Next generation storage tanks

A potential alternative for crude oil storage tanks
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by

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PREFACE

With this study I completed my Master of Science thesis in Civil Engineering at Delft University of Technology. My continuous fascination for water and ports motivated me to graduate within the section of Hydraulic Engineering, Ports and Inland Waterways.

This study was carried out in association with Shell Global Solutions in The Hague. The department Civil, Storage and Marine Engineering offered me the opportunity to set the first step within the Next Generation Storage Tanks Project.

The report has been put together for two groups of readers. Readers who have no knowledge of storage tanks are advised to read Appendix C first. Readers with significant tank knowledge can read the complete report or the key issues at the end of each chapter. The key issues contain the most important observations of the study.

I would like to thank the members of the graduation committee, all colleagues from the GSEC department, friends and contacts for their help, support and educational experiences during this final phase of my study.

The Hague, March 6 2007

R.E.J. Krol
Summary

Introduction
Within the oil industry storage tanks are used to store hydrocarbon products. The tank design has essentially remained the same for many years, consisting of vertical cylindrical aboveground tanks made of steel.
The Next Generation Storage Tanks Project explores new, groundbreaking tank alternatives. This study is the first within the project and will focus on crude oil tanks only. Crude oil is a volatile product. In order to reduce the emission of product from the storage tanks, crude oil is mostly stored in floating roof tanks. These tanks adjust their capacity to the stored quantity of product.

Objective
This study is intended to come up with potential alternatives for present crude oil storage resulting in benefits to the oil business based on developments in- and outside the storage and oil industry.

Approach
In order to accomplish realistic storage alternatives, first an inventory of existing problems is drawn up. Used information is obtained from public domain, literature, tank courses, interviews and meetings with Shell experts, a Shell internal-refinery enquiry, simulation and a site visit to one of Shell’s main refineries Pernis in The Netherlands.

Based on this inventory the main drawbacks of the traditional storage tanks are defined. Subsequently conceptual, out of the box, alternatives to solve the observed problems are generated and gathered. Next several tank specialists participated in the concept assessment: Health, Safety and Environment consultant, oil-movement technologist, tank engineer, storage and integrity engineer and a structural tank engineer.

From all evaluated concepts, the underground storage in a caisson structure was assessed as one of the promising solutions, as it results in the reduction of:
- The Health, Safety and Environmental risks.
- The risk of financial losses due to failure.
- The costs related to construction and inspection & maintenance.
- The spatial use.

Therefore this solution has been selected for further detailing. The design location is the prospective land reclamation/port extension project “Maasvlakte 2” in the Port of Rotterdam. The underground storage tank, continuously filled with oil and/or water, is integrated with a container on- and offloading terminal and a quay structure.
The engineering part comprised:
• Terminal design for future sized container vessels.
• Concrete dimensioning.
• Stability calculations during floating transport and installation of the caisson.
• Overall stability calculations during the operational phase.
• Foundation calculations.
• Calculations concerning scour and piping.
• Cost estimation.
Information is obtained from literature and interviews.

Present opportunities of improvement
• Crude oil storage tanks are subjected to degradation leading to several failure modes with a significant frequency of occurrence. The damage results in significant financial losses, possible negative consequences for the environment and reputation. The frequency of occurrence strongly depends on the inspection and maintenance policy. This kind of work is expensive (1 euro/m$^3$/storage capacity/year), difficult to execute unambiguously and may lead to dangerous and unhealthy situations for personnel.

• Beside this, storage tanks use much space (average storage capacity is 5m$^3$/m$^2$) resulting spatial problems in situations where space is scarce.

• Tank design enhancements are generally speaking driven by the oil industry for economic reasons and by legislation for environmental reasons. Dutch legislation developments indicate the main targets: amount of emission and the risk of soil contamination need to be further reduced in the future. In the year 2010 an emission reduction of 30% compared to the year 2000 needs to be achieved.

• The related design enhancements for the future, translated into The Base Case, will result in more complex and higher (10%) structural design costs (expressed per unit storage: 220 euros/m$^3$ compared to 200 euro/m$^3$).

Improvements
A potential alternative for crude oil storage that deals with the above-mentioned opportunities of improvement is an underground storage design using a caisson structure integrated with a container on- and offloading terminal and a quay structure.
• The degradation mechanism have been removed and the number of failure modes has been reduced significantly due to the use of concrete, a simple and rigid structure with fewer appendages. This, in turn, reduces the environmental- and fire risks and the inspection and maintenance effort, resulting in less health, safety and financial consequences.

• Emission has been eliminated due to the application of a closed reservoir, which is continuously filled with oil and/or water. The tank design completely anticipates to the Dutch legislation requirement of further emission reduction. Also the financial losses related to product loss are removed completely. Due to the absence of emission and vapour space the fire safety increases as well.

• Improvements in space utilisation are achieved as the ground level can be used as well, e.g. as a container on- and offloading terminal.
• Reduction of the construction costs is achieved by a combination of crude oil storage with other functionalities, e.g. a quay structure and a container on- and offloading terminal.

Outcome
• The total costs, for the storage function only, expressed per unit storage will be in the order of 215 euros/m$^3$. Compared to The Base Case (220 euros/m$^3$), which stands for the traditional tank design incl. expected design enhancements for the future.

• The concept assessment indicated that traditional tank design, translated into the Base Case, scores well compared to the generated alternatives.

Conclusions
A potential alternative for present crude oil storage tanks, which reduces the related,
• Health, Safety and Environmental risks (HSE).
• Risk of financial losses due to tank failure.
• Costs for tank inspection & maintenance.
• Tank spatial use.
Can only be made financially feasible by combining crude oil storage with other functionalities, e.g. a quay structure and a container on- and offloading terminal.

Traditional crude oil tank design, including the expected design enhancements for the future, still is a good alternative on the condition that tank inspection and maintenance is carried out thoroughly.

Recommendations
The following is recommended for successive studies:

• The underground storage design using a caisson structure integrated with a container on- and offloading terminal and a quay structure needs to be technically elaborated into more detail. The construction costs can be reduced by design optimisation.

• The Port of Rotterdam could sponsor part of the project, reducing the construction costs further, as the designed alternative complies with the demand of space intensification. In such a case the degree of innovation and the additional business for the port would be a subject for a feasibility study.

• The other generated alternatives can be promising for other conditions, for example onshore and Greenfield$^1$ or Brownfield$^2$ soil conditions. The alternatives with almost or equal high scores can be further assessed resulting in other potential solutions.

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$^1$ Clean soil conditions.
$^2$ Contaminated soil conditions.
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1. Introduction

Introduction
Within the oil industry storage tanks are used to store all kinds of liquid products. These tanks have essentially remained the same for many years, still consisting of vertical cylindrical aboveground tanks made of steel. The Next Generation Storage Tanks Project is intended to explore new, groundbreaking tank alternatives.

Objective
This study forms the first within the project and will focus on crude oil tanks only. The study is intended to come up with potential alternatives for crude oil storage resulting in benefits to the oil business based on developments in- and outside the storage and oil industry.

Report composition
In order improve legibility; the report has been put together for two groups of readers. Readers who have no knowledge of storage tanks are advised to read Appendix C first. Readers with significant tank knowledge can read the complete report or the key issues at the end of each chapter. The key issues contain the most important observations of this study.

Report content and approach
First the current Shell businesses are presented in Chapter 2 in order to indicate the total amount and dominance of crude tanks. The analysis is based on data obtained from Shell refinery Pernis located in The Port of Rotterdam in The Netherlands.

In order to accomplish realistic storage alternatives, the present improvement opportunities are analysed and defined successively in Chapter 3 and 4. The chapters deal with:
- Health, Safety and Environment (HSE).
- Fire safety.
- Degradation and failure.
- Inspection and maintenance.
- Spatial use.
- Legislation developments.
- Future expectations and adjustments “The Base case”.

Used information is obtained from public domain, literature, tank courses, interviews and meetings with Shell experts, a Shell internal-refinery enquiry, simulation and a site visit to one of Shell’s main refineries Pernis in The Netherlands.

Conceptual, out of the box, alternatives to solve the observed problems are generated in Chapter 5. The chapter discusses:
- Concept requirements and premises.
- Generated concepts.
- Concept assessment.

The concepts consist of own designs, designs gathered from a previous creative meeting and existing applications. Several tank specialists participated in the assessment: health, safety and environment consultant, oil movement technologist, tank engineer, storage and integrity engineer and a structural tank engineer.
From all evaluated concepts, the underground storage in a caisson structure was assessed as one of the promising solutions. Therefore this solution has been selected for further detailing. The design location is the prospective land reclamation/port extension project “Maasvlakte 2” in the Port of Rotterdam. The underground storage tank, continuously filled with oil and/or water, is integrated with a container on- and offloading terminal and a quay structure.

The engineering phase contains:
- Introduction.
- Boundary conditions.
- Requirements.
- Premises.
- Container terminal design.
- Pre-design calculations.
- Cost estimation.
- Key issues.

Information for this part of the study is obtained from literature and interviews.

Subsequently the improvements and outcomes are discussed in Chapter 7, finalizing the report with the conclusions and recommendations in Chapter 8.
2. Business analysis

2.1 Oil industry

Within the Shell organisation the oil industry consists of the divisions Exploration & Production and Downstream [51] (see Appendix A).

Exploration & Production
Besides gas, this division finds and produces crude oil. The oil production sites are indicated in Figure 1.

![Figure 1: Shell's worldwide Exploration & Production activities [51]](image)

After production the crude oil will be stored in onshore or offshore facilities before it will be transported to the downstream businesses where it is stored again and treated further. Worldwide the division Exploration & Production owns approximately 300 crude oil storage tanks.

Downstream
Shell Downstream includes all the activities necessary to process crude oil and produce petroleum products (see Appendix B). Shell Downstream may roughly be divided into the divisions Supply & Distribution and Manufacturing.

Supply & Distribution
This division is involved in the transport and delivery of finished products and uses approximately 4,000 tanks. These tanks contain all kinds of finished products and have all kind of dimensions smaller than crude oil storage tanks.

Manufacturing
The division Manufacturing comprises refineries and chemical plants. The division holds a majority interest in 30 refineries and 17 chemical plants, with lesser interests in a further 25 refineries. The manufacturing sites are indicated in Figure 2.
The refineries are indicated with numbers, chemical plants with letters.

**Figure 2: Worldwide Shell manufacturing locations [51]**

In order to get more insight into the total storage capacity of the different kind of product tanks, the Shell Pernis refinery located at Pernis in The Netherlands is analysed. The total storage capacity per product type is presented in Figure 3.

**Figure 3: Product distribution Pernis refinery in The Netherlands**

Shell Pernis has a total storage capacity of 4.7 million m$^3$ (all products). The crude oil storage capacity counts for 2.2 million m$^3$, which is 46% of the total capacity.

Pernis refinery, including Europoort, has approximately 36 crude oil storage tanks. Taking into account the majority interest in 30 refineries the total amount of crude oil storage tanks within the manufacturing division is estimated to be 1.100.
2.2 Key issues

- Crude oil forms the basic product in the manufacturing division (see Figure 3).
- Due to the large diversity in products and tank sizes this study will consider crude tanks only.
- The total estimated amount of crude tanks belonging to Shell are presented in Table 1. The number will be used in Chapter 3.3 for the estimation of the yearly financial damage caused by degradation mechanisms.

<table>
<thead>
<tr>
<th>Business division</th>
<th>Number of crude oil tanks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration &amp; Production</td>
<td>Ca. 300</td>
</tr>
<tr>
<td>Downstream</td>
<td>Ca. 1,100</td>
</tr>
<tr>
<td>Total</td>
<td>Ca. 1,400</td>
</tr>
</tbody>
</table>

Table 1: Estimated number (order of magnitude) of crude oil storage tanks within Shell
3. **Problem analysis**

3.1 **Health, Safety and Environment (HSE)**

3.1.1 **Health**
Tanks require inspection and maintenance work at regular intervals (see also chapter 3.4.1). The work may lead to chemical and physical hazards and situations without sufficient oxygen [5, 19].

Chemical hazards may arise from:
- Skin contact with crude oil, sludge, or from contact with certain chemicals.
- Inhalation of vapours.
- Accidental swallowing of liquids or solids.

The concentration of oxygen in air is approximately 21%. In workplace situations, the lowest level for safe working without air-fed respiratory protection is considered to be 20% of oxygen. In the tank storage business oxygen deficiency may arise from:
- Inert atmosphere, i.e. where nitrogen or other inert gas mixtures have been used as a blanket above the stored liquid or during gas freeing of the tank.

- High concentrations of hydrocarbon vapours.

- Internal corrosion in a closed tank. When a tank has been cleaned and resealed oxygen, contained in the air within the tank, may be consumed by corrosion. Such reactions are enhanced by heat and high humidity. On reopening the tank, oxygen levels must be checked before allowing personnel to enter without appropriate respiratory protection.

Physical hazards may arise from:
- Heavy working conditions inside the tank, like high temperatures and excessive noise conditions.

3.1.2 **Safety**
*Inspection and maintenance work*
During work execution the following points need attention [5]:
- Walking on tank roofs whilst the tank is in service is a potential hazardous undertaking. The condition and thickness of the roof plates should be confirmed before anyone is permitted to walk on a tank roof. If there is any doubt concerning the condition of the roof, and if access to the roof is essential, then methods of spreading the load should be used.

- If access to an external floating roof is permitted by the company safety code, then the tank roof should be in the highest practicable position, preferably within 1.5 m of the top of the shell. With the purpose to avoid a semi-confined area, which is a safety concern as it implies poor ventilation and the possibility of accumulating of dangerous fumes. Furthermore there should be no movement whilst people are on the roof, hence no filling or emptying of the tank.
• Any roof compartment should be considered as an enclosed space, gas tested, and only entered with precautions.

• Access to an internal floating roof whilst the tank is in-service should only be considered under special circumstances, and requires strict access control (permitting) and will require breathing apparatus, lifelines and dedicated rescue procedures.

• When a tank is opened for maintenance, gas may be released from the sludge for many days. If there are openings in the tank shell then gases may escape from the tank, and there may be a flammable mixture in the bund area. This situation should be especially considered at the start of each day’s work. The tank should be gas tested frequently whilst work is in progress. The frequency will depend on the condition of the tank, and should continue until the tank is clean.

**Potential for injuries or fatalities during fire fighting activities [5,9,12] (see also Chapter 3.2)**

The contents of the tank may be flammable to a greater or lesser degree. An important property is the flashpoint, which is defined as the lowest temperature at which the liquid gives off sufficient vapour to form a flammable gas mixture near the surface of the liquid. For crude oil this is approximately 18 °C.

Tank fires are very hazardous events. If people are involved during the initial ignition event, for example whilst performing hot work or being close to the external ignition source, severe injury or death may occur.

Once the fire is established, there is considerable potential to cause harm to people fighting the fire or to bystanders. This has been illustrated by a number of historical incidents where several people have been killed such as at Tacoa, Venezuela in 1982, at which 150 fire fighters and spectators were killed [9].

A combination of advanced technology, full awareness of the potential hazards and good fire incident management and fire fighting skills, may reduce the risk of fatalities (see also Figure 9 in Chapter 3.2).

**Instrumentation [58]**

At present more frequently robots or other advanced instruments are used to carry out specific inspection work, which in the past was done by personnel. This is however still in development and the majority of tank internal access is still by personnel.
3.1.3 Environment

Environmental issues may occur due to accidental product releases, emission of product and tank fires.

Accidental releases

If a tank leaks, collapses or flows over, the bund area (see Appendix C.10) has the function to contain the spillage. If the floor of the bund area is permeable the leakage may infiltrate in the subsoil and possibly reaches the groundwater. This may eventually result in the contamination of the subsoil, the surface water and eventually the drinking water (see Figure 4 for the ecological receptors). The release causes are presented in chapter 3.3. An accidental release also increases the fire risk (see chapter 3.2).

![Figure 4: Tank leak scenario including ecological receptor](image)

The bund area requires inspection and maintenance work. If this is neglected the chance that the bund area will not fulfil its function during a product release will increase.

Emission

The vapour pressure of crude oil (320 mbar) under normal conditions is high enough to significantly vaporize [33]. These VOC emissions (Volatile Organic Compounds) are an important air pollutant, involve financial losses and increase the fire risk (see chapter 3.2). The emission figures presented in this chapter are taken from Appendix D.

Note: the indication of turnover in the figures stands for tank level between full and dead stock level.

The amount of emission depends on [1]:
- The true vapour pressure and the average storage temperature of the product (high vapour pressure products will result in an increase of the evaporation).
- The type of product.
- The wind speed (see Appendix 0).
• The annual net throughput.
• The type of rim seal system (see appendix C.5) and its condition (see Figure 5).

![Chart showing emission for different seal types in good and average conditions (euro/year)](image)

**Figure 5: Emission for different seal types in good and average conditions (euro/year)**

• The tank diameter or volume (see Figure 6).

![Chart showing emission for vapour mounted primary seal in average condition, tank volume=10.000m³ and 100.000m³, turn over 0,1,6 and 48](image)

**Figure 6: Emission for different tank diameters/volumes (euro/year)**
• The type of floating roof (external or internal, see appendix C.4 and Figure 7 below).

![Emission [euro/year] for vapour mounted primary seal in average condition for floating roof and geodesic dome tank, tank volume=100,000 m³, turn over 0, 1, 6 and 48](chart.png)

**Figure 7: Emission for floating roof tank and geodesic dome tank (euro/year)**

**Emission reduction**
Emission reduction is mainly driven by legislation. See chapter 3.6.1 for the Dutch emission legislation developments.

**Fires**
A large tank fire (see Appendix E and Figure 8) may have a significant impact on public image.

![Figure 8: Smoke plume during the Buncefield fire incident [31]](image.png)

One criterion for the environmental impact is the air quality at ground level. Another potential environmental impact arises from the large quantities of used firewater and foam. The wastewater containment areas and treatment plants are sized to be able to cope with the maximum amount of waste water that is likely to be generated during any planned fire fighting response.
3.1.4 Key issues

- Tank inspection and maintenance work and fire fighting activities may lead to unhealthy and unsafe situations for personnel. At present more frequently robots or other advanced equipment is used to carry out specific dangerous inspection work. However this is still in development and the majority of tank internal access is still by personnel.

- Environmental issues may occur due to accidental product releases, emission of product and tank fires. Leading to enormous damage to the business image.

The following points lead to better mitigation of emission but extra direct costs. The costs may be returned by the reduction of product loss.

- The selection of the rim seal (see Appendix C.5) is very important considering emission reduction. Mechanical shoe type and liquid mounted seals are the preferred types while one should avoid the use of average conditioned vapour mounted rim seals. Secondary rim mounted seals are preferred over the secondary shoe mounted seals.

- The condition of the seal strongly influences the amount of emission as well, indicating the importance of a proper inspection and maintenance policy.

- The application of a geodesic dome roof (see Appendix C.4) over a floating roof tank results in a further reduction of emission.
3.2 Fire safety

The fire safety of tanks is the degree to which the risk of fire and/or explosion is managed to a level, which is as low as reasonably practicable in terms of likelihood of occurrence and associated potential consequences. Data for this chapter is obtained from the LASTFIRE project (see Appendix F) [9].

When a fire incident occurs, although infrequent, media interest is high (see for example the Buncefield oil depot incident [31], Appendix E) and consequently there is much pressure on tank operators to demonstrate that they were taking all reasonable measures to minimise the risk.

Fire hazards occur from ignition of accidentally product leakages or explosions. The fire safety depends on many factors (see Figure 9).

![Figure 9: Fire hazard management [9]](image)

3.2.1 Flashpoint

Crude oil belongs to class I of petroleum products indicated with a flashpoint smaller than 21 °C. The flashpoint is the minimum temperature of a liquid at which sufficient vapour is emitted to form an ignitable mixture with the air, near the surface of the liquid or within the storage space.

3.2.2 Fire scenarios, frequencies and financial damage

The LASTFIRE project [9] (see Appendix F) states the following fire scenarios:

**Rim seal fire**

A rim seal fire may occur from the situation where the seal has lost integrity and an ignitable vapour is formed in the seal area. The amount of seal involved in the fire may vary from a small-localised area up to the full circumference of the tank. At present fire retardant seals are available.
Spill-on-roof fire
A spill-on-roof fire is a fire in a spill of limited depth on a roof that still maintains its buoyancy. It may result from a number of different hydrocarbon releases:
- Cracks in the skin of the roof may allow a pool of hydrocarbon liquid to form on the roof.
- If a tank roof loses buoyancy and partially sinks, liquid can be exposed over part of the roof.
- Escaped flammable vapours.

Full surface fire
A full surface fire is one where the entire liquid surface in the tank is exposed and involved in a fire. The tank roof is assumed to have completely sunk.

Bund fire
A fire in the bund is any type of fire that occurs within the containment area around the tank shell. These types of fire may range from a small spill incident up to a fire covering the entire bund area. In some cases the resulting fire could incorporate some jet or spray fire characteristics due to the hydrostatic head of the product source.

Explosion in pontoon or other confined space
An explosion may occur if flammable vapour builds up and is ignited in a pontoon or other confined space. Such explosions may also occur when the roof is landed on its legs and air is pulled into the vapour space under the roof.

Fire scenario frequencies and financial damage
Table 2 lists the 62 initial fire events that were recorded within the scope of the LASTFIRE project [9].

<table>
<thead>
<tr>
<th>Type of fire</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rim seal fire</td>
<td>55</td>
</tr>
<tr>
<td>Spill on roof fire</td>
<td>1</td>
</tr>
<tr>
<td>Small bund fire</td>
<td>3</td>
</tr>
<tr>
<td>Large bund fire</td>
<td>2</td>
</tr>
<tr>
<td>Full surface fire following sunken roof</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>62</td>
</tr>
</tbody>
</table>

Table 2: Initial fire events [9]
Rim seal fires

52 of the 55 rim seal fires were ignited by lightning strikes (see Appendix G). Two others were caused by hot work on tanks and the cause of one fire was not recorded. The related fire frequency and financial damage are presented in Table 3.

<table>
<thead>
<tr>
<th>Type of fire</th>
<th>Base frequency (x 10^-3)/tank-year</th>
<th>Type of fire</th>
<th>Financial damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rim seal fire</td>
<td>2</td>
<td>Short duration rim seal fire</td>
<td>20k to 100k or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prolonged rim seal fire</td>
<td>100k to 700k</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full surface fire</td>
<td>See Table 5</td>
</tr>
</tbody>
</table>

Table 3: Fire event frequencies and financial damage (euros) for rim seal fires[^9]

There is a strong geographical variation in the likelihood of a tank being ignited by lightning strikes (see also Appendix G). Tanks in countries that have a large number of thunderstorms per year also tend to have a higher frequency of lightning ignited rim seal fires per tank year (see Figure 11).

![Figure 11: Thunderstorm days distribution][4]

Some tanks appear to be located in lightning black spots and have suffered lightning ignitions more than once in the fifteen-year survey period.

[^9]: The costs do not include any down time costs associated with the repair or public image related costs. To include these factors a factor 10 can be applied, according to LASTFIRE project.
Table 4 presents the frequencies for those regions and countries in the LASTFIRE survey [9] where lightning ignited rim seal fires occurred.

