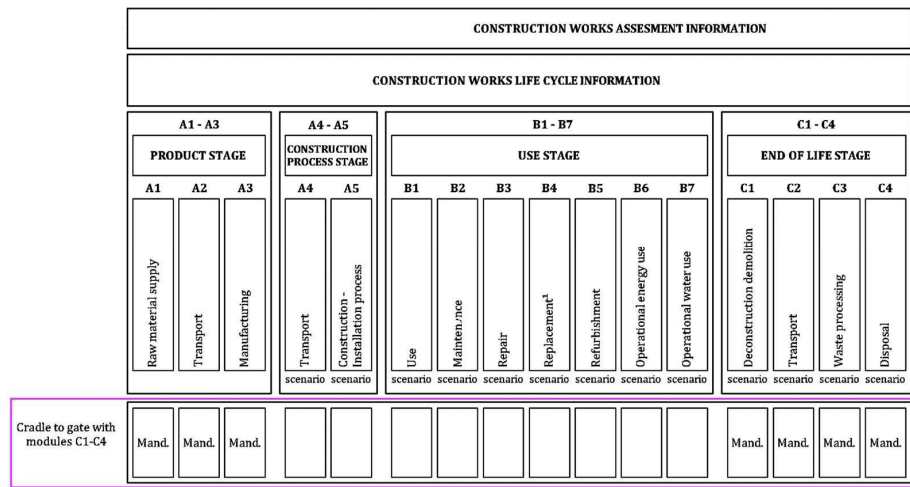


Figure 1: system boundary adapted from SS-EN 15804.

As an LCA with the aim of laying the groundwork for a potential EPD for the Wavebreaker product, this thesis will aim at adhering to the International Organization for Standardization (ISO) standard 15804 as closely as possible and therefore follow the cradle to gate method with the addition of the end-of-life (EOL) impacts.

The large difference between the two wall materials, and the different markets in which they compete complicates the choice of where to draw the system boundary.

The sources for the raw materials for the different options can vary widely from case to case. Therefore, market specific sources have been considered for both options with the Swedish standard wooden wall's construction material being sourced from specific producers in Scandinavian countries and EPD's, while the concrete walls components as well as the plastic material for Wavebreaker modules are being gathered from European averages and are mainly collected from Ecoinvent.

Ecoinvent is a Life Cycle Inventory database developed by the Swiss centre for Life Cycle Inventory, the database was deemed suitable for the project partly based on its high performance in the Martínez-Rocamora et al. (2016) paper "LCA databases focused on construction materials: A review", where it (together with GaBi) receives high marks in all categories and is concluded to be the database of choice for construction related projects based on (among other factors) its consistency, transparency and its broad cover of construction materials (Martínez-Rocamora et al 2016)

1.3. The intended audience

This thesis aims at producing performance results useful to the company Wavebreaker. The results of this thesis would likely also be of interest for future and current prospective customers weighing between the options compared in this thesis, as well as infrastructure researchers, acoustic researchers, LCA experts, as well as construction planners; currently working on maintenance and construction of railroad projects near residential areas.

As the comparisons in this thesis are theoretical, measures need to be taken to assure a correct understanding of the limitations of the results, before communicating them to the customers as

any form of decision support. Researchers and planners need to take into account that height and foundation requirements may vary for their projects and understand that it might have an effect on their expected results.

1.4. Comparative assertions

This LCA only intends to compare the Wavebreaker products environmental performance to that of the two base case options of extending two walls of different materials upwards enough to achieve the same noise reduction. Comparative assertions beyond this accompaniment as stated above is not the intended use of this LCA.

1.5. Limitations

As the field of acoustics is highly complex, and the methods for modelling and predicting the performance of noise mitigation measures are many, the author must make many simplifications and assumptions. The modelling of the acoustic performance depends to a large extent on choice of method for calculation. Hence, the real-world results from testing can also vary wildly, as both are highly dependent on a large variety of factors. These uncertainties will have an impact on the results of the study, but all assumptions will be based on realistic scenarios, expert recommendations, or reliable literature sources. The acoustic calculation factors are narrowed down to wavelength of the source, the height of the wall and the distance from the wall.

Distance and frequency are set to generic examples and kept constant while the height of the wall is varied to calculate the same insertion loss for different materials and characteristics using the Fresnel equation based on Sahraei and Ghaemi (2013) application of Kurze and Anderson simplified equation with a maximum limit of 20dB.

This means that the results may vary in real-world application as height might need to be adjusted for change in frequency, space constraint affecting distances and type of material used.

The same goes for contributions to the results from the walls foundations. As the author lacks the time and expertise to make proper foundation calculations, the choices regarding foundation will be less accurate than for the rest of the wall as the need for foundation is highly dependent on location and current ground conditions. As the author lacks a case study for proper measurements, and results from these only would be relevant for that specific location, assumptions and rough estimates will make up the majority of justifications regarding decisions relating to the choice of foundation type and dimensions.

1.6. Assumptions

The length of the wall does affect the level of Insertion loss (IL) and therefore the wall length is assumed infinite for ease of calculation as seen in Sahraei and Ghaemi, (2013), but to allow for comparison between the alternatives only a 40 m segment of the assumed infinitely long walls are being compared.

For the EOL processes the transportation is assumed to carry the entire mass of the wall segment without any losses to a waste treatment centre that recycles, incinerates, or landfills the material on site. The distance to waste treatment varies throughout Europe, but for the sake of comparison an arbitrary distance of 50km was assumed for all 4 wall segments.

Because of licensing issues, the version of Ecoinvent being utilised for this study is the Ecoinvent 3,2 2015 version (Version 3.7.1 2020 being the most recent as of time of writing),

therefore the system boundary in relation to time is down prioritized and data sets made in the late 1990's and early 2000's is assumed to still hold true.

All transportation is assumed to fall under EURO-06 standard and all data suggesting transportation within Europe with standard below EURO-06 is ignored and instead the transportation is updated to EURO-06.

2. Background

Mitigating noise pollution has a high priority in Sweden. Since the late 1990's the Swedish traffic administration has been working on a large project utilising every measure at their disposal to try to bring all building interiors and backyards in close proximity to railway tracks as close to within European standards as possible (Samari, 2011).

2.1. The expected increase in railway infrastructure

According to the IEA, the entire rail infrastructure can expect an approximately 100% increase in person transportation and freight traffic by rail within the next three decades and emphasises the contribution to energy consumption and greenhouse gas emissions that this could entail. They do emphasise however the crucial part that rail may play as a part of the solution to reduce the large greenhouse gas emissions contribution from the transportation sector (IEA, 2019).

According to the European Rail Research Advisory Council (ERRAC), (2017), rail has the environmental benefits of helping to provide sustainable mobility alternatives for passengers and freight transport, improving energy efficiency of the urban and long-distance transportation market, and by contributing much lower levels of pollution compared to most other modes of transportation. However, they also point out that between 2015 and 2017 an additional 280 km of tram rails and 73 km of metro lines was introduced on the European market with an additional 371 km under construction and another 500 km being planned.

These infrastructure projects are not without their own impacts and in interest of reaching the European net-zero carbon dioxide emissions goal of 2050 set out by the European Union in their "2050 long-term strategy", in the same decades as the IEA expect a 100% capacity increase in the already expanding rail infrastructure system, careful planning must be implemented as to not cause an unnecessary impact in an effort to reduce the environmental impact overall.

2.2. Types of noise mitigation measures

Noise mitigation measures can be implemented in a wide variety of ways. According to the EEA 2020, most common types of noise mitigation measures can be broken down to four main categories:

- Measures at source
- Measures at the path
- Measures through urban planning and infrastructure change, and
- Other physical measures

There is also a difference in preferred measures depending on type of noise being mitigated. European traffic noise mitigation 2017 was according to the EEA Report (2020) focused on a variety of solutions with the following three measures being the three largest:

- Path mitigation measures noise barrier (29.5%),
- Source measure traffic management (21.3%),
- And road surface measures (17.2%).

Rail on the other hand seems to have focused during the same period on:

- Source mitigation measure rail track improvements (30.3%),

- Urban planning and infrastructure change measure of Land use planning and design (18.2%),
- Followed by the path mitigation measure noise barriers (15.2%).

Sweden's focus has in the last decades been concentrated on path mitigating measures. The Swedish Rail Administration have since 1997 conducted an extensive large-scale project to reduce noise exposure from pre-existing railway infrastructure. The project has focused on improving indoor environment through improving building exteriors, including replacing windows and ventilation ducts, as well as through sound barriers along the tracks (Samari, 2011).

Before noise barrier measures can be implemented however, measures need to be taken to explore other avenues of noise mitigation. Such as measures through urban planning and infrastructure change, measures at source such as maintenance and improvement, reduction of traffic flow and lowering of speed and improvement of technical standards on locomotives to name a few. However, the legislation also states that measures only should be considered when and if they can be considered technically possible and economically feasible, giving many actors an optout to instead go with the simplest possible option (Samari, 2011).

Noise barriers work by casting a "audio shadow zone" protecting everything outside of sightline with the noise source behind the barrier. The amount of protection depends on factors such as source of the noise, the barriers material, and the barriers dimensions. Barriers usually come in two different types which are either low in height and placed close to the tracks, or greater in height and placed further away. The barrier is more effective the closer to the track its placed as the closer to the source, the steeper the angle between source of the noise and the crest of the barrier, thereby casting a taller shadow zone behind it, in the same way the higher the wall is the greater the protection because of the same principle as for distance. Higher walls can be much more expensive than the lower alternative, as height and material requirement is not a linear correlation but rather an exponential one considering all the foundation work required to support higher barriers, considering natural pressures from weather and corrosion. Therefore, higher barriers are seldom considered when protecting old buildings, and becomes more compelling when considered for new projects requiring higher standards of protection. Making tall and high performing noise barriers more common in newly developed densely populated areas. Considering the rate of urbanisation, the higher thicker noise barriers can therefore be expected to become more common as requirements are raised and cities become denser (Samari, 2011).

2.3. Types of noise barriers

Noise barriers are usually constructed as either a trench or a wall and can differ wildly in appearance while performing the same function.

Noise barriers in the form of walls are categorized either as a low wall (approximately 0,8 m) or a high wall (2-3 m). walls are very seldom constructed higher than 4 m in Sweden, mainly because of safety and aesthetics concerns (Samari, 2011).

Barriers can consist of many different types of material. It can consist of heavy materials such as concrete or brick, but it can also be a wall made of wood or different types of metals. One of the most important aspects of a noise barrier is that it does not contain any gaps or holes that allow sound to leak over to the other side. If the barrier is not adequately designed, noise can end up traveling straight through the barrier negating the reason for its whole existence (Samari, 2011).

In Sweden, wood is heavily favoured when it comes to material choice when erecting noise barriers for railway and traffic projects. Wood is lightweight and abundant and can be locally sourced. Wood is also often considered environmentally favourable over other more energy-consuming materials such as concrete, glass, or steel (Samari, 2011).

However, several recent publications have pointed to heavier materials such as concrete and brick being the preferable choices for constructing noise barriers. A Croatian multicriteria analysis from 2021 of concrete, aluminium, steel, timber, and willow placed concrete at the top and timber and willow at the bottom. The results showed that even though concrete has the lowest sustainability performance, concrete outperformed the rest of the materials in several areas such as acoustic properties, non-acoustic properties, and long-term performance (Ahac et al, 2021). Another Swedish multicriterial analysis of noise barriers from 2015 looking at noise reduction performance, cost and environmental aspects found brick to be the preferable option, closely followed by wood and then fibre cement (Björk et al. 2015). Therefore, the study will look at both a concrete alternative as well as a wooden alternative in interest of transparency and fairness regarding the effect of material choice for comparison.

2.4. The functions of the product systems

Insertion loss (IL) is a measurement of the reduced noise pollution level because of the introduction of a noise mitigation measure in the line of sight between a noise source and a receiver, usually measured in decibel (dB). IL is how you predict and compare the effects of noise barriers and other noise mitigation measures. In this case, that would mean the reduction in noise pollution level at the receiver caused by the introduction of the barrier. IL is a tricky measurement to get precise as it is highly dependent on a large number of different factors that are constantly changing. The amount of IL a barrier can achieve depends on (among other things) the barriers dimensions in both width and height, as waves have a tendency to diffract around objects that are placed in their way, as well as temperature and wind direction. This is partly why guidelines for noise exposure are given in yearly averages and allow for the limit to be exceeded a set number of instances per measurement period (Kragh, 2011).

The mechanisms through which noise barriers reduce noise pollution typically fit into one of four distinct types:

- Sound absorption.
- Sound transmission.
- Sound reflection.
- Or by extending the path of the sound wave.

Reflective noise barriers do not absorb any of the energy directed towards it, and therefore simply redirect all of that energy back towards the receiver, or in a new path direction depending on the angle of the surface of the impact. This can be compared to the way that mirrors reflect light. When considering reflective noise barriers careful consideration must therefore be taken as to not increase the noise on one side of the track by protecting the other by a reflective barrier, thereby redirecting this noise towards the residence on the other side who now might be subjected to higher levels of noise pollution than they were before the noise barrier was erected (Joynt, 2005).

The absorptivity of a wall is usually dependent on the porosity of the material that line the wall face, facing the direction of the source of the noise. The mechanism of which an absorptive wall reduces the noise reflection is usually by perforation of the surface material and then mechanisms through which the energy is absorbed and converted to heat by the porous material

structure. Different materials have different absorptive mechanisms and coefficients of absorption, but it usually has a strong correlation to the porosity of the material. By integrating large amounts of porous materials such as mineral wool into the structure the amount of noise that passes through the barrier can thereby be practically reduced to zero (Joynt, 2005).

The level of absorptivity depends on the coefficient of absorption (α) ranging from 0,0 to 1,0 with 1,0 representing a 100% absorptive material, but this may vary throughout a material or structure as the amount of noise that makes it through the wall depend on several factor such as frequency of noise and angle of the incident wave (Joynt, 2005).

According to a study by van Leeuwen (1970) the difference in IL between a reflective and an absorptive noise barrier can vary widely between different prediction models. The van Leeuwen (1970) study sets out to compare the predicted IL using 14 different models from all around the globe. The results show a large variation, depending on choice of model but also indicate that an absorptive barrier performs between 0 and 5 dB better than a reflective barrier.

A 2 m high reflective barrier achieved between 5,9- and 10,5-dB IL at a distance of 4,5 m from rail centre line to the closest track of a two-track railway, while an absorptive barrier achieved between 12,4- and 13-dB IL at the same distance. Assuming that the performance lay in the middle of these ranges, the expected IL for a 2 m reflective barrier at a distance of 4,5 m from centreline is 8,2 dB and for an absorptive barrier is 12,7 dB. Giving us a difference of 4,5 dB between a reflective and an absorptive barrier material which is rounded up to a 5 dB difference between the two (Van Leeuwen, 1970).

The fourth type of mechanism of reduction “extending the path of the sound wave” is the most relevant to noise barriers as these barriers are erected to impede the travel of noise emanating from a source from reaching the specific receiver in question by breaking the sightline between the two.

In a publication by Sahraei and Ghaemi from 2013, the authors calculate the IL contribution from raising a sound barrier at different distances from the source using the Fresnel method. They plot the predicted results of varying the height from 1-8 m at the distances of 10, 15, 20, and 25 m with source and receiver both at a height of 2,5 m and the receiver at a distance of 30 m from source. Utilising the same method as Sahraei and Ghaemi, (2013) the contribution curve for varying the height between 1 and 8 m at a distance of 5 m from source with a receiver 25 m from source can be derived as shown in fig 2. This gives us an estimated IL per meter height increase shown in Table 1 (see Appendix A for detailed calculations).

Table 1: IL per height interval in meter.

Height intervals [m]	IL difference [dB]
1-2	4,8
2-2,7	3,2
2,7-3	1,1
3-4	2,9
4-5	1,2
5-6	0,0
6-7	0,0

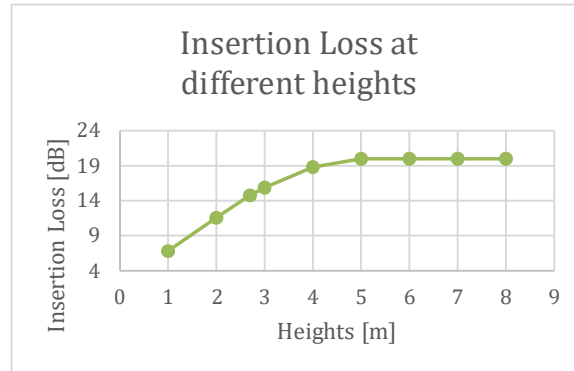


Figure 2: Graph of IL per meter height.

2.5. Life cycle assessment approach

The chosen method of this study is LCA analysis. The following text aims to describe LCA methodology in greater detail.

2.5.1. Life cycle assessment

LCA is becoming the dominant method of evaluating the environmental impacts of a specific product or service during its entire lifetime. The four main steps of the LCA procedure are: (Tillman, & Baumann, 2004)

- Goal and scope definition,
- Inventory analysis,
- Impact assessment and
- Interpretation of results

2.5.2. Goal and scope

You need to specify the goal of the LCA and the reason for study the chosen product or service and the intended audience of the study. The scope of the study should provide a preliminary flowchart schematic of the system, the functional unit stating the function of interest, and relevant impact categories for the study as well as method of impact assessment (Tillman, & Baumann, 2004).

The scope definition should also specify the type of LCA to be conducted, data quality requirements, assumptions, limitations, and finally system boundaries of the system being analysed (Tillman, & Baumann, 2004).

2.5.3. Initial flowchart

The initial flowchart is a preliminary flowchart schematic of the system depicting the main parts of the processes and transportation flows involved in the life cycle of the product or service being studied (Tillman, & Baumann, 2004).

2.5.4. Functional unit

The functional unit is a crucial element of the LCA as this describes the performed function of the system of interest. The mass flow through the system is expressed relative to this unit and the choice of expressed functional unit can have a massive impact on a LCA's result.

Dimensions of interest when deciding on a functional unit can broadly be boiled down to the following three:

- Quality
 - Which most commonly refer to properties such as aesthetics and price.
- Quantity
 - Which refers to the mass and energy required in order to fulfil the function of the system.
- Durability
 - Which mainly refers to the service life of the function.

2.5.5. Inventory analysis

In the subsequent life cycle inventory analysis (LCI) you expand on the preliminary flowchart mentioned in the goal and scope definition, with more precisely defined system boundary with carefully modelled mass and energy flows going in and out of the system as well as the flows between processes within the system which also is modelled in greater detail. The flows are now calculated from the collected data to relate to the functional unit (Tillman, & Baumann, 2004).

2.5.6. Impact assessment

The purpose of the life cycle impact assessment (LCIA) can be described as the process of transforming inventory results from the LCI into more easily understandable and environmentally relevant information, such as translating the amount of emission of specific gasses into more general impact categories. This is usually followed by characterisation and weighting of these result to further simplify their implications. Thereby expressing their relative magnitude and significance to the chosen environmental impact categories (Tillman, & Baumann, 2004).

2.5.7. Interpretation

Understanding and grasping the implication of the LCA results to draw meaningful conclusions can sometimes be seem like a daunting task for a novice not familiar with the LCA methodology. Therefore, in the last step of the LCA we take the results and further distill them into presentational material such as bar graphs and pie charts helping to visualize the meaning of the results to make it easier to draw meaningful conclusions. To assess the quality of the subsequent conclusions is also considered a part of the LCA that is performed in the interpretation phase. This is usually done through Variation analyses, uncertainty analyses and data quality assessments (Tillman, & Baumann, 2004).

2.5.8. LCA software

The choice of software tool to perform this thesis LCA study was OpenLCA. There are a lot of different software tools for LCA on the market with varying levels of complexity. LCA can be performed in Microsoft Excel which was one of the early tools which LCA researchers used to make the first calculations and create databases. But now there are very specific software tools for specific industries and applications with a large set of databases to choose from and combine depending on type of product or service and the purpose of the study.

3. Method

To obtain the environmental performance results necessary to compare the two wall types and the Wavebreaker product, the choice of method for this thesis was an LCA. The thesis will be based on the Swedish standard SS-EN 15804 which sets up the standard for sustainability of construction works and environmental product declarations with the purpose to assure as useful data as possible for the Wavebreaker company, should they choose to develop this into a EPD later on. The standard is based on the ISO 14040 and ISO 14044 standards that sets out to standardise structure and requirements for LCA respectively, therefore these will be consulted regarding methodological decisions during the LCA as well.

The thesis will follow an attributional approach. Since informational schemes such as EPDs are usually based on attributional LCA. Arguments for this, which are further detailed in Tillman and Baumann (2004), are that the LCA methodology for such applications needs to be broadly accepted among those using the schemes and that even though purchasing involves choices (which is more commonly associated with a consequential approach), the sender of information does not know what the alternative choices are. Moreover, for information schemes such as EPDs additivity is an important feature and is only rendered by an attributional approach (Sonesson, et al, 2010).

To make sure that the two alternatives are comparable, both LCAs will be performed in OpenLCA. OpenLCA is the software chosen for the project based on the authors' prior experience and ease of accessibility.

3.1. Product system to be studied.

The objects of interest for this study are four different wall alternatives, two lower noise barriers with Wavebreaker installed, one in wood and the other in concrete. Both designed to reduce noise pollution from railway traffic by the same amount. The other two walls being wood and concrete options without Wavebreaker installed but designed to achieve the same reduction of noise pollution from railway traffic by extending the walls upwards.

3.1.1. Wavebreaker's noise mitigation solution

Wavebreaker is a type of passive noise cancelling product designed in a modular fashion and are initially intended to be attached on top of noise barriers alongside railway tracks (see Figure 3 below) to reduce the diffracted noise that would otherwise curve over the crest of the barrier. Wavebreaker can be added on to walls of any material and any height. The product is initially intended for the Swedish railway infrastructure market, but pending a successful launch intends to expand on to the European market and potentially also expand into the growing market for traffic noise mitigation. The product is made up of two pieces of plastic consisting of an outer shell and an inner acoustical module. The acoustic module is replaceable and can therefore allow for fine tuning towards specific noise spectrum without discarding the entire product.

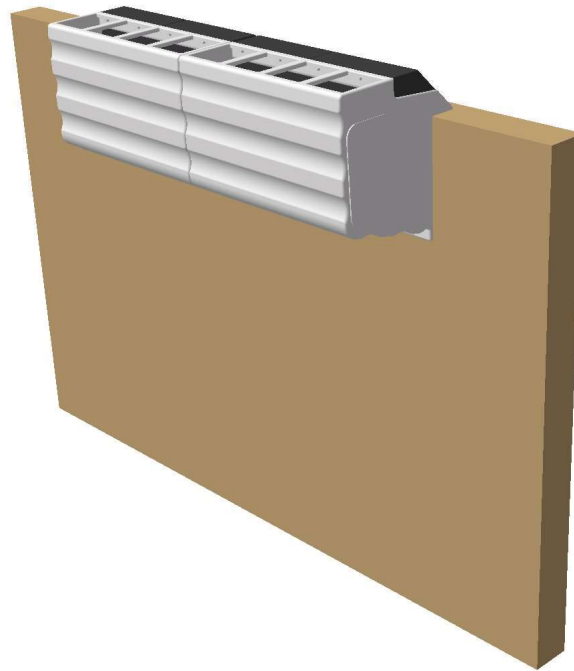


Figure 3: Wavebreaker noise mitigation module prototype rendering.

The plastic design allows for a relatively light weight, meaning that the additional load the product contributes to already erected noise barriers does not require extensive reinforcement of the barrier's foundation. The product when added to a noise barrier reduces the exposure of noise pollution on the residential side of the wall by an additional 4-6 dB according to the company's preliminary laboratory tests. The product utilises an acoustic interference technique based around the long ago established Quincke-effect. According to the company the expected 4-6 dB IL are high estimates for real life application and is expecting results along the range of 3-5 dB reduction, roughly corresponding to an upwards extension of the barrier by an additional 1-1,5 m. The product is still in development and a pilot project is planned for further testing and measurements during the latter half of 2021.

3.1.2. Wooden noise mitigation solution

The noise barrier chosen as the starting point of this study is a theoretical standardised modular system designed by Djulstedt and Gronowski 2014 for Trafikverket in collaboration with PEAB and the Royal Institute of Technology (KTH). The modular noise barrier system will be referred to as Bsk-14F, which stands for Noise Barrier 14 experimental, which is the English translation of the original Swedish name "Bullerskärm 14 Försök". The Bsk-14F was developed as a solution to the increasing range in variation of noise barriers available on the Swedish market, leading to inefficiencies in both time and cost optimization efforts meant to minimize wasteful spending in what is usually highly costly and tax subsidized infrastructure projects (Djulstedt, & Gronowski, 2014).

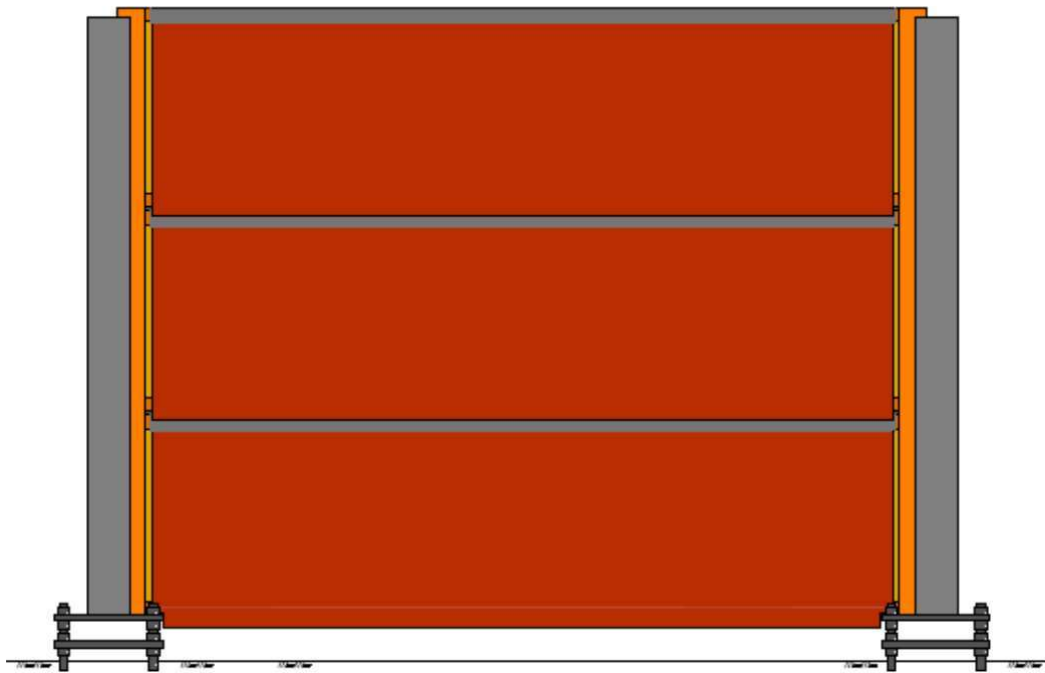


Figure 4: Bsk-14F segment 2 m in height with three modules stacked vertically between 2 times 2 m HES140 steel beams (Djulstedt, & Gronowski, 2014).

