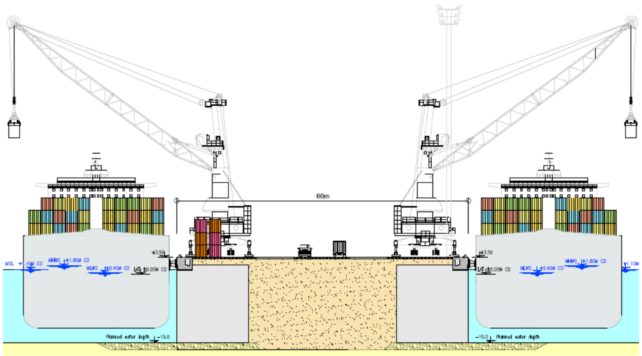

# Carbon Footprint of Common Quay Structures


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Thesis to obtain the degree Master of

## Civil Engineering

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Declaration:

I declare that this thesis is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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# Resumo

A Avaliação do Ciclo de Vida (ACV) é uma ferramenta que pode ser usada para analisar a pegada ambiental de produtos ao longo da sua vida. Nesta tese, foi estimada a pegada de carbono, com o método da ACV, dos vários tipos de estruturas de cais de acostagem, que são usados tipicamente em portos marítimos para terminais de contentores. Só as etapas do ciclo de vida de produção, transporte e construção foram consideradas. Os estágios de utilização e fim de vida não foram avaliados. Os tipos de cais de acostagem que foram considerados, foram caixões de betão, cortinas de estacas-pranchas e tabuleiro do cais fundado em estacas. Foi concluído que os cortinas de estacas-pranchas têm a pegada de carbono mais baixa e que os caixões de betão os tabuleiros do cais fundado em estacas têm a mais alta. Para todos os tipos de muros de cais, a etapa de produção de materiais contribuiu entre 83 % a 88 % para a pegada de carbono. Isso foi atribuído à alta pegada de carbono do aço e do cimento Portland. A análise de sensibilidade mostrou que quando o conteúdo reciclado do aço é aumentado para cerca de 85 %, e substituindo 65 % do cimento Portland por escória de alto-forno, a pegada carbónica total reduzida entre 26 % a 40 %, dependendo do tipo de estrutura. Para estudos futuros é recomendado investigar a contribuição da etapa de ciclo de vida de construção com mais pormenor para determinar esta contribuição para a pegada de carbono com maior precisão. Seria interessante incluir cenários de recuperação e reciclagem para componentes de aço em estudos futuros.

**Palavras-chave**

Avaliação do Ciclo de Vida (ACV), Estruturas de Muros de Cais, Pegada de carbono, Geotécnica, Construção, Obras Portuárias

# Abstract

Life Cycle Assessment (LCA) is a tool that can be used to analyse the environmental footprint of a product from cradle to grave. In this thesis, the carbon footprint of various quay wall structures, typically used in the construction of container terminals in seaports, was estimated using an LCA approach. Only the life cycle stages of materials production, materials transport and construction were considered. The operational and end of life stages were not evaluated. The quay wall types that were investigated were concrete caissons, sheet piled combi-walls and open piled suspended decks. It was concluded that sheet pile walls have the lowest carbon footprint followed by concrete caissons and open piled decks. For all three designs, the production life cycle stage contributed between about 83% and 88% to the total carbon footprint due to the high carbon footprint from the production of steel and Portland cement. The sensitivity analysis revealed that by increasing the recycled steel content to about 85% and replacing 65% of the Portland Cement content with Ground Granulated Blast Furnace Slag, the total carbon footprint can be reduced by about 26% to 40% depending on the structure type. For future investigations it is recommended that the contribution from the construction life cycle stage be investigated in more detail to determine its contribution with a higher degree of accuracy. It would also be of interest to include recovery and recycling scenarios for steel elements in future studies.

**Key Words**

Life Cycle Assessment (LCA), Quay Wall Structures, Carbon Footprint, Geotechnics, Construction, Port Construction Works

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# List of Abbreviations and Acronyms

BMUB The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Germany)

BSRIA Building Services Research and Information Association

CD Chart Datum

CFP Carbon Footprint of a Product

$CH_4$ Methane

$CO_2$ Carbon Dioxide

$CO_2e$ Carbon Dioxide equivalent

DQIs Data Quality Indicators

DUF Daily Usage Factor for machines

dwt Dead Weight Tonnes

EC Eurocode

EP Earth Pressure

EPD Environmental Product Declaration

EU European Union

FA Fly Ash

GGBS Ground Granulated Blast-Furnace Slag

GHG Greenhouse Gas

GWP Global Warming Potential

GW Ground Water Level

HFCs Hydrofluorocarbons

ICE Inventory of Carbon and Energy

IEA International Energy Agency

ISO International Organisation for Standardisation

kN Kilo Newton

kW Kilo Watt

LAT Lowest Astronomical Tide

| | |
|---|---|
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory analysis |
| LCIA | Life Cycle Impact Assessment |
| mCD | Meters Chart Datum |
| MHWS | Mean High Water Spring |
| MLWS | Mean Low Water Spring |
| MPa | Mega Pascals |
| MSL | Mean Sea Level |
| mt | Metric Tonnes |
| $N_2O$ | Nitrous Oxide |
| NACE | European Classification of Economic Activities |
| $O_3$ | Ozone |
| PFCs | Perfluoro Carbons |
| $SF_6$ | Sulphur Hexafluoride |
| SLS | Serviceability Limit State |
| TEU | Twenty Foot Equivalent Unit |
| UDL | Uniformly Distributed Load |
| ULS | Ultimate Limit State |
| UNEP | United Nations Environment Programme |

# List of Symbols

$\phi'$ Effective Angle of Shearing Resistance of a Drained Soil

$\phi'_k$ Characteristic Effective Angle of Shearing Resistance of a Drained Soil

$\phi'_d$ Design Effective Angle of Shearing Resistance of a Drained Soil

$C_u$ Undrained Shear Strength of a Cohesive Soil

$\delta'$ Effective Angle of friction of a Drained Soil

$K_a$ Active Earth Pressure Coefficient

$\mu$ utilisation factor = design action / design resistance

# 1. Introduction

## 1.1Background

Climate change due to global warming is a reality that is significantly threatening the wellbeing of the planet and its inhabitants. Climate change is caused by anthropogenic greenhouse gas (GHG) emissions (WRI and WBCSD, 2011). There are various greenhouse gases, for example carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$), which are released to the atmosphere from different sources.

In 2017 the construction industry was responsible for more than 11% of global carbon dioxide emissions which included production of materials and construction products such as steel and cement (IEA and UNEP, 2018). In the European Union (EU), the construction sector contributed with an average of 1.7% to the total carbon footprint in 2017 (Eurostat, 2020), whereas in Portugal the construction sector contributed 2% to the country's total carbon footprint (Pordata, 2017). However, in both statistics, construction is classified as an economic activity according to the European Classification of Economic Activities (NACE). According to NACE, processes such as raw material extraction, the manufacturing of construction materials and transport of construction materials are classified as different economic sectors such as Mining and Quarrying, Manufacturing and Transport (Eurostat, 2008). In the United Kingdom, for example, it is estimated that infrastructure (roads, buildings, ports, railways and so on) is associated with approximately half of the total GHG emissions (HM Treasury, 2013). Of this portion, approximately 30% are associated with the construction, operation and maintenance of these infrastructures whereas the remainder is associated emissions due to the use of the infrastructure.

In order to reduce the environmental impacts of climate change, the EU has committed to reduce greenhouse gas emissions by 20% by 2020 and by 40% by 2030 compared with 1990 (Eurostat, 2019). However, not only in Europe, but globally, the civil engineering and construction industry clearly has an important role to play in the effort to reduce carbon emissions. This will require innovation in designing and planning in order to achieve the goals of carbon reduction. On a project level, Life Cycle Assessment is a very useful tool that needs to be used in order to identify carbon reduction opportunities.

This dissertation is a study of a project where the carbon footprint of various alternative designs and construction methods, for a quay wall of a container terminal expansion in a port in sub-Saharan Africa, were analysed using Life Cycle Assessment.

## 1.2 Problem Statement

The problem statement for the thesis is:

"Compare the carbon footprint of the alternative designs of the piers to determine the differences in carbon footprint based on a life cycle assessment".

## 1.3 Case Study Description

A project for a container terminal expansion in sub-Saharan Africa, for which Inros Lackner did a layout study, was used as a basis for this thesis. Due to confidentiality reasons the details of this project cannot be revealed. The port is the main port of the country and handles approximately 80% of its imports and exports excluding oil and crude. In 2018, the port handled approximately 7 million tons of cargo, 80% of which was containerised cargo. There are five terminals in the port one of which is a container terminal. In 2018, the container terminal handled 268 000 TEU's (Twenty Foot Equivalent Units) out of a total of 620 000 that were handled in the port that year. However, the terminal operator intends to add additional berths to the container terminal to accommodate larger sized vessels and to increase the throughput capacity of the terminal.

Currently, the container terminal has a total quay wall length of approximately 550 m and consists of three berths. There is a bend in the quay wall between berths 2 and 3 (see Figure 1). The nominal draft of the terminal varies between about 11 m CD and 12 m CD.

Inros Lackner SE prepared a layout study for the client to provide alternative conceptual designs for a finger pier construction as an extension to the container terminal in order to provide additional berthing space. The future port needs, bathymetric aspects and the manoeuvring situations were all considered.

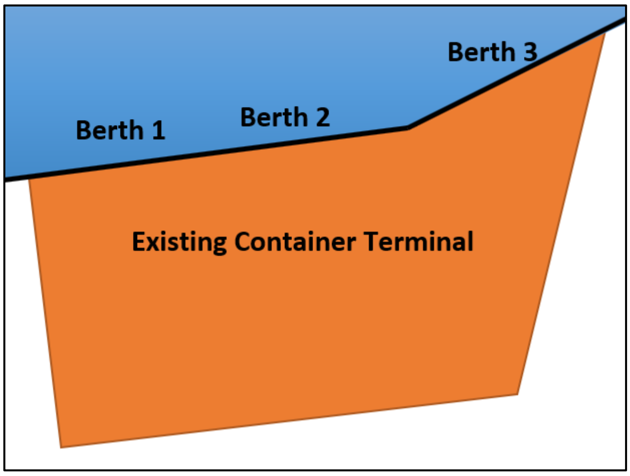



*Figure 1 – View of Existing Container Terminal*

### 1.3.1 Proposed Layout of Finger Pier

The new finger pier would extend perpendicularly from the existing key at the berth 2 and berth 3 interface. For the caisson, sheet pile combi-wall and open piled suspended deck options, the new pier would have sufficient capacity to accommodate two design vessels (see Figure 2).

For the design option of a floating deck, the pier would only have enough capacity to accommodate one design vessel as illustrated in Figure 3.

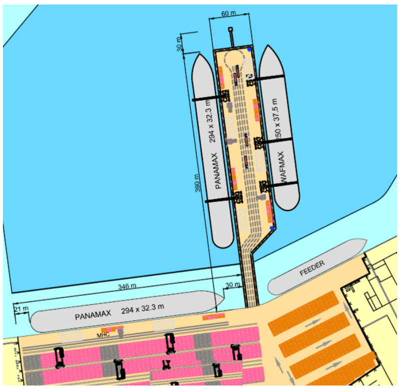



*Figure 2 - Layout of new finger pier for Caisson, Combi-Wall and Suspended Deck design options*

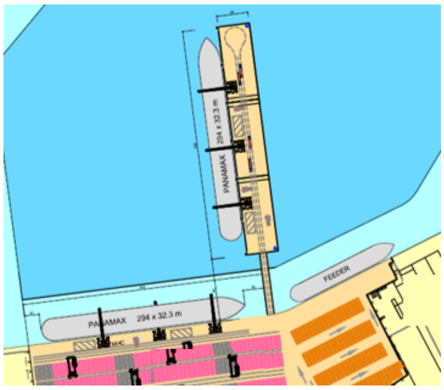



*Figure 3 - Layout of new finger pier for floating dock design option. Only one design ship Berthing capacity*

## 1.3.2 Alternative Designs Description

The four alternative designs that were considered for the new quay structure were:

a) Concrete Caissons
b) Sheet Pile Wall (cofferdam)
c) Open Piled Suspended Deck
d) Floating Pier

Refer to Figure 4 for a typical cross section drawing for each of these structures.

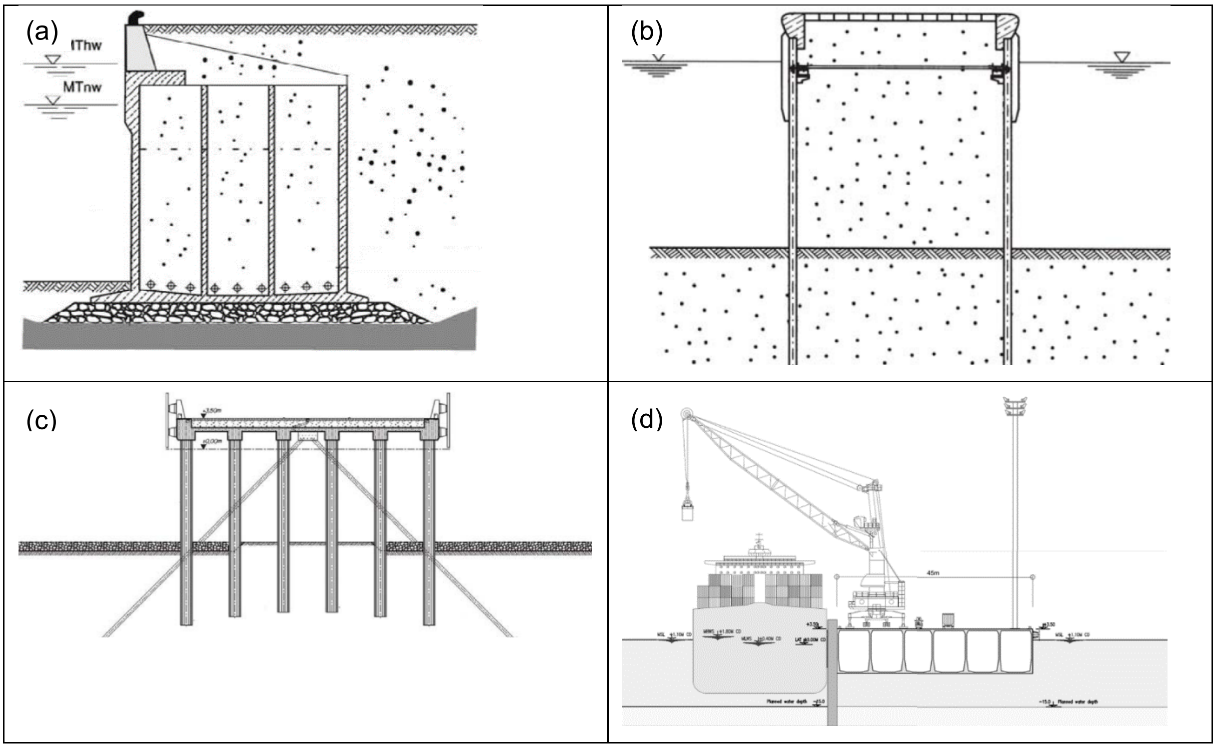



*Figure 4 - Typical cross section of (a) Caisson, (b) Sheet Pile Wall, (c) Open Pile Structure and (d) Floating Pier. Figures (a), (b) & (c) adapted from EAU (2012) figures R101-3, R157-1 and R79-1 respectively.*

### *a) Caissons*

Caissons are reinforced or pre-stressed concrete elements which are constructed in a dry dock or on shore. In the case of the dry dock, once the caisson construction is completed, the dock is filled with water which causes the caisson to float. In the case of construction on shore, the caisson is launched into the water by means of a hydraulic jack and launching system.

The floating caisson is then towed into position by means of a tugboat. Once in position, its chambers are filled with water causing it to sink down to a gravel bed foundation. The area behind the caisson, as well as the voids within the caisson are then backfilled with a granular material to the required level and the top slab of the caisson will act as the deck of the container pier.

***b) Sheet Pile Combi-Wall (Cofferdam)***

A sheet pile combi-wall consists of steel sheet pile elements combined with steel king pile elements. The sheet piles can be U-sections or Z-Sections and the king piles are typically tubular piles or I-sections with a high moment of inertia. The combi-wall will require some form of anchoring and in the case of a finger pier (cofferdam) a horizontal anchoring system was proposed.

***c) Open Piled Suspended Deck***

An open piled suspended deck consists of raking and vertical concrete or steel piles. Precast concrete beams and planks are then placed on top of the piles and an additional in situ concrete slab is placed to form the deck of the pier.

***d) Floating Pier***

The floating pier is a construction consisting of floating caissons, held in place by vertical piles which are embedded in the seafloor. The caissons are reinforced, hollow concrete or steel boxes with a rectangular cross section and consist of a top slab, bottom slab, outer walls, longitudinal and transverse stiffening panels. They are prefabricated onshore or on floating docks and after fabrication they are connected to the platform which is towed to the required location. The pier is ballasted to limit heeling during operation by pumping water into different trimming compartments. Floating piers are a relatively cheap solution to construct with minimal disturbance to other berthing operations during the construction period. However, they have a significantly shorter design life (approximately 20 years) than other typical quay wall structures (50 years), only one ship can berth at a time and are typically only used as a finger pier. For these reasons floating piers are not a common solution and were not considered in this investigation.

***e) Other Types of Quay Wall Structures***

Diaphragm walls, gravity concrete block walls and counterfort walls are other types of quay wall structures that are sometimes used. However, these were not considered in this thesis as only the most common designs, namely sheet piled combi-walls, concrete caissons and open piled suspended decks were considered.

## 1.4 Goals

### 1.4.1 Outline Designs of Alternative Piers

As part of this thesis an outline design for concrete caissons, sheet piled combi-wall and open piled suspended decks was developed.

Once these dimensions and material types were determined, the materials quantities could be estimated as well as the required construction equipment and procedures to execute the project in a realistic time period.

### 1.4.2 Carbon Footprint Calculation and Comparison

The goal of this thesis is to calculate the carbon footprint of the various designs and construction methods in order to quantify the difference between the different types of quay wall structures. This was done by Life Cycle Assessment (LCA) method considering the life cycle phases from raw materials extraction to construction.

It is intended that the results of this calculation can add to the body of knowledge on global warming potential of quay wall construction projects and therefore be used as a reference to assist designers and planners in finding innovative solutions for reducing the carbon footprint of construction of quay walls.

## 1.5 Structure of the Thesis

This Thesis has been divided into eight chapters.

The first chapter provides a brief introduction to climate change and the role that infrastructure and quay walls play in the contribution towards climate change. The case study is introduced with an overview of the different designs that were investigated.

In the second chapter, the state of the art and literature review is presented. This includes the main definitions used in Life Cycle Assessment (LCA) and Carbon Footprint studies, a review of LCA standards and methodology, a review of databases and LCA tools and finally a review of specific studies related to the subject matter.

In chapter three, the outline designs that were done for the various quay walls are presented.

In chapter four to seven, the four main stages of a Life Cycle Assessment are presented. These are the Goal and Scope Definition (chapter four), Life Cycle Inventory (chapter five), Life Cycle Impact Assessment (chapter six) which presents the actual carbon footprints and finally, the discussion and interpretation (chapter seven).

In chapter 8, the conclusions of the thesis are summarised.

# 2. State of the Art and Literature Review

## 2.1 Definitions

For the purpose of this thesis the most important applicable definitions are described in this Section. The parts indicated in quotation marks are direct quotes from ISO14067 (2018).

***Greenhouse Gas (GHG)***

"*Gaseous constituent of the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and the clouds*."

The primary GHG's in the earth's atmosphere are water vapour ($H_2O$), Carbon Dioxide ($CO_2$), Nitrous Oxide ($N_2O$), Methane ($CH_4$) and Ozone ($O_3$). The Kyoto Protocol also considers GHGs Sulphur Hexafluoride ($SF_6$), Hydrofluorocarbons (HFCs) and Perfluoro carbons (PFCs) in addition to $CO_2$, $N_2O$ and $CH_4$ (IPCC, 2013).

According to ISO14067 (2018) water vapour and ozone which are also GHG's are not included in a CFP.

***Global Warming Potential (GWP)***

"*Index, based on radiative properties of GHG's, measuring the radiative forcing following a pulse emission of a unit mass of a given GHG in the present-day atmosphere integrated over a chosen time horizon, relative to that of $CO_2$*." Typically, a time-horizon of 100 years is adopted as per the Kyoto Protocol (IPCC, 2013, p. 1455). GWP's are not always consistent and therefore have some uncertainties associated with them (IPCC, 2013, p. 58). Nevertheless, typical GWP characterisation factors are recommended by the Intergovernmental Panel on Climate Change (IPCC, 2013) as displayed in Table 1.

*Table 1 - Typical GWP's adapted from table 8.A.1 (IPCC, 2013)*

| Greenhouse Gas | $GWP_{100\text{-}year}$ Characterisation Factor |
|---|---|
| Carbon Dioxide | 1 |
| Methane | 28 |
| Nitrous Oxide | 265 |
| Sulphur Hexafluoride | 23 500 |

***Carbon Dioxide Equivalent ($CO_2e$)***

"*Unit for comparing the radiative forcing of a GHG to that of carbon dioxide*." This is done by converting the mass of a given GHG into $CO_2e$ by multiplying the mass of the GHG by the characterisation factor for the GWP. For example, with reference to Table 1, if a certain process causes 1 kg of methane to be emitted to the atmosphere this would be calculated as being equivalent to 28 kg's of carbon dioxide, i.e. 28 kg $CO_2e$.

***Carbon Footprint of a Product (CFP)***

"*Sum of GHG emissions and GHG removals in a product system expressed as $CO_2$ equivalents ($CO_2e$) and based on a life cycle assessment using the single impact category of climate change*." For example, Maas *et al.* (2011) calculated the carbon footprint of a steel sheet-pile combi-wall to be approximately 47 t $CO_2e$ per meter length of quay wall. Here GHG emissions due to production and transportation of materials and the construction phase were considered. An example of GHG removals could be when a timber product is used since trees absorb carbon dioxide from the atmosphere.

***Partial CFP***

"*Sum of the GHG emissions and GHG removals of one or more selected process(es) in a product system expressed as $CO_2$ equivalents and based on the selected stages or processes within the life cycle.*" An example of a partial CFP may be the kg $CO_2e$ emitted due to the production of concrete and could be expressed as kg $CO_2e$/ cubic meter of concrete.

***Product***

"*Goods or service*"

***Functional Unit***

"*Quantified performance of a product system for use as a reference unit.*" For example, when the carbon footprint of different mix designs of a 30 MPa concrete are compared, the functional unit may be kg $CO_2e/m^3$ of concrete. Each cubic metre of 30 MPa concrete fulfils the same function and therefore these different mixes can be compared.

***Life Cycle***

"*Consecutive and interlinked stages related to a product, from raw material acquisition or generation from natural resources to end-of-life treatment*". Table 2 describes some of the life cycle stages of a building as defined in European Standard EN 15978:2011. For each stage an example for a quay wall is presented. In this study, only stages A1 – A5 were considered in the Life Cycle Assessment of various quay structures.

*Table 2 - Building Life Cycle Stages, adapted from Figure 6 in EN 15978 (CEN/TC 350, 2011)*

| Stage | Stage Number | Description | Example for Quay Wall |
|---|---|---|---|
| Production Stage | A1 | Raw Material Extraction | Mining of Iron Ore |
| | A2 | Transport of raw Materials | Transporting Ore from mine to steel Smelter |
| | A3 | Manufacturing Constr. Materials | Producing Steel Piles |
| Construction Stage | A4 | Transport | Transport Steel Piles to constr. Site |
| | A5 | Construction | Installation of Steel Piles |
| Use Stage | B1 | Use | Use of pier, e.g. vessels offloading/loading cargo |
| | B2 | Maintenance | Replacing anodes on piles |
| | B3 | Repair | Repairing damaged concrete sections |
| | B4 - B7 | … | … |
| End-of life | C1 | Demolition / De-construction | Demolish pile caps / Extract piles |
| | C2 - C4 | … | … |
| R / R / R | D | Reuse / Recovery / Recycling | Recycle steel |

## 2.2 LCA Standards

Large inconsistencies have been noted in the reporting of life cycle $CO_2$ emission analysis of buildings (Fenner *et al.,* 2018). There are various standards that have been developed to increase the reliability of carbon footprint analysis. However, there is not a single standard that is internationally used for quantifying the carbon footprint of infrastructure. The main ones discussed in this section are:

- ISO 14040:2006 Environmental Management - Life Cycle Assessment – Principles and Framework
- ISO 14044:2006 Environmental Management - Life Cycle Assessment – Requirements and Guidelines
- ISO 14067:2018 Greenhouse Gases – Carbon footprint of Products – Requirements and guidelines for quantification
- PAS 2050:2011 Specification for the assessment of life cycle greenhouse gas emissions of goods and services
- Greenhouse Gas Protocol: Product Life Cycle Accounting and Reporting Standard

### 2.2.1 ISO Standards

The International Organisation for Standardisation (ISO) published the ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards in 2006. ISO 14040 describes the principles and framework for Life Cycle Assessment (LCA) which is based on the four main phases of a life cycle assessment depicted in the flow diagram in Figure 5.

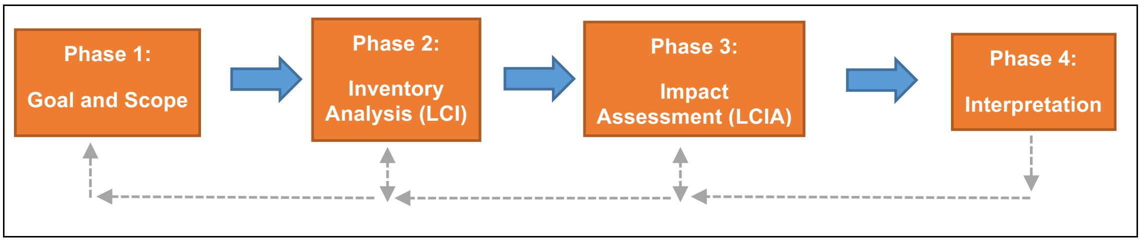



*Figure 5 - The four phases of a Life Cycle Assessment Phases according to ISO 14040*

a) Phase 1: Goal and scope definition

In this phase, the goal of the Life Cycle Assessment is defined as well as the system boundary and level of detail of the study, i.e. which processes will be included, and which processes will be excluded in the study.

b) Phase 2: The Life Cycle Inventory analysis phase (LCI)

This phase consists of compiling an inventory of all the necessary input and output data for the system that is being studied. For example, in a CFP study for a construction project this could involve quantifying the amounts of materials required, the processes associated with producing these materials (inputs) as well as the emissions that are a result of each of these processes (outputs).

c) Phase 3: The Life Cycle Impact Assessment phase (LCIA)

In this phase, the potential environmental impacts for the various processes within the study are quantified. In this thesis, only one impact category (climate change) is investigated. So, for example the impact assessment phase would be to quantify the weight (e.g. tons) of $CO_2e$ emitted due to the construction of a pier.

d) Phase 4: The interpretation phase

In this phase, the results of the inventory analysis phase and the impact assessment phase are discussed and analysed in order to draw conclusions and recommendations. This phase also includes a sensitivity analysis of significant process and methodological choices in order to understand to what extent changes in these processes may influence the result.

The grey dotted lines in Figure 5 represent the iterative nature of a Life Cycle Assessment. In each phase of an LCA, one might discover certain issues and therefore revise previous phases. For example, after executing a sensitivity analysis on a certain process in a products life cycle one might discover that variations in this process have a significant impact on the results of the LCA. Therefore, one might revise the life cycle inventory by gathering higher quality data associated with this process in order to get a more accurate result.

ISO 14044 provides a detailed methodological framework and techniques for executing the four main phases of an LCA listed above. In addition, it also provides detailed guidelines and requirements for the reporting of the study as well as the critical review.

ISO 14040 and 14044 are more generic standards that guide a user for performing an LCA. ISO 14067 is based on ISO 14040 and ISO 14044. However, in contrast to these two standards, it is a more specific standard that focuses only on the environmental impact category of climate change and therefore serves as a guideline for the quantification of the carbon footprint of a product. The latest version of ISO 14067 was published in 2018. The ISO14067 Standard was used as a basis for determining the carbon footprints of the various quay wall structure types in this thesis.

The seven principles used to quantify GHG emissions in ISO 14067 are listed and explained in Table 3 (ISO, 2018). ISO14067 provides guidelines on assessing data and data quality as well as requirements on how to make comparisons of various product CFP's.

*Table 3 - Principles for conducting a CFP according to ISO 14067*

| Principle | Meaning |
|---|---|
| 1) Relevance | Use of data and methods that are applicable to the system being studied. |
| 2) Completeness | All GHG emissions that provide a significant contribution should be included. |
| 3) Consistency | Assumptions, methods and data should be applied in the same way throughout the various stages of the LCA study. |
| 4) Coherence | Use of methodologies, standards and guidance documents internationally recognized. |
| 5) Accuracy | Quantification of the CFP in an accurate way and biases and uncertainties reduced as far as possible. |
| 6) Transparency | Methodologies, assumptions and data documented and referenced in an open manner. |
| 7) Double Counting | Prevention of double counting of GHG emissions. |

### 2.2.2 Publicly Available Specification (PAS)

The PAS 2050 was the first carbon footprint product standard to be developed (Liu *et al.*, 2016). The latest version was published by the British Standards Institute (BSI) in 2011. It is based on the LCA framework as specified in ISO 14040 and ISO 14044 (Fenner *et al.*, 2018; and Liu *et al.*, 2016).

The principles covered by PAS 2050 are relevance, completeness, consistency, accuracy and transparency. This standard provides detailed guidelines on determining system boundaries, emission sources, data requirements and the quantification of emissions and removals. PAS 2050 does not cover the requirements for reporting of the results (BSI, 2011).

### 2.2.3 Greenhouse Gas Protocol

The GHG Protocol was developed by the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) and published in 2011.

Like PAS 2050, the GHG Protocol also covers the principles of relevance, completeness, consistency, accuracy and transparency. This standard also provides the guidelines and requirements for the quantification of a CFP and the communication thereof.

One of the main features of this standard is that it divides its emission sources into three scopes. Scope one and two are the emissions that are associated with the production processes of a product (WRI and WBCSD, 2011) and are attributed to direct emissions from sources owned by the company and emissions due to energy used by the organisation (Fenner *et al.*, 2018). Scope three are emissions due to activities that occur upstream and downstream of the production process. These are, for example, material acquisition and pre-processing, distribution and storage, use and end of life.

### 2.2.4 Comments

A summary and comparison of the various carbon footprint standards discussed above is presented in Table 4.

*Table 4 - Comparison of Carbon Footprint Standards. Adapted from Fenner et al. (2018) and Liu et al. (2016)*

| | ISO 14067 | PAS 2050 | GHG Protocol |
|---|---|---|---|
| Focus | Standardized quantification and communication of CFP results | Uniform guideline on GHG Assessment Process | Detailed specification for assessment and reporting |
| Scope | Assessment<br>Reporting | Assessment | Assessment<br>Reporting |
| Assessment Principle | Relevance<br>Completeness<br>Consistency<br>Accuracy<br>Transparency<br>Coherence<br>Avoidance of Double Counting | Relevance<br>Completeness<br>Consistency<br>Accuracy<br>Transparency | Relevance<br>Completeness<br>Consistency<br>Accuracy<br>Transparency |
| System Boundary | Cradle to Gate<br>Cradle to Grave<br>Gate to Gate<br>Partial Carbon Footprint | Cradle to Gate<br>Cradle to Grave | Cradle to Gate<br>Cradle to Grave |
| Climate Change Method and Characterisation Factors | According to the GWP of IPCC and integrated over a 100-year time horizon | According to the GWP of IPCC and integrated over a 100-year time horizon | According to the GWP of IPCC and integrated over a 100-year time horizon |

In this thesis, ISO 14067 is used as the basis for quantifying the CFP of the various designs. The methodology and process are followed in the sequence and steps as specified in this standard. Where more information for guidance was required the other standards were consulted.

## 2.3 Databases

Databases provide, amongst other information, the emissions factors associated with various materials and processes of a products life cycle. For example, the Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011) has an emission factor for High Density Polyethylene (HDPE) pipe of 2,52 kg $CO_2e$ / kg of pipe. For this reason, databases are an important tool to be used for assessing a CFP as they contain most of the required information regarding the emissions. However, some databases provide information that may be more accurate or appropriate for the case study than others.

In this section, several databases that were available in order to execute a life-cycle assessment for evaluating the environmental impacts of the pier under investigation are reviewed. The advantages, disadvantages and other relevant factors that need to be considered for the use of a database are discussed.

The databases were developed by various organisations located in specific countries. Several issues have been noted with the use of LCA databases (Martinez-Rocamora *et al.*, 2016). These are typically associated with a difference between the geographic location of the study and the area where the database is applicable. Another significant issue is the lack of transparency and traceability of a database. For researchers and practitioners, it is important to have a detailed description of how the emission factor was determined to know what processes were included and excluded in the determination of an emission factor. This assists the person executing the LCA study to determine how relevant and accurate the available data are to the product under investigation and if more data are required.

Martinez-Rocamora *et al.* (2016) performed a review of the European and American LCA databases containing data on construction materials, as summarised below. Six features were chosen, and a subsequent criterion developed in order to analyse and compare each database (see Table 5).

*Table 5 - Features and Criteria for the assessment of LCA studies. Adapted from Martinez-Rocamora et al. (2016)*

| **Feature:** | Scope | Completeness | Transparency | Comprehensiveness | Update | Licence |
|---|---|---|---|---|---|---|
| **Criteria:** | Territory<br>Categories | Variety | Traceability<br>Methodology | Documentation | Last<br>Update | Required? |

### 2.3.1 Ecoinvent

The Ecoinvent database was developed by the Swiss Centre for Life Cycle Inventories (Martinez-Rocamora *et al.*, 2016). Geographical coverage of construction materials, electricity, metals and petroleum (amongst others) extend to various countries beyond Europe, for example Brazil, India and South Africa (Ecoinvent, 2020). It scored a high grade due to its high level of consistency and transparency. For most items in Ecoinvent, a report providing in-depth details on how the LCA for that item was executed is available. However, it was only possible to access these reports with a costly Ecoinvent account, and therefore not available to the author. For most of the data sets in the Ecoinvent library, the associated emissions were determined using LCAs that adopted a cradle-to-gate approach. Martinez-Rocamora *et al.* (2016) highly recommended Ecoinvent for use of construction materials since every category of construction material is included with a large variety of products. A license is required for Ecoinvent, but it is included in the SimaPro software (Faculty license) which was available to the author.

### 2.3.2 ELCD

The European reference Life Cycle Database (ELCD) was developed by the European commission and the JRC (Joint Research Centre). The latest version is ELCD 3.2 (Rodriguez, 2016) from 2016. The ELCD was discontinued from 29 June 2018 (European Comission, 2020), but is still available free of charge.

ELCD complies with ISO 14040 and ISO 14044. Information such as flow diagrams life cycle inventories, comments, literature references and reviews are available (Martinez-Rocamora *et al.*, 2016). However, Martinez-Rocamora *et al.* (2016) recommended that ELCD would need to be used with other databases due to its limited number of data sets.

### 2.3.3 GaBi

GaBi Database is also a large database with approximately 2600 processes for construction materials (OpenLCA, 2020). Each of the product categories have a large degree of variety and transparency with the required documentation available online (Martinez-Rocamora *et al.*, 2016). GaBi also requires a license to be used.

### 2.3.4 U.S. Life Cycle Inventory Database

The U.S. Life Cycle Inventory Database was developed by the National Renewable Energy Laboratory (NREL) of the US department of Energy and was last updated in 2009 (NREL, 2009). The database has 600 processes of which 80 consist of metal, wood and plastic products (Martinez-Rocamora *et al.*, 2016). The energy sources used in the production of materials are not clearly explained in this database.

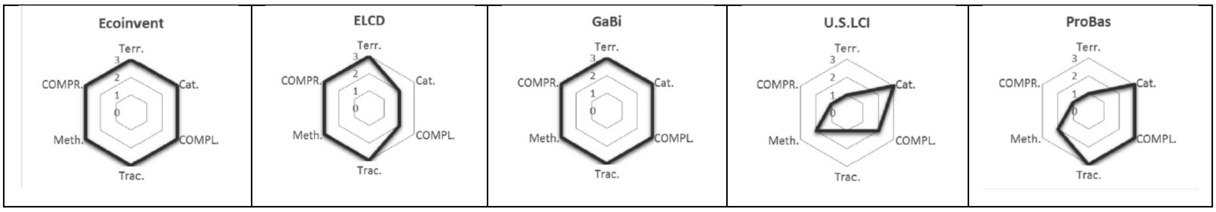
### 2.3.5 ProBas

ProBas contains about 7000 processes of which approximately 700 are construction materials (Martinez-Rocamora *et al.*, 2016). It is a German database library and was developed by the German Federal Environment Agency (Umweltbundesamt). Most of the processes are based in Germany, although other countries are also represented. Accordingly, most of the datasets are available in German (OpenLCA, 2020). Martinez-Rocamora *et al.* (2016) consider this a "complete" database since, for each data set references, life cycle inventories and information is provided. The academic license of ProBas is available free of charge.

Martinez-Rocamora *et al.* (2016) evaluated each of the above databases based on the criteria of Territory, Categories, Completeness, Traceability, Methodology, Comprehensiveness (see Table 5). A scoring system was used with 0 being the worst score ("not accomplished") and 3 the best score ("fully accomplished").

The results of the evaluation from Martinez-Rocamora *et al.* (2016) of the various databases are depicted in the spider diagrams in Table 6. Ecoinvent and GaBi database clearly score the best in all the categories. Of all the free databases considered in the review by Martinez-Rocamora *et al.* (2016) the ELCD database scores the highest. This was attributed to the fact that it received input from other high-quality databases.

*Table 6 - Scoring of various LCA databases. Adapted from Martinez-Rocamora et al. (2016)*




### 2.3.6 Inventory of Carbon and Energy

The Inventory of Carbon and Energy (ICE) was developed by G. Hammond and C. Jones (Hammond & Jones, 2008). This database contains approximately 1800 records of embodied carbon and energy for 34 different types of construction materials from a cradle to gate boundary (Hammond & Jones, 2011). This database typically used values that are representative for the UK. When this was not possible, average European and in some cases world averages were used (Hammond & Jones, 2008). The latest version of the database is from November 2019 (Circular Ecology, 2020) and can be downloaded free of charge in Microsoft Excel format. With regard to steel and cement, this database considers degrees of recycling and cement substitutions respectively (Hammond & Jones, 2011).

The data in this inventory was selected from peer reviewed articles, technical reports and specialised studies on the material (Hammond & Jones, 2008).

The ICE database is accessible in excel format and displays a comment for each material type that explains sources of information, assumptions, limitations and so on about the respective material. The system boundary (e.g. cradle to gate) and units and density of the material are also provided.

Data quality indices are also provided for each dataset.

### 2.3.7 Ökobaudat

Ökobaudat is a German database containing data on building materials as well as construction, transport, energy and disposal processes. It is published by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) (Figl & Kusche, 2018).

The database contains more than 1300 datasets of materials.

### 2.3.8 Summary

Various databases containing construction materials and processes are described in this section (see Table 7). There are advantages and disadvantages associated with each of the databases. Various factors such as the geographical territory, categories of material, completeness, traceability of data sources, methodology of data collection and comprehensiveness influence the quality of a database as explained by Martinez-Rocamora *et al.* (2016).

Ecoinvent and GaBi databases stand out in this regard as they perform well when considering all of the above criteria. However, the high license costs are for obvious reasons a major obstacle in using these databases. The ELCD, ProBas, ICE and Ökobaudat databases provide extensive and transparent databases for building materials, but they are limited to specific geographic zones more than Ecoinvent as the latter includes datasets covering several developing countries and regions as well as global averages.

Undoubtedly, it is important to have a large degree of transparency in the data being used, so that it is clear how, where and when the data were determined. This can assist in deciding how relevant the data are to a study. Finally, it is also important to have data quality indicators based on certain criteria to enable the LCA practitioner and others to understand the limitations of the data that were used.

*Table 7 - Databases Review Summary*

| **Inventory Name** | **Location/Region** | **Approximate number of data points on construction materials** | **License Cost - €** (OpenLCA, 2020) |
|---|---|---|---|
| Ecoinvent | Europe, Global | 4000 (Martinez-Rocamora *et al.*, 2016) | € 1900 |
| ELCD | Europe | 300+ (Martinez-Rocamora *et al.*, 2016) | Free |
| GaBi | Europe | 3600+ (OpenLCA, 2020) | € 1605 |
| U.S. Life Cycle Inventory Database | USA | 600 (Martinez-Rocamora *et al.*, 2016) | |
| ProBas | Germany | 700 (Martinez-Rocamora *et al.*, 2016) | Free (Academic User) |
| ICE | UK | 1800 (Hammond & Jones, 2011) | Free |
| Ökobaudat | Germany | 1300+ (OpenLCA, 2020) | €150 (Academic User) |

## 2.4 LCA tools

The construction of a quay involves a complex network of processes that start from raw material extraction all the way through to commissioning. Therefore, when performing an LCA, in order to quantify the carbon footprint of a pier, a large amount of data relating to each of these processes needs to be managed (e.g. quantity of materials, operating hours of the construction machines and so on), along withtheir respective emission factors. For this it is useful to use a software tool in order to effectively manage the data and then calculate and analyse the results. In this section various LCA tools are reviewed and discussed.