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>Thunder-storm days per year</th>
<th>Fire Frequency (x 10^-3)/tank-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nigeria</td>
<td>160</td>
<td>21</td>
</tr>
<tr>
<td>Southern Europe</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Northern Europe</td>
<td>10-20</td>
<td>1</td>
</tr>
<tr>
<td>North America</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>Venezuela</td>
<td>60</td>
<td>13</td>
</tr>
<tr>
<td>Singapore</td>
<td>120</td>
<td>2</td>
</tr>
<tr>
<td>Thailand</td>
<td>70</td>
<td>13</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>10</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 4: Fire frequencies caused by lightning per country/region [9]

Spill on roof, bund and full surface fires
Table 5 presents the initial fire event frequencies and related financial damage for fires other than rim seal fires.

<table>
<thead>
<tr>
<th>Type of fire</th>
<th>Base frequency (x 10^-5) /tank-year</th>
<th>Type of fire</th>
<th>Financial damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill on roof fire</td>
<td>3</td>
<td>Short duration roof spill fire</td>
<td>50k</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prolonged roof spill fire</td>
<td>700k or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full surface fire</td>
<td>See below</td>
</tr>
<tr>
<td>Small bund fire (mixers, pipes, valves or flanges)</td>
<td>9</td>
<td>Contained bund fire</td>
<td>10mil or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bund fire escalated to include single tank</td>
<td>10mil or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prolonged, large scale bund fire (No tank involved)</td>
<td>10mil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensive fire beyond bund</td>
<td>300mil</td>
</tr>
<tr>
<td>Large bund fire (major spillage)</td>
<td>6</td>
<td>Rapidly extinguished single tank fire</td>
<td>10mil or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prolonged single tank fire</td>
<td>10mil to 20mil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple tank/Bund Fire</td>
<td>20mil</td>
</tr>
</tbody>
</table>

Table 5: Fire event frequencies and financial damage (euros) for fires other than rim seal fires [9]

4 The costs do not include any down time costs associated with the repair or public image related costs. To include these factors a factor 10 can be applied, according to LASTFIRE project.
Fire escalation
Once a fire has started, the following escalations to a more severe fire may occur:

- Rim seal fire to full surface fire.
- Spill on roof fire to full surface fire.
- Fire on tank top to bund fire.
- Ignition of another tank by radiant heating, flame impingement or impact of flying fragments from an explosion.
- Boilover.

3.2.3 Product release scenarios and frequencies
Before fire may originate there has to be a product release first. The following types of product releases have been observed to occur in the past on large diameter floating roof storage tanks.

Releases into the rim seal area
- The primary seal may fail from excessive tank movement or rubbing against tank walls corroded by salt air or from foreign objects falling into the rim seal gap.
- Failure of process monitoring may lead to overfill of a tank (this was the main cause of the Buncefield incident [31], Appendix E).
- Tank settling may cause a tank to go out of round, leading to rim seal gaps. When a tank is out of round, there is also the possibility that the roof could stick or jam. Subsequent sudden movement of the roof could cause product and flammable vapour to escape into the rim seal area.

Product in floating roof pontoons or between the decks of the roof
- Corrosion or bad construction of pontoons has lead to product inside pontoons.
- If pontoon inspection hatches are not closed tightly, overflow of product onto the roof from vents, drains or from the rim seal area may lead to product in pontoons.

Product on the roof
- Escalation of releases in the rim-seal area or into pontoons or roof spaces may lead to product on the roof if large amounts of product are involved.
- Leaks directly onto roofs may occur in single skin roofs which have cracked from wind induced stressing or corrosion.
- Leaks onto roofs have also been known to occur from the fracture of double deck roofs.
- Wind may blow rainwater to one side of a roof resulting in tilting of the roof.
- Rolling ladders on roofs may come off their rails and puncture single skin roofs or cause the roofs to jam.
• If pontoon inspection hatches are not secured in place, they may be blown off by the wind, allowing rainwater in and causing the roof to lose buoyancy.

• Failure of non-return valves on roof drain sumps combined with a leak in the roof drainage system may lead to product on the roof in case of single skin roofs. Product will flow up onto the roof because the weight of the roof causes it to form a shallow saucer shape such that the product level at the edge of the roof is higher than the upper side of the roof in the centre.

• Product may leak from leg sleeves or the hole for the gauging pole.

• It has been known for a roof to be landed with some of its legs in the normal operating position and the others in the lower, maintenance position. The roof may tilt and jam as it comes to rest on its legs at different heights. If operators do not notice the jamming of the roof, subsequent filling of the tank pushes product on top of the roof. The same problem may occur if corrosion of legs leads to some of them failing when the roof is landed.

Figure 12 shows the spill on roof causes according to LASTFIRE project update 2005/2006.

![Spill on Roof Causes](image)

Figure 12: Spill on roof causes [9]

**Product in bund**

• Escalation of releases in the roof area may lead to product or flammable vapour escaping into the bund.

• The shell-to-bottom joint may fail from corrosion, low cycle fatigue of the weld, tank settlement or erosion of the tank foundations.

• The tank bottom plate may fail from corrosion, may buckle and fail due to settlement or erosion of the tank foundation or may puncture due to failure of the roof leg pads.

• Roof drains and mixers may fail allowing product to enter the bund.

• Pipe work within the bund may leak at flanges, valves or measurement tapings.
• Sumps for water or product take off are sometimes installed at the base of tanks. Excessive settlement of the tank may result in the collapse of the pipe connections leading to a release into the bund.

• Product can collect in the bund drainage system.

Figure 13 shows the spill outside the tank shell causes according to LASTFIRE project update 2005/2006.

![Spills Outside Shell - Causes](image)

Figure 13: Spills outside the shell causes [9]

**Leaks from shell fittings**
• Connections through the tank shell may leak at flanges or valves. Such incidents usually begin as a small seepage and should be detected by routine inspection. If there is a significant hydrostatic head of product, the leak may form a jet or spray of liquid.

**Vapour-air mixture under the roof**
• When a roof is landed on its legs and emptying continues air is sucked into the vapour space under the roof and may form a flammable atmosphere. Landing the roof during operation is not a recommended procedure, however, it is happening more frequently as tanks are cycled more often. When there is a vapour space under the roof, there is an increased risk of an explosion under the roof and an increased risk of fire when the flammable vapour is pushed out of the tank as the tank is refilled.
Sinking roofs

- Roofs may sink from larger spills of hydrocarbons on the roof, heavy rainfall which either exceeds the capacity of the roof drains or which overloads the roof before the roof drain can be opened, damage to pontoons or fracture of the roof. A roof may also sink if it jams and sticks and product continues to be pumped into the tank.

Figure 14 shows the sunken roof causes according to LASTFIRE project [9] update 2005/2006.

![Figure 14: Sunken roof causes [9]](image)

Product release frequencies

There were 37 recorded roof sinkings, 55 recorded liquid hydrocarbon release incidents in the roof area that did not lead to sinking of the roof and 96 recorded liquid spills outside the tank. The related release frequencies are presented in Table 6.

<table>
<thead>
<tr>
<th>Type of release</th>
<th>Base frequency (x 10^-3) /tank-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill on roof</td>
<td>1.6</td>
</tr>
<tr>
<td>Sunken roof</td>
<td>1.1</td>
</tr>
<tr>
<td>Release outside tank shell</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 6: Frequencies of hydrocarbon spills [9]
3.2.4 Ignition sources

Figure 15 shows the occurrence of the main ignition sources according to LASTFIRE project [9] update 2005/2006. Other possible ignitions sources are described in Appendix F.2.

![Ignition sources frequencies](image)

**Figure 15: Ignition sources frequencies [9]**

3.2.5 Key issues

- Notwithstanding the chance of a tank fire is small it leads to enormous negative consequences for health, safety and environment and results in large financial and reputation damages.

- A fire can only occur if the situation fulfils the equation presented in Figure 16.

![Fire necessities](image)

**Figure 16: Fire necessities**

- One of the first barriers that are required to fail before most fires can take place is the release of liquid hydrocarbon to form a flammable vapour. Emission reduction results in an increase of the fire safety.

- The condition of a tank and it fittings greatly affects the fire risk. This emphasizes the importance of a proper inspection maintenance policy.

- Rim seal fires are the most common type of tank fires.

- The dominant ignition source of a tank fire is lightning.
3.3 Degradation and failure

This chapter treats the most common degradation and failure mechanisms to which the tanks may be subjected [5].

3.3.1 Degradation mechanisms

Corrosion

Corrosion is the major cause of deterioration of steel storage tanks and accessories. Locating and evaluating the extent of corrosion is therefore the most important reason for inspection. Corrosion may occur both internally and externally (see Figure 17).

![Figure 17: External corrosion [60]](image)

Both the nature of the stored product (amount of water and salts) and the water vapour in the space above the product, are determining factors for the corrosion rate. Another factor is the quality of the tank material in respect of its resistance to the aggressiveness of the stored product. The corrosion rates for two crude types are presented in Table 7.

<table>
<thead>
<tr>
<th>Crude type</th>
<th>Tank detail</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bottom</td>
<td>Shell</td>
<td>Floating roof</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plates</td>
<td>Liquid exposed area</td>
<td>Vapour space area</td>
<td>Plates</td>
<td>Pontoon/rim area</td>
<td></td>
</tr>
<tr>
<td>High sulphur crude oil</td>
<td>0.4-0.8</td>
<td>0.2-0.4</td>
<td>0.4-0.6</td>
<td>0.4-0.6</td>
<td>0.5-0.7</td>
<td></td>
</tr>
<tr>
<td>Low sulphur crude oil</td>
<td>0.3-0.5</td>
<td>0.1-0.3</td>
<td>0.2-0.4</td>
<td>0.2-0.4</td>
<td>0.3-0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Corrosion rates in mm/year for crude types and tank details [5]

5 No bottom coating or internal lining applied

6 Vapour space corrosion can be as high as 1mm/year depending on sulphur content of the crude oil and the ruling climate
The steel thicknesses of an 80m diameter crude tank with a volume of 100,000m$^3$ are in the order of:

- 8-12.5 mm for the bottom plate.
- 32 mm for the shell at the ground level and 8 mm at the top level.
- 5 mm for the floating roof plates.

**Causes of corrosion**

Internal corrosion may result from:

- The presence of aggressive substances or contaminants in the stored product. An example is vapour space corrosion, degrading of the top part of the inner tank shell and the underside of the tank roof (see Figure 18) due to, for instance the presence of sulphur components in an air-vapour mixture under relatively warm and humid conditions.

![Figure 18: Tank roof vapour space corrosion [60]](image)

- Entrance and accumulation of water in the tank caused by breathing of the tank due to temperature differences and condensation of water vapour, presence of water in the stored medium, or leakage of rainwater through the floating roof seal.
- Poor welding of the annular and bottom plates.

External corrosion may result from:

- Sub-standard quality of the sand-bitumen top layer of the foundation pad. Contaminants in the foundation pad, including clay, stones, cinders, or other sharply pointed materials. These may set up an oxygen concentration cell where they touch the tank bottom. The relatively small areas of contact between the bottom and the contaminants become anodic, and the large remaining area of the tank becomes cathodic$^7$. Accelerated attack of the contact area results in pitting corrosion (see Figure 19).

---

$^7$ In cathodic protection, a metal anode that is more reactive to the corrosive environment of the system to be protected, is electrically linked to the protected system, and partially corrodes or dissolves, which protects the metal of the system it is connected to. As an example, an iron or steel ship's hull may be protected by a zinc sacrificial anode, which will dissolve into the seawater and prevent the hull from being corroded. Sacrificial anodes are particularly needed for systems where a static charge is generated by the action of flowing liquids, such as pipelines and watercraft.
Figure 19: Pitting corrosion [60]

- Contact with rainwater by permeation and capillary action (see Figure 20) due to unevenness in the top of the foundation pad.

Figure 20: Contact with capillary water [60]

- Corrosion at a water trap formed by mounding of the tank foundation and/or edge settlement (see Figure 21).

Figure 21: Corrosion at a water trap [60]

- Poor welding of the annular and bottom plates.
Settlements and consequential problems

Steel tanks are flexible structures, which expands during filling and shrinks during emptying procedures. In order to prevent excessive tensions in the construction, the foundation needs to be flexible as well. Frequent filling and emptying may result in settlements.

Settlements may arise from:

- Uneven settlement and edge settlement of the tank pad shoulder due to erosion (see Figure 22).

![Figure 22: Edge settlements (left figure), uneven settlements (right figure) [5]](image)

- General settlement of the tank pad leading to instability and ultimately slip failure (see Figure 23).

![Figure 23: General settlement of the tank pad [5]](image)

- Damage to the liner underneath the tank due to (uneven) settlements.

- Jamming of floating roof structure around guide pole due to settlements (this may also occur in fixed roof tanks equipped with internal floating covers)

The vulnerability for settlements also depends on the subsoil conditions at the storage location.
3.3.2 Incidents enquiry
Degradation may finally result into tank (part) failure or incidents. According to the EEMUA no.159 [5], crude oil storage tanks proved to have many different failure modes. The report does not mention the frequency of occurrence.

Most common failure modes
In order to get more insight in the main failure modes and their frequencies of occurrence, as such statistics are not available, contact was made with 12 Shell storage locations. 6 locations (A-F), worldwide, randomly participated in the questionnaire resulting in a total of 87 crude oil storage tanks (see Appendix H). The 87 tanks form 6% of the total estimated number of crude tanks belonging to Shell (see Table 1 in Chapter2).

The results for the last 5 years of the 6 locations (A-F) are presented in Figure 24.

![Main failure mode frequencies within the last 5 years](image)

**Figure 24: Main failure mode frequencies within the last 5 years for 6 storage sites**

These numbers were used to estimate the yearly frequency of occurrence of each most common failure mode within the estimated total of approximately 1.400 crude oil storage tanks within Shell. The frequencies of occurrence and the related costs in the best case and worst case, for an 80m-diameter tank with a volume of 100,000m$^3$, are presented in Table 8.

**Note:**
Generally speaking it is of much difficulty to define the related financial damage sharply due to occurring different magnitudes and character of failure, incidents and the chance of escalation. Consequently the costs are estimated and split up in best-case and worst-case scenarios. The estimation is established in consultation with a tank engineer. The frequencies of occurrence and the related cost levels can vary across the globe.
<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Average frequency per year</th>
<th>Related financial damage (euros) for 80m diameter tank V=100,000m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Best case</td>
</tr>
<tr>
<td>Internal corrosion leading to product leakage</td>
<td>22</td>
<td>10k</td>
</tr>
<tr>
<td>External corrosion leading to product leakage</td>
<td>6</td>
<td>10k</td>
</tr>
<tr>
<td>Settlements</td>
<td>51</td>
<td>10k</td>
</tr>
<tr>
<td>Floating roof leakage</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>Floating roof drain leakage</td>
<td>29</td>
<td>10k</td>
</tr>
</tbody>
</table>
Table 8: Most common failure mode frequencies per year and related financial damage (business interruption, image damage and cleaning was not considered). Pictures source [60]

With the data from Table 8 the lowest and highest yearly financial damage was estimated. The results are presented in Table 9.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Best case</th>
<th>Worst case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion of floating roof supporting legs</td>
<td>19</td>
<td>10k</td>
</tr>
<tr>
<td>Failure of rolling ladder on top of floating roof</td>
<td>13</td>
<td>100k</td>
</tr>
<tr>
<td>Seal failure</td>
<td>22</td>
<td>10k</td>
</tr>
</tbody>
</table>

Table 9: Estimated yearly financial damage (euros) for the most common failure modes (business interruption, image damage and cleaning was not considered)

\(^8\) Only crude tanks considered.
Less common failure modes

The less common failure modes, which were not included in the enquiry, have been estimated and are presented in Table 10. Other effects leading to failure are presented in Appendix H.3.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Average frequency per year</th>
<th>Related costs (euros) for 80m diameter tank V=100,000m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jamming of the floating roof</td>
<td>3</td>
<td>Best case 100k, Worst case 1mil</td>
</tr>
<tr>
<td>Floating roof leakage leading to completely sinking of the roof</td>
<td>3</td>
<td>Best case 1mil, Worst case 10mil</td>
</tr>
<tr>
<td>Floating roof leakage leading to product on roof</td>
<td>6</td>
<td>Best case 0, Worst case 10k</td>
</tr>
<tr>
<td>Overfilling</td>
<td>16 ≥</td>
<td>Best case 10k, Worst case 100k</td>
</tr>
</tbody>
</table>

Table 10: Less common failure mode frequencies per year and related financial damage (business interruption, image damage and cleaning was not considered). Picture source [60]

With the data from Table 10 the lowest and highest yearly financial damage was estimated. The results are presented in Table 11.

<table>
<thead>
<tr>
<th>Estimated yearly financial damage¹⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best case</td>
</tr>
<tr>
<td>Ca. 4mil</td>
</tr>
</tbody>
</table>

Table 11: Estimated yearly financial damage (euros) for the less common failure modes (business interruption, image damage and cleaning was not considered)

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⁹ The enquiry in Appendix H states that overfilling does not occur. Though it is known to occur frequently.
¹⁰ Only crude tanks considered.
Total financial damage
With data from Table 9 and Table 11 the total yearly financial damage for Shell has been estimated (see Table 12).

| Estimated total yearly financial damage |  |
| Best case | Worst case |
| Ca. 7mil | Ca. 63mil |

Table 12: Estimated total yearly financial damage (euros) (business interruption, image damage and cleaning was not considered)

3.3.3 Key issues
• Tanks involve degradation mechanisms consisting of corrosion and settlements.

• Degradation may lead to many failure modes and incidents, with a high frequency of occurrence. This results in significant yearly financial losses, order of magnitude 10-50 million euros.

• The frequency of occurrence and the related financial damage strongly depends on the inspection and maintenance policy.
3.4 Inspection and maintenance

As mentioned in the previous chapters, storage tanks require inspection and maintenance work at regular chosen intervals to ensure that signs of deterioration are detected at an early stage. It identifies the need for remedial action to be taken, before deterioration progresses to the point where emission increases and leakage or other incidents occurs.

A storage tank is designed and operated such that it remains in service for many years without being opened for internal inspection and maintenance. Before internal inspection and maintenance can take place the tank needs to be cleaned completely (see Appendix C.9) [19]. This is required due to the possible presence of flammable vapours, which originate from remained product inside the tank. Tank cleaning takes approximately 8 weeks and costs approximately 250,000 euro.

3.4.1 Frequency

The total inspection scheme for a tank depends on three main elements [5]:

- Observations made by the operating personnel as they carry out their routine duties.
- Scheduled in-service inspection examinations made by the inspection engineer at an approximate annual frequency or at intervals as suggested in Table 13.
- The out-of-service inspection when the tank is gas freed and cleaned (for internal inspection and maintenance). This is carried out at much greater intervals, established either in accordance with the suggested periods outlined in Table 13, by a risk-based approach or dictated by local regulations.

<table>
<thead>
<tr>
<th>Inspection frequency</th>
<th>External routine visual (months)</th>
<th>External detailed visual including ultrasonic thickness measurements of shell and roof (years)</th>
<th>Internal detailed visual including ultrasonic thickness measurements of bottom and shell (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climate code</strong></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td><strong>Crude oil storage tanks</strong></td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

*Climate code:
A = warm and humid, e.g. tropical and subtropical areas
B = temperate climate with frequent rain and wind
C = warm and dry, e.g. desert locations

Table 13: Inspection frequencies [5]

The inspection frequencies indicated above are for guidance only. After each detailed external or internal inspection, the Tank Integrity Assessor (TIA) should determine the date for the next inspection. If the inspection results indicate a more rapid deterioration due to corrosion or settlements, other similar tanks may need to be inspected earlier. On the other hand, if the inspection results are favourable, an extension of the inspection interval may be considered.

On average crude tanks need a total thorough inspection once every 15-18 years. This is also driven by the need for external bottom inspection. At Shell Pernis refinery in The Netherlands the...
tanks will then be out of service for 1 year. After the necessary repairs (see for example the tank bottom repairs in Figure 25) the tanks shall fulfil their function for another 15-18 years.

Figure 25: Elevated tank for bottom reconstruction [60]

3.4.2 Costs
Figure 26 indicates that much effort is expensive and reduces the risk and too little effort is cheap and increases the risk for incidents. The optimal effort for which the total costs/risks are minimal is driven by a risk-based approach.

Figure 26: Maintenance effort versus costs [60]

At European Shell refineries, tank inspection and maintenance costs approximately 1 euro per m³ product per year. For example:

- A refinery with a total of 200 tanks (all kind of products).
- An average tank capacity of 10,000 m³.

The maintenance costs will be 2 million euros per year.
3.4.3 Key issues

- Inspection and maintenance is essential for risk reduction.
- This requires a frequent and thorough inspection scheme.
- Inspection and maintenance involves significant costs (1 euro per m$^3$ product per year).
3.5 Spatial use

Worldwide, most of the manufacturing locations can be found within or nearby port area. For example the Port of Rotterdam in The Netherlands (see Appendix I) [14]. The port needs more harbour space in order to keep on growing to maintain its port position in the world. The expected growth results from other businesses, like the container sector, as the progress of crude oil transhipment is expected to stay constant (see Appendix I.3).

To solve the spatial problem, the port is about to realize the second port extension Maasvlakte 2 and strongly stimulates innovative intensive utilisation of existing and future port area. Figure 27 shows the Rotterdam port area. The pink coloured area shows the spatial use by the oil and chemical industry.

![Figure 27: Industrial spatial use Port of Rotterdam [49]](image)

The industry confiscates 40% of the Rotterdam port area from which 58% counts for the refinement sector and 26% for the chemical sector [49].

3.5.1 Area storage capacity

The port of Rotterdam has a total tank storage capacity of more than 30 million m$^3$ for all types of liquids. As indicated in Figure 28 tanks in general use much space.

![Figure 28: Tanks in the Port of Rotterdam, all kinds of tanks (left), crude oil storage tanks (right) [62]](image)
According to the tank spacing proposal from Appendix C.7 the average area capacity per unit storage is 5m³/m². This is caused by several factors:

- The inter tank distances (see Appendix C.7).
- The distances between tanks and buildings/roads/railways etc (see Appendix C.7).
- The bund area requirements (see Appendix C.10).
- The aboveground construction type of large volume storage tanks, which results in more wide than high structures.

3.5.2 Intensive utilisation of port area

As stated earlier the Port of Rotterdam stimulates innovative intensive utilisation of existing and future port area. Within this framework the possibilities for Shell, within the port, have been studied (see Appendix I.4) with the following results:

- The lease charges for the port area, which contains crude oil storage is on average 3-5 euros/m² per year.

- This results in 2 million euros per year for the area lease charges for crude oil (only) at Shell Pernis refinery located in the port.

- There is a possibility for partially financial support by the port of Rotterdam for intensive utilisation projects.

3.5.3 Key issues

- Tanks use a significant amount of space, resulting in an average area storage capacity of 5m³/m².

- Port authorities can favour space intensification as more space comes available for other purposes.