The product was developed to fulfil the broadest noise reduction requirements based on Trafikverkets guidelines while still allowing for future expansion in railway traffic. The system is designed as wooden frames made from 25x75 mm wood in segments of 2625 mm in length and 667 mm in height with three layers of solid wood and two layers of sound absorbing glass wool. The segments are layered with a first layer of 50 mm of glass wool sound absorbent facing the rails covered by a sparse layer of wooden panel, followed by a 12 mm layer of plywood followed by an additional 50 mm glass wool and another 12 mm plywood with a finishing panel of 22x145 mm pine panel added to the side facing away from the tracks. This in order to assure a reduction of noise transmission through the barrier by at least 24 dB to achieve the required sound absorption classification of B3 required by Trafikverket (Djulstedt, & Gronowski, 2014).

The panels are stacked on top of each other in enough segments of 667 mm to achieve a sufficient height to compensate for refracting lower wavelengths bending over the crest of the wall. The segments are kept upright by attaching to 90 x 90 mm wooden beams resting between two HEA140 steel beams with additional insulation tucked in between. The HEA140 beams are then bolted to concrete foundations. The wall segments are designed to accommodate the standard measurement for railway noise barriers which is: (Djulstedt, & Gronowski, 2014)

- 1 m above rail top (RÖK) (one panel in height)
- 1,5 m RÖK (two panels in height) or
- 2 m RÖK (three panels in height).

But could theoretically be stacked further to achieve any desired height of 667 mm increments. The space between the underside of the module and the ground is then insulated with porous rockwool to ensure an adequate noise insulation and to protect the module from moisture

exposure. The limiting factor for height only being regulations, budget, and the fact that at a certain height, noise reduction will reach the theoretical 20 dB insertion loss maximum and increasing the wall further would no longer contribute any further significant noise reduction (Djulstedt, & Gronowski, 2014).

The Bsk-14F is currently not being mass produced as it was intended when first imagined. The segments are still a valid option for construction sight however, offering high performance at a low price and therefore makes for an adequate base case for Wavebreaker to be combined with for this study (Djulstedt, & Gronowski, 2014).

3.1.3. Concrete noise mitigation solution

For the purpose of comparison, a second wall segment material alternative was chosen to represent a more internationally comparable market alternative. As mentioned above, other non-Scandinavian countries with less forestry tends to go with heavier materials such as concrete or brick, as these materials tend to make more sense in regions without an abundant supply of cheap domestically produced wood.

An in-depth online research into precast concrete barrier segments on the European market yielded no clear image of any existing standard or market leading manufacturer. In order to find a comparable alternative to the Bsk-14F wall segments, an American concrete alternative was chosen as this was the only good source of data that could be obtained within the confines of the LCA study.

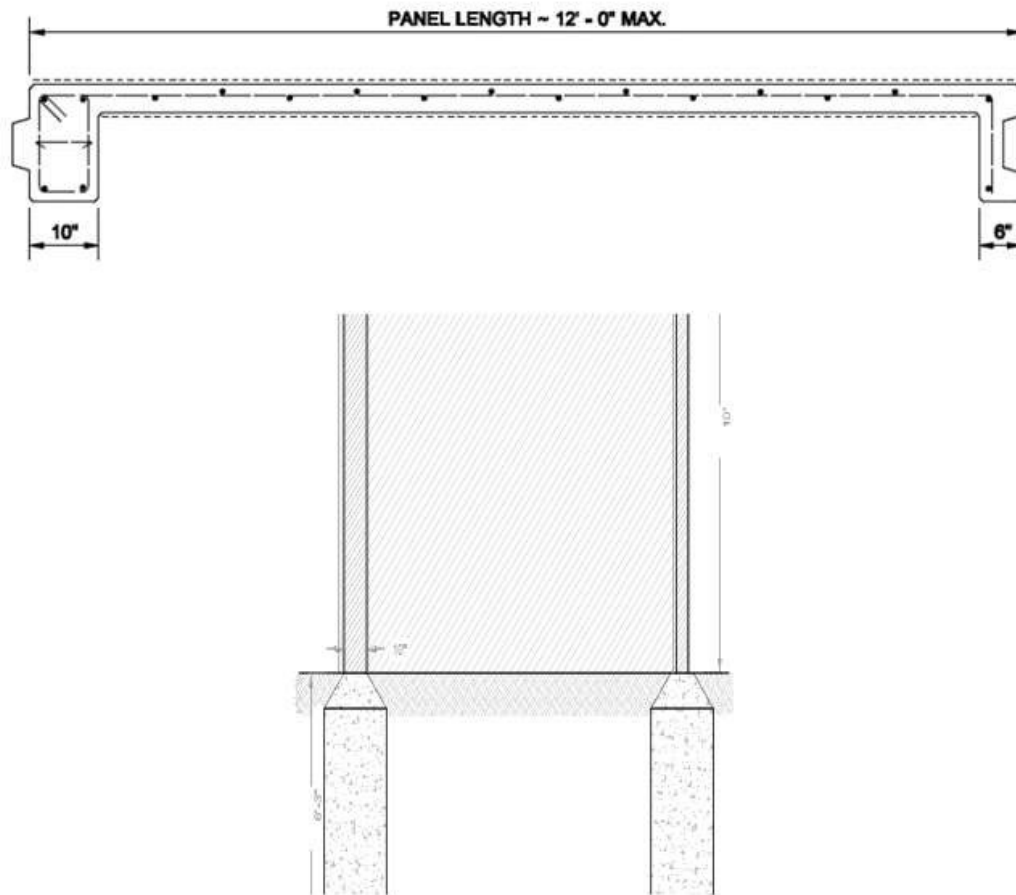


Figure 5: CNB concrete barrier segment illustration (Valdebenito & Dahmen, 2013).

The Concrete Conventional Noise Barrier (CNB) is marketed as its name suggests as a Conventional Concrete Noise Barrier in the north American market (specifically in the northwest) (Valdebenito & Dahmen, 2013).

The interlocking wall segments are designed to only be limited in their dimensions by shipping and handling constraints. To allow for easy shipping each segment is limited to a maximum length of 4,5 m while the segments can be stacked lengthwise in however many segments one would require. The thickness of the barrier is highly related to the amount of reinforcement of the concrete but are usually approximately 0,1 m thick to comply with American structural standards. The height varies with the need of the specific project, but the wall segments are typically within the span of 1,8 m to 7,3 m. For this study, the thickness and length of the segments follow previous dimensions under study, 3,65 m in length and 0,1 m thick in order to ease the complexities of mass calculations (Valdebenito & Dahmen, 2013).

The segments are cast in wet cast concrete with no compression requirement and a high water-content to assure proper hardening. The cast is then vibrated to minimise imperfections and air bubbles in the mix before it is set to harden for approximately 8 hours. The cast is then removed by crane and reused to cast the next set of wall segment (Valdebenito & Dahmen, 2013).

This type of concrete wall requires a reinforced concrete foundation which the barrier can then be bolted down upon for structural stability. The foundations are typically placed 3,5 m apart and are installed by the help of midsized all terrain drilling equipment (Valdebenito & Dahmen, 2013).

3.1.4. Mofix concrete foundation solution.

The foundation design choice was based on internet research into simple standardised modular solutions with good sources of environmental and material consumption data readily available. One such alternative stood out among the results (Mofix) as this was the only alternative with a published EPD and that was locally produced and aimed towards railway infrastructure. The Mofix cylindrical reinforced concrete foundation also fitted the type of foundation recommended for the concrete noise barrier alternative mentioned above (Stenman, 2005).



Figure 6: Mofix¹ foundation pillar installed example.

The Mofix foundation is a prefabricated concrete foundation product that Steiner Mo, track and roads As, Norway has developed. The foundations are factory produced, and the producer “Strängbetong” is the main distributor on the Swedish market. In Norway “Strängbetong”’s subsidiary “Spenncom” acts as the main distributor in the Norwegian market (Stenman, 2005).

The foundation was developed as an Overhead line posts foundation solution but have since found uses for several different types of applications including noise barrier installations. The

¹ <https://www.strangbetongrail.se/produkttyp/fundament/>

foundation comes in two models, a 355 mm in diameter version and a 555 mm in diameter version. The standard length is 4 m, but the length varies and can be individually tailored based on ground conditions and outer forces acting on the structure in question (Stenman, 2005).

The foundation are cylindrical concrete structures made from concrete with a quality of at least C55 with an inert filler material of 16 mm in size or smaller, with a reinforcement spiral made out of rebar with a thickness of 8 mm and a PVC pipe of 63 mm in diameter and a wall thickness of 3 mm that runs down the middle for concrete injection to fill out dead space between the drilled hole and the inserted Mofix cylinder (Stenman, 2005).

3.1.5. Initial flow charts for the different noise mitigation solutions

Below are 4 initial flow charts depicting the systems under study in very low level of detail with Figure 7 and 8 depicting Bsk-14F noise barrier lifecycle systems, Figure 7 showing the Bsk-14F with Wavebreaker included and Figure 8 showing a Bsk-14F solution without Wavebreaker included. And similarly Figure 9 and 10 depict the life cycle systems under study related to CNB noise barriers with Figure 9 including Wavebreaker elements and Figure 10 depicting a CNB barrier without Wavebreaker elements.

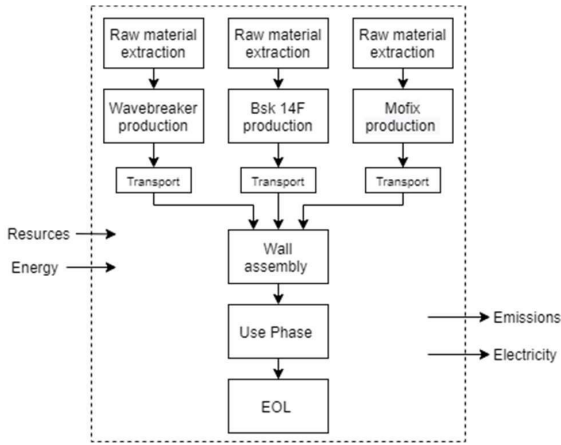


Figure 7: Initial flowchart Wall 1A, wooden wall of 2 m in height with Wavebreaker installed.

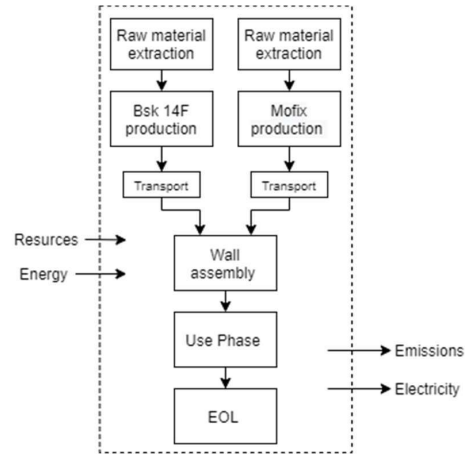


Figure 8: Initial flowchart Wall 1B, wooden wall of 2,7 m in height without Wavebreaker installed.

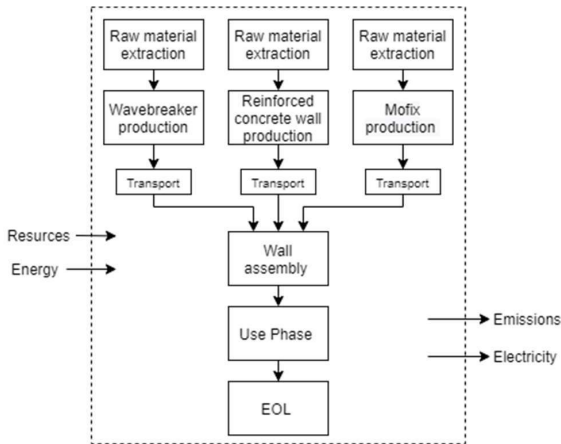


Figure 9: Initial flowchart Wall 2A, concrete wall of 3 m in height with Wavebreaker installed.

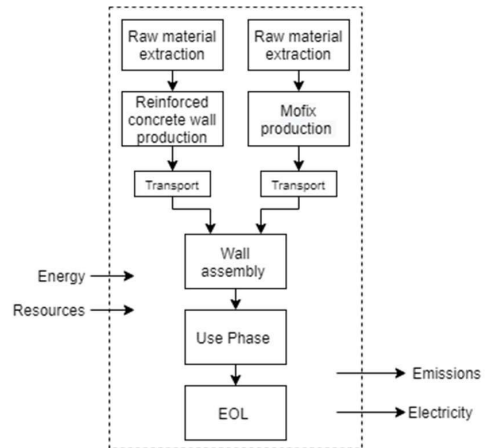


Figure 10: Initial flowchart Wall 2B, concrete wall of 4 m in height without Wavebreaker installed.

3.2. Functional unit

For LCA results to be comparable between the different alternatives, the functional unit needs to be expressed in relation to the same performance characteristics. The ISO standard 14040 sets out the guidelines for creating fair and justified comparisons between products using LCA, the standard emphasizes the importance of choosing a well thought out functional unit.

As both options aim at performing a noise reduction of railway traffic-related noise pollution, and the unit in which this is usually measured is the insertion loss, the functional unit for this study will be per noise barrier having 19 dB insertion loss for the market standard lifetime of

40 years. This functional unit will allow for the results of the two alternatives to be compared on equal dB of sound mitigation.

The length of the wall does affect the level of IL and therefore the wall length is assumed infinite, but to allow for comparison between the alternatives only a 40 m segment of the assumed infinitely long walls are being considered.

To achieve an IL of 19 dB the wall and the Wavebreaker product must together reduce insertion by 19 dB. As the Wavebreaker product claims to reduce insertion by approximately 3 dB, then two wall heights that achieve the remaining 16 dB IL and two wall heights that achieve 19 dB IL needs to be calculated. The calculation method follows the Fresnel/Kurze and Anderson method and is applied in the same manner as its seen being used in the paper “Influence of Height and Distance of Traffic Noise barriers for Noise Mitigation” by Sahraei and Ghaemi, (2013). This calculation in detail can be found in Appendix A.

These calculation results of IL as seen in Appendix A are as follows:

- Wall 1A: A wooden wall of 2 m in height with Wavebreaker installed resulting in an IL of 19 dB.
- Wall 1B: A wooden wall of 2,7 m in height without Wavebreaker installed resulting in an IL of 19 dB.
- Wall 2A: A Concrete wall of 3 m in height with Wavebreaker installed resulting in an IL of 19 dB and
- Wall 2B: A Concrete wall of 4 m in height without Wavebreaker installed resulting in an IL of 19 dB.

The comparison in environmental impact performance will then be performed between Wall 1A and Wall 1B and then between Wall 2A and Wall 2B as shown in chapter 4.

3.3. Allocation procedures

As most of the barrier materials are made for construction of a wide range of structures and sold by weight, the value of the product is determined based on mass allocation. The production of plastic, wood, and concrete for use in the assembling of the products are therefore determined to follow mass allocation. Regarding the production of the components themselves varies regarding the output but are for simplicity's sake excluded from this LCA.

3.4. Data requirements

Since the study focus on Wavebreaker's noise cancelling product, data for its processes are attempted to keep as close to site specific data as possible. When site specific data is not available European averages is instead being used. The data for the wall segments are meant to be generic examples that could be erected anywhere by anyone and therefore more generalised data is gathered for their processes. Since the wooden alternative is meant to be representative for the Scandinavian market, Scandinavian sources of data is being preferred for its systems processes. While the concrete alternative is representing a European market alternative, European averages are therefore prioritized when gathering data for its processes.

Data on the noise barriers material composition as well as their dimensions and design were gathered from previous academic research papers. The concrete wall alternative was gathered from a previous LCA analysis on the proposed design and the wooden alternative was chosen from a paper proposing a standardised construction design for noise barriers in Sweden.

3.5. Impact categories selected and methodology of impact assessment.

The impact assessment selection for this LCA study is a midpoint impact indicator based on ReCiPe 2016 Midpoint Hierarchies version. ReCiPe 2016 seems to be the most commonly used and preferred method within the field of LCA research and therefore this paper will also follow the ReCiPe 2016 Midpoint Hierarchies version. The tool was developed by the “National Institute for Public Health and the Environment” (RIVM), the creators of the CML-IA database named after the “Institute of Environmental Sciences” (CML) at Leiden University in the Netherlands, and PRé Consultants in cooperation with the Radboud University Nijmegen for the “Dutch Ministry of Infrastructure and the Environment” 2008 and then expanded upon in an update released 2016.

ReCiPe is a method to perform LCIA in LCA. This helps us to translate complex emissions data into a smaller limited amount of environmental impact scores and Tables through the use of characterization factors.

Below in Table 2 all included impact categories, their perspective Units and their associated Characterization factor for the utilised ReCiPe 2016 Midpoint Hierarchies version can be seen in greater detail.

Table 2: Impact categories included in ReCiPe.

All LCI results		
Mid-point impact category	Unit	Characterization factor
Climate change (CC)	kg (CO ₂ to air)	Global warming potential
Ozone depletion (OD)	kg (CFC-11 to air)	Ozone depletion potential
Terrestrial acidification (TA)	kg (SO ₂ to air)	Terrestrial acidification potential
Freshwater eutrophication (FE)	kg (P to fresh water)	Freshwater eutrophication potential
Marine eutrophication (ME)	kg (N to fresh water)	Marine eutrophication potential
Human toxicity (HT)	kg (14DCB to urban air)	Human toxicity potential
Photochemical oxidant formation (POF)	kg (NMVOC to air)	Photochemical oxidant formation potential
Particulate matter formation (PMF)	kg (PM to air)	Particulate matter formation potential
Terrestrial ecotoxicity (TET)	kg (14DCB to industrial soil)	Terrestrial ecotoxicity potential
Freshwater ecotoxicity (FET)	kg (14DCB to fresh water)	Freshwater ecotoxicity potential
Marine ecotoxicity (MET)	kg (14DCB to marine water)	Marine ecotoxicity potential
Ionizing radiation (IR)	kg (U235 to air)	Ionizing radiation potential
Agricultural land occupation (ALO)	m ² × year (agricultural land)	Agricultural land occupation potential
Urban land occupation (ULO)	m ² × year (urban land)	Urban land occupation potential
Natural land transformation (NLT)	m ² × year (natural land)	Natural land transformation potential
Water depletion (WD)	m ³ (water)	Water depletion potential
Metal resource depletion (MRD)	kg (Fe)	Metal depletion potential
Fossil resource depletion (FD)	kg (oil)	Fossil depletion potential

3.6. Life cycle inventory

In order to perform the comparison, the material requirement for the two wall alternatives were gathered from their respective publications mentioned in Chapter 3.1 above and then Mass

calculations presented in them for their given dimensions were reverse engineered and redone for all 4 wall dimensions of interest for this specific paper.

3.6.1 Life cycle inventory: wooden noise mitigation solution

As mentioned above the papers from which the two design alternatives come from provided Tables with material data that was gathered and normalised for use in this LCA. However, not all data was included in the paper from which the Wooden noise mitigation solution was borrowed. Therefore, the following chapter (Chapter 3.6.1.) details the gathering and normalization required to arrive at a Table of content for the Wooden noise mitigation solution. The initial material requirement list that was given in Djulstedt and Gronowski (2014) with their exact numbers can be seen in Table 3 below.

Table 3: Compilation of weight and material cost for a Bsk-14F module with two layers of plywood (Djulstedt, & Gronowski, 2014).

<i>Bsk-14F material</i>	LPM	m2/St.	m2/m	m3/St.	m3/m	Density kg/m ³	Total kg	Price/ m ² , m	Price total
<i>Timber Impregnated 45x145</i>	6,6				0,007	420,0	18,0	23,6	154,9
<i>Timber Impregnated 34x70</i>	3,3				0,002	420,0	3,3	12,5	41,5
<i>Glass wool 50x555x1155</i>	2,3	1,28			0,064	50,0	4,1	45,0	57,7
<i>Rockwool 50x555x1155</i>	2,3	1,28		0,064		140,0	9,0	68,5	87,8
<i>Plywood 12x600x2400</i>	4,8	3,12		0,037		520,0	19,5	84,6	263,9
<i>Polyester mesh 0,6x25m(15m²)</i>	2,4	15,00	0,600				0,0	31,3	45,0
<i>Timber beam Impregnated 90x90x600</i>	1,2	0,05	0,090		0,008	420,0	4,1	35,2	42,2
<i>Wood Panel 22x145</i>	11,0	0,10	0,145		0,003	420,0	14,7	18,6	204,2
<i>Timber Impregnated 25x75</i>	14,0				0,002	420,0	11,0	10,4	145,7
<i>Rubber sealant</i>	3,6								
<i>Other</i>									

Breaking down the numbers of segments and modules for each Bsk-14F gives us the multiplication factor (see Table 4) to arrive at mass amounts for both Wall 1A and Wall 1B. see detailed calculations in Appendix B.

Table 4: Number of segments and modules per wall.

<i>Wall</i>	<i>High [m]</i>	<i>Segments/wall</i>	<i>Modules/segment</i>	<i>Modules/wall</i>
<i>Wall 1A</i>	2	15	3	45
<i>Wall 1B</i>	2,7	15	4	60

This result in Table 4 gives us a multiplier (modules/wall) which we can use to arrive at the Table of content for the Bsk-14F alternatives by multiplying the results from Table 3 to arrive at the amount of each material per wall as seen in Table 5.

Table 5: Compilation of materials and weights per wall segment.

Bsk-14F material	Total kg / 1 module	Wall 1A	Wall 1B
Timber Impregnated 45x145	18	810	1080
Timber Impregnated 34x70	3,3	149	198
Glass wool 50x555x1155	4,1	185	246
Rockwool 50x555x1155	9	135	135
Plywood 12x600x2400	19,5	878	1170
Timber beam Impregnated 90x90x600	4,1	185	246
Wood Panel 22x145	14,7	662	882
Timber Impregnated 25x75	11	495	660

This Table of content in Table 5 is very detailed so we simplify the calculations by grouping materials together, the untreated and the treated wood products are condensed down to one wood production process, one plywood production process and an impregnated wood production process simplifying this Table 6 on the left, to this simplified Table 7 on the right.

Table 6: Compilation of materials and weights per wall.

Bsk-14F material	Wall 1A	Wall 1B
Timber Impregnated 45x145	810	1080
Timber Impregnated 34x70	149	198
Glass wool 50x555x1155	185	246
Rockwool 50x555x1155	135	135
Plywood 12x600x2400	878	1170
Timber beam Impregnated 90x90x600	185	246
Wood Panel 22x145	662	882
Timber Impregnated 25x75	495	660

Table 7: Simplified list of materials and weights per wall segment.

Bsk-14F material	Wall 1A	Wall 1B
Imp wood beam	1638	2184
Plywood	878	1170
Wood	662	882
Glass wool	185	246
Rockwool	135	135

3.6.1.1. Polyester mesh and rubber sealant

As seen in Table 3 above taken from the Djulstedt and Gronowski (2014) report, polyester mesh and rubber were missing data on density and mass, so a density of 0,16 kg/m³ for polyester mesh was taken from a product fact sheet for Vintur® filtervæv² which was assumed to be an adequate alternative for this type of application. Giving us the subsequent amount of polyester as seen in Table 8.

Table 8: Weight of polyester mesh for a Bsk-14F module.

Bsk-14F materials	LPM	m2/St	m2/m	m3/set	m3/m	Density; kg/m3	Total kg
Polyester mesh 0,6x25m(15m2)	2,400		0,600			0,160	0,230

² <https://mediacache2.bgflux.com/97/e1/4f7a-8ec3-4eb7-93bc-5c6c2299b06e/vintur-0916-2.100.pdf>

Rubber was also missing all data except for length so this data was substituted with data for a market alternative from Silentswede.se³ deemed to be an adequate representation of the intended product based on the intended use case. Giving us the subsequent amount of rubber as seen in Table 9.

Table 9: Weight of rubber sealant for a Bsk-14F module.

Bsk-14F materials	LPM	m2/St	m2/m	m3/St	m3/m	Density kg/m3	Total kg
Rubber sealant	3,600				0,002	60	0,407

This gives us a new list of material for both wooden alternative as seen in Table 10.

Table 10: Table of content for a Bsk-14F Wall 1A and Wall 1B.

Bsk-14F material	Wall 1A [kg]	Wall 1B [kg]
Imp wood	1638	2184
Plywood	878	1170
Wood	662	882
Glass wool	185	246
Rockwool	135	135
Polyester mesh	10	14
Rubber	18	24

3.6.1.2. Steel

There is also HEA 140 steel beams placed over each foundation and their mass also needs to be calculated.

Giving us the total amount of steel as seen in Table 11 for the wooden walls. See Appendix B for detailed calculations.

Table 11: Simplified list of materials and weights in kg per wall segment with steel added.

Bsk-14F material	Wall 1A [kg]	Wall 1B [kg]
Imp wood	1638	2184
plywood	878	1170
Wood	662	882
Glass wool	185	246
Rockwool	135	135
Polyester mesh	10	14
Rubber	18	24
Steel	804	1071

³ <https://www.silentswede.se/tatningslist-till-dorr-och-fonster-silentswede-seal>

3.6.1.3. Paint

Both the wooden walls and the steel beams require a layer of paint. The wood needs to reapply the paint about every 6 years for their 40 yearlong expected lifespans while the beams which is encased in wood is assumed to get a layer of paint at production and are never repainted during their lifetime. These calculations are based on data sampled from a couple of different paint EPDs from EPD Norway and a LCA study on paint by Axelsson et al, (1999). Based on Axelsson et, al. (1999) LCA study on paint, the paint is assumed to last 6 years, it is assumed to cover 8 m²/litres, have a density of 1,3 kg/litres and a water-based solvent and a water content of 32%.

For the HEA140 beams a protective cover of paint is also assumed based on data from another EPD from EPD Norway using the assumption that the EPD being representative for an average production. The data used for the beam production process is that 0,3% of the weight of the beam are coming from the paint and that the paint still contains 5% solvent. As the amount of paint is so small and the amount of solvent in the paint is a fraction of that the study chose to exclude the solvent for steel beam (Hansen 2017).

