Comparison of quay wall designs in concrete, steel, wood and composites with regard to the CO_2-emission and the Life Cycle Analysis

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Abstract

In this paper quay wall designs in different materials are compared with regard to the CO_2-emission and the Life Cycle Analysis (LCA). For this study the requirements and boundary conditions of the quay wall in the Euromax Terminal, the Port of Rotterdam, have been used. An overview of preliminary designs of the tender phase with a concrete diaphragm wall and a steel combi wall are presented. Due to the absence of designs in wood and composites, new designs have been proposed for these materials. The designs resulted in a retaining wall of Azobé and a sandwich panel of Fiber Reinforced Polymers. For these four designs a cost estimation is made.
Next the CO_2-emission during the lifetime of these structures is calculated. In addition several other impact categories have been determined with help of an LCA. They are causing emissions, resulting in pollution to air, water and soil, depletion and land use. With help of the so called "shadow prices" the costs for the preventive measures that must be taken to reduce the emissions to a sustainable level can be determined. It can be concluded that Azobé results in the lowest Carbon Footprint and FRP in the highest. An FRP structure must be circa 37 times lighter than a concrete structure to obtain the same level of sustainability.

Keywords: Quay wall, Concrete, Steel, Wood, Fiber Reinforced Polymer, CO_2-emission, Life Cycle Analysis

1 Introduction

This paper is the result of a master thesis for the specialization Hydraulic Structures at Delft University of Technology. It involves a comparison of quay wall designs in different materials with regard to the CO_2-emission and the Life Cycle Analysis. This thesis focuses on quay wall structures in the Port of Rotterdam. A quay wall is a soil retaining structure where ships can moore and transfer goods. The developments in quay wall structures over the centuries have been tremendous, due to increasing ship dimensions, loads and crane designs. Traditional materials like wood have been replaced by concrete and steel. A relatively new material in civil engineering is the use of composites, which result in fiber reinforced polymers.
Next to that climate change is a hot topic nowadays. The building sector is one of the sectors which have a large impact on the environment. Constructing durable and sustainable throughout the entire life cycle is becoming more and more important. CO_2-emission is a widely excepted parameter to estimate sustainability. Besides CO_2 many other environmental effects, so called impact categories, have an impact on air, water and soil. These impacts can be shown with help of a Life Cycle Analysis (LCA).
In this paper the impacts on the environment of a quay wall constructed in four different materials will be analyzed. The materials will be: concrete, steel, wood and composites.

To make a good comparison the designs must be based on the same requirements and boundary condition. For this purpose the quay wall of the Euromax Terminal is used. This quay wall is situated in the "Maasvlakte 1", which is a section of the Port of Rotterdam and has a length of 1900 meters. The quay wall is able to accommodate large vessels and has a

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retaining height of 27.0 meters. Operation of the Euromax Terminal started in 2008.

2 Concrete

The first design that is used in the LCA is the design as shown in Fig. 1.

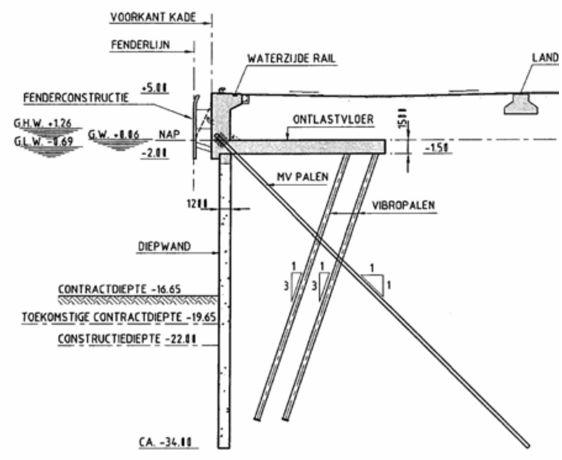

Fig. 1 Cross-section concrete quay wall

It presents an overview of the preliminary design of the structure that is in reality designed and constructed. The quay wall consists of a concrete diaphragm wall of 1200 mm with a length of 32.0 meters. On top of that a concrete L-shaped relieving structure is constructed. The stability of the total structure is guaranteed by a combination of mv-piles for tension and vibro-piles for compression.

3 Steel

The second design is shown in Fig. 2.