- Space intensification could also be favoured by the oil industry. Reduction of the spatial use of tanks may result in less area lease charges at location where this is an issue.
3.6 Legislation developments

In order to study the general tank developments for the future a meeting was arranged with the secretary of VOTOB (Dutch association of six independent tank storage companies see Appendix O.1) [55]. The results are presented in the following chapter.

3.6.1 Dutch legislation

Dutch legislation is trying to achieve further reduction of emission in the future (see Appendix O.2). With the goal to achieve part of this reduction, the storage business was asked to set up a VOC emission reduction plan resulting in a reduction of 30% in the year 2010 compared to the year 2000. The emission in this year was established to be 2559 ton. According to the authorities the 30% reduction should lead to a maximum VOC emission of 1791 ton in the year 2010 [55].

A head of the IMKO-2 (integral environmental frame for storage and transhipment companies) agreement, a framework for the realisation of an environmental plan for the years 2006-2010 has been presented [55] (see Appendix O.3). It gives a good indication concerning the future developments in the storage business with the following results:

Emission

- External floating roof tanks need to be changed into internal floating roof tanks.
  The effectiveness due to this adjustment is indicated in Figure 29 taken from Appendix D.4.

![Figure 29: Emission in tons/year for floating roof tank and geodesic dome tank with internal floating roof for vapour mounted primary seal in average condition, tank volume 100.000m³ (ton/year)](image-url)
• Or the External floating roof tanks need to be equipped with secondary seals. The effectiveness due to this adjustment is indicated in Figure 30 taken from Appendix D.2.

![Figure 30: Emission in tons/year for different seal types in good and average condition for 48 turnovers (ton/year)](image)

• Or internal floating roof tanks need to be equipped with a primary rim seal.

• Loading emission. All systems containing emission during loading and unloading need to be equipped with a vapour recovery system.

• Emission calculation. In the past several calculation models for the calculation of emission to the atmosphere were applied. From now on a uniform calculation model (CARUSO) will be used to unambiguously determine the magnitude of the emission.

• Vapour treatment. Vapour treatment systems need to be improved.

• Emission prevention. Emission prevention needs to be achieved by maintenance work for already installed facilities. All joints, connections and transhipment from floating roofs need to be sealed. Beside this stocktaking needs to be carried out and plans need to be composed in order to achieve vapour tightness of bad roofs and replacement of low affective seals (see the differences between good and average condition in Figure 30).

\[\text{Leakage}\]

• Concerning the soil, there exist a distinction between historical soil contamination and prevention of soil contamination.

• The Dutch soil protection law states that every license holder is obliged to recover soil contamination caused by its own.

• Within 2 years after signing the IMKO-2 agreement (see Appendix Appendix O) every terminal, which does not have an agreement with the authority concerning historical soil contamination, shall have a rehabilitation program or a location administer plan in accordance with the soil protection law. This includes contamination risks, the locations and the nature of the soil quality, monitoring of the contamination and the purpose of the rehabilitation (end quality of the soil).
Within the program or administer plan there is flexibility for the application of the cost effective rehabilitation method.

- All new tanks and other installations need to have negligible risks for the soil. First the existing situation requires a soil risk analysis conform NRB/BoBo [63]. After this the tanks and installation, which do not belong to the negligible risk category, require an approach plan including measures to let these tanks and installation belong to the negligible risk category. The most risk full situation will receive the highest priority. All tanks and other facilities should belong to the negligible risk category within 15 years after signing the IMKO-2 agreement (see Appendix Appendix O). It is stressed that the majority of the tanks and facilities should have achieved this requirement within 5-10 years after signing the agreement.

**Waste material**
Waste material needs to be prevented or the environmental damage needs to be reduced by source reduction or internal recycling.

### 3.6.2 Key issues

- Dutch legislation developments indicate a further reduction of emission from storage tanks. In the year 2010 a reduction of 30% compared to the year 2000 needs to be achieved.

- Historical soil contamination needs to be recovered. Within 2 years after signing the IMKO-2 agreement (see Appendix O) every storage terminal is required to have a soil rehabilitation program.

- All new tanks need to have negligible risks for soil contamination.
3.7 Expectations “The Base Case”

The basic design concept of floating roof tanks has not changed since the first tanks of this type were built. However there have been improvements in detailed design and material specification as operating experience has developed. The previous chapter indicates that these design enhancements mainly have been aimed at the reduction of emission and soil contamination. The question rises what the tank appearance will be over 20 years, assuming the continuous application of legislation and economic driven adjustments. This chapter gives a possible indication, presented as “The Base Case”.

3.7.1 Adjustments

The prediction is mainly based on Dutch legislation developments. Beside this also possible adjustments derived from developments in the storage business itself have been added to The Base Case.

First the adjustments that fulfil possible legislation developments are presented.

**Bund area:**

- If a tank suddenly collapses a product wave will enter the bund area. Present bund walls are not designed to deal with this type of load resulting in the wave running over the wall. In order to prevent soil contamination of the surrounding area, the wave must not reach the outer side of the bund area. To overcome this problem the bund area needs have some kind of wave impact dissipating structure. This can be realised by a higher bund wall with intermediate slopes or a wide ditch, not to be confused with the traditional bund area draining system (see Figure 60 in Appendix C.10) surrounding the tank. Several bridges over these ditches need to be built for the tank accessibility during inspection, maintenance or fire fighting activities.

- To prevent possible groundwater, open water and soil contamination no fluid or product may infiltrate into the bund floor. This can be achieved by designing a complete guaranteed impermeable bund floor. A solution may be the use of an artificial impermeable layer. This is already applied in Germany where a storage site is located nearby a drinking water extraction area. At the location the complete bund area is constructed from an artificial impermeable layer, costs 400,000 euro for a tank with a diameter of 80m and a volume of 100,000m$^3$. Also tanks with double walls and double bottoms are applied. The choice may consist of a double walled tank or the artificial impermeable layer in combination with a double bottom.

**Tank:**

- In order to reduce the emission from floating roof tanks all tanks will possibly be constructed as internal floating roof tanks with a geodesic dome roof. Dome construction costs for a tank volume of 100,000m$^3$ is approximately 1.5 million euros.

- For further emission reduction the rim seals will be double sealed.

- The vapour space underneath the dome structure needs to have a vapour recovery system in order to be able to completely mitigate emissions. The costs for such kind of system may be in the range of 300,000-800,000 euro (excluding operational costs) [7].
**Inspection and maintenance:**
- Inspection and maintenance will be done more frequently to reduce all the tank related risks.

Adjustments to solve disadvantages recognized by the storage business.

**Tank:**
- A dome structure will also be applied to reduce the weather loads on the floating roof. This will result in less degradation of the floating roof.

**Fire safety:**
- The inter tank distances will need to be bigger in order to reduce the chance of igniting surrounding tanks during a tank fire. For an inter tank distance proposal see Appendix C.7 Figure 54.

### 3.7.2 Key issues
- Tank design enhancements are generally speaking driven by the oil industry for economic reasons and by legislation for environmental reasons. The main target is the reduction of emission and the prevention of soil contamination.

- The tank building costs will increase due to the adjustments. The total costs for an 80-meter diameter tank with storage capacity of 100,000 m$^3$ may be in the order of 22 million euros (220 euros/m$^3$). This is an increase of 2 million euros (10%) compared to the present tank design (200 euro/m$^3$ see Appendix C.13).

- The investment resulting in emission reduction can be recaptured due to the reduction of product loss.

- Spatial use by tanks will increase as the inter tank distances are expected to increase.

- Inspection and maintenance work is of great importance in reducing the main drawbacks concerning the traditional tank design. It will be done more frequently resulting in higher costs.
4. Opportunities of improvement

- Crude oil storage tanks are subjected to degradation leading to several failure modes with a significant frequency of occurrence. The damage results in significant financial losses, possible negative consequences for the environment and reputation. The frequency of occurrence strongly depends on the inspection and maintenance policy. This kind of work is expensive, difficult to execute unambiguously and may lead to dangerous and unhealthy situations for personnel.

- Beside this, storage tanks use much space (average storage capacity is $5\text{m}^3/\text{m}^2$) resulting spatial problems in situations where space is scarce.

- Tank design enhancements are generally speaking driven by the oil industry for economic reasons and by legislation for environmental reasons. The main target is the reduction of emission and the prevention of soil contamination. Dutch legislation developments indicate that emission and the risk of soil contamination need to be further reduced in the future. In the year 2010 an emission reduction of 30% compared to the year 2000 needs to be achieved.

- The related expected design enhancements, translated into The Base Case, will result in more complex and higher (10%) structural design costs (expressed per unit storage: 220 euros/$\text{m}^3$ compared to 200euro/$\text{m}^3$).

To improve the traditional tank design, several conceptual solutions are generated in the subsequent chapter.
5. Conceptual designs

First the requirements and premises are stated. Subsequently concepts will be generated followed by their assessment. Eventually one concept will be chosen and elaborated in a pre design for a specific location.

5.1 Requirements and premises

The requirements are divided into business, functional and technical requirements.

5.1.1 Business

In order to achieve benefits for the oil business the concepts need to address the following problem areas:

- Reduce the Health, Safety and Environmental (HSE) risks.
- Reduce the risk of financial losses due to failure.
- Reduce the costs related to construction and inspection & maintenance.
- Reduce the spatial use.

5.1.2 Functional

From a functional point of view the concepts need to have:

- Be suitable for crude oil storage.
- A unit storage volume of 50,000m³-100,000m³.

5.1.3 Technical

The above-mentioned business requirements have been translated into the following technical requirements:

- Be less sensitive for degradation.
- Have less failure modes.
- Contain an integrated sludge (see Appendix C.9) removal system.
- Reduction of emission.
- Intensification of space utilisation.

The correlation between the business requirements and the technical requirements is presented in Table 14. Correlation is indicated with the mark X, no correlation is indicated with the mark 0. The table indicates that to fulfil the business requirements the technical requirements need to be achieved.
Technical requirements

<table>
<thead>
<tr>
<th>Business requirements</th>
<th>Be less sensitive for degradation</th>
<th>Have less failure modes</th>
<th>Integrated sludge removal system</th>
<th>Reduction of emission</th>
<th>Intensification of space utilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce the risk of Health, Safety and Environmental (HSE) issues</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
</tr>
<tr>
<td>Reduce the risk of financial losses due to failure</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>0</td>
</tr>
<tr>
<td>Reduce the inspection and maintenance costs</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reduce the lease charges related to the spatial use of the tanks</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 14: Correlation between business and technical requirements.

The technical requirements can be fulfilled by the following solutions:

- Less sensitivity for degradation can be achieved by the prevention of corrosion and settlements. Applying non-corrosive materials other than steel prevents corrosion and the application of a rigid structure prevents uneven settlements (see chapter 3.3.1). Resulting in less inspection and maintenance effort.

- Preventing corrosion by the use of non-corrosive materials and striving for a simple structure with fewer appendages can result in less failure modes.

- An integrated sludge removal system has the advantage that personnel do not have to enter the tank for unhealthy and unsafe cleaning operations.

- Reduction of emission can be achieved by the application of a closed reservoir.

- The intensification of space utilisation can be achieved by:
1) Reduction of the inter tank distances. These distances can possibly be reduced if there is no product release scenario. This calls for the prevention of corrosion using non-corrosive materials and preventing emission by the application of a closed reservoir. If this reservoir is continuously filled or injected with an inert gas the vapour space will disappear and so the chance for explosions. This solution possibly allows the inter tanks distances to reduce even further.

2) Removal of the bund area. If there is no possible leak scenario the secondary containment function of bund area can possibly be removed.

3) Multiple utilisation of space. For example underground storage with container storage on top.

4) Different storage location. For example underground or offshore.

Summarised the concepts need to have the following properties to address to the technical and business requirements:
- Non-corrosive materials.
- Rigid structure.
- Simple structure with fewer appendages.
- An integrated sludge removal system.
- A closed reservoir, which is continuously filled or injected with an inert gas.
- Multiple utilisation of space.
- Other construction location than aboveground.

5.1.4 Premises

The following premises are considered:
- The future interface between crude oil production, manufacturing and transport will still be realised by storage tanks.

- The concepts will not be generated for a specific location.
5.2 Concepts

According to the requirements and premises, several “out of the box” concepts are designed (see Table 15 and Appendix P). The concepts consist of own designs, designs gathered from a previous creative meeting and existing applications. The concepts are divided into the following classifications:
- Underground.
- Aboveground.
- Submerged.
- Floating.

<table>
<thead>
<tr>
<th>Underground</th>
<th>Concept</th>
<th>Impression</th>
<th>Concept</th>
<th>Impression</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-A²</td>
<td><img src="image1.png" alt="Image" /></td>
<td>U-I²</td>
<td><img src="image2.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>U-B²</td>
<td><img src="image3.png" alt="Image" /></td>
<td>U-J²</td>
<td><img src="image4.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>U-C²</td>
<td><img src="image5.png" alt="Image" /></td>
<td>U-K²</td>
<td><img src="image6.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>U-D²</td>
<td><img src="image7.png" alt="Image" /></td>
<td>U-O³</td>
<td><img src="image8.png" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>
### Aboveground

<table>
<thead>
<tr>
<th>U-E²</th>
<th>U-P³</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>U-G²</th>
</tr>
</thead>
</table>

**Base Case¹** = Traditional tank design incl. expected design enhancements for the future (see Chapter 3.7)

### Submerged

<table>
<thead>
<tr>
<th>S-A³</th>
<th>S-C¹</th>
</tr>
</thead>
</table>

---

Next Generation Storage Tanks
A potential alternative for crude oil storage tanks
Table 15: Concept impressions

The concepts are presented in more detail in Appendix P. Each concept is described conform:

- Impression.
- Specific properties.
- Structural design.
- Operation.
- Inspection and maintenance.
- Fire safety.
- Spatial use.
- Fulfilment of the technical requirements.
5.3 Concept assessment

The assessment process was based on two analyses with different objectives:

- First a multi criteria analysis has been executed to indicate the fulfilment of the technical requirements, stated in Chapter 5.1.3, to discern potential concepts in order to achieve improvements.

- Secondly these potential concepts were analysed with a more detailed multi criteria analysis in order to assess their operate ability.

5.3.1 Results

First analysis

To indicate the fulfilment of the technical requirements, at the end of each concept description (see Appendix P) a multi criteria analysis is performed conform Table 16 and Table 17. Note: each concept is compared to “The Base Case” (Traditional tank design incl. expected design enhancements for the future see Chapter 3.7).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less sensitive for degradation</td>
<td></td>
</tr>
<tr>
<td>Less failure modes</td>
<td></td>
</tr>
<tr>
<td>Integrated sludge removal system</td>
<td></td>
</tr>
<tr>
<td>No emission</td>
<td></td>
</tr>
<tr>
<td>Intensification of space utilisation</td>
<td></td>
</tr>
</tbody>
</table>

Table 16: Multi criteria analysis parameters

<table>
<thead>
<tr>
<th>Score</th>
<th>Technical requirements fulfilment</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>Worse</td>
</tr>
<tr>
<td>-</td>
<td>Bad</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>+</td>
<td>Good</td>
</tr>
<tr>
<td>++</td>
<td>Best</td>
</tr>
</tbody>
</table>

Table 17: Multi criteria analysis scores

The results from the first analysis (see also Appendix P.1 and Appendix Q.2) are presented in Table 18-Table 21. The potential concepts per classification and the highest scores are indicated in green. The impressions are presented in Table 15 and in more detail in Appendix P.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 18: Fulfilment results technical requirements underground concepts
Table 19: Fulfilment results technical requirements aboveground concepts

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Aboveground</th>
<th></th>
<th></th>
<th></th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>A-A</td>
<td>A-B</td>
<td>A-C</td>
<td>A-D</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 20: Fulfilment results technical requirements submerged concepts

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Submerged</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>S-A</td>
<td>S-B</td>
<td>S-C</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 21: Fulfilment results technical requirements floating concepts

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Floating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>F-A</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>
Second analysis
The potential concepts marked in green (see Table 22 and Table 15) have been analysed in more detail. The following tank specialists with different business interests participated in the analysis:

- Health, safety and environment consultant.
- Oil movement technologist.
- Tank engineer.
- Storage and integrity engineer.
- Structural tank engineer.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Underground</th>
<th>Aboveground</th>
<th>Submerged</th>
<th>Floating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>U-G</td>
<td>U-I</td>
<td>U-K</td>
<td>A-A</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 22: Potential concepts scores (see Appendix P for concept descriptions)

Note:
- Due to the fact that the underground concept U-A and U-K are almost similar and have equal scores it was decided to remove concept U-A from the analyses.
- Despite the low score of The Base Case, the concept was considered in the analysis for reference.

Parameter scores
Each concept was compared to “The Base Case” (traditional tank design incl. expected design enhancements for the future, see Chapter 3.7) granting different parameters a score. The parameters and their description are presented in Table 23.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSE (health, safety and environment)</td>
<td>Emission, leak prevention and detection, fire safety, general safety</td>
</tr>
<tr>
<td>Inspection and maintenance</td>
<td>Degradation mechanisms, failure modes, inspection frequency, costs, accessibility</td>
</tr>
<tr>
<td>Oil movement</td>
<td>Filling and emptying</td>
</tr>
<tr>
<td>Spatial use</td>
<td>Inter tank distances, multiple spatial use</td>
</tr>
<tr>
<td>Technical</td>
<td>Constructional feasibility, implementation time</td>
</tr>
<tr>
<td>Aesthetical impression</td>
<td>Cosmetics</td>
</tr>
<tr>
<td>Building costs$^{12}$</td>
<td>Costs compared to aboveground structures: Underground x2 Offshore x10</td>
</tr>
</tbody>
</table>

Table 23: Analysis parameters

$^{12}$ A high score for the parameter building costs indicates that the actual costs are low, which is interpreted as positive.
The parameter scores are presented in Table 24.

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Much worse</td>
</tr>
<tr>
<td>1</td>
<td>Worse</td>
</tr>
<tr>
<td>2</td>
<td>Neutral</td>
</tr>
<tr>
<td>3</td>
<td>Better</td>
</tr>
<tr>
<td>4</td>
<td>Much better</td>
</tr>
</tbody>
</table>

Table 24: Analysis parameter scores

Parameter weights
Due to the application of different parameters, differences exist in the mutual importance or weight of each parameter. To establish the weight, each parameter is mutually compared, conform the scores presented Table 26. The result is presented in Table 25.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Score</th>
<th>Percentage/weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSE (Health, Safety and Environment)</td>
<td>X</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td></td>
<td>23.8</td>
</tr>
<tr>
<td>Inspection and maintenance</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>11.9</td>
</tr>
<tr>
<td>Oil movement</td>
<td>1</td>
<td>2</td>
<td>X</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td>23.8</td>
</tr>
<tr>
<td>Spatial use</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>4.8</td>
</tr>
<tr>
<td>Technical</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>X</td>
<td>2</td>
<td>1</td>
<td>14.3</td>
</tr>
<tr>
<td>Aesthetical impression</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>1</td>
<td>2.4</td>
</tr>
<tr>
<td>Building costs</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>X</td>
<td>8</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Total 42 100%

Table 25: Analysis parameter weights

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Less important than</td>
</tr>
<tr>
<td>1</td>
<td>Equally important</td>
</tr>
<tr>
<td>2</td>
<td>More important than</td>
</tr>
</tbody>
</table>

Table 26: Analysis parameter weight scores
After rating the concepts conform Table 24, an average score and subsequently a normalised score have been calculated. The normalised score was then multiplied with each parameter weight resulting in the parameter scores presented in Table 131 in Appendix Q.2. The final results are presented in Figure 31 (see Table 15 for the concept impressions and Appendix P for the concept descriptions).

![Final analysis results](image)

**Figure 31: Final analysis results**

5.3.2 Key issues

- According to the analysis the aboveground concepts A-A, A-C and the underground concepts U-I and U-K reach the highest scores (see Table 15 for the concept impressions and Appendix P for the concept descriptions).

- The Base Case (traditional tank design incl. expected design enhancements for the future, see Chapter 3.7) also scores high, which indicates that the conventional tank including the adjustments (see Chapter 3.7.1) conform the expected developments (see Chapter 3.6) still is a good alternative. Note: To achieve the high score a well-executed tank inspection and maintenance policy is essential.

- Concept U-K scores the best of all concepts. This is caused by the confidence created by the conformity with the already applied concept U-A by Shell Brazil (see Appendix P.3).
6. Detailed concept design

6.1 Introduction

From all evaluated concepts, the underground storage in a caisson structure (see Appendix P.3) was assessed as one of the promising solutions, as it results in the reduction of:

- The Health, Safety and Environmental risks.
- The risk of financial losses due to failure.
- The costs related to inspection & maintenance.
- The spatial use.

Subsequently the concept has been selected to form the basis for a technical pre-design for the Port of Rotterdam. The concept will be integrated with a container terminal and a quay structure according to the layout presented in Figure 32 (see also Figure 36 in Chapter 6.6.4).

Figure 32: Underground crude oil storage in caissons integrated with a quay structure and a container on and offloading terminal
The reservoir is divided into smaller units and is continuously filled according to the exchange principle between water and oil (indicated with successively blue and black in the upper picture in Figure 32). The ballast water needs to be treated depending on the amount contamination. First the boundary conditions will be stated followed by the requirements and premises. Subsequently the construction will be described in more detail followed by pre-design calculations.
6.2 Boundary conditions

6.2.1 Natural
The natural boundary conditions are divided into:
• Topographical.
• Hydrographical.
• Geotechnical.
• Hydraulic.
• Environmental and climatologic.

The hydrographical, geotechnical, hydraulic, environmental and climatologic boundary conditions are successively described in detail in Appendices J.3, J.4, J.5 and J.6. A summary is presented in Table 27.

Topographical
As mentioned in Chapter 3.5 the Port of Rotterdam in The Netherlands needs more harbour space in order to keep on growing, willing to maintain its port position in the world. To solve the spatial problem, the port is about to realize the second port extension Maasvlakte 2 (see Appendix J.1) and strongly stimulates innovative intensive utilisation of existing and future port area.

The storage and quay structure will be located at the prospective land reclamation project Maasvlakte 2 (hatched orange area in Figure 33 on the seaside of the already existing extension Maasvlakte 1) in The Netherlands.
Figure 33: Maasvlakte 2 port extension location [49]

6.2.2 Technical

The technical boundary conditions are described in Appendix J.7 and included in Table 27.