### 2.4.1 SimaPro

SimaPro is an LCA software package developed by Pre-Sustainability in the Netherlands (SimaPro, 2020). It has the following features and abilities (The Green House, 2020):

- Modelling:
  - Intuitive user interface;
  - Use of parameters to change assumptions. This is useful for scenario and sensitivity analysis;
  - LCA compliant with ISO14040;
  - Allocation for several output processes;
  - Complex Waste scenarios;
  - Monte Carlo analysis for quantitative assessment of data uncertainty;
  - Adjusting a dataset for a different context (e.g. by replacing one electricity grid mix for another).
- Analysis:
  - Transparent unit data allowing traceability;
  - Process trees that enable one to isolate “hotspots”;
  - Grouping of results to analyse specific processes contributing to total results;
  - Filtering options.

- Databases:
  - SimaPro comes with the latest Ecoinvent database included. Several other databases such as the ELCD and specific Industry Databases such as the World Steel Association database are also included.

### 2.4.2 OpenLCA

OpenLCA is a free open source LCA software developed by GreenDelta in Germany. It has some features similar to SimaPro like an intuitive user interface, Monte Carlo analysis, use of parameters and process trees (GreenDelta, 2020).

Most of the databases discussed in Chapter 2.3 can be integrated into the OpenLCA software. Table 7 summarises the approximate costs of these databases. It should be noted that the ICE database cannot be directly integrated into the software, but emission factors can be inserted manually.

### 2.4.3 EFFC DFI Carbon Calculator

The EFFC DFI Carbon calculator was developed by Carbone4 for the European Federation of Foundation Contractors (EFFC) and the Deep Foundations Institute (DFI) (Carbone4, 2013). It is a Microsoft Excel tool and is focussed on calculating the carbon footprint for various geotechnical structures such as bored piles, sheet pile walls and anchors amongst others (Carbone4, 2013).

The emission sources were divided into the following categories:

- Material manufacturing;
- Materials transportation;
- Energy consumed on the construction site;
- Peoples transport to the construction site;
- Equipment transportation;
- Equipment manufacturing;
- Waste transportation;
- Waste treatment.

The EFFC DFI carbon calculator incorporates datasets from various databases. These include (Carbone4, 2013):

- Ecoinvent;
- Bilan Carbone V7;
- Sustainableconcrete;
- ICE;
- DEFRA;
- EcoTransit;
- EPA.

The EFFC DFI Carbon calculator is a very simple to use and transparent tool for calculating the carbon footprint of foundations. However, the user interface is limited to an Excel spreadsheet and hence does not produce flow diagrams and process trees as other LCA software, like SimaPro and OpenLCA. This makes an in-depth analysis of the results more difficult. Use of parameters is also more complicated which makes executing sensitivity or scenario analysis harder.

### 2.4.4 Other Tools

#### a) EC3 Tool

The Embodied Carbon in Construction Calculator (EC3) tool is a software package being developed by the Carbon Leadership Forum (CLF) as part of the University of Washington and C-change labs (CLF, 2019). At the time of writing, the tool was still in the development phase and the beta release of the software was in 2019 (CLF, 2019). It is a free and open access tool that concentrates on quantifying the embodied carbon in construction materials in a construction project, thereby enabling designers to identify possible means of cutting the emissions in these upstream processes. The tool is integrated with Autodesk´s BIM360 model to estimate material quantities. The database consists of EPDs and covers the geographic regions of the USA, Canada and Europe. Various material categories including concrete, steel, wood, glass and several others are covered in the tool.

#### b) CEET Tool

Sandanayake *et al.* (2019) present a study on the Construction Emission Estimation Tool (CEET). This is a Microsoft Excel based tool developed to estimate the carbon emissions of a construction project. The following emission sources are considered:

- Emissions from materials
- Emissions from equipment usage
- Emissions from transportation

This tool uses the US EPA and AGGA (Australian Greenhouse Gas Accounts) standards as a database to get its emission factors.

### 2.4.5 Summary

The most comprehensive LCA software on the market is SimaPro which comes with the extensive Ecoinvent database. The software can assess carbon footprint as well as other environmental impacts. The Instituto Superior Técnico (IST) CERIS (Civil Engineering Research and Innovation for Sustainability) research unit provides licenses for its students.

OpenLCA provides the best alternative to SimaPro as it also has similar advanced features such as a good user interface and data quality assessment for analysing results. It is a free open source software for which various database libraries can be imported, some at a cost and others for free as discussed in the previous section.

The EFFC DFI Carbon Calculator and the CEET are easy to use Excel based tools with limited capabilities for advanced analysis.

The EC3 tool was still under development at the time of writing. It is primarily aimed at estimating the embodied carbon of construction materials and does not consider all life cycle stages. It is integrated with BIM models.

The SimaPro software package with a “Faculty License” was used to carry out the Life Cycle Assessment for this study. Data from Ecoinvent, ELCD and the ICE (2019) database libraries were used. In addition to these databases, specific data were used in certain instances where this was not available in the Ecoinvent, ELCD or ICE libraries. It was either calculated or adopted from Environmental Product Declarations (EPDs). These specific instances are detailed in Chapter 5 (Life Cycle Inventory).

## 2.5 LCA and $CO_2$ Footprint Studies

In this section, various existing Life Cycle Assessment and Carbon Footprint studies are reviewed and investigated. First a generic LCA study on buildings is reviewed, followed by a review of two existing LCA studies on port structures, an LCA study on concrete deep foundations and another on the effect of fly ash on marine concrete.

Each of these studies provide some knowledge on aspects that should be considered when conducting an LCA study on a civil engineering related infrastructure product. Of particular interest are the two LCA studies on port structures since these have the potential to form useful comparisons to the study at hand. The last two studies provide some insight on how specific components of an infrastructure can be influenced in order to reduce the Carbon Footprint.

### 2.5.1 General

Buyle *et al.* (2013) present a review of life cycle assessment studies executed in the construction sector by focussing mainly on building projects. The various LCAs were compared and some general trends were noted: in most of the cases the use-phase of the building contributed the most to the environmental impacts. It was also noted that as buildings become more energy efficient, other phases of a building’s life cycle gained more (relative) importance on the total environmental impact. Another interesting conclusion drawn from many of the studies was that the transportation of materials played a minimal role in the contribution to the overall impact except when a very large portion of the materials required were imported over great distances.

Buyle *et al.* (2013) discuss limitations of their study as there are many differences in the LCA studies that were reviewed. They mention that, for example, the system boundaries, assumptions and Life Cycle Impact Assessment (LCIA) methods amongst others. In many of the studies reviewed by them, the functional unit was different or was simply the whole building. According to them, this emphasizes the importance of the selection of a good functional unit. It was also noted by Buyle *et al.* (2013) that aspects like feasibility, structural and quality requirements need to be considered in a life cycle assessment and not only environmental impacts as was the case in the reviewed studies. This is necessary since it is important that these problems are approached in a holistic manner since feasibility, structural and quality requirements will play a very important role when deciding what environmental impact mitigation measures are implemented. For example, when considering carbon reduction opportunities for a building one needs to understand the implicated costs (or savings) that may be associated with each specific measure. These implicated costs (or savings) will play a critical role when deciding if a measure will be implemented.

## 2.5.2 Port and Harbour Infrastructure Studies

### *2.5.2.1 Port of Gothenburg*

Stripple *et al.* (2016) performed an LCA study of port infrastructure and its operation for the Port of Gothenburg. The following port terminals were analysed:

- Oil terminal;
- Container;
- RoRo (roll-on roll-off) terminal 1;
- RoRo Car terminal 2;
- RoPax.

The functional unit of the study was per metric ton (1000 kg) of handled cargo. For the container terminal, an average load of 8112 kg/TEU was estimated. For the passenger terminal, the results were presented per passenger.

Besides the GWP (kg$CO_2$e/1000 kg cargo) five other environmental impact categories were considered as part of the study (energy use, resource use, acidification potential, photochemical ozone creation potential, ozone layer depletion potential).

A lifetime of 60 years was applied for the calculations on each of the terminals.

The information in the report was intended to be used for various purposes, from assessing environmental performance, increasing knowledge in port technology, comparing different ports as well as the planning of future ports. For the interpretation of the results, it was noted that the functions of the various terminals were different (for example an oil terminal cannot replace a container terminal) which meant that one could not simply compare one terminal to another. Nevertheless, one could conclude that various cargo types are easier or more difficult to handle. The results of the analysis by Stripple *et al.* (2016) of the GWP of the various terminals in the Port of Gothenburg is displayed in Figure 6. The RoRo car terminal had a low transport volume whereas the container terminal was largely influenced by the operation phase. Easy handling of oil products (pumping) was attributed to the low GWP of the oil terminal.

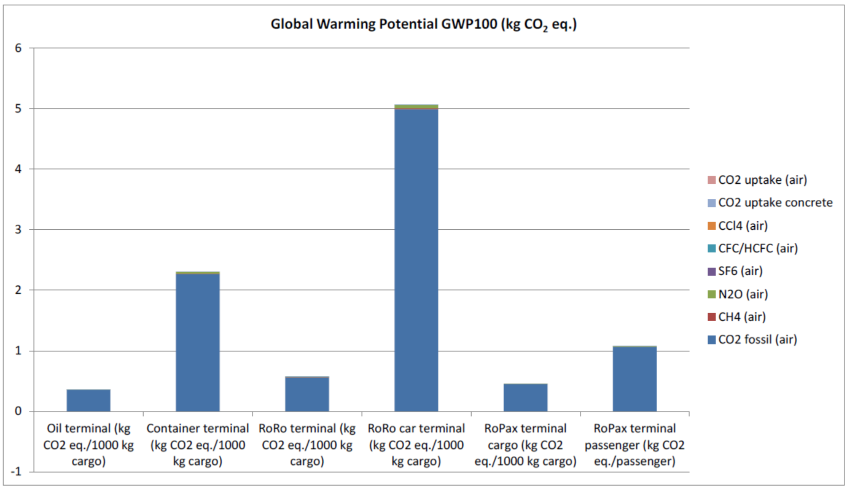



*Figure 6 - Global Warming Potential of various terminal in Gothenburg Port, Figure B from Stripple et al. (2016)*

Stripple *et al.* (2016) drew attention to the question of the representativeness of the results from the Gothenburg Port compared to other major ports in the world by considering the example of container traffic: in 2013 Gothenburg handled approximately 0.78 million TEU, versus e.g. 33.62 million TEU (Shanghai) and 11.62 million TEU (Rotterdam). It was noted that the port operation methods are similar for each of these ports. Since cargo handling techniques are one of the most important factors for determining capacity of a port, no large differences in environmental footprints between the various ports were expected. However, this remained to be verified.

The life cycle stages considered in the study were construction (including material extraction and production), operation and maintenance of the port facilities. As part of the LCA, various models were developed separately for the port foundation, surface pavement, port buildings and the various terminals. However, in the report, the design of the port foundation and surface pavement is not presented. Therefore, it is unclear what structures the investigation is based on. It appears that Stripple *et al.* (2016, p. 22) used a generic structure of a typical port. However, the design of this structure is also not provided.

The results for the impact category of GWP of the container terminal in the port of Gothenburg is presented in Figure 7 (Stripple *et al.*, 2016) in terms of kg $CO_2$e/ 1000kg of cargo. From the results it can be concluded that the various phases which are responsible for the following portions of emissions over the life cycle are:

- Construction: 15.8 %
- Maintenance: 15.9 %
- Operation: 68.4%

The construction phase included the extraction of raw materials and production (LCA stages A1-A3), transport of construction materials (A4) and operation of construction machinery (A5).

Maintenance included the maintenance of structural elements of the terminal such as the quay wall, foundation and surface pavement. Maintenance of port buildings and port equipment such as STS cranes, reach stackers and the like were also considered. The exact assumptions with regard to the maintenance requirements were not detailed in the report by Stripple *et al.* (2016).

Operation included emissions due to operations of lighthouses, container cranes, container refrigeration, diesel engine machines, vehicles, maintenance dredging, port buildings and so on.

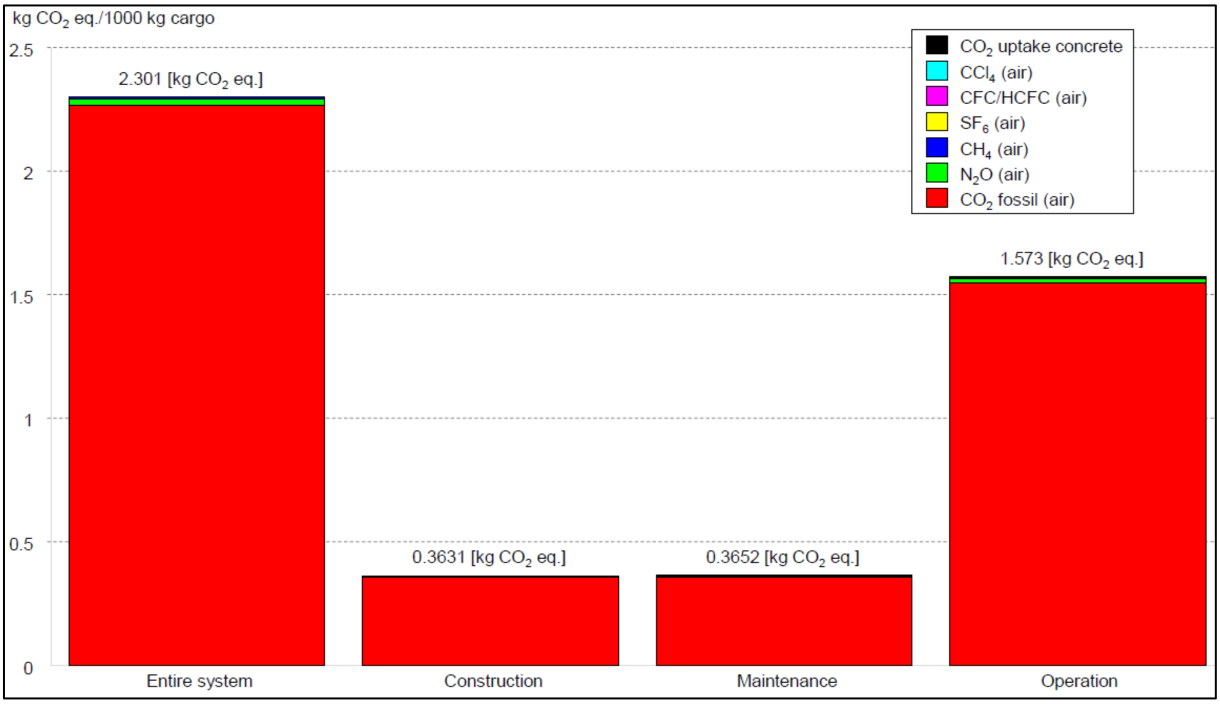



*Figure 7 - GWP (kg $CO_2$e/1000kg of cargo) for Container Terminal in Gothenburg. (Stripple et al., 2016, p. 114)*

As seen for the case of buildings where increased energy performance of buildings resulted in greater importance of the construction phase (Buyle *et al.*, 2013), it can be expected that in the future port operations will be optimised, and therefore the relative importance of the construction life cycle phase may increase.

#### *2.5.2.2 Port of Rotterdam*

Maas *et al.* (2011) conducted a study of different quay wall designs made of concrete, steel, wood and fibre reinforced polymers and compared the carbon footprints of the various designs. The case study used was the Euromax Container Terminal in the Port of Rotterdam. The terminal has a length of 1900 m and a retaining wall height of 27 m (Maas *et al.*, 2011).

Two alternative designs already existed for the project, namely a concrete diaphragm wall of 1.2 m thickness and 32 m length and a steel combi-wall with tubular and sheet piles with 35 m and 32 m lengths respectively. Maas *et al.* (2011) proceeded to make outline designs for a timber wall structure using AZOBE hardwood (retaining wall thickness of 1.4 m) and another design using fibre reinforced polymer panel with a thickness of 2.08 m. Typical sections of the four different designs are depicted in Figure 8.

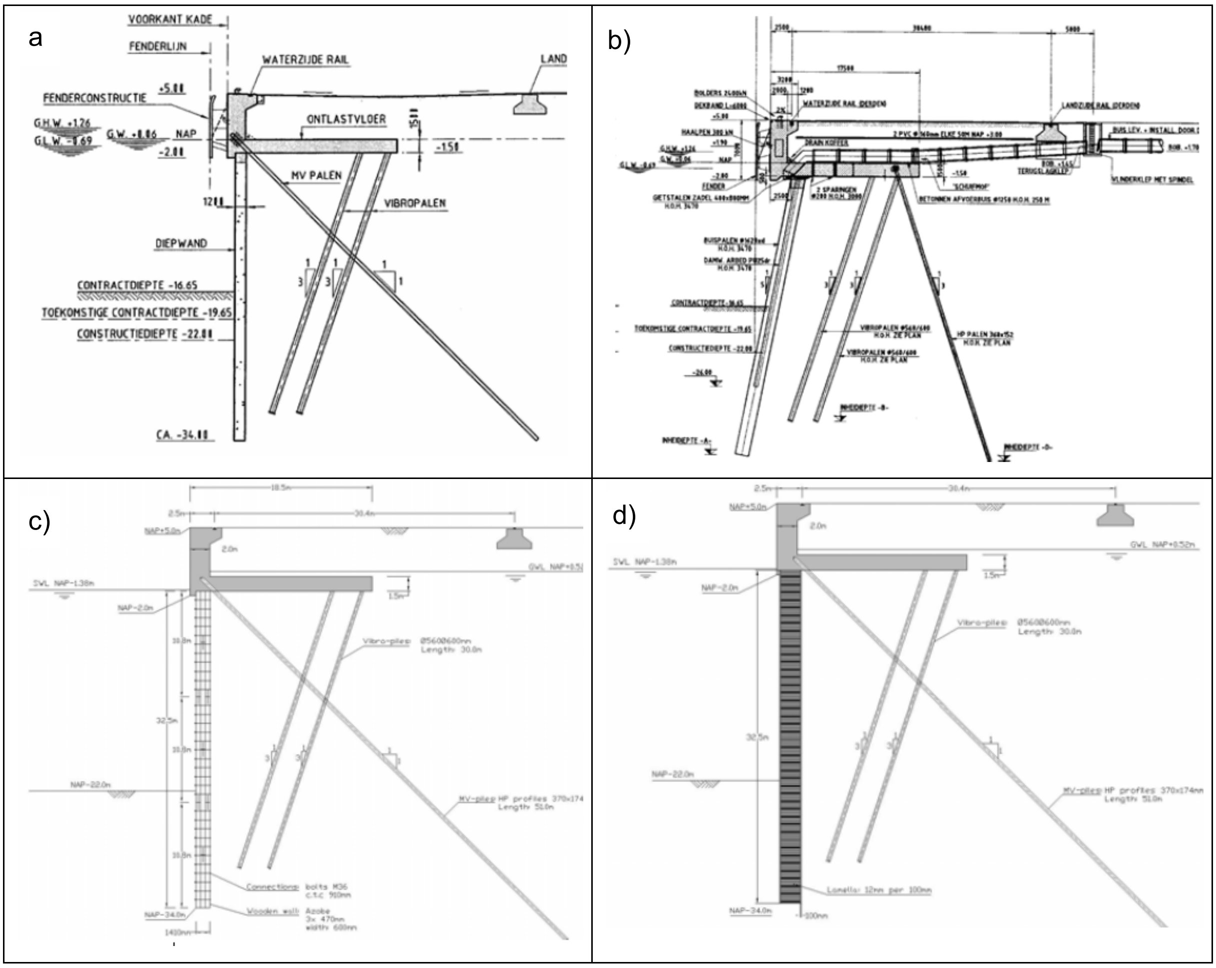


*Figure 8 - Alternative designs for Euromax Terminal: a) Concrete Diaphragm Wall b) Steel Combi-Wall c) Timber Wall d) Fibre Reinforced Polymer (Maas et al., 2011)*

The functional unit of the study by Maas *et al.* (2011) was one m of quay wall. The design lifetime of the structure was 50 years. Besides global warming 12 other environmental impacts were also considered. The following life cycle phases were considered as part of the study:

- Production of Materials;
- Transportation of Materials to site;
- Construction.

The databases used by Maas *et al.* (2011) were from IVAM (Department of Environment, University of Amsterdam) and the database from the carbon calculator of Dutch contractor, BAM.

The carbon footprint of the four different quay wall designs as determined by Maas *et al.* (2011) are presented in Figure 9. This represents the emissions due to the quay wall and the entire superstructure. From the figure it can be seen that the Fibre Reinforced Polymer design has the highest carbon footprint (approximately 145 tons $CO_2$e/m length of quay) whereas the concrete (~50 tons $CO_2$e/m), steel (~46,6 tons $CO_2$e/m) and timber (~46 tons $CO_2$e/m) designs are similar.

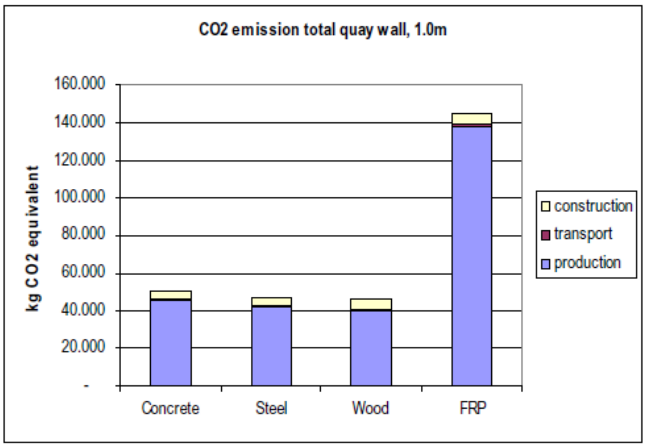



*Figure 9 - Carbon footprint of various quay wall designs in kg $CO_2e$ / m length of quay wall in Port of Rotterdam. (Maas et al., 2011)*

### 2.5.3 Other Studies

#### *2.5.3.1 Concrete Deep Foundations*

Pujadas-Gispert *et al.* (2020) conducted an LCA study to determine the influence of prefabrication, concrete strength and different design codes on the environmental impact of constructing concrete deep foundations (CDF). The functional unit of a CDF consisted of a reinforced concrete pile cap with three concrete piles with different degrees of prefabrication, compressive strength and designed according to different codes. The life cycle phases considered in the study ran from raw material extraction to completion of construction works.

Conclusions drawn by Pujadas-Gispert *et al.* (2020) were:

- Pre-fabrication of CDF´s (including transportation associated with prefabricated elements) resulted in up to 44% decrease in carbon footprint compared to in situ construction. This is because driven (precast) piles have a higher resistance for the same section and can therefore be designed with smaller section and hence less materials when compared to bored piles;
- Increasing compressive strength in concrete in bored piles reduced environmental impacts between 18-24% in all categories. The reason being that a higher strength of concrete enabled the design with less materials;
- Bored piles designed based on Eurocode with the UK annex have 11-31% less impact in most categories compared to ones designed with Spanish codes (EHE-08 and CTE). This is because the Spanish codes include an upper limit for concrete strength that may be used which results in larger cross sections and therefore more concrete;
- For driven piles, the Spanish codes result in 11-18% less environmental impact in most categories. This is because the minimum steel reinforcement specifications in the Spanish codes is lower than in the others.

#### *2.5.3.2 Effect of Fly Ash on Marine Concrete*

Nath *et al.* (2018) conducted a study to determine the effect that adding fly-ash to the binder content in concrete would have on service life, carbon footprint and embodied energy on concrete in the marine environment. It was found that concrete with fly-ash had lower levels of chloride diffusion and a binder with 40% fly ash content could increase the service life between 1.6 - 1.75 times for concrete covers between 35 mm and 50 mm.

As part of the study, Nath *et al.* (2018) conducted an LCA to determine the carbon footprint of concrete with 30% and 40% fly ash binder content. It was found that the carbon footprint would reduce by approximately 22% for both cases. Once service life was considered by analysing the concrete per $m^3$ per year, it was found that the carbon footprint was reduced by between 36% - 38% for covers varying from 35 mm to 50 mm.

# 3. Design

## 3.1 Introduction

In this chapter, the outline designs that were developed for the caisson, sheet pile combi-wall and open piled suspended deck type structures is presented. The requirements, assumptions and calculations are all discussed here. A conceptual description of each design was presented in Section 1.3.2.

## 3.2 Basis of Design

Unless otherwise indicated, the information in this section was gathered from the Basis of Design report which Inros Lackner executed as part of their work for the client.

### 3.2.1 Fundamentals

The new pier will extend perpendicularly from Berth 2, refer to Figure 2. The overall dimensions of the new pier will be:

- Total length 400 m
- Total width 60 m

The new pier will be connected to the existing quay by means of an access bridge with a total length of 90 m and a total width of 7.5 m.

The design life of the caisson, combi-wall and open piled structures will be 50 years as per the BS 6349-1-1:2013 (BSI, 2013a, p. 51).

### 3.2.2 Level Data

Table 8 details the level data used for the design of the new pier.

*Table 8 - Level Data for the Design of the New Pier*

| Description | Level (m CD) |
|---|---|
| Top of the new pier structure | + 4.9 m CD |
| Top of existing pier structure | +3.5 m CD |
| Mean High Water Spring (MHWS) | + 1.8 m CD |
| Mean Sea Level (MSL) | +1.1 m CD |
| Mean Low Water Spring (MLWS) | +0.4 m CD |
| Lowest Astronomical Tide (LAT) – reference level | 0 m CD |
| Dredging depth | - 17.5 m CD |

The dredging depth considers the vessel draught (15 m), load distribution, maximum squat, wind, swell & current effects, under keel clearance, bathymetric and dredging tolerances.

### 3.2.3 Ground Conditions

The existing geotechnical investigation was executed in 2008 and consisted of drilling 23 boreholes and executing SPT tests in each; the location of the most relevant boreholes is indicated in Figure 10. The ground investigation determined various litho-geological complexes. These are summarised in Table 9, along with the corresponding strength characteristics and densities.

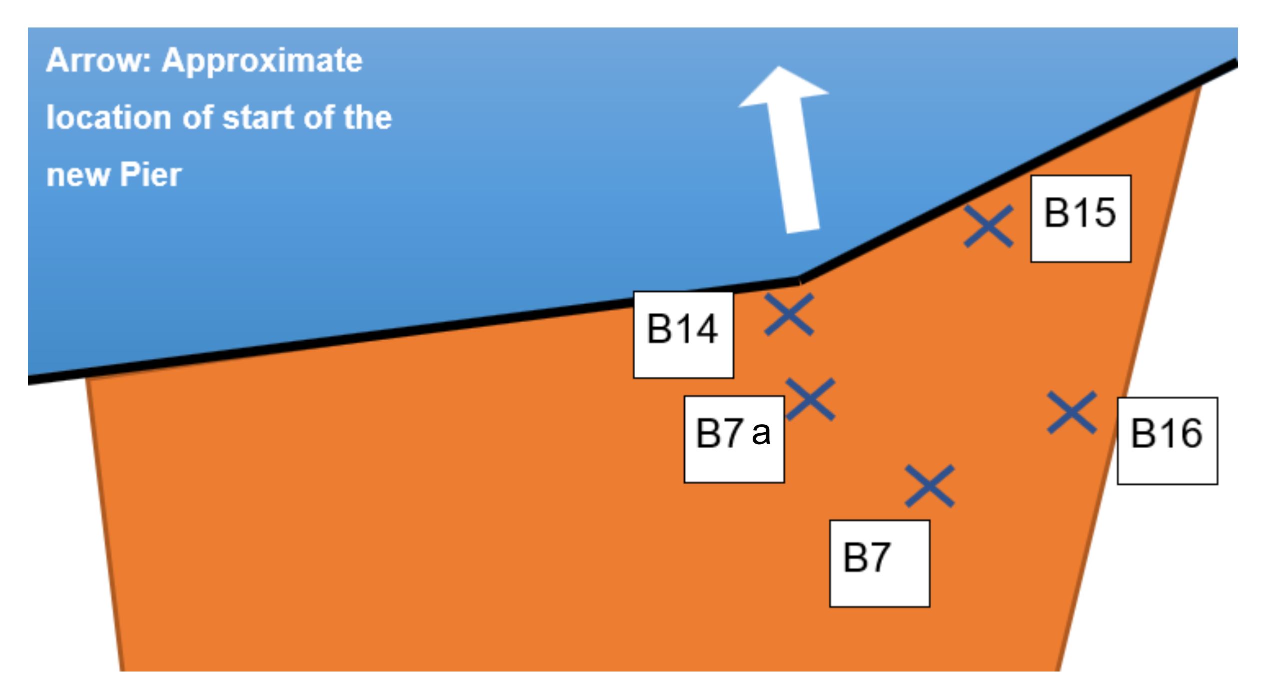



*Figure 10 - Borehole Locations of existing ground investigation*

Since none of the boreholes fall within the footprint of the new pier, the closest five boreholes were chosen for calculation purposes, namely boreholes B7, B7a, B14, B15 and B16. These are indicated in Figure 10. The white arrow in Figure 10 indicates the approximate position of the starting point where the new pier extends from the existing quay structures. A summary of the SPT logs relative to depth with the corresponding litho-geological complexes is provided in Appendix A for these five boreholes.

*Table 9 - Geotechnical Characterisation. Adapted from Inros Lackner SE report*

| Geological Age | Complexes | Lithology | SPT-N (blows/30cm) | Unit weight, $\gamma$ ( kN/m$^3$) * | Angle of shearing resistance, $\phi$' (deg) * | Undrained shear strength, $c_u$ (kPa) * |
|---|---|---|---|---|---|---|
| Current to Recent | C1A | Medium sands, medium compact | 12 - 30 | 21 | 25º - 30º | |
| Quarternary | C1B | Medium to coarse sands, very loose to loose | 2 - 10 | 19.5 | 25º | |
| Tertiary - Miocenic | C2A | Fine sands, medium compact | 12 - 30 | 20 | 25º - 30º | |
| | | Contains Passages of brownish clays with silts | 8 - 15 | 18.5 | | 100 |
| | C2B | Fine, compact sands | 30 - 50 | 21.5 | 35º | |
| | | Contains blemishes of brownish clays | 15 - 30 | 19 | | |
| | C2C | Fine silty sands, very compact | >50 | 22.5 | 40º | |
| | | Contains passages of brownish silty clays, stiff | >30 | 20.5 | | |
| | C3A | Silty clays, very hard | 15 - 30 | 20.1 | | 250* |
| | C3B | Silty clays, stiff to very stiff | >30 | 21.0 | | 250* |

* These values were determined based on correlations proposed by Kulhawy & Mayne (1990) for an SPT-N value of 30.

Concrete caissons are a suitable solution when the founding conditions consist of dense sand, stiff clay, rock or improved soil (Ackhurst, 2020, p. 3). Therefore, for the concrete caisson design it was assumed that the foundation soil along the quay wall would be similar to that of borehole B14 which consists of mainly dense sands. The other boreholes were not considered for the caisson design.

For the sheet piled combi-wall, two of the boreholes were considered, namely, B14 (mainly dense sands) and B16 (mainly hard clays). Only these two boreholes were chosen for the purpose of simplifying the calculations as they represented the two extremes of the ground conditions encountered.

For the open piled suspended deck all five boreholes (B7, B7A, B14, B15 and B16) were considered in the calculations. This type of structure is more versatile in its scope of applications since it can, theoretically, simply adapt to the ground conditions either by designing longer or shorter piles as required to achieve capacity.

The boreholes that were used in the calculations for each of the alternative designs are summarised in Table 10.

*Table 10 - Summary of boreholes used in the calculations for various designs*

| Quay Wall Design: | Boreholes considered in the calculations: |
|---|---|
| Concrete Caissons | B14 |
| Sheet Piled Combi-Wall | B14 and B16 |
| Open Piled Suspended Deck | B7, B7A, B14, B15 and B16 |

### 3.2.4 Design Vessels

The specifications of the two design vessel types are summarised in Table 11.

*Table 11 - Design Vessel Specifications adapted from an Inros Lackner SE Report*

| | Design Vessel 1 | Design Vessel 2 |
|---|---|---|
| **Carrying Capacity (dwt)** | 115 700 dwt | 126 000 dwt |
| **Maximum displacement (metric tons - mt)** | 164 200 mt | 180 500 mt |
| **Overall Length (m)** | 367 m | 325 m |
| **Moulded Breadth (m)** | 43 m | 48 m |
| **Draught** | 15 m | 16.5 m |

### 3.2.5 Design Loads

#### *3.2.5.1 Self-Weight*

The self-weight for reinforced concrete of 25 kN/m$^3$ and for steel 78.5 kN/m$^3$ were considered. The various unit weights of the soils (Table 9) were applied as appropriate.

#### *3.2.5.2 Water Pressure*

For caissons and the sheet pile combi-wall, the water pressure was calculated based on the recommendations in EAU (2012, p. 75). Accordingly, the ground water level (GW) behind the quay wall was calculated to be at +1.4 m CD and the sea water was taken at mean low water spring (MLWS) at +0.4 m CD.

#### *3.2.5.3 Live Loads*

Following the Inros Lackner basis of design report, a uniformly distributed live load (UDL) of 50 kN/m$^2$ was allowed for operations of light cranes and general traffic such as trucks, light forklifts and general cargo storage.

Mobile harbour cranes of the model type Liebherr LMH 600-2 were considered for the loading of the new pier. During operation, this crane has a maximum outrigger pad loading of 4139 kN (as per Inros Lackner) for the most loaded outrigger pad.

Since the above two loads cannot act simultaneously on the same area, two load combinations (LC's) were checked for the designs. The two load combinations are indicated schematically in Figure 11.

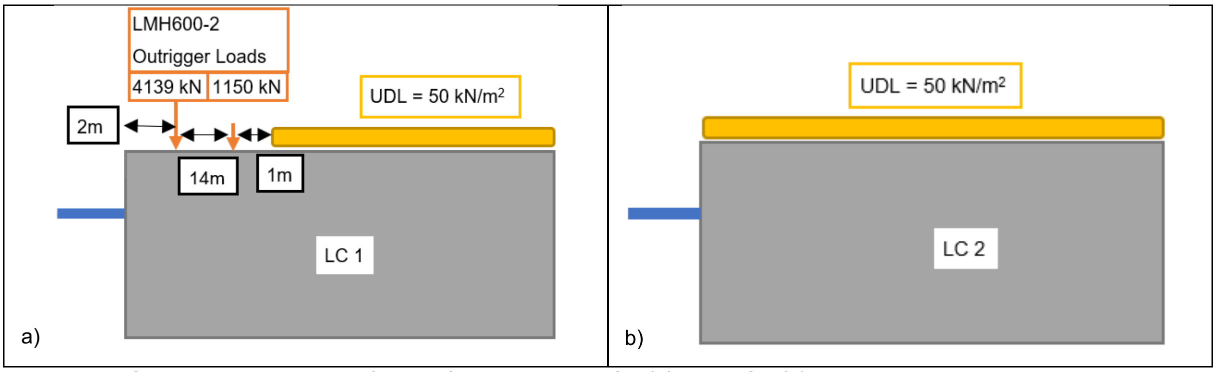



*Figure 11 - Schematic indication of Load Combinations LC1 (a) and LC2 (b)*

Other berth equipment such as ship to shore cranes, reach stackers, heavy forklifts and truck and trailers were not considered in the design.

### *3.2.5.4 Safety Concept and Limit States*

The Ultimate Limit State (ULS) was checked for all the designs whereas the Serviceability Limit State (SLS) was only checked in certain cases. The verifications for each design are described in more detail in the following sections.

For the geotechnical verifications, the design followed the Eurocode (EC) 7 guidelines following Design Approach (DA) 2 as specified by the German National Annex. The permanent (DS-P) and transient (DS-T) design situations were considered. The partial safety factors for the various geotechnical limit states are summarised below in Table 12.

*Table 12 - Partial Safety Factors According to EC7, DA2 from EAU (2012)*

| **EQU** | | | **STR & GEO-2** | | |
|---|---|---|---|---|---|
| | DS-P | DS-T | | DS-P | DS-T |
| $\gamma_{G,dst}$ | 1.1 | 1.05 | $\gamma_G$ | 1.35 | 1.2 |
| $\gamma_{G,stb}$ | 0.9 | 0.9 | $\gamma_{G,fav}$ | 1.0 | 1.0 |
| $\gamma_{Q,unf}$ | 1.5 | 1.25 | | | |
| **Sliding** | | | $\gamma_Q$ | 1.5 | 1.3 |
| $\gamma_{R,h}$ | 1.1 | 1.1 | $\gamma_{Q,fav}$ | 0 | 0 |
| **Bearing** | | | | | |
| $\gamma_{R,v}$ | 1.4 | 1.3 | $\gamma_{c'}$ ; $\gamma_{\varphi'}$ | 1.0 | 1.0 |

For determining the resistances of the driven piles for the open piled structure, the partial safety factors and distribution factors as recommended by EC7 were used. These are summarised in Table 13.

*Table 13 - Partial Safety Factors and distribution factors for determining resistance of displacement piles. Adapted from Eurocode 7, Table A.06 and Table A.10*

| Partial Safety Factors according to DA2 | | | Distribution factors (ξ) for determining the characteristic values from ground investigations (n – number of ground investigation profiles) | | |
|---|---|---|---|---|---|
| **Resistance** | **Symbol** | **Value** | **ξ for n =** | **1** | **5** |
| Base resistance | $\gamma_b$ | 1.1 | $\xi_3$ | 1,4 | 1,29 |
| Skin Friction | $\gamma_s$ | 1.1 | $\xi_4$ | 1,4 | 1,15 |
| Total resistance | $\gamma_t$ | 1.1 | | | |

### 3.2.6 Scour Protection

Each of the three design options will have scour protection consisting of two layers:

- Armour Layer 1: Top layer with a thickness of 0.9 m and stone weight from 60 -300 kg.
- Armour layer 2: Bottom layer with a thickness of 0.5 m and a stone weight of 1 – 80 kg.

The thickness and stone grading were adopted from an existing container terminal design by Inros Lackner for a different project. The extents of the scour protection were calculated to be 32.5 m from the coping beam edge as per the recommendations of EAU (2012, p. 565). Refer to the design drawings in Appendices B, C and D which indicate the scour protection.

### 3.2.7 Pavement

The pavement surface for the caisson and combi-wall design will consist of an 80 mm thick concrete block pavement above various granular base and subgrade layers with a total thickness of 1200 mm. This is detailed in the various “typical section” drawings in Appendix B and Appendix C. This pavement design was also adopted from an existing container terminal design by Inros Lackner for a different project.

### 3.2.8 Reinforced Concrete Specifications

The nominal concrete cover for concrete elements was 60 mm as recommended by EAU (2012, p. 488) for marine structures. The exposure classes for the concrete was XC4, XS3 and XA2 as recommended by EAU (2012). The concrete strength class for all major concrete components is to be C35/45 with steel reinforcing with a yield strength of 420 MPa. The mix design that was used as a baseline for this case study is presented in Table 14. A sensitivity analysis was done to analyse the effects of changing the binder composition, as described in Chapters 5, 6 and 7. Table 14 is based on a concrete mix design from an existing project by Inros Lackner.

*Table 14 - Baseline Concrete Mix Design*

| Component | Quantity | Comment |
|---|---|---|
| Water | 152 Litres | Water cement ratio: 0,33 |
| Cement (CEM I 42,5 N) | 391 kg | Total Binder content (Cement and Fly Ash) = 460 kg. Therefore, cement content = 85% and Fly Ash content = 15% |
| Fly Ash | 69 kg | |
| Sand (4,75mm) | 615 kg | |
| Stone (5-10mm) | 358 kg | |
| Stone (10 -20 mm) | 835 kg | |
| Plasticizer | 5 kg | Sika ViscoCrete 3088 |

The steel reinforcement content used for the various components of each design are summarised in Table 15.

*Table 15 - Steel Reinforcement Content used in Various Designs*

| Component | Reinforcement | Comment |
|---|---|---|
| Concrete Caisson | 210 kg/m$^3$ | Based on an existing project (Transnet, 2019). According to Voorendt *et al.* (2011, p. 42) the steel reinforcement can vary between 100-300 kg/m$^3$ for caissons. This is greatly influenced by the requirements to satisfy crack with limitations. Therefore, the reinforcement value of 210 kg/m$^3$ was used as a "baseline" with a sensitivity analysis done to assess the effects of increasing or decreasing the reinforcement content. The sensitivity analysis is described in more detail in chapters 6 and 7. |
| Concrete Coping Beam | 147 kg/m$^3$ | Based on an existing project (PMI Ltd. , 2016). This reinforcing content was used for the cope beam for the caisson design and for the sheet pile combi wall design. |
| Precast Beam, Plank, Pile Cap, In situ slab and plugs | 180 kg/m$^3$ | Based on an existing project by Inros Lackner. All these components were used in the open piled suspended deck structure. |

## 3.3 Caisson

This section describes the design assumptions and calculations that were done to execute a predesign for the caisson option. The concrete caisson structure was adopted from an existing design for a container terminal in the Port of Durban, South Africa. The dimensions were retrieved from the environmental impact assessment report written by Brueton *et al.* (2013).