Giving us the following Table 12 in Chapter 3.6.1.4 of all material per wall alternative including paint. See Appendix B for detailed calculations.

3.6.1.4. Final bill of content for the wall sections for Wall 1A and Wall 1B

After adding all the missing data to the bill of content and simplifying and grouping together as much material as possible, we finally arrive at a final bill of content for both the Bsk-14F alternatives Wall 1A and Wall 1B as seen in Table 12.

Table 12: Final bill of content in kg per wall for Wall 1A and Wall 1B.

Bsk-14F material	Wall 1A [kg]	Wall 1B [kg]
<i>Imp wood</i>	1638	2184
<i>Plywood</i>	878	1170
<i>Wood</i>	662	882
<i>Glass wool</i>	185	246
<i>Rockwool</i>	135	135
<i>Polyester mesh</i>	10	14
<i>Rubber</i>	18	24
<i>Steel</i>	804	1071
<i>Water</i>	43	56
<i>Paint</i>	120	162

Below is a flow-chart depicting the final model of the production process (see Figure 11) and material required (see Table 12) to produce the necessary Bsk-14F modules per wall alternative.

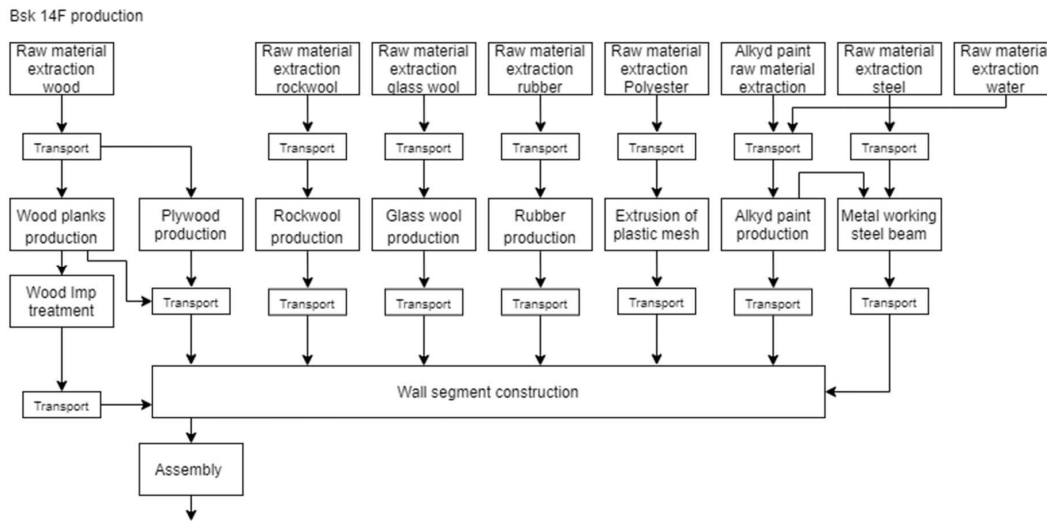


Figure 11: Flowchart of Bsk-14F production.

3.6.2. Life cycle inventory: concrete wall noise mitigation solution

The data for the concrete alternative were gathered from the “Life Cycle Assessment Screening: Environmental Impacts of a Novel Vegetative Sound Structure” paper by Valdebenito and Dahmen (2013) where they compare a vegetation covered sound barrier to a “Concrete Conventional Noise Barrier” (CNB) which was borrowed for comparison against the wooden alternative in this paper. The paper submits their calculation of bill of content for a CNB of 3 m in height and as this study looks at CNB’s at both 3 m and 4 m in height the calculations was borrowed directly from the paper for the 3 m wall and then redone for the 4 m wall. The full calculation in detail is provided in Appendix C.

3.6.2.1. Final bill of content for the CNB wall sections for Wall 2A and Wall 2B

Below is a flow-chart depicting the final model of the production process (see Figure 12) and material required (see Table 13) to produce the necessary CNB reinforced concrete wall segments.

Table 13: Final bill of content per wall for Wall 2A and Wall 2B.

Material	Wall 2A	Wall 2B	Unit
Concrete	38 552	51 402	kg
Steel	1 169	1 475	kg

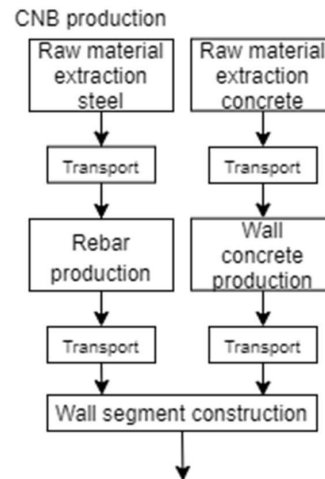


Figure 12: Flowchart of CNB production.

3.6.3. Life cycle inventory: Mofix concrete Foundation solution

The foundations were chosen based on the cylindrical type of foundation mentioned in the Valdebenito and Dahmen 2013 paper from which the CNB concrete barrier was borrowed, and then matched to a similar product on the market with an EPD, of which Mofix was the only suitable option. Based on the Mofix EPD for both a 355 mm and 555 mm in diameter foundations pillars of 4 m in length, the material requirement for the 4 different lengths of foundation pillars was calculated using the percentage in length difference multiplied with the weight of a 4 m foundation as seen in Appendix G.

The length is highly dependent on ground conditions and the lengths for the scenarios in this paper were determined by using values for a normal “medium soil” right in the middle of the grain group scale, with the following assumed values:

- Unit Weight of soil: 0,100 kip/ft³,
- Angle of internal friction: 30,0 degrees
- And soil bearing pressure: 0,630 kip/ft².

Approximately the same values come as a pre-set in the free foundation dimensioning software tool POLEFDN.xls version 2.3 used for this study, but the numbers used was also verified by the use of a Table borrowed from García-Rodríguez, et al. (2008) from which the above-mentioned values are taken.

Borrowing the calculation method to determine the wall segments dimensioning outer forces from Nylander and Jorga, (2007) the remaining input parameters for the POLEFDN.xls version 2.3 software was calculated as seen in Appendix D.

See Appendix E for the POLEFDN.xls results for the base case conditions and see Appendix G for detailed calculations of mass based on POLEFDN.xls results.

Using the free foundation dimensioning tool POLEFDN.xls version 2.3 the lengths for the 4 walls in normal ground conditions was calculated in Appendix G to be the following foundation weights:

Wall 1A: **18667 kg Mofix**

Wall 1B: **23195 kg Mofix**

Wall 2A: **27262 kg Mofix**

Wall 2B: **33546 kg Mofix**

Table 14 below is a Table containing Product specifications for 1 ton and 1 Mofix foundation, incl. Details and is borrowed from the Mofix EPD published by Rambøll 2017.

Table 14: Product specification 1 ton and 1 st Mofix ø555 and ø355 foundation, incl. Details.

Materials	ø355		ø555		ø355		ø555	
	kg	%	kg	%	ton	%	ton	%
Sand	330,4	30,4	833,0	36,1	0,30	30,4	0,36	36,1
Ballast	330,4	30,4	833,0	36,1	0,30	30,4	0,36	36,1
Cement	142,2	13,1	358,3	15,5	0,13	13,1	0,16	15,5
Additive	1,6	0,2	4,1	0,2	0,002	0,2	0,002	0,2
Water	57	5,2	143,6	6,2	0,05	5,2	0,06	6,2
Steel rebar	211,1	19,4	127,4	5,5	0,19	19,4	0,06	5,5
Details (plastic pipes, crosses, rock bolt and lifting anchor)	15,9	1,5	10,9	0,5	0,01	1,5	0,005	0,5
Total	1088,6	100	2310,3	100	1,0	100	1,0	100

The choice of foundation was also narrowed down to the use of only the 555 mm in diameter Mofix foundation for simplicity, therefore the data for the 355 mm alternative is stripped away. Next step was to breakdown the data on row number 9 in Table 14 above named “Details (plastic pipes, crosses, rock bolt and lifting anchor)” and this was assumed to be made up of 30% PVC plastics and 70% steel, the steel was added on to the rebar section resulting in this modified Table 15 below. The assumption about ratio was corroborated by data gathered from Stenman’s 2005 paper “Grundläggningsmetoder för kontaktleddningsfundament” thereby further strengthening the ratio assumption.

Table 15: Simplified and corrected Product specification 1 ton and 1 ø555 Mofix foundation, incl. Details.

Materials	ø555		ø555	
	kg	%	ton	%
Sand	833,0	36,1	0,360	36,1
Ballast	833,0	36,1	0,360	36,1
Cement	358,3	15,5	0,160	15,5
Additive	4,1	0,2	0,002	0,2
Water	143,6	6,2	0,060	6,2
Steel rebar	135,03	5,9	0,062	5,9
PVC plastic	3,27	0,2	0,002	0,2
Total	2310,3	100	1	100

3.6.3.1. Final bill of content for the foundations for Wall 1A, Wall 1B, Wall 2A and Wall 2B

Below in Table 16 the final in depth bill of content for the required amount of Mofix foundation per wall segment alternative is provided.

Table 16: Simplified and corrected bill of content for the foundations for Wall 1A, Wall 1B, Wall 2A and Wall 2B.

Materials	Wall 1A		Wall 1B		Wall 2A		Wall 2B	
	ø555	2 m wood	2,7 m wood	3 m concrete	4 m concrete	unit		
Sand	36%	6739	8374	9841	12110	kg		
Ballast	36%	6739	8374	9841	12110	kg		
Cement	16%	2893	3595	4226	5200	kg		
Additive	0%	37	46	55	67	kg		
Water	6%	1157	1438	1690	2080	kg		
Steel rebar	6%	1092	1357	1595	1962	kg		
PVC plastic	0%	28	35	41	50	kg		
Total	100%	18667	23195	27262	33546	kg		

Below in Figure 13 is an in-depth flow-chart depicting the final model of the production process and material required to produce the Mofix foundations for all wall alternatives.

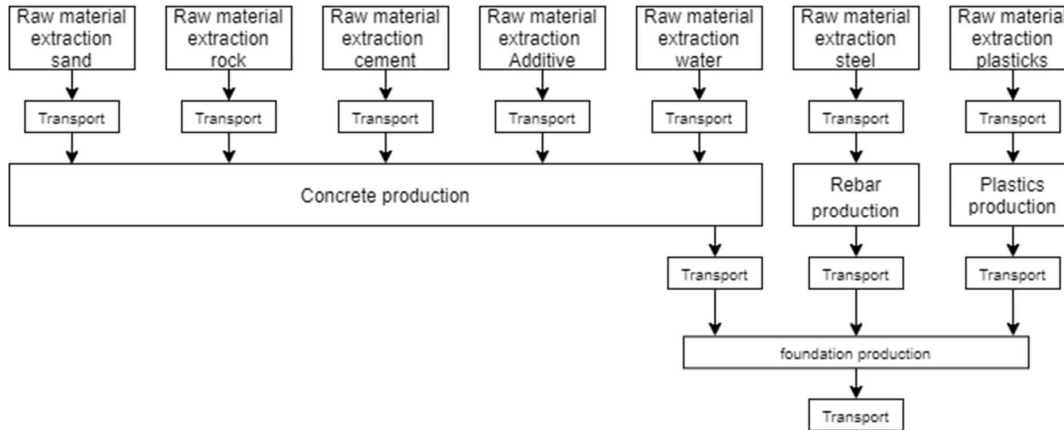


Figure 13: Flowchart of Mofix production.

3.6.4. Life cycle inventory: Wavebreaker’s noise mitigation solution

According to the company Wavebreaker, the product consists of two pieces of plastics with one blow moulded outer casing made from 3,5 kg of HD-PE plastics and an injection moulded inner casing made of 4 kg of HD-PE plastics giving the product an expected weight of 7,5 kg of HD-PE plastics sourced from 100% virgin material (at the moment) per 0,5 m long Wavebreaker unit.

The product will be installed on top of the barrier all along the entirety of the wall. As the wall segment is 40 m long and the product is 0,5 m long a total of 80 units of 7,5 kg will be required resulting in a total mass of 600 kg HD-PE plastics for both Wall A alternatives.

3.6.4.1. Final bill of content for the Wavebreaker's noise mitigation solution

Below is a flow-chart depicting the final model of the production process (see Figure 14) and Table of material required (see Table 17) to produce the necessary Wavebreaker units per wall alternative.

Table 17: Bill of content for the Wavebreaker products which are the same for both Wall 1A and Wall 1B.

Production process	Mass	Unit
Blow moulded HD-PE	280	Kg
Injection moulded HD-PE	320	Kg
<i>Total</i>	600	Kg

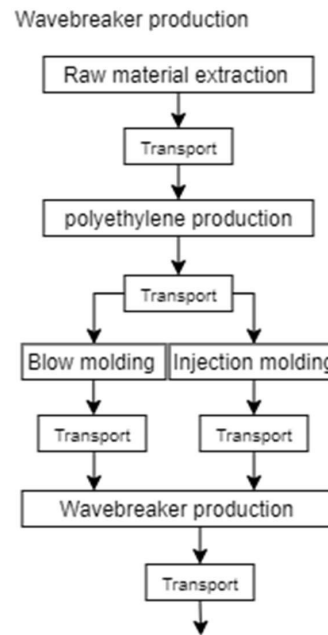


Figure 14: Flowchart of Wavebreaker production.

3.6.5. Life cycle inventory: end of life processes

The end-of-life treatment for the four wall alternatives are simplified based on mass conservation without any losses and chosen based on the most fitting Ecoinvent processes available. For Wall 1A and Wall 1B the inputs are matched with a Ecoinvent waste treatment process deemed most suitable for the material. The water is assumed to remain bound to the concrete and are therefore excluded while the amount of paint and PVC were deemed too small to expect any meaningful separation from the wood being incinerated or the concrete and steel beams being recycled. See Table 18 below.

Table 18: EOL processes.

Material	treatment process
Bsk-14F	
<i>Imp wood</i>	treatment of waste building wood, chrome preserved, municipal incineration with fly ash extraction
<i>Plywood</i>	treatment of waste wood, untreated, municipal incineration with fly ash extraction
<i>Wood</i>	treatment of waste wood, untreated, municipal incineration with fly ash extraction
<i>Glass wool</i>	treatment of waste mineral wool, inert material landfill
<i>Rockwool</i>	treatment of waste mineral wool, inert material landfill
<i>Polyester mesh</i>	treatment of waste plastic, mixture, municipal incineration with fly ash extraction
<i>Rubber</i>	treatment of waste rubber, unspecified, municipal incineration with fly ash extraction
<i>Steel</i>	treatment of scrap steel, inert material landfill
<i>Water</i>	excluded
<i>Paint</i>	excluded
Concrete wall	
<i>Concrete</i>	treatment of waste concrete gravel, recycling
<i>Steel</i>	treatment of waste reinforcement steel, recycling
Mofix Foundations	
<i>Sand</i>	treatment of waste concrete gravel, recycling
<i>Ballast</i>	treatment of waste concrete gravel, recycling
<i>Cement</i>	treatment of waste concrete gravel, recycling
<i>Additive</i>	treatment of waste concrete gravel, recycling
<i>Water</i>	treatment of waste concrete gravel, recycling
<i>Steel rebar</i>	treatment of waste reinforcement steel, recycling
<i>PVC plastic</i>	excluded
Wavebreaker	
<i>Blow moulded HD-PE</i>	treatment of waste plastic, mixture, municipal incineration with fly ash extraction
<i>Injection moulded HD-PE</i>	treatment of waste plastic, mixture, municipal incineration with fly ash extraction

3.6.5.1. Energy recovery

As seen above in Table 18 there are some materials going to landfill, some being recycled, and some being incinerated. The incineration processes do not account for the energy saved from electricity recovery during incineration, but the net electricity that can be recovered per wall segment was calculated based on the data regarding net electricity per kg of the material that was included in the process data as shown in Table 19 below. The electricity that the recovery displace is assumed to be “electricity, high voltage, production mix” from “European network of Transmission Systems Operators for Electricity 2015” as this was the closest source of data to European electricity mix available in the Ecoinvent 3.2 database.

Table 19: Net energy production MJ/kg electric energy from incineration EOL Processes.

Incinerated material	Energy content	Unit	Source (Ecoinvent 3.2 process)
<i>Imp wood</i>	1,74	MJ electric energy /kg	treatment of waste wood, untreated, municipal incineration with fly ash extraction
<i>Plywood</i>	1,74	MJ electric energy /kg	
<i>Wood</i>	1,74	MJ electric energy /kg	
<i>Rubber</i>	3,25	MJ electric energy /kg	treatment of waste rubber, unspecified, municipal incineration with fly ash extraction
<i>Polyester mesh</i>	3,93	MJ electric energy /kg	treatment of waste plastic, mixture, municipal incineration with fly ash extraction
<i>Blow moulded HD-PE</i>	3,93	MJ electric energy /kg	
<i>Injection moulded HD-PE</i>	3,93	MJ electric energy /kg	

Based on this data above in Table 19 and the Tables of contents above for the four different wall segments the following amount of electricity could be recovered per wall segment as seen in table 20.

Table 20: Energy recovery per wall segment.

<i>Material</i>	MJ/kg	Wall 1A		Wall 1B		Wall 2A		Wall 2B	
		Kg	MJ	Kg	MJ	Kg	MJ	kg	MJ
<i>Wood</i>	1,7	1539	2678	2052	3570	0	0	0	0
<i>Imp wood</i>	1,7	1638	2850	2184	3800	0	0	0	0
<i>Rubber</i>	3,3	18	60	24	79	0	0	0	0
<i>Plastic</i>	3,9	10	41	14	54	0	0	0	0
<i>HDPE</i>	3,9	600	2358	0	0	600	2358	0	0
<i>Total</i>		3806	7986	4274	7504	600	2358	0	0

Notice how all values are equal to zero for Wall 2B as this wall solely consists of reinforced concrete and reinforce concrete foundations lacking any energy released during incineration.

3.6.6. Life cycle inventory: transportation

For each process step in the flowcharts above some amount of transportation is included in the raw material extraction and product production process taken from Ecoinvent. However, the transportation from the production to the assembly of the wall segments is not. Therefore, some assumptions had to be made in order to compare the different options. Most distances are taken from product EPDs that include their own estimates of transportation needs from production to use phase, and the distances is assumed to be representative for all similar product and processes.

Below is a table with type, distance, and source for all material transportation assumptions. All transportation that was expressed in the respective EPD to be lower than EURO-06 has been upgraded to EURO-06 for all transportation, as these recommendations or declarations suggesting otherwise are assumed to have been written before introduction of EURO-06 and therefore ignored in interest of keeping this study as up to date as possible. The mode of transportation is not as interesting as the suggested distance and therefore transportation has been upgraded to fit the current time frame only keeping the distance in some cases.

For some materials, a suitable EPD could not be located and therefore are assumed to follow the transportation needs as for some other type of material. In this case the rubber sealant was one such example and to be able to make the comparison the rubber sealant is assumed to be produced as far away as the furthest material on the list, in an attempt to not underestimate the transportation contribution. Therefore, the rubber sealant is assumed to require the same transportation as the mineral wool produced in Denmark. As for the polyester mesh the same problem to identify a suitable EPD was encountered and therefore the polyester mesh was assumed to require the same transportation needs as for the PVC piping produced in Norway as this was deemed adequately close in a production and material perspective.

Table 21: Transportation needs and mode per material and source.

Material	Transport	distance	unit	EPD number
<i>Imp wood</i>	Freight, lorry EURO6, >32 ton	150	km	NEPD-474-330-NO
	Freight, lorry EURO6, 16-32 ton	50	km	
<i>Wood</i>	Freight, lorry EURO6, >32 ton	270	km	NEPD-2547-1284-SE
	Freight, lorry EURO6, 16-32 ton	30	km	
<i>Glass wool</i>	Freight, lorry EURO6, 16-32 ton	230	km	NEPD-474-330-NO
<i>Mineral wool</i>	Freight, lorry EURO6, >32 ton	761	km	NEPD-2605-1326-EN
	Freight, inland waterways, barge	10	km	
<i>Polyester mesh</i>	Freight, lorry EURO6, 16-32 ton	300	km	NEPD-2732-1425-NO
<i>Rubber sealant</i>	Freight, lorry EURO6, >32 ton	761	km	NEPD-2605-1326-EN
	Freight, inland waterways, barge	10	km	
<i>Steel</i>	Freight, lorry EURO6, 16-32 ton	300	km	NEPD-2364-1104-NO
<i>Mofix 555</i>	Freight, lorry EURO6, 16-32 ton	211	km	NEPD-1259-405-NO
<i>PVC</i>	Freight, lorry EURO6, 16-32 ton	300	km	NEPD-2732-1425-NO
<i>Concrete</i>	Freight, lorry EURO6, 16-32 ton	16,9	km	NEPD-2041-914-SE
<i>Rebar</i>	Freight, lorry EURO6, 16-32 ton	64	km	NEPD-2676-1376-NO
<i>Wavebreaker</i>	Freight, lorry EURO6, 16-32 ton	730	km	Wavebreaker data.
<i>EOL transport</i>	Freight, lorry, unspecified, EURO6	50	km	Assumed

Based on data supplied from the company Wavebreaker the distances from the blow moulding facility (450km) and the injection moulding facility (13km) to the assembly facility amounts to approximately 460km. An additional delivery transportation is required from assembly facility to use face and is being assumed to equate the average distance from assembly facility to Gothenburg or Stockholm Sweden resulting in approximately 270km, giving us a total of 730km transportation.

For the EOL processes the transportation is assumed to carry the entire mass of the wall segment without any losses to a waste treatment centre that recycles, incinerates, or landfills the material on site. The distance to waste treatment varies throughout Europe, but for the sake of comparison an arbitrary distance of 50km was assumed for all 4 wall segments.

3.6.7. Final system flow charts

Below the systems, processes and connections mapped and included in the Life Cycle Inventory for the 4 wall alternatives can be found, with Wall 1A (figure 15) followed by Wall 1B (figure 16) followed by Wall 2A (figure 17) and finally Wall 2B (figure 18). These were modelled in OpenLCA according to above calculated Life Cycle Inventory to arrive at the result presented in chapter 4.

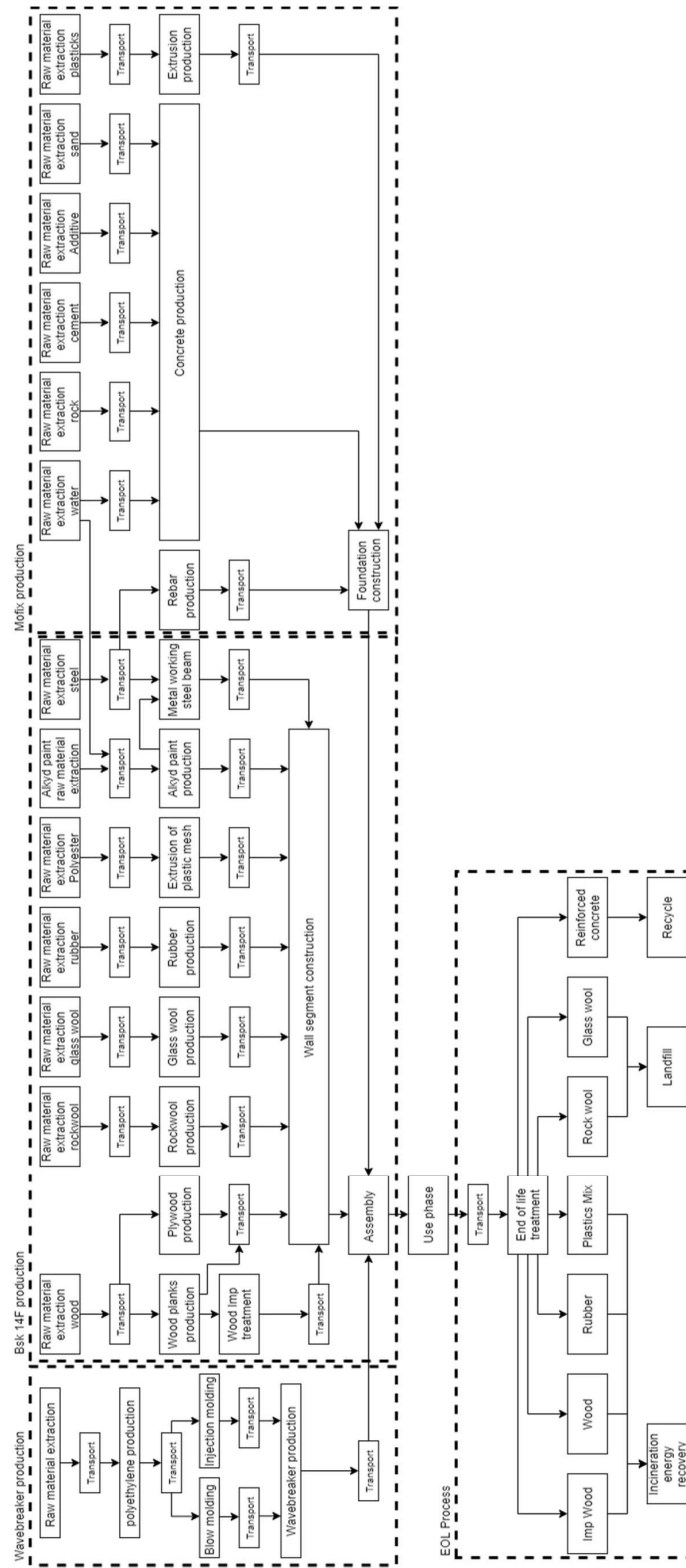


Figure 15: Flow chart cradle to grave Wall 1A.