<table>
<thead>
<tr>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrographical</strong></td>
</tr>
<tr>
<td>Present water depth at The MV2 location</td>
</tr>
<tr>
<td>Navigation depth at MV2 location</td>
</tr>
<tr>
<td>Port of Rotterdam</td>
</tr>
<tr>
<td><strong>Geotechnical</strong></td>
</tr>
<tr>
<td>Surface level</td>
</tr>
</tbody>
</table>
| Coarse sand | $\gamma_{wet} = 20 \text{kN/m}^3$  
$\gamma_{dry} = 8 \text{kN/m}^3$  
$\alpha = 30^\circ$ |
<p>| Ground water (salt) | $\gamma_w = 10,25 \text{kN/m}^3$ |</p>
<table>
<thead>
<tr>
<th><strong>Hydraulic</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Harbour water (salt)</strong></td>
<td>$\gamma_w = 10.25 \text{ kN/m}^3$</td>
</tr>
</tbody>
</table>
| **Design water level** | HDWL = 5.50 + NAP (meter)  
LDWL = 2.50 - NAP (meter)  
AWL = 1.11 + to 0.63 - NAP (meter) |

<table>
<thead>
<tr>
<th><strong>Environmental</strong></th>
<th></th>
</tr>
</thead>
</table>
| **Class [45]** | XS3 (new arrangement) or  
3,4,5 (old arrangement) |

<table>
<thead>
<tr>
<th><strong>Technical</strong></th>
<th></th>
</tr>
</thead>
</table>
| **Concrete** | Quality B35  
$\gamma_{\text{concrete}} = 25 \text{ kN/m}^3$  
Reinforcement steel FeB500  
$\gamma_{\text{ballast}} = 23 \frac{\text{kN}}{\text{m}^3}$ |
| **Crude oil** | $\gamma_{\text{oil}} = 8.5 \text{ kN/m}^3$ |
| **Ballast water** | $\gamma_w = 10.25 \text{ kN/m}^3$ |
| **Design ship [11]** | Length overall 470 meter  
Capacity 18,000 TEU  
Draught 15.7 meter  
Width 60m  
Main propeller power 100,000 kW, diameter 10 meter  
Bow propeller power 5,000 kW, diameter 4 meter |
| **Maasvlakte 2 navigation depth** | 20.8 - NAP (meter) |
| **Container terminal** | Berth productivity 1,350 TEU moves/quay meter/year  
Quay crane productivity 25 moves/crane/hour |

*Table 27: Boundary conditions*
6.3 Requirements

Crude oil storage:
• The volume of a single storage unit will need to be approximately 50,000m$^3$ - 100,000m$^3$.
• The structure needs to be impermeable for liquids and gases.

Nautical:
• The harbour basin and the quay will be designed for a future Ultra Large Container Ships (ULCS) (see Table 27 and Appendix J.7).

Container terminal:
• The terminal needs to have sufficient crane capacity to deal with the cargo related to the design vessel.

Retaining.
The quay structure needs to retain permanent and variable loads.
Permanent loads result from:
• Harbour water (partly variable).
• Ground water.
• Soil.
• Deadweight of the structure.

Variable loads result from:
• Crude oil and ballast water.
• External loads (crane, terminal).
• Ship (mooring and propeller wash).
6.4 Premises

The following premises are considered:

- As no building facilities (see Appendix L.4) are available at the prospective location and to interfere as less as possible with the land reclamation project, the caissons will be constructed in a shipping dock in the port of Rotterdam (see Appendix J.3). After construction they will be transported floating to the end-location.

- Effects from waves, tidal currents, harbour basin resonance and ice, are assumed to be negligible (see Appendix J.5).

- Meteorological effects and earthquakes are not considered within the framework of this study (see Appendix J.6).

- The lifespan of the construction is assumed to be 50 years.

- Effects from ship collision are not considered. Mooring facilities like breasting dolphins are considered constructed independently from the quay structure (see Appendix K). The design is recommended for further studies.

- Calamities like for example accidental falling cargo are not considered. The consequences need to be elaborated in further studies.

- Concrete is considered to be liquid and gas tight and will not corrode due to reactions with crude oil. The behaviour needs extra attention in further studies.

- The container terminal and crane design is based on a general layout.

- The removal of sludge is not considered.

- Piping and related installation, and water treatment installation will not be designed.
6.5 Container terminal design

The terminal is designed conform the layouts presented in Appendix L.2 and L.3 the result is presented in Figure 34. Relevant terminal and crane data is presented in Table 27 and Table 28.

<table>
<thead>
<tr>
<th>Terminal data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation depth</td>
<td>20,8 - NAP (meter)</td>
</tr>
<tr>
<td>Berth length</td>
<td>500 meter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Crane data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cranes per berth</td>
<td>6</td>
</tr>
<tr>
<td>Distance water- landside portals</td>
<td>30,5 meter</td>
</tr>
<tr>
<td>Distance between buffers</td>
<td>27,2 meter</td>
</tr>
<tr>
<td>Hart to hart distance wheel set</td>
<td>17,2 meter</td>
</tr>
</tbody>
</table>

Table 28: Terminal and crane data [35]
The considered mooring configuration is presented in Figure 35 (see also Appendix L.1).

Figure 35: Mooring configuration [10]
6.6 Pre-design calculations

The pre-design calculation considers two designs for the underground caisson alternative:
- Tank design, which can possibly be set dry.
- Tank design, which is continuously filled.

The following pre-design calculations are executed:
- Overall structural stability.
- Concrete dimensions.
- Foundation bearing capacity and settlements.
- Stability during transport and installation.
- Piping.
- Scour and protection.

The calculations are done for 2 tank designs:
- Tank, which can possibly be set dry.
- Tank, which is continuously filled.

6.6.1 Load combinations

The calculations will consider the extreme or unfavourable load combinations as presented in Table 29.

<table>
<thead>
<tr>
<th>Loads</th>
<th>Stability calculations</th>
<th>Other calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overturning</td>
<td>Uplift</td>
</tr>
<tr>
<td>Permanent</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Reservoir deadweight</td>
<td>1</td>
<td>X</td>
</tr>
<tr>
<td>Soil</td>
<td>2</td>
<td>X</td>
</tr>
<tr>
<td>Ground water</td>
<td>3</td>
<td>X</td>
</tr>
<tr>
<td>Variable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harbour water level</td>
<td>HDWL</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>LDWL</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>AWL</td>
<td>6</td>
</tr>
<tr>
<td>Reservoir content</td>
<td>Water</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Empty</td>
<td>9</td>
</tr>
<tr>
<td>Crane operation</td>
<td>Normal</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Storm</td>
<td>11</td>
</tr>
<tr>
<td>Terminal</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Ship mooring</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Ship propeller wash</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

Table 29: Extreme load combinations
6.6.2 Results

Overall stability

- Overturning calculated in Appendix M.5.
- Uplift calculated in Appendix M.6.
- Horizontal sliding calculated in Appendix M.7.

The governing load combination occurs during the Lowest design Water Level (LDWL) for horizontal sliding (see Appendix M.8). In order to comply with the overall stability, the weight of the tank should at least be \( G_{\text{required}} > 164 \cdot 10^4 \text{kN} \).

For the tank design, which can possibly be set dry, this results in the requirement:

\[ G_{\text{required}} > 164 \cdot 10^4 \text{kN} . \]

For the tank design, which is continuously filled, this results in the requirement:

\[ G_{\text{oil}} + F_{\text{concrete}} \geq 164 \cdot 10^4 \text{kN} . \]

Note: To fulfil the weight requirement for overall stability several options exist:

- Over dimensioning (increases the weight and the navigation depth during floating transport).
- Foundation on tension piles.
- Use of soil anchors.
- Application of a toe structure.
- Use of ballast (concrete, iron ore, basalt split).

The application of ballast is considered to be the most economically attractive option. For the material concrete is considered.

Concrete dimensions

- Tank, which can possibly be set dry, see Table 30 (calculations are presented in Appendix M.9.3).

<table>
<thead>
<tr>
<th>Storage volume</th>
<th>Concrete volume</th>
<th>Ballast concrete volume</th>
<th>Roof height</th>
<th>External walls thickness</th>
<th>Internal walls thickness</th>
<th>Floor thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.000m³</td>
<td>28.000m³</td>
<td>41.000m³</td>
<td>0.40m</td>
<td>1.0m</td>
<td>0.90m</td>
<td>0.80m</td>
</tr>
</tbody>
</table>

Table 30: Concrete dimensions for tank, which can possibly be set dry

The tank is not suitable for floating transport, as the navigation depth of 19m is too large.

- Tank, which is continuously filled, see Table 31 (calculations are presented in Appendix M.9.4).

<table>
<thead>
<tr>
<th>Storage volume</th>
<th>Concrete volume</th>
<th>Ballast concrete volume</th>
<th>Roof height</th>
<th>External walls thickness</th>
<th>Internal walls thickness</th>
<th>Floor thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.000m³</td>
<td>15.000m³</td>
<td>33.000m³</td>
<td>0.40m</td>
<td>0.70m</td>
<td>0.40m</td>
<td>0.70m</td>
</tr>
</tbody>
</table>

Table 31: Concrete dimensions for tank, which is continuously filled

The tank is suitable for floating transport, as the navigation depth is 10m.
Foundation bearing capacity and settlements
The foundation bearing capacity is sufficient for both tank designs as the maximum foundation pressure is smaller than \( q_{\text{allowable}} = 1.600 \, \text{kN/m}^2 \) (calculations are presented in Appendix M.10).

Depending on the conditions foundation settlements may be expected. The settlements can be in the order of \( s = 0.40 \text{m} \) (calculations are presented in Appendix M.10).

Construction, transport and installation
- The tank design, which can possible be set dry, is not suitable for floating transport. Weight reducing methods are required unless the tank will be fabricated at the location itself (see Appendix L.4).
- The tank design, which is continuously filled, is suitable for floating transport. The tank can be fabricated in the Keppel-Verolme ship dock in the Port of Rotterdam [54] (see Appendix J.3) after which it can be transported floating. The stability during transport and installation has been calculated in Appendix M.11 and is sufficient.

Piping
The actual percolation length, calculated in Appendix M.12, is sufficiently large and piping is considered to be not an issue.
Note: Possibly the caissons will not be placed closely adjacent to each other. Depending on the closure of this space the stability against piping around the caisson needs extra attention. A drainage system around the caissons is a possible solution.

Scour and protection
The stern screw creates the maximum current velocity at the bottom of the harbour \( V_{\text{bottom max}} = 5 \, \text{m/s} \) (considering 10% of the maximum screw output). Related scour protection requires a stone diameter of \( d_{\text{required}} \geq 1 \text{m} \) equal to a stone grading of 1000-3000kg (calculated in Appendix M.13).

Note: The thickness and the build up of the scour protection layers need to be studied. As the calculation is based on 10% of the max stern screw power, additional bottom survey is needed to check the thickness and location of the bottom material during time. For pre design calculations 75% of the max stern screw output is advised [3]. In practise this results in uneconomically scour protection dimensions. The large required stone diameter results in several granular filter layers with the consequence that the height of the protection increases and the bottom keel clearance decreases. Preliminary dredging is a possible expensive solution, which may have a negative influence on the stability of the quay wall.

Solution: If dimensioning according to 75% of the engine power is preferred a solution to overcome uneconomical scour protection can be formed by the use of geo-textile combined with a single filter layer and a top layer impregnated with asphalt or concrete.
6.6.3 Construction costs

The cost for the design, which is continuously filled (see Table 31), is estimated in Appendix N. The estimation is based on benchmarking. Information is obtained from an equal recorded Shell project. The costs will be in the order of 19 million euros per tank. Each tank has a storage capacity of approximately 58,000 m$^3$ resulting in 330 euros/m$^3$ storage.

However, the design combines several functionalities, e.g. a quay structure and port/terminal area. These costs (see Table 32) need to be deducted to achieve the costs for the storage function only. Resulting in the approximate total costs, expressed per unit storage for the storage function only, of 270 euros/m$^3$ (16 million euros).

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Unit rate (euro/m$^2$)</th>
<th>Quantity (m$^2$)</th>
<th>Costs (euro)</th>
<th>Costs/unit storage (euro/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quay structure$^1$</td>
<td>1500</td>
<td>64x26=1664</td>
<td>2,500,000</td>
<td>Ca. 45</td>
</tr>
<tr>
<td>New reclaimed port/terminal area$^2$</td>
<td>200 [59]</td>
<td>64x64=4096</td>
<td>820,000</td>
<td>Ca.15</td>
</tr>
</tbody>
</table>

Table 32: Costs per unit storage (euro/m$^3$) for the quay and port/terminal functionalities

Note:
1: considering length and height of the quay LxH
2: considering port surface LxW

• Design optimisation will result in reduction of the costs (215 euros/m$^3$).
  For example, the amount of ballast can possibly be reduced by the use of heavier material.
  Increase of the ballast volumetric weight with factor 2 results in an increase of the storage capacity of approximately 15,000 m$^3$. Reducing the costs, expressed per unit storage for the storage function only, to 215 euros/m$^3$.

• As the alternative complies with the demand of space intensification the port of Rotterdam could sponsor part of the project resulting in an even further reduction of the costs. In such a case the degree of innovation and the additional business for the port would be a subject for a feasibility study.
6.6.4 Tank impressions

In association with an architect several tank impressions have been designed (see Figure 36).

Figure 36: Tank impressions (blue= ballast water, black= crude oil) [65]
6.6.5 Key issues

- The possibility to set the tank dry
  Results in larger dimensions of the construction concrete, more ballast concrete, less storage capacity and no possibility for floating transport unless weight-reducing methods are considered. The design is considered to be inconvenient.

- Total storage capacity
  The designed tank, which is continuously filled, has a storage capacity of 58,000 m$^3$. Maasvlakte 2 will have in total 12 km of quay [38]. Considering Figure 33 approximately 6 km will consist of a quay structure in front of a container terminal. Assuming one row of tanks over 6 km this will result in 5.4 million m$^3$ of storage capacity. This is equal to 2.5 times the present crude storage capacity of Shell Pernis (incl. Europoort) (see Figure 3 in Chapter 2.1).

- Spatial gain
  According Chapter 3.5.1, the average area storage capacity for traditional aboveground tanks is 5 m$^3$/m$^2$. Considering a total storage capacity of 5.4 million m$^3$, the design gains space in the order of 108 hectares.

- Construction costs
  The total costs after design optimisation will be in the order of 215 euros/m$^3$ (expressed per unit storage). Compared to The Base Case$^{13}$ (220 euros/m$^3$) this is a reduction of 1%.

---

$^{13}$ Traditional tank design incl. expected design enhancements for the future, see Chapter 3.7.
7. **Improvements and outcome**

*Improvements*

A potential alternative for crude oil storage tanks that reduces the:

- The Health, Safety and Environmental risks.
- The risk of financial losses due to failure.
- The costs related to construction and inspection & maintenance.
- The spatial use.

Is realised by an underground storage design using a caisson structure integrated with a container terminal and a quay structure.

- The degradation mechanism have been removed and the number of failure modes has been reduced significantly due to the use of concrete and a simple and rigid structure with fewer appendages. This, in turn, reduces the environmental- and fire risks and the inspection & maintenance effort, resulting in less health, safety and financial consequences.

- Emission has been eliminated due to the application of a closed reservoir, which is continuously filled with oil and/or water. The tank design completely anticipates to the Dutch legislation requirement of further emission reduction. Also the financial losses related to product loss are removed completely. Due to the absence of emission and vapour space the fire safety increases as well.

- Improvements in space utilisation are achieved as the ground level can be used as well, e.g. as a container on- and offloading terminal.

- Reduction of the construction costs is achieved by a combination of crude oil storage with other functionalities, e.g. a quay structure and a container on- and offloading terminal.

*Outcome*

- The total costs expressed per unit storage, after design optimisations, will be in the order of 215 euros/m$^3$, this counts for a reduction of 1% compared to The Base Case$^{14}$ (220 euros/m$^3$).

  Note: 215 euros/m$^3$ includes the subtraction of the costs related to the functionalities of a quay structure and new reclaimed port/terminal area (see Chapter 6.6.3).

- Beside the designed potential alternative, the concept assessment indicated that The Base Case still is a good alternative as it scores well compared to the other alternatives.

---

$^{14}$ Traditional tank design incl. expected design enhancements for the future, see Chapter 3.7.
8. Conclusions and recommendations

Conclusions
A potential alternative for crude oil storage tanks that reduces the present related:
• Health, Safety and Environmental risks (HSE).
• Risk of financial losses due to tank failure.
• Costs for tank inspection & maintenance.
• Tank spatial use.
Can only be made financially feasible by combining crude oil storage with other functionalities, e.g. a quay structure and a container on- and offloading terminal.

Traditional crude oil tank design, including the expected design enhancements for the future, still is a good alternative on the condition that tank inspection and maintenance is carried out thoroughly.

Recommendations
A potential alternative for crude oil storage with benefits to the oil business has been accomplished by the design of an underground storage in a caisson, integrated with a container terminal and a quay structure. The following is recommended for successive studies.

Financial:
• The construction costs can be further reduced by design optimisations. This is a subject for further studies. A structural alternative is presented in Appendix M.9.5.

• Another possibility to lower the costs is by cooperation with the Port of Rotterdam. As the designed alternative complies with the demand of space intensification the port could sponsor part of the project. In such a case the degree of innovation and the additional business for the port would be a subject for a feasibility study.

• The costs estimation is based on benchmarking. After an optimised design, including all the costs reduction measures, a more precise estimation needs to be formulated.

Technical:
• The designed concrete tank is considered to be impermeable for the tank content and gasses. Besides, no negative interaction is considered between the concrete and different types of crude oil. The permeability and the interaction deserve confirmation as they influence possible leakage and emission. If necessary concrete with a higher quality or different composition may be chosen.

• Hydraulic effects like waves, currents and harbour basin resonance are assumed to be negligible. The negligibility needs to be verified as it has an effect on the required strength of the structure in operational conditions and during floating transport.

• The scour protection in front of the quay wall is certainly required. The protection is not designed into detail and needs to be elaborated further. Some points of attention are presented in Chapter 6.6.2.
• The container terminal is based on a general layout. The terminal needs to be designed into more detail according to the prospective required cargo handling capacity.

• Geotechnical data from the planned location is hard to obtain as the Maasvlakte 2 project is in its tender phase and the data is considered as confidential. At the prospective location considerable variations in the sub soil composition may be expected due to the geological history and prospective dredging activities [3]. Detailed geotechnical information from the location is required to precisely predict the foundation bearing capacity and the to be expected magnitude of settlements.

• Temperature effects are not considered and need further attention as they result in extra external and internal loads. Depending on the freezing point of the reservoir water, ice forming may be expected. The effect can be solved by the application of heating elements inside the tank. At present these elements are frequently used for tanks in very cold areas where the oil becomes less fluid due to low temperatures. Heating up of the product makes it more fluid and suitable for transport through pipelines.

Oil movement:
• A system for sludge removal has not been designed. Depending on the type of crude oil the amount of sludge, which settles at the bottom of the tank, will vary. It is strongly recommended to design an integrated sludge removal system so personnel do not have to enter the tank during the unhealthy and unsafe operations.

• The filling and emptying procedure is not considered as well as the layout of the piping network. As oil will float on top of water it is conceivable to put the oil entrance and exit point at the topside of the tank and for water at the bottom side of the tank. The system needs to be designed in further studies conform required pumping capacities.

• The ballast water will be contaminated to a certain extent due to contact with the oil and sludge (see Appendix R) and needs to be cleaned before it can be discharged to the open water. This cleaning installation is of great importance for the designed alternative. The capacity depends much on the possibility to store the water in other tanks, as the average present storage capacity utilisation is less than 50% (see Figure 156 in Appendix R). Besides, it also depends on the possible already existing water treatment installation capacity. The cleaning system requires space and involves significant investment costs. The application is subject for further studies.

• Instead of ballast water, the use of an inert gas system needs to be studied. Due to the high investment costs of the required ballast water cleaning installation the use of an inert gas system is a possible alternative to reach the required fire safety. The application will result in a heavier construction and higher related costs due to the fact that the tanks will be empty at certain times.

Inspection and maintenance:
• The inspection and maintenance effort and related costs are expected to decrease as some of the degradation mechanisms are eliminated (corrosion), but they will be partly offset by extra inspection costs (divers). A more detailed comparison between the operational costs for the underground storage and the conventional storage tank is subject of further studies.
• Future demolition of the tank is not treated and needs attention in further studies. The tank will contain oil deposits, which may pollute the surroundings. After emptying of the tank and weight reduction measures, it can be transported floated to a shipping dock where it can be demolished under controlled circumstances.

Calamities:
• Legislation regarding underground oil storage combined with container terminal activities has not been studied. It deserves further attention, as the combination is rather unique.

• Influence from calamities like the collision of a ship with the tank or falling cargo from the quay cranes are not considered. Damage due to may lead to tank failure. Prevention can be achieved by the design of breasting dolphins and/or an increase of the construction strength. It is recommended to study the effects from possible calamities in a risk analysis.

• The effects from earthquakes need to be studied if the concept will be applied in regions where these are to be expected.

Concerning the other generated alternatives the following is recommended:
• The designed tank is not the only appropriate alternative but this one was selected as it combined good prospects for more effective spatial use with removing some of the degradation mechanisms. However, this solution can only be applied in new port developments where crude oil storage can be combined with other activities, e.g., a quay structure and a container on- and offloading terminal.

The other alternatives can be promising for other applications, for example onshore and Greenfield\textsuperscript{15} or Brownfield\textsuperscript{16} soil conditions. The alternatives with almost or equal high scores can be further assessed resulting in other potential solutions.

• The other alternatives contain assumptions up to a certain level. In a further design, these need to be studied.

• The applied concrete is considered to be non-corrosive. At present, more frequent Glass Reinforced Epoxy (GRE) is applied in the storage business. The use of this material or other non-corrosive material is of interest and the possibilities need to be studied.

\textsuperscript{15} Clean soil conditions.
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Appendix A. Shell businesses

The Shell organisation can be divided into the following businesses [51].

**Exploration & Production**
Searches for, finds and produces oil and gas. It also builds the infrastructure needed to deliver hydrocarbons to the market.

**Gas & Power**
Commercialises natural gas, supplies liquefied natural gas, develops markets and infrastructures, markets and trades natural gas and electricity, develops power plants and converts gas to liquids.

**Downstream**
Sells and markets transportation fuels, lubricants and speciality products. Refines, supplies, trades and ships crude oil and petroleum products.

**Renewables & Hydrogen**
Generates "green" electricity and provides renewable energy solutions. Develops and operates wind farms, manufactures and markets solar systems and develops business opportunities related to hydrogen and fuel cells.

**Shell Global Solutions**
Provides business and operational consultancy, technical services, and research and development expertise to the energy industry worldwide.

**Shell Trading**
Shell trading is a business organisation integrating Shell's worldwide trading activities and possessing a global portfolio in crude oil, refined products, natural gas, electrical power and chemicals. Shell trading encompasses the many successful trading activities throughout Royal Dutch Shell. Integrating these activities positions Shell to utilise its global reach, talent and financial strength to compete strongly in the evolving energy trading market.
Appendix B. Fractional distillation process

Crude oil is not very useful in the form it comes in out of the ground. To make it useful, crude oil is separated into fractions by fractional distillation [57] (see Figure 37).

![Fractional distillation process diagram]

The fractionating column is cooler at the top than at the bottom. The vapours condense while they are moving up the column. The heavier fractions that emerge from the bottom of the fractionating column are often broken up (cracked) to make more useful products.