### 3.3.1 Limit States and Verifications

The following ULS limit states were verified:

- Sliding
- Vertical Bearing Capacity
- Overturning

For the SLS limit state, the immediate (elastic) settlement was checked and is described in more detail in Section 3.3.3.4.

### 3.3.2 Design Loads and Model

For the verifications for the caissons only, Load Combination 2 (refer to Figure 11b) was considered since this was the most critical case. The permanent and the transient design situations were verified. The transient situation was considered as the point at which the caissons had been placed and backfilled to the top of caisson level. No live loads were applied for the transient situation.

The weight of the structure was calculated for both design situations. Table 16 summarises these weights and indicates the various components that were considered.

*Table 16 – Characteristic weight of structure calculated for Permanent and Transient Design Situations*

| | DS-P | | DS-T | |
|---|---|---|---|---|
| **Structure Weight** | 18 396 | kN | 18 396 | kN |
| **Infill Weight** | 63 691 | kN | 63 691 | kN |
| **Gravel Seal Infill** | 4 052 | kN | 4 052 | kN |
| **Coping Beam** | 2 513 | kN | | |
| **Overburden / Backfill** | 22 278 | kN | 12 114 | kN |
| **Totals =** | **110 930** | **kN** | **98 253** | **kN** |

According to recommendation R73 from EAU (2012) sand or gravel should be used as a backfill material. For the calculation of the earth pressures (EP's), it was assumed that an offshore source of sand could be found in the vicinity of the harbour with the appropriate characteristics for backfill and infill material. It was assumed that this sand had a characteristic effective angle of shearing resistance ($\phi'_k$) of 32,5°, based on recommendation R9 from EAU (2012) for empirical values of soil parameters. A characteristic friction angle ($\delta'_k$) between concrete and sand equal to two thirds of $\phi'_k$ ($\delta'_k = \frac{2}{3} \times \phi'_k = 21{,}7°$) was assumed. Based on this, tan active earth pressure coefficient ($K_a$) of 0.27 was determined according to Coulomb's earth pressure theory for a horizontally retained surface.

The characteristic active earth pressure and resulting forces are indicated in Figure 12.

The water uplift pressure was calculated based on the following water levels: at +1,4 m CD on the active side and at +0,4 m CD on the passive side. These levels were determined as discussed in Section 3.2.5.2.

The water uplift pressure with the resulting force is indicated in Figure 12b.

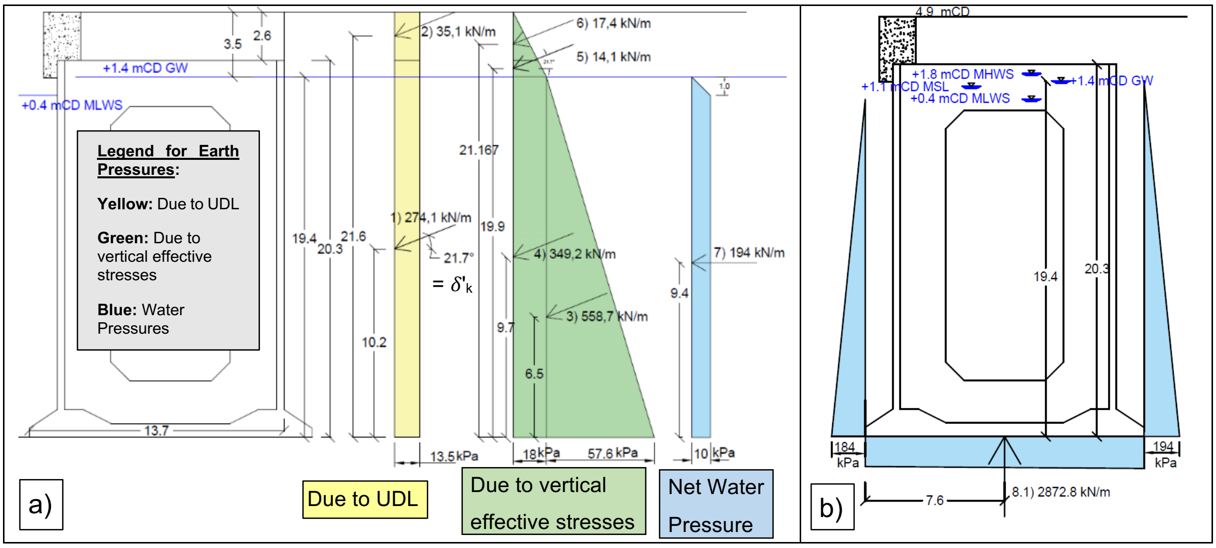



*Figure 12 - a) Characteristic Active Earth Pressures for Caisson Option with resultant forces indicated b) Characteristic water uplift pressure with resultant force indicated*

### 3.3.3 Design Calculations

As mentioned previously, concrete caissons are a suitable solution when the founding conditions consist of dense sand, stiff clay, rock or improved soil. Since at the time of writing there was not enough information on the ground conditions in the area of the new pier, the caisson design assumed that the material in the new pier area would be primarily dense sands like the profile of borehole B14. Therefore the soil characteristics as summarised in Table 42 in Appendix B were used for the calculations of the caisson design.

#### *3.3.3.1 Sliding Verification*

For the sliding resistance, it was assumed that the friction angle ($\delta$') between the base of the of the caisson and the stone bed was equal to the effective angle of shearing resistance (ϕ'). This means that the base of the caisson needs to be constructed to have a serrated base with the depth of the grooves equal to approximately the average stone size (50 mm) as per the recommendations of BS 6349-2:2010 (BSI, 2010, p. 61).

The calculations for the sliding resistance are presented in Appendix B. The horizontal design forces $E_{d,h}$ and the horizontal design sliding resistances $R_d$ are summarised in Table 17. The utilisation ratio (μ) in Table 17 is defined as the ratio of the design forces over the design resistances. This means that when μ is lower than one, safety is verified.

*Table 17 - Sliding Resistance Summary - Caissons*

| Design Situation | $E_{d,h}$ (kN/m) | $R_d$ (kN/m) | μ - utilisation | Safety Verified? |
|---|---|---|---|---|
| DS-P | 1 880 | 2 377 | 0.79 | Yes |
| DS-T | 1 247 | 2 097 | 0.59 | Yes |

#### *3.3.3.2 Vertical Bearing Capacity Verification*

For the vertical bearing capacity, the drained bearing capacity equation was applied by assuming a uniform layer of soil below the base of the caisson. For the effective angle of shearing resistance, $\phi'_k$ = $\phi'_d$ = 33.0 ° was used by calculating the weighted average of the ϕ' of the various soil layers from borehole B14 up to a depth of 23 m (= 1.5 x caisson base width) below the base of the caisson. The vertical bearing capacity equation is as follows:

*Equation 1*

$$q'_{R,k} = \frac{1}{2}\gamma B N_\gamma s_\gamma i_\gamma + q' N_q s_q i_q + c' N_c s_c i_c$$

Where:

- $q'_{R,k}$ is the characteristic drained bearing capacity of the soil
- $N_x$ are the bearing capacity factors
- $s_x$ and $i_x$ are the foundation shape and load inclination factors respectively

The soil was assumed to have zero effective cohesion (c') and therefore the third term in Equation 1 is zero.

The calculations for the vertical bearing capacity are displayed in Appendix B. The vertical design forces ($\mathbf{V_d}$) and the design bearing capacity ($R_d$) as well as the utilisation ratio are summarised in Table 18.

Table 18 - Vertical Bearing Capacity Summary - Caissons

| Design Situation | $V_d$ (kN/m) | Rd (=$q'_{R,d}$ x A') kN/m | μ - utilisation | Safety Verified? |
|---|---|---|---|---|
| DS-P | 6 576 | 6 993 | 0.94 | Yes |
| DS-T | 4 479 | 8 677 | 0.52 | Yes |

#### 3.3.3.3 Overturning Verification

The calculations for the verification against overturning are displayed in Appendix B. The destabilising and the stabilising moments as well as the utilisation ratio are summarized in Table 19.

Table 19 - Verification against Overturning Summary - Caissons

| Design Situation | Destabilising Moments, $E_d$ (kNm / m) | Stabilising Moments, $R_d$ (kNm / m) | μ - utilisation | Safety Verified? |
|---|---|---|---|---|
| DS-P | 39 350 | 52 209 | 0.75 | Yes |
| DS-T | 31 892 | 44 524 | 0.72 | Yes |

#### 3.3.3.4 Settlement Verification

As part of the SLS verification, only the immediate settlements of a caisson were estimated. This can be justified since it was assumed that the caissons would be founded on a sandy material, with no significant clay layers, as per the profile of borehole B14. Since consolidation and creep settlements are only associated with clayey materials, these long-term settlements were not considered.

The calculations for the settlements are presented in Appendix B. The settlements are estimated to be approximately 27 cm. Settlements in this range can be compensated for in various manners, for example by making the stone bedding layer thicker, dredging to a higher level or by adding extra fill material after the caissons have been installed.

### 3.3.4 Dimensions

Detailed drawings of a typical section and layout of the caisson design option are presented in Appendix B. All relevant dimensions are displayed in these drawings. Figure 13 presents a sketch of a typical cross section of the Caisson design. The main dimensions of each caisson are summarised in Table 20.

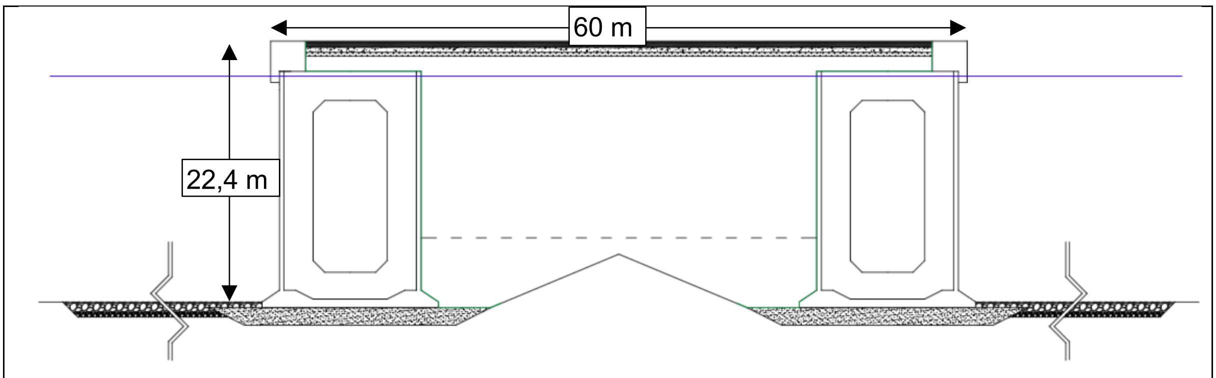



Figure 13 - Sketch of Typical Cross Section of Caisson Design

*Table 20 - Caisson Dimension Summary*

| | |
|---|---|
| **Total Number of Caissons** | 52 No |
| **Total Caisson Height** | 20,3 m |
| **Total Caisson Width** | 15,2 m |
| **Total Caisson Length** | 17.0 m |
| **Caisson Volume** | 736 $m^3$ |
| **Cope Beam Volume** | 7,8 $m^3$ / m |

### 3.3.5 Construction Sequence

A flow chart illustrating the general construction activities and the sequencing to be followed for the construction of the caisson quay wall structure described in this section is presented in Figure 14.

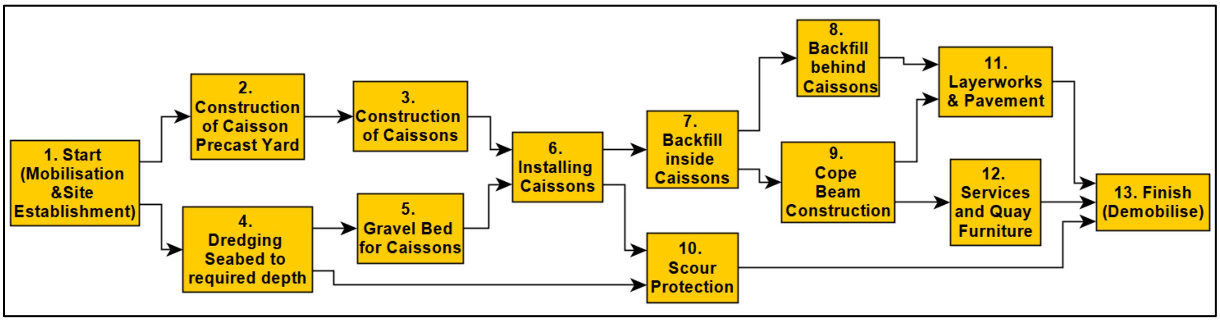



*Figure 14 - Caisson Construction Sequence*

## 3.4 Sheet Pile Combi-Wall

This section describes the design assumptions and calculations that were performed to execute a preliminary design for the sheet pile combi-wall option anchored by tie-rods. GGU, a geotechnical software programme, was used to perform the calculations of the sheet piled combi-wall option.

### 3.4.1 Limit States and Verifications

The following ULS limit states were verified:

- Rotational failure (this determines the required embedment depth and the magnitude of the support reaction for the tie rods) as per EC7,
- Vertical bearing capacity of the King Piles as per EC7,
- Equivalent stress, shear and buckling analysis of the King Piles (as per EC3 -The king piles were designed based on a characteristic yield strength of 430 MPa,
- Tensile resistance of the tie rods.

For the SLS limit state, it was checked that the tie-rod extension would not exceed 50 mm.

### 3.4.2 Design Loads and Model

The two load combinations (LC1 and LC2) as described in Figure 11 were checked. A characteristic load of 194 kN/m, representing the weight of the coping beam, was applied directly on top of the sheet pile wall.

A differential water pressure was considered as described in Section 3.2.5.2.

In the GGU-Retain software, a strut was used to determine the reaction forces.

The permanent (DS-P) and the transient (DS-T) design situations were checked. For the transient design situation, it was assumed that the combi-wall would be backfilled to tie-rod level and that dredging in front of the quay wall would only commence once the tie-rods had been installed. For this temporary phase, it was also assumed that the water level would be equal on both sides and therefore no resulting water pressure would act during this period.

### 3.4.3 Design Calculations

The outputs of the calculations from GGU-retain are presented in Appendix C.

An allowance for corrosion of 4 mm on the outer edge of the seawards flange was allowed for over a design life of 50 years. This was as per the recommendations of EAU (2012, p. 307) for the mean corrosion rate in the low water zone. Since the sheet piles will have cathodic protection in the form of sacrificial anodes, and the concrete capping beam will extend to 500 mm below MLWS level it was considered that this corrosion allowance was realistic given these protection measures. Since the corrosion would occur towards the end of the structure's lifetime the partial safety factors for DS-T were adopted in the corrosion calculations.

The verifications were performed based on two soil profile types, namely borehole B14 (primarily sandy soils) and borehole B16 (primarily clayey soils). For borehole B16, it was assumed that the clays would be of a low plasticity and therefore have a $\phi'_k$ = 25° as per Kulhawy and Mayne (1990, pp. 4-22). The soil properties used for each verification are displayed in the calculation outputs presented in Appendix C.

A summary of the design calculation outputs is presented Table 21. In this table, for each load combination the following is indicated:

- Design situation considered (DS-T or DS-P)
- minimum required embedment lengths $L_{emb.}$,
- maximum utilisation ratio (μ) for the steel section,
- required king pile section,
- bearing capacity utilisation ratio ($\mu_{bear.}$),
- characteristic tie rod load ($N_k$).

Note that the utilisation ratio was calculated as the ratio of the design action divided by the design resistance. With reference to Table 21, only the outputs for calculation 2) and 6) are presented in Appendix C as these were the two most conditioning cases.

*Table 21 - Summary of Combi-Wall Design Calculation Outputs*

| Calculation Number | Borehole | Load Combination | Design Situation | min $L_{emb.}$ (m) | μ | Required Section | $\mu_{bear.}$ | Tie Rod load, $N_k$ (kN/m) |
|---|---|---|---|---|---|---|---|---|
| 1) | B14 (Sandy) | LC1 - No Corrosion | DS-P | 13.1 | 0.99 | HZ1080 MB 24 | 0.61 | 879.4 |
| 2) | | LC2 - No Corrosion | DS-P | 13.3 | 0.91 | HZ1080 MB 26 | 0.58 | 713.2 |
| 3) | | LC1 - Corrosion | DS-T | 12.0 | 0.78 | Only verified with HZ1080 MB 26 | 0.58 | 861.2 |
| 4) | | LC2 - Corrosion | DS-T | 12.1 | 0.80 | | 0.55 | 693.8 |
| 5) | | Construction Phase | DS-T | 12.6 | 0.67 | | 0.26 | Not Applicable |
| 6) | B16 (Clayey) | LC1 - No Corrosion | DS-P | 18.0 | 0.99 | HZ1180 MA 26 | 0.73 | 1111.4 |
| 7) | | LC2 - No Corrosion | DS-P | 16.9 | 0.93 | HZ1080 MC 26 | 0.65 | 752.0 |

With reference to Table 21 :

- According to calculation 2), corresponding to sandy soils as per borehole B14:
    - Required embedment = 13.3 m,
    - Required pile section = HZ1080 MB26 (709 kg/m),
    - This corresponds to a total pile length of 32.9 m and a total pile weight of 23.3 tons.
- According to calculation 6), corresponding to clayey soils as per borehole B16:
    - Required embedment = 18.0 m,
    - Required pile section = HZ1180 MA26 (871 kg/m),
    - This corresponds to a total pile length of 37.6 m and a total pile weight of 32.8 tons.

The required king pile section and length results in king piles that are approximately 40% heavier in clayey soils than for sandy soils. This would greatly reduce the feasibility of the sheet pile combi-wall option. Therefore, this design is based on the assumption that the underlying ground conditions are mainly founded on sandy soils similar to that of the profile of borehole B14. Accordingly, the king piles were selected to be type HZ 1080 MB 26 with intermediary sheet piles of type AZ18/700.

The design calculations for the tie-rods are included in Appendix C. Allowance was made for 4mm of corrosion along the circumference of the tie rod as was done on a combi-wall project in the Port of Durban (Anker Schroeder, 2016). The required tie rod is an Anker Schroeder ASDO500 130/100. This means an upset thread of 130 mm and a shaft diameter of 100 mm.

Four 15,5 kg sacrificial alloy anodes will be attached to each sheet pile as corrosion protection. This form of corrosion protection was adopted by the author from a similar project. As can be seen on the drawings in Appendix C, the coping beam extends to 500 mm below MLWS level and therefore protects the steel wall in the inter-tidal and splash zone which has the highest corrosion rates.

### 3.4.4 Dimensions

Drawings of a typical section and layout of the sheet piled combi-wall design option are presented in Appendix C. All relevant dimensions are displayed in these drawings. The dimensions of the main elements for the combi wall are summarised in Table 22. A sketch of a typical cross section of the sheet piled combi wall design is presented in Figure 15.

*Table 22 - Combi Wall Dimension Summary*

| | |
|---|---|
| **King Pile HZ1080 MB 26 (Main Pier) Length =** | 32.9 m (23.3 tons) |
| **Sheet Pile AZ 18-700 (Main Pier) Length =** | 23.9 m (3.7 tons) |
| **Tie Rods ASDO500 130/100 (Main Pier) Length =** | 5 x 11.1 m |
| **Cope Beam Volume =** | 7.4 $m^3$ / m |

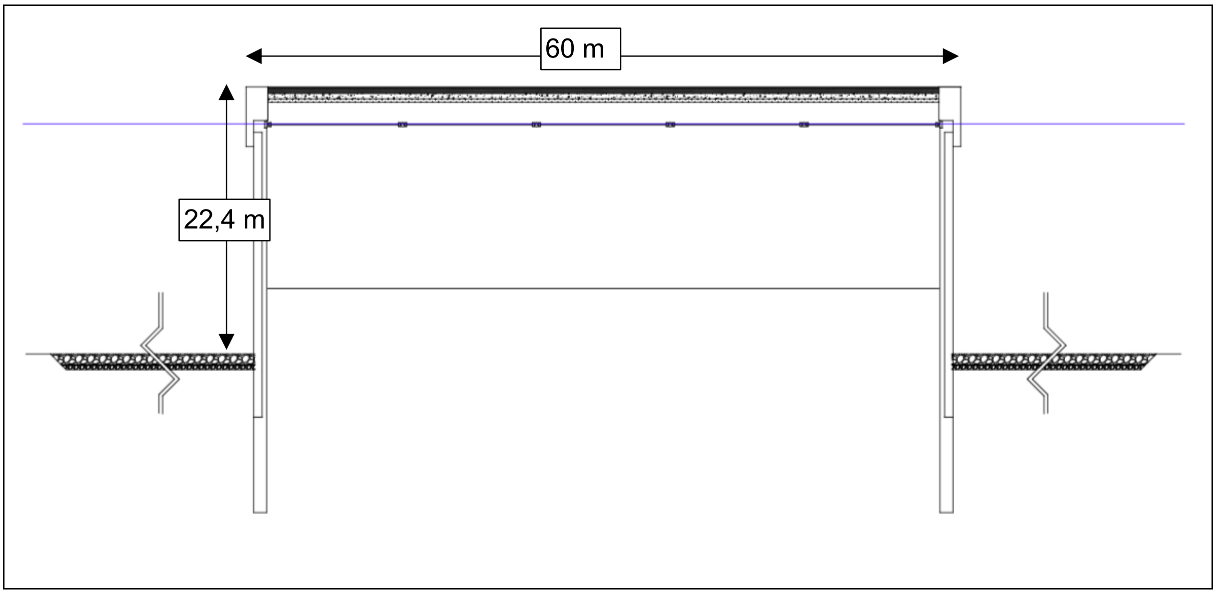



*Figure 15 - Sketch of a Typical Cross Section of the Sheet Piled Combi Wall Design*

### 3.4.5 Construction Sequence

A flow chart illustrating the general construction activities and the sequencing to be followed for the construction of a sheet pile combi wall project as described in this section is detailed in Figure 16.

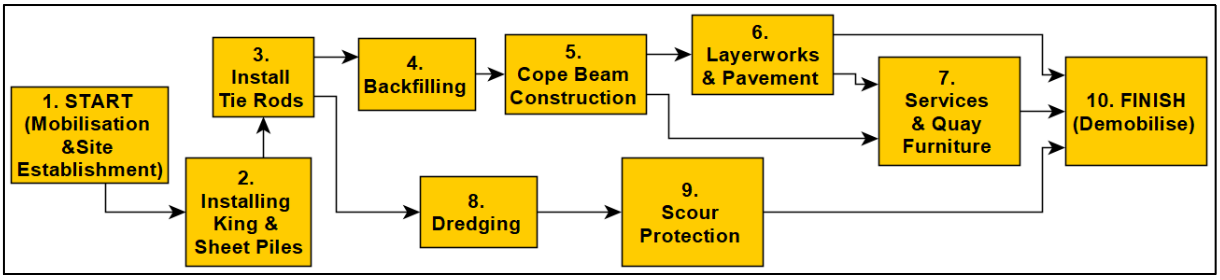



*Figure 16 - Sheet Pile Combi-Wall Construction Sequence*

## 3.5 Open-Piled Suspended Deck

This section describes the design assumptions and calculations that were done to execute a predesign for the open piled suspended deck design option.

### 3.5.1 Limit States and Verifications

The following ULS limit states were verified:

- Vertical bearing capacity of the piles,
- Pile steel section resistance as per EC3 (equivalent stress, shear and buckling analysis),
- Bending resistance for concrete elements (beams and slab).

## 3.5.2 Design Loads

### *3.5.2.1 Vertical Loads to Pile*

The design compressive vertical load ($V_d$) for a single pile was calculated to be 6042 kN as presented in Table 48 (see Appendix D) which is due to the self-weight of the structure and the maximum load of an outrigger from a harbour mobile crane.

### *3.5.2.2 Horizontal Loads*

As per the recommendation of EAU (2012, p. 103), the horizontal load equal to the bollard pull force was used for the purposes of preliminary design. For the design vessels as indicated in Table 11, a corresponding characteristic horizontal action of 1000 kN was used.

### *3.5.2.3 Loads to Slab and Beams*

The piles spacing for the open piled structure was 6 m x 5.8 m which is adopted from a different project designed by Inros Lackner. Load Combination 1 (refer to Figure 11) resulted in the highest bending and shear moments. The self-weight of the reinforced concrete slab and beams was also considered.

## 3.5.3 Design Calculations

### *3.5.3.1 Vertical Bearing Capacity of the Piles*

The calculated skin friction ($q_{s,cal}$) and the calculated base resistance of the piles ($q_{b,cal}$) was determined by using the equations presented in Table 23. These were analysed for a pile with 900mm diameter and 20 mm wall thickness.

*Table 23 - Formulas used to calculate skin friction and base resistance of piles*

| | **Effective Stress Analysis** | **Total Stress Analysis** |
|---|---|---|
| **$q_{s,cal}$ (kN/m$^2$) =** | $\beta$ x $\sigma'_v$ (Fleming *et al.*, 2009, p. 105) | $\alpha$ x $c_u$ (Fleming *et al.*, 2009, p. 109) |
| **$q_{b,cal}$ (kN/m$^2$) =** | $N_q$ x $\sigma'_v$ (Fleming *et al.*, 2009, p. 99) | $N_c$ x $c_u$ (Fleming *et al.*, 2009, p. 108) |
| Notes to adhesion factors: | $\beta = K_s$ x tan(δ') = 1 x tan(δ') (for driven piles) | α (adhesion), assume = 0.5; conservative |
| Notes to bearing capacity factors: | $N_q$ = 13 for ϕ' = 25° (for low plasticity clay) | $N_c$ = 9 (assumed non-sensitive clay) |

The skin friction and base resistance were calculated for five different soil profiles based on the boreholes B7, B7a, B14, B15 and B16. The distribution factors and partial safety factors as per EC7 design approach 2 (refer to Table 13) were applied to the calculated resistance in order to determine the characteristic and the design resistance respectively.

The sandy soil in general becomes very dense and the clay is very stiff at depth. These types of soils tend to dilate when they are loaded (Potts & Zdrakovic, 1999, p. 113). For this reason, it was assumed that a plug would form whilst driving the pile and therefore the entire base cross-sectional area was used to calculate the base resistance.

The calculations of the pile resistances were done by analysing four different scenarios as summarised in Table 24. For each scenario, a certain assumption was made between the ratio of $\delta'$ and ϕ'. Similarly, for each scenario an assumption was made for if the clay layers have an undrained response (short term) or a drained response (long term).

*Table 24 - Scenarios for Vertical Bearing Resistance of Tubular Piles*

| Scenario | $\delta'$ assumption | Clay Layers Strength assumption |
|---|---|---|
| a) | $\delta' = \phi'_{peak}$ | Assumed undrained response with $C_u$=250 kPa |
| b) | $\delta' = 2/3 \times \phi'_{peak}$ | Assumed undrained response with $C_u$=250 kPa |
| c) | $\delta' = 2/3 \times \phi'_{peak}$ | Assume drained response for a low plasticity clay with $\phi'$ = 25° |
| d) | $\delta' = 2/3 \times \phi'_{cv}$* | Assume drained response for a low plasticity clay with $\phi'$ = 25° |
| *Note $\phi'_{cv}$ is the critical state angle of shearing resistance. Assume $\phi'_{cv} = 0.8 \times \phi'_{peak}$ | | |

The calculations with the various scenarios are presented in Appendix D. For each scenario the bearing capacity of the pile was analysed based on the analysis considering all five borehole profiles (B7, B7a, B14, B15, B16) and only considering the profile of the closest borehole, B14, which had a predominantly dense sands profile. The summary of the results of the pile capacity calculations is presented in Table 25. The design pile resistances with the corresponding pile lengths are indicated in the table for the various scenarios.

*Table 25 - Summary of results of Pile Capacity calculations with corresponding minimum required pile lengths*

| Scenario | All Boreholes Considered (B7, B7a, B14, B15, B16) | | Only considered Borehole B14 | |
|---|---|---|---|---|
| | Design Pile Resistance, $R_{cd}$ | Pile Length | Design Pile Resistance, $R_{cd}$ | Pile Length |
| a) | 6 239 kN | 40 m | 6 052 kN | 37 m (toe at -34 m CD) |
| b) | 6 051 kN | 42 m | 6 061 kN | 45 m |
| c) | 6 265 kN | 43 m | 6 160 kN | 42 m |
| d) | 6 159 kN | 46 m | 6 169 kN | 46 m (toe at -43 m CD) |

From Table 25, it can be seen that according to the calculations the estimated minimum required pile length is 37 m and the estimated maximum required pile length is 46 m. These lengths correspond to pile toe levels of -34 mCD and -43 mCD respectively.

It is noted again that these estimations are based on a very limited ground investigation which consisted of drilling boreholes and executing SPT tests. Ideally, the pile length would need to be determined by executing one or more preliminary test piles in combination with an extensive ground investigation that shows the soil stratification over the area under study.

Nevertheless, with reference to the SPT log of the five boreholes attached in Appendix A, it should be noted that the average SPT-N number below -34 m CD is approximately equal to 45. In borehole B14 there were significant layers with SPT-N numbers higher than 50 from a depth of approximately – 25 mCD onwards. These high SPT numbers could imply hard driving conditions and therefore the piles might well achieve capacity at a much shallower depth in some areas.

#### *3.5.3.2 Pile Steel Section Resistance*

The concrete deck on piles acts as a rigid slab that transfers the horizontal and vertical loads to the piles. The mechanism by which the horizontal loads get distributed through the structure can only be accurately modelled with advanced numerical modelling. However, this level of detail was beyond the scope of this thesis and therefore, to verify the bending and shear resistance due to horizontal actions, a number of very simplified assumptions were made:

1) 50% of the design load (=50% x 1500 kN = 750kN) would be absorbed by piles within an 18 m radius from the point where the load was applied. This meant that 18 piles would absorb the load of 750 kN.
2) A set of springs, spaced at one-meter intervals, were used to model the soil stiffness. A subgrade reaction modulus ($n_h$), increasing with depth (z – in meters), of 11 000 kN/m$^3$ was used, corresponding to dense, submerged Sands. The stiffness of each spring (k) was calculated as follows:

$$k = n_h \times z \times pile\ diameter$$

   The spring stiffnesses are indicated in Figure 17 a).

3) The deck of the structure was rigid enough so that the head of the pile was fixed against rotation.

Based on the above assumptions, it was calculated that a single pile (900 mm diameter and 20 mm wall thickness) has a stiffness of 1068 kN/m per pile. It was assumed that a group of 17 piles would therefore have a collective "system" stiffness of 1068 kN/m/pile x 17 piles = 18 162 kN/m.

The resulting displacements, moments and shear forces were calculated using Ftool software. The model and the results are displayed in Figure 17.

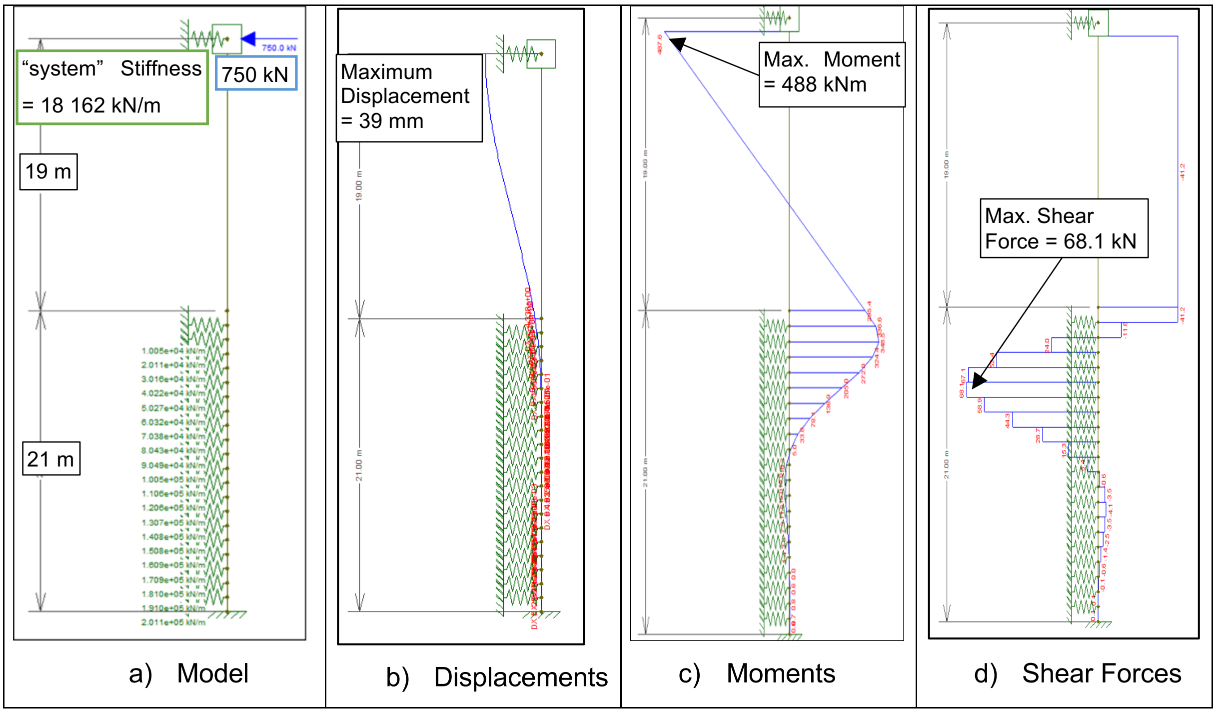



*Figure 17 - Model and Results to Calculate Resistances to Horizontal Actions*

The calculations for equivalent stress, buckling and shear resistance (according to EC3) are presented in Appendix D for a steel pile with a yield stress of 355 MPa.

#### *3.5.3.3 Concrete Beams and Slabs Bending Resistance*

The dimensions for the beam and slabs are presented in Figure 18. They were adopted from the design of a container terminal in a different project done by Inros Lackner.

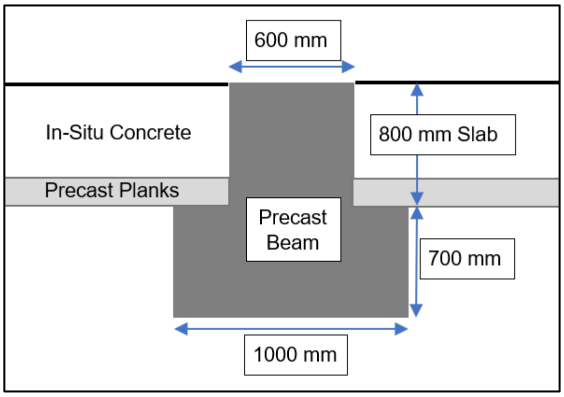



*Figure 18 - Dimensions for Beam and Slab*

The maximum bending moments were determined according to LC1 (see Figure 11). The required steel rebar for the maximum bending moments over the supports and the spans for the slab and beams is summarised in Table 26.

*Table 26 - Maximum Bending Moments over Support and Spans with Corresponding required Rebar for Beams and Slabs*

| Component | Max. BM over Support | Max. BM in Span | Max. Required Rebar over Support | Max. Required Rebar in Span |
|---|---|---|---|---|
| Beams | 3367 kNm | 4344 kNm | 8 x 25 mm diameter | 15 x 28 mm diameter |
| Slabs | 1367 kNm | 1568 kNm | 28 mm diameter at 11 cm spacing | 28 mm diameter at 9 cm spacing |

#### *3.5.3.4 Corrosion Protection*

Each of the piles will be protected from corrosion with a coating and a sacrificial alloy anode as described in Table 27.

*Table 27 - Corrosion Protection for Piles*

| Element | Description |
|---|---|
| Coating | Every pile is to be painted with three coats up to approximately one meter below seabed level. The coats are as follows, and were based on the specifications of an existing project by Inros-Lackner:<br>• First Coat: 50 microns SikaCor Zinc R (primer based on epoxy resin)<br>• Second Coat: 500 microns SikaCor SW-500 (based on epoxy resin)<br>• Third Coat: SikaCor EG-5 (topcoat based on polyurethane) |
| Alloy Anode | 109 kg sacrificial alloy anode per pile. Adapted to from the specifications of an existing project by Inros-Lackner. |

### 3.5.4 Dimensions

Drawings for the design detailing all the relevant dimensions are presented in Appendix D. The dimensions of the main components are summarised in Table 28. A sketch of a typical cross section of the Open Piled Suspended Deck is presented in Figure 19.

*Table 28 - Open Piled Structure: Summary of Dimensions of Main Components*

| | | | |
|---|---|---|---|
| **Tubular Piles:** | | **Precast Planks:** | |
| Diameter = | 914 mm | Length x Width x Height = | 5.2 m x 2.4 m x 0.25 m |
| Wall Thickness = | 20 mm | **Precast Beams:** | |
| Length = | 37 m to 46 m | Length = | 4.5 m |
| **Coping Beam:** | 11.7 $m^3/m$ | Volume = | 5.31 $m^3$ |

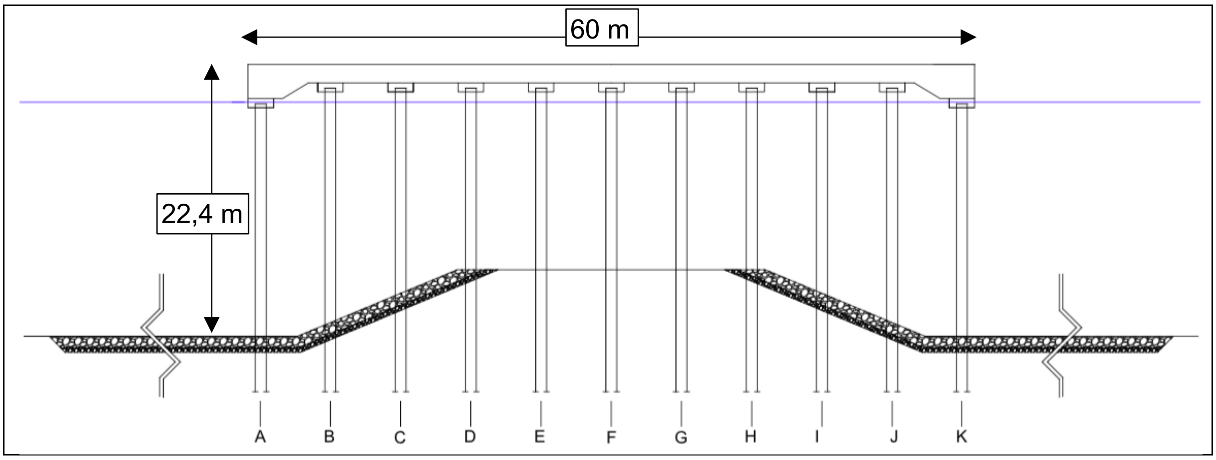



*Figure 19 - Sketch of Typical Cross Section of Open Piled Suspended Deck Design*

### 3.5.5 Construction Sequence

A flow chart illustrating the general construction activities and the sequencing to be followed for the construction of an open piled suspended deck project as described in this section is detailed in Figure 20.

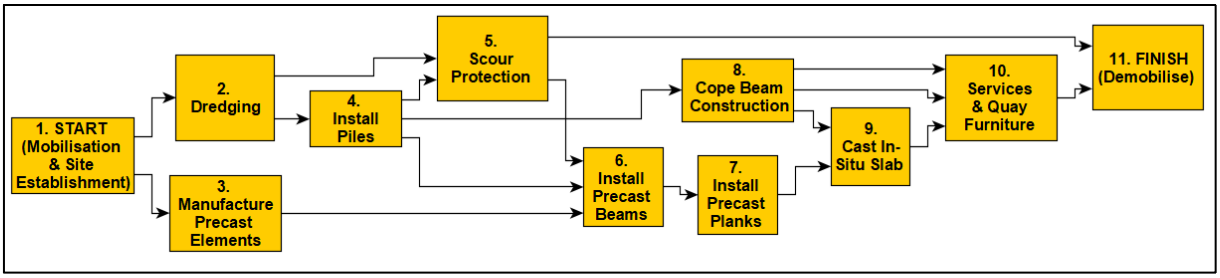



*Figure 20 - Construction Sequence for Open-Piled Structure*

# 4. Goal and Scope of the LCA

## 4.1 Goal

The goal of conducting this study is to estimate the carbon footprint of various quay wall structure types, expressed in metric tons of $CO_2e$ in order to determine the differences in carbon footprint between the various designs and construction methods.

In accordance with ISO 14067, the intended application, reasons for carrying out the CFP study and the intended audience are clearly defined in Table 29.

*Table 29 - Application, Reasons and Audience definition as per ISO14067*

| | |
|---|---|
| **Intended Application** | The intended application is that this study can add to the body of knowledge on global warming potential of quay wall construction projects and therefore be used as a reference point to assist designers and planners in finding innovative solutions for reducing the carbon footprint of quay wall structures. |
| **Reasons** | The reason for carrying out this CFP study is to determine the differences in carbon footprints between various quay structure designs and construction methods. |
| **Intended Audience** | The intended audience are civil engineers, designers, contractors and planners involved in harbour design, construction and operation. |

## 4.2 Scope

### 4.2.1 System

The system under study is a pier that will be used as a container terminal in a port in sub-Saharan Africa. Its functions are to provide safe and efficient berthing opportunities for container vessels, defined in Table 11 (refer to Section 3.2.4). It should also function as a platform for container handling equipment to enable the safe and efficient loading and unloading of container vessels.