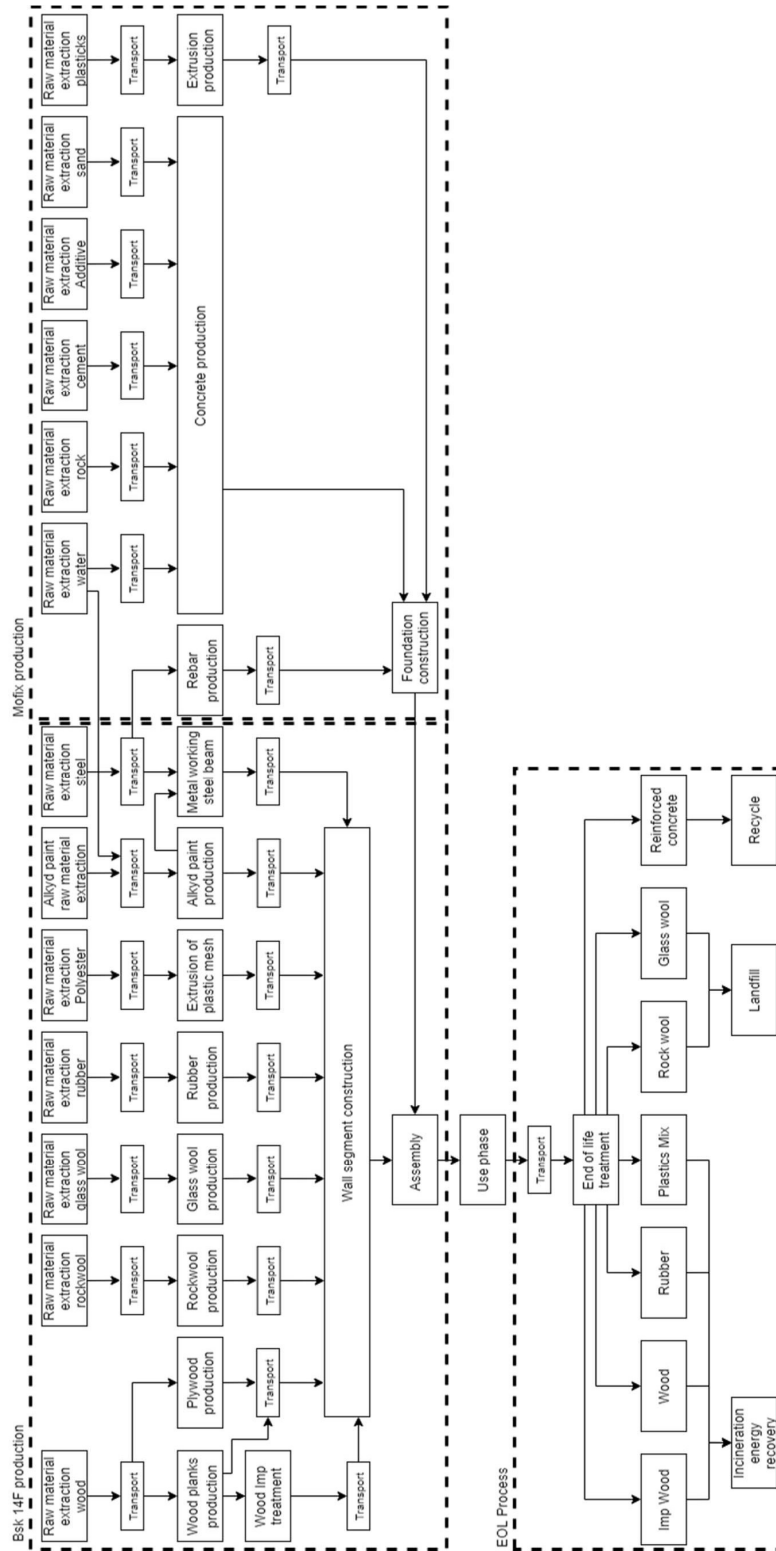


Figure 16: Flow chart cradle to grave Wall 1B.

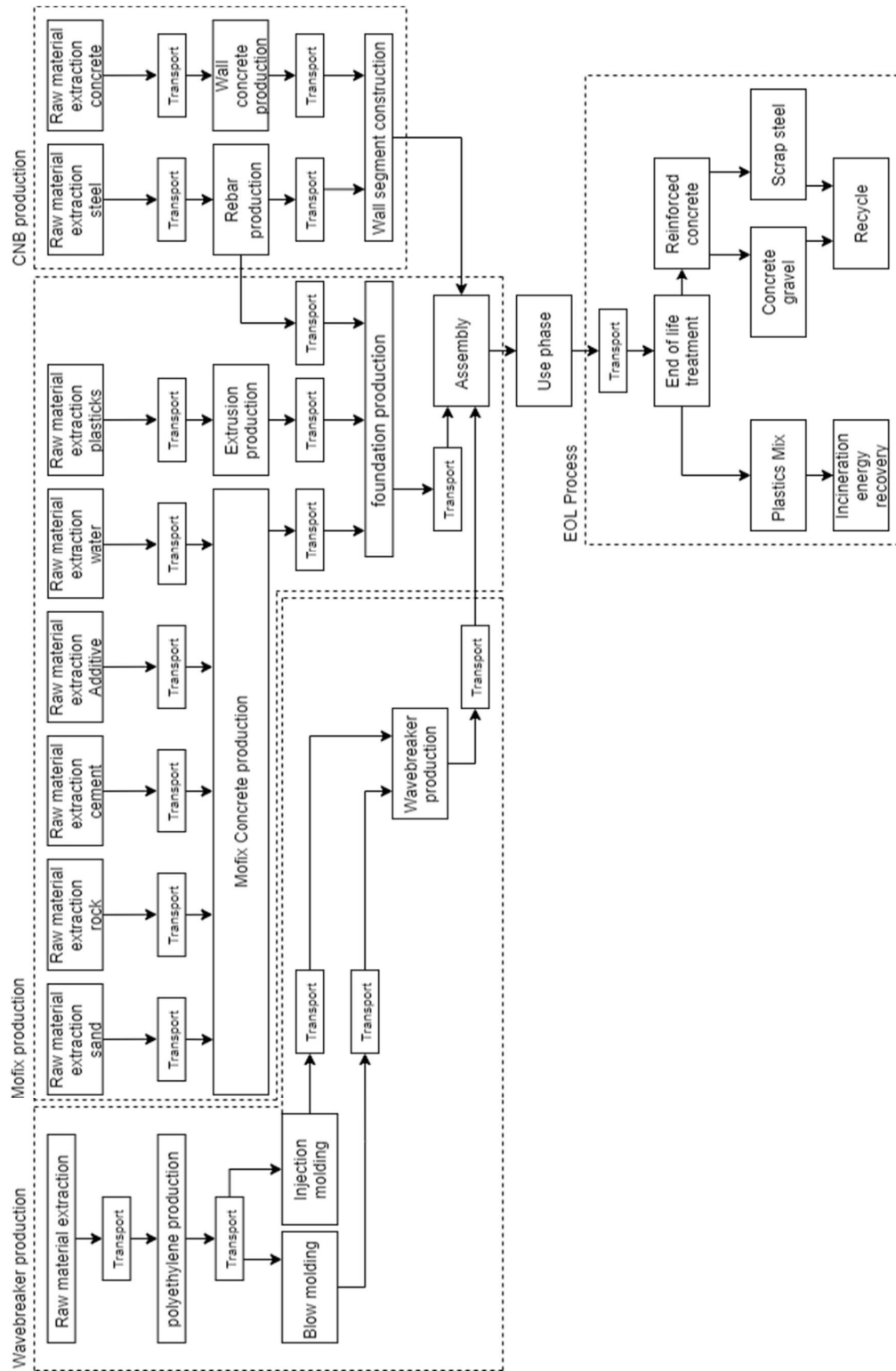


Figure 17: Flow chart cradle to grave Wall 2A.

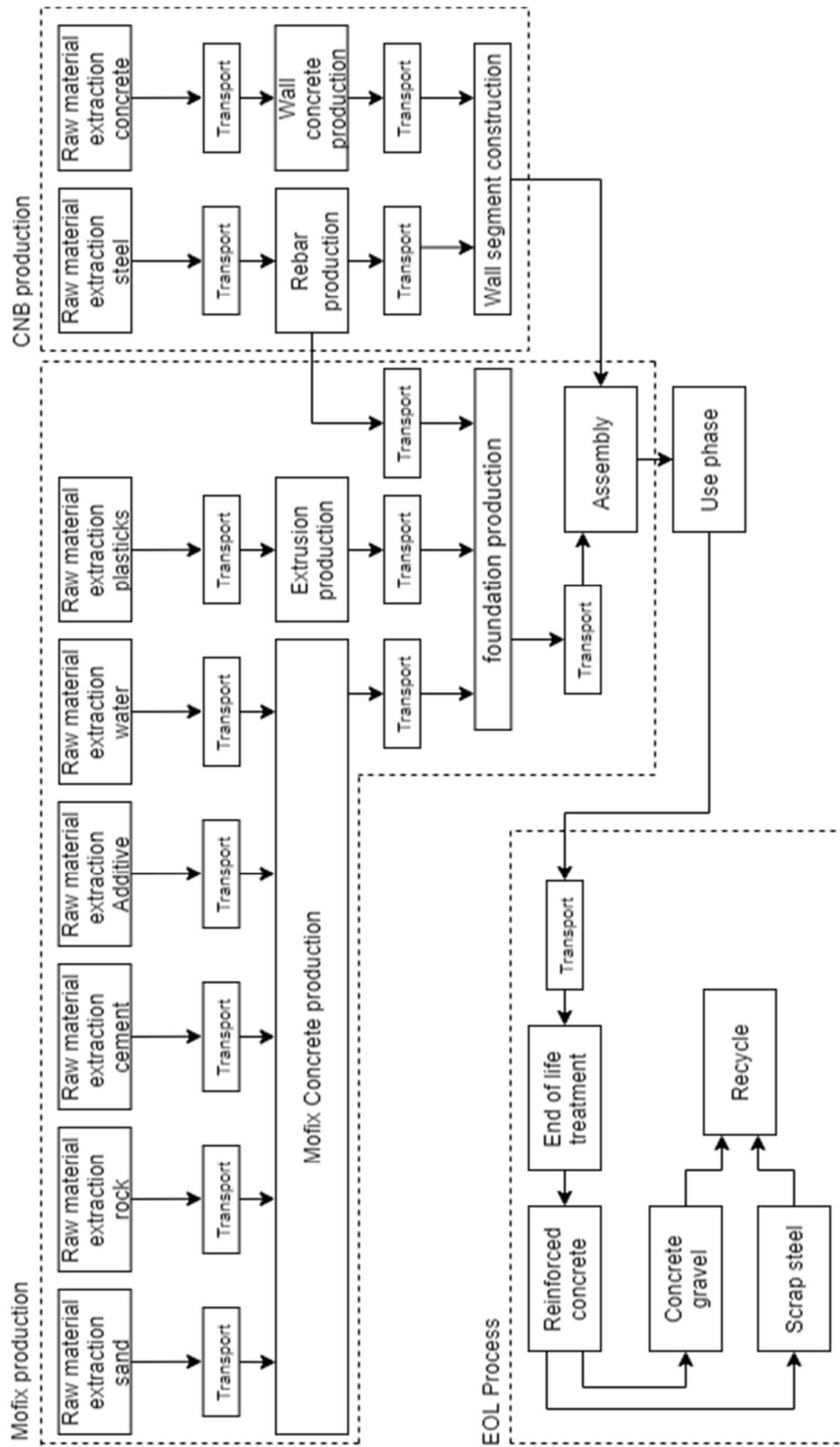


Figure 18: Flow chart cradle to grave Wall 2B.

4. Results

Below are the results taken from OpenLCA after putting in all of the LCI data and creating a flow model for all 4 wall segments and then comparing them through a ReCiPe 2016 Midpoint Hierarchies version perspective. Followed by a simple variation analysis covering three different ground conditions affecting the size of the foundation requirement. Followed by a breakeven point analysis of at what amount of DH-PE production that the performance of Wavebreaker outperforms the higher wall alternative in all 18 categories.

4.1. LCIA results from OpenLCA

As seen in the column labelled “Absolute change” in Table 22 and Table 23 below, the impact for different indicators varies from close to zero all the way up to tens of thousands, creating a need for adapting a logarithmic scale on the x axis in order to more clearly see the difference for all indicators in one graph as seen in Figure 19 and Figure 20 below.

Table 22: LCIA results for Wall 1A and Wall 1B.

Indicator	Wall 1A	Wall 1B	Absolute change	Relative change [%]	Unit
<i>Fine particulate matter formation</i>	34,3	42,5	8,2	19%	kg PM2.5 eq
<i>Fossil resource scarcity</i>	4 180,0	3 979,0	-201,0	-5%	kg oil eq
<i>Freshwater ecotoxicity</i>	840,2	992,5	152,3	15%	kg 1,4-DCB
<i>Freshwater eutrophication</i>	4,4	5,5	1,1	20%	kg P eq
<i>Global warming</i>	17 544,7	18 559,5	1 014,8	5%	kg CO2 eq
<i>Human carcinogenic toxicity</i>	4 782,9	6 214,2	1 431,4	23%	kg 1,4-DCB
<i>Human non-carcinogenic toxicity</i>	16 842,9	19 768,5	2 925,6	15%	kg 1,4-DCB
<i>Ionizing radiation</i>	782,1	903,9	121,8	13%	kBq Co-60 eq
<i>Land use</i>	161,5	201,5	40,0	20%	m2a crop eq
<i>Marine ecotoxicity</i>	1 181,7	1 401,2	219,6	16%	kg 1,4-DCB
<i>Marine eutrophication</i>	0,4	0,5	0,1	17%	kg N eq
<i>Mineral resource scarcity</i>	1 560,0	2 062,3	502,4	24%	kg Cu eq
<i>Ozone formation, Human health</i>	38,5	45,1	6,6	15%	kg NOx eq
<i>Ozone formation, Terrestrial ecosystems</i>	40,7	47,5	6,8	14%	kg NOx eq
<i>Stratospheric ozone depletion</i>	0,0	0,0	0,0	15%	kg CFC11 eq
<i>Terrestrial acidification</i>	54,9	64,9	10,0	15%	kg SO2 eq
<i>Terrestrial ecotoxicity</i>	150 595,0	191 402,0	40 807,0	21%	kg 1,4-DCB
<i>Water consumption</i>	122 442,0	159 474,0	37 032,0	23%	m3

Table 22 shows positive percentage improvements for all categories except the negative improvement attributed to the fossil resource scarcity results on row 2, indicating an expected performance reduction for this category when choosing to install the Wavebreaker product over installing the higher wooden barrier.

Table 23: LCA results for Wall 2A and Wall 2B.

Indicator	Wall 2A	Wall 2B	Absolute change	Relative change [%]	Unit
<i>Fine particulate matter formation</i>	24,4	28,8	4,4	16%	kg PM2.5 eq
<i>Fossil resource scarcity</i>	4 238,5	3 999,9	-238,6	-2%	kg oil eq
<i>Freshwater ecotoxicity</i>	500,7	527,6	26,9	7%	kg 1,4-DCB
<i>Freshwater eutrophication</i>	4,3	5,3	0,9	18%	kg P eq
<i>Global warming</i>	20 628,5	22 353,4	1 724,9	9%	kg CO2 eq
<i>Human carcinogenic toxicity</i>	2 194,5	2 673,6	479,1	18%	kg 1,4-DCB
<i>Human non-carcinogenic toxicity</i>	13 403,9	14 848,9	1 445,0	11%	kg 1,4-DCB
<i>Ionizing radiation</i>	691,2	771,3	80,2	12%	kBq Co-60 eq
<i>Land use</i>	181,6	225,4	43,8	19%	m2a crop eq
<i>Marine ecotoxicity</i>	725,7	775,5	49,8	8%	kg 1,4-DCB
<i>Marine eutrophication</i>	0,25	0,28	0,03	12%	kg N eq
<i>Mineral resource scarcity</i>	369,3	459,9	90,6	20%	kg Cu eq
<i>Ozone formation, Human health</i>	41,2	48,1	6,8	15%	kg NOx eq
<i>Ozone formation, Terrestrial ecosystems</i>	42,8	49,7	6,8	14%	kg NOx eq
<i>Stratospheric ozone depletion</i>	0,007	0,008	0,001	11%	kg CFC11 eq
<i>Terrestrial acidification</i>	45,8	52,1	6,3	13%	kg SO2 eq
<i>Terrestrial ecotoxicity</i>	97 523,4	118 712,0	21 188,6	18%	kg 1,4-DCB
<i>Water consumption</i>	36 736,7	44 282,5	7 545,8	17%	m3

Just like the results in Table 22 the results in Table 23 shows positive percentage improvements for all categories except the negative improvement attributed to the fossil resource scarcity results on row 2, indicating an expected performance reduction for this category when choosing to install the Wavebreaker product over installing the higher concrete barrier.

The results are all in their respective units as seen in Table 22 and Table 23s column titled “Unit”. To allow for comparison between the different alternatives the ReCiPe 2016 Midpoint Hierarchies version LCIA method normalizes the impact categories to allow for a comparison of the results in the same graphs, by multiplying the results with their respective normalisation factors. Thereby changing the values somewhat in order to strip away the units and to turn the results into unitless numbers while still preserving the ratio between the different results. Below are the normalised values presented in bar graphs in Figure 19 and Figure 20 showing the consistently lower impact for the lower walls beside the bars for the higher barriers on a logarithmic unitless axes.

Figure 19 shows normalised LCIA results for comparison between Wall 1A and Wall 1B and Figure 20 shows normalised LCIA results for comparison between Wall 2A and Wall 2B.

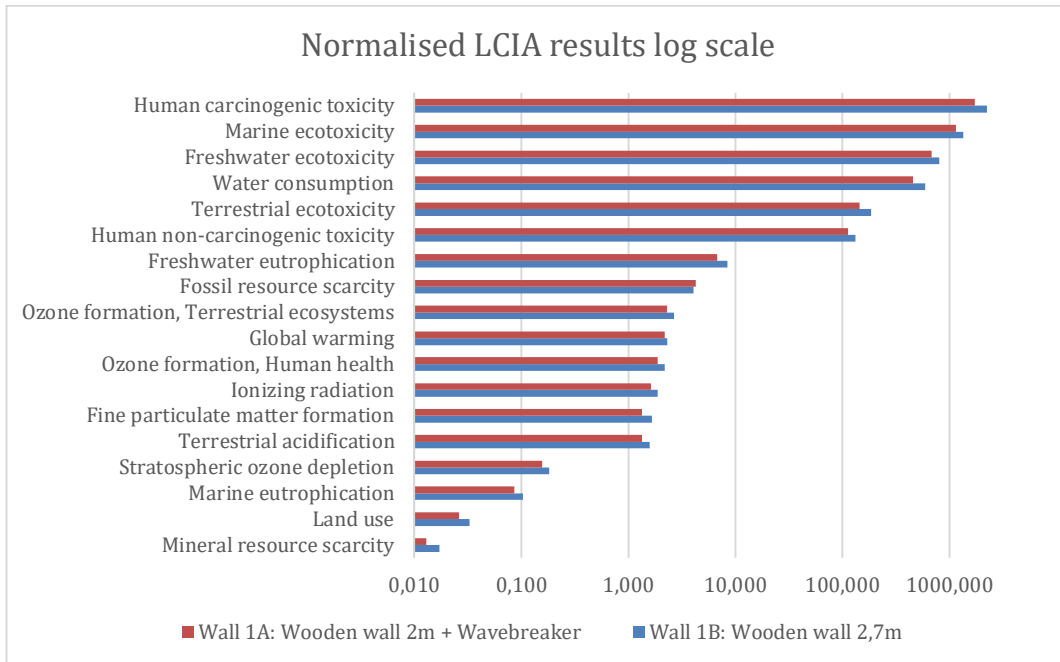


Figure 19: Normalised LCA results Wall 1A and Wall 1B with a logarithmic scale unitless axis.

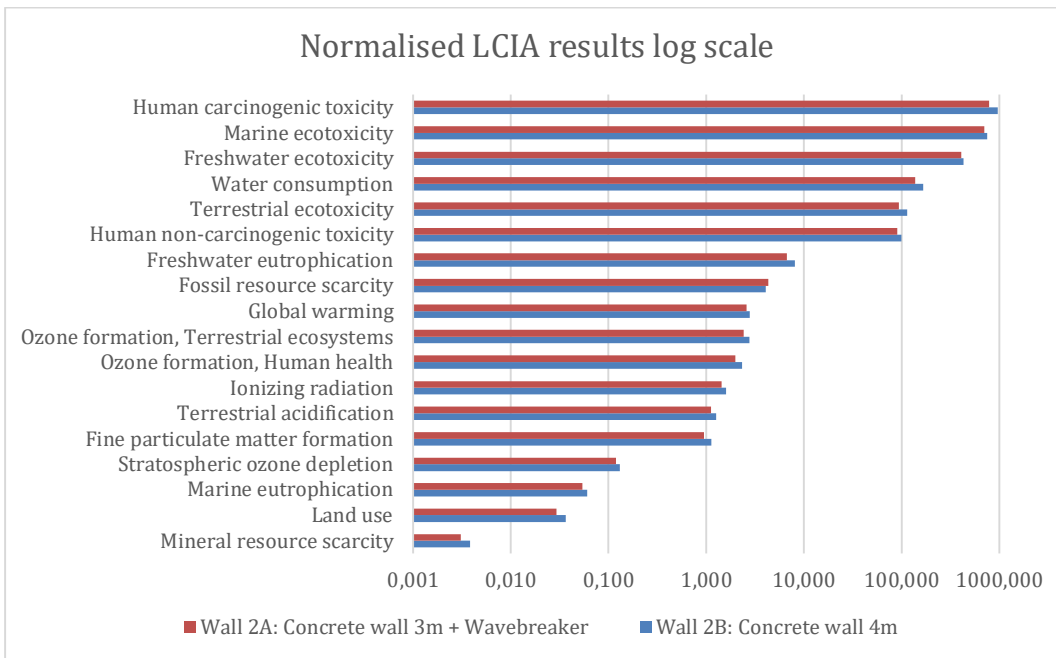


Figure 20: Normalised LCA results Wall 2A and Wall 2B with a logarithmic scale unitless axis.

As seen in Table 22 and Table 23 above, the results show improvement in all impact categories except for one “Fossil fuel scarcity”, demonstrated with a negative improvement result in the improvement column in said Tables. This becomes more obvious when the normalised results are plotted and ranked after improvement per category as seen in Figure 21 and Figure 22 below.

These show the improvement relative to the worst of the alternatives in each category, clearly showing an overall improvement in all but one category for both comparisons.

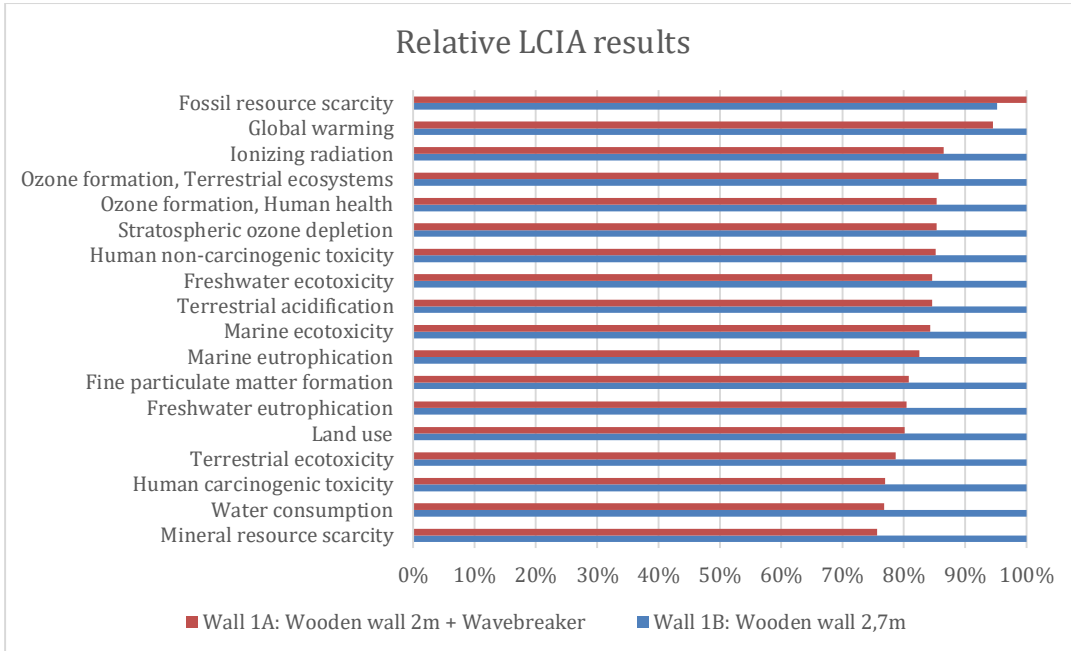


Figure 21: Relative LCA results Wall 1A and Wall 1B.

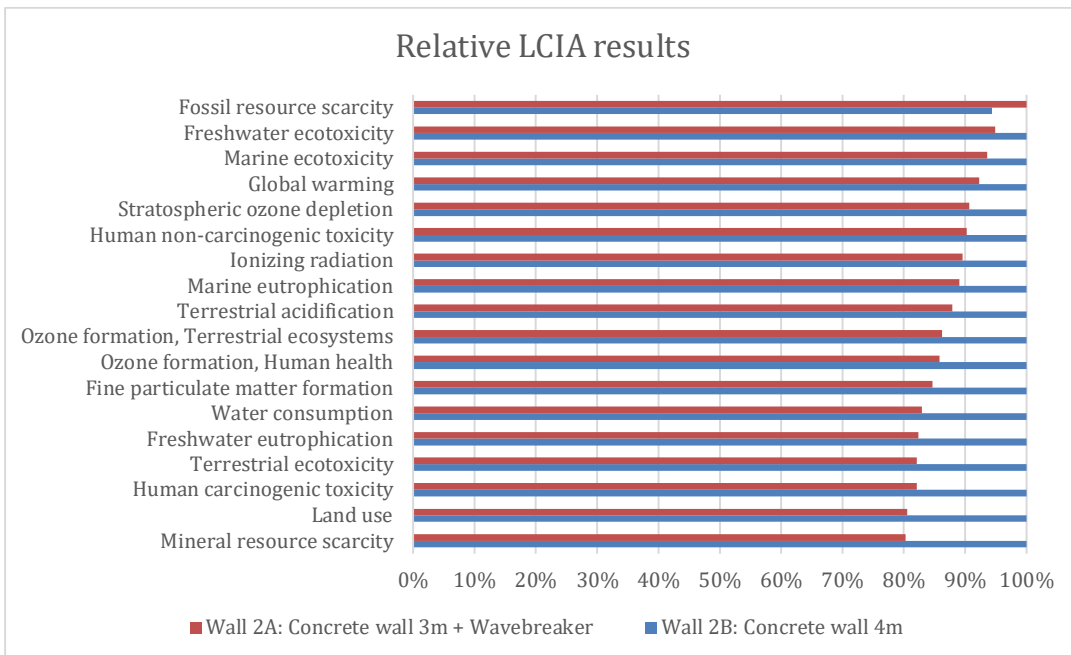


Figure 22: Relative LCA results Wall 2A and Wall 2B.