**Figure 37: Crude oil distillation process [57]**

From a typical barrel of North Sea crude oil (1 barrel equals 158.99 litre), approximately 3% becomes LPG, 37% petrol, 25% diesel, 20% kerosene and 12% fuel oil.
Appendix C. Crude oil floating roof storage tanks

This chapter discusses the general functionalities and designs of crude oil floating roof storage tanks (see Figure 38). Crude oil is a volatile product. In order to reduce the emission of product from the storage tanks, crude oil is mostly stored in floating roof tanks. These tanks adjust their volume to the stored amount of product. Firstly it is clarified why fixed roof tanks are not preferred for storing crude oil.

Figure 38: Crude oil floating roof tank (D=80m, V=100,000m³) [64]
C.1 Design

Fixed roof design
Fixed roof storage tanks containing volatile products induce product emission from the tank through the opening on top of the roof to the atmosphere. The opening, also called P/V valve, has the function to reduce the excessive over or under pressure inside the tank. If a P/V valve is not applied the tank may collapse due to the over or under pressure.

The emission can have two causes. The first cause is formed by the fluctuation of the surrounding air temperature (see Figure 39). During daytime the tank warms up resulting in a vapour overpressure inside the tank, which pushes vapour out of the tank into the atmosphere. During nighttimes the tank cools down creating an under pressure inside the tank, which results in air flowing inwards. This type of emission is called standing loss or “breathing loss”.

![Emission from fixed roof tanks](image)

Figure 39: Emission from fixed roof tanks (standing losses or “breathing losses”) [60]

The filling and emptying of the tank forms the second cause (see Figure 40). During the filling of the tank the overpressure inside the tank pushes vapour out of the tank into the atmosphere. Emptying of the tank creates under pressure inside the tank and causes air to flow inwards. This type of emission is called withdrawal losses.

![Emission from fixed roof tanks](image)

Figure 40: Emission from fixed roof tanks (withdrawal losses) [60]

Floating roof design
To reduce the standing and withdrawal losses crude oil is mostly stored in floating roof tanks. These atmospheric storage tanks consist of vertical cylindrical tanks made of steel, generally situated on an elevated sand pad. Atmospheric means that the tanks operate under the air pressure range of the atmosphere. The tanks can have volumes ranging from 20,000 to 100,000 m$^3$. 
The basic design concept of floating roof tanks has not changed since the first tanks of this type were built in the 1920s (see Figure 41). The design namely consists of a circular roof floating on the product surface within a tank shell and sealing the gap between the shell and roof with a flexible device, also called a rim seal (see Appendix C.5).

![Figure 41: Crude oil floating roof tank [60]](image)

The roof drain has the function to drain away rainwater, which accumulates on top of the floating roof. The floating roof also contains roof-supporting legs (not indicated in Figure 41), which support the roof when the tank is emptied and the roof is lowered to its lowest position. The lowest position is situated just above the product outflow point.

**C.2 Functionalities**

The primary function of crude oil tanks is storage. The storage takes place at intermediate positions at the oil reservoirs and the refineries (see Figure 42).

![Figure 42: Storage locations within the process chain [62]](image)
C.3 Capacity

The storage capacity at the oil terminal (see Figure 42) depends on the oil production rate and the kind of transport. For example, if transportation is by ship, the storage facility needs to have a capacity big enough to store the amount of oil produced between two ship arrivals. The frequency and reliability of the ship arrivals together with the production rate determine the required amount of storage.

The capacity at the refinery storage and the storage and transfer depot (see Figure 42) depends on the required flexibility to cope with changes in the throughput of products in the manufacturing division.

C.4 Floating roof tank types

Floating roof tanks can be applied as External Floating Roof Tanks (EFRT) without a fixed roof (see Figure 43) and Internal Floating Roof Tanks (IFRT) with a fixed roof (see Figure 44). The roof is than called a geodesic dome.

![Figure 43: External Floating Roof Tank (EFRT) [60]](image-url)
The fixed roof reduces emission by blocking the direct sun radiation on the floating roof and reduces the weather loads on the floating roof, like rainwater and snow.

The floating roofs may have a single deck, usually applied for tanks with a diameter from 15 to 50 meters (see Figure 45) or a double deck, usually applied for tanks larger than 15 meters (see Figure 46).
Tank constructors and operators are of the opinion that double deck roofs provide a higher safety factor than single deck, pontoon-type roofs. Double deck roofs ensure that rainwater is distributed more evenly over the roof surface than annular pontoon type roofs and hence the roof is less likely to deform. The costs for the roof types are presented in Table 33.

<table>
<thead>
<tr>
<th>Roof Type</th>
<th>Single Deck</th>
<th>Double Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Components</td>
<td>Installation</td>
</tr>
<tr>
<td>40m Tanks</td>
<td>125k</td>
<td>200k</td>
</tr>
<tr>
<td>80m Tanks</td>
<td>520k</td>
<td>800k</td>
</tr>
</tbody>
</table>

Table 33: Costs (euros) for single deck and double deck floating roofs [9]

At present also internal floating roofs of Fiberglas are applied with the advantage that the roof is less sensitive for corrosion and will lead to a reduction of the inspection and maintenance costs. These tanks are called Combi Floating Roof Tanks (CFRT) (see Figure 47 and Figure 48).
Figure 48: Combi Floating Roof Tank with geodesic dome roof (CFRT) [5]

The estimated costs for the fixed geodesic dome roof structure are presented in Table 34.

<table>
<thead>
<tr>
<th>Type of System</th>
<th>Geodesic Dome</th>
<th>Installation</th>
<th>Annual Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>40m diameter tank</td>
<td>180k</td>
<td>150k</td>
<td>5k</td>
</tr>
<tr>
<td>80m diameter tank</td>
<td>500k</td>
<td>400k</td>
<td>7k</td>
</tr>
</tbody>
</table>

Table 34: Geodesic dome roof costs (euros) [9]
C.5 Rim seal types

In order to reduce the emission from floating roof tanks, rim seals are applied.

- A rim seal closes the gap between the floating roof and the tank shell (rim space). It also keeps the roof centred. The main construction is called the primary seal. The primary seal structure may be located partly within the liquid and is then called 'liquid mounted' (see Figure 49).

![Figure 49: Liquid mounted primary seal [8]](image)

- When located above the liquid level it is called 'vapour mounted' (see Figure 50).

![Figure 50: Vapour mounted primary seal [8]](image)

- The primary seal may have additional protection like a weather shield to prevent deterioration of the seal fabric by direct sun radiation and accumulation of rainwater on the seal (see Figure 51).
Over the last few years secondary rim seals were introduced which improve the effectiveness of the total rim seal structure even further and also act as a weather shield. The secondary seals are made and constructed either as a so-called “shoe” mounted (see Figure 52) or as a “rim” mounted secondary seal (see Figure 52).
C.6 Wind effect

The wind contributes significantly to the loss of product from the rim space, when only a primary seal is installed. This effect is called the wind drag effect (see Figure 53) [8]. The roof drifts in the direction of the wind when the roof floats at a high level (tank full or almost full); this is indicated in Figure 53 with the black lines. However, turbulence makes the roof drift opposite to the wind direction when the roof floats deep in the tank (tank less than half full); indicated in Figure 53 with the blue lines. As the rim seal is flexible, both scenarios will result in a gap at the rim space through which emission occurs.

A solution to overcome the wind drag effect is the application of a dome roof structure (aluminium geodesic dome) over an existing floating roof tank. The geodesic dome will keep the wind outside the open top tank and there is no longer any wind drag effect within the rim space. A similar result may be achieved when installing a secondary rim mounted seal. In both solutions the floating roof movements caused by the wind are eliminated and the performance and the lifetime of the seal will improve considerably.

![Diagram of wind drag effects for floating roof tanks with primary seals only](image)

Black line: wind drag effect with the roof in high position
Blue line: wind drag effect with the roof in low position

Figure 53: Wind drag effects for floating roof tanks with primary seals only [8]
C.7 Fire safety

- Tank spacing
  The tank spacing recommendations are not clear. It appears they have two objectives. Firstly preventing flames from a full surface fire on a tank from impinging on a nearby tank. Secondly of enabling access for fire fighters to get close enough to cool exposures on nearby tanks.

Various companies, national and international standards give definitions of required spacing between tanks and between tanks and bund walls. Each standard gives different definitions of tank spacing requirements. The NFPA 30 [12] gives the following definitions for minimum tank spacing (shell to shell) for floating roof tanks:
- All tanks not over 45 m in diameter: 1/6 sum of adjacent tank diameters but not less than 1 m.
- Tanks larger than 45 m in diameter with remote impounding: 1/6 sum of adjacent tank diameters.
- Tanks larger than 45 m in diameter where impounding is around tanks: 1/4 sum of adjacent tank diameters.

Within Shell there is a new proposal for the tanks spacing (see Figure 54), which results in larger tank spacing compared to The NFPA 30 code.

![Figure 54: Proposal tank spacing](image_url)

Beside tank spacing the tanks may be equipped with:

- Level alarms to prevent overfill. A High-High level alarm means an independent alarm from the High alarm. It is intended as a back up to the High-level alarm and would operate only
when no appropriate action has been taken to prevent overfilling after the High-level alarm has activated. The costs for high-high level alarm systems are presented in Table 35.

<table>
<thead>
<tr>
<th>Type of System</th>
<th>High-High Level Alarm</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Component</td>
<td>Installation</td>
<td>Annual Maintenance</td>
</tr>
<tr>
<td>40m diameter tank</td>
<td>10k</td>
<td>1k</td>
<td>200</td>
</tr>
<tr>
<td>80m diameter tank</td>
<td>10k</td>
<td>1k</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 35: Costs (euros) for high-high level alarm system [9]

- Secondary seals to reduce vapour emissions. The costs are presented in Table 36.

<table>
<thead>
<tr>
<th>System</th>
<th>Provision of secondary seal</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Component</td>
<td>Installation</td>
<td>Annual Maintenance</td>
</tr>
<tr>
<td>40m diameter tank</td>
<td>10k</td>
<td>8k</td>
<td>1k</td>
</tr>
<tr>
<td>80m diameter tank</td>
<td>20k</td>
<td>15k</td>
<td>2k</td>
</tr>
</tbody>
</table>

Table 36: Costs (euros) for secondary seals [9]

- Fire retardant rim seals to prevent fire escalation during a rim seal fire (see chapter 3.2.2). The costs are presented in Table 37.

<table>
<thead>
<tr>
<th>System</th>
<th>Extra cost of fire retardant rim seal</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Component</td>
<td>Installation</td>
<td>Annual Maintenance</td>
</tr>
<tr>
<td>40m diameter tank</td>
<td>7k</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>80m diameter tank</td>
<td>13k</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 37: Costs (euros) for fire retardant rim seal material [9]

- Stainless steel shunts (see Figure 55) for electrically conducting the floating roof across the rim space.
Shunts are designed to equalise the electrical potential of the roof and the tank shell but they are not designed to take the current that can be generated by a nearby lightning strike. Different companies appear to have different recommendations concerning the best spacing of shunts around the rim seal. The minimum spacing of shunts is 3m apart around the rim. Some companies place the shunts more frequently. There has been no definitive study to determine the spacing or types of shunt required to provide adequate electrical bonding for different types of roof design. Shunts should, however, be placed above the rim seal and any secondary seals or weather shields so that they can be inspected easily and so that they are away from areas where flammable vapours may be present. At the moment there are developments going on to submerge the shunts in the liquid where there is no air (or oxygen) to permit combustion.

- Heat detection system in the rim seal area to detect a fire. The costs are presented in Table 38.

<table>
<thead>
<tr>
<th>System Type</th>
<th>Linear Heat Detectors</th>
<th>Point Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Components</td>
<td>Installation</td>
</tr>
<tr>
<td>40m</td>
<td>4k</td>
<td>6k</td>
</tr>
<tr>
<td>80m</td>
<td>4k</td>
<td>7k</td>
</tr>
<tr>
<td>Bund Fittings</td>
<td>4k</td>
<td>9k</td>
</tr>
</tbody>
</table>

Table 38: Costs (euros) heat detection systems [9]
- Flame detection systems to monitor spill fires on the roof or rim seal fires. They may also be used to monitor bunds. The costs are presented in Table 39.

<table>
<thead>
<tr>
<th>System Type</th>
<th>IR FLAME DETECTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Installation</td>
</tr>
<tr>
<td>40m - Roof spill fire + rim seal</td>
<td>50k</td>
</tr>
<tr>
<td>80m - Roof spill fire + rim seal</td>
<td>90k</td>
</tr>
<tr>
<td>Bund area - Total coverage</td>
<td>90k</td>
</tr>
<tr>
<td>Bund area - Specific items</td>
<td>20k</td>
</tr>
</tbody>
</table>

Table 39: Costs (euros) flame detection systems [9]

- Thermal imaging. Infrared thermal imaging cameras monitor the complete roof area including the rim seal. They may also be used to monitor for bund fires. The costs are presented in Table 40.

<table>
<thead>
<tr>
<th>System Type</th>
<th>Thermal Imaging Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Installation</td>
</tr>
<tr>
<td>40m</td>
<td>25k</td>
</tr>
<tr>
<td>80m</td>
<td>25k</td>
</tr>
<tr>
<td>Bund areas</td>
<td>50k</td>
</tr>
</tbody>
</table>

Table 40: Costs (euros) thermal detection systems [9]

- Gas detection systems to monitor released vapours. The costs are presented in Table 41.

<table>
<thead>
<tr>
<th>System Type</th>
<th>Point Gas Detectors</th>
<th>Beam Gas Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Installation</td>
<td>Annual Maintenance</td>
</tr>
<tr>
<td>40m tank</td>
<td>25k</td>
<td>10k</td>
</tr>
<tr>
<td>80m tank</td>
<td>40k</td>
<td>15k</td>
</tr>
<tr>
<td>Bund Areas</td>
<td>30k</td>
<td>20k</td>
</tr>
</tbody>
</table>

Table 41: Costs (euros) gas detection systems [9]

- Liquid detection systems to detect a major build up of liquid (either water or product) on the roof. The costs are presented in Table 42.
Next Generation Storage Tanks
A potential alternative for crude oil storage tanks

<table>
<thead>
<tr>
<th>System Type</th>
<th>Fibre Optic Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Components</td>
</tr>
<tr>
<td>40m tank</td>
<td>14k</td>
</tr>
<tr>
<td>80m tank</td>
<td>21k</td>
</tr>
</tbody>
</table>

Table 42: Costs (euros) fibre optic liquid detection systems [9]

- Drain liquid detection system. A hydrocarbon monitor can be fitted at the roof drain ground level outlet for detection of product in the drain system. Automatic sensors, based on conductivity measurements, are available to determine if liquid is in the drain line and to differentiate between product and water and automatically close the drain valve. The costs are presented in Table 43.

<table>
<thead>
<tr>
<th>System Type</th>
<th>All Other Types</th>
<th>Fibre Optic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Components</td>
<td>Installation</td>
</tr>
<tr>
<td>40m tank</td>
<td>16.5k</td>
<td>2k</td>
</tr>
<tr>
<td>80m tank</td>
<td>33k</td>
<td>4k</td>
</tr>
</tbody>
</table>

Table 43: Costs (euros) drain liquid detection system [9]

- Foam systems. Foam systems may be used for rim seal protection, spill fires on roof and full surface fires and bund fires. The costs are presented in Table 44, Table 45 and Table 46.

<table>
<thead>
<tr>
<th>System Type</th>
<th>Rim seal Pourer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Component</td>
</tr>
<tr>
<td>40m Tank</td>
<td>15k</td>
</tr>
<tr>
<td>80m Tank</td>
<td>30k</td>
</tr>
</tbody>
</table>

Table 44: Costs (euros) of rim seal foam systems [9]
### System Type

<table>
<thead>
<tr>
<th>Component</th>
<th>Installation</th>
<th>Annual Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>40m Tank</td>
<td>20k</td>
<td>150k</td>
</tr>
<tr>
<td>80m Tank</td>
<td>35k</td>
<td>200k</td>
</tr>
</tbody>
</table>

Table 45: Costs (euros) of spill on roof and full fire foam systems [9]

<table>
<thead>
<tr>
<th>Component</th>
<th>Installation</th>
<th>Annual Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>80m Tank</td>
<td>20k</td>
<td>150k</td>
</tr>
<tr>
<td>40m Tank</td>
<td>35k</td>
<td>200k</td>
</tr>
</tbody>
</table>

Table 46: Costs (euros) of bund fire foam system [9]

- Water spray systems for tank cooling purposes. The costs are presented Table 47.

<table>
<thead>
<tr>
<th>Component</th>
<th>Installation</th>
<th>Annual Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>40m Tank</td>
<td>50k</td>
<td>30k</td>
</tr>
<tr>
<td>80m Tank</td>
<td>100k</td>
<td>50k</td>
</tr>
</tbody>
</table>

Table 47: Costs (euros) water spray systems [9]

- Video imaging. Video camera signal analysis techniques have been developed which allow conventional camera signals to be used to detect smoke or vapour emissions. The signal is analysed to detect specific patterns of movement of these products.

**Rim seal**

It is now common policy in many countries to fit secondary seals which further reduce hydrocarbon emissions. Secondary seals are thus likely to reduce the chance of flammable mixtures formed above the rim seal area. However, fire fighters have sometimes experienced difficulties extinguishing the last remains of a rim seal fire due to the secondary seal construction. It has been necessary sometimes to pull back the secondary seal by hand to enable the foam to flow into the rim gap because the foam dam was of insufficient height to cover the secondary seal effectively.

**Bund area**

- Bund walls are designed to withstand a full hydrostatic head. However, the wave of product generated by the sudden catastrophic failure of a tank shell or a boil over may overtop bund walls or apply forces greater than the hydrostatic head. The forces may be sufficient to break down bunds walls.
• Concrete bund walls can be badly affected by direct fire impingement. Lumps of concrete may come off and product pipes passing through bund walls may burn away.

• Putting several tanks in a common bund increases the risk of escalation of a fire on one tank to others.

• High leak potential equipment such as pumps, strainers and manifolds should be located outside bunds. If fire-fighting equipment is located on the bund wall, controls should be outside the bund where they are protected from fire exposure.

• Tank nozzles near bund edges should be below the level of the bund wall to avoid jetting of product outside the bund.

Wind
Wind has the following effects on large storage tank fires. The flame is tilted downwind and spills over the edge of the tank into the low-pressure region created on the downwind side of the tank. It thus moves closer to a nearby tank, increasing radiation heat transfer. Foam and water sprays are more easily blown away from their intended paths.
C.8 Foundation

Tanks are relatively unique structures. The dead weight of the tank structure is relatively small compared with the live load of the contents. The tanks have very flexible construction such that the tank shell and bottom will generally follow the settlements of the subsoil. Because of this flexibility, foundation settlements may be tolerated provided they stay within acceptable limits. The limits for different kind of settlements are presented in the EEMUA publication [5].

The foundation needs to:
- Spread and transfer the load.
- Be flexible.
- Position the tank bottom above the groundwater, capillary water, surface water and minor spillages.
- Discharge rainwater away from the tank.

Because of the wide variety of surface, subsurface and climatic conditions at tank locations, it is not possible to prescribe a single type of foundation design. However it is common practice to build tanks on the following foundation types:
- ‘Traditional’ granular/sand pad (see Figure 56).

![Figure 56: Traditional foundation, all dimensions are in millimetres unless otherwise stated [5]](image)

- Sand pad with annular ring of coarse granular material.
- Concrete ring wall.
- Concrete plate under the entire tank.
- Piled concrete plate.
C.9  Tank cleaning

- Depending on the type, crude oil contains water and sediment (sludge). As the water and the sediment are heavier than oil, both will settle at the bottom of the tank. This process is slowed down by the use of mixers. These mixers keep the product in motion to slow down the settlement process.

- In order to be able to drain away the water the tank bottom is usually constructed as a cone down profile with a sump in the middle (see Figure 57).

![Figure 57: Cone down bottom profile with sump](image)

- The sludge may form a thick solid layer of sludge at the bottom and can be removed by a cleaning system.

- The periodic cleaning of storage tanks is an inherently hazardous and dirty activity. Over the past 30 years tank cleaning has increasingly been contracted out to specialist tank cleaning contractors and in-house expertise has decreased. Tank cleaning has led to a number of incidents at installations resulting in serious injury, fires or explosions.
• Tank cleaning is a HSE critical operation involving a number of very hazardous activities [19]. The main hazard is the possible ignition of flammable gases. Other hazards can be divided into those resulting from toxic properties of the stored product, and those associated with the physical operations in and around the tank.

• The Shell group procedure for an HSE (Health Safety and Environment) management system requires for all critical operations and installations an assessment of the related risks, implementation of measures to control these risks and to recover in case of control failure. The time spent by cleaners inside the tank and the associated risks should be as low as possible. Selection of a tank cleaning method should not be limited to a cost benefit analysis of the available alternatives. Specifically, a risk assessment should be carried out in each case, and it should demonstrate that the risks will be reduced to as low as reasonably practicable (ALARP) by the selected method.

• An example of a cleaning system is the BLABO system owned by the company ORECO [48]. The BLABO process can be split up in phases indicated in Figure 58.

Figure 58: BLABO cleaning process [48]

The system has been designed for difficult-to-clean tanks and simultaneously recovers oil from the cleaned-out sludge. The cleaning fluid from the system supply is distributed to a number of nozzles controlled by one or more pneumatically operated distribution units placed on the tank roof (see Figure 59).

Figure 59: BLABO cleaning system [48]
C.10 Bund area

Tanks are positioned inside a secondary containment area also called the bund area (see Figure 60 and Figure 62). The function of the bund area is the controlled containment and discharge of potential spillages in the bund area in order to minimize subsequent damage to adjacent tanks their contents and the surroundings.

To ensure liquid tightness of the bund, it is constructed partly or totally of impermeable or low-permeable materials. A bund constructed entirely with clay is normally preferred.

In locations where clay is scarce or not available, the following may be considered:

- A sand body with a clay cover of at least 300 mm thick.
- A sand body covered by a durable mix of sand, bitumen and cement, at least 75 mm thick.
- An artificial layer.

The bund wall may be constructed from earth or from concrete (see Figure 61) or as a combination of both.

![Diagram of bund area](image)

Figure 60: Bund area [60]

![Diagram of earthen and concrete bund walls](image)

Figure 61: Earthen bund wall (upper figure), concrete bund wall (lower figure) [60]
According to “the guideline of aboveground storage of flammable liquids in vertical cylindrical tanks” the bund area should at least have the capacity to store the volume of the biggest tank increased with the following volumes:

- 10% of the volume from the remaining tanks inside the bund area.
- The volume of firewater that can be deposited inside the bund area in one hour during fire fighting activities of a tank fire.

![Figure 62: Bund area](image)

**C.11 Leak detection**

At present tanks are equipped with a leak detection system. The system consists of an impermeable artificial layer integrated with the tank foundation, which collects a spillage and guides it to a collecting compartment.

**C.12 Coating**

Tanks are internally and externally coated because of:

- Corrosion prevention.
- Sun reflection to reduce the temperature and the amount of emission.
- Cosmetic reasons
C.13 Building costs

The building costs for a crude oil floating roof tank with a diameter of 80 meters and a storage capacity of 100,000m$^3$ have been requested in association with a Dutch tank building company MERCON. The costs are indicated in Table 48. On average it will take 1.5 years to built a tank.