Three different quay wall designs have been considered: 1. Concrete Caissons, 2. Sheet Pile Combi-Wall and 3. Open Piled Suspended Deck. These were described in detail in Chapter 3 of this thesis.

### 4.2.2 Functional Unit

The functional unit for this study is metric tons (t) of $CO_2e$ / m of berthing length provided for a quay wall structure with a design life of 50 years.

### 4.2.3 System Boundary

The life cycle stages that will be considered as part of this study are the production stage (A1-A3), transportation (A4) and the construction stage (A5). Refer to Table 2 (Section 2.1) for a more detailed definition of the life cycle stages.

The use stages of the life cycle (B1 – B7) were excluded from this analysis since the goal of this CFP study was to determine the carbon footprint of the actual structures and not the carbon emissions associated with the use of these structures. Since the structures would each fulfil the same function, namely a port container terminal, it can be reasonably assumed that methods of terminal operation for all three options would be similar and therefore the carbon footprint associated with the use stage would not differ significantly.

Port structures are often left in place, or only partially demolished, at the end of their life spans. For example, for a combi wall structure the old combi wall is typically left in place and a new wall is built in front of it. Some demolition would likely be necessary in order to integrate the new structure with the old structure. However, the extent of the demolition of the existing structure depends greatly on the design of the new structure. Therefore, the end of a life stage was also excluded from this study.

The detail and extent of temporary work (e.g. piling frames, formwork, scaffolding, site office containers and so on) is determined during the tender and construction stage by the contractor as it is specific to each project. It was beyond the scope of this thesis to design and quantify necessary temporary works and therefore they were omitted from the CFP study.

The various processes that were considered as part of the system boundary are summarised in Table 30.

*Table 30 - Processes Considered as part of the System Boundary*

| Process | Comment | Include/Excl. |
|---|---|---|
| 1. Mobilisation | Major equipment such as barges, cranes, piling hammers mobilised from overseas. | Included |
| 2. Dredging and Reclamation | This includes dredging and dumping of dredged materials. Reclamation includes the dredging, transporting and placing of fill material to form the new pier. | Included |
| 3. Quay Structure | This includes all the structural components for the various quay structure designs, for example, piles, caisson, precast concrete elements, corrosion protection and so on. | Included |
| 4. Scour Protection | Rock scour protection as per the designs. | Included |
| 5. Services & Quay Furniture | 5.1 Services: Lighting, firefighting system, electricity supply, water supply and so on.<br>5.2 Furniture: Road furniture, signalisation, buildings.<br>Since the services and the furniture will be approximately the same for all the different designs these have been excluded as they will not influence the conclusions of the CFP. | Excluded |
| 6. Berth Equipment | Fenders, bollards, safety ladders, hydrants, navigation aids. Will be approximately the same for the different designs and were therefore not included. | Excluded |
| 7. Earthworks and Pavement | Includes the layer works and pavement. | Included |
| 8. De-Mobilisation | De-mobilisation of major equipment to country of origin. | Included |

### 4.2.4 Data Quality Requirements

According to ISO 14067, the data quality should be characterised according to the following criteria:

a) Time-related coverage: age of data and the minimum length of time over which data should be collected;
b) Geographical coverage: geographical area from which data for unit process should be collected;
c) Technology coverage: specific technology or technology mix;
d) Precision: measure of variability of each data value.

The purpose of characterising the data quality according to these parameters is to develop data quality indicators which can help the LCA practitioner to quantitatively assess short comings in the data. However, the data used in this master thesis were not characterised in terms of the above data quality requirements, as this level of detail is outside the scope of this thesis.

# 5. Life Cycle Inventory

## 5.1 Introduction

In this chapter, the Life Cycle Inventory analysis (LCI) for the three designs (caissons, combi-wall and open piled structure) is described. This includes the methods that were used to quantify the amount of materials, travel distances and machine operating hours for each of the designs as well as the emission factors assigned to each of these processes.

## 5.2 Material Quantities

A concrete mix for a C35/45 grade concrete as described in Table 14 was used for all concrete elements of all three designs. The emission factors used for the various concrete components (binder, aggregate, sand, plasticizer) and steel reinforcing are described in Appendix E.

The material quantities were calculated based on the designs and drawings as described in Chapter 3. The tables with the quantities of materials for all three designs is also included in Appendix E. The emission factors (EF's) corresponding to Life Cycle stages A1-A3 (production) and A4 (transportation) that were used are also detailed in these tables.

## 5.3 Transport Distances

For the various materials certain transport distances were assumed. The distances as well as the applicable materials are summarised in Table 31. For the delivery of materials from a quarry or factory to site, the return trip distance was used since it could be assumed that a truck would deliver its load to site and return to the quarry directly and not share deliveries on the same trip.

For each of the modes of transport described in Table 31, the corresponding emission factors are detailed in Appendix F.

*Table 31 - Transport Distances for LCI*

| Item | Distance | Comment |
|---|---|---|
| Quarry to site | 50 km | Used for scour rock, gravels, layer works, aggregates, sands. Return trip = 100km |
| Cement factory to site | 30 km | Transporting Portland Cement from factory to site. Return trip = 60 km. |
| Steel factory to site | 25 km | Transporting reinforcing steel from factory to site. Return trip = 50 km. |
| International Shipping & Mobilisation | 9825 km | Used as the shipping distance for materials shipped from overseas for example steel piles, fly ash, slag, geotextiles. Also used as the mobilisation distance for mobilisation of construction equipment from overseas. |

For the mobilisation, it is common practise that a tugboat tows a barge loaded with the equipment needed by the contractor. Therefore, the emission factors associated with the operation of a tugboat were calculated as per the recommendations of the IPCC background paper on Emissions from Transportation-water-borne Navigation (Jun *et al.*, 2002). These calculations are also detailed in Appendix F.

## 5.4 Machines

The machine operating hours were considered under the construction life cycle stage (A5). In order to determine the required operating hours of the various machines, an outline construction programme was developed, based on the construction sequences detailed in Chapters 3.3.5, 3.4.5 and 0. The programmes were developed by the author based on his previous experience of working on similar quay wall construction projects. The required production rates were estimated in order to achieve a construction programme of approximately two years for each of the designs.

Once the duration of each activity was estimated, the required machines were allocated to each activity. Therefore, the number of weeks required for each machine could be estimated. It was assumed that construction activities would occur six days per week with 10-hour days. For each machine, a daily usage factor (DUF) was assumed. This represented the fraction of the day where the machines were operating. For example, it was assumed that a generator would only operate half a day, corresponding to a DUF of 50%. Accordingly, the machine operating hours were calculated as per Equation 2:

*Equation 2*

$$h = w \times 6 \times 10 \times DUF$$

Where:

- h = total hours of machine operation over the project time period
- w = total amount of weeks of machine on site
- 6 = six days per week
- 10 = ten hours per day of construction activities
- DUF = daily usage factor in % (value assumed for each machine)

The construction programmes as well as the total machine operating hours are indicated in Appendix G.

A different method was used to calculate the operating hours of concrete mixer trucks. It was estimated that each mixer truck with six cubic meters capacity was able to process its load and return to the batch plant in one hour. Therefore, for each cubic meter of concrete on the project $\frac{1}{6}$ hour of concrete mixer truck operation was considered.

The emission factors used for the machines stem from the Ecoinvent 3 Database included in SimaPro. An emission factor was chosen based on the machines rated power as well as the machines load factor. A load factor represents the proportion of the actual rated power that is used by a machine. Since machines operate at varying speeds and loads, they usually do not operate at the rated power for long periods (US EPA , 2010, p. 8). For example, at a load factor of 40 percent a machine with an engine power rated at 100 kW (kilowatt) would be producing an average of 40 kW of power. The recommendations as per the United States Environmental Protection Agency (US EPA , 2010) for load factors were followed for deciding on the relevant load factor. Table 32 summarises the emission factors that were used for the construction machinery.

*Table 32 – Summary of Emission Factors used for Construction Machinery*

| Emission Factor | Description |
|---|---|
| 18,3 kg $CO_2$e/h | Ecoinvent 3 Dataset “Machine Operation Diesel >= 18,64 and < 74,57 kW, generator” |
| 20,0 kg $CO_2$e/h | Ecoinvent 3 Dataset, "Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state load factor” |
| 31,1 kg $CO_2$e/h | Ecoinvent 3 Dataset, “Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor” |
| 81,4 kg $CO_2$e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW, steady state load factor" |
| 149,0 kg $CO_2$e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW, High load factor" |

The tables in Appendix G indicate which emission factor was used for each specific machine as well as the rated power of the various machines.

It should be noted that there is a considerable degree of uncertainty when it comes to the emissions that can be expected from construction equipment. This is because of a large amount of factors that influence the emissions, such as the equipment’s make and conditions, degree of maintenance, equipment operations and operating conditions (Fan, 2017). These are summarised in Figure 21.

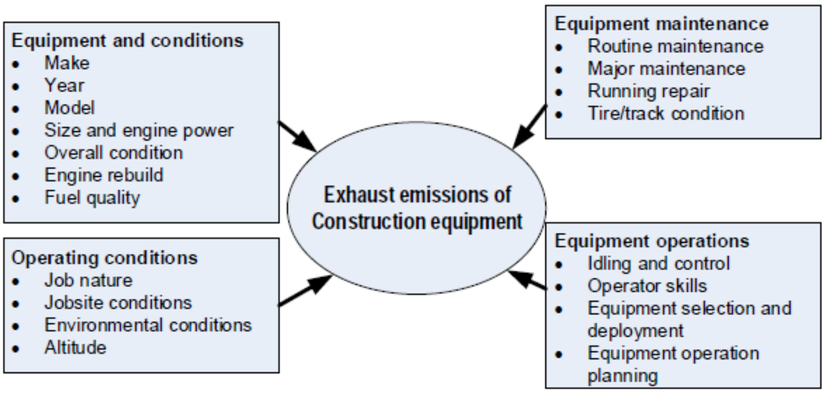



*Figure 21 - Factors influencing emissions from construction equipment adopted from Figure 1,Fan (2017)*

From the tables in Appendix G, it can be seen that the larger machines used in the construction of quay walls have a rated power output ranging from approximately 119 kW (Cat 930G Loader) to 247 kW (Crawler Crane) and even 444 kW (Vibro Hammer). In this thesis, a simplified approach was taken by using the emission factors displayed in Table 32 for machines with rated power outputs greater than 74,57 kW. Therefore, it is noted that the actual $CO_2$e emissions could deviate significantly from the emissions calculated for the construction Life Cycle stage (A5) in this thesis. However, due to the many variables influencing construction equipment emissions, as described above, this approach was considered sufficient to get an estimate of the emissions from the construction life cycle stage (A5) in order to compare this to the other life cycle stages (A1-A4).

# 6. Carbon Estimates (Life Cycle Impact Assessment)

## 6.1 Introduction

In this chapter, the results of the carbon footprint calculations for the various quay wall designs and construction methods will be presented. The contribution from each life cycle stage to the total carbon footprint will also be quantified. In the first part of this chapter, the estimates for the baseline carbon footprint are detailed. In the second part of this chapter, the results of the sensitivity analysis are presented which show how the carbon footprint is affected when certain parameters are changed.

The carbon footprint will be quantified in the functional unit of metric tons of $CO_2e$ per meter of berthing length provided by the pier (t $CO_2e/m$). With reference to the design drawings in Appendix B, Appendix C and Appendix D, the berthing length provided by the pier amounts to approximately 800 m, as indicated in Figure 22.

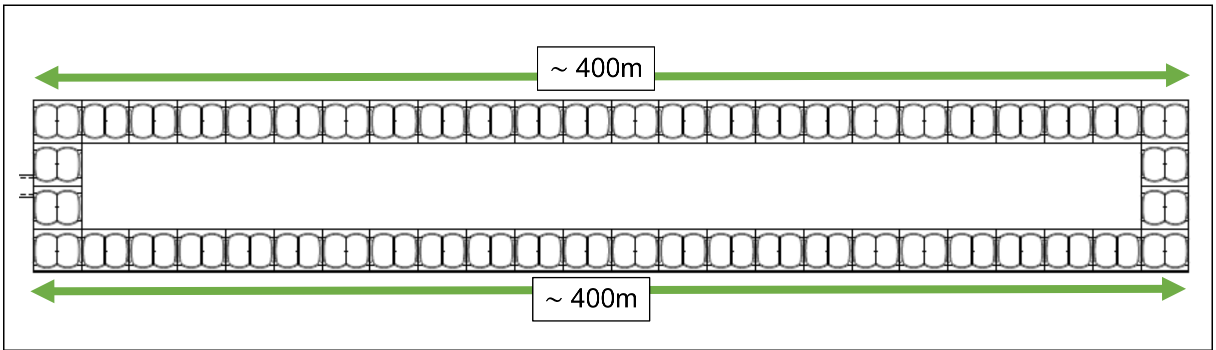



*Figure 22 - Plan view of Caisson design option with green arrows indicating the berthing length provided by the pier*

## 6.2 Baseline Carbon Estimates

The following assumptions were made to estimate the baseline carbon footprints:

- The emission factor used for steel reinforcing was as per the global World Steel Association LCA dataset included in the SimaPro Industry Data database, namely 1930 kg $CO_2e/t$;
- The emission factor used for the steel sheet piles as per the global World Steel Association LCA dataset included in the SimaPro Industry Data database, for steel sections, namely 1550 kg $CO_2e/t$;
- The emission factor used for the spirally welded tubular piles as per the global World Steel Association LCA dataset included in the SimaPro Industry Data database, namely 2780 kg $CO_2e/t$;
- For the concrete caissons a steel reinforcement content of 210 kg/m$^3$ was used (Transnet, 2019);
- All concrete components were made according to the concrete mix design detailed in Table 14 (Section 3.2.8).

The baseline carbon footprint estimates of the alternative quay wall designs in metric tons of carbon dioxide equivalent per linear meter of berthing length provided (t $CO_2e/m$) are displayed in Figure 23. The contribution from the various life cycle stages, production (A1-A3), transport (A4) and construction (A5) are also detailed in the same figure.

For comparison purposes when referring to the results in Figure 23, the carbon footprint for one return flight between London and New York is approximately 986 kg $CO_2$ per person (Kommenda, 2019). This implies that the $CO_2e$ emissions of constructing one meter of a concrete caisson quay wall, for example, is equivalent to over 60 return flights between London and New York for one person.

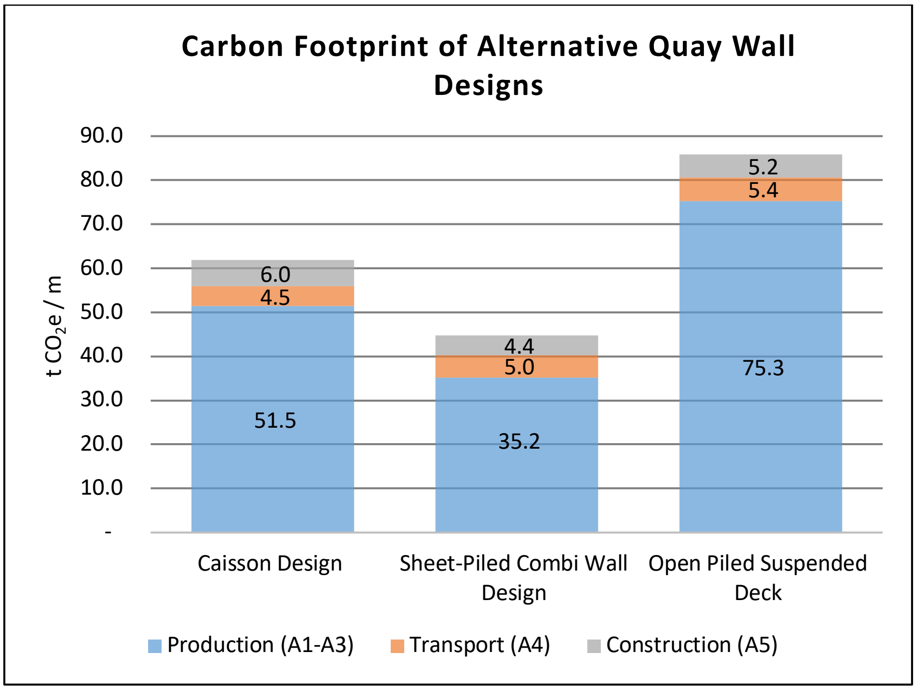



*Figure 23 - Baseline carbon footprint estimates of alternative quay wall designs in metric tons of $CO_2e$ / m*

The Sankey diagrams indicating the cumulative contribution of each process to the baseline carbon footprint for each of the designs are displayed in Appendix H. These Sankey diagrams were plotted with a 2% cut-off, meaning that any process that contributed less than 2% to the total carbon footprint was not displayed on the network. The thickness of the red arrows in the diagrams, in Appendix H, are proportional to the contribution of each specific process.

## 6.3 Sensitivity Analysis

The following parameters were investigated for the sensitivity analysis:

- Content of recycled steel for the steel reinforcing, sheet piles and tubular piles;
- The content of steel reinforcing for the caissons;
- The binder composition was adjusted for different amounts of fly ash and ground granulated blast furnace slag (GGBS);
- The length of the tubular piles.

The assumptions for each of these parameters are discussed below and the results presented afterwards.

### 6.3.1 Recycled Steel Content

#### *6.3.1.1 Recycled Steel Reinforcing*

The effects of using 85% recycled steel content for the steel reinforcing were investigated for all three design options. For steel reinforcement with a recycled content of 85%, an emission factor of 1200 kg $CO_2$e/t was used. The emission factor was taken from the Inventory of Carbon and Energy (ICE) version 3 (Hammond & Jones, 2019) which is based on World Steel Association data.

The effects of using an 85% recycled steel content for the rebar on each of the design options is presented in Figure 24, Figure 25 and Figure 26.

#### *6.3.1.2 Recycled Steel Sheet Piles*

For recycled steel in the sheet piled combi wall, the Environmental Product Declaration (EPD) from Arcelor Mittal for its sheet piles was used. The emission factor from the EPD for LCA stages A1-A3 is 937 kg $CO_2$e/t. The EPD states that the scrap steel content is 909 kg of scrap steel per ton of sheet pile produced. Assuming a ratio of scrap input to steel output (yield ratio) of 1,092 (Broadbent, 2016), this would translate to a recycled content of approximately 85%.

#### *6.3.1.3 Recycled Tubular Piles*

For the welded tubular piles with a recycled steel content of approximately 85%, an emission factor of 1470 kg $CO_2$e/t was used. This emission factor was based on the ICE version 3 database (Hammond & Jones, 2019) which is based on World Steel Association data.

### 6.3.2 Caisson Steel Reinforcement Content

The baseline steel reinforcement content for the concrete used in the caissons was 210 kg/$m^3$. This value can vary between approximately 100 kg/$m^3$ up to 300 /$m^3$, in order to satisfy crack width limitations and requirements for secondary reinforcement (Voorendt *et al.*, 2011). For this reason, the effect of adjusting the baseline rebar content to 210 kg/$m^3$ +- 40 kg/$m^3$ was investigated. The results are presented in Figure 24.

### 6.3.3 Binder Composition

In marine concrete, it is important to design a durable concrete in order to prevent corrosion of the steel reinforcement. This is particularly important due to the aggressive marine (saltwater) environment. The two main ways in which the binder composition and the concrete mix design can influence the durability of the concrete is by:

- preventing chloride ingress and,
- limiting the heat of hydration in order to reduce early age thermal cracking.

Fly Ash and GGBS are cementitious materials with suitable characteristics as they both reduce chloride ingress and reduce temperature rise during hydration (BSI, 2013b, p. 9 & 11).

As detailed in the baseline mix design in Table 14 (Section 3.2.8), the binder content was made up of 85% Portland cement and 15% Fly Ash. British Standards BS 6349-1-4:2013 (BSI, 2013b) recommends a maximum of 35% Fly Ash and 65% GGBS as part of the binder content.

Therefore, for the purposes of the sensitivity analysis, the effects of using 35% Fly Ash or 65% GGBS in the binder for all concrete components in the three designs was investigated. The results are presented in Figure 24, Figure 25 and Figure 26.

### 6.3.4 Tubular Pile Length

For the baseline calculations, a tubular pile length of 37 m was used as per the design calculations (see Section 3.5). However, the existing ground investigation was not very detailed and was not executed in the exact location for where the new pier would be built. Some of the boreholes had thick layers of very dense sands, underlain by very stiff clays. For such layers, the pile length could be even shorter than 37 m and therefore the effects of reducing the average length of the tubular piles by 3 metres from 37m to 34m was investigated. The results are presented in Figure 26.

### 6.3.5 Sensitivity Analysis Results

Figure 24, Figure 25 and Figure 26 show the results of the sensitivity analysis. For comparison purposes the first bar in each of these figures shows the result of the baseline carbon footprint LCA. The following bars then show how the carbon footprint is affected when only one parameter is adjusted. The final bar in each figure, labelled as “Total Optimisation” shows the reduced carbon footprint when all the following parameters are combined:

- All concrete components with an 85% recycled steel rebar content;
- For piles (sheet piles or tubular piles) approximately, 85% recycled steel content;
- Binder content with 65% GGBS and 35% Portland Cement content;

In Figure 24, the total optimisation result considers concrete caissons with a steel reinforcement content of 210 kg/m$^3$ as per the baseline.

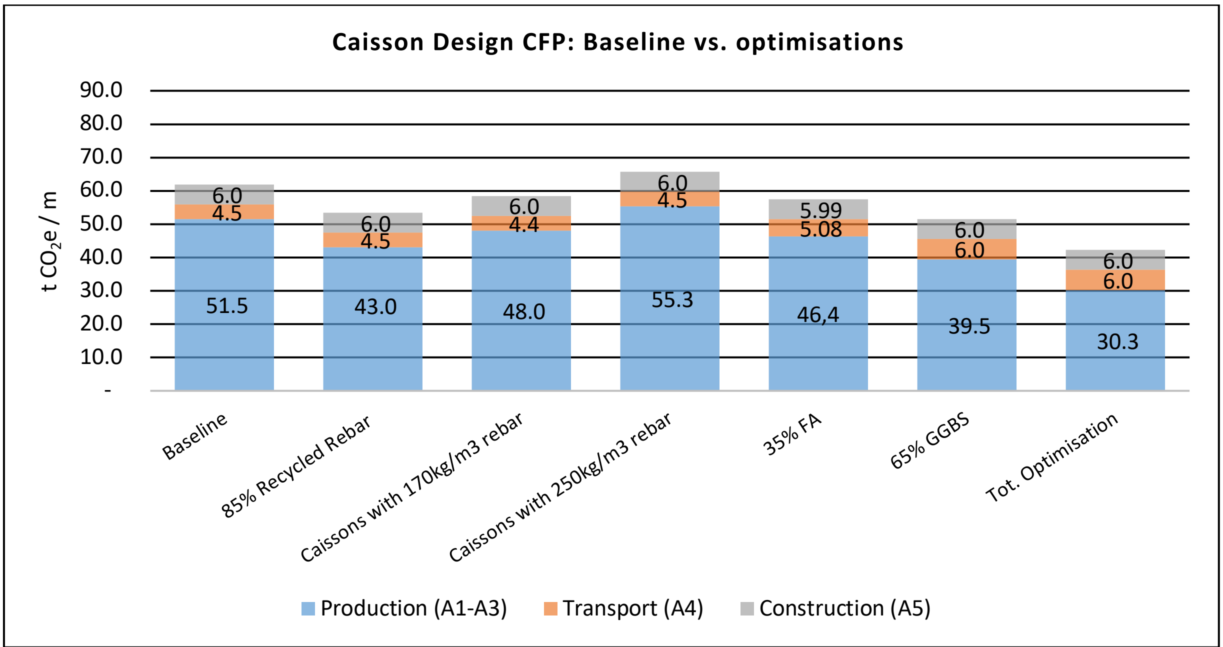



*Figure 24 - Caisson Design Carbon footprint results in metric tons $CO_2$e/m of berthing length provided*

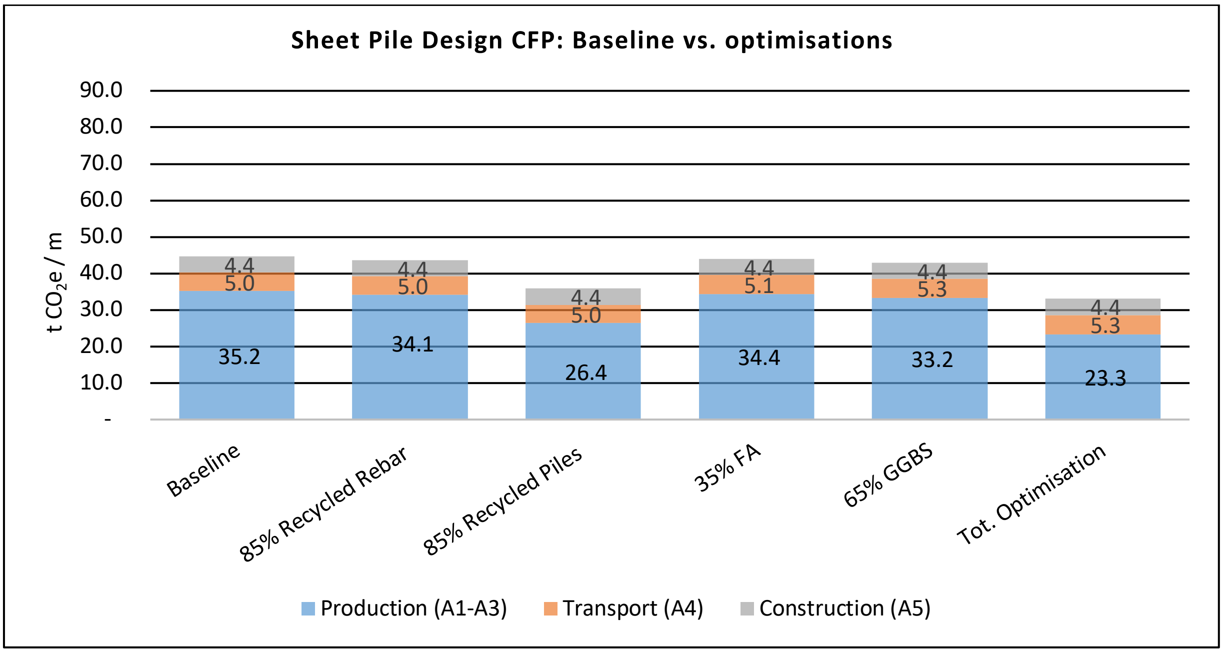



*Figure 25 - Sheet Piled Combi-Wall Design Carbon Footprint in metric tons $CO_2$e/m of berthing length provided*

In Figure 26 the total optimisation result considers tubular piles with a length of 34m.

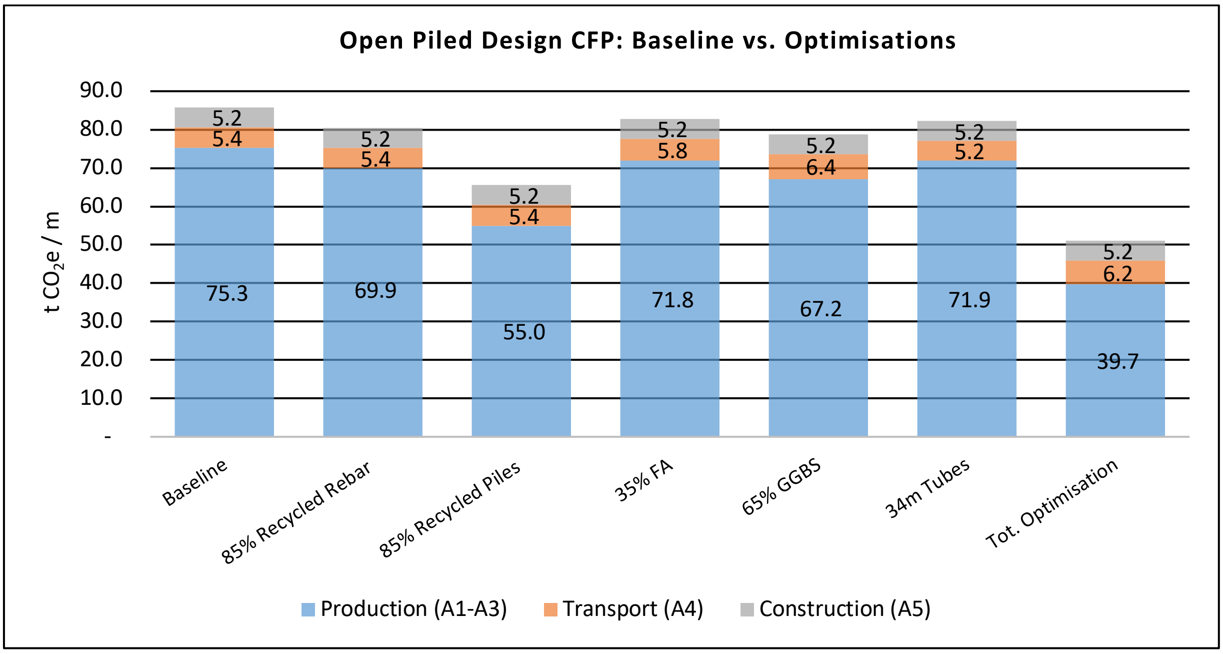



*Figure 26 - Open Piled Suspended Deck Design Carbon Footprints in metric tons CO2e/m of berthing length provided*

### 6.3.6 Sensitivity Analysis Summary

A summary of the results of the sensitivity analysis is presented in Figure 27. In this figure the baseline results are plotted against the results with "total optimisations". In Table 33, the parameters that were considered under the "total optimisations" are summarised.

*Table 33 - Parameters considered under total optimisations for each design option*

| Design | 85% Recycled Rebar | 85 % Recycled Piles | 65 % GGBS in Binder | 34m tubular piles | Caisson Steel reinforcement |
|---|---|---|---|---|---|
| **Caisson** | ✓ | ✓ | ✓ | Not Applicable | 210 kg/m$^3$ |
| **Sheet Pile Wall** | ✓ | ✓ | ✓ | Not Applicable | Not Applicable |
| **Open Piled Deck** | ✓ | ✓ | ✓ | ✓ | Not Applicable |

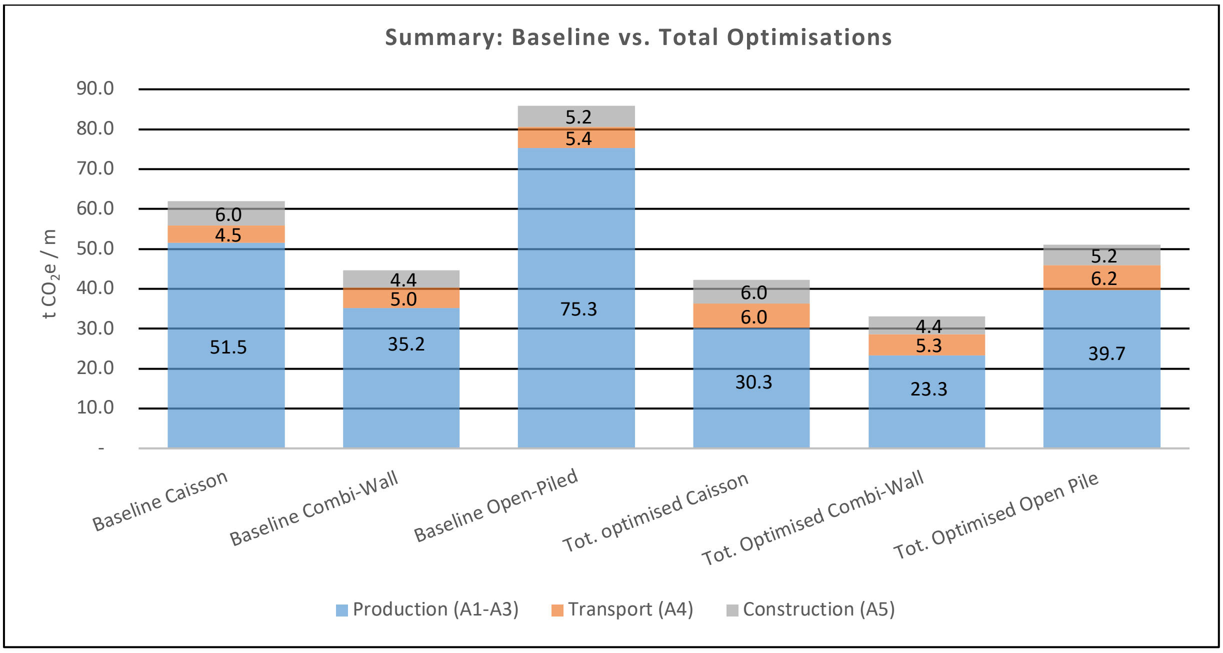



*Figure 27 - Summary of the baseline results plotted against the total optimisations (from sensitivity analysis) results*

# 7. Discussion and Interpretation

## 7.1 Introduction

According to ISO 14067 (ISO, 2018), the interpretation phase of a CFP study should:

- Identify significant contributors to the carbon footprint, for example specific life cycle stages or specific processes;
- Include a sensitivity analysis of significant inputs;
- Evaluate the completeness and consistency of the CFP study;
- Identify limitations of the CFP study, and
- Formulate conclusions and recommendations.

In this chapter, the results that were presented in Chapter 5 (Life Cycle Inventory) and Chapter 6 (Life Cycle Impact Assessment) are discussed and interpreted.

First, the results of the baseline carbon footprint LCA will be analysed and the significant $CO_2$ contributors will be identified and discussed. In the next section, the results from the sensitivity analysis will be interpreted.

This is followed by a rough cost estimate which was done in order to get an idea of the relative costs between the different design options and compare this to the estimated carbon footprint.

The completeness and consistency of the CFP were evaluated and are discussed in the following section along with the limitations of the study.

Finally, in the last section of this chapter the main points of the results and interpretation are summarised, and recommendations are made.

## 7.2 Discussion and Interpretation of Results

### 7.2.1 Baseline Results Discussion

In Figure 23, the results of the baseline carbon footprint LCA are displayed. From the figure it can be deduced that the sheet piled combi-wall has the lowest carbon footprint, followed by the caisson design and the open piled suspended deck option having the highest carbon footprint. The sheet piled combi-wall has a 48% lower carbon footprint than the open piled deck and the caisson option has a 28% lower carbon footprint than the open piled deck structure.

From Figure 23, it is also clear that the life cycle stages for production (A1-A3) are the major contributing stages for the carbon footprint of each of the three design options:

- For the caisson design the production stage contributes 83%;
- For combi-wall design the production stage contributes 79%, and
- For open piled deck design the production stage contributes 88%.

The network diagrams in Appendix H assist in identifying the sources of major contributors to the carbon footprint within each design option and in all three design options these can be identified as being from

Portland cement (in concrete) and steel. These are summarised in Table 34 with the contribution, in percentage, of each source to the total carbon footprint.

*Table 34 - Major Sources of $CO_2$ in the Baseline LCA for each Design Option, contribution to the total Carbon Footprint Indicated in Percent*

| Design | Portland Cement | Steel Reinforcing | Sheet and King Piles | Tubular Piles | Total steel and Portland Cement contribution |
|---|---|---|---|---|---|
| **Caisson** | 35 % | 36 % | Not Applicable | 2 % | **73 %** |
| **Combi-Wall** | 8 % | 6 % | 51 % | Not Applicable | **65 %** |
| **Open Piled Deck** | 17 % | 17 % | Not Applicable | 50 % | **84 %** |

It is not surprising to see that steel and Portland cement are the major contributors since the manufacture and processing of these materials is a very energy intensive process and accordingly, they have high carbon emission factors.

One of the more surprising results from the baseline LCA is that the open piled suspended deck structure has the highest carbon footprint, since this is the lightest structure by mass, as can be seen in Table 35. The details of how the masses in Table 35 were calculated are presented in Appendix E, Table 58.

*Table 35 - Summary of total material masses (in metric tons) of each design option*

| Material: | Caisson | Combi-Wall | Open Piled |
|---|---|---|---|
| Concrete | 124.877 | 20.350 | 82.509 |
| Steel Rebar | 9.547 | 1.197 | 5.941 |
| Tubular Piles | 370 | - | 12.396 |
| Sheet Piles and King Piles | - | 11.882 | - |
| Tie Rods and Connectors | - | 834 | - |
| Dredging | 1.398.400 | 1.043.556 | 1.185.144 |
| Backfill | 718.170 | 603.738 | - |
| Gravel (Joints and Bed) | 71.606 | - | - |
| Scour Protection | 105.210 | 105.210 | 164.088 |
| Layer works & Pavement | 63.404 | 138.300 | - |
| **TOTAL Mass (tons)** | **2.491.583** | **1.925.066** | **1.450.078** |

With reference to Table 35 it can be seen that the open piled structure has about four times more concrete than the combi-wall design and about 1,7 times more steel than the caisson design. The combination of these two factors is part of the reason that the open piled deck has the highest carbon footprint out of the three designs. Another point that should be considered is that the emission factors (kg $CO_2e$/t of steel) for the sheet piles was significantly lower than that of the welded tubular piles namely, 1550 kg $CO_2e$/t vs 2780 kg $CO_2e$/t respectively. These emission factors were the world averages taken from the SimaPro IndustryData database which uses the World Steel Association values. It was not clear why there were such significant differences between the two values. However, it is likely that one of the major reasons for this difference is that globally more scrap is used in the production of hot rolled steel sections (such as sheet piles) than for spirally welded tubes. In addition to this, the process of manufacturing a spirally welded tube involves more steps than the hot rolling of a steel section. Refer to Figure 28 for a diagram illustrating the production process of spirally welded steel pipes and the various steps included in the process.

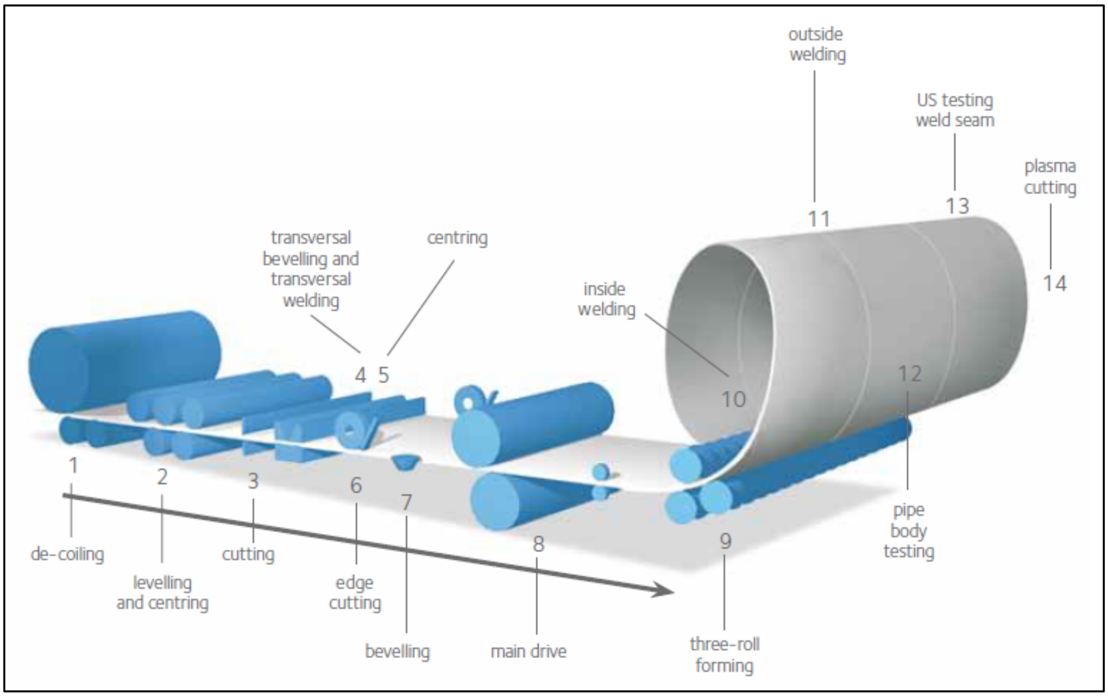



*Figure 28 - Production Process of Spirally Welded Pipes, adopted from Arcelor Mittal Brochure on Spirally Welded Steel Pipes (Arcelor Mittal, 2010)*

## 7.2.2 Sensitivity Analysis Results Discussion

All of the results of the sensitivity analysis are displayed in Figure 24, Figure 25 and Figure 26 and should be referred to when reading this section.

### *7.2.2.1 Recycled Steel Content*

Steel Reinforcing

In Figure 24, it can be seen that the baseline carbon footprint for the caissons was reduced by approximately 14% when using 85% recycled steel reinforcing. For the combi-wall, the reduction was only about 2,5% (Figure 25) which can be explained by the relatively low concrete volume in the design. The reduction for the open piled structure was approximately 6% compared to its baseline carbon footprint (Figure 26).