When breaking down the contribution differences for the fossil fuel depletion impact category for each alternative, it becomes apparent that the addition of the approximately 600 kg of HD-

PE plastics for Wall 1A and Wall 2A has a large impact regarding the performance in this category.

As the lower wall segments contain the plastic Wavebreaker component while the other two do not, this places the lower wall segments at a large disadvantage as no other large quantity of plastics in the other materials are sourced from fossil fuels. And no large enough contributor to the fossil fuel depletion category is concentrated enough in the top 1 m part of the wall alternatives to have a large enough impact when reducing the height of the wall, the addition of the Wavebreaker and therefore the alternative containing the most plastics will therefore almost always perform worse in this category. As the HD-PE is a plastic sourced from fossil fuel production, the material contains relatively large amounts of energy, therefore the incineration does give an energy savings related impact credit, lowering its contribution somewhat, which can be seen as the energy savings credit for Wall 1A is larger than for Wall 1B even though Wall 1B contains about 25% more wood, but as seen in Figure 23 and Figure 24 below not nearly enough to swing the results to fall in Wavebreaker's favour considering the current circumstances under study.

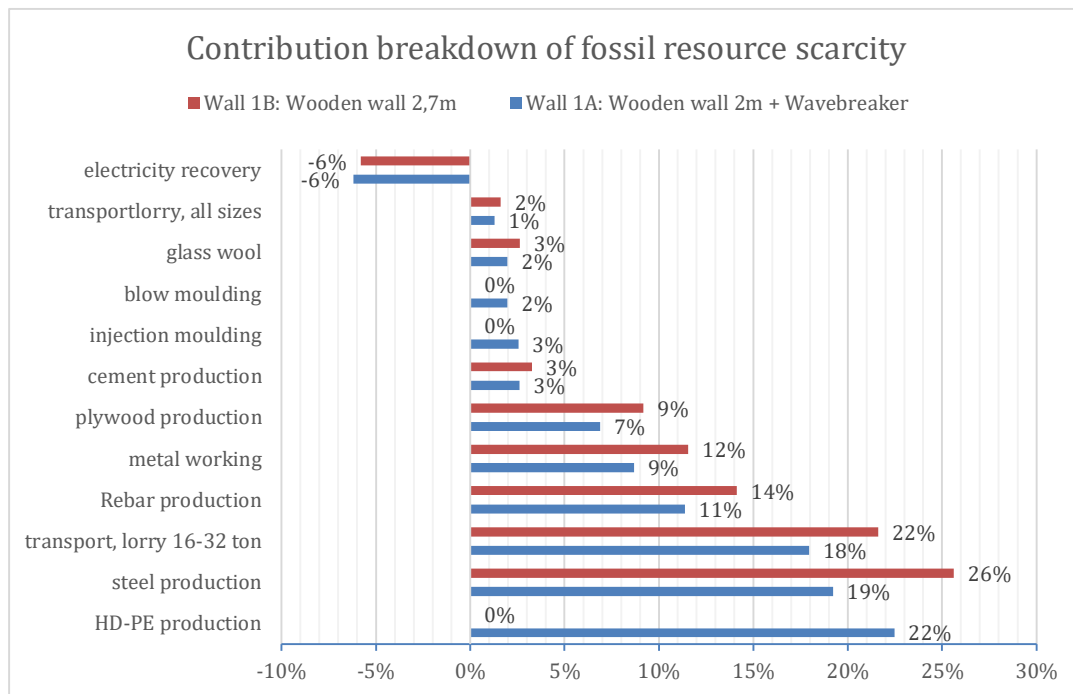


Figure 23: Contribution breakdown of fossil resource scarcity for Wall 1A and Wall 1B.

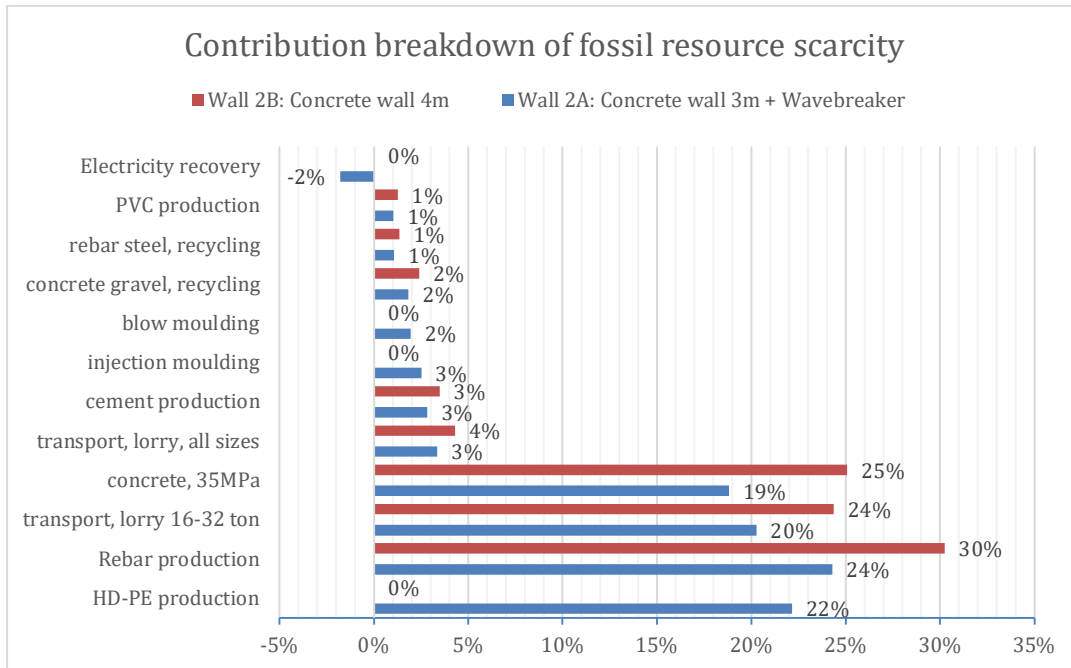


Figure 24: Contribution breakdown of fossil resource scarcity for Wall 2A and Wall 2B.

As seen in Figure 23 and Figure 24 above, the reduction in height does lead to a reduction on fossil fuel depletion in all contributing flows and processes. But apparently not enough to compensate for the large contribution from the HD-PE production and blow/injection moulding required for the Wavebreaker product production. The results show that this reduction in height is not enough to achieve a performance that is as good or better in this specific category, but it indicates that there is a point where the height reduction is enough to compensate for the addition of the Wavebreaker elements. The amount of Wavebreaker units required is only dependent on length of the barrier and therefore remains constant regardless of height. Therefore, it would stand to reason that at some point the contribution reduction from material reduction will at some point outgrow the constant contribution addition from Wavebreaker. However, at what height decrease this breaking point is to be found for these specific examples is yet to be determined but taking into consideration the small positive difference in favour for the higher barrier, this indicate that it may not be far off.

4.2. Variation analysis

The results above in chapter 4.1 are only representative for the specific circumstances mentioned and established in chapter 2 where the ground is harmonious and falls under medium soil conditions (Class 4) as seen in Table 24 below. The walls are designed in such a way that they can be erected anywhere as long as they have a foundation to be bolted down upon, but as soil conditions change so does the foundation requirements.

To evaluate the effect of alternative scenarios in the life cycle model a limited variation analysis was performed. One of the only variables that could be drastically different from case to case was the soil condition and therefore the amount of foundation needed and their contribution from steel, concrete, and PVC as broken down in Table 16 in Chapter 2, The wall alternatives

all have the same IL at the same distance and height and width would remain constant regardless of where in Europe they were to be erected. The foundation however is highly dependent on ground conditions and can vary from one part of the wall to the other. The aforementioned example scenarios all assume a uniform middle case scenario regarding soil conditions, and this results in the results shown above in Table 21 and Table 22 as well as in Figure 19 until Figure 24. When looking at Figure 23 and Figure 24 it becomes apparent that rebar and concrete production has a sizable contribution to the fossil fuel depletion category and that were these to increase or shrink with the amount of required foundation this would affect the results as well.

Therefore, different scenarios have been applied to switch from normal soil condition to a worst-case scenario as well as a best-case scenario and look at the effect that a placement of the barrier in worse and in better soil would entail.

The soil conditions are borrowed from a Table gathered from García-Rodríguez, et al. (2008) and converted to the input units used by the free foundation dimensioning software tool POLEFDN.xls version 2.3. and presented in Table 24 below. Detailed calculations can be found in Appendix G.

Table 24: Geotechnical parameters: unit weight, friction angle and effective cohesion (García-Rodríguez, et al. 2008).

Class	Classification	Unit Weight		Friction angle	Cohesion	
		[kN/m ³]	[kip/ft ³]		[kN/m ²]	[kip/ft ²]
1	Hard rock	26	0,166	45	300	6,266
2	Soft rock	22	0,140	40	200	4,177
3	Hard soil	11	0,070	30	60	1,253
4	Medium soil	15	0,096	30	30	0,627
5	Soft soil	11	0,070	20	30	0,627
6	Very soft soil	11	0,070	20	23	0,480

Best-case scenario was determined to be class 1 from Table 23 above. And the worst-case scenario was chosen to be class 6 from Table 23 above. The results after running the new numbers through POLEFDN.xls version 2.3 results in the following Table 25 of new foundation weights. See Appendix F for POLEFDN.xls results and Appendix G for detailed mass calculations.

Table 25: Mass calculation results based on 3 different types of soil conditions.

	Good soil conditions [kg]	Normal soil conditions [kg]	Bad soil conditions [kg]
Wall 1A	12559	18667	23935
Wall 1B	15544	23195	29683
Wall 2A	18311	27262	34932
Wall 2B	22502	33546	42927

After running the analysis with the worst-case (bad soil conditions) and best-case scenario (good soil conditions) alongside the original normal scenario (normal soil conditions) we can

get a better understanding of what results that can be expected when you are dealing with better or worse ground conditions, when erecting future noise barriers.

The results can be separated into three different brackets, a high improvement bracket (as seen in Table 26 and Table 27) including all impact categories where the average improvement of all three soil conditions equal to or above 20%, a middle improvement bracket (as seen in Table 28 and Table 29) including all impact categories where the average improvement of all three soil conditions ranges from 11% up to 19%, and a small difference bracket (as seen in Table 30 and Table 31) including all impact categories where the average improvement of all three soil conditions equal 10% or lower.

4.2.1. High improvement bracket

Table 26 and Table 27 contain the impact categories for the two comparisons where the results show an improvement equal to or above 20% when comparing the Wall A alternatives containing the Wavebreaker elements against the Wall B alternatives representing the higher barriers. Table 26 presenting high relative changes between Wall 1A and Wall 1B, and Table 27 presenting high relative changes between Wall 2A and Wall 2B.

Table 26: High improvement bracket results of variation analysis for difference in ground conditions for Wall 1A and Wall 1B.

Indicator	Relative change [%]		
	Good soil conditions	Normal soil conditions	Bad soil conditions
<i>Mineral resource scarcity</i>	24%	24%	24%
<i>Water consumption</i>	23%	23%	23%
<i>Human carcinogenic toxicity</i>	23%	23%	23%
<i>Terrestrial ecotoxicity</i>	21%	21%	21%
<i>Land use</i>	20%	20%	20%

Table 27: High improvement bracket results of variation analysis for difference in ground conditions for Wall 2A and Wall 2B.

Indicator	Relative change [%]		
	Good soil conditions	Normal soil conditions	Bad soil conditions
<i>Mineral resource scarcity</i>	20%	20%	19%

4.2.2. Medium improvement bracket

Table 28 and Table 29 contain the impact categories for the two comparisons where the results show an improvement between above 10% and below 20% when comparing the Wall A alternatives containing the Wavebreaker elements against the Wall B alternatives representing the higher barriers. Table 28 presenting medium relative changes between Wall 1A and Wall 1B, and Table 29 presenting medium relative changes between Wall 2A and Wall 2B.

Table 28: Medium improvement bracket results of variation analysis for difference in ground conditions for Wall 1A and Wall 1B.

Indicator	Relative change [%]		
	Good soil conditions	Normal soil conditions	Bad soil conditions
<i>Freshwater eutrophication</i>	19%	20%	19%
<i>Fine particulate matter formation</i>	19%	19%	19%
<i>Marine eutrophication</i>	17%	17%	18%
<i>Marine ecotoxicity</i>	15%	16%	16%
<i>Terrestrial acidification</i>	15%	15%	16%
<i>Freshwater ecotoxicity</i>	15%	15%	16%
<i>Human non-carcinogenic toxicity</i>	14%	15%	15%
<i>Ozone formation, Human health</i>	14%	15%	15%
<i>Stratospheric ozone depletion</i>	14%	15%	15%
<i>Ozone formation, Terrestrial ecosystems</i>	13%	14%	15%
<i>Ionizing radiation</i>	12%	13%	14%

Table 29: Medium improvement bracket results of variation analysis for difference in ground conditions for Wall 2A and Wall 2B.

Indicator	Relative change [%]		
	Good soil conditions	Normal soil conditions	Bad soil conditions
<i>Land use</i>	19%	19%	19%
<i>Human carcinogenic toxicity</i>	18%	18%	18%
<i>Terrestrial ecotoxicity</i>	18%	18%	18%
<i>Freshwater eutrophication</i>	18%	18%	18%
<i>Water consumption</i>	17%	17%	17%
<i>Fine particulate matter formation</i>	15%	16%	16%
<i>Ozone formation, Human health</i>	14%	15%	15%
<i>Ozone formation, Terrestrial ecosystems</i>	14%	14%	15%
<i>Terrestrial acidification</i>	12%	13%	14%
<i>Marine eutrophication</i>	11%	12%	13%
<i>Ionizing radiation</i>	10%	12%	13%
<i>Stratospheric ozone depletion</i>	9%	11%	12%
<i>Human non-carcinogenic toxicity</i>	9%	11%	12%

4.2.3. Small difference bracket

Table 30 and Table 31 contain the impact categories for the two comparisons where the results show an improvement equal to or below 10% when comparing the Wall A alternatives containing the Wavebreaker elements against the Wall B alternatives representing the higher barriers. Table 26 presenting low relative changes between Wall 1A and Wall 1B, and Table 27 presenting low relative changes between Wall 2A and Wall 2B.

Table 30: Small difference bracket results of variation analysis for difference in ground conditions for Wall 1A and Wall 1B.

Wall 1A vs Wall 1B <i>Indicator</i>	Relative change [%]		
	Good soil conditions	Normal soil conditions	Bad soil conditions
<i>Global warming</i>	3%	5%	7%
<i>Fossil resource scarcity</i>	-10%	-5%	-2%

Table 31: Small difference bracket results of variation analysis for difference in ground conditions for Wall 2A and Wall 2B.

Wall 2A vs Wall 2B <i>Indicator</i>	Relative change [%]		
	Good soil conditions	Normal soil conditions	Bad soil conditions
<i>Global warming</i>	7%	9%	10%
<i>Marine ecotoxicity</i>	6%	8%	10%
<i>Freshwater ecotoxicity</i>	4%	7%	9%
<i>Fossil resource scarcity</i>	-7%	-2%	0%

A detailed discussion of these results as seen in Table 28 to Table 31 can be found in Chapter 5.2 below.

4.3. Finding the breakeven point of HD-PE production on fossil fuel scarcity

Noticing the relatively small reduction in Fossil resource scarcity as seen in Table 30 and Table 31 above in combination with the contribution breakdown of fossil resource scarcity in Figure 23 and Figure 24, the only variable that Wavebreaker has control over in these scenarios in Chapter 4.1 and Chapter 4.2 is the HD-PE production required per Wavebreaker unit. To see if this performance loss associated with Wavebreaker units can be alleviated through a reduction of HD-PE plastics we vary the HD-PE amount to find the breakeven point and try to pinpoint roughly what percentage of reduction that would be required.

Running the simulations again in OpenLCA but this time multiplying HD-PE flow throughout the system with a percentage ranging from 70% of the original 600 kg required for the 40 m wall segments up to 110% of the HD-PE flows gives us the following six graphs as seen below.

4.3.1. Results for varying HD-PE production for Wall 1A and Wall 1B

Below the results for a comparison between wall 1A and Wall 1B can be found with Figure 25 depicting the comparison in bad soil conditions, Figure 26 depicting the comparison in normal soil conditions and Figure 27 depicting the comparison in good soil conditions, with the amount of HD-PE production varying between 70% and 110% of the original 600kg.

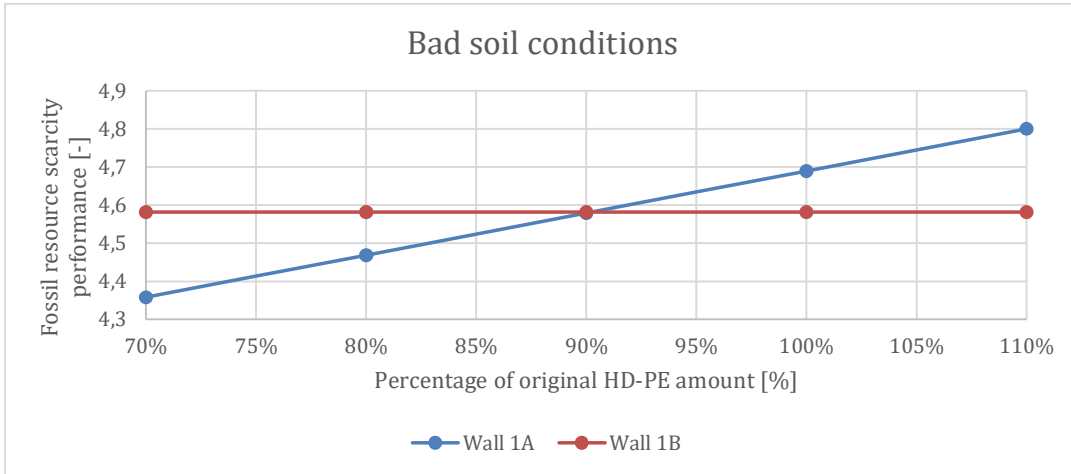


Figure 25: Variation analysis HD-PE amount on fossil fuel scarcity for Wall 1A and Wall 1B in bad soil conditions.

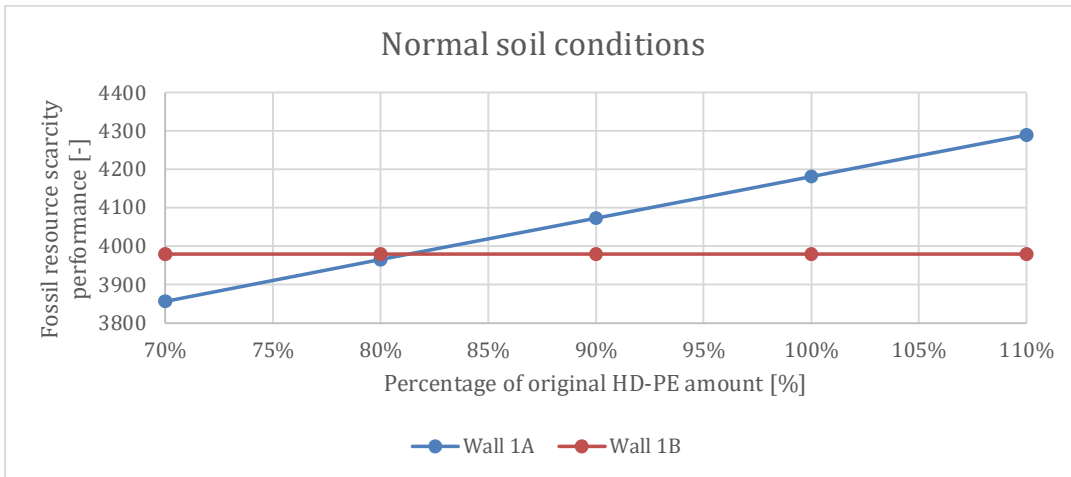


Figure 26: Variation analysis HD-PE amount on fossil fuel scarcity for Wall 1A and Wall 1B in normal soil conditions.

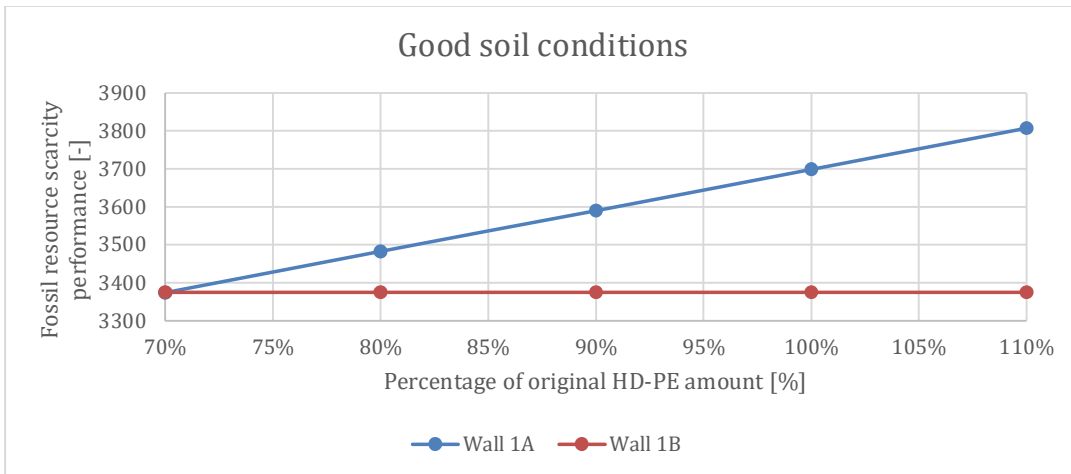


Figure 27: Variation analysis HD-PE amount on fossil fuel scarcity for Wall 1A and Wall 1B in good soil conditions.

As seen in Figure 25 until Figure 27 above the breakeven point for the Wall 1 comparison falls somewhere between a 10-30% material reduction required to achieve the same performance for the Wavebreaker alternative as for the installation of the higher wall alternative when considered in the combination with the wooden Bsk-14F barrier design alternative, depending on soil conditions.

4.3.2. Results for varying HD-PE production for Wall 2A and Wall 2B

Below the results for a comparison between Wall 2A and Wall 2B can be found, with Figure 28 depicting the comparison in bad soil conditions, Figure 29 depicting the comparison in normal soil conditions and Figure 30 depicting the comparison in good soil conditions, with the amount of HD-PE production varying between 70% and 110% of the original 600kg.

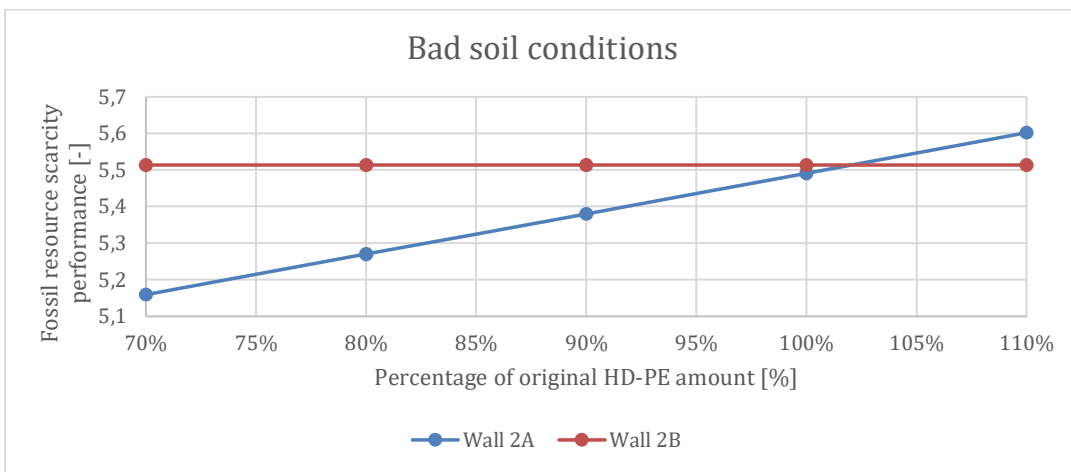


Figure 28: Variation analysis HD-PE amount on fossil fuel scarcity for Wall 2A and Wall 2B in bad soil conditions.

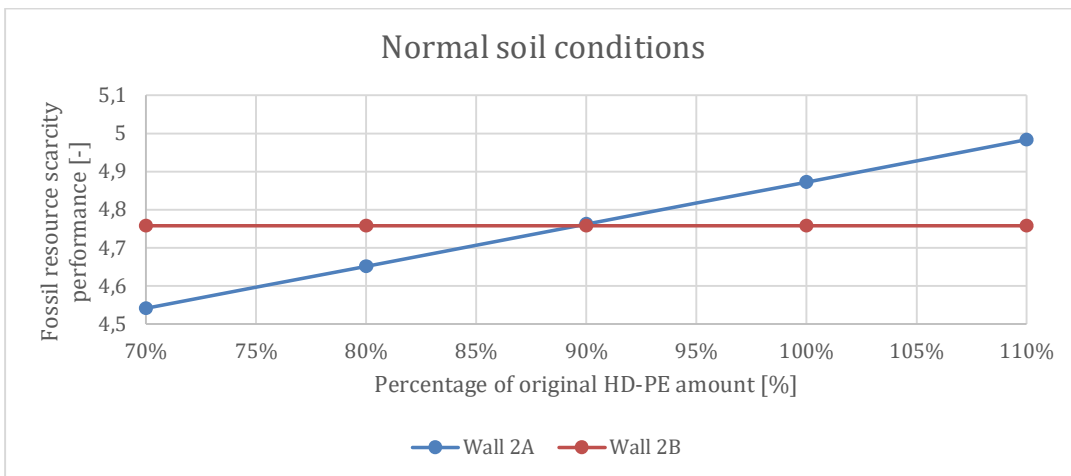


Figure 29: Variation analysis HD-PE amount on fossil fuel scarcity for Wall 1A and Wall 1B in normal soil conditions.