<table>
<thead>
<tr>
<th>Detail</th>
<th>Costs (euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bund area incl. bund wall, foundation,</td>
<td>550k</td>
</tr>
<tr>
<td>detection foil</td>
<td></td>
</tr>
<tr>
<td>Floating roof tank</td>
<td>4.5mil</td>
</tr>
<tr>
<td>Mechanical seal</td>
<td>120k</td>
</tr>
<tr>
<td>Roof drains</td>
<td>35k</td>
</tr>
<tr>
<td>Roll ladder</td>
<td>25k</td>
</tr>
<tr>
<td>Painting external</td>
<td>350k</td>
</tr>
<tr>
<td>Painting internal</td>
<td>125k</td>
</tr>
<tr>
<td>Piping</td>
<td>750k</td>
</tr>
<tr>
<td>Valves</td>
<td>100k</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>6.5mil (excl taxes)</strong></td>
</tr>
</tbody>
</table>

Table 48: Building costs 80m diameter tank, volume 100,000m$^3$

The costs are low. In practice the total costs including labour and taxes will rise up to 20 million euros for a tank with 80 meters in diameter and a storage capacity of 100,000m$^3$ (200euro/m$^3$). The costs are influenced by the location, steel price and oil price.

C.14 Key issues

- Crude oil is a volatile product. In order to reduce the emission of product from the storage tanks, crude oil is mostly stored in floating roof tanks. These tanks adjust their volume to the stored amount of product.

- The primary function of crude oil tanks is storage.
Appendix D. Emission

D.1 General

The report “Guidelines to the reduction of volatile compounds emission from conventional storage tanks” treats emission calculations [8]. The emission calculations have been made for floating roof tanks and geodesic dome tanks with internal floating roofs. The calculations are based on the method described in the “Manual of Petroleum Measurement Standard section 2 evaporative loss from floating roof tanks” [1].

The calculations are made for a typical Dutch climate, consequently adjustments are needed for colder or warmer/sunny climates. For colder climates, an average reduction of 15-20% needs to be applied. For warm/hot climates, an increase of 35-40% may be expected.

The calculation results for a single tank are presented in Figure 63-Figure 67. It has been assumed that the storage tanks, and in particular the floating roof rim seals were in a reasonable maintained condition, i.e. within the guideline requirements such as the EEMUA 159 document.

Furthermore, turnover stands for the tank level between full and the dead stock level. The dead stock level is the lowest position of the product level, which is approximately 1-1,30m above the bottom of the tank. It is difficult to indicate the average frequency of turnovers. At Shells Pernis refinery in the Netherlands some tanks are continuously filled resulting in 0 turnovers per year and some tanks are constantly filled and emptied. For an indication an average frequency of 30 turnovers per tank per year may be assumed.

The frequency of heel turnovers is not considered as in practise the heel space is never emptied due to the increase of emissions and the increase of the fire risk due to the resulting vapour space.

The results from the report (annual losses in tons/year) have been modified into annual losses in euros/year and are presented in a different way, taking into account the following information:

• The density (ρ) for crude oil is approximately 0,85 kg/litre.
• The long-term steering value for the year 2006 was 42 US dollar/barrel.
• 1 barrel is equal to 159 litres.
• 1 US dollar is approximately equal to 0,78 euro.
• 1 ton of crude oil costs 240 euros.
D.2 Seal types in good and average condition

<table>
<thead>
<tr>
<th>SEAL TYPES</th>
<th>GOOD CONDITION</th>
<th>AVERAGE CONDITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour mounted primary</td>
<td>8</td>
<td>38</td>
</tr>
<tr>
<td>Vapour mounted primary+weather shield</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>Mechanical shoe primary</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Vapour mounted primary+rim mounted secondary</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Mechanical shoe primary+shoe mounted secondary</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Liquid mounted primary</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Liquid mounted primary+weather shield</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Liquid mounted primary+rim mounted secondary</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mechanical shoe primary+rim mounted secondary</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 49: Emission in tons/year for different seal types in good and average condition for 48 turnovers

Figure 63: Emission in tons/year for different seal types in good and average condition for 48 turnovers
Table 50: Emission in euros/year for different seal types in good and average condition for 48 turnovers

<table>
<thead>
<tr>
<th>SEAL TYPES</th>
<th>GOOD CONDITION</th>
<th>AVERAGE CONDITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour mounted primary</td>
<td>1920</td>
<td>9360</td>
</tr>
<tr>
<td>Vapour mounted primary+weather shield</td>
<td>1680</td>
<td>5520</td>
</tr>
<tr>
<td>Mechanical shoe primary</td>
<td>1200</td>
<td>1440</td>
</tr>
<tr>
<td>Vapour mounted primary+rim mounted secondary</td>
<td>480</td>
<td>3360</td>
</tr>
<tr>
<td>Mechanical shoe primary+shoe mounted secondary</td>
<td>480</td>
<td>480</td>
</tr>
<tr>
<td>Liquid mounted primary</td>
<td>240</td>
<td>480</td>
</tr>
<tr>
<td>Liquid mounted primary+weather shield</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Liquid mounted primary+rim mounted secondary</td>
<td>240</td>
<td>240</td>
</tr>
</tbody>
</table>

Figure 64: Emission in euros/year for different seal types in good and average condition for 48 turnovers
D.3  Tank volumes 10,000m$^3$ and 100,000m$^3$

<table>
<thead>
<tr>
<th>SEAL TYPE</th>
<th>Data</th>
<th>EMISSION [euro/year]</th>
</tr>
</thead>
</table>
| Vapour mounted primary seal in average condition | Tank volume = 10,000m$^3$ | 9,860  
|                                              | Tank volume = 100,000m$^3$| 23,520 |

Table 51: Emission in euros/year for tank volumes 10,000m$^3$ and 100,000m$^3$ and vapour mounted primary seal in average condition

Figure 65: Emission in euros/year for tank volumes 10,000m$^3$ and 100,000m$^3$ and vapour mounted primary seal in average condition
D.4 Floating roof and internal floating roof tank

Table 52: Emission in tons/year for floating roof tank and geodesic dome tank with internal floating roof for vapour mounted primary seal in average condition, tank volume 100.000m$^3$

<table>
<thead>
<tr>
<th>SEAL TYPE</th>
<th>Data TANK VOLUME = 100.000m$^3$, EMISSION (ton/year)</th>
<th>TURN OVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour mounted primary seal in average condition</td>
<td>Floating roof tank</td>
<td>98 98 98 100</td>
</tr>
<tr>
<td></td>
<td>Aluminium dome tank with internal floating roof</td>
<td>25 25 25 25</td>
</tr>
</tbody>
</table>

Table 53: Emission in euros/year for floating roof tank and geodesic dome tank with internal floating roof for vapour mounted primary seal in average condition, tank volume 100.000m$^3$

<table>
<thead>
<tr>
<th>SEAL TYPE</th>
<th>Data TANK VOLUME = 100.000m$^3$, EMISSION (euro/year)</th>
<th>TURN OVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour mounted primary seal in average condition</td>
<td>Floating roof tank</td>
<td>23520 23520 23520 24000</td>
</tr>
<tr>
<td></td>
<td>Aluminium dome tank with internal floating roof</td>
<td>8400 8400 8400 8880</td>
</tr>
</tbody>
</table>

Figure 66: Emission in tons/year for floating roof tank and geodesic dome tank with internal floating roof for vapour mounted primary seal in average condition, tank volume 100.000m$^3$

Figure 67: Emission in euros/year for floating roof tank and geodesic dome tank with internal floating roof for vapour mounted primary seal in average condition, tank volume 100.000m$^3$
Appendix E. Buncefield fire incident

General [31]
The Buncefield oil storage and transfer depot is a large tank farm occupied by three companies. These are: Hertfordshire Oil Storage Limited, a joint venture between Total UK Limited and Chevron Limited; United Kingdom Oil Pipelines Limited and West London Pipeline and Storage Limited, whose site is operated by British Pipeline Agency Limited; and British Petroleum Oil UK Limited. Each site is under the Control of the Major Accident Hazards Regulations 1999 (COMAH).

The Buncefield depot forms part of a national petroleum refinery, pipeline and storage system. Fuel products were supplied to Buncefield by three pipeline systems. The three pipelines all transported fuel products.

Summary of the incident [31]
In December 2005 there was a massive escape of unleaded motor fuel from a storage tank on the west part of the depot. Investigation indicated that a hydrocarbon and air rich vapour mixture was generated inside the bund area. This cloud possibly drifted away in the direction of an industrial car park where the ignition took place, followed by several explosions over 20 storage tanks. The precise ignition source is unclear but it was most likely a generator house.

Figure 68: Buncefield fire [31]
The incident resulted in 43 people with minor injuries and the loss of a large number of storage tanks. Approximately 2000 residents in the surrounding area were evacuated and there was worldwide news coverage for several days. Additionally there was significant environmental impact on land, surface water and ground water from the fuel and firewater that left the site. The drinking water may possibly become contaminated in the future. The economic damages have been estimated to be over 400 million USD.

Causes [31]
- The instrumentation to prevent overfills malfunctioned during the filling of a conventional unleaded fuel tank. This resulted in overfill and an ignitable vapour cloud.
- Loss of the secondary containment (bund area see Figure 69) due to the explosions and persistent fire resulted in the spreading of the contamination.
Figure 69: Destroyed concrete bund wall at Buncefield [31]

For more information see [www.buncefieldinvestigation.gov.uk](http://www.buncefieldinvestigation.gov.uk).
Appendix F. LASTFIRE project

F.1 General

The project [9] summarises the results of a survey of fires and un-ignited releases on greater than 40 m diameter open-top floating roof tanks. The primary objective of the survey was to establish the frequencies at which such incidents occur on operational tanks.

The survey recorded numbers of tanks and numbers of years of tank operation. In order to obtain accurate data, from which to derive frequencies of incidents, the survey was restricted to tanks owned or operated by 16 companies participating in the project and to incidents on tanks in operation during the fifteen-year period between 1981 and 1996 inclusive. Completed questionnaires were returned from 164 sites in 36 countries. Valid data was submitted from 2420 tanks (all kinds of products) representing 33909 tank years of operation.

F.2 Ignition sources

Ignition by lightning
Lightning is by far the most frequent source of ignition of fires on floating roof storage tanks. Table 54 presents the costs of a lightning prevention or mitigation system.

<table>
<thead>
<tr>
<th>Type of System</th>
<th>Lightning Dissipation/Prevention System</th>
<th>Component</th>
<th>Installation</th>
<th>Annual Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>40m diameter tank</td>
<td></td>
<td>10k</td>
<td>5k</td>
<td>1k</td>
</tr>
<tr>
<td>80m diameter tank</td>
<td></td>
<td>17k</td>
<td>7k</td>
<td>2k</td>
</tr>
</tbody>
</table>

Table 54: Costs (euros) of lightning prevention or mitigation system [9]

Ignition by hot work
Sparks from hot work can be carried from gas free areas into regions where flammable mixtures exist.

Ignition by flare fall-out
Fire incidents have been caused by incandescent particles from flare stacks. Ideally, flare stacks should not be positioned upwind in the prevailing wind direction from storage tanks.

Ignition outside the tank
Some of the worst recorded fire incidents started with ignition outside the tank. Overfilling of tanks has lead to the formation of a flammable cloud, which then found an ignition source outside the bund area (see for example The Buncefield incident presented Appendix E).

Ignition by electrostatic discharge
Electrostatic discharge may occur if the electrical bonding between roof and shell or the earthing of the tank is inadequate (see Appendix C.7).
**Ignition by cathodic protection**
Cathodic protection is sometimes used to inhibit corrosion in storage tanks. The main method of cathodic protection is to lower its potential with respect to earth and make corrosion thermodynamically impossible. There is the potential for a spark if any section of current carrying pipe work or cable is disconnected.

**Ignition by operators**
 Operators have ignited several serious fires. They were performing inspection work after a process problem has occurred.

**Ignition by pyrophoric reaction**
 Pyrophoric iron or scale is iron or its compounds in a form capable of such rapid oxidation on exposure to air that heating to incandescence may occur. It can form in tanks containing products rich in sulphur compounds (usually sour crude oil).

---

17 In cathodic protection, a metal anode that is more reactive to the corrosive environment of the system to be protected is electrically linked to the protected system, and partially corrodes or dissolves, which protects the metal of the system it is connected to. As an example, an iron or steel ship’s hull may be protected by a zinc sacrificial anode, which will dissolve into the seawater and prevent the hull from being corroded. Sacrificial anodes are particularly needed for systems where a static charge is generated by the action of flowing liquids, such as pipelines and watercraft.
Appendix G.  Lightning strike scenarios

G.1  Lightning strikes to ground and objects

The lightning process usually starts in the clouds. A stepped “ladder” descends to earth, often with side branches. The path of this “ladder” is very irregular due to random variations in the local air conditions. When the leader is within < 150m from the ground or tank, the electric field at the ground or tank rises high enough to launch an upward streamer in the direction of the downward leader. The upward streamer then makes the connection and allows the high current return stroke. In practice, many upward leaders may rise simultaneously (see Figure 70) [4, 60].

![Lightning diagram](image)

Figure 70: Lightning strikes to ground and objects [4, 60]

The attachment point is affected by the function of the lightning protection system air termination network. Once the current starts to flow, the air termination network has no further influence on the direction of the current. After attachment, the current flows over all conducting objects. The route of the lightning is determined by the inductance of the path, due to the high frequency of the current.
G.2 Lightning strikes causing current to flow in floating roof storage tanks

A lightning strike may cause current to flow in a floating roof tank in 3 scenarios [4]:

- Strike to the tank shell (see Figure 71)

![Figure 71: Lightning strike to a tank shell [4, 60]](image1)

- Strike to the tank floating roof (see Figure 72)

![Figure 72: Lightning strike to the tank floating roof [4, 60]](image2)

- Strike to the earth/ground (see Figure 73)

![Figure 73: Lightning strike to the earth/ground [4, 60]](image3)
Appendix H. Tank enquiry

H.1 General

According to the EEMUA no.159, crude oil storage tanks contain many different failure modes. The report does not mention the frequency of occurrence. In order to get more insight in the most common failure modes and their frequencies of occurrence, contact was made with 12 Shell storage locations worldwide. 6 locations (A-F) randomly participated in the questionnaire with a total of 87 crude oil storage tanks (see Table 55). The 87 tanks form 6% of the total estimated number of crude tanks (1380).

<table>
<thead>
<tr>
<th>Storage location</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crude oil storage tanks per location</td>
<td>8</td>
<td>34</td>
<td>11</td>
<td>11</td>
<td>7</td>
<td>16</td>
<td>87</td>
</tr>
</tbody>
</table>

Table 55: Number of tanks within the enquiry

H.2 Results

The results within the last 5 years for the locations (A-F) are presented in Table 56 and Figure 74.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Location</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Total frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal corrosion leading to product leakage</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Settlements</td>
<td>5</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Floating roof leakage</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Roof drain leakage</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Failure of rolling ladder on top of a floating roof tank</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Corrosion of floating roof supporting legs</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Seal failure</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Jamming of floating roof</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Overfilling</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 56: Failure mode frequencies per 5 years for 87 tanks

Figure 74: Most common failure mode frequencies within the last 5 years for 6 storage sites
These numbers were used to estimate the yearly frequency of occurrence of each most common failure mode within the estimated total of 1380 crude oil storage tanks belonging to Shell (see Table 57). The 87 tanks from the enquiry stand for 435 tank years.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Frequency per 5 years</th>
<th>Frequency per year for 1380 tanks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal corrosion leading to product leakage</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>External corrosion leading to product leakage</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Settlements</td>
<td>16</td>
<td>51</td>
</tr>
<tr>
<td>Floating roof leakage</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>Roof drain leakage</td>
<td>9</td>
<td>29</td>
</tr>
<tr>
<td>Failure of rolling ladder on top of a floating roof tank</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Corrosion of floating roof supporting legs</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>Seal failure</td>
<td>7</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 57: Most common failure mode frequencies per year for 1380 tanks

**H.3 Other effects leading to failure**

*Effects by nature*

Extreme effects from nature, like hurricanes and earthquakes, may lead to failure of storage tanks. A detailed study [37] over the period 1970-2004 showed that the number of heavy hurricanes grew from 11 per year to 18 per year. The consequence can be disastrous (see Figure 75).

![Figure 75: Hurricane damage to oil storage tanks [36]](image)

The figure shows a massive oil spill, which threatens the town St. Bernard Parish in the United States of America. The tank was forced from its foundation by hurricane Katrina’s massive storm surge in the year 2005 [36].

Figure 76 shows an example of an empty floating roof tank, which collapsed during a cyclone. The costs related to the damage are in the order of 10 million euros.
As more and more seismographs are installed worldwide, more earthquakes can be and have been located. However, the number of large earthquakes (magnitude 6.0 and greater) has stayed relatively constant [37, 43]. For failure numbers due to earthquakes see Figure 13 and Figure 14 on page 18 and 19.
Appendix I. Port of Rotterdam

I.1 General

The port needs more harbour space in order to grow willing to maintain its port position in the world. To solve the spatial problem, the Port of Rotterdam is about to realize the second port extension Maasvlakte 2 and strongly stimulates innovative intensive utilisation of existing and future port area [14].

I.2 Oil and refining division

The refinery oil supply in North west of Europe, in total almost 200 million ton, mainly takes place through a few harbours in the Hamburg-Le Havre range. In this range the port of Rotterdam [49] has a market share of more than 50%. The transhipment of crude oil counts for 30% of the total trans-shipment within the Port. The oil and refining division within the port is indicated in Figure 77 with orange.

![Figure 77: Port of Rotterdam layout [49]](image)

The crude oil supplied to the port of Rotterdam can be divided into 50 types of crudes and gas condensates coming from mainly the Middle East, the North Sea area and Russia. The crude oil is unloaded at the oil terminals Europoort and Maasvlakte 1. At these locations the crude oil is blended according to the required refinery specification. Subsequently the crude oil will be transported by pipeline. 50% is transported to 5 refineries within the port and the other 50% is transported to refineries in Vlissingen and Germany.
I.3 Crude oil transhipment developments

Within the near future the port authority expects a more or less steady progress of crude oil trans-shipment within its harbour (Figure 78).

![Crude oil transhipment Port of Rotterdam](image)

**Figure 78: Crude oil transhipment Port of Rotterdam [49]**

The high values in the years ’73–’79 resulted from the ruling oil crises. It was assumed the oil was used as strategic storage.

I.4 Area lease charges and joint venture possibilities

The possibilities for Shell within the framework intensive space utilisation for the Port of Rotterdam have been studied.

The following questions were formulated:

- What are the port area renting charges for crude oil storage per m$^2$?
- Is the Port of Rotterdam willing to (partially) finance innovative projects for intensive utilisation of port area?

First answer

The lease charges for port area, which contains crude oil storage is on average 3-5 euros/m$^2$ per year, on the condition that the location includes quays and/or jetties. The charges may differ depending on the location properties, like the presence of a quay structure or a bank.

Shell Pernis, located in the Port of Rotterdam, has a storage capacity of 4.7 million m$^3$ for all kind of product types from which 2.2 million m$^3$ is crude storage (see Figure 3 in Chapter 2.1). Assuming an area storage capacity of 5m$^3$/m$^2$ this will result in a spatial use of 0.4 million m$^2$ for crude storage. With an average lease charge of 4 euros/m$^2$ per year this will result in 2 million euros per year for the area lease charges for crude oil.
The port income from the lease charges is quite low (1/3) compared to the ship and quay charges (2/3). At the moment there is a legal procedure going on between the Port of Rotterdam and several oil companies [30, 34]. The companies challenge the height of the ship and quay charges for oil tankers. According to the companies the price for oil tankers is 3 times more as for container vessels. Ship and quay charges for oil tankers yield the port authority each year 40-50 million euros. The procedure was started in 1997 by Shell. At present Nerefco, Kuwait Petroleum and ExxonMobil join Shell in the procedure. According to these the port authority finances different sectors in its harbour area with the money collected from the oil tanker ship and quay charges.

The intermediate judgement in 2002 by the court of Rotterdam was in favour of Shell. If the companies win the process the port authority has to pay back 230 million euros.

Second answer
There is a possibility for partially financial support by the port of Rotterdam on the condition that the transhipment of any kind of product passing the already existing quay increases. This clarified due to the fact that the port earns most of the money by the shipping taxes. The earnings will increase as the transhipment increases.
Appendix J. Maasvlakte 2 port extension

J.1 General

The port will need almost another 2000 hectares in the year 2020 to follow the expected expansion in goods handling, distribution and industry. The goal is to strengthen the mainport and to improve the quality of the living and working environment, resulting in three projects \([16, 38, 39]\):

- Land reclamation of 1000 hectares (net) suitable for allocation (Maasvlakte 2), including measures to compensate for natural assets that will be lost in the process.

- The execution of several projects in the existing port and industrial area to facilitate more intensive use of the space and to improve the quality of the living and working environment.

- The construction of 750 hectares of new recreational and natural areas near Rotterdam.
J.2 Topographical

Maasvlakte 2 will be located on the seaside of the already existing Maasvlakte 1 (see the hatched area in Figure 79).

![Topographical map of Maasvlakte 2](image)

Figure 79: Maasvlakte 2 port extension location [49]

The proposed design for Maasvlakte 2 has its entry through the existing port area. Figure 79 also indicates the allocation areas of the port activities. In total the project will have 12km of quay length.
J.3 Hydrographical

Present water depth [46]
The present water depth at the prospective Maasvlakte 2 location is 10-20 meter (see Figure 80). As a matter of fact the water depth develops from 0 meter at the seaside of existing port area to around 20 meter at the prospective Maasvlakte 2 location.

Figure 80: Hydrographical map of the North Sea [46]

Future water depth [14]
To achieve accessibility for future ship sizes (see Table 62 in Appendix J.7) the depth of Maasvlakte 2 will be 20 meter (contract depth). It was assumed that this depth is according to lowest low water level (0,84 - NAP (meter) (see Table 61 in Appendix J.5) for the water levels) resulting in a total depth 20,84 - NAP (meter). This implies the ships may enter the port without the application of a tidal window at all times.