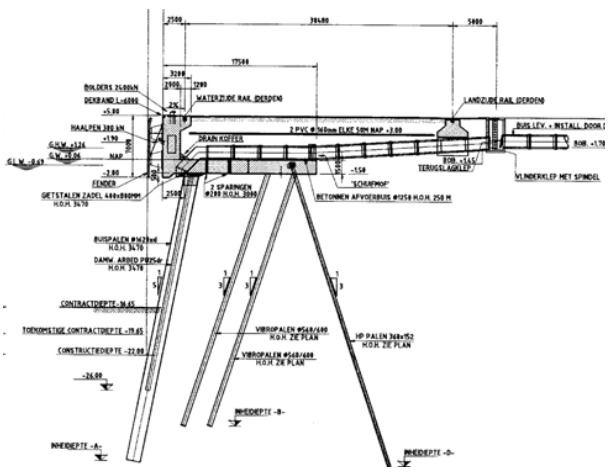

Fig. 2 Cross-section steel retaining wall

It presents a cross-section of another design that is proposed during the tendering phase. The retaining wall consists of a combi wall with steel tubes of circa 35 meters and sheet piles with a length of 32 meters.
Furthermore, this design makes use of the same relieving structure as the design shown in Fig 1. The only difference is the position of the mv-piles.

4 Wood

The third design makes use of wood as the main building material. Since there is no design of the Euromax terminal using wood, a new design is proposed. The preference for this design was to make use of European softwood. Firstly because of the supposition that softwood grows faster than hardwood. Secondly because of the irresponsible forest management that is going on in tropical rainforests. The growth of softwood appears to be almost just a long as hard wood.
Furthermore the durability of wood species is an important matter. Structures are classified in hazard classes depending on the loads and environmental exposure. Besides that, wood species are assigned to durability classes. When combining these two, it follows that for the design of the quay wall structure only several hardwood species are suitable "(CUR 2003)". Their chemical composition and density are able to withstand fungus and marine boorers. Modification of woods is not advisable.
As been said before, sustainability is an important subject in this research. Forestry is considered sustainable when the ecosystem of the forest is being preserved on the long time. The Forest Stewardship Council (FSC) has a certification system for sustainable produced wood. With help of the chain-of-custody the origin of products can be traced. Developments towards responsible forestry are difficult, but initiatives are there. For these reasons it is decided to make use of Azobé for the design of the quay wall.
Several types of quay walls have been discussed. Designs have been proposed for a wooden retaining wall with a relieving structure and furthermore a wharf "(NEN committee 2007)". These designs have been compared to each other with respect to several criteria: use of material, durability,

construction techniques, etc. The wooden wall combined with a relieving structure appeared to be the best design. This was mainly because the material use in this design is less than the wharf. A cross-section of the wooden wall is shown in Fig. 3.

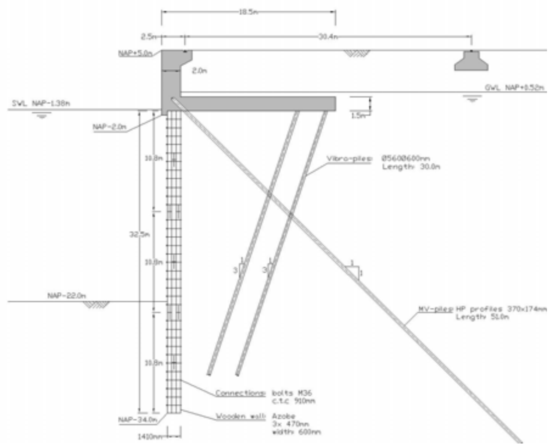

Fig. 3 Cross-section wooden wall

The wooden wall has a thickness of 1400 mm and the concrete relieving structure has the same dimensions as shown in Fig. 1. Large Azobé elements must be connected with help of bolts creating larger elements. These can be lowered in a trench supported by bentonite slurry.

5 Fiber Reinforced Polymer

The fourth design is made with composites, resulting in the use of Fiber Reinforced Polymers (FRP). The use of this material in civil engineering is relatively new. Several bridges for pedestrians have been constructed and some bridge decks suitable for heavy traffic have been realized "(Hejll 2005)". The application of FRP in large hydraulic structures is new.

Since all three foregoing designs make use of the L-shaped relieving structure combined with a retaining wall, decided was to design an FRP sandwich panel as a retaining wall.

FRP consists of a polymer matrix reinforced by fibers. Mostly used fibers are glass fibers and carbon fibers. The properties of carbon fibers with respect to glass fiber are much better, but the costs are circa 25 times higher. Mostly used resins for this purpose are polyester, vinyl ester and epoxy. A vinyl ester resin reinforced with glass fibers has the best mechanical properties in relation to the costs for this purpose. The choice of the fiber configuration determines the strength of the composite. Both isotropic as anisotropic materials can be obtained.