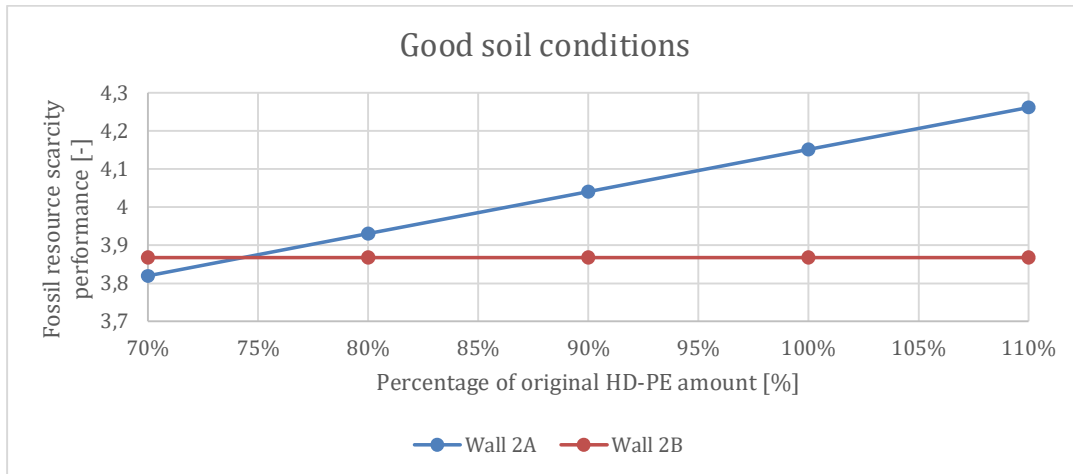


Figure 30: Variation analysis HD-PE amount on fossil fuel scarcity for Wall 1A and Wall 1B in normal good conditions.

In the resulting graphs for the breakeven point analysis for the Wall 2 comparison as seen in Figure 28 until Figure 30, the results show that the reduction requirements fall somewhere between a 0-26% material reduction required to achieve the same performance for the Wavebreaker alternative as for the installation of the higher wall alternative when considered in the combination with the CNB reinforced concrete barrier design alternative, depending on soil conditions.

5. Discussion

5.1. Results

The results in Table 22 and Table 23 above indicate a majority of large improvements in terms of relative change which is expected to be a result of the large reduction in material required for a 0,7-1 m reduction in height of the walls. Reducing the material consumption usually results in a reduction in most impacts roughly corresponding to the percentage difference in material consumption. The question was how the addition of the plastic Wavebreaker element was going to negate these impact reductions or not, in what categories, and by how much.

Looking at Table 22 and Table 23 above for the base case assuming normal ground conditions, the results show an average reduction of 16% between Wall 1A and Wall 1B (the wooden wall alternatives) and an average of 13% reduction between Wall 2A and Wall 2B (the concrete alternatives) in all categories, including the increase in fossil fuel depletion. When separating the impact categories where decrease was achieved from the one resulting in an increase, the average decrease in those 17 out of 18 categories where an impact reduction was achieved, now averages 17% between Wall 1A and Wall 1B and 14% between Wall 2A and Wall 2B. These results when compared to the approximately 25% reduction in wall material and approximately 20% reduction in foundation material between Wall A and Wall B in both comparisons, may indicate a sizable contribution from some component, but not enough to negate a majority of the gain associated with wall height reduction in these 17 impact categories.

The one notable impact category out of the 18 covered by ReCiPe 2016 Midpoint Hierarchies version is the fossil resource scarcity category, where the results in Table 22 and Table 23 indicate that the choice of going with a lower noise barrier with Wavebreaker installed (Wall 1A and Wall 2A) will result in a 2-5% decrease in performance compared with extending the wall upwards to achieve the same IL for the base case, depending on choice of wall material. This means that despite the 20-25% material reduction, some process in the Wavebreaker's lifecycle contributes a large enough impact to this category to negate the improvement from the overall 20-25% material reduction.

These results in combination with the contribution breakdown of fossil resource scarcity shown in Figure 23 and Figure 24 above, one of the easiest solutions for Wavebreaker AB to alleviate this performance decrease would be to minimize the amount of HD-PE plastics being used. If the Wavebreaker company were to redesign future iterations of their noise mitigation solution, to require less HD-PE plastics per unit, switch material or incorporate closed or even open loop recycling, this relatively small decrease in performance could potentially be eliminated or even lead to an overall performance increase in this category as well.

5.2. Variation analysis

For the results of the variation analysis, the small difference bracket as seen in Table 30 and Table 31, the performance results clearly indicate that the choice of material to combine the Wavebreaker product with, can hold some significance. This as the use of Wavebreaker to lower the wall height for a reflective CNB concrete noise barrier by 1 m can result in a 0% decrease all the way up to 7% increase in the fossil fuel scarcity impact category (depending on soil conditions). While the results indicate that the use of Wavebreaker to lower a wooden Bsk-14F noise barrier by 0,7 m would result in an increase in impact ranging from 2% all the way up to 10% in the impact category fossil fuel scarcity. Thereby suggesting a slightly more

favourable pairing between the Wavebreaker product and the CNB barrier than with the Bsk-14F barrier.

The results in Table 30 and Table 31 in the variation analysis also shows that the global warming impact category, results in a roughly similar result for both materials regardless of choice, with an improvement ranging from 3% to 7% in performance when choosing Wall 1A over Wall 1B depending on soil conditions, and an improvement between a 7% to 10% in performance when choosing Wall 2A over Wall 2B depending on soil conditions.

When only looking at Table 31 for results between Wall 2A and Wall 2B, Marine ecotoxicity, and Freshwater ecotoxicity also does not appear to offer any substantial improvement regardless of choice. The predicted improvement is expected to range between 4% and 10% depending on type of ground conditions. Taking the level of uncertainty for the modelling of the system into consideration, even in the most optimistic scenarios, the results that fall under the small difference bracket results in Table 30 and Table 31 for these impact categories, can be deemed at risk of falling below the margin of error and would therefore justify caution regarding promises of improvement in these categories covered in Table 30 and Table 31.

Looking at the high bracket results in Table 26 and Table 27 of the variation analysis, the results show a significant improvement in several important categories, where the results show an improvement of 20% or more when averaging out the percentage improvement for all 3 soil conditions. In all three soil conditions tested in the variation analysis between Wall 1A and Wall 1B, Mineral resource scarcity, Water consumption, Human carcinogenic toxicity, Terrestrial ecotoxicity and Land use all performed an average of 20-24% better when choosing Wall 1A over Wall 1B. In the variation analysis between Wall 2A and Wall 2B however, the only impact category that saw an average of 20% or more improvement by reducing the wall height in favour of installing Wavebreaker elements, was the impact category Mineral resource scarcity.

However, looking at the variation analysis results for the middle bracket as shown in Table 28 and Table 29, it becomes apparent that a majority of the impact categories covered by ReCiPe 2016 Midpoint Hierarchies version for both wall materials stand to see an 11-19% performance improvement when choosing Wall 2A over Wall 2B and a 13% to 19% performance improvement when choosing Wall 1A over Wall 1B, depending on soil conditions, which is large enough to confidently expect measurable real-world improvements regardless of soil conditions.

5.3. Breakeven point analysis

The breakeven analysis in Chapter 3.4 show that the amount of material reduction that would be needed for Wavebreaker to outperform the higher barriers in all 18 impact categories covered by the ReCiPe 2016 Midpoint Hierarchies version as detailed in Table 2 above would fall within a span of 30-0% material reduction for both materials, depending on soil condition.

With a 30% material reduction per unit, Wavebreaker could be confident that their product would outperform or tie in all impact categories when compared with the alternative of installing higher noise barriers when considering both wooden and reinforced concrete barriers, regardless of soil conditions. Taking into consideration that the good soil conditions that would require the largest material reduction of 30% is not reasonable to expect everywhere along the wall when erecting a noise barrier. More likely you would see a mix of all three soil conditions along the 40 m wall segment, meaning that a reduction of 20-25% would probably be enough to reach a breakeven point for a large majority of use cases.

5.4. Contribution to the ongoing research

The research into effects of material choice and choice of mitigation method appears to be starting to accumulate a growing body of literature. Papers from researchers such-as Ahac et al, (2021) and Björk et al. (2015) are helping to further the discussion regarding the long-term impacts that the choice of mitigation solution might result in. Considering the growing research and interest into the changes in trends regarding modes of international (as well as national) transportation and what consequences that these might bring. Research into alternative solutions and assessment of existing solutions for reasons and concerns hindering implementation of certain choices or solutions, may hold potential to play a key role in laying the foundation for European (as well as the rest of the worlds) mobility infrastructure that future generations may come to depend on.

This LCA does not offer any concrete solutions to these problems mentioned above. However, the results from this thesis and similar like it, such as research from Valdebenito and Dahmen, (2013), Djulstedt and Gronowski (2014), Lakušić et al (2012) as well as Ahmadi and Wirell (2019) to name a few, are examples of papers in the field of evaluating or assessing the feasibility of improving on decades old research and product development, in interest of improving the soundscape of cities. As well as to contribute to the noble cause of preventing unnecessary losses of life and productivity, lost to noise pollution related health concerns in rapidly growing cities as effectively as possible, without straining the already severely strained and complex ecosystems of which these cities inhabit.

5.5. Research methodology

The LCA was heavily focused on the upstream activities of the construction process and production processes for noise barrier wall alternatives. Large data gaps were left regarding effect of choices regarding machinery, personnel, maintenance, and storage. Data regarding averages in these areas proved hard to come by as these were left out on a large majority of the EPD's that was screened for this LCA, and the lack of a real-world case to study and evaluate resulted in the choice between speculation or exclusion. These results were deemed too likely to potentially lower the accuracy of the results if assumptions regarding these holes in data were to be filled with low certainty estimates. After the pilot program of implementation is actualized, a new LCA taking into consideration the data gathered from this construction would be of interest to further strengthen the conclusion regarding potential performance increase associated with the Wavebreaker product.

All material data was deemed to be covered and included except for the method of attaching the different components together for the Bsk-14F modules for Wall 1A and Wall 1B. The paper from which it was borrowed suggested the components being kept together using adhesives applied during mass production of the modules. But as mass production of these modules is not an available option as of time of writing, the assumed individual construction of the Bsk-14F modules on site during construction was assumed to rely on nails or screws rather than adhesives. The amount of screws or nails, required per square meter wall, proved difficult to find data on. The amount was deemed to probably not be significant enough to have a large effect and the effect that it would have would potentially risk being of detriment for the results because of the low level of certainty.

The energy recovery from incineration, at the end-of-life stage for the wall alternatives, were assumed to exclude heat recovery and only generate electricity. If the walls were to be disposed of in a Scandinavian country, the heat from incineration would probably displace central heat

production because of the large demand for heating in colder climates. But as the study kept a European geographic perspective the heat was not assumed to be of interest for all countries equally, and were therefore excluded as the means of central heating that the heat would potentially displaced would potentially differ widely from country to country and would in certain places potentially hold no value at all. Were this to be included, the results would with high certainty improve the potential Life Cycle Analysis results for Wall 1A and Wall 2A as this would have resulted in even larger energy recovery related impact discounts in the contribution breakdown of fossil resource scarcity.

The ground conditions and the dimensioning of the foundations were one of the hardest parts to decide upon for this study. The choice of foundation method and material is of large importance for the results of this types of studies but the fact that this study is placed in a theoretical location with uniform conditions without the expertise, to perform the calculations and measurements, hold the potential to cast a large part of the results into question. The experts and literature that was consulted all agreed that there was no way around the lack of a good simplification without large margins of errors. In the end the calculations were made using a software tool that was assumed to work in combination with the chosen Mofix foundations, but the software's apparent lack of consideration regarding amount of reinforcement might have caused some over estimation of the foundation required. Would this study be expanded upon the consultation of a proper geotechnical engineer and validation against real case studies of foundation requirements, would potentially stand to improve the validity of the results considerably.

The most recent version of Ecoinvent that was available to the author for this study ended up being the Ecoinvent 3,2 2015 version. This is not a specifically bad, or particularly old data set to use, but it is somewhat outdated in comparison to the most recent version of the database which is the 3.7.1 version from 2020 as of time of writing. Future evaluations of this product were the company Wavebreaker to develop an EPD or to evaluate the pilot project after the construction have come to fruition, a newer data set then the 3,2 2015 version would be recommended in service of transparency.

5.6. Ethical considerations

As the entire thesis revolves around environmental research the topic is highly connected to ethical planning and implementation in relation to development of railway infrastructure. However, as the research does not contain or relate to anything dealing with ethical question regarding subject such as personal information or any type of animal treatment, this subject is not taken into consideration while performing the research.

6. Conclusion

This LCA study in collaboration with the company Wavebreaker AB investigated the effects of implementation of Wavebreaker's new noise mitigation system. The analysis did present some interesting challenges regarding the specific situation of which the product was to be considered as the product is yet to be produced and tested as of time of writing.

The comparison of the Wavebreaker products environmental performance, to that of the two base case options of extending two walls of different materials upwards, enough to achieve the same noise reduction, in three different soil conditions was chosen based on its relatability to real world required decision support.

Two high quality and highly reasonable wall alternatives for comparison were identified and the choice of including at least two material alternatives with three soil conditions proved to yield interesting result regarding the effect of combination of material when considering implementation of Wavebreaker's new noise mitigation product.

The existing body of research into noise mitigation does point to further development and research in this field to be in high demand in the near future. If the models for the future of rail transportation from agencies such as the IEA are to be believed, this type of products and research may have large influence in shaping the preference of noise mitigation options going forward.

As the results clearly show, the effect of innovation and implementation of the latest in noise mitigation solutions such as Wavebreaker's new product can potentially save future projects up to 20-25% of their negative effects in certain impact categories, and a low estimate of overall improvement ranging from 10 to 15%, and a high estimate of overall improvement ranging from 15% to 20% depending on choice of construction design, construction material and the projects specific soil conditions. If we are to see a development of over 100% rail infrastructure increase in the next 30 years, at the same timeframe as Europe is expected to reach net zero emissions, this field of research could lead to substantial reductions in material use and related environmental concerns from both politicians, the public, as well as other interest groups.

The relatively small drawback of a maximum of 10%, and minimum of 2% worse performance in solely the fossil resources scarcity impact category, will probably not be considered a large deterring factor for large scale infrastructure companies and city planners looking for greener noise mitigation solutions options. At least not when considering the relatively large improvement in the remaining 17 out of 18 impact categories.

Even though a hot spot analysis was not of interest for this study, it is worth to point out that results indicating a 2-10% worse performance in fossil fuel scarcity, in combination with the contribution breakdown of fossil resource scarcity shown in Figure 23 and Figure 24 above, that one of the easiest suggestions to alleviate some of this performance decrease would be to minimize the amount of HD-PE plastics being used. As seen in the breakeven point analysis in Chapter 4.3, a material reduction of approximately 20% would help to relieve a majority of this performance reduction associated with the Wavebreaker product in this category.

As mentioned in chapter 5, If the Wavebreaker company were to redesign future iterations of their noise mitigation solution, to require less production of HD-PE plastics per unit, switch material or incorporate closed or even open loop recycling, this relatively small decrease in performance could potentially be eliminated or even lead to an overall performance increase in this category as well.

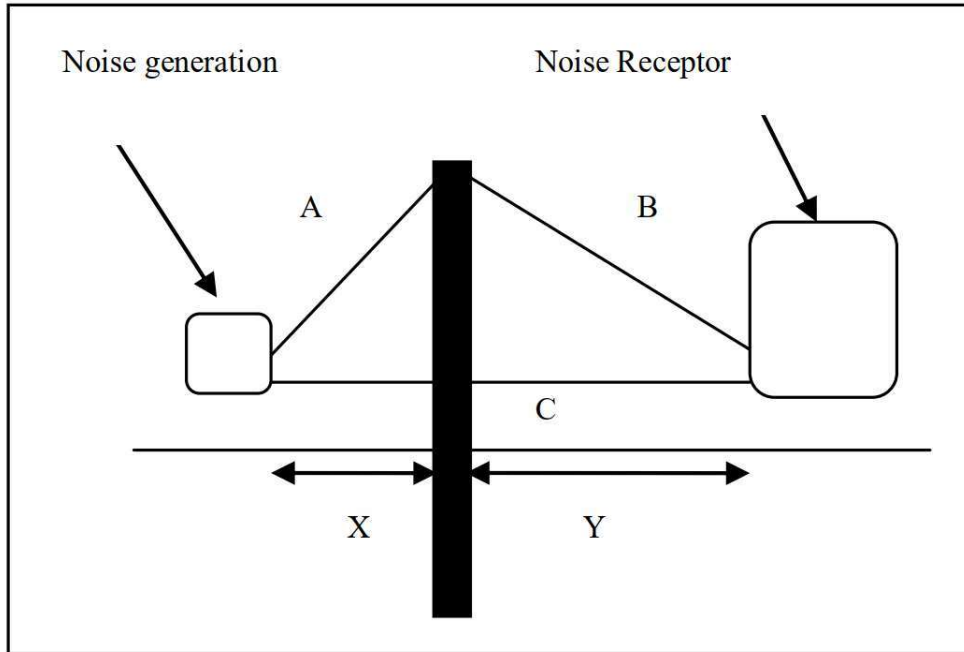
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8. Appendices

Appendix A: calculations of height using IL.



$x = \text{distance from fracks to wall} = 5,5\text{m}$
 $y = \text{distance from wall to reciver} = 20\text{m}$
 $h = \text{height of wall}$
 $g = \text{height on the noise generator} = 0,5\text{m}$
 $i = \text{height of the receptor} = 1,7\text{m}$
 $C = x + y = 25,5\text{m}$
 $\lambda = \text{acoustic wavelength asumed to be } 0,6$

Absorptive wood wall at 2m:

$$A = \sqrt{x^2 + (h - g)^2} = \sqrt{5,5^2 + (2 - 0,5)^2} = 5,701\text{m}$$

$$B = \sqrt{y^2 + (h - i)^2} = \sqrt{20^2 + (2 - 1,7)^2} = 20,002\text{m}$$

$$\delta = A + B - C = 5,701 + 20,002 - 25,5 = 0,203$$

$$N = \frac{2 * \delta}{\lambda} = \frac{2 * 0,203}{0,6} = 0,677$$

$$\begin{aligned}
 IL_{height} &= 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * N}}{\tanh(\sqrt{2 * \pi * N})} \right) = 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * 0,677}}{\tanh(\sqrt{2 * \pi * 0,677})} \right) \\
 &= 11,569
 \end{aligned}$$

$$IL_{tot} = IL_{heig} + IL_{adsorption} + IL_{Wavebreaker} = 11,569 + 4,5 + 3 = 19,069 \text{ dB IL}$$

Reflective concrete wall at 3m:

$$A = \sqrt{x^2 + (h - g)^2} = \sqrt{5,5^2 + (3 - 0,5)^2} = 6,042\text{m}$$

$$\begin{aligned}
B &= \sqrt{y^2 + (h - i)^2} = \sqrt{20^2 + (3 - 1,7)^2} = 20,042m \\
\delta &= A + B - C = 6,042 + 20,042 - 25,5 = 0,584 \\
N &= \frac{2 * \delta}{\lambda} = \frac{2 * 0,584}{0,6} = 1,946 \\
IL_{height} &= 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * N}}{\tanh(\sqrt{2 * \pi * N})} \right) = 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * 1,946}}{\tanh(\sqrt{2 * \pi * 1,946})} \right) \\
&= 15,889 \\
IL_{tot} &= IL_{height} + IL_{adsorption} + IL_{Wavebreaker} = 14,768 + 0 + 3 = 18,889 \text{ dB IL}
\end{aligned}$$

With the difference in IL being: $19,069 - 18,889 = 0,180 \text{ db}$

Without the Wavebreaker product the wall height will have to achieve the entire IL of 19 dB all on their own so new height for the two alternatives are therefore calculated that achieve the same 19 dB IL without the 3 dB IL contribution from the Wavebreaker product.

Absorptive wood wall at 2,7m:

$$\begin{aligned}
A &= \sqrt{x^2 + (h - g)^2} = \sqrt{5,5^2 + (2,7 - 0,5)^2} = 5,924m \\
B &= \sqrt{y^2 + (h - i)^2} = \sqrt{20^2 + (2,7 - 1,7)^2} = 20,025m \\
\delta &= A + B - C = 5,924 + 20,025 - 25,5 = 0,449 \\
N &= \frac{2 * \delta}{\lambda} = \frac{2 * 0,449}{0,6} = 1,496 \\
IL_{height} &= 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * N}}{\tanh(\sqrt{2 * \pi * N})} \right) = 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * 1,496}}{\tanh(\sqrt{2 * \pi * 1,496})} \right) \\
&= 14,768 \\
IL_{tot} &= IL_{height} + IL_{adsorption} + IL_{Wavebreaker} = 14,768 + 4,5 + 0 = 19,268 \text{ dB IL}
\end{aligned}$$

Reflective concrete wall at 4m:

$$\begin{aligned}
A &= \sqrt{x^2 + (h - g)^2} = \sqrt{5,5^2 + (4 - 0,5)^2} = 6,519m \\
B &= \sqrt{y^2 + (h - i)^2} = \sqrt{20^2 + (4 - 1,7)^2} = 20,132m \\
\delta &= A + B - C = 6,519 + 20,132 - 25,5 = 1,151 \\
N &= \frac{2 * \delta}{\lambda} = \frac{2 * 1,151}{0,6} = 3,837 \\
IL_{height} &= 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * N}}{\tanh(\sqrt{2 * \pi * N})} \right) = 5 + 20 * \log_{10} \left(\frac{\sqrt{2 * \pi * 3,837}}{\tanh(\sqrt{2 * \pi * 3,837})} \right) \\
&= 18,822 \\
IL_{tot} &= IL_{height} + IL_{adsorption} + IL_{Wavebreaker} = 18,822 + 0 + 0 = 18,822 \text{ dB IL}
\end{aligned}$$

With the difference in IL being: $19,268 - 18,822 = 0,445 \text{ db}$

Appendix B: calculations for normalization and bill of content for Bsk 14F

This appendix describes the detailed calculations left out of the chapter 3.6.1 where detailed calculation of number of wall segments and modules for each Bsk 14F alternative, calculation of mass amount of steel per Bsk 14F wall alternative and paint per Bsk 14F wall alternative where performed.

Number of wall segments and Bsk 14F modules

As the first wall (Wall 1A) is 2m high and 40 m long with 2,683m c/c the number of segments and modules is calculated to be:

Segments: $40/2,683 \approx 15$ St.

modules: $2/0,667 \approx 3$ St.

And for Wall 1B with a height of 2,7m and 40 m long with 2,683m c/c the number of segments is calculated to be:

Segments: $40/2,683 \approx 15$ St.

modules: $2,7/0,667 \approx 4$ St.

Steel

Density HEA140 beams assumed 25,1kg/m taken from http://www.wermac.org/steel/dim_he.html

The 2m high wall with 16 foundations requires

$$2 \left[\frac{m}{st} \right] * 16[st] * 25,1 \left[\frac{kg}{m} \right] = 803,601 \text{ kg steel.}$$

The 2,7m high wall with 16 foundations requires

$$2,7 \left[\frac{m}{st} \right] * 16[st] * 25,1 \left[\frac{kg}{m} \right] = 1071,469 \text{ kg steel.}$$

Paint

For the 2m high wooden wall with Wavebreaker.

Length	40	m	
Height	2	m	
Area	$40*2*2=$	160	m ²
Paint	$160/8=$	20	L paint
Water	$20*0,32=$	6,4	L water
Paint	$20-6,4=$	13,6	L paint

Paint for the Steel beams for the 2m high wooden wall.

$$803,601 * 0,003 = 2,411 \text{ kg paint}$$

Total for 2m wall 40 years

Density of water: 1 kg/l

$$6,4[l] * 1[kg/l] * 40[yr] / 6[yr] = 42,7 \text{ kg water}$$

$$13,6[l] * 1,3[kg/l] * 40[yr] / 6[yr] + 2,411 = 120,3 \text{ kg paint}$$

For the 2,7m high wooden wall.

length	40	m	
high	2,7	m	
area	$40*2,7*2=$	216	m ²
paint	$216/8=$	27	L paint
Water	$27*0,32=$	8,37	L Water
paint	$27-8,37=$	18,36	L paint

Paint for the Steel beams for the 2,7m tall wall

$1071,469*0,003=3,214$ kg paint

Total for 2,7m wall

$8,37[l]*1[kg/l] *40[yr]/ 6[yr]=55,8$ kg water

$18,36[l]*1,3[kg/l] *40[yr]/ 6[yr]+3,214=162,3$ kg paint

Appendix C: bill of quantity calculations for CNB

Bill of Quantity Calculations

This appendix includes the detailed description of the calculations done to obtain the Bill of Quantities for concrete and rebar.

Concrete – Standard Noise Barrier

TYPICAL PANEL

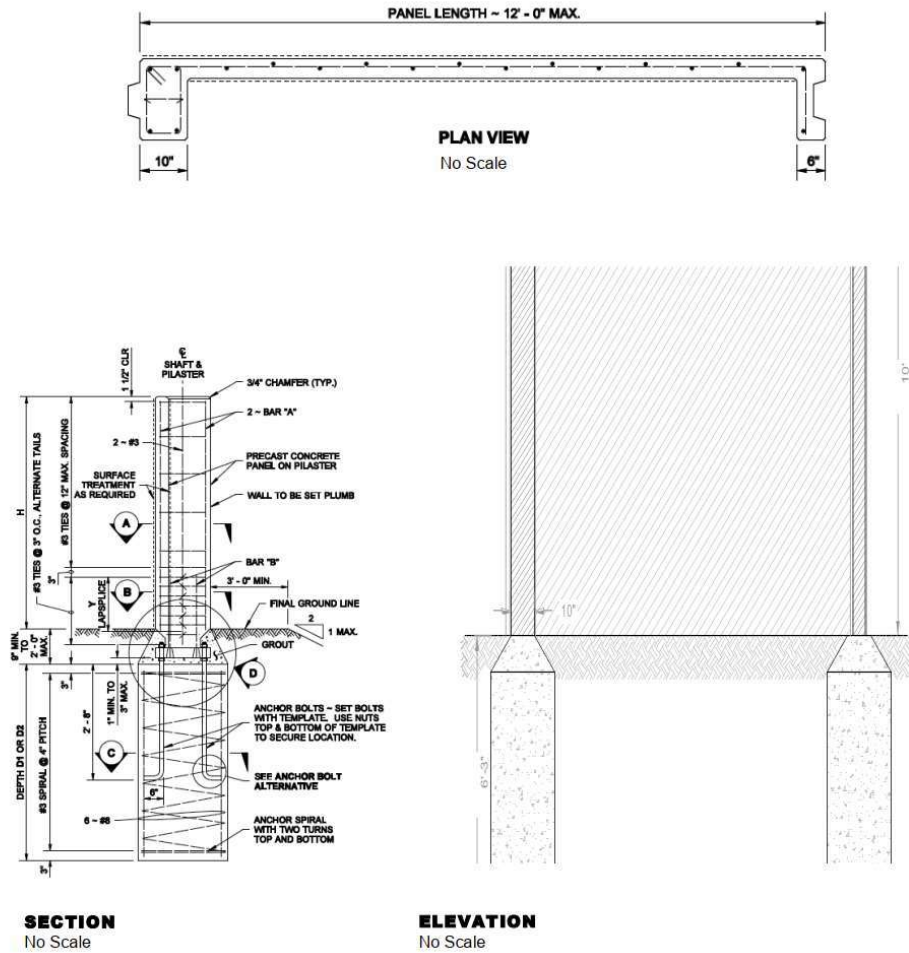


Fig. 1. Standard details of Precast Concrete Wall on Shaft Foundation "Noise Barrier Wall Type 11", provided by WSNW and adapted by Maria Valdebenito

The acoustical modeling was done under the assumption that the barriers were infinitely long. For the purpose of material quantity calculations, a barrier length of 33 m (108') was chosen arbitrarily, considering it to be an appropriate length for common noise barriers along highways. The same length was assumed for both barriers. Also, for the case of the standard noise barrier, 9 panels and 10 foundations fit within this length.