Navigation depths Port of Rotterdam

<table>
<thead>
<tr>
<th>Nieuwe Waterweg</th>
<th>After leaving the Maasgeul depth 23.4 meters MLLWS, the Splitsingsdam separates the Nieuwe Waterweg from the Caland Canal. Minimum depth 14.20 meters MLLWS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwe Maas</td>
<td>The Nieuwe Waterweg river becomes the Nieuwe Maas river. Minimum depth 13.80 meters MLLWS to Waalhaven, from Waalhaven to Erasmusbrug 10.85 meters MLLWS, after Erasmusbrug 6.85 meters MLLWS.</td>
</tr>
<tr>
<td>Calandkanaal</td>
<td>Minimum depth 22.75 meters MLLWS. Beerkanaal Entry to the Europoort area is via the Beer Canal. Minimum depth 22.6 meters MLLWS.</td>
</tr>
<tr>
<td>Oude Maas</td>
<td>When passing the Oude Maas, two bridges must be passed: Botlek bridge and Spijkenisse bridge. Permission is required to navigate this river with seagoing vessels with a length of 150 meters or more, or a beam of over 25 meters, or if the draught is more than 7.50 meters (in fresh water). Minimum depth Oude Maas 9.60 meters MLLWS to Spui. After Spui 9.40 meter MLLWS.</td>
</tr>
</tbody>
</table>

Table 58: Navigation depths Port of Rotterdam [15, 50]
Keppel Verolme shipping dock information [54]

Figure 81: Keppel Verolme dock Nº 7 [54]

<table>
<thead>
<tr>
<th>Location</th>
<th>Port of Rotterdam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth at waterfront (low tide)</td>
<td>9.50/10.50 m</td>
</tr>
<tr>
<td>Water depth at waterfront (high tide)</td>
<td>11.00/12.50 m</td>
</tr>
<tr>
<td>Water depth in channel to open water (&quot;New Waterway&quot;) (low tide)</td>
<td>15.00 m</td>
</tr>
<tr>
<td>Distance from yard to North Sea</td>
<td>11.00 miles</td>
</tr>
</tbody>
</table>

There are no restrictions between the yard and open water for vessels or offshore units regarding height, or width at/or above the water line.

Table 59: Keppel Verolme shipping dock information [54]

<table>
<thead>
<tr>
<th>Dock no. 7 properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall width (m)</td>
</tr>
<tr>
<td>Open width (m)</td>
</tr>
<tr>
<td>Depth of water over keelblock (m) at mean high water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dock no. 7 properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
</tr>
<tr>
<td>Overall width (m)</td>
</tr>
<tr>
<td>Open width (m)</td>
</tr>
<tr>
<td>Depth of water over keelblock (m) at mean high water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dock no. 7 properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
</tr>
<tr>
<td>405</td>
</tr>
<tr>
<td>Overall width (m)</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>Open width (m)</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>Depth of water over keelblock (m) at mean high water</td>
</tr>
<tr>
<td>11.60</td>
</tr>
</tbody>
</table>

Table 60: Keppel Verolme dock no. 7 properties [54]
J.4 Geotechnical

Ground level
According to the Port of Rotterdam [16] the ground level of Maasvlakte 1 is constructed at the 5,50 + NAP (meter). This counts for an occurrence of 1 in 10,000 years (see Table 61 in Appendix J.5). The chance takes into account:
- Tidal elevation.
- Level elevation caused by wind.
- A sea level rise for the coming 100 years due to climate changes.

It is assumed that Maasvlakte 2 will be constructed at 5,50 + NAP (meter) as well.

Soil
Beside hard sea defences and quay walls Maasvlakte 2 will be constructed with sand (in total approximately 325 million m$^3$). The sand will be gained from the specified area presented in Figure 82.

![Figure 82: Maasvlakte 2 sand gaining area [16]](image)

It was assumed the sand has the following properties:
- Coarse sand.
- Wet volumetric weight $\gamma_{\text{wet}} = 20\text{kN/m}^3$.
- Dry volumetric weight $\gamma_{\text{dry}} = 8\text{kN/m}^3$.
- Angle of internal friction $\alpha = 30^\circ$.

Sub soil [6]
Sub soil data from the planned location is hard to obtain as the Maasvlakte 2 project is in its tender phase and the data is considered as confidential. For this study sub soil data is obtained from the existing Maasvlakte 1. The CPT result (cone penetration test) is presented in Figure 83. Note: At the prospective location considerable variations in the sub soil composition may be expected due to the geological history.
Figure 83: CPT-1 results Maasvlakte 1 location [6]
Groundwater

- The groundwater is assumed to be salt with a volumetric weight $\gamma_w = 10,25$ kN/m$^3$.
- The average level is assumed to be equal to the average sea level $(0,07 + \text{NAP (meter)})$.
- The highest level is assumed to be equal to the high sea water level $(1,11 + \text{NAP (meter)})$.

The sea water levels are presented in Table 61 in Appendix J.5.
J.5 Hydraulic

Harbour water
According to the Port of Rotterdam the water density ranges from $\rho=1025 \text{ kg/m}^3$ during high water to $\rho=1012 \text{ kg/m}^3$ at low water, depending on seasonal, tidal and meteorological influences. For this study the density is assumed to be $\rho=1025 \text{ kg/m}^3$ (salt water), which counts for a volumetric weight of $\gamma_w=10,25 \text{ kN/m}^3$.

Design water levels [53, 56]
The levels are obtained from Table 61.

<table>
<thead>
<tr>
<th>Water levels at Hoek van Holland (North Sea, The Netherlands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source: <a href="http://www.verkeerenwaterstaat.nl/">http://www.verkeerenwaterstaat.nl/</a></td>
</tr>
<tr>
<td><a href="http://www.waternormalen.nl/index.cfm?page=waternormalen">http://www.waternormalen.nl/index.cfm?page=waternormalen</a></td>
</tr>
</tbody>
</table>

General data
- 1 November 1863: Start observation
- 1 August 1887: Equipment positioned
- 16 January 1988: DNM positioned

Average water levels

<table>
<thead>
<tr>
<th>Tide type</th>
<th>HW level</th>
<th>LW level</th>
<th>Tidal difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>cm</td>
<td>cm</td>
</tr>
<tr>
<td>Average tide</td>
<td>111</td>
<td>-63</td>
<td>174</td>
</tr>
<tr>
<td>Spring tide</td>
<td>130</td>
<td>-60</td>
<td>190</td>
</tr>
<tr>
<td>Neap tide</td>
<td>88</td>
<td>-60</td>
<td>148</td>
</tr>
</tbody>
</table>

Average water levels
- 7

Average frequencies of occurrence per year

<table>
<thead>
<tr>
<th>High water occurrence</th>
<th>Low water occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Level in cm + NAP</td>
</tr>
<tr>
<td>1x per 10,000 year</td>
<td>505</td>
</tr>
<tr>
<td>1x per 1,000 year</td>
<td>430</td>
</tr>
<tr>
<td>1x per 100 year</td>
<td>360</td>
</tr>
<tr>
<td>1x per 50 year</td>
<td>340</td>
</tr>
<tr>
<td>1x per 20 year</td>
<td>315</td>
</tr>
<tr>
<td>1x per 10 year</td>
<td>300</td>
</tr>
<tr>
<td>1x per 5 years</td>
<td>280</td>
</tr>
<tr>
<td>1x per 2 year (boundary level)</td>
<td>260</td>
</tr>
<tr>
<td>2x per year</td>
<td>245</td>
</tr>
<tr>
<td>5x per year</td>
<td>230</td>
</tr>
<tr>
<td>10x per year</td>
<td>210</td>
</tr>
<tr>
<td>Basic level</td>
<td>505</td>
</tr>
<tr>
<td>Detailed</td>
<td></td>
</tr>
</tbody>
</table>

Table 61: Water levels at Hoek van Holland, The Netherlands [53, 56]

- The Highest Design Water Level (HDWL) is assumed to be 5.50 + NAP (meter). This counts for an occurrence of 1 in 10,000 years.
• The Lowest Design Water Level (LDWL) is defined as the low water level with a chance of 5% to exceed over the construction lifespan of 50 years. This is equal to a low water level with an occurrence of 1 in 1000 years. The low water level frequencies in Table 61 have been extrapolated in order to be able to estimate the level with this occurrence. According to Figure 85 the level is assumed to be 2,50 - NAP (meter).

![Extrapolated low water levels according to NAP at Hoek van Holland (The Netherlands)](image)

Figure 85: Extrapolated low water levels

• Average Water Level (AWL). The average daily water levels are presented in Figure 86. Maximum level 1,11 + NAP (meter) and minimum 0,63 - NAP (meter).

![Average tidal elevation at Hoek van Holland, The Netherlands](image)

Figure 86: Average water level [53, 56]

Waves
• Sea waves. Due to the sheltered position within Maasvlakte 2 (see the hatched area in Figure 79) it is assumed that wave transmission from sea is negligible.

• Ship waves. It is assumed that the influence of ship waves is negligible due to the low speed of the large ships inside the harbour basin. Smaller ships, like tugboats and harbour patrol boats have higher speeds. These short and low waves are neglected as well.

• Wind waves. Wind waves are negligible as well due to the absence of sufficient fetch to develop them into high waves.
Tidal currents [13]
According executed studies the expected depth average ebb and flood currents over the top 14,5 meters in the planned harbour basin will be maximal 0,1 m/s. These currents are assumed to be negligible.

Harbour basin resonance
In case the period of incident waves equals or approximates the natural oscillation period of a harbour basin, resonance phenomena may be expected. As the above-mentioned waves are assumed to be negligible harbour basin resonance will not be considered in this study.

Ice
The port authority indicates that navigation from sea to the port is possible at all times [15]. According to this the possible presence of ice is not considered.

J.6 Environmental and climatologic

Environment
The construction will be located in an environment containing seawater, thaw salts and crude oil. According to the new arrangement the structure is located in the environmental class XD3 (corrosion due to chlorides like thaw salts), XS3 (corrosion because of chlorides from seawater in tidal zones) and possibly also XA3 (corrosion because of chemicals from the crude oil). The environmental class determines the composition and the armour layer of the concrete. Due to the indistinct chemical reaction between crude oil and the concrete the environmental class XS3 was assumed (according to the old arrangement class 3,4,5).

Note: It is not the concrete that will corrode but the reinforcement steel. If the concrete armour layer is not sufficient, chlorides may infiltrate the concrete and reach the reinforcement steel. The steel will corrode and expands. This leads to cracks in the concrete.

Meteorological
- The prevailing winds measured at Hoek van Holland (The Netherlands) are: W-SW, force 4 or 5 Beaufort (20-28 or 29-38 km/h) [15].

- Temperature effects are not considered within the framework of this study.

Earthquakes
Earthquakes are not considered.

J.7 Technical

Phasing
According to the port authority the precise phasing of the land reclamation project is uncertain at the moment. For a general indication the construction will elapse in the following phases [16]:
- Phase 1 contains the realisation of a 2,7 km long hard sea defence (breakwater). Inside this defence 700 hectare of port area will arise.
• Phase 2 contains the extension of the hard sea defence with 1.3 km to a total length of 4 km. Inside the extension an extra 300 hectare of port area will arise resulting in a total net area of 1000 hectare. In the year 2033 the total Maasvlakte 2 is expected to be in use.

Requirements
The port authority states the following requirements during construction:
• The accessibility of other parts of the harbour needs to be guaranteed.
• The safety of Maasvlakte 1 needs to be guaranteed.

Concrete
Concrete with the following properties is considered:
• Concrete quality B35.
• Volumetric weight $\gamma_{\text{concrete}}=25 \text{ kN/m}^3$.
• Reinforcement steel FeB500.
• Ballast concrete $\gamma_{\text{ballast}}=23 \text{ kN/m}^3$.

Crude oil storage
• The density of crude oil is considered to be $\rho = 0.85 \text{ kg/litre}$ equal to a volumetric weight $\gamma_{\text{oil}}=8.5 \text{ kN/m}^3$.
• The density of ballast water is considered to be $\rho = 1025 \text{ kg/m}^3$ equal to a volumetric weight $\gamma_{\text{w}}=10.25 \text{ kN/m}^3$.

Ship data [11, 40]
The considered container design ship is indicated in Table 62.

<table>
<thead>
<tr>
<th>Ship particulars and propulsion</th>
<th>SMCR power demand of average vessels</th>
<th>Future</th>
<th>Design ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship size</td>
<td>Post-Panamax</td>
<td>Post-Panamax</td>
<td>Suezmax</td>
</tr>
<tr>
<td>Container ship class</td>
<td>6,000 (6,500)</td>
<td>8,000 (8,500)</td>
<td>12,000</td>
</tr>
<tr>
<td>Deadweight (design)</td>
<td>70,000</td>
<td>93,000</td>
<td>137,000</td>
</tr>
<tr>
<td>Length overall</td>
<td>305</td>
<td>335</td>
<td>400</td>
</tr>
<tr>
<td>Length between pp</td>
<td>290</td>
<td>320</td>
<td>390</td>
</tr>
<tr>
<td>Breadth</td>
<td>43.0</td>
<td>43.0</td>
<td>52.5</td>
</tr>
<tr>
<td>Design draught</td>
<td>12.5</td>
<td>13.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Ballast coefficient, Lpp</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Sea margin</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Engine margin</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Ship speed</td>
<td>25.0</td>
<td>25.3</td>
<td>25.5</td>
</tr>
<tr>
<td>SMCR power</td>
<td>52,000</td>
<td>67,000</td>
<td>85,700</td>
</tr>
<tr>
<td>Main engine options:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>12K80MC-CME-C</td>
<td>12K80MC-CME-C</td>
<td>12K80MC-CME-C</td>
</tr>
<tr>
<td>2.</td>
<td>12K80MC-MCE</td>
<td>12K80MC-MCE</td>
<td>12K80MC-MCE</td>
</tr>
<tr>
<td>3.</td>
<td>12K80MC-MCE</td>
<td>12K80MC-MCE</td>
<td>12K80MC-MCE</td>
</tr>
<tr>
<td>4.</td>
<td>12K80MC-MCE</td>
<td>12K80MC-MCE</td>
<td>12K80MC-MCE</td>
</tr>
</tbody>
</table>

Table 62: Container ship data [11, 40]

The engine power, propeller diameters and other information are presented in Figure 87 and Figure 88.
Figure 87: Container ship engine power [11, 40]

Figure 88: Container ships propeller diameter [11, 40]

Container terminal [35]
- Berth productivity 1.350 TEU moves/quay meter/year.
- Quay crane productivity 25 moves/crane/hour.
Appendix K. Mooring facilities

K.1 Breasting dolphins

*Breasting dolphins* [20] (see Figure 89) have to be able to absorb the kinetic energy of the berthing vessel, which requires them to be flexible. Other functions consist of the holding of the vessel during onshore wind and the connection of spring lines. The required flexibility can be achieved either by an elastic deformation of the dolphin itself (e.g. by using a number of relatively small-diameter, thick walled steel piles) or by elastic deformation of the fenders, or by a combination of the two.

**Figure 89: Flexible breasting dolphins [2]**

Effects from ship collision/hits are not considered assuming the breasting dolphins to be constructed independently from the quay structure. This may result in a wider distance between the vessel and the quay construction, which in turn requires the outreach of the container crane to be longer. This will possibly result in changes to the container crane dimensions, crane capacity and the associated loads.
K.2 Mooring dolphins

*Mooring dolphins/bollards [20]* (see Figure 90) serve to fasten the breast and stern mooring lines and are part of the quay structure. They have to withstand only quasi-static loads, which require them to be designed as stiff structures. Each single bollard has a maximum allowable force of 2,400 kN.

![Figure 90: Mooring dolphin or bollard [2]](image-url)
Appendix L. Container terminal design

L.1 Mooring configuration

For a single berth the quay length is determined by the length of the largest vessel frequently calling at the port, increased with 15 meters extra length at the front side and back side of the vessel (see Figure 91). According to the considered vessel length of 470 meter (see Table 62) this will result in a berth length of [10]:

\[
L_q = L_s + (2 \cdot 15m) = 470m + 30m = 500m
\]

In which:
- \( L_s \) = Vessel length.
- \( L_q \) = Berth quay length.

\[64\text{m} \quad 500\text{m} \quad 470\text{m} \]

**Figure 91: Mooring configuration [10]**

It is assumed that the bollards (see Appendix K.2) will be placed in pairs with a hart to hart distance of 2,7 meter and that each pair will be positioned at a hart to hart distance of 20 meter [35]. This results in 25 bollard pairs over the total berth length. On average a vessel will use 6 mooring lines (see Figure 91). Each line is connected to 1 bollard resulting in a total use of 6 bollards.

During loading condition the ship will rotate around its centre point. If the rotation is counter clockwise the governing loads occur in lines 1, 2 and 3, if the rotation is clockwise in lines 4, 5 and 6. It is assumed that maximum 3 bollards will be maximally loaded.

Assuming a caisson length of 64 meters the quay with a length of 500 meters will have approximately 8 caissons. Each caisson would have \( 64/20 = 3 \) bollard pairs.

Each single bollard has a maximum allowable force of 2.400 kN.

It is assumed that per caisson a maximum load of 1 bollard pair would occur. Per pair the maximum force is \( 2 \times 2400 \text{kN} = 4800 \text{kN} \). Resulting in \( q_s = 4800\text{kN}/64\text{m}=75\text{kN/m} \).
L.2 Terminal

Layout
A general container terminal layout is presented in Figure 92.

![General container terminal layout](image)

Figure 92: General container terminal layout (dimensions in meters) [10]
Terminal loads
Cargo and vehicles cause the loads outside the waterfront in the cargo handling area (see Table 63).

<table>
<thead>
<tr>
<th>Load type</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light traffic (cars)</td>
<td>5 kN/m²</td>
</tr>
<tr>
<td>General traffic (trucks)</td>
<td>10 kN/m²</td>
</tr>
<tr>
<td>Containers:</td>
<td></td>
</tr>
<tr>
<td>Empty, stacked 4 high</td>
<td>15 kN/m²</td>
</tr>
<tr>
<td>Full, stacked 2 high</td>
<td>35 kN/m²</td>
</tr>
<tr>
<td>Full, stacked 4 high</td>
<td>55 kN/m²</td>
</tr>
</tbody>
</table>

Table 63: Loads outside the waterfront at the cargo handling area [3]

When calculating the active pressure of retaining structures, as a rule the different loads in the cargo handling and container area can be grouped together to produce an average surface load of 30 to 50 kN/m² [3]. A terminal load $Q_{t1}$ and $Q_{t2}$ of 50kN/m² is considered.
### L.3 Container quay crane

#### Crane dimensions
A general container quay crane is presented in Figure 93.

![Figure 93: General rail mounted container quay crane (dimensions in meters)](image)

#### Number of cranes per berth

The following data is considered (see Appendix J.7):
- Berth productivity 1.350 TEU moves/quay meter/year.
- Quay crane productivity 25 moves/crane/hour.

An estimation of the berth productivity can be calculated as follows [10]:

\[ c_b = p \cdot f \cdot N_b \cdot t_n \cdot m_b \]

This formula can be rewritten into:

\[ N_b = \frac{c_b}{p \cdot f \cdot t_n \cdot m_b} \]

In which:
- \( c_b \) = Total berth productivity (TEU/year)
- \( N_b \) = Number of cranes per berth
- \( p \) = Berth productivity (TEU moves/quay meter/year)
- \( f \) = Quay crane productivity (moves/crane/hour)
- \( t_n \) = Number of cranes
- \( m_b \) = Berth length (m)

\[ c_b = 1.350 \frac{TEU}{meter/year} \cdot L_q = 1.350 \frac{TEU}{meter/year} \cdot 500m = 675.000 \frac{TEU}{year} \]

\( L_q = \) Berth length=500m (see Appendix L.1)
\[ p = \text{Crane productivity (TEU/crane/hour)} \]
\[ p = 25 \frac{\text{TEU}}{\text{hour}} \]
\[ f = \text{TEU factor} \]
\[ f = \frac{N_{20'} + 2 \cdot N_{40'}}{N_{\text{tot}}} = 1,5(-) \]
\[ N_{20'} = \text{Number of TEU's} \]
\[ N_{40'} = \text{Number of FEU's} \]
\[ N_{\text{tot}} = \text{Sum of } N_{20'} \text{ and } N_{40'} \]
\[ t_n = \text{Number of operational hours/year} \]
\[ t_n = 365 \cdot 24 = 8.760 \frac{\text{hours}}{\text{year}} \]
\[ m_b = \text{Berth occupancy} \]
\[ m_b = 0,35(-) \]
\[ N_b = \text{Number of cranes per berth} \]
\[ N_b = 2(-) \]

Calculation results in \[ N_b = \frac{675.000 \frac{\text{TEU}}{\text{year}}}{25 \frac{\text{TEU}}{\text{hour}} \cdot 1,5 \cdot 8.760 \frac{\text{hours}}{\text{year}} \cdot 0,35} = 6 \text{ cranes per berth.} \]

Note: In theory the cranes may operate directly beside each other. From an operational point of view this will not result in effective loading or unloading of the ship, which requires the cranes to be evenly distributed over the berth length resulting in \[ \frac{500 \text{ meters}}{6 \text{ cranes}} \approx 84 \text{ meters/crane.} \]

But during storm conditions (cranes out of order) they can possibly be positioned directly beside each other \[ [35] \]. Assuming a caisson width of 64 meters and a crane width of 17,5 meters this may result in the extreme loading case of \[ 64/17,25 = 4 \text{ cranes per caisson.} \]
Crane loads [35]
The crane loads can be divided into horizontal and vertical loads during operational conditions and storm conditions (see Table 64).

<table>
<thead>
<tr>
<th>Container quay crane data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance water-landside portals</td>
<td>30,5 meter</td>
</tr>
<tr>
<td>Distance between buffers</td>
<td>27,2 meter</td>
</tr>
<tr>
<td>Hart to hart distance wheel set</td>
<td>17,2 meter</td>
</tr>
<tr>
<td>Wheels</td>
<td>8 wheels per portal hart to hart 1 meter</td>
</tr>
<tr>
<td>Average operational wind speed</td>
<td>25 m/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Representative vertical load</th>
<th>Per wheel (kN)</th>
<th>Corner load (kN)</th>
<th>Load per meter (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landside in operation ($q_{craneV2}$)</td>
<td>2.500</td>
<td>19.700</td>
<td>2.700</td>
</tr>
<tr>
<td>Waterside in operation ($q_{craneV1}$)</td>
<td>2.000</td>
<td>15.700</td>
<td>2.200</td>
</tr>
<tr>
<td>Landside during storm ($q_{craneV2}$)</td>
<td>2.000</td>
<td>16.000</td>
<td>2.200</td>
</tr>
<tr>
<td>Waterside during storm ($q_{craneV1}$)</td>
<td>1.400</td>
<td>10.400</td>
<td>1.400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Representative horizontal load perpendicular to crane track</th>
<th>Per wheel (kN)</th>
<th>Corner load (kN)</th>
<th>Load per meter (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landside in operation ($q_{craneH2}$)</td>
<td>30</td>
<td>240</td>
<td>40</td>
</tr>
<tr>
<td>Waterside in operation ($q_{craneH1}$)</td>
<td>30</td>
<td>240</td>
<td>40</td>
</tr>
<tr>
<td>Landside during storm ($q_{craneH2}$)</td>
<td>90</td>
<td>660</td>
<td>100</td>
</tr>
<tr>
<td>Waterside during storm ($q_{craneH1}$)</td>
<td>80</td>
<td>630</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 64: Crane loads [35]
L.4 Building method

For the construction method several possibilities exists. As a rule one should avoid construction in water because of the difficulty and the related higher costs.
The preferred method is the construction in dry conditions. Construction may be done at the location itself or at a different location.

At the destination
Several methods are available in order to construct in dry conditions. The construction may elapse in:

Building excavation (see Figure 94). Banks bound the excavation. During construction the groundwater level will be lowered to a level below the excavation bottom. This will take place with the help of pumping wells. The excavation uses a lot of space due to the required bank stability and it needs to be checked if lowering of the groundwater level is allowed.