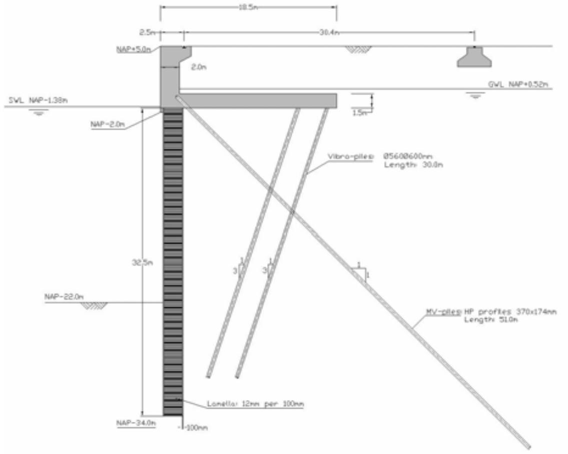

Fig. 4 Cross-section FRP sandwich panel

The maximum allowable strain (0.27%) in the outer fibers was normative for the design of the sandwich panel "(CUR Committee 2003)". This strain must be limited, since the diffusion of water rapidly destroys the bond between resin and glass fibers. The dimensions of the sandwich panel resulted in a total thickness of 2.08 meters. A cross section of the design is shown in Fig. 4.

6 Costs

Next a cost estimation is made for 1.0 m quay wall which is shown in Fig. 5. For each design it includes the following:

- Building pit
- Anchor piles: Vibro- and Mv-piles
- Drainage system
- Relieving structure
- Mooring and fender systems
- Dredging
- Scour protection
- Maintenance

- Retaining wall in concrete, steel, wood and FRP

From this it can be seen that the traditional building methods have the lowest costs. The Azobé design is circa twice as expensive and the costs for the quay wall with the FRP retaining wall are circa 7-10 times higher.

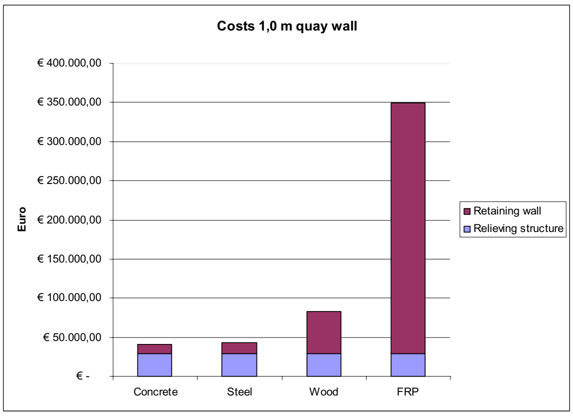

Fig. 5 Cost estimation per 1.0 m quay wall

7 Material properties

Table 1 shows an overview of the material properties used in the four designs.

8 CO_2-emission and Life Cycle Analysis

Finally the CO_2-emission of each structure was calculated. The main excepted idea is that global warming is induced by the green house effect, although sceptics do not agree with this opinion.
The six most important greenhouse gases include CO_2, CH_4, N_2O, HFC's, PFC's and SF_6. For each of these gases their potential contribution to global warming relative to CO_2 can be determined.

The result is that the contribution of all greenhouse gases can be expressed CO_2-equivalents.
Furthermore the emissions of several other impact categories have been determined with help of a Life Cycle Analysis (LCA). They represent emissions causing pollution to air, water and soil, depletion and land use.
An LCA can be performed, following several steps:

Step 1: Goal and scope definition
The functional unit expresses the unit that shall be compared. This is determined to be 1.0 meter quay wall.

The effects that are taken into account are:
1. Global warming potential
2. Ozone depletion potential
3. Human toxicity potential
4. Fresh water aquatic ecotoxicity potential
5. Salt water aquatic ecotoxicity potential
6. Terrestrial ecotoxicity potential
7. Photochemical oxidant creation potential
8. Acidification potential
9. Eutrophication potential
10. Biotic depletion potential
11. Abiotic depletion potential
12. Energy depletion potential
13. Land use

These effects will be taken into account over a time horizon of 50 years, since this is set to be the lifetime of the structures.

Table 1: Overview material properties

	Concrete	**Steel**		**Wood**	**FRP**
Property [N/mm^2]	**B35**	**X70**	**S240**	**D70**	
Bending strength				70	
Density [kg/m^3]	2500	7800	7800	1100	1880
E-modulus, 0°	34.000	210.000	210.000	20.000	25.800
E-modulus, 90°	34.000	210.000	210.000	1330	15.900
G-modulus	5.700	81.000	81.000	1250	5600
Compression strength, 0°	35	485	240	34	310
Compression strength, 90°	35	485	240	13,5	191
Tensile strength, 0°	3,2	485	240	42	310
Tensile strength, 90°	3,2	485	240	0,6	191
Shear strength	0,56	280	139	6,0	25

Step 2: Inventory analysis
The impacts during all phases of the life cycle have been taken into account:

- Production of materials
- Transport
- Construction
- Use
- Demolish
- Process

Step 3: Impact Assessment
Since all processes have been defined, the quantities of materials, transport kilometres and use of equipment during the construction phase are calculated.
Subsequently the emissions per impact category have been determined.