Panel:

Height: 3.0 m

Width: 0.10 m

Length*: 40 m – 12 panels,

Each panel is 3.65 length

Panels

1 panel volume:

 $3. \text{ m} \times 0.10 \text{ m} \times 3.65 \text{ m} = 1,095 \text{ m}^3$ **Pilasters (40cm thick with 25cm belong to one panel and 15cm belonging to the other)**

1 Pilaster volume:

 $3. \text{ m} \times 0.32 \text{ m} \times 0.40 \text{ m} = 0.384 \text{ m}^3$ **Total volume concrete:**11 panels: $1,095 \times 11 = 12,045 \text{ m}^3$ 12 Pilasters: $0.384 \times 12 = 4,608 \text{ m}^3$ Total = $12,045 + 4,608 = 16,653 \text{ m}^3$ Density of concrete with 35MPa strength: 2315 kg/m³

(taken from Process used from Ecoinvent 3.2 “concrete production 35MPa”)

Weight concrete: $16,653 \times 2315 = 38,551,695 \text{ kg}$ **Rebar mass calculation****Pilasters:**

4 ~ #7

1 m x 4 = 4 m

4 m x 3.049 Kg/m = **12.19 Kg**

6 ~ #3

3 m x 6 = 18 m

18 m x 0.561 Kg/m = **10.09 Kg**

#3 ties @ 3’’ (0.07m) O.C max. within a length of 1m

 $1 / 0.07 = 14$ Bar length = $0.35 \text{ m} + 0.17 \text{ m} \times 2 = 1.04 \text{ m}$ Then, $1.04 \text{ m} \times 14 = 14.86 \text{ m}$

+ #3 ties @ 12’’ (0.3m) max. spacing, within a length of 2.05 m

 $2.05 / 0.3 = 7$ Then, $1.04 \text{ m} \times 7 = 7,107 \text{ m}$ $14.86 \text{ m} + 7,107 \text{ m} = 21.964 \text{ m}$ $21.964 \text{ m} \times 0.561 \text{ Kg/m} = \mathbf{12.322 \text{ Kg}}$ $12.19 \text{ Kg} + 10.09 \text{ Kg} + 12.322 \text{ Kg} = \mathbf{34,616 \text{ Kg}}$

Panel joint:

+ 3 ~ #3 (on panel joint)

 $3 \text{ m} \times 3 = 9 \text{ m}$ $9 \text{ m} \times 0.561 \text{ Kg/m} = \mathbf{5.049 \text{ Kg}}$

+ #3 ties @ 3’’ (0.07m) O.C max. within a length of 1m

+ #3 ties @ 12’’ (0.3m) max. spacing, within a length of 2.05 m

Then, $14 + 7 = 21$
Then, $0.35 \text{ m} \times 21 = 7.35 \text{ m}$
 $7.35 \text{ m} \times 0.561 \text{ Kg/m} = \mathbf{4.12 \text{ Kg}}$
Total on panel joint = **9.17 Kg**
Total rebar on joint foundations:
 $34.616 \text{ Kg} + 9.17 \text{ Kg} = \mathbf{43.788 \text{ Kg}}$

Panels:

Typical length:
 $3.65 \text{ m length} - \text{pilasters (0.40 m)} = 3.25 \text{ m}$
 $3.25 \text{ m} \times 21 \sim \#3 = 68.25 \text{ m}$
 $68.25 \text{ m} \times 0.561 \text{ Kg/m} = \mathbf{38.28 \text{ Kg}}$
 $+ 3 \text{ m} \times 12 \sim \#3 = 36 \text{ m}$
 $36 \text{ m} \times 0.561 \text{ Kg/m} = \mathbf{20.19 \text{ Kg}}$
Total per panel:
 $38.28 \text{ Kg} + 20.19 \text{ Kg} = \mathbf{58.47 \text{ Kg}}$

Total volume rebar:

11 panels: $58,4 \times 11 = 642,4 \text{ kg}$
12 Pilasters: $43,788 \times 12 = 525,456 \text{ kg}$
Total = $642,4 + 525,456 = 1167,856 \text{ kg}$

Panel:

Height: 4.0 m
Width: 0.10 m
Length*: 40 m – 12 panels,
Each panel is 3.65 length

Panels

1 panel volume:
 $4 \text{ m} \times 0.10 \text{ m} \times 3,65 \text{ m} = 1,46 \text{ m}^3$
Pilasters (40cm thick with 25cm belong to one panel and 15cm belonging to the other)
1 Pilaster volume:
 $4 \text{ m} \times 0.32 \text{ m} \times 0.40 \text{ m} = 0.512 \text{ m}^3$

Total volume concrete:

11 panels: $1,46 \times 11 = 16,06 \text{ m}^3$
12 Pilasters: $0,512 \times 12 = 6,144 \text{ m}^3$
Total = $16,06 + 6,144 = 22,204 \text{ m}^3$

Density of concrete with 35MPa strength: 2315 kg/m^3
(taken from Process used from Ecoinvent 3.2 “concrete production 35MPa”)

Weight concrete: $22,204 \times 2315 = 51402,26 \text{ kg}$

Rebar mass calculation

Pilasters:

4 ~ #7

1 m x 4 = 4 m

4 m x 3.049 Kg/m = **12.19 Kg**

6 ~ #3

4 m x 6 = 24 m

24 m x 0.561 Kg/m = **13,464 Kg**

#3 ties @ 3'' (0.07m) O.C max. within a length of 1m

1 / 0.07 = 14

Bar length = 0.35 m + 0.17 m x 2 = 1.04 m

Then, 1.04 m x 14 = 14.86 m

+ #3 ties @ 12'' (0.3m) max. spacing, within a length of 3.05 m

3.05 / 0.3 = 10

Then, 1.04 m x 10 = 10,573 m

14.86 m + 10,573 m = 25,430 m

25,430 m x 0.561 Kg/m = **14,266 Kg**12. 19 Kg + 13,464 Kg + 14,266 Kg = **39,926 Kg****Panel joint:**

+ 3 ~ #3 (on panel joint)

4m x 3 = 12 m

12 m x 0.561 Kg/m = **6,732 Kg**

+ #3 ties @ 3'' (0.07m) O.C max. within a length of 1m

+ #3 ties @ 12'' (0.3m) max. spacing, within a length of 2.05 m

Then, 14 + 10 = 24

Then, 0.35 m x 24 = 8,558 m

8,558 m x 0.561 Kg/m = **4,801 Kg**Total on panel joint = **11,533 Kg**

Total rebar on joint foundations:

39,926 Kg + 11,533 Kg = **51,460 Kg****Panels:**

Typical length:

3.65 m length – pilasters (0.40 m) = 3.25 m

3.25 m x 28 ~ #3 = 91 m

91 m x 0.561 Kg/m = **51,051 Kg**

+ 4 m x 12 ~ #3 = 48 m

48 m x 0.561 Kg/m = **26,928 Kg**

Total per panel:

51,051 Kg + 26,928 Kg = **77,979 Kg****Total volume rebar:**

11 panels: 77,979*11=857,769 kg

12 Pilasters: 51,460*12=617,52 kg

Total=857,769 +617,52=1475,289 kg

	Concrete [kg]	Steel [kg]
Concrete wall 3m	38551,695	1168,783316
Concrete wall 4m	51402,26	1475,285666

Appendix D: calculation of horizontal force

5.1.1 Beräkning av horisontalkraft

Väggarna samt fundamenten kommer att bli belastade olika mycket av den horisontella lasten beroende på var de befinner sig. Med hjälp av den andra utgåvan av handboken "Snö och Vindlast" kunde vi beräkna fram den totala vindlasten för hela väggen samt få fram vilken vägg och fundament som blir belastad mest. Eftersom dessa kulisser inte har något tak räknas väggarna som vanliga skärmar när det gäller beräkningar. Ekvationen vi använder oss utav är:

$$W_k = q_k * \mu_{tot} * A_f$$

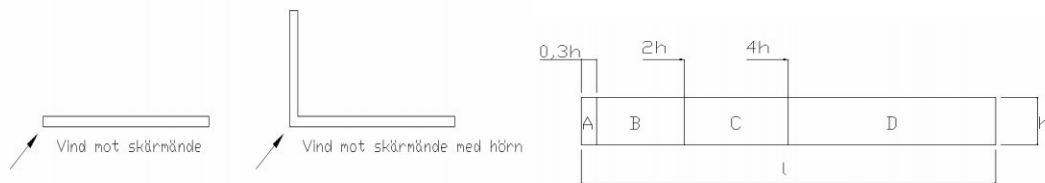
q_k = karakteristiskt värde på vindens hastighet

μ_{tot} = formfaktor för vindlasten

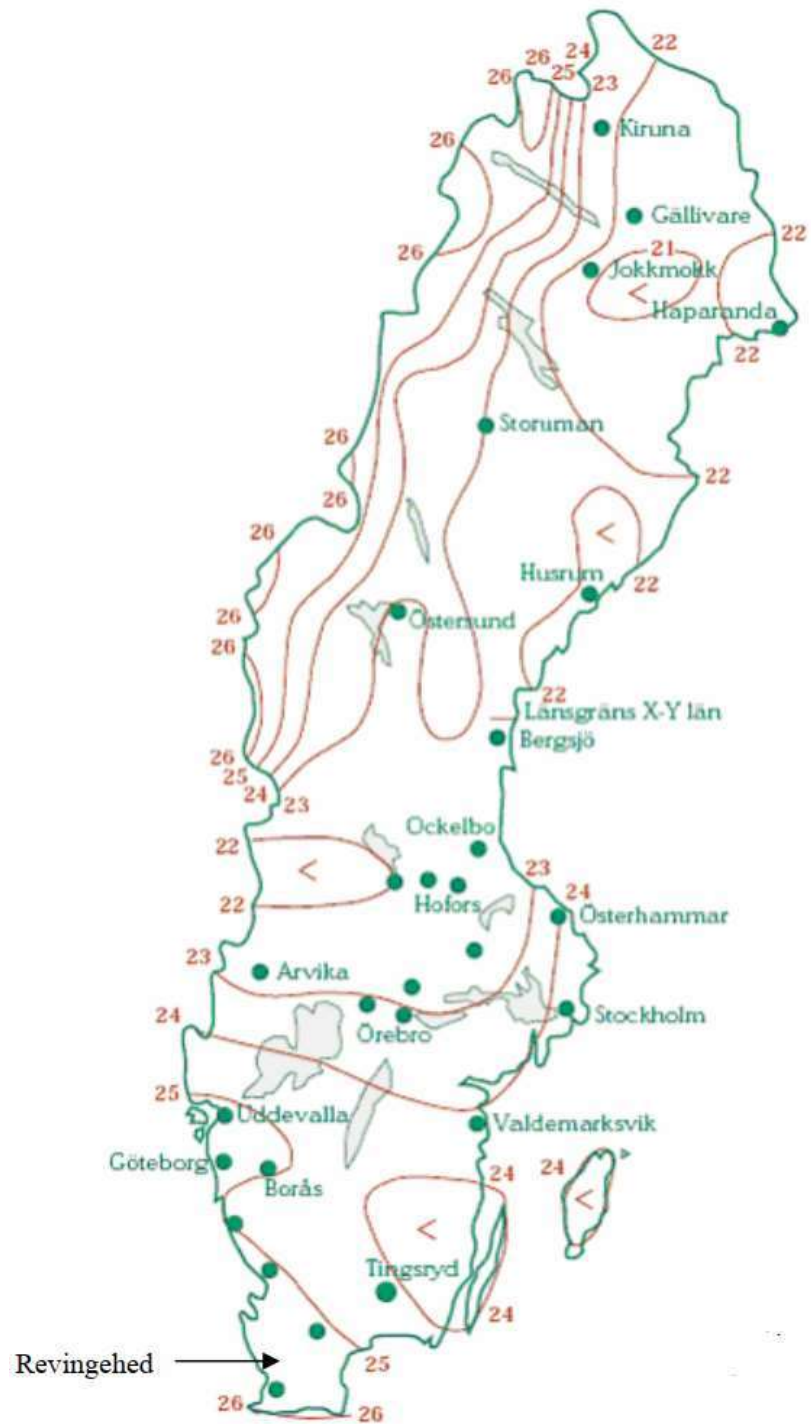
A_f = nettoarea på använt väggyta

För bestämning av q_k används givet tabell 5.3 ur [10] med känd referenshastighet, terrängtyp och konstruktionshöjd. Referenshastigheten är given i figur 5.1 ur [8]. Terrängtypen byggnationen sker i är terrängtyp II, detta konstateras genom tabell 5.2 ur [10]. Terrängtyp II beskrivs som öppen terräng med små hinder t.ex. kuperade slättlandskap med spridda träd och enstaka grupper av byggnader. Detta stämmer bra med miljö på Revingeled i Skåne. Höjden för väggen är 2m-4m, i tabell 5.3 finns värden på q_k för 2m-4m är 0,69 kN/m².

Väggarean A_f är 100%=1. Sedan är det bara μ_{tot} som är okänt, det värdet varierar beroende på var på väggen man befinner sig samt om det är hörn på skärmen eller ej. På den aktuella kulissen finns hörn och då blir det de värden man använder sig. Figur 5.2 ur [9] beskriver hur väggens yta delas in i olika zoner. När väggen delats in i de olika områdena är det möjligt att få fram μ_{tot} genom att räkna ut hur stort värdet blir när man beräknar A_f / A (=1) för att sedan få fram ett värde genom tabell [8]



Figur 5.1, Vind mot skärmar ur [9]



Figur 5.2, Karta över referensvindhastighet i

Table 5.2, Terrängtyperna ur.[10]

Terrängtyp	β	$z_o(m)$	$z_{min}(m)$
I, Öppen terräng med få eller inga hinder, t.ex. kuster och stränder vid öppet vatten, utpräglad slättlandskap, kalfjäll.	0,17	0,01	2
II, Öppen terräng med små hinder t.ex. kuperade slättlandskap med spridda träd och enstaka grupper av byggnader.	0,19	0,05	4
III, Terräng med stora spridda hinder, t.ex. förortsbebyggelse, mindre tätorter.	0,22	0,3	8
IV, Tätortsbebyggelse där minst 15 % av ytan är bebyggd och där byggnadernas medelhöjd är > 15m.	0,24	1	16

Table 5.3, Karakteristiskt värde på vindens hastighetstryck. Vårt värde ligger i det gråa fältet på rad 1 (0,69) ur [10]

HÖJD h (m)	Vref = 22m/s				Vref = 24m/s				Vref = 26m/s			
	Terrängtyp				Terrängtyp				Terrängtyp			
	1	2	3	4	1	2	3	4	1	2	3	4
2	0,52	0,5	0,45	0,42	0,62	0,59	0,53	0,5	0,73	0,69	0,62	0,59
4	0,63	0,5	0,45	0,42	0,75	0,59	0,53	0,5	0,88	0,69	0,62	0,59
8	0,74	0,61	0,45	0,42	0,88	0,73	0,53	0,5	1,04	0,86	0,62	0,59
12	0,81	0,69	0,52	0,42	0,97	0,82	0,62	0,5	1,13	0,96	0,73	0,59
16	0,86	0,74	0,58	0,42	1,03	0,88	0,69	0,5	1,21	1,04	0,81	0,59
20	0,9	0,78	0,63	0,47	1,08	0,93	0,75	0,56	1,26	1,1	0,88	0,66
25	0,95	0,83	0,67	0,52	1,13	0,99	0,8	0,62	1,32	1,16	0,94	0,72
30	0,98	0,87	0,72	0,56	1,17	1,03	0,85	0,66	1,37	1,21	1	0,78

Table 5.4, Värdet på μ_{tot} i de olika zonerna på väggen ur [9].

A_f/A	Typ	A	B	C	D
$\geq 0,8$	Vind mot skärmande utan hörn	3,4	2,1	1,7	1,2
$\geq 0,8$	Vind mot skärmande med hörn	2,1	1,8	1,4	1,2
$< 0,8$	Alla skärmar	$1,2 \times \frac{A_f}{A}$	$1,2 \times \frac{A_f}{A}$	$1,2 \times \frac{A_f}{A}$	$1,2 \times \frac{A_f}{A}$

Wall 1A: Bsk 14F 2m

Sektion	L [m]	μ_{tot}	Wk[kN]
A	1,2	3,4	2,8152
B	8	2,1	11,592
C	16	1,7	18,768

D	80	1,2	66,24
---	----	-----	-------

zon	Wk =karakteristisk vindkraft [kN/m ²]	fundamen t	Af effektiva area [m ²]	S hk = Wk × Af = Koncentrerad karakteristisk kraft [kN]	Shd = 1,3× S hk = Koncentrerad dimensionerand e kraft [kN]
a	2,346	1	1,2	8,851734	11,5072542
b	1,449		4,166		
b	1,449	2	3,834	7,352502	9,5582526
c	1,173		1,532		
c	1,173	3	5,366	6,294318	8,1826134
c	1,173	4	5,366	6,294318	8,1826134
c	1,173	5	3,736	5,731968	7,4515584
d	0,828		1,63		
d	0,828	6	5,366	4,443048	5,7759624
d	0,828	7	5,366	4,443048	5,7759624
d	0,828	8	5,366	4,443048	5,7759624
d	0,828	9	5,366	4,443048	5,7759624
d	0,828	10	5,366	4,443048	5,7759624
d	0,828	11	5,366	4,443048	5,7759624
d	0,828	12	5,366	4,443048	5,7759624
d	0,828	13	5,366	4,443048	5,7759624
d	0,828	14	5,366	4,443048	5,7759624
d	0,828	15	5,366	4,443048	5,7759624
				summa Shd	102,641916

Den största kraften fås på fundament nr 1 där den karakteristiska vindkraften är 2,35 kN/m² och effektiva arean 1,2 m² vilket resulterar i en dimensionerande kraft på 11,5 kN. Vi väljer att dimensionera samtliga fundament med denna kraft för att vara på säkra sidan.

Pelarens egentyngd	0,492462	kN		
Väggelementets egentyngd	2,876858	kN		
			Enhetsomvandlings	
∑Gk	3,36932	kN	faktor	Ny enhet
Svd	3,36932	kN	0,2248	0,757423 kips
Smd	11,50725	kNm	0,737562	8,487313 ft-kips
höjd	2	m	3,281	6,562 ft
diameter	0,555	m	3,281	1,820955 ft

Wall 1B: Bsk 14F 2,7m

Sektion	L [m]	μtot	Wk[kN]
A	2,187	3,4	5,130702
B	14,58	2,1	21,12642

C	29,16	1,7	34,20468
D	108	1,2	89,424

zon	Wk =karakteristisk vindkraft [kN/m ²]	fundament	Af effektiva area [m ²]	S hk = Wk × Af = Koncentrerad karakteristisk kraft [kN]	Shd = 1,3× S hk = Koncentrerad dimensionerande kraft [kN]
a	2,346	1	2,187	12,45844	16,19597
b	1,449		5,0571		
b	1,449	2	7,2441	10,4967	13,64571
b	1,449	3	2,2788	9,126278	11,86416
c	1,173		4,9653		
c	1,173	4	7,2441	8,497329	11,04653
c	1,173	5	7,2441	8,497329	11,04653
c	1,173	6	7,2441	8,497329	11,04653
c	1,173	7	2,4624	2,888395	3,754914
d	0,828		4,7817		
d	0,828	8	7,2441	5,998115	7,797549
d	0,828	9	7,2441	5,998115	7,797549
d	0,828	10	7,2441	5,998115	7,797549
d	0,828	11	7,2441	5,998115	7,797549
d	0,828	12	7,2441	5,998115	7,797549
d	0,828	13	7,2441	5,998115	7,797549
d	0,828	14	7,2441	5,998115	7,797549
d	0,828	15	7,2441	5,998115	7,797549
				summa Shd	140,9807365

Den största kraften fås på fundament nr 1 där den karakteristiska vindkraften är 2,683 kN/m² och effektiva arean 2,34 m² vilket resulterar i en dimensionerande kraft på 16,2 kN. Vi väljer att dimensionera samtliga fundament med denna kraft för att vara på säkra sidan.

Pelarens egentyngd 0,664824 kN

Väggelementets egentyngd 3,792019 kN

∑Gk 4,456842 kN

Svd 4,456842 kN

Smd 21,86456 kNm

höjd 2,7 m

diameter 0,555 m

Enhetsomvandlings

faktor Ny enhet

0,2248 1,001898 kips

0,737562 16,12647 ft-kips

3,281 8,8587 ft

3,281 1,820955 ft

Wall 2A: CNB 3m

Sektion	L [m]	μ _{tot}	Wk[kN]
A	2,7	3,4	6,3342
B	18	2,1	26,082
C	36	1,7	42,228
D	120	1,2	99,36

zon	Wk =karaktterisk vindkraft [kN/m ²]	fundament	Af effektiva area [m ²]	S hk = Wk × Af = Koncentrerad karaktterisk kraft [kN]	Shd = 1,3× S hk = Koncentrerad dimensionerande kraft [kN]
a	2,346	1	2,7	18,28845	23,77499
b	1,449		8,25		
b	1,449	2	9,75	15,53535	20,19596
c	1,173		1,2		
c	1,449	3	10,95	15,86655	20,62652
c	1,173	4	10,95	12,84435	16,69766
c	1,173	5	10,95	12,84435	16,69766
c	1,173	6	1,95	9,73935	12,66116
d	0,828		9		
d	0,828	7	10,95	9,0666	11,78658
d	0,828	8	10,95	9,0666	11,78658
d	0,828	9	10,95	9,0666	11,78658
d	0,828	10	10,95	9,0666	11,78658
d	0,828	11	10,95	9,0666	11,78658
				summa Shd	169,58682

Den största kraften fås på fundament nr 1 där den karakteristiska vindkraften är 2,346 kN/m² och effektiva arean 2,7 m² vilket resulterar i en dimensionerande kraft på 23,8 kN. Vi väljer att dimensionera samtliga fundament med denna kraft för att vara på säkra sidan.

Pelarens egentyngd	9,150258	kN			
Väggelementets egentyngd	25,97844	kN			
			Enhetsomvandlings		
∑Gk	967,8767	kN	faktor	Ny enhet	
Svd	967,8767	kN		0,2248	217,5787 kips
Smd	35,66248	kNm		0,737562	26,30329 ft-kips
höjd	3	m		3,281	9,843 ft
diameter	0,555	m		3,281	1,820955 ft

Wall 2B: CNB 4m

Sektion	L [m]	μ _{tot}	Wk[kN]
A	4,8	3,4	11,2608
B	32	2,1	46,368
C	64	1,7	75,072
D	160	1,2	132,48

zon	Wk =karaktterisk vindkraft [kN/m ²]	fundament	Af effektiva area [m ²]	S hk = Wk × Af = Koncentrerad karaktterisk kraft [kN]	Shd = 1,3× S hk = Koncentrerad dimensionerande kraft [kN]
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a	2,346	1	4,8	25,461	33,0993
b	1,449		9,8		
b	1,449	2	14,6	21,1554	27,50202
b	1,449	3	7,6	19,2234	24,99042
c	1,173		7		
c	1,173	4	14,6	17,1258	22,26354
c	1,173	5	14,6	17,1258	22,26354
c	1,173	6	14,6	17,1258	22,26354
c	1,173	7	12,6	16,4358	21,36654
d	0,828		2		
d	0,828	8	14,6	12,0888	15,71544
d	0,828	9	14,6	12,0888	15,71544
d	0,828	10	14,6	12,0888	15,71544
d	0,828	11	14,6	12,0888	15,71544
				summa Shd	236,61066

Den största kraften fås på fundament nr 1 där den karakteristiska vindkraften är 2,346 kN/m² och effektiva arean 4,8 m² vilket resulterar i en dimensionerande kraft på 33 kN. Vi väljer att dimensionera samtliga fundament med denna kraft för att vara på säkra sidan.

Pelarens egentyngd 12,13242 kN
Väggelementets
egentyngd 33,92179 kN

		Enhetsomvandlings		
			faktor	Ny enhet
ΣG_k	1282,794	kN		
S _{vd}	1282,794	kN	0,2248	288,3721 kips
S _{md}	66,1986	kNm	0,737562	48,82557 ft-kips
höjd	4	m	3,281	13,124 ft
diameter	0,555	m	3,281	1,820955 ft

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:	Subject:	
Job Number:	Originator:	Checker:

Input Data:

Pier Data:

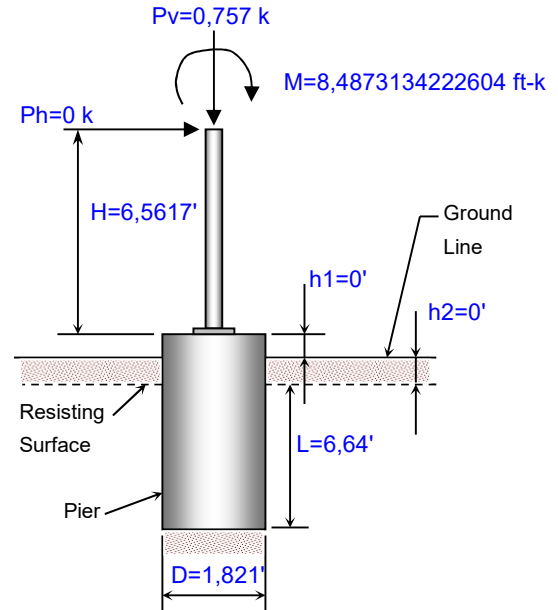
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,100	kcf
Angle of Internal Friction, ϕ =	30,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	0,630	ksf

Pier Loadings:

Axial Load, Pv =	0,757	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	6,562	ft.
Externally Applied Moment, M =	8,487	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	4,66	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	4660,80	ft.	E = Mo/Ho
Kp =	3,000		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,300	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	6,64	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	3,65		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	6,64	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	4,428	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	0,664	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	0,664	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	1,992	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	1,992	ksf	Pt(allow) = R*L Pt(allow)>=Pt, O.K.