Steel Piles

Since the caisson design contains only very few piles (approx. 370 tons), the effect of using recycled steel in the tubular piles in this design option are negligible. For the sheet piled combi-wall, the carbon footprint was reduced by approximately 20% (compared to the baseline) when using piles with a recycled steel content of about 85%. For the open piled structure, the reduction was approximately 24% compared to the baseline.

Scrap Steel Supply

Arcelor Mittal (2019) states that currently scrap steel can only supply about 22% of global demand for steel and predicts that by 2050 this figure may be between 40% and 50%. In the developed world, the demand for steel has almost plateaued, while in the developing world the demand is still growing as economies grow rapidly and infrastructure expands. Therefore, it is estimated that global steel production will continue to depend on primary resources (iron ore) until about 2100 when global steel demand is expected to stabilise and can be fully satisfied by scrap steel (Arcelor Mittal, 2019). Therefore, the steel industry is focusing on additional methods for reducing the carbon footprint of steel such as yield improvements, energy efficiency and adoption of low-emission technologies (Arcelor Mittal , 2019). However, the exact time horizon for implementation and effectiveness of these practices remain to be seen.

Considering the limited supply of scrap steel as described above, it may not be realistic to use a recycled steel content of 85% as was done in the sensitivity analysis of this study. For project managers, designers and contractors it is therefore important to understand the steel supply chain to be able to estimate the carbon footprint of steel used on projects.

When quay walls are upgraded, significant quantities of steel from an existing quay structure are usually left in place. For example, when a new sheet piled combi-wall is installed, the existing sheet pile structure is typically left in place. A point of discussion may be to specify further demolitions, in projects, in order to recover larger amounts of existing steel elements. For example, project specifications could include the requirement to extract existing steel piles to be salvaged for recycling. The feasibility of such operations may make them unattractive to clients as they may be associated with extra costs. However, the actual life cycle carbon savings that can be achieved through this recycling could be a topic for further investigation within a Life Cycle Assessment approach in order to help incentivise the recovery of steel elements.

#### *7.2.2.2 Caisson Steel Reinforcement*

The steel reinforcing content for the caissons is strongly influenced by the need to limit crack widths and the amount of secondary reinforcement that is specified. The steel rebar content can therefore vary between approximately 100 kg/m$^3$ and 300 kg/m$^3$ (Voorendt *et al.*, 2011). In order to investigate the effect of different steel reinforcement contents, the carbon footprint was calculated for reinforcement contents of 170 kg/m$^3$ and 250 kg/m$^3$ which correspond to the baseline reinforcement content (210 kg/m$^3$) ±40 kg/m$^3$. The change in the reinforcement content in this range results in a carbon footprint change of approximately ±6% respectively, compared to the baseline.

It is worthwhile to note this variance since the steel reinforcing content of a caisson will be different for each design as it is influenced by the loading conditions, shape, design codes and the structural engineer's approach to the design.

#### *7.2.2.3 Binder Composition*

As described in Section 6.3.3, the effect on the carbon footprint of the alternative quay wall structures was investigated by changing the binder composition for different amounts of Portland cement, Fly Ash (up to 35%) and GGBS (up to 65%) content. These results are presented in Figure 24, Figure 25 and Figure 26. The possible reductions in the carbon footprint with these binder compositions compared to the baseline are presented in Table 36.

In this study, it was assumed that Fly Ash and GGBS would be imported to the country of production whereas as Portland cement would be produced locally. The transport distances for the international shipping of Fly Ash and GGBS as well as the transport of Portland cement from factory to site are detailed in Table 31 in Section 5.3. The respective emission factor per unit of material is summarised in the tables in Appendix E and is separated per life cycle stage for production (A1-A3) and transportation (A4). The carbon footprint during the production stage (A1-A3) of Fly Ash and GGBS is significantly lower than that for Portland cement. Therefore, the increased emissions due to the import (transport – A4) of Fly Ash and GGBS are overwhelmingly outweighed by their low production carbon footprint which still results in an overall reduction of carbon footprint.

*Table 36 - Possible Reductions of the Carbon Footprint with increased amounts of Fly Ash and GGBS vs Baseline*

| Design Option | CFP reduction with 35% Fly Ash | CFP reduction with 65% GGBS |
|---|---|---|
| Caissons | 7 % | 17 % |
| Sheet Piled Combi-Wall | 2 % | 4 % |
| Open Piled Suspended Deck | 4 % | 8 % |

Since BS 6349-1-4 permits a greater amount of GGBS (up to 65% of binder content), greater reductions can be achieved by adding GGBS as can be seen in Table 36. It should be noted that in the baseline mix design the binder already had a 15 % Fly Ash content.

Fly Ash is a by-product from the burning of coal in coal fired power stations. The production of energy from coal is a carbon intensive process and therefore in many countries the use of coal fired power stations is being phased out and as a result the supply of Fly Ash is becoming more limited. Fly Ash is considered as a waste product during the coal fired energy production process and therefore very little carbon emitted during this process is allocated to the Fly Ash production which results in its technically "low" $CO_2e$ emission factor. However, considering the source of the Fly Ash, its intrinsic sustainability is questionable and may therefore not be a long-term solution.

Typically concretes containing GGBS or Fly Ash will have a lower early strength than concretes containing only Portland cement (The Concrete Centre, 2020). Traditionally concrete specifications are for a concrete strength at 28 days. However, specifying a concrete strength at a later stage such as 56 days may enable the use of larger amounts of GGBS and Fly Ash. However, lower early strengths could influence the construction programme as this may increase the time for formwork removal. Use of water reducing and accelerating admixtures may also increase the early strength of concrete and thereby enable higher usage of GGBS or Fly Ash (The Concrete Centre, 2020).

It is therefore important for designers to engage with suppliers and contractors from an early stage in a project to assess and understand the opportunities and limitations associated with the carbon reduction in the concrete for a specific project. For example, having knowledge of the supply chain and availability of GGBS over a project period can influence the mix design specifications.

#### *7.2.2.4 Tubular Pile Length*

Reducing the average tubular pile length by 3 m for the open piled deck design results in a 4 % reduction of total carbon footprint as displayed in Figure 26. The required length of the tubular piles can be significantly optimised at an earlier stage depending on the available ground information. This again emphasises the fact that a good ground investigation at an early stage can contribute to a lower carbon footprint. This is particularly relevant for quay wall structures since the design is greatly influenced by the ground conditions.

In addition to boreholes with SPT tests, particle size distribution, CPT tests and Atterberg Limit testing should also be executed as a minimum in order to provide more information about the soil conditions. Geophysical surveys would also be very useful in order to understand the stratigraphy of the soil better as this also influences pile lengths significantly.

#### *7.2.2.5 Sensitivity Analysis Summary*

Combining each of the above parameters (recycled steel, binder composition and shortened tubular piles) the “total optimisation” of the design in terms of carbon footprint was estimated. The results of this total optimisation are displayed in Figure 27 and plotted against the baseline carbon footprint estimates. The exact parameters that were considered under the total optimisations are summarised in Table 33. Both this figure and table are described in Section 6.3.6.

Figure 27 demonstrates that with all the optimisation parameters combined, the carbon footprint for the caisson, sheet pile wall and open piled deck structures reduce by 32%, 26% and 40%, respectively, when compared to the baseline carbon footprint. The sheet piled combi-wall design still achieves the lowest carbon footprint followed by the caisson design whereas the open piled deck still has the highest carbon footprint.

## 7.3 Cost Estimate

A rough cost estimate was made for each of the design options. The unit prices were based on a previous study done by Inros Lackner. The cost estimates for the caisson, sheet piled combi-wall and the open piled deck are presented in Table 37, Table 38 and Table 39 respectively. The currency used is United States Dollar (USD) and the final value of the cost estimate is presented in USD per meter of berthing length provided.

*Table 37 - Cost Estimate for Caissons Design*

| Description | Unit | Quantity | Unit Cost (USD) | Total Amount (USD) |
|---|---|---|---|---|
| Concrete (Caissons) incl. formwork | $m^3$ | 38.251 | 2.000,00 | 76.502.400,00 |
| Concrete (Cope beam) incl. formwork | $m^3$ | 7.301 | 1.600,00 | 11.681.280,00 |
| Pavement | $m^2$ | 22.624 | 325,00 | 7.352.800,00 |
| Dredging | $m^3$ | 736.000 | 8,00 | 5.888.000,00 |
| Backfill (Sand) | $m^3$ | 377.984 | 15,00 | 5.669.759,88 |
| Backfill (Gravel) | $m^3$ | 9.576 | 200,00 | 1.915.274,40 |
| Gravel Bed Foundation | $m^3$ | 28.111 | 300,00 | 8.433.360,00 |
| Scour Protection | $m^2$ | 32.533 | 200,00 | 6.506.500,00 |
| Tubular Piles (Bridge) | No. | 28 | 65.940,00 | 1.846.320,00 |
| Concrete (Bridge) incl. formwork | $m^3$ | 602 | 1.600,00 | 963.607,45 |
| Concrete (Precast Yard) incl. formwork | $m^3$ | 2.237 | 1.600,00 | 3.578.400,00 |
| Fender | No. | 48 | 54.000,00 | 2.592.000,00 |
| Bollard | No. | 23 | 13.500,00 | 310.500,00 |
| Ladder | No. | 23 | 4.050,00 | 93.150,00 |
| Water /Electricity / Navigation Aids | | | 15% | 20.000.002,76 |
| Mobilisation and construction | | | 15% | 23.000.003,17 |
| Design | | | 2% | 3.526.667,15 |
| Contingencies | | | 10% | 17.986.002,48 |
| **Total Cost (USD)** | | | | **197.846.027,29** |
| Berthing Length of Caisson Pier | 817 | m | | |
| **Cost per m (USD / m)** | | | | **242.300,99** |

*Table 38 - Cost estimate for the Sheet Piled Combi-Wall Design*

| Description | Unit | Quantity | Unit Cost (USD) | Total Amount (USD) |
|---|---|---|---|---|
| Sheet piling (incl. anchoring). L= 32,9m; 333kg/$m^2$ | lin. m | 920 | 70.547,56 | 64.903.752,54 |
| Concrete (Cope beam) incl. formwork | $m^3$ | 6.808 | 1.600,00 | 10.892.800,00 |
| Pavement | $m^2$ | 22.420 | 325,00 | 7.286.620,77 |
| Dredging | $m^3$ | 549.240 | 8,00 | 4.393.920,00 |
| Backfill (Sand) | $m^3$ | 317.757 | 15,00 | 4.766.352,53 |
| Scour Protection | $m^2$ | 32.533 | 200,00 | 6.506.500,00 |
| Sheet piling bridge (incl. anchoring). L= 26,3m; 348kg/$m^2$ | lin. m | 180 | 58.935,48 | 10.608.386,79 |
| Concrete (Bridge) incl. formwork | $m^3$ | 1.332 | 1.600,00 | 2.131.200,00 |
| Fender | No. | 48 | 54.000,00 | 2.592.000,00 |
| Bollard | No. | 23 | 13.500,00 | 310.500,00 |
| Ladder | No. | 23 | 4.050,00 | 93.150,00 |
| Water /Electricity / Navigation Aids | | | 15% | 17.172.777,39 |
| Mobilisation and construction | | | 15% | 19.748.694,00 |
| Design | | | 2% | 3.028.133,08 |
| Contingencies | | | 10% | 15.443.478,71 |
| **Total Cost (USD)** | | | | **169.878.265,81** |
| Berthing Length of Sheet Piled Combi Wall Pier | 800 | m | | |
| **Cost per m (USD/m)** | | | | **212.347,83** |

*Table 39 - Cost Estimate for the Open Piled Suspended Deck Design*

| Description | Unit | Quantity | Unit Cost (USD) | Total Amount (USD) |
|---|---|---|---|---|
| Vertical Piles for Main Pier (L= 37m, 441 kg/m) | No. | 737 | 97.902,00 | 72.153.774,00 |
| Concrete (Main Pier) incl. formwork | $m^3$ | 32.389 | 1.600,00 | 51.821.608,23 |
| Dredging | $m^3$ | 623.760 | 8,00 | 4.990.080,00 |
| Scour Portection | $m^2$ | 50.739 | 200,00 | 10.147.709,00 |
| Vertical Piles Bridge (L= 30m, 441kg/m) | No. | 28 | 79.380,00 | 2.222.640,00 |
| Concrete (Bridge) incl. formwork | $m^3$ | 615 | 1.600,00 | 984.180,53 |
| Fender | No. | 48 | 54.000,00 | 2.592.000,00 |
| Bollard | No. | 23 | 13.500,00 | 310.500,00 |
| Ladder | No. | 23 | 4.050,00 | 93.150,00 |
| Water /Electricity / Navigation Aids | | | 15% | 21.797.346,26 |
| Mobilisation and construction | | | 15% | 25.066.948,20 |
| Design | | | 2% | 3.843.598,72 |
| Contingencies | | | 10% | 19.602.353,49 |
| **Total Cost (USD)** | | | | **215.625.888,44** |
| Berthing Length of Open Piled Suspended Deck | 800 | m | | |
| **Cost per m (USD/m)** | | | | **269.532,36** |

As indicated in the above tables, it can be seen that the sheet piled combi-wall is the cheapest design (USD 212.347 / m) followed by the caisson (USD 242.300 / m) and the open piled deck (USD 269.532 / m).

The baseline carbon footprint estimates for each design are compared to the estimated costs in Figure 29.

It should be noted that this is only a very rough analysis with the purpose of getting an impression of the relative costs of the various quay wall structures. It is therefore recommended that a more detailed cost analysis with a life cycle approach be done in a future study. The cost effects of reducing the carbon footprint would also be a topic for future investigation.

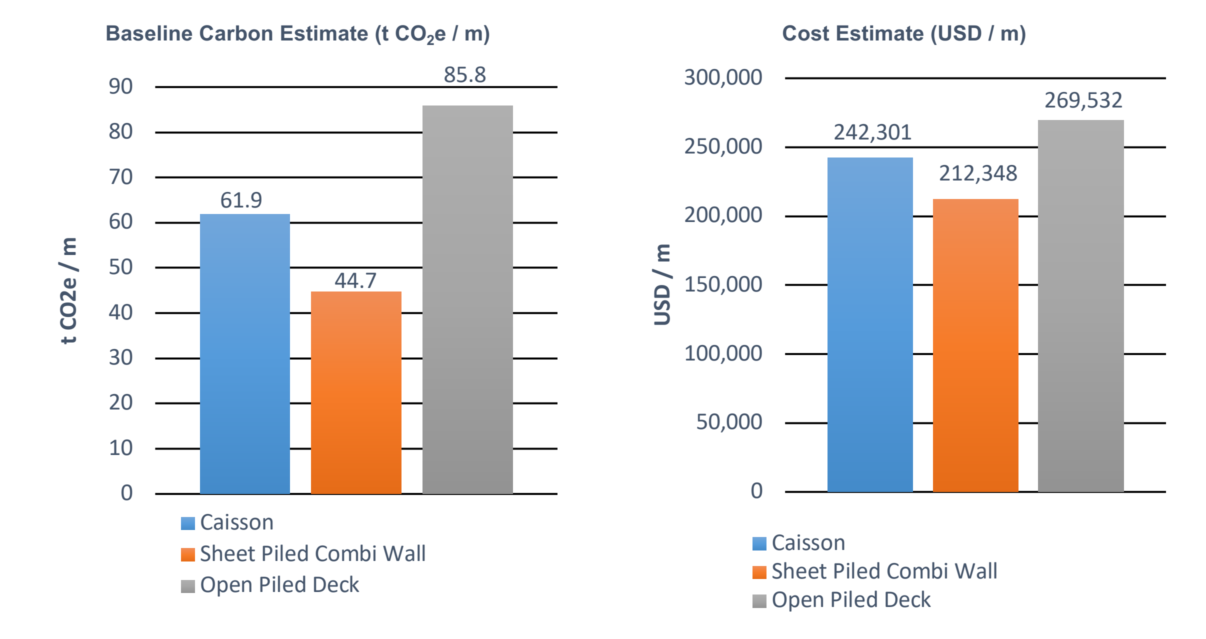



*Figure 29 - Comparison of baseline Carbon Footprint and the Cost Estimate for each design*

## 7.4 Completeness, Consistency and Limitations

### 7.4.1 Completeness

As described in the system boundaries in Table 30 (Section 4.2.3), services, quay furniture and berth equipment were omitted in this study since these items would be the same for all the designs and therefore not influence the comparison between the designs.

Temporary construction works were also omitted in each of the carbon footprint studies as this level of detail is difficult to assess at such an early stage of a project. The temporary works are usually only designed by the contractor as the project proceeds. This may be a topic for further research.

### 7.4.2 Consistency

As explained in Chapters 5 and 6, the assumptions, methods and data were applied in the same way to each of the different designs throughout the carbon footprint study. Therefore, the comparisons between the designs were done in a fair manner without bias to any one design type or construction methodology.

### 7.4.3 Limitations

#### *7.4.3.1 Data Quality Requirements*

As described in Section 4.2.4 the data quality should be characterised according to various parameters such as temporal relevance, geographical coverage, technology coverage and several others in order to provide the LCA practitioner with a way of quantitatively assessing the quality of the data. Temporal relevance refers to the age of the data, i.e. ensuring that it is not outdated and still relevant. Geographical coverage refers to the geographical zone for which the data is relevant, i.e. to measure if the data used is relevant to the specific country or area where the system under study is located. The technology coverage parameter serves to quantify how accurately the technology mix used represents the system under study. However, the data in this thesis were not categorised as this level of detail was beyond the scope of this thesis.

#### *7.4.3.2 Construction Machinery*

The number of hours required for each type of construction machinery was determined based on personal experience by the author in planning similar construction projects. However, there are many ways that a project can be executed, and methods and programmes proposed in this thesis are only one of those methods as well as a very high-level time estimate. Therefore, the actual required hours might differ to some extent for an actual project.

The exhaust emissions from construction machinery are influenced by many variables summarised in Figure 21 (see page 49). A simplified approach was adopted for the use of emission factors for construction machinery as described in Section 5.4. However, this is associated with a degree of uncertainty which means that the actual construction (A5) emissions may deviate from the ones calculated in this thesis. Therefore, it would be of interest to investigate the emissions from construction machinery on a marine construction project in more detail in a future investigation.

#### *7.4.3.3 Quay Wall Structure Types*

In this study only three of the most common quay wall structure types were investigated. However, it would be interesting to investigate other types of structures in future studies, namely:

- Gravity blockwork quay wall structures. These concrete structures are usually very lightly reinforced or consist of mass concrete (Ackhurst, 2020, p. 4). Less or no steel reinforcing could provide a significant reduction in carbon footprint. With less or no steel reinforcing the exposure class could be reduced and therefore the required concrete strength class. Lower grade concretes usually have lower cement contents. This could also be a significant source of carbon footprint reduction.
- Floating pier type structures. These types of structures are a light and cheap solution compared to the conventional types of quay walls. However, floating piers have shorter design lives and provide less berthing capacity. It would need to be determined if these advantages really outweigh the disadvantages.

#### *7.4.3.4 End-of-Life Scenarios*

Only the life cycle stages from production to construction (A1 - A5) were considered in this study. However, steel is a material that can be completely recycled (Arcelor Mittal , 2019). Therefore, there may be benefits by considering other life cycle stages from the end-of-life such as recycling (life cycle stage D, refer to Table 2) of steel elements, particularly in the design types with significant steel content like the sheet piled combi-wall. The feasibility of end-of-life recycling of steel elements in regard to time, cost and actual $CO_2e$ savings would be a topic for further investigation as it did not form part of the scope of this thesis.

## 7.5 Summary

In this chapter, the results of the Life Cycle Inventory and the Life Cycle Impact Assessment were discussed and interpreted.

In the baseline carbon footprint LCA, it was determined that the sheet piled combi-wall had the lowest carbon footprint followed by the caissons. The open piled deck had the highest baseline carbon footprint.

In the sensitivity analysis, certain parameters like recycled steel content, cementitious binder composition, and tubular pile length were optimised in order to determine the reduction opportunities of carbon. Combining these various parameters resulted in carbon footprint reduction of between approximately 26 to 40 % for the various designs.

For the caissons, the influence of steel reinforcing was also discussed, and it was determined that for an adjustment in the steel reinforcing content by ±40 kg /$m^3$ the carbon footprint would change by about ±6% respectively.

A rough cost estimate was also made, and it was determined that the sheet piled combi-wall was the cheapest option, followed by the caisson design and the open piled deck as the most expensive option. However, this was a very rough cost estimate and needs to be investigated in more detail in future studies.

One of the limitations that was discussed was the absence of a quantitative data quality assessment. Another limitation was the accuracy of the emissions emitted from the construction machinery, especially the machines with a greater power output. Both aspects should be investigated in more detail in future studies. Other types of quay wall structures as well as end-of-life scenarios are further topics for future investigations.

# 8. Conclusion

Climate change, which is accelerated by the emission of greenhouse gases, is causing a growing global crisis and poses a threat to the wellbeing of people and eco systems around the world. Most countries around the world are legally committed to limiting global average temperature increases to below 2°C as part of the 2015 Paris Climate Agreement. As part of achieving this goal, the European Union has set a target of reducing greenhouse gas emissions by 40% by 2030 compared to 1990. The construction of infrastructure results in significant emissions of various greenhouse gases which cause climate change. The various life cycle stages in infrastructure construction are:

- Production of construction material: this includes the extraction of the raw material, transporting raw material to factory and processing the raw material into a construction material. According to the EN 15978 life cycle classification, these production life cycle stages are defined as stages A1-A3.
- Transportation of construction material from a factory to the construction site, defined as life cycle stage A4.
- Construction of the specific piece of infrastructure, defined as life cycle stage A5.

This thesis specifically investigated the carbon footprint of various quay wall structure types which are typically used for the construction of a berthing structure for a container terminal. The structures that were considered were concrete caissons, sheet piled combi-wall and open piled suspended deck structures. The carbon footprint was calculated by using a Life Cycle Assessment approach and considered only the life cycle stages of production (A1-A3), transportation (A4) and construction (A5).

In order to calculate the carbon footprint, outline designs of the various quay structures were required so that the material quantities and the required construction equipment to build the pier could be quantified. The design and the assumptions on which the designs were based, were summarised in Chapter 3. A soil investigation consisting of boreholes and SPT tests was used as a basis for ground conditions where each of the design options would be feasible from a technical perspective. For the concrete caissons and the open piled deck, many of the structural components were based on existing designs. However, the main geotechnical and structural ultimate limit states were checked to ensure that these designs were realistic. The concrete mix design was based on an existing one from a project managed by Inros-Lackner for a strength class of C35/45.

Chapters 4 to 7 describe the four main stages of a carbon footprint study as specified by ISO 14067, namely the Goal and Scope Definition, Life Cycle Inventory analysis, Life Cycle Impact Assessment and Interpretation stage respectively. As described in Chapter 4, the goal of this thesis was to determine the carbon footprint of the three different quay wall structure types in order to determine if there were any differences. In Chapter 5, Life Cycle Inventory analysis, the material quantities, transport distances and machine operating hours required for the construction of each type of quay wall structure were presented. The emission factors used for each of these components was also presented. In Chapter 6, the carbon footprint of each of the various quay wall structures was presented. The baseline assessment was presented first, which used the world average for recycled steel content and the concrete as per the baseline mix design.

From the baseline carbon estimate it could be seen that the sheet piled combi-wall type quay wall structure had the lowest carbon footprint followed by the caisson and the open piled suspended deck with the highest carbon footprint. Table 40 summarises the results of the baseline carbon footprint estimate as well as the main contributing components.

As evidenced in Table 40, the sheet pile wall had a 48% lower carbon footprint than the open piled deck. The caisson type structure had a 28% lower carbon footprint than the open piled deck. For each of the design types the production life cycle stage (A1-A3) contributed the most to the overall carbon footprint, with steel and Portland cement being the highest contributors. It was interesting to note that the open piled suspended deck had the highest carbon footprint despite being the lightest structure of the three by mass. This was explained by the fact that the open piled deck had relatively large quantities of both steel and concrete (and therefore cement) compared to the other two options.

*Table 40 - Baseline Carbon Footprint Results and Summary of Main Contributing Components*

| Structure Type | Baseline Carbon Footprint | Contribution from Production Life Cycle Stages (A1-A3) | Steel and Portland Cement contribution to total Carbon Footprint |
|---|---|---|---|
| **Caisson** | 62,0 t $CO_2e$ / m | 83 % | 73 % |
| **Sheet Pile Wall** | 44,7 t $CO_2e$ / m | 79 % | 65 % |
| **Open Piled Deck** | 85,9 t $CO_2e$ / m | 88 % | 84 % |

The sensitivity analysis investigated the effects of increasing the recycled content of steel, increasing the Fly Ash and GGBS content in the concrete binder and reducing the length of the tubular piles by about 3 meters. It considered the following variations:

- Recycled content of the steel increased to approximately 85%,
- Cementitious binder composed of approximately 35% Portland Cement and 65% GGBS, and
- Length of the tubular piles reduced by about 3 metres,

The results of the sensitivity analysis showed that the total carbon footprint for the caisson, sheet pile wall and open piled deck could be reduced by 32%, 26% and 40%, respectively. After conducting the sensitivity analysis, it became clear that the sheet pile wall still had the lowest carbon footprint, followed by the caisson structure. The open piled deck had the highest carbon footprint. Figure 30 summarises the results of the baseline carbon footprint against the total optimisations from the sensitivity analysis.

The results of the sensitivity analysis emphasize the fact that significant reductions in the carbon footprint of each structure can be achieved by reducing the Portland cement content and by having a higher recycled steel content.

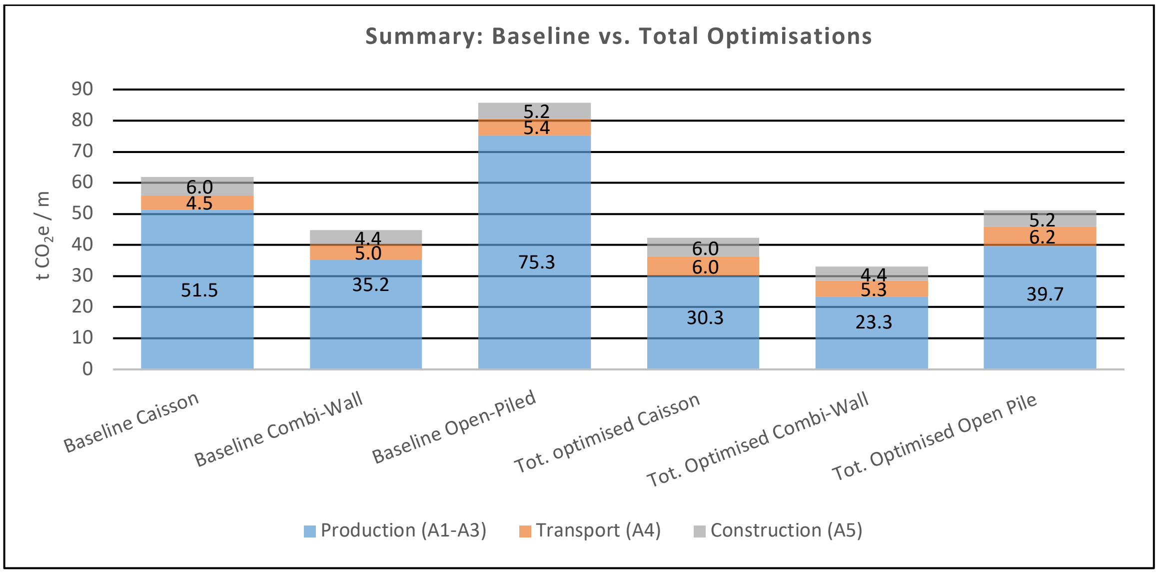



*Figure 30 - Carbon Footprint: Summary of the baseline results against the total optimisations from the sensitivity analysis*

A rough cost estimate was done, based on unit prices used by Inros-Lackner in other studies. It was estimated that the sheet pile wall was the cheapest option followed by the caisson option while the open piled deck option was the most expensive option. It is interesting to note that the cheapest option also has the lowest carbon footprint whilst the most expensive option has the highest carbon footprint.

***Recommendations for Future Studies***

A simplified set of emission factors was used to determine the $CO_2e$ emissions from construction machinery due to many influencing facets such as the load power output, operator skills and so on. As a result, the actual $CO_2e$ emissions calculated for the construction life cycle stage (A5) may deviate from the ones calculated in this study. Therefore, it is recommended that this life cycle stage is investigated in more detail in future studies in order to determine with greater accuracy the actual emissions from the construction life cycle stage (A5).

Investigations of other quay wall structure types like gravity concrete blocks and floating piers would be topics of interest for future studies. End-of-life scenarios, particularly related to the recovery and recycling of steel, was an aspect not covered in this thesis and would be interesting to investigate in a future study.

The possible savings (or additional costs) associated with adjusting various parameters, such as the Portland Cement content, as discussed in the sensitivity analysis was not investigated and would be an interesting topic for a future study.

Future investigations may also consider other environmental impact categories besides global warming.

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# Appendices

## Appendix A

*Table 41 - SPT log of boreholes B7, B7a, B14, B15, B16 with geotechnical zones indicated*

| Elevation | BH No: | B14 | | B7A | | B7 | | B15 | | B16 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (mCD) | Depth | Zones | SPT-N | Zones | SPT-N | Zones | SPT-N | Zones | SPT-N | Zones | SPT-N |
| 3,5 | 0 | | | | | | | | | | |
| 2,5 | 1 | | | | 43 | | 30 | | 12 | | 23 |
| 1,5 | 2 | | | C1A | 33 | C1A | 40 | | 12 | C1A | 28 |
| 0,5 | 3 | | | | | | | | | | |
| -0,5 | 4 | | | | 15 | | 6 | | 14 | | 8 |
| -1,5 | 5 | | | | 14 | | 2 | | 8 | | 6 |
| -2,5 | 6 | | | | | | | | | | |
| -3,5 | 7 | | | | 15 | | 4 | C1A | 5 | | 2 |
| -4,5 | 8 | | | | 11 | | 6 | | 21 | | 6 |
| -5,5 | 9 | | | | | | | | | | |
| -6,5 | 10 | | | C1B | 20 | C1B | 6 | | 20 | C1B | 12 |
| -7,5 | 11 | | | | 17 | | 11 | | 60 | | 13 |
| -8,5 | 12 | | | | | | | | | | |
| -9,5 | 13 | | | | 14 | | 11 | | 60 | | 7 |
| -10,5 | 14 | | | | 17 | | 11 | | 15 | | 15 |
| -11,5 | 15 | | | | | | | | | | |
| -12,5 | 16 | | 45 | | 10 | | 8 | | 11 | | 14 |
| -13,5 | 17 | | 17 | | 16 | | 17 | | 60 | | 25 |
| -14,5 | 18 | C1A | | C2A | | | | C1B | | | |
| -15,5 | 19 | | 23 | | 60 | | 24 | | 2 | C2A | 23 |
| -16,5 | 20 | | 25 | | 60 | C2A | 25 | | 28 | | 20 |
| -17,5 | 21 | | | | | | | | | | |
| -18,5 | 22 | | 60 | C2C | 48 | | 16 | | 26 | | 60 |
| -19,5 | 23 | | 60 | | 60 | | 32 | | 28 | | 25 |
| -20,5 | 24 | | | | | | | | | | |
| -21,5 | 25 | | 47 | | 41 | C2B | 36 | C3A | 25 | | 26 |
| -22,5 | 26 | C2C | 45 | C2B | 60 | | 36 | | 28 | | 23 |
| -23,5 | 27 | | | | | | | | | C3A | |
| -24,5 | 28 | | 60 | C2C | 60 | C3A | 27 | | 32 | | 25 |
| -25,5 | 29 | | 52 | C3B | 60 | | 36 | | 25 | | 26 |
| -26,5 | 30 | C2B | | | | | | | | | |
| -27,5 | 31 | | 60 | | | | 42 | | 37 | | 27 |
| -28,5 | 32 | | 54 | | | | 60 | | 44 | | 31 |
| -29,5 | 33 | C2C | | | | C3B | | | | | |
| -30,5 | 34 | | 57 | | | | 60 | | 41 | | 37 |
| -31,5 | 35 | | 50 | | | | 60 | | 41 | | 42 |
| -32,5 | 36 | | | | | | | | | | |
| -33,5 | 37 | | 48 | | | | | | 46 | | 35 |
| -34,5 | 38 | | 43 | | | | | | 37 | | 33 |
| -35,5 | 39 | C3B | | | | | | C3B | | | |
| -36,5 | 40 | | 60 | | | | | | 60 | | 35 |
| -37,5 | 41 | | 60 | | | | | | 39 | | 30 |
| -38,5 | 42 | | | | | | | | | C3B | |
| -39,5 | 43 | | | | | | | | 39 | | 36 |
| -40,5 | 44 | | | | | | | | 42 | | 34 |
| -41,5 | 45 | | | | | | | | | | |
| -42,5 | 46 | | | | | | | | 52 | | 39 |
| -43,5 | 47 | | | | | | | | 60 | | 60 |
| -44,5 | 48 | | | | | | | | | | |
| -45,5 | 49 | | | | | | | | 60 | | |
| -46,5 | 50 | | | | | | | | | | |

# Appendix B

*Table 42 - Soil characteristics used for the Caisson design verifications*

| Soil Layer | Densities (kN/m3) γ_sat | γ_dry | γ' | $\phi'_k = \phi'_d$ | $\delta_k = \delta_d$ | c‘ (kN/m$^2$) |
|---|---|---|---|---|---|---|
| **Sand Fill** | 21 | 19 | 11 | 32,5 | 21,7 | 0 |
| **Gravel Bed (50mm stone)** | 22 | 19,5 | 12 | 40 | 40,0 | 0 |
| **C1A (medium dense Sands)** | 23 | 21 | 13 | 27,5 | Not Applicable | 0 |
| **C2C (very compact silty sands)** | 23,5 | 22,5 | 13,5 | 40 | Not Applicable | 0 |
| **C2B (compact sands)** | 22 | 21,5 | 12 | 35 | Not Applicable | 0 |
| **C3B (stiff to very stiff silty clays)** | 21 | 21 | 11 | 25 | Not Applicable | 0 |

*Table 43 - Calculations for Sliding Verification*

| | | Characteristic EP Forces ; $E_k$ | | | Horiz. Design EP Forces ; $E_{d,h}$ | | Vertical Design EP Forces ; $E_{d,v}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Load** | **Force Number** | **Magn. (kN/m)** | **Vertical** | **Horizontal** | **DS-P** | **DS-T** | **γ** | **DS-P** | **γ** | **DS-T** |
| **Distributed Live Load** | **1** | 274,1 | 101,2 | 254,7 | 382,0 | - | 0,0 | 0,0 | - | - |
| | **2** | 35,1 | 13,0 | 32,6 | 48,9 | - | 0,0 | 0,0 | - | - |
| **Eff. Stresses** | **3** | 558,7 | 206,4 | 519,2 | 700,9 | 623,0 | 1,35 | 278,6 | 1,2 | 247,7 |
| | **4** | 349,2 | 129,0 | 324,5 | 438,1 | 389,4 | 1,35 | 174,1 | 1,2 | 154,8 |
| | **5** | 14,1 | 5,2 | 13,1 | 17,7 | - | 1,35 | 7,0 | 1,2 | 6,3 |
| | **6** | 17,4 | 6,4 | 16,2 | 21,8 | - | 1,35 | 8,7 | 1,2 | 7,7 |
| **Water** | **7** | 194,0 | 71,7 | 180,3 | 270,4 | 234,4 | - | - | - | - |
| | | | | | **1879,9** | **1246,8** | kN/m | **468,5** | kN/m | **416,4** kN/m |

| Characteristic Wall Weights | | | Caisson Length (m) | Design Wall Weights ($W_d$) kN/m | | | |
|---|---|---|---|---|---|---|---|
| **Permanent** | **Temporary** | **Units** | | **γ** | **DS-P** | **γ** | **DS-T** |
| 110.929,7 | 98.253,1 | kN | 17 | 1 | 6525,3 | 1 | 5779,6 |
| 6.525,3 | 5.779,6 | kN/m | | | | | |

| Water Uplift Force (U) kN/m | | | | |
|---|---|---|---|---|
| **Characteristic** | **γ** | **DS-P** | **γ** | **DS-T** |
| 2872,8 | 1,35 | 3878 | 1,2 | 3447 |

| Design Vertical Forces ($V_d$ ) kN/m | | |
|---|---|---|
| **DS-P** | | **DS-T** |
| 3.115,5 | | 2.748,6 |

| | Design Horizontal Sliding Resistances ($R_d$) kN/m | | | |
|---|---|---|---|---|
| | **γ** | **DS-P** | **γ** | **DS-T** |
| | 1,1 | **2.376,5** | 1,1 | **2.096,7** |
| | | OK | | OK |
| utilisation (μ) | | 0,79 | | 0,59 |

*Table 44 - Calculations for Vertical Bearing Capacity of Caissons*

| | | Characteristic EP Forces ; E,k | | | Horiz. Design EP Forces ; $E_{d,h}$ | | | | Vertical Design EP Forces ; $E_{d,v}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Force Number | Magn. (kN/m) | Vertical | Horizontal | γ | DS-P | γ | DS-T | γ | DS-P | γ | DS-T |
| **Distributed Live Load** | 1 | 274,1 | 101,2 | 254,7 | 1,50 | 382,0 | - | - | 1,50 | 151,8 | - | - |
| | 2 | 35,1 | 13,0 | 32,6 | 1,50 | 48,9 | - | - | 1,50 | 19,4 | - | - |
| **Eff. Stresses** | 3 | 558,7 | 206,4 | 519,2 | 1,35 | 700,9 | 1,20 | 623,0 | 1,35 | 278,6 | 1,2 | 247,7 |
| | 4 | 349,2 | 129,0 | 324,5 | 1,35 | 438,1 | 1,20 | 389,4 | 1,35 | 174,1 | 1,2 | 154,8 |
| | 5 | 14,1 | 5,2 | 13,1 | 1,35 | 17,7 | - | - | 1,35 | 7,0 | 1,2 | 6,3 |
| | 6 | 17,4 | 6,4 | 16,2 | 1,35 | 21,8 | - | - | 1,35 | 8,7 | 1,2 | 7,7 |
| **Water** | 7 | 194,0 | 71,7 | 180,3 | 1,50 | 270,4 | 1,30 | 234,4 | - | - | - | - |
| | | | | | | **1879,9** kN/m | | **1246,8** kN/m | | **639,7** kN/m | | **416,4** kN/m |

| aracteristic Wall Weigh | | Caisson Length (m) | Design Wall Weights ($W_d$) kN/m | | | |
|---|---|---|---|---|---|---|
| Permanent | Temporar | | γ | DS-P | γ | DS-T |
| 110.929,7 | 98.253,1 | 17 | 1,35 | 8809,1 | 1,2 | 6935,5 |
| 6.525,3 | 5.779,6 | | | | | |

| Water Uplift Force (U) kN/m | | | | |
|---|---|---|---|---|
| Charc. | γ | DS-P | γ | DS-T |
| 2872,8 | 1 | 2873 | 1 | 2873 |

| Eccentricities (m) | | | |
|---|---|---|---|
| | DS-P | DS-T | |
| $e_O$ | 5,591 | 5,928 | $e_O=\|M_{O,d}\|/V_d$ |
| $e_B$ | 2,009 | 1,672 | $e_B=0,5*B-e_O$ |
| B (m) | 15,2 | | |
| B' (m) | 11,182 | 11,856 | $B'=B-\|2*e_B\|$ |
| L' (m) | 17 | 17 | |
| B'/L' | 0,658 | 0,697 | |

| $\phi'_k = \phi'_d$ ( ° ) |
|---|
| 33,0 |

| | Moments | | | | | |
|---|---|---|---|---|---|---|
| | Magnitudes (kN/m) | | Lever Arm | Moment (kNm/m ) | | Direction |
| Force Descri | DS-P | DS-T | (m) | DS-P | DS-T | |
| E,d,h: | | | | | | |
| 1 | 382,0 | - | 10,2 | 3.896,4 | - | clockwise |
| 2 | 48,9 | - | 21,6 | 1.056,8 | - | |
| 3 | 700,9 | 623,0 | 6,5 | 4.556,0 | 4.049,8 | |
| 4 | 438,1 | 389,4 | 9,7 | 4.249,4 | 3.777,2 | |
| 5 | 17,7 | - | 19,9 | 352,5 | - | |
| 6 | 21,8 | - | 21,2 | 462,2 | - | |
| 7 | 270,4 | 234,4 | 9,4 | 2.541,9 | 2.203,0 | |
| E,d,v: | | | | | | |
| 1 | -151,8 | - | 13,7 | - 2.080,3 | - | anti-cl.wise |
| 2 | -19,4 | - | 13,7 | - 266,4 | - | |
| 3 | -278,6 | -247,7 | 13,7 | - 3.817,0 | - 3.392,9 | |
| 4 | -174,1 | -154,8 | 13,7 | - 2.385,6 | - 2.120,6 | |
| 5 | -7,0 | -6,3 | 13,7 | - 96,5 | - 85,7 | |
| 6 | -8,7 | -7,7 | 13,7 | - 118,7 | - 105,5 | |
| 7 | - | - | 13,7 | - | - | |
| Wall Weight | -8809,1 | -6935,5 | 7,6 | - 66.949,3 | - 52.709,9 | |
| Water Uplift | 2873 | 2873 | 7,6 | 21.833,3 | 21.833,3 | clockwise |
| | | | $M_{O,d}$ = | **- 36.765,25** | **- 26.551,31** | kNm/m |

| Bearing Capacity Equation | | | |
|---|---|---|---|
| | DS-P | DS-T | |
| $m_B$ | 1,603 | 1,589 | |
| $i_q$ | 0,583 | 0,595 | |
| $i_\gamma$ | 0,416 | 0,430 | |
| $N_q$ | 26,0 | 26,0 | |
| $N_\gamma$ | 32,4 | 32,4 | |
| $s_q$ | 1,358 | 1,380 | |
| $s_\gamma$ | 0,893 | 0,886 | |
| γ' | 13 | 13 | $kN/m^3$ |
| q' | 0 | 0 | $kN/m^2$ |
| $q'_{R,k}$ | 875,6 | 951,5 | $kN/m^2$ |
| $\gamma_{R,v}$ | 1,4 | 1,3 | |
| $q'_{R,d}$ | 625,4 | 731,9 | $kN/m^2$ |
| $q'_{R,d}$ | **6.993,4** | **8.677,0** | kN/m |
| | OK | OK | |
| utilisation (μ) | 0,94 | 0,52 | |

| Design Vertical Forces ($V_d$ ) kN/m | | |
|---|---|---|
| DS-P | | DS-T |
| **6.576,1** | | **4.479,1** |
| $V_d = E_{d,v} + W_d - U$ | | |