National and international, a variety of databases is composed of which some are public and some not. It is best to make use of local databases, since they are based on local processes and material production. For determining the Carbon Footprint of the quay wall designs two databases have been used. The first one is composed by IVAM (Department of environment, University of Amsterdam). They make use of the Ecoinvent 2.0 database and IVAM LCA Data 4. The last contains data concerning construction products and processes, gathered in projects executed by IVAM.

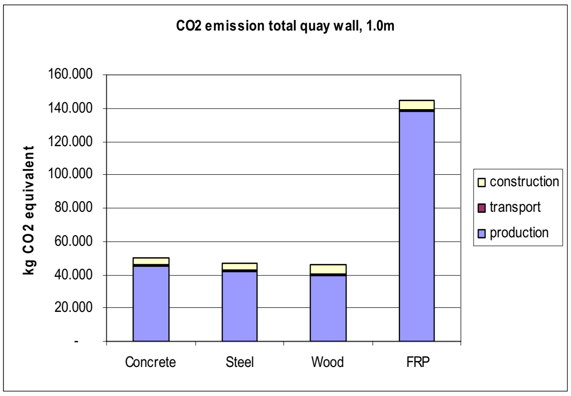

Fig. 6 CO_2-emissions per 1.0 m quay wall

The second database used is the Carbon Calculator of Dutch contractor BAM. It gives emissions for production of materials, use of equipment and transport. The results of the Carbon Footprint are shown in Fig. 6.
Next, the emissions due to the 13 impact categories specified in step 1 are calculated. These emissions have been determined with help of a material database of NIBE (Dutch institute for building biology and ecology). NIBE made environmental assessments for building products based on the LCA methodology. The database contains circa 250 materials with their emission per impact category, including monetization numbers.
With help of monetization the so called "shadow prices" of each structure can be calculated. They represent the costs for the preventive measures which must be taken to reduce the emissions to a sustainable level. Monetization is a weighing factor, which makes it possible to add the emissions of each impact category, resulting in one final indicator for each design. In this way the designs can be compared. The shadow costs per design are shown in Fig. 7.

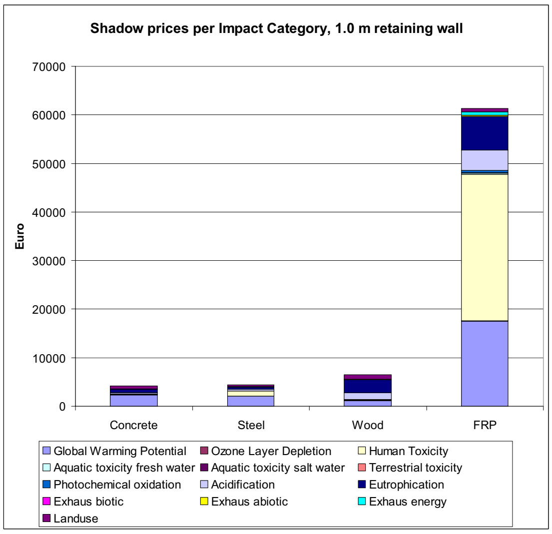

Fig. 7 Shadow costs per 1.0 m retaining wall

9 Conclusions

In general it can be concluded, that each material needs its own design method, depending on its specific material properties.

Due to the mechanical and chemical properties of hardwood and softwood, it can be concluded that with respect to durability, hardwood is the better choice for constructing a quay wall in a salty environment. Note that sustainable forestry is an important matter.

Production of the materials has the highest impact on the Carbon Footprint of a structure. The wooden retaining wall results in the lowest Carbon Footprint. The Carbon Footprint of the FRP sandwich panel is much higher. A FRP structure needs to be 37 times lighter than a concrete structure to have a lower impact on the environment. Due to the small allowed strains in the sandwich panel this seems difficult to realize in hydraulic structures. Therefore it can be concluded that the "sustainability" of a material is not only depending on the emissions per kg material, but also on its application. When the specific properties of a material are used in their best way, this result in the use of less material, creating a lower Carbon Footprint.

From Fig. 7 can be concluded, that the other impact categories which are weighed with monetization, give a comparable output to the Carbon Footprint. Although Azobé results in higher values than concrete and steel. Attention must be paid to the end of life scenarios. In this study variations in reuse, recycling, incineration or dump have not been taken into account. Note that these scenarios can have a high impact on the sustainability of a structure.

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