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	2,59	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	3,35	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	1,287	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	
		Checker:	

Input Data:

Pier Data:

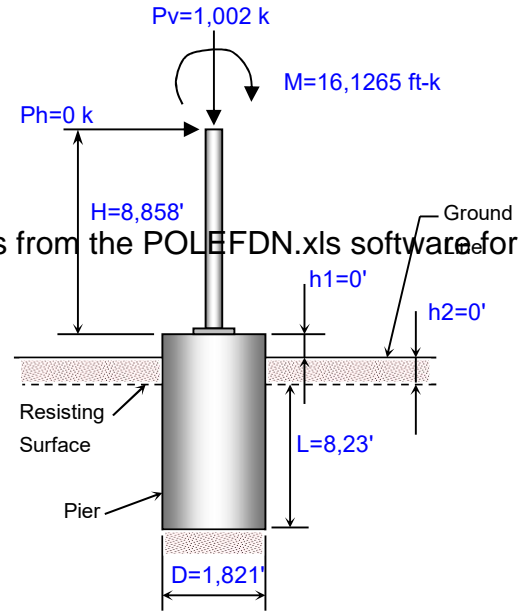
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,500	ksi

Soil Data:

Unit Weight of Soil, γ =	0,100	kcf
Angle of Internal Friction, ϕ =	30	deg
Depth to Resisting Surface, h_2 =	0,000	ft.
Allow. Soil Bearing Pressure, P_c =	0,630	ksf

Pier Loadings:

Axial Load, Pv =	1,002	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	8,858	ft.
Externally Applied Moment, M =	16,127	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	8,86	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	8855,85	ft.	E = Mo/Ho
Kp =	3,000		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,300	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	8,23	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	4,52		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	8,23	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	5,484	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	0,822	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	0,823	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	2,468	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	2,468	ksf	Pt(allow) = R*L Pt(allow)<Pt

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	3,21	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	4,22	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	1,618	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:	Subject:	
Job Number:	Originator:	Checker:

Input Data:

Pier Data:

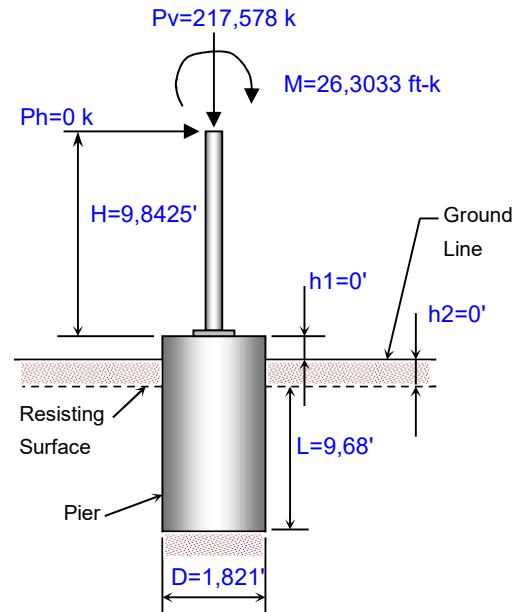
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,500	ksi

Soil Data:

Unit Weight of Soil, γ =	0,100	kcf
Angle of Internal Friction, φ =	30,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	0,630	ksf

Pier Loadings:

Axial Load, Pv =	217,578	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	9,843	ft.
Externally Applied Moment, M =	26,303	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	14,44	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	14444,43	ft.	E = Mo/Ho
Kp =	3,000		Kp = TAN^2(45+φ/2) (passive soil pressure coefficient)
R =	0,300	ksf/ft.	R = Kp*γ (passive soil resistance/ft. depth)
L =	9,68	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	5,32		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	9,68	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	6,455	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	0,968	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	0,968	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	2,905	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	2,905	ksf	Pt(allow) = R*L Pt(allow)>=Pt, O.K.

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π*D^2/4 (pier base area)
Wf =	3,78	kips	Wf = (Af*Lt)*0.150 (pier weight)
ΣPv =	221,36	kips	ΣPv = Pv+Wf (total vertical load)
P(bot) =	84,994	ksf	P(bot) = ΣPv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	
		Checker:	

Input Data:

Pier Data:

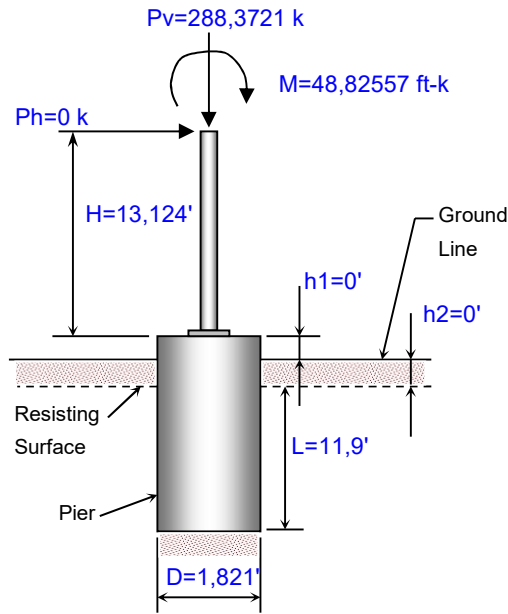
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,500	ksi

Soil Data:

Unit Weight of Soil, γ =	0,100	kcf
Angle of Internal Friction, ϕ =	30,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	0,630	ksf

Pier Loadings:

Axial Load, Pv =	288,372	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	13,124	ft.
Externally Applied Moment, M =	48,826	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	26,81	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	26812,50	ft.	E = Mo/Ho
Kp =	3,000		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,300	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	11,90	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	6,53		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	11,90	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	7,933	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	1,190	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	1,190	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	3,570	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	3,570	ksf	Pt(allow) = R*L Pt(allow)>=Pt, O.K.

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	4,65	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	293,02	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	112,509	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	Checker:

Input Data:

Pier Data:

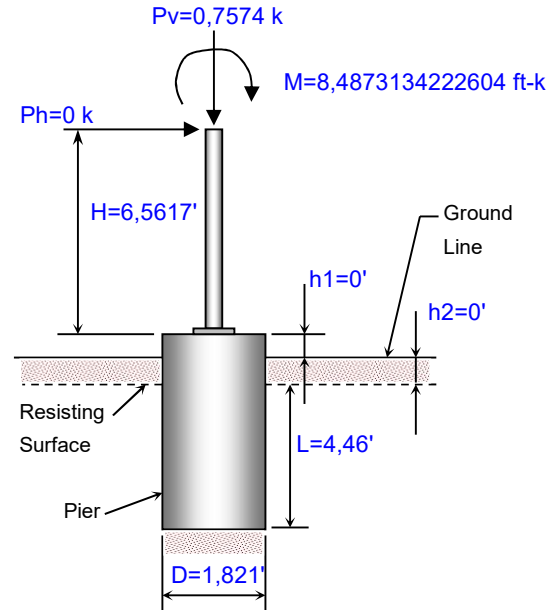
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,170	kcf
Angle of Internal Friction, ϕ =	45,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	6,270	ksf

Pier Loadings:

Axial Load, Pv =	0,757	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	6,562	ft.
Externally Applied Moment, M =	8,487	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	4,66	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	4660,80	ft.	E = Mo/Ho
Kp =	5,828		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,991	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	4,46	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	2,45		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	4,46	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	2,973	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	1,473	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	1,473	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	4,419	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	4,418	ksf	Pt(allow) = R*L Pt(allow)<Pt

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	1,74	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	2,50	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	0,960	ksf	P(bot) = Σ Pv/Af Pa>=P(bot), O.K.

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	Checker:

Input Data:

Pier Data:

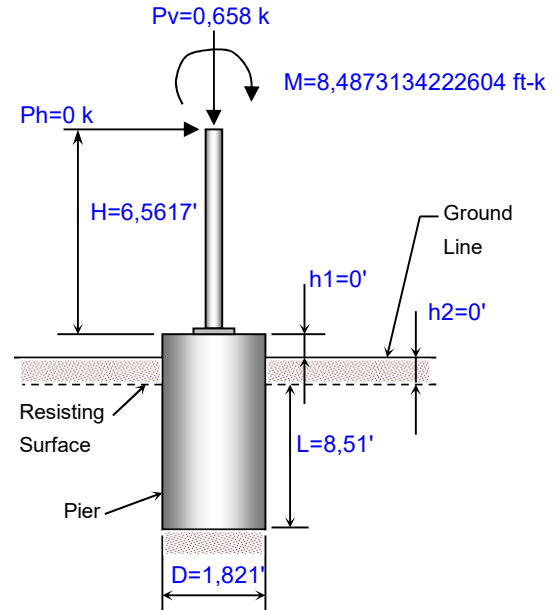
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,070	kcf
Angle of Internal Friction, ϕ =	20,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	0,480	ksf

Pier Loadings:

Axial Load, Pv =	0,658	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	6,562	ft.
Externally Applied Moment, M =	8,487	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	4,66	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	4660,80	ft.	E = Mo/Ho
Kp =	2,040		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,143	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	8,51	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	4,67		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	8,51	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	5,672	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	0,405	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	0,405	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	1,214	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	1,214	ksf	Pt(allow) = R*L Pt(allow)>=Pt, O.K.

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	3,32	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	3,98	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	1,529	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:	Subject:	
Job Number:	Originator:	Checker:

Input Data:

Pier Data:

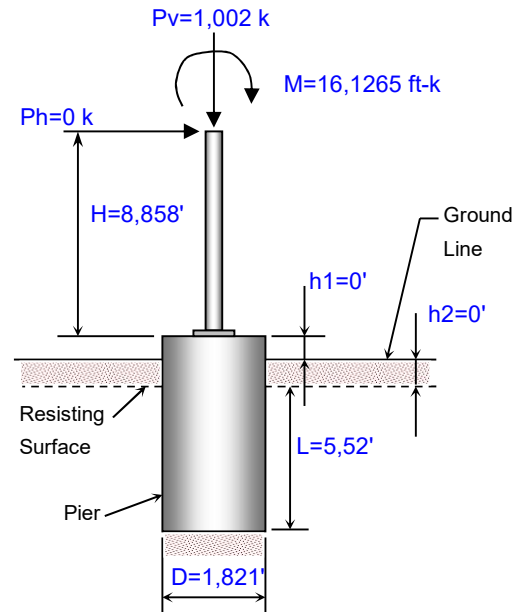
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,170	kcf
Angle of Internal Friction, φ =	45,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	6,270	ksf

Pier Loadings:

Axial Load, Pv =	1,002	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	8,858	ft.
Externally Applied Moment, M =	16,127	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	8,86	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	8855,85	ft.	E = Mo/Ho
Kp =	5,828		Kp = TAN^2(45+φ/2) (passive soil pressure coefficient)
R =	0,991	ksf/ft.	R = Kp*γ (passive soil resistance/ft. depth)
L =	5,52	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	3,03		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	5,52	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	3,682	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	1,824	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	1,824	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	5,473	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	5,472	ksf	Pt(allow) = R*L Pt(allow)<Pt

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π*D^2/4 (pier base area)
Wf =	2,16	kips	Wf = (Af*Lt)*0.150 (pier weight)
ΣPv =	3,16	kips	ΣPv = Pv+Wf (total vertical load)
P(bot) =	1,213	ksf	P(bot) = ΣPv/Af Pa>=P(bot), O.K.

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	
		Checker:	

Input Data:

Pier Data:

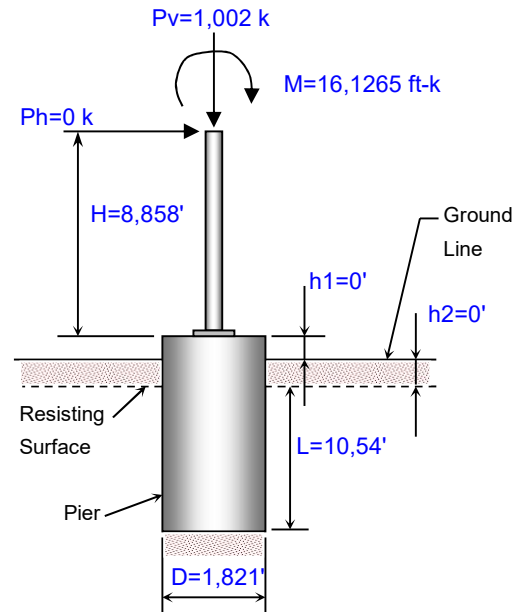
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,070	kcf
Angle of Internal Friction, ϕ =	20,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	0,480	ksf

Pier Loadings:

Axial Load, Pv =	1,002	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	8,858	ft.
Externally Applied Moment, M =	16,127	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	8,86	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	8855,85	ft.	E = Mo/Ho
Kp =	2,040		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,143	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	10,54	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	5,79		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	10,54	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	7,024	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	0,501	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	0,501	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	1,504	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	1,504	ksf	Pt(allow) = R*L Pt(allow)>=Pt, O.K.

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	4,12	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	5,12	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	1,965	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	
		Checker:	

Input Data:

Pier Data:

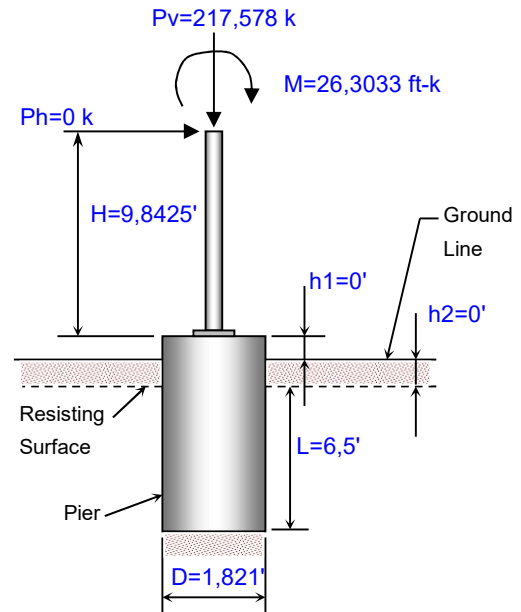
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,170	kcf
Angle of Internal Friction, ϕ =	45,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	6,270	ksf

Pier Loadings:

Axial Load, Pv =	217,578	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	9,843	ft.
Externally Applied Moment, M =	26,303	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	14,44	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	14444,43	ft.	E = Mo/Ho
Kp =	5,828		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,991	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	6,50	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	3,57		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	6,50	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	4,334	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	2,147	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	2,147	ksf	Pc(allow) = R*(a/2) Pc(allow)<Pc
Pt =	6,442	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	6,441	ksf	Pt(allow) = R*L Pt(allow)<Pt

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	2,54	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	220,12	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	84,517	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	
		Checker:	

Input Data:

Pier Data:

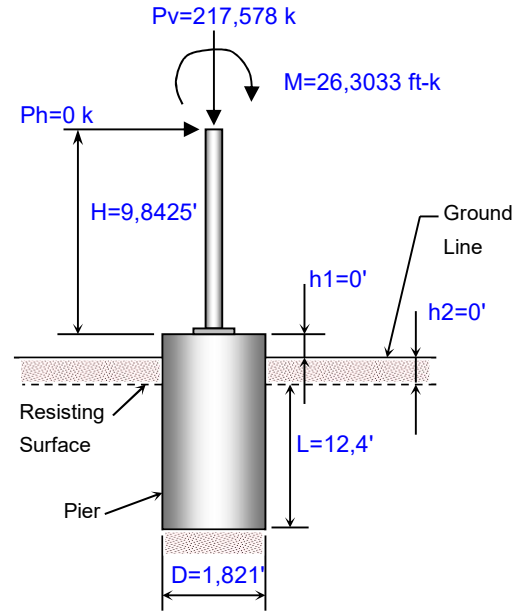
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,500	ksi

Soil Data:

Unit Weight of Soil, γ =	0,070	kcf
Angle of Internal Friction, ϕ =	20,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	0,480	ksf

Pier Loadings:

Axial Load, Pv =	217,578	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	9,843	ft.
Externally Applied Moment, M =	26,303	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	14,44	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	14444,43	ft.	E = Mo/Ho
Kp =	2,040		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,143	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	12,40	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	6,81		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	12,40	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	8,268	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	0,590	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	0,590	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	1,771	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	1,771	ksf	Pt(allow) = R*L Pt(allow)>=Pt, O.K.

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	4,84	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	222,42	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	85,402	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	Checker:

Input Data:

Pier Data:

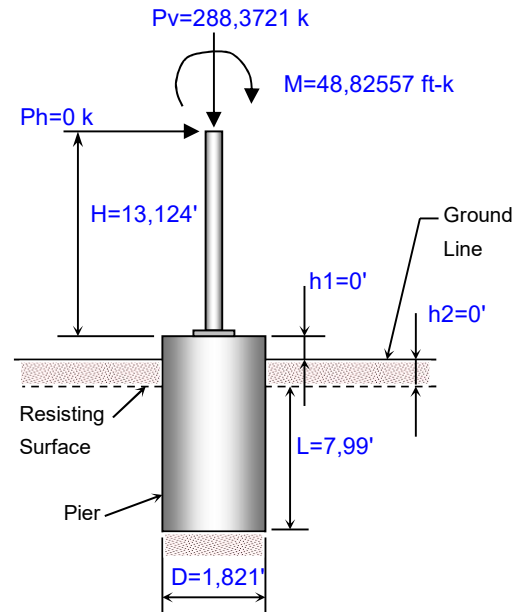
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,170	kcf
Angle of Internal Friction, ϕ =	45,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	6,270	ksf

Pier Loadings:

Axial Load, Pv =	288,372	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	13,124	ft.
Externally Applied Moment, M =	48,826	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	26,81	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	26812,50	ft.	E = Mo/Ho
Kp =	5,828		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,991	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	7,99	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	4,39		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	7,99	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	5,327	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	2,639	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	2,639	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	7,917	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	7,917	ksf	Pt(allow) = R*L Pt(allow)<Pt

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	3,12	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	291,49	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	111,923	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

POLE FOUNDATION ANALYSIS
For Free-Top (Unconstrained) Rigid Round Piers Using Czerniak / PCA Method
Subjected Vertical Load, Horizontal Load, and/or Moment

Job Name:		Subject:	
Job Number:		Originator:	
		Checker:	

Input Data:

Pier Data:

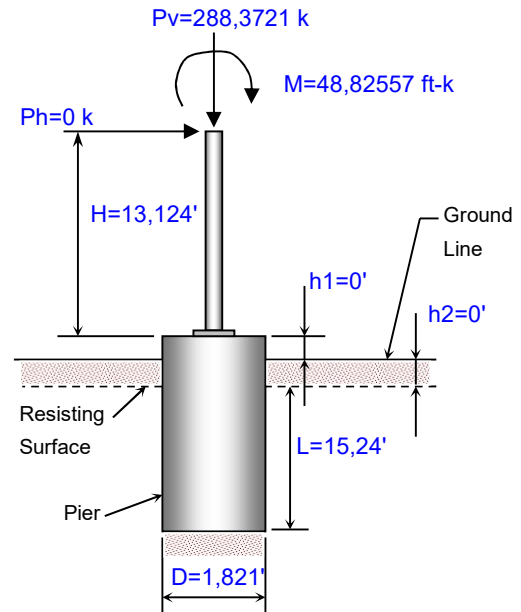
Pier Foundation Diameter, D =	1,821	ft.
Pier Height Above Soil, h1 =	0,000	ft.
Concrete Strength, f'c =	4,000	ksi

Soil Data:

Unit Weight of Soil, γ =	0,070	kcf
Angle of Internal Friction, ϕ =	20,00	deg.
Depth to Resisting Surface, h2 =	0,000	ft.
Allow. Soil Bearing Pressure, Pa =	4,000	ksf

Pier Loadings:

Axial Load, Pv =	288,372	kips
Horizontal Load, Ph =	0,000	kips
Distance from Ph to Top/Pier, H =	13,124	ft.
Externally Applied Moment, M =	48,826	ft-kips



Nomenclature

Results:

Pier Embedment and Total Length:

Ho =	0,00	kips/ft.	Ho = Ph/D
Mo =	26,81	ft-kips/ft.	Mo = (M+Ph*(H+h1+h2))/D
E =	26812,50	ft.	E = Mo/Ho
Kp =	2,040		Kp = TAN^2(45+ ϕ /2) (passive soil pressure coefficient)
R =	0,143	ksf/ft.	R = Kp* γ (passive soil resistance/ft. depth)
L =	15,24	ft.	L = solution of cubic equation: L^3-14.14*Ho*L/R-18.85*Mo/R=0
L/D =	8,37		L/D <= 10 for valid short, rigid pier analysis L/D<=10, O.K.
Lt =	15,24	ft.	Lt = h1+h2+L (total length)

Pier Side Soil Pressures:

a =	10,161	ft.	a = L*(4*E/L+3)/(6*E/L+4) ("pivot" point from top of resisting surface)
Pc =	0,725	ksf	Pc = 1.178*(4*Mo+3*Ho*L)^2/(L^2*(3*Mo+2*Ho*L))
Pc(allow) =	0,725	ksf	Pc(allow) = R*(a/2) Pc(allow)>=Pc, O.K.
Pt =	2,176	ksf	Pt = 9.425*(2*Mo+Ho*L)/L^2
Pt(allow) =	2,176	ksf	Pt(allow) = R*L Pt(allow)>=Pt, O.K.

Pier End Bearing Pressure:

Af =	2,60	ft.^2	Af = π *D^2/4 (pier base area)
Wf =	5,95	kips	Wf = (Af*Lt)*0.150 (pier weight)
Σ Pv =	294,33	kips	Σ Pv = Pv+Wf (total vertical load)
P(bot) =	113,011	ksf	P(bot) = Σ Pv/Af Pa<P(bot)

(continued)

Appendix G: calculations of mass of Mofix foundation per wall alternative

This appendix describes the detailed calculations left out of the chapter 3.6.3 and chapter 4.2 where detailed calculations of mass of Mofix foundation per wall alternative in three different soil conditions based on results from appendix 6 where performed.

number of wall segments and modules for each Bsk 14F alternative, calculation of mass amount of steel and paint per Bsk 14F wall alternative

Table 32, García-Rodríguez, M. J., Havenith, H. B., & Benito, B. (2008, October). Evaluation of Earthquake-Triggered Landslides in El Salvador Using A GIS-Based Newmark Model. In Proc. 14th World Conference on Earthquake Engineering, October 12 (Vol. 17).

Class	Classification	Unit weight(KN/m ³)	Friction Angle (°)	Cohesion (KN/m ²)
1	Hard rock	26	45	300
2	Soft rock	22	40	200
3	Hard soil	11	30	60
4	Medium soil	15	30	30
5	Soft soil	11	20	30
6	Very soft soil	11	20	23

Transformed to the units used by the POLEFDN.xls version 2.3. software results in table 2 below.

Table 33, Table 32 with unit conversion.

Class	Classification	Unit Weight		friction angle	Cohesion	
		[KN/m ³]	[kip/ft ³]		[KN/m ²]	[ksf]
1	hard rock	26	0,165516	45	300	6,26563
2	soft rock	22	0,140052	40	200	4,177087
3	hard soil	11	0,070026	30	60	1,253126
4	medium soil	15	0,09549	30	30	0,626563
5	soft soil	11	0,070026	20	30	0,626563
6	very soft soil	11	0,070026	20	23	0,480365

Calculation of normal conditions based on calls 4 soil.

Lengths in feet taken from POLEFDN.xls results in appendix G after putting in values form table 2 above and results from appendix G.

Wall 1A: 6,64 feet= 2,02 m

Wall 1B: 8,23 feet=2,51 m

Wall 2A: 9,68 feet=2,95 m

Wall 2B: 11,9 feet=3,63 m

Dividing the lengths with the length of a 2310,3 kg, 555 mm diameter Mofix foundation (4 m) and multiplying with 2310,3 kg gives us the weights of each foundation to be:

Wall 1A: $2,02/4 * 2310,3 * 16$ foundations = **18667.2 kg Mofix**

Wall 1B: $2,51/4 * 2310,3 * 16$ foundations = **23195.412 kg Mofix**

Wall 2A: $2,95/4 * 2310,3 * 16$ foundations = **27261.54 kg Mofix**

Wall 2B: $3,63/4 * 2310,3 * 16$ foundations = **33545.556 kg Mofix**

Calculation of Bad soil conditions based on class 6 soil.

Worst case was chosen to be represented by bad soil conditions based on class 6 from table 2 above.

Wall 1A: 8,51 feet = 2,59 m

Wall 1B: 10,54 feet 3,212 m

Wall 2A: 12,4 feet 3,78 m

Wall 2B: 15,24 feet 4,645152 m

Again, dividing the lengths with the length of a 2310,3 kg 555 mm diameter Mofix foundation (4m) and multiplying with 2310,3 kg gives us the weights of each foundation in the worst case to be:

Wall 1A: $2,59/4 * 2310,3 * 16$ foundations = **23934.708 kg Mofix**

Wall 1B: $3,212/4 * 2310,3 * 16$ foundations = **29682.7344 kg Mofix**

Wall 2A: $3,78/4 * 2310,3 * 16$ foundations = **34931.736 kg Mofix**

Wall 2B: $4,645152/4 * 2310,3 * 16$ foundations = **42926.7787 kg Mofix**

Calculation of good soil conditions based on class 1 soil.

Wall 1A: 4,46 feet = 1,359 m

Wall 1B: 5,52 feet = 1,682 m

Wall 2A: 6,5 feet = 1,981 m

Wall 2B: 7,99 feet = 2,435 m

Again, dividing the lengths with the length of a 2310,3 kg 555 mm diameter Mofix foundation (4m) and multiplying with 2310,3 kg gives us the weights of each foundation in the best case to be:

Wall 1A: $1,359/4 * 2310,3 * 16$ foundations = **12558.7908 kg Mofix**

Wall 1B: $1,682/4 * 2310,3 * 16$ foundations = **15543.6984 kg Mofix**

Wall 2A: $1,981/4 * 2310,3 * 16$ foundations = **18311.4378 kg Mofix**

Wall 2B: $2,435/4 * 2310,3 * 16$ foundations = **22502.322 kg Mofix**



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