*Table 45 - Verification for Overturning for Caissons*

| | Force Number | Characteristic EP Forces ; E,k: Magn. (kN/m) | Vertical | Horizontal | Horiz. Design EP Forces ; $E_{d,h}$: γ | DS-P | γ | DS-T | Vertical Design EP Forces ; $E_{d,v}$: γ | DS-P | γ | DS-T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Distributed Live Load** | **1** | 274,1 | 101,2 | 254,7 | 1,50 | 382,0 | - | - | 1,5 | 151,8 | - | - |
| | **2** | 35,1 | 13,0 | 32,6 | 1,50 | 48,9 | - | - | 1,5 | 19,4 | - | - |
| **Eff. Stresses** | **3** | 558,7 | 206,4 | 519,2 | 1,10 | 571,1 | 1,05 | 545,2 | 1,1 | 227,0 | 1,05 | 216,7 |
| | **4** | 349,2 | 129,0 | 324,5 | 1,10 | 357,0 | 1,05 | 340,7 | 1,1 | 141,9 | 1,05 | 135,4 |
| | **5** | 14,1 | 5,2 | 13,1 | 1,10 | 14,4 | - | - | 1,1 | 5,7 | 1,05 | 5,5 |
| | **6** | 17,4 | 6,4 | 16,2 | 1,10 | 17,8 | - | - | 1,1 | 7,1 | 1,05 | 6,7 |
| **Water** | **7** | 194,0 | 71,7 | 180,3 | 1,50 | 270,4 | 1,25 | 225,3 | - | - | - | - |
| | | | | | | **1661,6** kN/m | | **1111,2** kN/m | | **553,0** kN/m | | **364,4** kN/m |

| Characteristic Wall Weights: Permanent | Temporary | Length (m) | Design Wall Weights ($W_d$) kN/m: γ | DS-P | γ | DS-T |
|---|---|---|---|---|---|---|
| 110.929,7 | 98.253,1 | 17 | 0,9 | 5872,7 | 0,9 | 5201,6 |
| 6.525,3 | 5.779,6 | | | | | |

| Water Uplift Force (U) kN/m: Character | γ | DS-P | γ | DS-T |
|---|---|---|---|---|
| 2872,8 | 1,1 | 3160 | 1,05 | 3016 |

| Design Vert. Forces ($V_d$) kN/m: DS-P | | DS-T |
|---|---|---|
| **3.265,7** | | **2.549,5** |
| $V_d = E_{d,v} + W_d - U$ | | |

| Force Description | Moments: Force Magnitudes DS-P | DS-T | Force Lever | Moment (kNm/m) DS-P | DS-T | Direction |
|---|---|---|---|---|---|---|
| $E_{d,h}$: | | | | | | |
| 1 | 382,0 | - | 10,2 | 3.896,4 | - | clockwise |
| 2 | 48,9 | - | 21,6 | 1.056,8 | - | clockwise |
| 3 | 571,1 | 545,2 | 6,5 | 3.712,3 | 3.543,6 | clockwise |
| 4 | 357,0 | 340,7 | 9,7 | 3.462,5 | 3.305,1 | clockwise |
| 5 | 14,4 | - | 19,9 | 287,2 | - | clockwise |
| 6 | 17,8 | - | 21,2 | 376,6 | - | clockwise |
| 7 | 270,4 | 225,3 | 9,4 | 2.541,9 | 2.118,3 | clockwise |
| $E_{d,v}$: | | | | | | |
| 1 | - 151,8 | - | 13,7 | - 2.080,3 | - | anti-cl.wise |
| 2 | - 19,4 | - | 13,7 | - 266,4 | - | anti-cl.wise |
| 3 | - 227,0 | - 216,7 | 13,7 | - 3.110,2 | - 2.968,8 | anti-cl.wise |
| 4 | - 141,9 | - 135,4 | 13,7 | - 1.943,9 | - 1.855,5 | anti-cl.wise |
| 5 | - 5,7 | - 5,5 | 13,7 | - 78,6 | - 75,0 | anti-cl.wise |
| 6 | - 7,1 | - 6,7 | 13,7 | - 96,7 | - 92,3 | anti-cl.wise |
| 7 | - | - | 13,7 | - | - | anti-cl.wise |
| Wall Weight | - 5.872,7 | - 5.201,6 | 7,6 | - 44.632,9 | - 39.532,4 | anti-cl.wise |
| Water Uplift | 3.160,1 | 3.016,4 | 7,6 | 24.016,6 | 22.924,9 | clockwise |
| | Destabilisng Moments | | $E_d$ | **39.350,4** | **31.891,9** | **kNm/m** |
| | Stabilising Moments: | | $R_d$ | **52.208,9** | **44.524,1** | **kNm/m** |
| | | | | OK | OK | |
| | | | utilisation (μ) | 0,75 | 0,72 | |

*Table 46 - Elastic Settlement Calculation for Caissons*

| | | | |
|---|---|---|---|
| $V_{d,SLS}$ | 110.929,7 | kN | Weight of Filled Structure |
| $U_{d,SLS}$ | - 2.872,8 | kN | Water Uplift Force |
| $UDL_{d,SLS}$ | 50,0 | kPa | Live Load |
| L | 17 | m | Length of caisson base |
| B | 15,2 | m | Breadth of caisson base |
| L/B | 1,118 | ratio of length to breadth | |
| $I_f$ | 0,86 | Shape factor for Rigid Rectangular Foundation corresponding to above L/B ratio | |
| v | 0,33 | Poisson Ratio for drained soil | |
| E | 20.000,0 | kPa | Elastic Stiffness |
| $q_{d,SLS}$ | 468,2 | kPa | Design SLS earth pressure |
| **s =** | **0,271** | **m** | **Elastic Settlement** |
| $s = qB/E\,(1-v^2)I_f$ | | | |

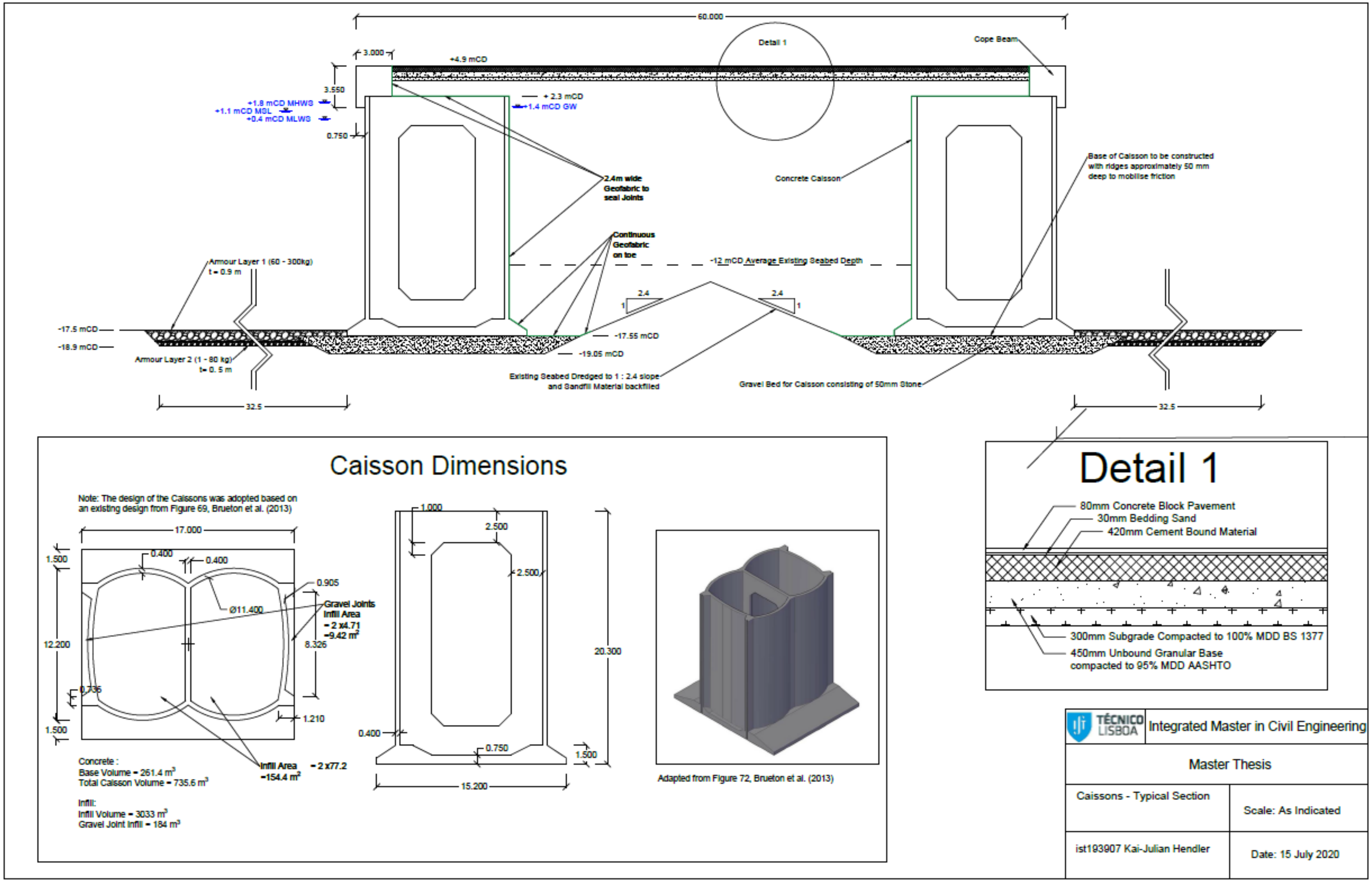



*Figure 31 - Caisson: Typical Section*

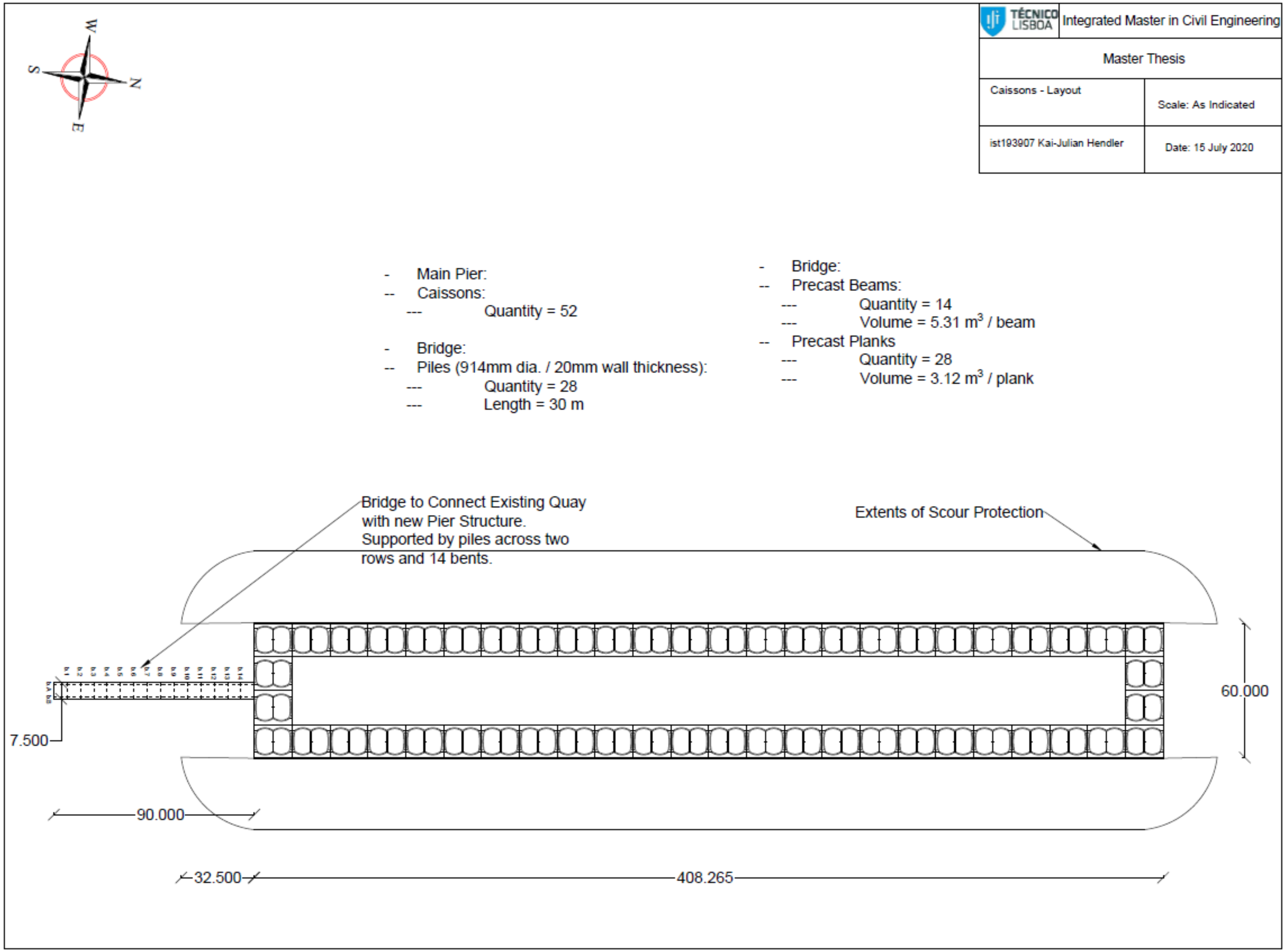



*Figure 32 - Caisson: Layout*

## Appendix C

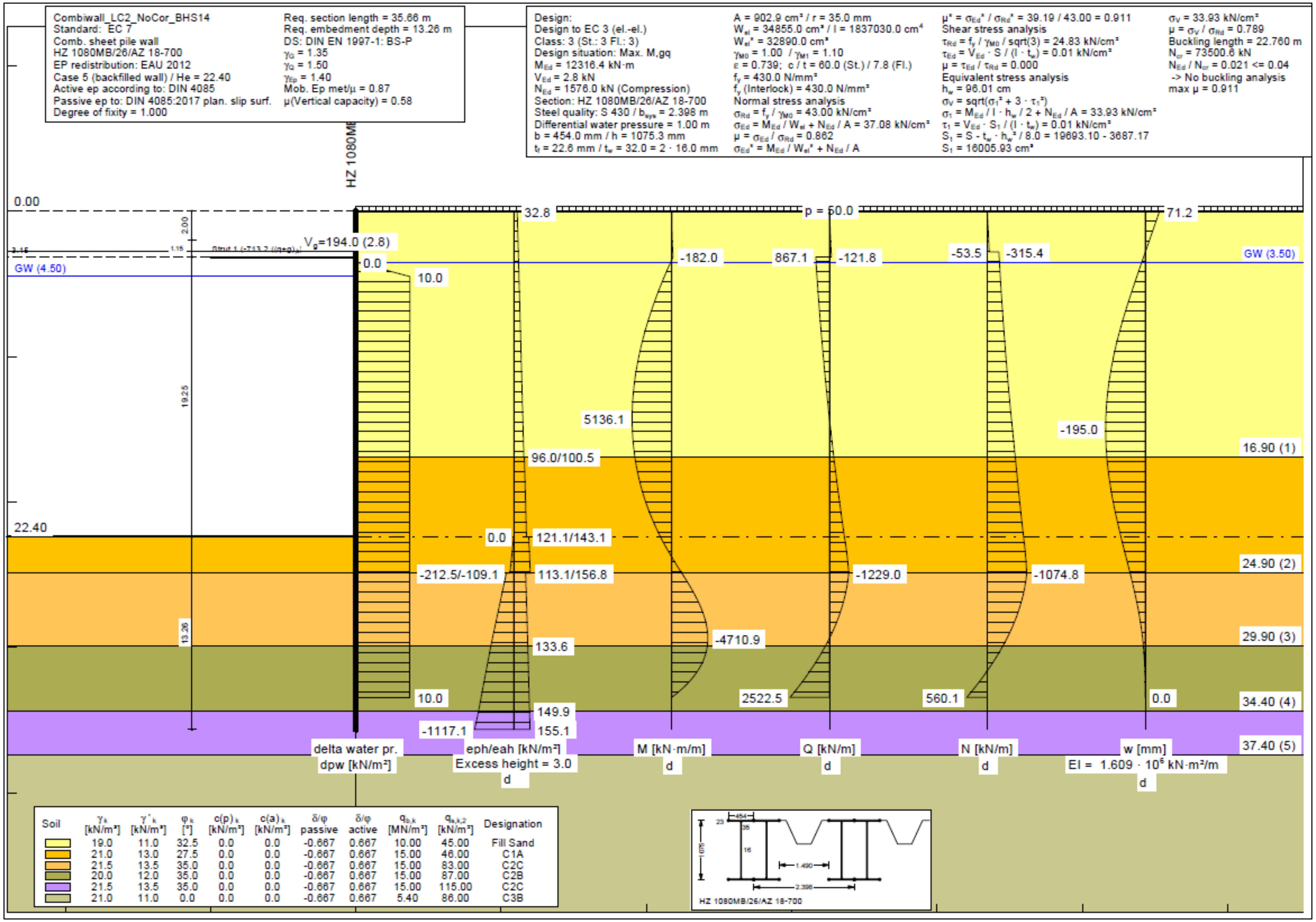



*Figure 33 - Combi Wall Calculation: LC2 No Corrosion, Ground Conditions as per Borehole B14*

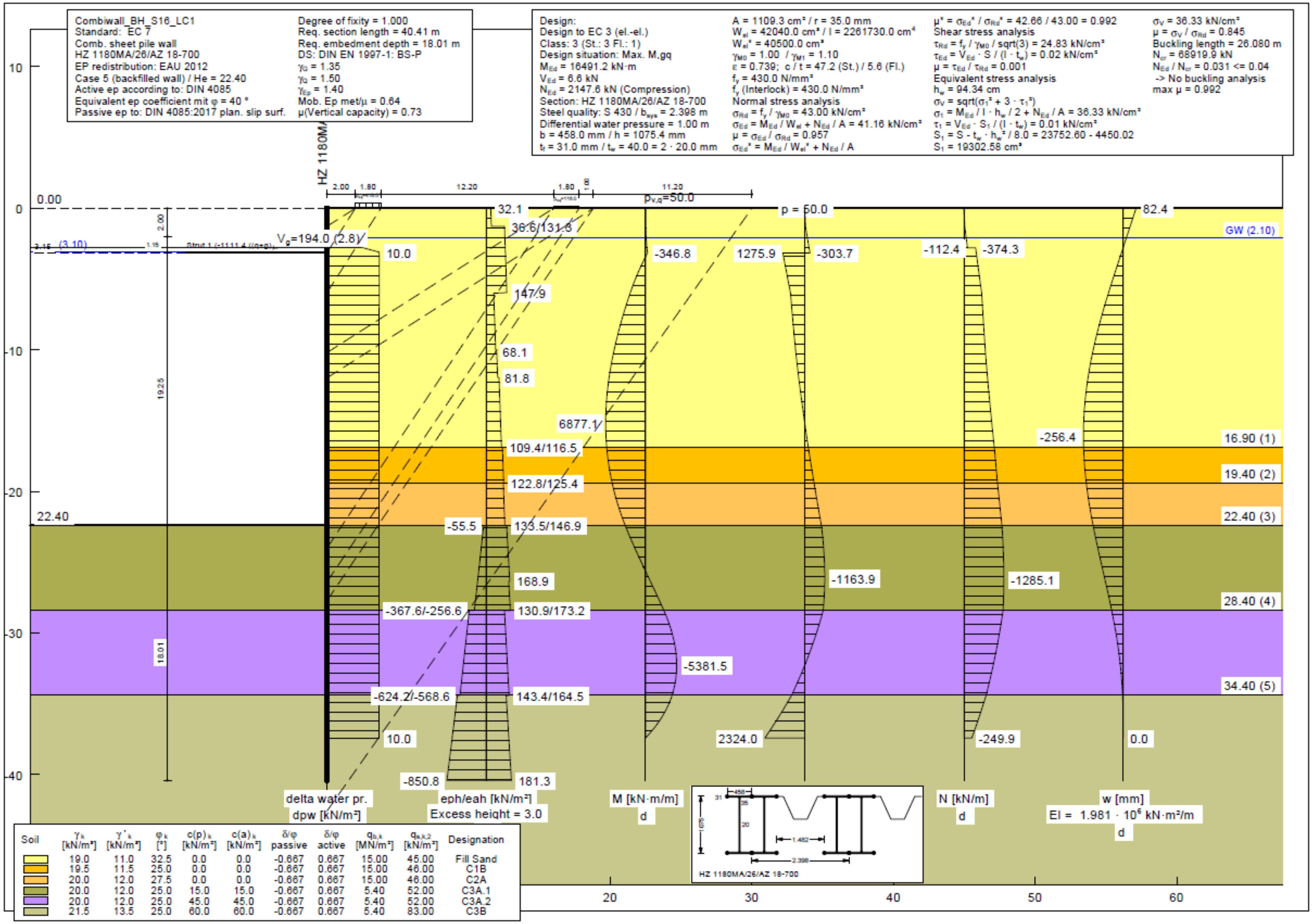



*Figure 34 - Combi Wall Calculation: LC1, No Corrosion, Ground conditions as per borehole B16*

*Table 47 - Calculations for Tie Rods*

| Tie Rod Design Criteria | | |
|---|---|---|
| ULS Design Load | 1238 | kN/m |
| System width | 2,4 | m |
| Design ULS Load for tie rod, $F_{,Ed}$ | 2971 | kN |
| Tie Bar Length | 30 | m |
| SLS Load | 879 | kN/m |
| Serviceability Characteristic Load, $F_{t,serv}$ | 2111 | kN |
| Tie bar extension limit | 50 | mm |
| Design life | 50 | years |
| Thread Notch factor , $k_t$ | 0,6 | |

| Tie Rod Details | | |
|---|---|---|
| Grade | ASDO500 | |
| **Thread Size** | **120** | **mm** |
| **Shaft size** | **90** | **mm** |
| Shaft Area, $A_s$ | 6362 | $mm^2$ |
| $f_y$ | 500 | $N / mm^2$ |
| $f_{ua}$ | 660 | $N / mm^2$ |
| Modulus of Elasticity | 210.000 | $N / mm^2$ |

| Design Tensile Resistance: | OK | |
|---|---|---|
| $F_{t,Rd}$ | 3181,0 | kN |
| Note: $F_{t,Rd}$ from Anker Schroeder Catalgue | | |

| Elongation Check: | OK | |
|---|---|---|
| Stress in Shaft, σ: | 331,8 | Mpa |
| Elongation= | 47 | mm |

| Serviceability Check: | | |
|---|---|---|
| $\gamma_{Mt,serv}$ | 1,1 | |
| $f_y*A_s/\gamma_{Mt,serv} =$ | 2891,7 | kN |
| $F_{t,serv} < f_y*A_s/\gamma_{Mt,serv}$ | OK | |

| Corrosion Allowance: | | |
|---|---|---|
| allow corrosion per side : | 4 | mm |
| Thread Size with corrosion | 128 | mm |
| Shaft Size with corrosion | 98 | mm |
| **Therefore use:** | | |
| **Thread Size** | **130** | **mm** |
| **Shaft Size** | **100** | **mm** |

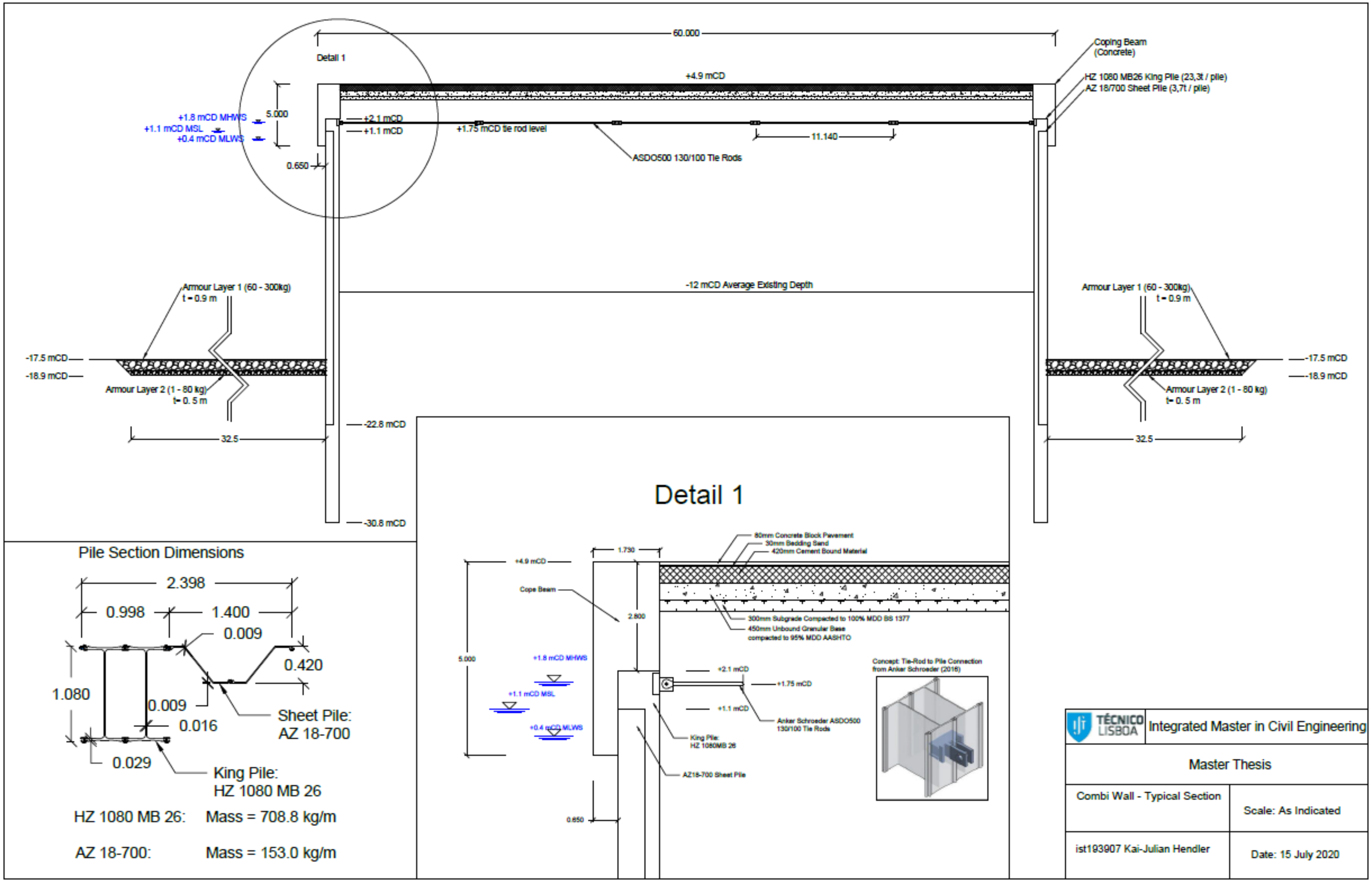



*Figure 35 - Combi Wall: typical Section and Details*

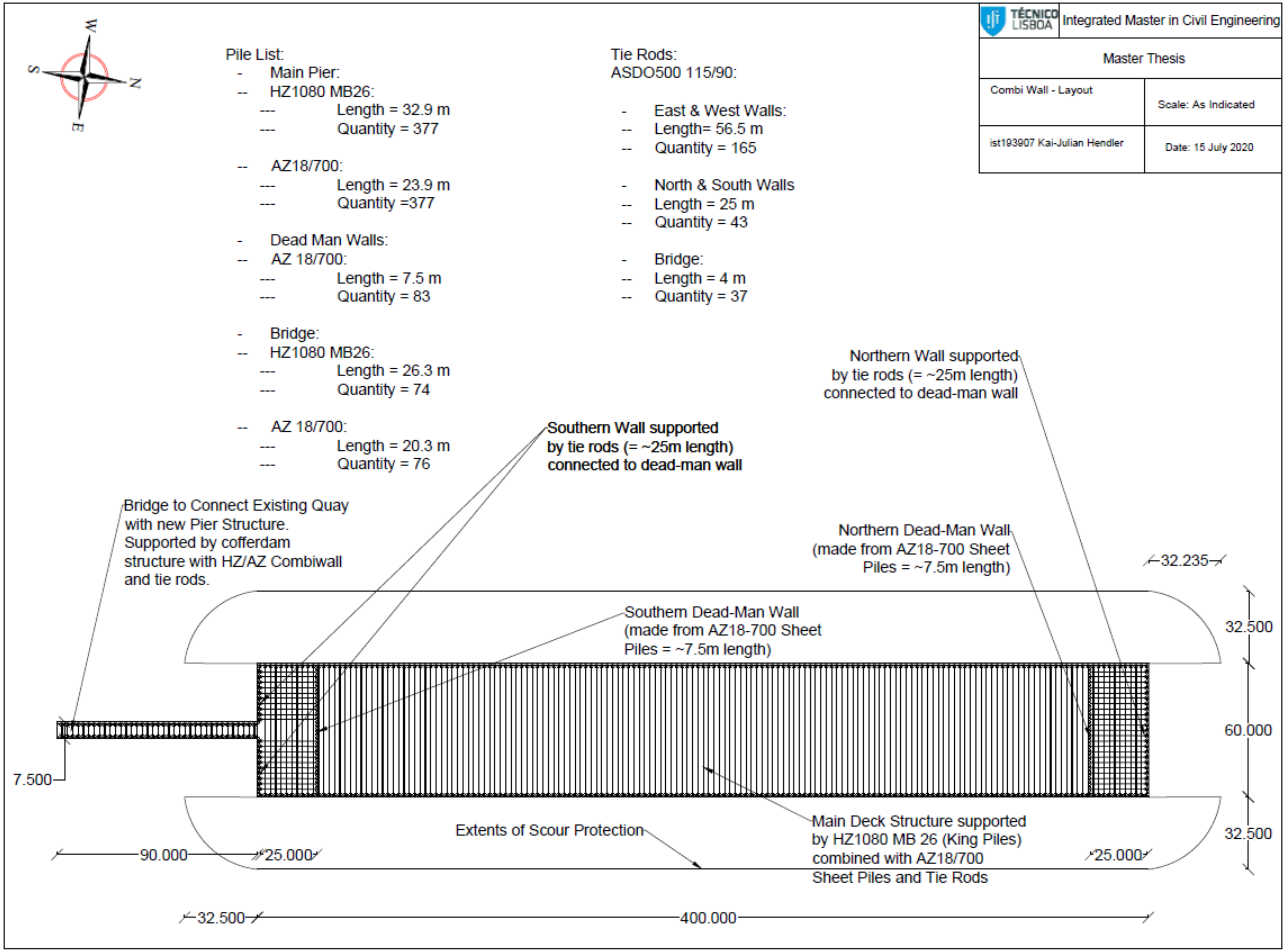


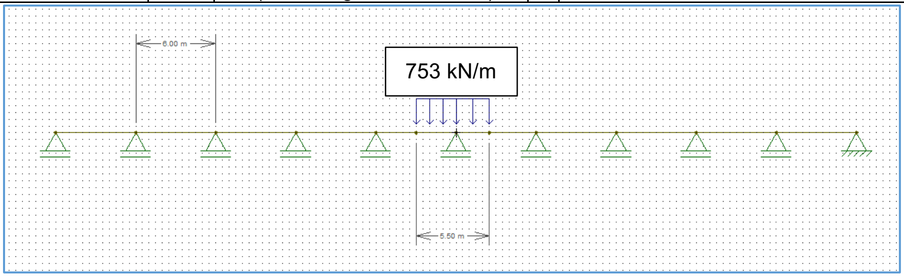

*Figure 36 - Combi Wall: Layout*

# Appendix D

*Table 48 - Open Piled Structure: Calculations for design vertical load of piles*

| **Design Vertical Load** | | | | | | |
|---|---|---|---|---|---|---|
| Liebherr LMH 600-2 | 4139 | kN Max outrigger Pad Loading | | $\gamma_G$ | 1,35 | |
| Outrigger pad Length | 5,5 | m | | $\gamma_Q$ | 1,5 | |
| Pad Load | 753 | kN/m | | **$G_d$** | 1436 | kN |
| Reaction | 3613 | kN | | **$Q_d$** | 4607 | kN |
| Assume load redistribution | 15% | due to pile settlement | | **Design Vertical Load, $V_d$** | **6042** | **kN** |
| Characteristic Live Load, $Q_k$ | 3071 | kN | | | | |
| Characteristic Dead Load, $G_k$ | 1064 | kN (Self Weight of Structure) | | | | |

Ftool Screenshot




Ftool Screenshot

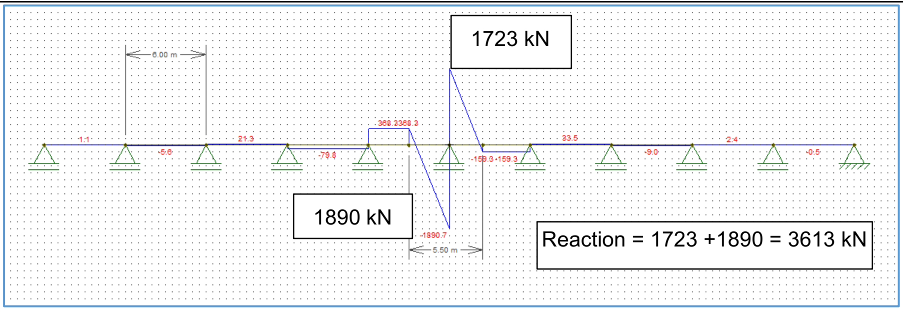


*Table 49 - Open Pile Structure: Pile Capacity Calculations, Scenario a)*

| Scenario a) | | | | | | |
|---|---|---|---|---|---|---|
| **Pile OD** | 0,9 m | R_c_calc_Average | 8.852,9 | ξ_3 = | 1,29 | |
| **Pile Circumf** | 2,8 m | R_c_calc_Min | 8.219,7 | ξ_4 = | 1,15 | |
| **t** | 0,0 m | | | | | |
| **Pile ID** | 0,9 m | Rc_k = | 6863 kN | | | |
| **Area (Total)** | 0,6 m2 | γ_t = | 1,1 | | | |
| **Pile Length** | **40,0 m** | **Rc_d =** | **6.239 kN** | **OK** | All Boreholes | |
| | | **Vd =** | **6.042 kN** | | | |

**Borehole B14**

| Pile Length | 40,000 m | Soil Type | | σ´ (kPa) | ϕ´=δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 2,5 m | Sand (Areia) | C1A | 172,5 | 27,5 | | | 0,52 | 89,8 | 7,1 | 634,7 |
| Layer 2 | 4,5 m | Sand Silty Clay | C2C | 207,5 | 40 | | | 0,84 | 174,1 | 12,7 | 2215,3 |
| Layer 3 | 4,5 m | Sand Silty Clay | C2B | 252,5 | 35 | | | 0,70 | 176,8 | 12,7 | 2249,5 |
| Layer 4 | 3 m | Sand Silty Clay | C2C | 290 | 40 | | | 0,84 | 243,3 | 8,5 | 2064,1 |
| Layer 5 | 5,1 m | Clay Silted | C3B | 330,25 | | 250 | 0,5 | | 125,0 | 14,3 | 1784,8 |
| | | | | | | | | | | | 8.948,49 |
| ξ_3 =ξ_4= | γ_t = | **Rc_d =** | Only Borehole S14 | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| 1,4 | 1,1 | **6.740** | **OK** | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,4 |
| | | | | | | | | | | | **R_c_calc** |
| | | | | | | | | | | | 10.379,9 |

**Borehole B7A**

| Pile Length | 40,000 m | Soil Type | | σ´ (kPa) | ϕ´=δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 4 m | Sand Silty Clay | C2C | 180 | 40 | | | 0,84 | 151,04 | 11,3 | 1708,2 |
| Layer 2 | 1,5 m | Sand Silty Clay | C2B | 207,5 | 35 | | | 0,70 | 145,29 | 4,2 | 616,2 |
| Layer 3 | 1,5 m | Sand Silty Clay | C2C | 222,5 | 40 | | | 0,84 | 186,70 | 4,2 | 791,8 |
| Layer 4 | 12,6 m | Clay Silted | C3B | 292,75 | | 250 | 0,5 | | 125,0 | 35,5 | 4435,5 |
| | | | | | | | | | | | 7.551,77 |
| | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | **R_c_calc** |
| | | | | | | | | | | | 8983,2 |

**Borehole B7**

| Pile Length | 40,000 m | Soil Type | | σ´ (kPa) | ϕ´=δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 2,5 m | Sand Silty Clay | C2A | 172,5 | 27,5 | | | 0,52 | 89,80 | 7,1 | 634,7 |
| Layer 2 | 3 m | Sand Silty Clay | C2B | 200 | 35 | | | 0,70 | 140,04 | 8,5 | 1187,9 |
| Layer 3 | 3 m | Clay Silted | C3A | 230 | | 250 | 0,5 | | 125 | 8,5 | 1060,3 |
| Layer 4 | 11,1 m | Clay Silted | C3B | 300,25 | | 250 | 0,5 | | 125 | 31,2 | 3905,4 |
| | | | | | | | | | | | 6.788,30 |
| | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | **R_c_calc** |
| | | | | | | | | | | | 8.219,69 |

**Borehole B15**

| Pile Length | 40,000 m | Soil Type | | σ´ (kPa) | ϕ´=δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 7 m | Clay Silted | C3A | 195 | | 250 | 0,5 | | 125 | 19,8 | 2474,0 |
| Layer 2 | 12,6 m | Clay Silted | C3B | 292,75 | | 250 | 0,5 | | 125 | 35,5 | 4435,5 |
| | | | | | | | | | | | 6.909,54 |
| | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | **R_c_calc** |
| | | | | | | | | | | | 8.340,93 |

**Borehole B16**

| Pile Length | 40,000 m | Soil Type | | σ´ (kPa) | ϕ´=δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 11,5 m | Clay Silted | C3A | 217,5 | | 250 | 0,5 | | 125 | 32,5 | 4064,4 |
| Layer 2 | 8,1 m | Clay Silted | C3B | 315,25 | | 250 | 0,5 | | 125 | 22,8 | 2845,1 |
| | | | | | | | | | | | 6.909,54 |
| | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | **R_c_calc** |
| | | | | | | | | | | | 8.340,93 |

*Table 50 - Open Pile Structure: Pile Capacity Calculations, Scenario b)*

| Scenario b) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Pile OD | 0,9 m | R_c_calc_Average | 9.672,14 | ξ_3 = | 1,29 | | |
| Pile Circumfe | 2,827 m | R_c_calc_Min | 9.300,04 | ξ_4 = | 1,15 | | |
| t | 0,02 m | | | | | | |
| Pile ID | 0,86 m | Rc_k = | 7498 kN | | | | |
| Area (Total) | 0,636 m2 | γ_t = | 1,1 | | | | |
| **Pile Length** | **45,0 m** | **Rc_d (All boreholes** | **6816 kN** | **OK** | | Vd = | 6042 kN |

**Borehole B14**

| Pile Length | 45,000 m | Soil Type | | σ´ (kPa) | ϕ´ | δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 2,5 m | Sand (Areia) | C1A | 172,5 | 27,5 | 18,3 | | | 0,33 | 57,16 | 7,1 | 404,0 |
| Layer 2 | 4,5 m | Sand Silty Clay | C2C | 207,5 | 40 | 26,7 | | | 0,50 | 104,21 | 12,7 | 1325,9 |
| Layer 3 | 4,5 m | Sand Silty Clay | C2B | 252,5 | 35 | 23,3 | | | 0,43 | 108,92 | 12,7 | 1385,8 |
| Layer 4 | 3 m | Sand Silty Clay | C2C | 290 | 40 | 26,7 | | | 0,50 | 145,64 | 8,5 | 1235,4 |
| Layer 5 | 10,1 m | Clay Silted | C3B | 355,25 | | | 250 | 0,5 | | 125,00 | 28,4 | 3552,0 |
| | | | | | | | | | | | | 7.903,12 |
| ξ_3 =ξ_4= | γ_t = | **Rc_d (Only B14) =** | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| 1,4 | 1,1 | **6.061** | **OK** | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | | 9.334,51 |

**Borehole B7A**

| Pile Length | 45,000 m | Soil Type | | σ´ (kPa) | ϕ´ | δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 4 m | Sand Silty Clay | C2C | 180 | 40 | 26,7 | | | 0,50 | 90,40 | 11,3 | 1022,4 |
| Layer 2 | 1,5 m | Sand Silty Clay | C2B | 207,5 | 35 | 23,3 | | | 0,43 | 89,51 | 4,2 | 379,6 |
| Layer 3 | 1,5 m | Sand Silty Clay | C2C | 222,5 | 40 | 26,7 | | | 0,50 | 111,74 | 4,2 | 473,9 |
| Layer 4 | 17,6 m | Clay Silted | C3B | 317,75 | | | 250 | 0,5 | | 125,00 | 49,6 | 6202,7 |
| | | | | | | | | | | | | 8.078,61 |
| | | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | | 9510,0 |

**Borehole B7**

| Pile Length | 45,000 m | Soil Type | | σ´ (kPa) | ϕ´ | δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 2,5 m | Sand Silty Clay | C2A | 172,5 | 27,5 | 18,3 | | | 0,33 | 57,16 | 7,1 | 404,0 |
| Layer 2 | 3 m | Sand Silty Clay | C2B | 200 | 35 | 23,3 | | | 0,43 | 86,27 | 8,5 | 731,8 |
| Layer 3 | 3 m | Clay Silted | C3A | 230 | | | 250 | 0,5 | | 125,00 | 8,5 | 1060,3 |
| Layer 4 | 16,1 m | Clay Silted | C3B | 325,25 | | | 250 | 0,5 | | 125,00 | 45,4 | 5672,5 |
| | | | | | | | | | | | | 7.868,65 |
| | | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | | 9.300,04 |

**Borehole B15**

| Pile Length | 45,000 m | Soil Type | | σ´ (kPa) | ϕ´ | δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 7 m | Clay Silted | C3A | 195 | | | 250 | 0,5 | | 125,00 | 19,8 | 2474,0 |
| Layer 2 | 17,6 m | Clay Silted | C3B | 317,75 | | | 250 | 0,5 | | 125,00 | 49,6 | 6202,7 |
| | | | | | | | | | | | | 8.676,69 |
| | | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | | 10.108,07 |

**Borehole B16**

| Pile Length | 45,000 m | Soil Type | | σ´ (kPa) | ϕ´ | δ´ | Cu (kPa) | α | β | q_s (kN/m2) | A_s (m2) | R_s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer 1 | 11,5 m | Clay Silted | C3A | 217,5 | | | 250 | 0,5 | | 125,00 | 32,5 | 4064,4 |
| Layer 2 | 13,1 m | Clay Silted | C3B | 340,25 | | | 250 | 0,5 | | 125,00 | 36,9 | 4612,3 |
| | | | | | | | | | | | | 8.676,69 |
| | | | | | | | | **Cu_b** | **Nc** | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | | | | | 250 | 9 | 2250,0 | 0,636 | 1.431,39 |
| | | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | | 10.108,07 |

*Table 51 - Open Pile Structure: Pile Capacity Calculations, Scenario c)*

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Scenario c) | | | | | |
| Pile OD | 0,9 m | | R_c_calc_Average | 8.890,6 | | | ξ_3 = | 1,29 | | |
| Pile Circumference | 2,827 m | | R_c_calc_Min | 8.394,5 | | | ξ_4 = | 1,15 | | |
| t | 0,02 m | | | | | | | | | |
| Pile ID | 0,86 m | | Rc_k = | 6892 | kN | | | | | |
| Area (Total) | 0,636 m2 | | γ_t = | 1,1 | | | | | | |
| **Pile Length** | **43,000 m** | | **Rc_d(All bh's)=** | **6265** | **kN** | OK | | Vd = | 6042 | kN |
| | | | | | Borehole B14 | | | | | |
| **Pile Length** | **43,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 2,5 m | Sand (Areia) | C1A | 172,5 | 27,5 | 18,3 | 0,33 | 57,16 | 7,1 | 404,0 |
| Layer 2 | 4,5 m | Sand Silty Clay | C2C | 207,5 | 40 | 26,7 | 0,50 | 104,21 | 12,7 | 1325,9 |
| Layer 3 | 4,5 m | Sand Silty Clay | C2B | 252,5 | 35 | 23,3 | 0,43 | 108,92 | 12,7 | 1385,8 |
| Layer 4 | 3 m | Sand Silty Clay | C2C | 290 | 40 | 26,7 | 0,50 | 145,64 | 8,5 | 1235,4 |
| Layer 5 | 8,1 m | Clay Silted | C3B | 345,3 | 25 | 16,7 | 0,30 | 103,36 | 22,8 | 2352,6 |
| | | | | | | | | | | 6.703,7 |
| ξ_3 =ξ_4= | γ_t = | **Rc_d (Only B14)=** | | φ´ | σ´ (kPa) | Nq | | q_b (kN/m2) | A_b (m2) | R_b |
| 1,4 | 1,1 | **6.423** | **OK** | 25 | 385,5 | 13 | | 5011,5 | 0,636 | 3.188,18 |
| | | | | | | | | | | R_c_calc |
| | | | | | | | | | | 9.891,9 |
| | | | | | Borehole B7A | | | | | |
| **Pile Length** | **43,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 4 m | Sand Silty Clay | C2C | 180 | 40 | 26,7 | 0,50 | 90,40 | 11,3 | 1022,4 |
| Layer 2 | 1,5 m | Sand Silty Clay | C2B | 207,5 | 35 | 23,3 | 0,43 | 89,51 | 4,2 | 379,6 |
| Layer 3 | 1,5 m | Sand Silty Clay | C2C | 222,5 | 40 | 26,7 | 0,50 | 111,74 | 4,2 | 473,9 |
| Layer 4 | 15,6 m | Clay Silted | C3B | 307,75 | 25 | 16,7 | 0,30 | 92,13 | 44,0 | 4050,8 |
| | | | | | | | | | | 5.926,76 |
| | | | | φ´ | σ´ (kPa) | Nq | | q_b (kN/m2) | A_b (m2) | R_b |
| | | | | 25 | 385,5 | 13 | | 5011,5 | 0,636 | 3.188,2 |
| | | | | | | | | | | R_c_calc |
| | | | | | | | | | | 9114,9 |
| | | | | | Borehole B7 | | | | | |
| **Pile Length** | **43,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 2,5 m | Sand Silty Clay | C2A | 172,5 | 27,5 | 18,3 | 0,33 | 57,16 | 7,1 | 404,0 |
| Layer 2 | 3 m | Sand Silty Clay | C2B | 200 | 35 | 23,3 | 0,43 | 86,27 | 8,5 | 731,8 |
| Layer 3 | 3 m | Clay Silted | C3A | 230 | 25 | 16,7 | 0,30 | 68,86 | 8,5 | 584,1 |
| Layer 4 | 14,1 m | Clay Silted | C3B | 315,25 | 25 | 16,7 | 0,30 | 94,38 | 39,7 | 3749,3 |
| | | | | | | | | | | 5.469,2 |
| | | | | φ´ | σ´ (kPa) | Nq | | q_b (kN/m2) | A_b (m2) | R_b |
| | | | | 25 | 385,5 | 13 | | 5011,5 | 0,636 | 3.188,2 |
| | | | | | | | | | | R_c_calc |
| | | | | | | | | | | 8.657,3 |
| | | | | | Borehole B15 | | | | | |
| **Pile Length** | **43,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 7 m | Clay Silted | C3A | 195 | 25 | 16,7 | 0,30 | 58,38 | 19,8 | 1155,4 |
| Layer 2 | 15,6 m | Clay Silted | C3B | 307,75 | 25 | 16,7 | 0,30 | 92,13 | 44,0 | 4050,8 |
| | | | | | | | | | | 5.206,3 |
| | | | | φ´ | σ´ (kPa) | Nq | | q_b (kN/m2) | A_b (m2) | R_b |
| | | | | 25 | 385,5 | 13 | | 5011,5 | 0,636 | 3.188,18 |
| | | | | | | | | | | R_c_calc |
| | | | | | | | | | | 8.394,45 |
| | | | | | Borehole B16 | | | | | |
| **Pile Length** | **43,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 11,5 m | Clay Silted | C3A | 217,5 | 25 | 16,7 | 0,30 | 65,12 | 32,5 | 2117,3 |
| Layer 2 | 11,1 m | Clay Silted | C3B | 330,25 | 25 | 16,7 | 0,30 | 98,87 | 31,2 | 3089,0 |
| | | | | | | | | | | 5.206,3 |
| | | | | φ´ | σ´ (kPa) | Nq | | q_b (kN/m2) | A_b (m2) | R_b |
| | | | | 25 | 385,5 | 13 | | 5011,5 | 0,636 | 3.188,18 |
| | | | | | | | | | | R_c_calc |
| | | | | | | | | | | 8.394,5 |

*Table 52 - Open Pile Structure: Pile Capacity Calculations, Scenario d)*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Scenario d) | | | | | | |
| Pile OD | 0,9 m | | R_c_calc_Average | 8.739,9 | | ξ_3 = | 1,29 | | | | |
| Pile Circumfe | 2,827 m | | R_c_calc_Min | 8.363,0 | | ξ_4 = | 1,15 | | | | |
| t | 0,02 m | | | | | | | | | | |
| Pile ID | 0,86 m | | Rc_k = | 6775 kN | | | | | | | |
| Area (Total) | 0,636 m2 | | **γ_t =** | **1,1** | | | | | | | |
| **Pile Length** | **46,000 m** | | **Rc_d (all bh's) =** | **6159 kN** | | **OK** | | | Vd = | 6042 | kN |
| | | | | | Borehole B14 | | | | | | |
| **Pile Length** | **46,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | **φ´cv** | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 2,5 m | Sand (Areia) | C1A | 172,5 | 27,5 | 22 | 14,7 | 0,26 | 45,15 | 7,1 | 319,1 |
| Layer 2 | 4,5 m | Sand Silty Clay | C2C | 207,5 | 40 | 32 | 21,3 | 0,39 | 81,04 | 12,7 | 1031,1 |
| Layer 3 | 4,5 m | Sand Silty Clay | C2B | 252,5 | 35 | 28 | 18,7 | 0,34 | 85,30 | 12,7 | 1085,3 |
| Layer 4 | 3 m | Sand Silty Clay | C2C | 290 | 40 | 32 | 21,3 | 0,39 | 113,26 | 8,5 | 960,7 |
| Layer 5 | 11,1 m | Clay Silted | C3B | 360,25 | 25 | 20 | 13,3 | 0,24 | 85,38 | 31,2 | 2667,6 |
| | | | | | | | | | | | 6.063,9 |
| ξ_3 =ξ_4= | γ_t = | **Rc_d (Only B14) =** | | **φ´** | **σ´ (kPa)** | **φ´cv** | **Nq** | | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| 1,4 | 1,1 | **6.169** | **OK** | 25 | 415,5 | 20 | 13 | | 5401,5 | 0,636 | 3.436,29 |
| | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | 9.500,14 |
| | | | | | Borehole B7A | | | | | | |
| **Pile Length** | **46,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | **φ´cv** | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 4 m | Sand Silty Clay | C2C | 180 | 40 | 32 | 21,3 | 0,39 | 70,30 | 11,3 | 795,1 |
| Layer 2 | 1,5 m | Sand Silty Clay | C2B | 207,5 | 35 | 28 | 18,7 | 0,34 | 70,10 | 4,2 | 297,3 |
| Layer 3 | 1,5 m | Sand Silty Clay | C2C | 222,5 | 40 | 32 | 21,3 | 0,39 | 86,90 | 4,2 | 368,5 |
| Layer 4 | 18,6 m | Clay Silted | C3B | 322,75 | 25 | 20 | 13,3 | 0,24 | 76,49 | 52,4 | 4012,0 |
| | | | | | | | | | | | 5.472,9 |
| | | | | **φ´** | **σ´ (kPa)** | **φ´cv** | **Nq** | | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | 25 | 415,5 | 20 | 13 | | 5401,5 | 0,636 | 3.436,29 |
| | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | 8909,2 |
| | | | | | Borehole B7 | | | | | | |
| **Pile Length** | **46,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 2,5 m | Sand Silty Clay | C2A | 172,5 | 27,5 | 22 | 14,7 | 0,26 | 45,15 | 7,1 | 319,1 |
| Layer 2 | 3 m | Sand Silty Clay | C2B | 200 | 35 | 28 | 18,7 | 0,34 | 67,57 | 8,5 | 573,1 |
| Layer 3 | 3 m | Clay Silted | C3A | 230 | 25 | 20 | 13,3 | 0,24 | 54,51 | 8,5 | 462,4 |
| Layer 4 | 17,1 m | Clay Silted | C3B | 330,25 | 25 | 20 | 13,3 | 0,24 | 78,27 | 48,2 | 3773,3 |
| | | | | | | | | | | | 5.127,9 |
| | | | | **φ´** | **σ´ (kPa)** | **φ´cv** | **Nq** | | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | 25 | 415,5 | 20 | 13 | | 5401,5 | 0,636 | 3.436,3 |
| | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | 8.564,2 |
| | | | | | Borehole B15 | | | | | | |
| **Pile Length** | **46,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 7 m | Clay Silted | C3A | 195 | 25 | 20 | 13,3 | 0,24 | 46,22 | 19,8 | 914,7 |
| Layer 2 | 18,6 m | Clay Silted | C3B | 322,75 | 25 | 20 | 13,3 | 0,24 | 76,49 | 52,4 | 4012,0 |
| | | | | | | | | | | | 4.926,7 |
| | | | | **φ´** | **σ´ (kPa)** | **φ´cv** | **Nq** | | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | 25 | 415,5 | 20 | 13 | | 5401,5 | 0,636 | 3.436,3 |
| | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | 8.363,0 |
| | | | | | Borehole B16 | | | | | | |
| **Pile Length** | **46,000 m** | **Soil Type** | | **σ´ (kPa)** | **φ´** | | **δ´** | **β** | **q_s (kN/m2)** | **A_s (m2)** | **R_s** |
| Layer 1 | 11,5 m | Clay Silted | C3A | 217,5 | 25 | 20 | 13,3 | 0,24 | 51,55 | 32,5 | 1676,1 |
| Layer 2 | 14,1 m | Clay Silted | C3B | 345,25 | 25 | 20 | 13,3 | 0,24 | 81,83 | 39,7 | 3250,6 |
| | | | | | | | | | | | 4.926,7 |
| | | | | **φ´** | **σ´ (kPa)** | **φ´cv** | **Nq** | | **q_b (kN/m2)** | **A_b (m2)** | **R_b** |
| | | | | 25 | 415,5 | 20 | 13 | | 5401,5 | 0,636 | 3.436,3 |
| | | | | | | | | | | | R_c_calc |
| | | | | | | | | | | | 8.363,0 |

*Table 53 - Open Piled Structure: Calculations for equivalent stress, bending and shear resistance*

| Pile Properties: | | |
|---|---|---|
| Diameter | 900 | mm |
| thickness | 20 | mm |
| Section Area ($A_s$) | 0,056 | m² |
| $f_y$ | 355 | Mpa |
| ε | 0,81 | |
| Class | 2 | |
| $W_y$ | 0,012286 | m³ |
| $I_y$ | 0,005615 | $m^4$ |
| i | 0,316 | m |

| Equivalent Stress Analysis | | | | | | |
|---|---|---|---|---|---|---|
| Max. Moment | 488 | kNm | σ = | 39.720,6 | kPa | |
| Max Axial Load | 6042 | kN | σ = | 107.563,1 | kPa | |
| | | | | 147.283,8 | kPa | |
| | | | | 147,3 | Mpa | < 355 MPa, Ok |

| Buckling Resistance | | |
|---|---|---|
| Free Length | 19,25 | m |
| Assume k= | 1,25 | |
| Lcr | 24,0625 | |
| ε | 0,81 | |
| λ1 | 76,059 | |
| λ_bar | 1,000666 | |
| χ_curve c | 0,5399 | |
| N_b,Rd | 10766,12 | kN |
| N_Ed | 6042 | kN |
| Mel_Rd | 4361,46 | kNm |
| M_Ed | 488 | kNm |
| kyy=kzy | 1 | Worst Case (Conservative) |
| | 0,673094 < | 1 OK |

| Shear Resistance | | | |
|---|---|---|---|
| Max shear force | 68,1 | kN | |
| $A_v$ | 0,036 | $m^2$ | (Shear Area) |
| $A_v = 2 \times A_s / \pi$ | | | |
| $V_{pl,Rd}$ | 7329,3 | kN (Plastic Shear Resistance) | |
| $V_{pl,Rd} = A_v \times f_y / \sqrt{(3)}$ | | | |
| Shear force is less than half the plastic shear resistance and therefoe do not need to consider the effect of shear on moment resistance. | | | |

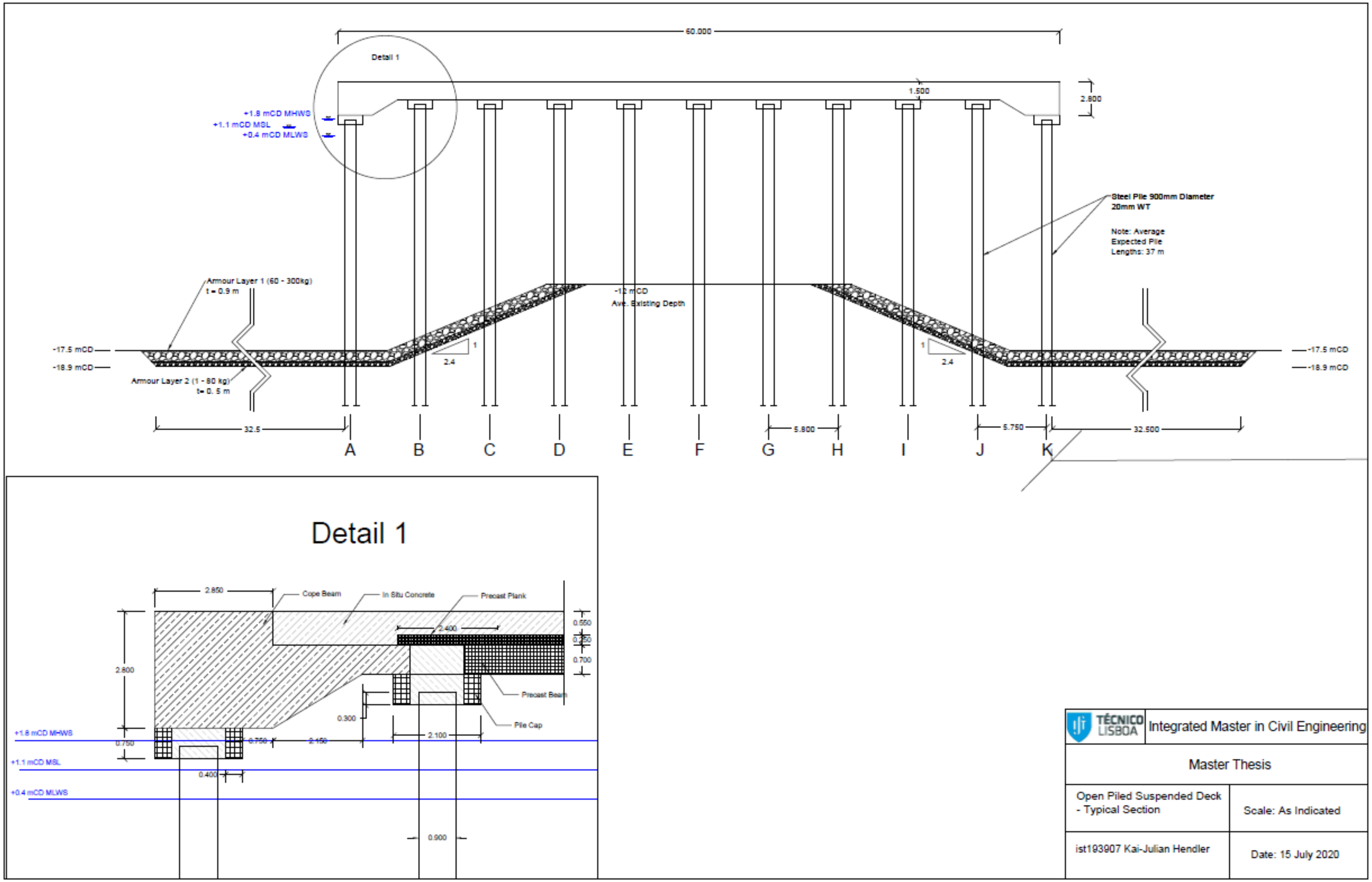



*Figure 37 - Open Piled Structure: Typical Section and Details*

| | |
|---|---|
| TÉCNICO LISBOA | Integrated Master in Civil Engineering |
| Master Thesis | |
| Open Piled Suspended Deck - Layout | Scale: As Indicated |
| ist193907 Kai-Julian Hendler | Date: 15 July 2020 |

- Main Pier:
-- Piles (900mm dia. / 20mm thickness):
--- Quantity = 737
--- Length = 37 m to 46 m
--- Mass = 441 kg/m

- Bridge:
-- Piles (900mm dia. / 20mm thickness):
--- Quantity = 28
--- Length = 30 m

- Main Pier:
-- Precast Beams:
--- Quantity = 670
--- Volume = 5.31 $m^3$ / beam
-- Precast Planks
--- Quantity = 1320
--- Volume = 3.12 $m^3$ / plank

- Bridge:
-- Precast Beams:
--- Quantity = 14
--- Volume = 5.31 $m^3$ / beam
-- Precast Planks
--- Quantity = 28
--- Volume = 3.12 $m^3$ / plank

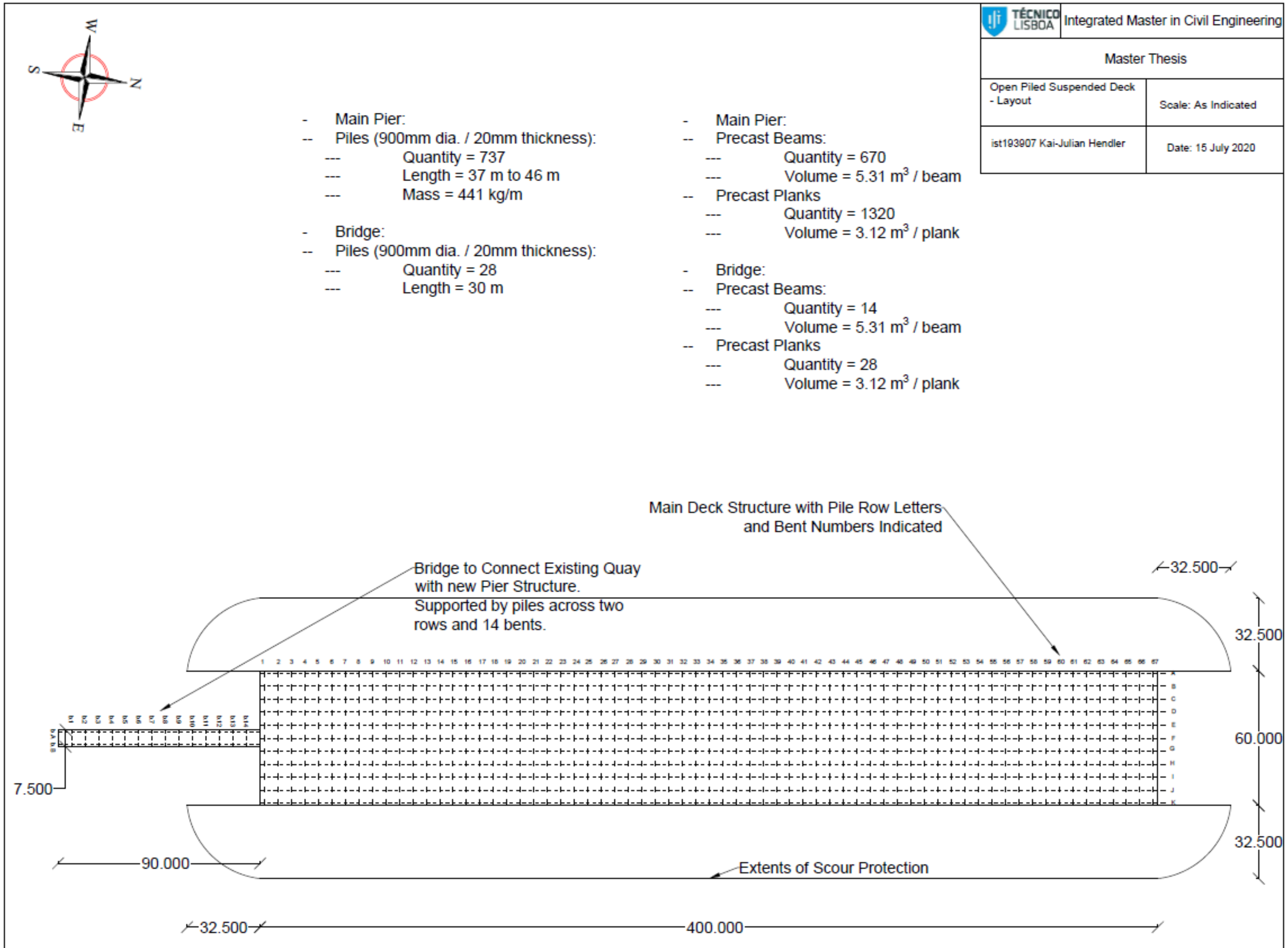



*Figure 38 - Open Piled Structure: Layout*

## Appendix E

*Table 54 - Concrete Components Emission Factors*

| Concrete Components | | | | |
|---|---|---|---|---|
| | Emission Factors | | | |
| **Component** | **(A1-A3)** | **(A4)** | **Unit** | **Comment** |
| **CEM I** | 907,00 | 5,46 | kgCO2e/t | This is the Portland cement EF that was used in the concrete as per the mix design for all concrete components. Used EcoInvent 3 "Cement, Portland {RoW} production \| Cut-off, S" . |
| **Fly Ash** | 4,00 | 111,00 | kgCO2e/t | This is the fly ash EF that was used in all concrete components as per the mix design. Includes the production (A1-A3) of the Fly Ash (according to Concrete Centre (2016)) and shipping (LCA stage A4) over average distance of 9825 km |
| **Limestone** | 15,77 | 111,00 | kgCO2e/t | Limestone was not part of the "original" mix design. Considered as part of sensitivity analysis. Includes the production (A1-A3) of the Limestone (according to ICE V3 database)) and shipping (LCA stage A4) over average distance of 9825 km |
| **GGBS (Ground Granulated Blast Furnace Slag)** | 41,62 | 111,00 | kgCO2e/t | GGBS was not part of the "original" mix design. Considered as part of sensitivity analysis. Includes the production (A1-A3) of the GGBS (according to EPD, number: MRPI code 20.1.00033.005)) and shipping (LCA stage A4) over average distance of 9825 km |
| **Aggregate** | 10,40 | 9,10 | kgCO2e/t | This is the aggregate EF that was used in all concrete components as per the mix design. Includes production of aggregate and transportation of aggregate. Used EcoInvent 3 Datasets "Gravel, crushed {RoW}\| production \| Cut-off, S" and "Transport, freight, lorry >32 metric ton, euro3 {RER}\| market for transport, freight, lorry >32 metric ton, EURO3 \| Cut-off, S". Assumed 100km return trip between quarry and site. |
| **Sand** | 4,20 | 9,10 | kgCO2e/t | This is the sand EF that was used in all concrete components as per the mix design. Includes production of sand and transportation thereof. Used EcoInvent 3 Datasets "Gravel, round {RoW}\| gravel and sand quarry operation \| Cut-off, S" and "Transport, freight, lorry >32 metric ton, euro3 {RER}\| market for transport, freight, lorry >32 metric ton, EURO3 \| Cut-off, S". Assumed 100km return trip between quarry and site. |
| **Superplasticizer** | 1,88 | 0,11 | kgCO2e/kg | This is the Superplasticizer EF that was used in all concrete components as per the mix design. Used EPD from SikaViscocrete - it is a generic EPD for all (Super)plasticizers from European Federation of Concrete Admixtures Associations Ltd. EPD: Number EPD-EFC-20150091-IAG1-EN. Also included a distance 9500km shipping. For shipping used Ecoinvent 3 "transport, freight, sea, transoceanic ship {GLO} \| market for \| Cut-off.S". |
| **Rebar (baseline)** | 1.930,00 | 4,55 | kgCO2e/t | This is the Rebar EF that was used in all concrete components as per the required rebar content. As per SimaPro Industry Data database, "Steel rebar/GLO" includes stages A1-A3 (1930kgCO2e/t). Based on World Steel LCA methodology. Considered "Transport, freight, lorry >32 metric ton, euro3 {RER}\| market for transport, freight, lorry >32 metric ton, EURO3 \| Cut-off, S". Assumed 50km return trip between steel supplier and site. |
| **Rebar (Recycled content)** | 1.200,00 | 4,55 | kgCO2e/t | This is the Rebar EF that was used in the sensitivity analysis to investigate the effect on recycling steel. As per ICE v3 database for a recycled content of 85%. This is based on world steel association data. |

*Table 55 - Caisson Design: Material Quantities and Emission Factors*

| Caisson: Materials Quantities and Emission factors | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Emission Factors | | | * Indicates that this process was counted under LCA stage A5 (Construction) |
| **Item** | **Quantity** | **Unit** | **Comment/Assumptions** | **(A1-A3)** | **(A4)** | **Unit** | **Comment** |
| Dredging | 736.000 | $m^3$ | | | 1,879* | kgCO2e/m3 | Based on article "Life cycle assessment for dredged sediment placement strategies" by Bates, Fox-Lent, Linda Seymour, Wender & Linkov (2015) http://dx.doi.org/10.1016/j.scitotenv.2014.11.003. Assumes a 16km travel distance between dredge and spoil sites. |
| Backfill - Inside Caisson | 157.712 | $m^3$ | 52 Caissons @ 3033 m3 each | | 1,879* | kgCO2e/m3 | Used same as dredging since backfill inside caisson will also be done with a dreger |
| Gravel Joint | 9.576 | $m^3$ | | 19,72 | 17,30 | kgCO2e/m3 | Based it on a gravel density of 1,9t/m3. Used EcoInvent 3 Datasets "Gravel, crushed {RoW}\| production \| Cut-off, S" |
| Backfill - Behind Caisson | 220.272 | $m^3$ | | | 1,879* | kgCO2e/m3 | Used same as dredging since backfill behind caisson will also be done with a dreger |
| **Main Pier:** | | | | | | | |
| Caissons Concrete | 38.251 | $m^3$ | 52 Caissons @ 735,6 $m^3$/ Caisson. 208 kg/m3 rebar content | | 821,00 | kgCO2e/m3 | These EF's represent the combination of the various concrete constituents as per mix design (stages A1-A4) for 1m3 of concrete and differ only due to different rebar content. Concrete batching, pumping and mixer truck movement is counted under LCA stage A5. |
| Cope Beam Concrete | 7.301 | $m^3$ | 147 kg/m3 rebar content | | 690,00 | kgCO2e/m3 | |
| Steel Rebar | 9.029 | tons | | | | | see rebar emission factor. |
| Gravel bed | 28.111 | $m^3$ | 540,6 $m^3$/ Caisson. Assume Bulk density of 1,9t/m3 (Schneider p11.24 | 19,72 | 17,30 | kgCO2e/m3 | Used Ecoinvent 3 datasets (same as Gravel Joint). |
| Geofabric | 11.287 | $m^2$ | Secutex 601 (Naue) 600g/m2 | 1,48 | 0,07 | kgCO2e/m2 | Based on EPD by Naue: EPD-NAUE-STX-001-ref1 2017 - stages A1-A3 (1,48kgCO2e/m2) . For stage A4 considered 200km truck transport from factory to port and 9500km shipping distance. |
| **Bridge:** | | | | | | | |
| Tubular Piles (900 dia.) | 370 | tons | 900mm diameter, 20mm wall thick, 30m length | 2.510,00 | 151,30 | kgCO2e/t | Based on EPD from Turkish manufacturer Emek Boru EPD Number: S-P-01307, stages A1-A3 2510kgCO2e/t. For stage A4 assumed 300km transport via road from Ankara to port of Eregli and then 11000km shipping transport distance. |
| Precast Planks | 140 | $m^3$ | 45 planks | | 753,00 | kgCO2e/m3 | This EF's represent the combination of the various concrete constituents as per mix design (A1-A4) for 1m3 of concrete and has a rebar content of 180 kg/m3 as per mombasa project. Concrete batching, pumping, mixer truck movements and precast element transport is counted under LCA stage A5. |
| Precast Beams | 74 | $m^3$ | 14 beams | | | | |
| In Situ Slab | 371 | $m^3$ | | | | | |
| Pile Plugs | 16 | $m^3$ | | | | | |
| Steel Rebar | 108 | tons | 180 kg/$m^3$ for deck on piles elements as per IL Project | | | | |
| SikaCor ZincR | 440 | kg | Coating for corrosion protection for piles is applied at the factory and not on site. Therefore the transportation (A4) of these materials was not included | 2,63 | Not applicable - see comment. | kgCO2e/kg | based on a generic EPD for reactive resins based on Epoxy resins stages A1-A3. Not 100% accurate but closest match.EPD Number: EPD-FEI-20150300-IBG1-EN |
| SikaCOr SW-500 | 1.319 | kg | | 2,63 | | kgCO2e/kg | Same as for SikaCor ZincR |
| SikaCor EG-5 | 300 | kg | | 5,37 | | kgCO2e/kg | As per EPD for resins based on Polyurethane, certified by Sika that this is applicable to SikaCor EG-5. Stages inlcuded are A1-A3 .EPD number: EPD-FEI-20150254-IBG1-EN |
| Alloy Anode | 3.052 | kg | | 0,71 | 0,11 | kgCO2e/kg | used Ecoinvent 3 dataset "Anode, for metal electrolysis {RoW}\| production \| Cut-off, S". Considered shipping of anodes. |
| **Caisson Yard :** | | | | | | | |
| Precast Piles (900 dia.) | 1.470 | $m^3$ | 494 no piles (123kg/m3 rebar as per Point Quay Project) | | 649,00 | kgCO2e/m3 | This EF's represent the combination of the various concrete constituents as per mix design (A1-A4) for 1m3 of concrete and differ only by rebar content. Concrete batching, pumping, mixer truck movements, pile handling and installationt is counted under LCA stage A5. |
| Support Beams | 2.237 | $m^3$ | 994m of beams - assumed 1,5x1,5 $m^2$ (Assumed 100kg/m3) rebar | | 590,00 | kgCO2e/m3 | |
| Steel Sheet Piles | 140 | tons | AZ18-700, 22m length , 42 No. | 937,00 | 107,20 | kgCO2e/t | As per Arcelor Mittal EPD for sheet piles EPD number EPD-ARM-20160125-IBD3-EN (stages A1-A3). Considers shipping from Rotterdam Port (9500km) |
| Concrete Jack Support Structure | 90 | $m^3$ | | | 690,00 | kgCO2e/m3 | As per mix design. 147kg of rebar per m3 as per PMI Project. |
| **Scour Protection:** | 45.546 | $m^3$ | Total Volume for Layer 1 and 2 Armour. Assume Basalt and bulking factor of 1.3 | 21,60 | 21,00 | kgCO2e/m3 | Assumes the use of basalt (~3t/m3 with bulking factor of 1,3) therefore bulk density = 3/1,3= 2,31 t/m3. Used ecoinvent datasets "basalt quarry operation RoW" and "Transport freight Lorry >32ton". Based on 100km round trip distance to site from Quarrry. |
| **Layerworks and Pavement :** | | | | | | | |
| Concrete Block Pavement | 1.810 | $m^3$ | Assume a local factory produces concrete block pavement. | 131,00 | 9,10 | kgCO2e/t | This process is based on an EPD from Interpave. EPD number is EPD-BPC-20170094-CCD1-EN (A1-A3). EPD is based on UK construction market. Density=2350kg/m3. For transport assume factory is 50km from site(i.e. 100km roundtrip) |
| Bedding Sand | 679 | $m^3$ | | 7,56 | 16,40 | kgCO2e/t | Assumed density of 1,8t/m3. Based on Ecoinvent 3 dataset "Sand {RoW}\| Gravel and Sand Quarry Operation" |
| Cement Bound Material | 9.502 | $m^3$ | | 105,20 | 21,00 | kgCO2e/m3 | Compacted density 2,35t/m3 (Choi et al. , 2018). 5% binder content (Wu, 2011), therefore 118 kg cement. Used Ecoinvent datasets "Gravel, Crushed ,Production {RoW}" "Cement alternative constituents 21-35% {RoW}" for CEMII/B. 100km roundtrip from site to quarry |
| Unbound Granular Base | 10.181 | $m^3$ | | 9,87 | 21,40 | kgCO2e/m3 | Assumed density of 2.35t/m3. Used Ecoinvent dataset "Gravel {RoW}\| Gravel and Sand Quarry Operation". |
| Compacted Subgrade | 6.787 | $m^3$ | | 4,24 | 15,70 | kgCO2e/m3 | Density 1,72 t/m3 (Choi et al. , 2018). Used ELCD dattaset "Sand 0/2 mm, wet and dry quarry, production mix, at plant, undried RER S". |

*Table 56 - Sheet Piled Combi-Wall Design: Material Quantities and Emission Factors*

| Sheet Piled Combi-Wall: Material Quantities and Emission Factors | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | **Emission Factor** | | | * Indicates that this process was counted under LCA stage A5 (Construction) |
| **Item** | **Quantity** | **Unit** | **Comment/Assumptions** | **(A1-A3)** | **(A4)** | **Unit** | **Comment** |
| **Dredging** | 549.240 | $m^3$ | | | 1,879* | kgCO2e/m3 | Based on article "Life cycle assessment for dredged sediment placement strategies" by Bates, Fox-Lent, Linda Seymour, Wender & Linkov (2015) http://dx.doi.org/10.1016/j.scitotenv.2014.11.003. Assumes a 16km travel distance between dredge and spoil sites. Considered as part of LCA stage A5 |
| **Main Pier:** | | | | | | | |
| King Piles | 8.791 | tons | 377 x HZ 1080 MB26 x 32,9m long | 1.530,00 | 107,20 | kgCO2e/t | Used "Steel Sections/GLO" dataset from SimaPro which is based on World Steel LCA - this is the world average used for the baseline analysis. Considers shipping from Rotterdam (9500km). |
| Sheet Piles | 1.474 | tons | 377 x AZ 18-700 x 23,9m long + 83 x 7,5 m lengths for dead man | | | | |
| Piles - Recycled Steel | Same as above. | | | 937,00 | 107,20 | kgCO2e/t | This line represents the emission factor used for the sensitivity analysis to investigate the effects of using a greater recycled steel content. This emission factor is taken from Arcelor Mittal EPD-ARM-20160125-IBD3-EN. |
| Cope Beam (C35/45) | 6.808 | $m^3$ | | | 690,00 | kgCO2e/m3 | See comment for cope beam on caissons. Concrete batching, pumping and mixer truck movement is counted under LCA stage A5. |
| Steel rebar Cope Beam | 1.001 | tons | 147 kg/$m^3$ rebar for Cope as per Pmi project | 1.930,00 | 4,55 | kgCO2e/t | Refer to Caisson inventory comment. |
| Tie-Rods | 633 | tons | ASDO500 130/100 tie rods Anker Schroeder | 1.460,00 | 118,61 | kgCO2e/t | Used "Steel Sections/EU" dataset from SimaPro which is based on World Steel LCA. Considered 9500km shipping and 300km rail transport from factory to port. |
| Tie-Rods link plates, pile connector, pins | 185 | tons | Steel plates grade 500 Mpa | 2.570,00 | 4,55 | kgCO2e/t | Used "Steel plate/GLO" dataset from SimaPro which is based on World Steel LCA. This only considers the production of the steel plates and not the cutting and welding into link elements etc. Considers 50km return trip to factory. |
| Alloy Anodes | 23 | tons | 4 x 15.5 kg anodes per sheet pile pair | 0,71 | 0,11 | kgCO2e/kg | used Ecoinvent 3 dataset "Anode, for metal electrolysis {RoW}\| production \| Cut-off, S". Consider average shipping distance of 9825 km |
| Backfill | 308.476 | $m^3$ | Up to tie-rod level | | 1,879* | kgCO2e/m3 | Used same as dredging since for bulk backfilling up to tie-rod level a dredger will also be used. Considered as part of LCA stage A5 |
| **Bridge:** | | | | | | | |
| King Piles | 1.381 | tons | 74 x HZ 1080 MB26 x 32,9m long | For all these elements the same emission factors as for the "Main Pier" were used. | | | |
| Sheet Piles | 236 | tons | 76 x AZ 18-700 x 23,9m long + 83 x 7,5 m lengths for dead man | | | | |
| Cope Beam (C35/45) | 1.332 | $m^3$ | | | | | |
| Steel rebar Cope Beam | 196 | tons | 147 kg/$m^3$ for Cope | | | | |
| Tie-Rods | 9 | tons | ASDO500 130/100 tie rods Anker Schroeder | | | | |
| pile connector, pins | 7 | tons | Steel plates grade 500 Mpa | | | | |
| Alloy Anodes | 5 | tons | 4 x 15.5 kg anodes per sheet pile pair | | | | |
| Backfill | 9.281 | $m^3$ | Up to tie-rod level | | | | |
| **Scour Protection:** | 45.546 | $m^3$ | Total Volume for Layer 1 and 2 Armour | 21,60 | 21,00 | kgCO2e/m3 | Assumes the use of basalt (~3t/m3 with bulking factor of 1,3) therefore bulk density = 3/1,3= 2,31 t/m3. Used ecoinvent datasets "basalt quarry operation RoW" and "Transport freight Lorry >32ton". Based on 100km round trip distance to site from Quarry. |
| **Layerworks and Pavement :** | | | | | | | |
| Concrete Block Pavement | 1.794 | $m^3$ | Density=2350kg/m3. | 131,00 | 9,10 | kgCO2e/t | This process is based on an EPD from Interpave. EPD number is EPD-BPC-20170094-CCD1-EN (A1-A3). EPD is based on UK construction market. For transport assume factory is 50km from site(i.e. 100km roundtrip) |
| Bedding Sand | 673 | $m^3$ | Assumed density of 1,8t/m3. | 7,56 | 16,40 | kgCO2e/t | Based on Ecoinvent 3 dataset "Sand {RoW}\| Gravel and Sand Quarry Operation". 100km roundtrip to material source(e.g. quarry) |
| Cement Bound Material | 9.417 | $m^3$ | Used a compacted density 2,35t/m3 (Choi et al. , 2018) & 5% binder content (Wu, 2011), therefore 118 kg cement. | 105,20 | 21,00 | kgCO2e/m3 | Used Ecoinvent datasets "Gravel, Crushed ,Production {RoW}" & "Cement alternative constituents 21-35% {RoW}" for CEMII/B. 100km roundtrip from site to quarry |
| Unbound Granular Base | 10.089 | $m^3$ | Assumed density of 2.35t/m3. | 9,87 | 21,40 | kgCO2e/m3 | Used Ecoinvent dataset "Gravel {RoW}\| Gravel and Sand Quarry Operation". |
| Compacted Subgrade | 6.726 | $m^3$ | Density 1,72 t/m3 (Choi et al. , 2018). | 4,24 | 15,70 | kgCO2e/m3 | Used ELCD dataset "Sand 0/2 mm, wet and dry quarry, production mix, at plant, undried RER S". 100km roundtrip to material source(e.g. quarry). |
| Fill above tie rod | 41.926 | $m^3$ | Assumed density of 1,8t/m3. | 7,56 | 16,40 | kgCO2e/m3 | Based on Ecoinvent 3 dataset "Sand {RoW}\| Gravel and Sand Quarry Operation". 100km roundtrip to material source(e.g. quarry). |

*Table 57 - Open Piled Suspended Deck Structure: material Quantities and Emission factors*

| Open Piled Suspended Deck: Material Quantities and Emission Factors | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Emission Factors | | | * Indicates that this process was counted under LCA stage A5 (Construction) |
| **Item** | **Quantity** | **Unit** | **Comment/Assumptions** | **(A1-A3)** | **(A4)** | **Unit** | **Comment** |
| **Dredging** | 623.760 | $m^3$ | | | 1,879* | kgCO2e/m3 | Based on article "Life cycle assessment for dredged sediment placement strategies" by Bates, Fox-Lent, Linda Seymour, Wender & Linkov (2015) http://dx.doi.org/10.1016/j.scitotenv.2014.11.003. Assumes a 16km travel distance between dredge and spoil sites. |
| **Main Pier:** | | | | | | | |
| Piles (737 no.) | 12.026 | tons | 900mm diameter tubular piles. 20mm wall thickness. 37m length | 2.780,00 | 151,30 | kgCO2e/t | For stage A1-A3 used the global World Steel Association LCA dataset for welded tubes. This dataset is part of the SimaPro "Industry Data" database. For stage A4 assumed 300km transport via road from Ankara to port of Eregli and then 11000km shipping transport distance. |
| Piles - Recycled | Same as above. This emission factor was only used in the sensitivity analysis to see the effect of using a greater recycled content in the steel | | | 1.470,00 | as above | | This emission factor was taken from the ICE V3 database for welded pipe with a recycled content of 85%. The dataset is based on World Steel Association LCA. |
| Pile Plugs | 2.116 | $m^3$ | 737 No. | 753,00 | | kgCO2e/m3 | This emission factor represents the combination of the various concrete constituents as per the mix design for LCA stages A1-A4 for one m3 of concrete with a rebar content of 180 kg/m3. Concrete pumping and mixer truck operation are counted under LCA stage 5. |
| Pile Caps | 1.503 | $m^3$ | 737 No. | | | | |
| Cope Beam | 10.764 | $m^3$ | 11,7 m3/m | | | | |
| Precast Beams | 3.558 | $m^3$ | 670 No. | | | | |
| Precast planks | 4.118 | $m^3$ | 1320 No. | | | | |
| Insitu Slab | 10.329 | $m^3$ | | | | | |
| Steel rebar | 5.830 | tons | 180 kg/$m^3$ for Open Piled structure (based on IL project) | See rebar emission factor | | | |
| Alloy Anodes | 80 | tons | 109 kg alloy anode per pile | 0,71 | 0,11 | kgCO2e/kg | used Ecoinvent 3 dataset "Anode, for metal electrolysis {RoW}\| production \| Cut-off, S". Considered shipping of anodes. |
| **Coating: (on average 22.2m coated length per pile). Coating for corrosion protection is applied at the factory and not on site. Therefore the transportation (A4) of these materials was not included.** | | | | | | | |
| 1st Coat - Sikacor Zinc R. | 4.134 | L | Density: 2,8 kg /l | 2,63 | Not applicable- see | kgCO2e/kg | based on a generic EPD for reactive resins based on Epoxy resins stages A1-A3. Not 100% accurate but closest match. EPD Number: EPD-FEI-20150300-IBG1-EN |
| 2nd Coat - SikaCor SW-500 | 23.151 | L | Density: 1,5 kg/l | 2,63 | | kgCO2e/kg | Same as for SikaCor ZincR |
| 3rd Coat - SikaCor EG-5 | 6.055 | L | Density: 1,3 kg/l | 5,37 | | kgCO2e/kg | As per EPD for resins based on Polyurethane, certified by Sika that this is applicable to SikaCor EG-5. Stages included are A1-A3 .EPD number: EPD-FEI-20150254-IBG1-EN |
| **Bridge:** | | | | | | | |
| Piles | 370 | tons | 900mm diameter tubular piles. 20mm wall thickness. 30m length | Same as for main pier | | | |
| Pile Plugs | 18 | $m^3$ | (C35/45) | | | | |
| Pile Caps | 93 | $m^3$ | (C35/45) | | | | |
| Precast Beams | 74 | $m^3$ | (C35/45) | | | | |
| Precast planks | 87 | $m^3$ | (C35/45) | | | | |
| Insitu Slab | 343 | $m^3$ | (C35/45) | | | | |
| Steel rebar | 111 | tons | 180 kg/$m^3$ for Open Piled structure (based on Mombasa) | | | | |
| Alloy Anodes | 3 | tons | 109 kg alloy anode per pile | | | | |
| Coating | | | | | | | |
| 1st Coat | 157 | L | Sikacor Zinc R. 2,8 kg / L . 50 Microns. As per Mombasa Specs. | | | | |
| 2nd Coat | 880 | L | SikaCor SW-500. 1,5 kg/l. 500 Microns. 22.2m coated length per p | | | | |
| 3rd Coat | 230 | L | SikaCor EG-5. 1,3 kg/l. 80 Microns | | | | |
| **Scour Protection:** | 71.034 | $m^3$ | Total Volume for Layer 1 and 2 Armour | 21,60 | 21,00 | kgCO2e/m3 | Assumes the use of basalt (~3t/m3 with bulking factor of 1,3) therefore bulk density = 3/1,3= 2,31 t/m3. Used ecoinvent datasets "basalt quarry operation RoW" and "Transport freight Lorry >32ton". Based on 100km round trip distance to site from Quarry. |

*Table 58 - Summary of Material Volume and Mass for each three design options*

| Caisson Pier Volume and Mass Summary | | | | |
|---|---|---|---|---|
| **Item** | **Quantity** | **Units** | **Density (t/m3)** | **Mass (tons)** |
| Concrete | 49.951 | m3 | 2,50 | 124.877 |
| Steel Rebar | | | | 9.547 |
| Tubular Piles | | | | 370 |
| Sheet Piles and King Piles | | | | - |
| Tie Rods and Connectors | | | | - |
| Dredging | 736.000 | m3 | 1,90 | 1.398.400 |
| Backfill | 377.984 | m3 | 1,90 | 718.170 |
| Gravel (Joints and Bed) | 37.688 | m3 | 1,90 | 71.606 |
| Scour Protection | 45.546 | m3 | 2,31 | 105.210 |
| Layerworks & Pavement | | | | 63.404 |
| | | | TOTAL MASS in metric tons = | **2.491.583** |

| Combi-Wall Pier Volume and Mass Summary | | | | |
|---|---|---|---|---|
| **Item** | **Quantity** | **Units** | **Density (t/m3)** | **Mass (tons)** |
| Concrete | 8.140 | m3 | 2,50 | 20.350 |
| Steel Rebar | | | | 1.197 |
| Tubular Piles | | | | - |
| Sheet Piles and King Piles | | | | 11.882 |
| Tie Rods and Connectors | | | | 834 |
| Dredging | 549.240 | m3 | 1,90 | 1.043.556 |
| Backfill | 317.757 | m3 | 1,90 | 603.738 |
| Gravel (Joints and Bed) | - | m3 | 1,90 | - |
| Scour Protection | 45.546 | m3 | 2,31 | 105.210 |
| Layerworks | | | | 138.300 |
| | | | TOTAL MASS in metric tons = | **1.925.066** |

| Open-Piled Pier Volume and Mass Summary | | | | |
|---|---|---|---|---|
| **Item** | **Quantity** | **Units** | **Density (t/m3)** | **Mass (tons)** |
| Concrete | 33.004 | m3 | 2,50 | 82.509 |
| Steel Rebar | | | | 5.941 |
| Tubular Piles | | | | 12.396 |
| Sheet Piles and King Piles | | | | - |
| Tie Rods and Connectors | | | | - |
| Dredging | 623.760 | m3 | 1,90 | 1.185.144 |
| Backfill | - | m3 | 1,90 | - |
| Gravel (Joints and Bed) | - | m3 | 1,90 | - |
| Scour Protection | 71.034 | m3 | 2,31 | 164.088 |
| Layerworks | | | | - |
| | | | TOTAL MASS in metric tons = | **1.450.078** |

## Appendix F

*Table 59 - Transport distances and associated emission factors*

| Transport Distances | | | | | | |
|---|---|---|---|---|---|---|
| This table summarises the assumptions used to calculate the emissions due to transportation of materials from factory to construction site (LCA stage A4). This is how the Emission factors in the tables in Appendix E for LCA stage A4 were calculated. | | | | | | |
| Item | Distance | | Comment | | | |
| Quarry to Site | 50 | km | for scour rock, gravels, layer works, aggregates, sands. return trip= 10 | 0,091 | kgCO2e/tkm | Transport freight lorry > 32 metric ton {RoW}, Ecoinvent 3 dataset. |
| Cement factory to Site | 30 | km | transporting cement from factory to site. return trip = 60km | 0,091 | kgCO2e/tkm | Transport freight lorry > 32 metric ton {RoW}, Ecoinvent 3 dataset |
| Steel Factory/Supplier to site | 25 | km | transporting smaller steel (rebar etc.) to site. ret trip = 50km | 0,091 | kgCO2e/tkm | Transport freight lorry > 32 metric ton {RoW}, Ecoinvent 3 dataset |
| International Shipping | 9.825 | km | International Shipping | 0,0113 | kgCO2e/tkm | from Ecoinvent 3 dataset. "Transport, freight, sea, transoceanic ship {GLO}" |
| Mobilisation / Demobilisation Distance | 9.825 | km | Average distance from Durban, Lisbon, Shanghai, Rotterdam to East or West Africa. | 22,29* | kgCO2e/km | *Counted under LCA stage A5. Used the recommendations from IPCC report "CO2, CH4 , AND N2O EMISSIONS FROM TRANSPORTATION -WATER - BORNE NAVIGATION" for a tug boat. Access: https://www.ipcc-nggip.iges.or.jp/public/gp/gpg-bgp.html . |

*Table 60 - Calculations for Tugboat Emission Factors*

| Tug Boat emission factor Calculations for Open Ocean Operation and Manoeuvring Operation | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | | **Unit** | | **Unit** | | **Unit** | **Source:** |
| **Fuel Oil Density** | 1.059.000,00 | l/Gg = | 1.059,00 | l/Mg | | | Jun, et al., 2002, Table 11 |
| **Tug Speed** | 12,50 | knots = | 23,15 | km/h = | 555,60 | km/day | Stan Tug 3011 |
| **Tug Boat fuel consumption (at full power)** | 14,40 | Mg/ day = | 15.249,60 | l/day = | **27,45** | **l/km** | Jun, et al., 2002, Table 13 |
| **Tug fuel consumption whilst Manoeuvring is 40% of full power:** | | | 6.099,84 | l/day = | **254,16** | **l/h** | Jun, et al., 2002, p.82 |
| **Q, Calorific Value, Fuel Oil** | 40,19 | TJ/Gg | 3,80E-05 | TJ/l | | | Jun, et al., 2002, Table 12 |
| **Emission factors:** | | | | | | | |
| $CO_2$ | 21.100,00 | kg/TJ = | 8,01E-01 | kg/l | | | Jun, et al., 2002, Table 4 |
| $CH_4$ | 5,00 | kg/TJ = | 1,90E-04 | kg/l | | | Jun, et al., 2002, Table 5 |
| $N_2O$ | 0,60 | kg/TJ = | 2,28E-05 | kg/l | | | Jun, et al., 2002, Table 5 |
| **Calculated Emission Factors:** | **Open Ocean (at full Power)** | | **Manoeuvring** | | Note: This table displays the methods used for the calculation of the emission factors for tug boats. The calculations were done following the recommendations from IPCC report "CO2, CH4 , AND N2O EMISSIONS FROM TRANSPORTATION -WATER - BORNE NAVIGATION" (Jun, et al. , 2002). The Global Warming Potential (GWP) for carbon dioxide, methane and Nitrous Oxide as per IPCC (2013). | | |
| $CO_2$ | 2,20E+01 | kg $CO_2$ /km | 2,04E+02 | kg $CO_2$ /h | | | |
| $CH_4$ | 5,21E-03 | kg $CH_4$/km | 4,82E-02 | kg $CH_4$/h | | | |
| $N_2O$ | 6,25E-04 | kg $N_2O$/km | 5,79E-03 | kg $N_2O$/h | | | |
| **Multiply by GWP to get equivalent $CO_2$ :** | **Open Ocean (at full Power)** | | **Manoeuvring** | | | | |
| GWP of $CO_2$ = 1 | 21,98 | kg $CO_2$ e/km | 203,52 | kg $CO_2$ e/h | | | |
| GWP $CH_4$ = 28 | 0,15 | kg $CO_2$ e/km | 1,35 | kg $CO_2$ e/h | | | |
| GWP $N_2O$ = 265 | 0,17 | kg $CO_2$ e/km | 1,53 | kg $CO_2$ e/h | | | |
| **Calculated Emission factors:** | **22,29** | **kg $CO_2$ e/km** | **206,41** | **kg $CO_2$ e/h** | | | |

# Appendix G

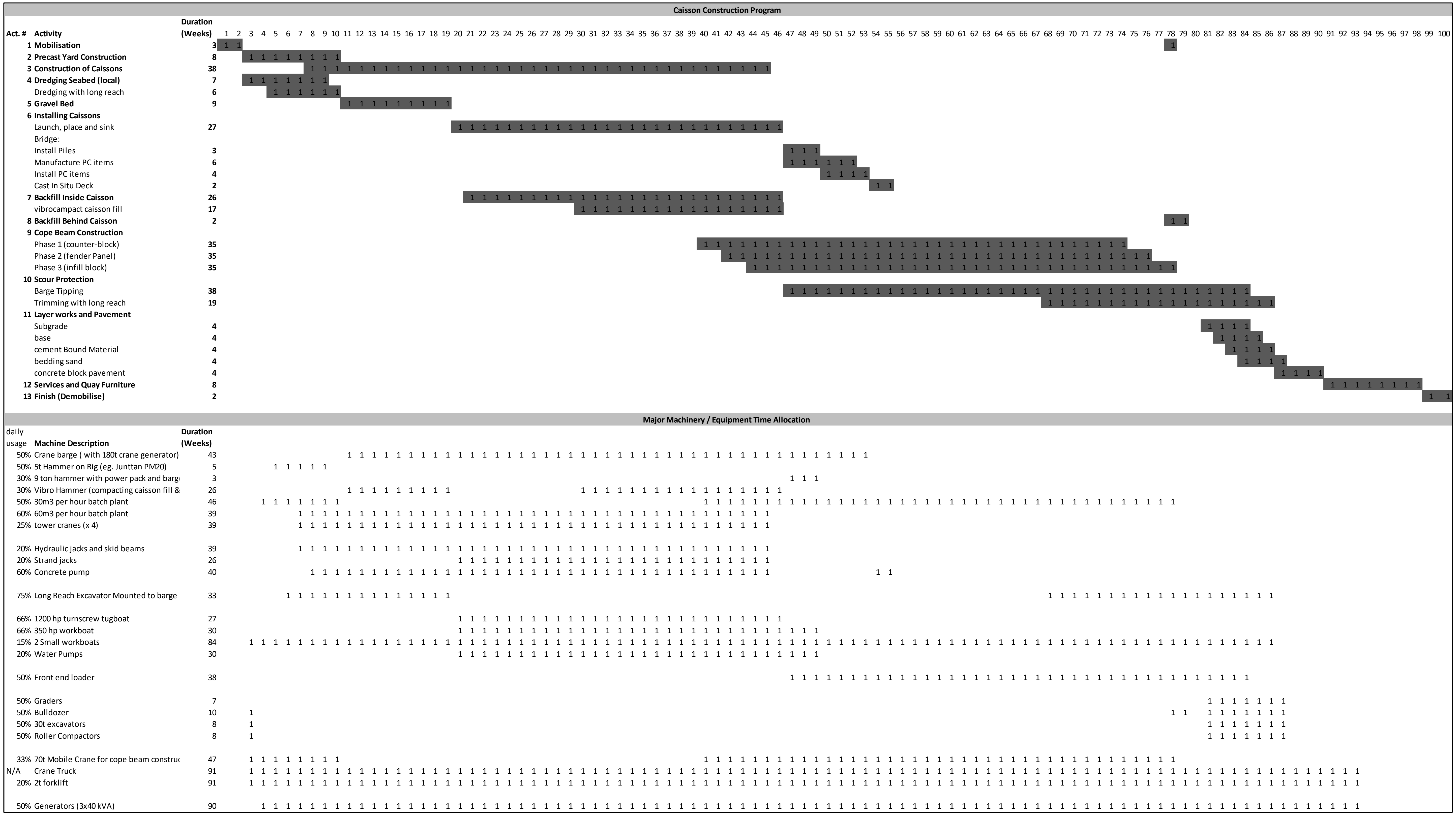



*Figure 39 - Caissons Design: Construction Programme and Major Machinery Time Allocation*


*Figure 40 - Sheet Piled Combi Wall Design: Construction Programme and Major Machinery Time Allocation*


*Figure 41 - Open Piled Suspended Deck Design: Construction Programme and Major Machinery Time Allocation*

*Table 61 - Caisson Design: Machine Hours and Emission Factors*

| Caissons: Major Machinery Hours and Emission factors (LCA Stage A5) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | | | | | **Emission factor** | | |
| Crane barge (with 180t crane & generator): | **Quantity** | **Unit** | **Comment/Assumptions** | **Power (kW)** | **(A5)** | **Unit** | **Emission Factor Description** |
| 180t Crane | 1.290 | h | Kobelco CKE1800 | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Generator | 1.290 | h | John Deere 4045 | 40 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| 5t Hammer on Rig (e.g. Junttan PM20) | 150 | h | for precast piles | 224 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 9 ton hammer with power pack and barge m | 54 | h | for steel piles (bridge) - PVE7/9 | 242 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Vibro Hammer (compacting caisson fill) | 468 | h | Compacting Caisson fill & "potato mashing " - ICE44B | 444 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 30m3 per hour batch plant | 1.380 | h | Turkuaz 40 | 34 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| 60m3 per hour batch plant | 1.404 | h | TurkuaZ 60 | 64,5 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| tower cranes (x 4) | 2.340 | h | Liebherr 125 EC-B 6 | 51 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| Hydraulic jacks and skid beams | 468 | h | | 55 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| Strand jacks | 312 | h | HSL-Series Enerpac 74 hp | 55 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| Concrete mixer trucks (x3) | 8.325 | h | Assume one 6m3 truck can process ist load in one hour | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Concrete pump truck | 1.440 | h | | 421 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Dredger (TSHD) - local | N/A | h | An emission factor was per cubic meter of dredged material as per Bates, et al. (2015).Refer to Appendix E for table quantifying dredged material. | | | | |
| Long Reach Excavator Mounted to barge | 1.485 | h | Trimming dredge trench, gravel bed and scour protection. Hitachi ZX870 | 397kW | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| 1200 hp turn screw tugboat | 1.069 | h | Towing Caissons, Mobilising Plant | 895 | 206,41 | kgCO2e/h | Based on recommendations of IPCC background paper on Emissions from Transportation-water-borne Navigation (Jun, et al., |
| 350 hp workboat | 1.188 | h | Towing caissons. assisting barge moves | 261 | 206,41 | kgCO2e/h | 2002) |
| 2 Small workboats | 1.512 | h | transporting personnel, assisting in barge moves. tot. hours for both boats. Assume 30hp outboard Motor | 22 | 20,02 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO} \| Cut-off, S" |
| Water Pumps | 416 | h | filling caissons. 1 pump can fill a caisson in 8h.. Diesel Set is a John Deere 4045D 71hp | 53 | 20,02 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO} \| Cut-off, S" |
| Front end loader | 1.140 | h | tipping scour. CAT 930G. | 119 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| Graders | 210 | h | Cat 140 Grade | 186 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| Bulldozer | 300 | h | Cat D6 Bulldozer | 187 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| Roller Compactor | 240 | h | | 75 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| 70t Mobile Crane for cope beam constructio | 931 | h | precast yard construction, cope beam construction | 200 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Crane Truck | 5.460 | km's | 10 km average daily travel distance (assume average load of 2 ton) | N/A | 1,02 | kgCO2e/km | Ecoinvent 3 Dataset, Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}\| Cut-off, S |
| 2t forklift | 1.092 | h | general use. Toyota | 36 | 31,07 | kgCO2e/h | Ecoinvent 3 Dataset, Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor {GLO}\| Cut-off, S |
| Generators (3x40 kVA) | 8.100 | h | general use. tot. hours for all three generators | 40 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |

*Table 62 - Sheet Piled Combi Wall Design: Machine Hours and Emission Factors*

| Sheet Piled Combi Wall: Major Machinery Hours and Emission factors (LCA Stage A5) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Item** | | | | | **Emission factor** | | |
| Crane barge ( with 180t crane generator) | **Quantity** | **Unit** | **Comment/Assumptions** | **Power (kW)** | **(A5)** | **Unit** | **Emission Factor Description** |
| 180t Crane | 1.320 | h | Kobelco CKE1800 | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Generator | 1.320 | h | John Deere 4045 | 40 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| 110t quayside crane | 792 | h | Kobelco CKE1100 | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 16 ton hammer with power pack for king piles | 792 | h | Junttan 14-16S | 298 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Vibro Hammer for temp piles and sheet piles | 792 | h | Temporary piles and sheet piles - ICE 44B | 444 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Dredger (TSHD) - local | N/A | h | An emission factor was per cubic meter of dredged material as per Bates, et al. (2015).Refer to Appendix E for table quantifying dredged material. | | | | |
| Long reach excavator | 1.080 | h | for dredging and scour protection. Hitachi ZX870 | 397 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| 70t Mobile Crane | 684 | h | tie rods installation and cope beam construction. Tadano GR700E | 200 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 30t Mobile Crane - 1 | 342 | h | tie rods installation. Tadano GR-300EX | 160 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 30t Mobile Crane -2 | 342 | h | tie rods installation. Tadano GR-300EX | 160 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 30m3 per hour batch plant | 1.080 | h | Turkuaz 40 | 34 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| Concrete mixer trucks (x3) | 1.357 | h | Assume one 6m3 truck can process the 6m3 in one hour | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Concrete Pump truck | 648 | h | As per Sandanayake et. al (2015) | 421 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Graders | 210 | h | Cat 140 Grade | 186 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| Bulldozer | 570 | h | Cat D6 Bulldozer | 187 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| Roller Compactors | 210 | h | | 75 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| Front end loader | 1.140 | h | tipping scour. CAT 930G. | 119 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| 350 hp workboat/tug | 792 | h | assisting barge moves | 261 | 0,00 | kgCO2e/h | Based on recommendations of IPCC background paper on Emissions from Transportation-water-borne Navigation (Jun, et al., 2002) |
| 1 Small workboat | 873 | h | transporting personnel, assisting in barge moves. Assume 30hp o | 22 | 20,02 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO} \| Cut-off, S" |
| Crane Truck | 6.000 | km | 10 km average daily travel distance (assume average load of 2 tor | N/A | 1,02 | kgCO2e/km | Ecoinvent 3 Dataset, Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}\| Cut-off, S |
| 2t forklift | 1.200 | h | general use , Toyota | 36 | 31,07 | kgCO2e/h | Ecoinvent 3 Dataset, Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor {GLO}\| Cut-off, S |
| Generators (3x40 kVA) | 8.100 | h | general use. tot. hours for all three generators | 40 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |

*Table 63 - Open Piled Suspended Deck Design: Machine Hours and Emission Factors*

| Open Piled Suspended Deck: Major Machinery Hours and Emission factors (LCA Stage A5) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Item | Quantity | Unit | Comment/Assumptions | Power (kW) | Emission factor (A5) | Emission factor Unit | Emission Factor Description |
| Dredger (TSHD) - local | N/A | h | An emission factor was per cubic meter of dredged material as per Bates, et al. (2015).Refer to Appendix E for table quantifying dredged material. | | | | |
| Long reach excavator | 1.620 | h | for dredging and scour protection. Hitachi ZX870 | 397 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| Concrete mixer trucks | 5.501 | h | Assume one 6m3 truck can process the 6m3 in one hour, for all co | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Concrete Pump truck | 1.746 | h | for all concrete works | 421 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| | | | | | | | |
| 30m3 per hour batch plant | 2.040 | h | Turkuaz 40 | 34 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| 70 t Mobile Crane | 2.040 | h | Tadano GR700EX | 200 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| | | | | | | | |
| Crane barge No 1 Piling | | | | | | | |
| 180t crane | 1.800 | h | Kobelco CKE1800 | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Generator | 1.800 | h | John Deere 4045 | 40 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| 110t quayside crane | 1.080 | h | Kobelco CKE1100 | 247 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 9 or 16 ton hammer with power pack | 1.080 | h | Junttan 14-16S | 298 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| Vibro Hammer | 1.080 | h | ICE 44B | 444 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| | | | | | | | |
| Front end loader | 1.800 | h | tipping scour. CAT 930G. | 119 | 149,04 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , High load factor {GLO} \| Cut-off, S" |
| | | | | | | | |
| Crane barge No 2 (180t crane + generator) | 1.740 | h | This barge is used for the installation of precast elements. Emission factors for crane and generator same as for crane barge 1 | | | | |
| | | | | | | | |
| 70t Mobile Crane | 1.422 | h | Tadano GR700EX | 200 | 81,36 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 74,57 kW , Steady State \| Cut-off, S" |
| 30m3 per hour batch plant | 1.422 | h | Turkuaz 40 | 34 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |
| | | | | | | | |
| 350 hp workboat/tug | 1.332 | h | assisting barge moves | 261 | 206,41 | kgCO2e/h | Based on recommendations of IPCC background paper on Emissions from Transportation-water-borne Navigation (Jun, et al., 2002) |
| 2 Small workboat | 1.746 | h | transporting personnel, assisting in barge moves. Assume 30hp o | 22 | 20,02 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO} \| Cut-off, S" |
| | | | | | | | |
| Crane Truck | 5.820 | km | 10 km average daily travel distance (assume average load of 2 tor | N/A | 1,02 | kgCO2e/km | Ecoinvent 3 Dataset, Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}\| Cut-off, S |
| 2t forklift | 1.164 | h | general use , Toyota | 36 | 31,07 | kgCO2e/h | Ecoinvent 3 Dataset, Machine operation, diesel, >= 18.64 kW and < 74.57 kW, high load factor {GLO}\| Cut-off, S |
| Generators (3x40 kVA) | 8.640 | h | general use. tot. hours for all three generators | 40 | 18,29 | kgCO2e/h | Ecoinvent 3 Dataset, "Machine Operation Diesel >= 18,64 and < 74,57 kW , generator \| Cut-off, S" |

## Appendix H

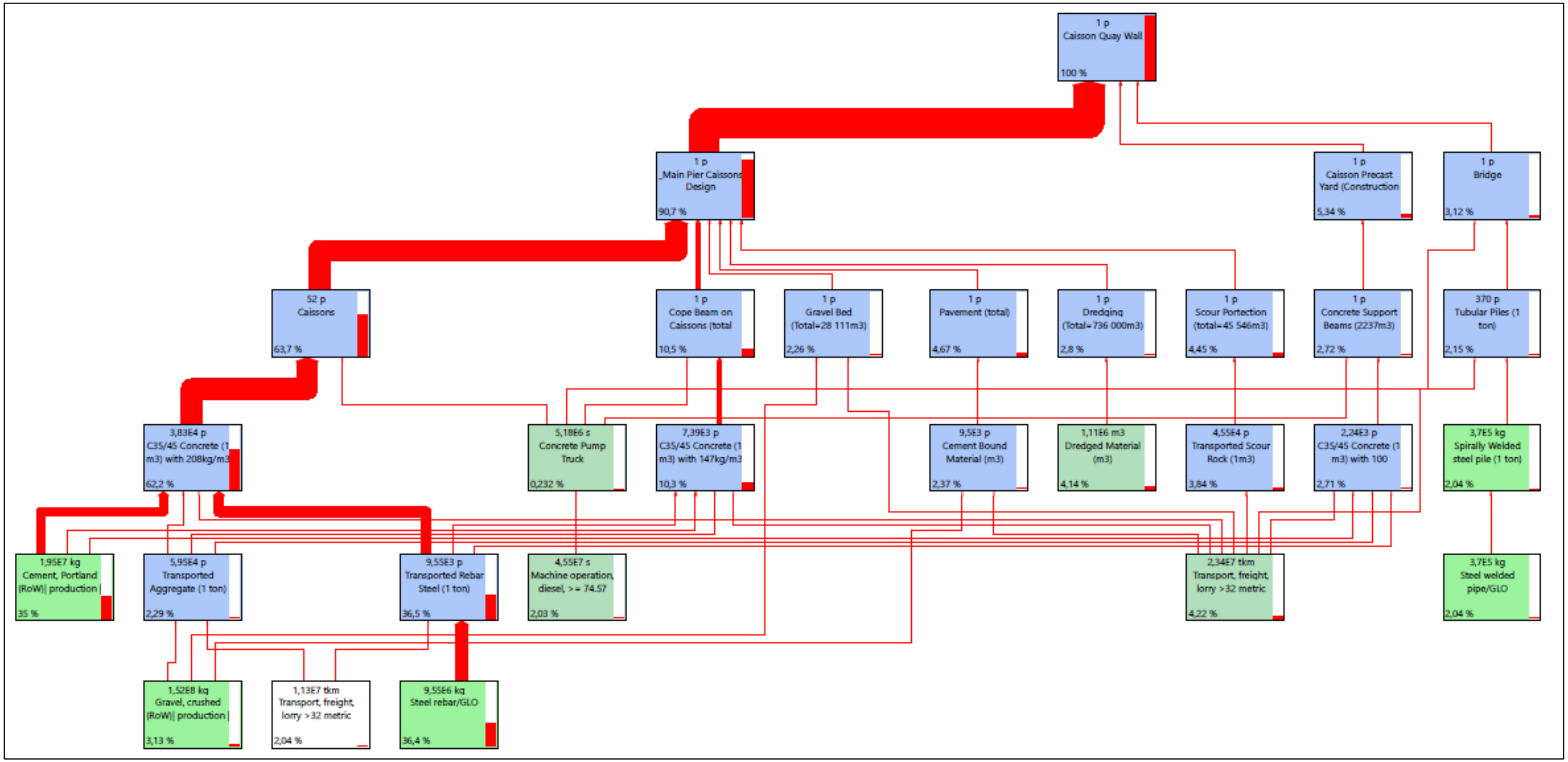



*Figure 42 - Screenshot of network diagram from SimaPro for the Caisson baseline design option. Node cut-off is 2%.*

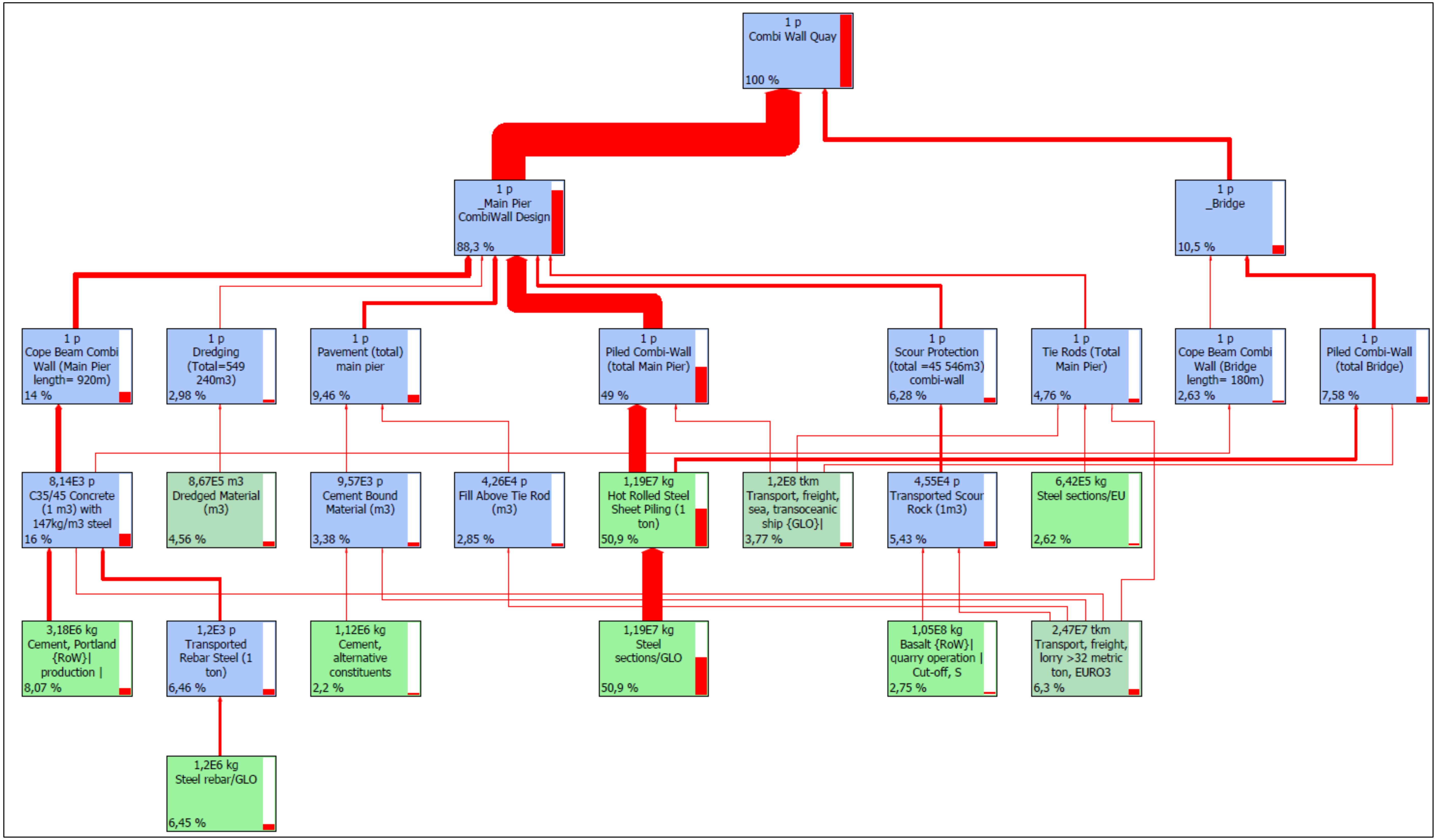



*Figure 43 - Screenshot of network diagram from SimaPro for the Sheet Piled Combi-Wall Baseline Design Option. Node cut-off is 2%.*

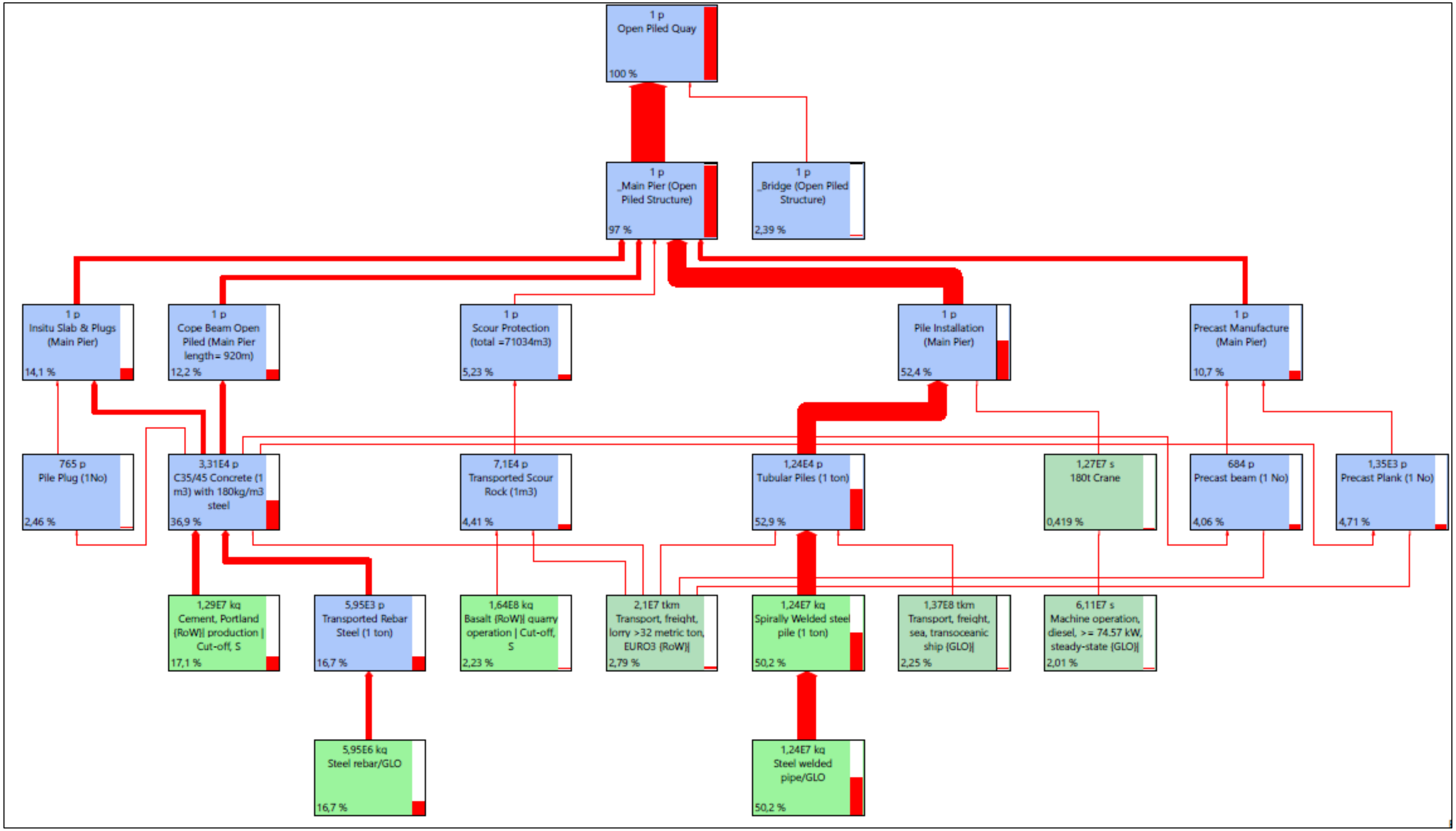



*Figure 44 - Screenshot of network diagram from SimaPro for the Open Piled Suspended Deck Baseline Design Option. Node cut-off is 2%.*