Figure 94: Building excavation [20]

Cofferdam or building pit (see Figure 95). A cofferdam or building pit consists of vertical walls and a horizontal bottom closure. The closure of the bottom can be an impermeable soil layer or an artificial layer (for example underwater concrete). One has to keep in mind a possible leakage of the floor, so temporary provisions like pumping systems are required. This method uses some space.

Figure 95: Cofferdam or building pit [57]
Membrane construction (see Figure 96). Another bottom closure is the membrane construction. In the excavation a membrane will be applied. This membrane will be covered with sand. The water level above the membrane will be kept low with the help of a drainage system. To deal with the upward water pressure the sand cover needs to be sufficiently thick. The method uses a lot of space due to the required bank stability.

![Membrane construction](image)

Figure 96: Membrane construction [20]

Or on the basis of:

The wall-roof method (see Figure 97). The construction consists out of diaphragm walls. This method has the advantage that after phase 4 (fill up) the ground level can be put into use again. The method uses some space and drainage is not required. Diaphragm walls are not guaranteed watertight, which forms a disadvantage.

![Wall-roof method](image)

Figure 97: Wall-roof method [20]

Pneumatic caissons (see Figure 98). The caisson will be constructed above the ground. During the digging the caisson will subside until the desired depth is reached. The digging will elapse in the working chamber. The working chamber contains overpressure so groundwater will not infiltrate the chamber. The weight of the caisson needs to be higher then the upward water pressure against the underside of the "air bubble" in the working chamber. When the caisson has reached the desired depth, the chamber will be filled with concrete. The method uses some space and drainage is not required.

![Pneumatic caisson](image)

Figure 98: Pneumatic caisson [20]
At a different destination:

Prefabricated caissons (see Figure 99). Prefabrication means fabrication of large construction parts, or the whole construction, somewhere else under conditional (dry) circumstances. After the fabrication the construction parts will be transported to their final destination by means of floating-transport. After arrival the parts will be installed and mutually connected if necessary.

![Figure 99: Prefabricated caissons](image)

**Phase 0: creation of the caissons**

**Phase 1: flooding of the excavation**

**Phase 2/3: floating of the caissons and transport**

**Phase 4: closure of the excavation**

The fabrication may take place in a building dock, an existing ship dock, an existing ship slope or at a nearby located construction area. A building dock is a temporarily building excavation located nearby a watercourse.

If the elements do not contain sufficient buoyancy extra buoyancy can be obtained from pontoons. Another possibility is the use of sinkable barges.

The installation of caissons, containing enough buoyancy, at the bottom of the water basin can be achieved by applying ballast water. The quick entrance speed of the water reduces the time span of the operation. Later in the project the water will be replaced by concrete.

For this study prefabricated caissons, which will be transported floating are considered. This method interferes little with the phasing of the Maasvlakte 2 project. Another advantage is that after the realisation of the hard sea defences in phase 1 or 2 mentioned in Appendix J.7 the
caissons can be positioned. Subsequently the area between the hard sea defence and the caissons can be filled up with sand.
Appendix M. Pre-design calculations

M.1 General

The pre-design calculation considers two designs for the underground caisson alternative:

- Tank design, which can possibly be set dry.
- Tank design, which is continuously filled.

The terminal layout conform Appendix L is presented in Figure 100.

Figure 100: Terminal layout

*Tank shape*

For the reservoir shape a choice can be made between circular and rectangular. As a result of a circular shape, the all-round ground- and/or water pressure distribution will mainly lead to circumferential normal compression inside the wall of the caisson. The use of concrete is convenient for in plane normal compression, which may result in a less heavy construction design.

In reality the pressure forces will not be evenly distributed because of an alternating water level on the harbour side of the construction and a constant soil level with an assumed constant groundwater level on the landside.

For a circular shaped caisson this may lead to extra tension forces within the structure. Beside this circular requires complex shuttering, which makes repetition of the formwork difficult. According to these disadvantages a rectangular shape will be considered (see Figure 101).

*Internal walls*

Internal walls will be applied for evenly distribution of the loads and achieving internal stability. According to this two of the walls will be positioned directly under the crane track (see Figure 100).
Tank dimensions
For the preliminary design the following dimensions are considered:
- LxBxH=64x64x26 meter (see Figure 101).

Figure 101: Reservoir dimensions (meter)

The pre-design calculations will consider:
- Overall structural stability (Appendix M.5-M.8).
- Concrete dimensions (Appendix M.9).
- Foundation bearing capacity and settlements (Appendix M.10).
- Stability during transport and installation (Appendix M.11).
- Piping (Appendix M.12).
- Scour and protection (Appendix M.13).
## M.2 Boundary conditions

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrographical</strong></td>
<td></td>
</tr>
<tr>
<td>Present water depth</td>
<td>20 - NAP (meter)</td>
</tr>
<tr>
<td>Navigation depth</td>
<td>20,8 - NAP (meter)</td>
</tr>
<tr>
<td><strong>Geotechnical</strong></td>
<td></td>
</tr>
<tr>
<td>Ground level</td>
<td>5,50 + NAP (meter)</td>
</tr>
</tbody>
</table>
| Coarse sand                          | $\gamma_{\text{wet}} = 20 \text{kN/m}^3$  
|                                     | $\gamma_{\text{dry}} = 18 \text{kN/m}^3$  
|                                     | $\alpha = 30^\circ$ |
| Ground water (salt)                  | $\gamma_w = 10,25 \text{kN/m}^3$  
|                                     | Level = 1,11 + NAP (meter) |
| **Hydraulic**                        |                   |
| Harbour water (salt)                 | $\gamma_w = 10,25 \text{kN/m}^3$ |
| Design water level                   | HDWL = 5,50 + NAP (meter)  
|                                     | LDWL = 2,50 - NAP (meter)  
|                                     | AWL = 1,11 + to 0,63 - NAP (meter) |
| **Environmental**                    |                   |
| Class [45]                           | XS3 (new arrangement) or  
|                                     | 3,4,5 (old arrangement) |
| **Technical**                        |                   |
| Concrete                             | Quality B35  
|                                     | $\gamma_{\text{concrete}} = 25 \text{kN/m}^3$  
|                                     | Reinforcement steel FeB500  
|                                     | $\gamma_{\text{ballast}} = 23 \frac{kN}{m}$ |
| Crude oil                            | $\gamma_{\text{oil}} = 8,5 \text{kN/m}^3$ |
| Ballast water                        | $\gamma_w = 10,25 \text{kN/m}^3$ |
| Design ship                          | Length overall 470 meter  
|                                     | Capacity 18,000 TEU  
|                                     | Draught 15,7 meter  
|                                     | Width 60m  
|                                     | Main propeller power 100,000 kW, diameter 10 meter  
|                                     | Bow propeller power 5,000 kW, diameter 4 meter |
| Navigation depth                     | 20,8 - NAP (meter) |
| Container terminal                   | Berth productivity 1.350 TEU moves/quay meter/year  
|                                     | Quay crane productivity 25 moves/crane/hour |

Table 65: Boundary conditions
M.3 Load combinations

The calculations will consider the extreme or unfavourable load combinations as presented in Table 66 and Table 67. NOTE: Assuming no other loads then crane loads at the crane track.

<table>
<thead>
<tr>
<th>Loads</th>
<th>Stability calculations</th>
<th>Other calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overturning</td>
<td>Uplift</td>
</tr>
<tr>
<td>Permanent</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Reservoir deadweight</td>
<td>1 X</td>
<td>X</td>
</tr>
<tr>
<td>Soil</td>
<td>2 X</td>
<td>X</td>
</tr>
<tr>
<td>Ground water</td>
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</tr>
<tr>
<td>Variable</td>
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<tr>
<td>Harbour water level</td>
<td>HDWL</td>
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<tr>
<td></td>
<td>LDWL</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>AWL</td>
<td>6</td>
</tr>
<tr>
<td>Reservoir content</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Water</td>
<td>7</td>
</tr>
<tr>
<td>Oil</td>
<td>8 X</td>
<td>X</td>
</tr>
<tr>
<td>Empty</td>
<td>9 X</td>
<td>X</td>
</tr>
<tr>
<td>Crane operation</td>
<td>Normal</td>
<td>10</td>
</tr>
<tr>
<td>Storm</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Terminal</td>
<td>12</td>
<td>X</td>
</tr>
<tr>
<td>Ship mooring</td>
<td>13</td>
<td>X</td>
</tr>
<tr>
<td>Ship propeller wash</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

Table 66: Extreme load combinations

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent</td>
<td></td>
</tr>
<tr>
<td>Reservoir deadweight</td>
<td>$F_{\text{concrete}}$</td>
</tr>
<tr>
<td>Soil</td>
<td>$\sigma'_{\text{soil H}}$</td>
</tr>
<tr>
<td>Ground water</td>
<td>$\sigma_2$</td>
</tr>
<tr>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>Harbour water</td>
<td>$\sigma_1$</td>
</tr>
<tr>
<td>Reservoir content</td>
<td>$V$</td>
</tr>
<tr>
<td>Crane operation (Appendix L.3)</td>
<td>$Q_{\text{crane H and crane V}}$</td>
</tr>
<tr>
<td>Terminal (Appendix L.2)</td>
<td>$Q_{t1}$ and $Q_{t2}$</td>
</tr>
<tr>
<td>Mooring (Appendix L.1)</td>
<td>$Q_b$</td>
</tr>
</tbody>
</table>

Table 67: Loads


### M.4 Soil and water pressure distribution landside

**Effective vertical soil pressure** ($\sigma'_{\text{soilV}}$ in Figure 102)

\[
\sigma'_{\text{soilV}} = \sigma_{\text{soilV}} - \sigma_{\text{water}}
\]

\[
\sigma'_{\text{soilV}0} = \sigma_{\text{soilV}0} = Q_{12} = 50 \frac{kN}{m^2}
\]

\[
\sigma'_{\text{soilV1}} = \sigma_{\text{soilV}0} + \gamma_{\text{dry}} \cdot h_2 = 50 \frac{kN}{m^2} + \left(18 \frac{kN}{m^3} \cdot 4,4 m\right) = 129,2 \frac{kN}{m^2}
\]

\[
\sigma_{\text{water}} = \sigma_2 = \gamma_w \cdot h_1 = 10,25 \frac{kN}{m^3} \cdot 21,9 m = 224,5 \frac{kN}{m^2}
\]

\[
\sigma'_{\text{soilV2}} = \sigma_{\text{soilV}2} - \sigma_2 = (\sigma_{\text{soilV}1} + \gamma_{\text{wet}} \cdot h_3) - \sigma_2 = \left(129,2 \frac{kN}{m^2} + 20 \frac{kN}{m^3} \cdot 21,9 m\right) - 224,5 \frac{kN}{m^2} = 342,5 \frac{kN}{m^2}
\]

![Figure 102: Vertical soil pressure, effective vertical soil pressure and ground water distribution](image)

**Effective horizontal soil pressure** ($\sigma'_{\text{soilH}}$ in Figure 103)

\[
\sigma'_{\text{soilH}} = K_{\text{neutral}} \cdot \sigma'_{\text{soilV}}
\]

\[
K_{\text{neutral}} = \frac{1}{2} \quad \text{Ratio between horizontal and vertical effective soil pressure considering no deformation [20].}
\]

\[
\sigma'_{\text{soilH0}} = \frac{1}{2} \cdot 50 \frac{kN}{m^2} = 25 \frac{kN}{m^2}
\]

\[
\sigma'_{\text{soilH1}} = \frac{1}{2} \cdot 129,2 \frac{kN}{m^2} = 64,6 \frac{kN}{m^2}
\]

\[
\sigma'_{\text{soilH2}} = \frac{1}{2} \cdot 342,7 \frac{kN}{m^2} = 171,4 \frac{kN}{m^2}
\]
Figure 103: Effective horizontal soil pressure and ground water distribution

**Total horizontal pressure** ($\sigma_{totalH}$ in Figure 104)

\[
\sigma_{totalH} = \sigma_{soilH} + \sigma_{water}
\]

\[
\sigma_{totalH0} = \sigma_{soilH0} = 25 \frac{kN}{m^2}
\]

\[
\sigma_{totalH1} = \sigma_{soilH1} = 64,6 \frac{kN}{m^2}
\]

\[
\sigma_{totalH2} = \sigma_{soilH2} + \sigma_2 = 171,4 \frac{kN}{m^2} + 224,5 \frac{kN}{m^2} = 395,9 \frac{kN}{m^2}
\]

Figure 104: Total horizontal pressure distribution
M.5 Overturning

General
The construction needs to have sufficient stability against overturning. The load combination is presented in Table 66. The stability can be determined from the following ratio (stability against overturning based on eccentricity is treated in Appendix M.10) [3]:

\[ F_0 \geq \frac{\Sigma M_r}{\Sigma M_o} \]

In which:
\( \Sigma M_r \) = Sum of moments to resist overturning about the wall toe, point T.
\( \Sigma M_o \) = Sum of overturning moments about the wall toe, point T.
\( F_o \) = Safety factor against overturning, for extreme loading \( F_o \geq 1.5 \). The stability will be calculated per meter length.

Note: Loads from the reservoir filled with water, crane loads and the terminal load \( Q_{t1} \) are not considered as they result in resisting moments and do not contribute to the extreme load combination. For the crane load this is clarified by the following calculation:

\[ M_{\text{crane}}/T = q_{v1} \cdot l \cdot x_1 + q_{v2} \cdot l \cdot x_2 - q_{h1} \cdot l \cdot y_2 - q_{h2} \cdot l \cdot y_2 \]
\[ x_1 = 3m \]
\[ x_2 = 33.5m \]
\[ y_2 = h_t = 26.3m \]
\[ q_{\text{crane}} = q_{v1}, q_{v2}, q_{h1}, q_{h2} \] According to Table 64 in Appendix L.3.

Operational conditions:
\[ M_{\text{crane}}/T = 2200 \frac{kN \cdot m}{m} \cdot 1m \cdot 3m + 2700 \frac{kN \cdot m}{m} \cdot 1m \cdot 33.5m - \]
\[ 40 \frac{kN}{m} \cdot 1m \cdot 26.3m - 40 \frac{kN}{m} \cdot 1m \cdot 26.3m = +94946kNm \]

Storm conditions:
\[ M_{\text{crane}}/T = 1400 \frac{kN \cdot m}{m} \cdot 1m \cdot 3m + 2200 \frac{kN \cdot m}{m} \cdot 1m \cdot 33.5m - 90 \frac{kN}{m} \cdot 1m \cdot 26.3m - \]
\[ 100 \frac{kN}{m} \cdot 1m \cdot 26.3m = +72903kNm \]

So for both conditions the crane load results in a positive (resistant) moment around point T.
Weight requirement for the highest design water level (HDWL)
The loads distribution is presented in Figure 105.

\[
\sigma_1 = \gamma_w \cdot h_1 = 10,25 \frac{kN}{m^2} \cdot 26,3m = 269,6 \frac{kN}{m^2}
\]
\[
F_1 = \frac{1}{2} \cdot \sigma_1 \cdot h_1 \cdot l = \frac{1}{2} \cdot 269,6 \frac{kN}{m^2} \cdot 26,3m \cdot 1m = 3545,2kN
\]

\[
\sigma_2 = \gamma_w \cdot h_2 = 10,25 \frac{kN}{m^2} \cdot 21,9m = 224,5 \frac{kN}{m^2}
\]
\[
F_{2H} = \frac{1}{2} \cdot \sigma_2 \cdot h_2 \cdot l = \frac{1}{2} \cdot 224,5 \frac{kN}{m^2} \cdot 21,9m \cdot 1m = 2458,3kN
\]
\[
F_{2V} = \sigma_2 \cdot B \cdot l = 224,5 \frac{kN}{m^2} \cdot 64m \cdot 1m = 14368,0kN
\]

\[
\sigma_3 = \sigma_1 - \sigma_2 = 269,6 \frac{kN}{m^2} = 224,5 \frac{kN}{m^2} = 45,1 \frac{kN}{m^2}
\]
\[
F_{3V} = \left( \frac{1}{2} \cdot \sigma_3 \cdot B \cdot l \right) = \frac{1}{2} \cdot 45,1 \frac{kN}{m^2} \cdot 64m \cdot 1m = 1443,2kN
\]

\[
\sigma'_{\text{soilH0}} = \frac{1}{2} \cdot 50 \frac{kN}{m^2} = 25 \frac{kN}{m^2} \text{ (See Appendix M.4)}
\]
\[
F_{\text{soilH0}} = \sigma'_{\text{soilH0}} \cdot H \cdot l = 25 \frac{kN}{m^2} \cdot 26m \cdot 1m = 650kN
\]
\[ \sigma_{\text{soil}1} = \frac{1}{2} \cdot 129.2 \frac{kN}{m^2} = 64.6 \frac{kN}{m^2} \] (See Appendix M.4)

\[ F_{\text{soil}1} = \frac{1}{2} \left( \sigma_{\text{soil}1} - \sigma_{\text{soil}0} \right) \cdot h_2 \cdot l = \frac{1}{2} \left( 64.6 \frac{kN}{m^2} - 25 \frac{kN}{m^2} \right) \cdot 4.4 m \cdot 1m = 87.1 kN \]

\[ F_{\text{soil}3} = (\sigma_{\text{soil}1} - \sigma_{\text{soil}0}) \cdot h_3 \cdot l = \left( 64.6 \frac{kN}{m^2} - 25 \frac{kN}{m^2} \right) \cdot 21.9 m \cdot 1m = 867.2 kN \]

\[ \sigma_{\text{soil}2} = \frac{1}{2} \cdot 342.7 \frac{kN}{m^2} = 171.4 \frac{kN}{m^2} \] (See Appendix M.4)

\[ F_{\text{soil}2} = \frac{1}{2} \left( \sigma_{\text{soil}2} - \sigma_{\text{soil}1} \right) \cdot h_3 \cdot l = \frac{1}{2} \left( 171.4 \frac{kN}{m^2} - 64.6 \frac{kN}{m^2} \right) \cdot 21.9 m \cdot 1m = 1169.5 kN \]

\[ q_b = 75 \frac{kN}{m} \] (See Appendix L.1)

\[ F_b = q_b \cdot l = 75 \frac{kN}{m} \cdot 1m = 75 kN \]

\[ \Sigma M_0 = F_{\text{soil}0} \cdot \frac{1}{3} \cdot h_3 + F_{\text{soil}2} \cdot \frac{1}{3} \cdot H + F_{\text{soil}1} \left( \frac{1}{3} \cdot h_2 + h_3 \right) + F_{\text{soil}3} \cdot \frac{1}{2} \cdot h_3 + F_{\text{soil}2} \cdot \frac{1}{3} \cdot h_3 + F_b \cdot \frac{1}{3} \cdot H + F_{\text{soil}2} \cdot \frac{1}{2} \cdot B = 538978,3 kNm \]

\[ \Sigma M_r = G \cdot \frac{1}{2} \cdot B + F_{\text{soil}} \cdot \frac{1}{3} \cdot h_1 = G \cdot 32m + 31079,6 kNm \]

\[ F_0 = \frac{\Sigma M_r}{\Sigma M_0} = \frac{G \cdot 32m + 31079,6 kNm}{538978,3 kNm} > 1,5 \]

Reservoir filled with oil:
\[ G_{\text{oil}} = F_{\text{concrete}} + F_{\text{oil}} > 24293,4 kN \]

Empty reservoir:
\[ G_{\text{empty}} = F_{\text{concrete}} > 24293,3 kN \]
Weight requirement for the lowest design water level (LDWL)

The loads distribution is presented in Figure 106.

\[ \sigma_1 = \gamma_w \cdot h_1 = 10,25 \frac{kN}{m^3} \cdot 18,3m = 187,6 \frac{kN}{m^2} \]

\[ F_{HH} = \frac{1}{2} \cdot \sigma_1 \cdot h_1 \cdot l = \frac{1}{2} \cdot 187,6 \frac{kN}{m^2} \cdot 18,3m \cdot 1m = 1716,5kN \]

\[ F_W = \sigma_1 \cdot B \cdot l = 187,6 \frac{kN}{m^2} \cdot 64m \cdot 1m = 12006,4kN \]

\[ \sigma_2 = \gamma_w \cdot h_3 = 224,5 \frac{kN}{m^2} \]

\[ F_2 = \frac{1}{2} \cdot \sigma_2 \cdot h_3 \cdot l = 2458,3kN \]

\[ \sigma_3 = \sigma_2 - \sigma_1 = 224,5 \frac{kN}{m^2} - 187,6 \frac{kN}{m^2} = 36,9 \frac{kN}{m^2} \]

\[ F_{W1} = \left( \frac{1}{2} \cdot \sigma_3 \cdot B \cdot l \right) = \frac{1}{2} \cdot 36,9 \frac{kN}{m^2} \cdot 64m \cdot 1m = 1180,8kN \]

\[ F_{\text{soil}H0} = \sigma_{\text{soil}H0} \cdot H \cdot l = 650kN \]

\[ F_{\text{soil}H1} = \frac{1}{2} \cdot \left( \sigma_{\text{soil}H1} - \sigma_{\text{soil}H0} \right) \cdot h_2 \cdot l = 87,1kN \]

\[ F_{\text{soil}H2} = \frac{1}{2} \cdot \left( \sigma_{\text{soil}H2} - \sigma_{\text{soil}H1} \right) \cdot h_3 \cdot l = 1169,5kN \]

\[ F_{\text{soil}H3} = \left( \sigma_{\text{soil}H3} - \sigma_{\text{soil}H0} \right) \cdot h_3 \cdot l = 867,2kN \]

\[ F_b = q_b \cdot l = 75kN \]

Next Generation Storage Tanks
A potential alternative for crude oil storage tanks
\[ \sum M_0 = F_2 \cdot \frac{1}{3} \cdot h_3 + F_{\text{soil}H0} \cdot \frac{1}{2} \cdot H + F_{\text{soil}H1} \left( \frac{1}{3} \cdot h_2 + h_3 \right) + F_{\text{soil}H3} \cdot \frac{1}{2} \cdot h_3 + F_{\text{soil}H2} \cdot \frac{1}{3} \cdot h_3 + F_b \cdot H + F_{1V} \cdot \frac{1}{2} \cdot B + F_{3V} \cdot \frac{2}{3} \cdot B = 508190,0 \text{kNm} \]

\[ \sum M_r = G \cdot \frac{1}{2} \cdot B + F_{1H} \cdot \frac{1}{3} \cdot h_1 = G \cdot 32m + 10470,7 \text{kNm} \]

\[ F_0 = \frac{\sum M_r}{\sum M_0} = \frac{G \cdot 32m + 10470,7 \text{kNm}}{508190,0 \text{kNm}} > 1,5 \]

Reservoir filled with oil:
\[ G_{\text{oil}} = F_{\text{concrete}} + F_{\text{oil}} > 23494,2 \text{kN} \]

Empty reservoir:
\[ G_{\text{empty}} = F_{\text{concrete}} > 23494,2 \text{kN} \]
M.6 Uplift

General
The construction needs to have sufficient stability against uplifting. The load combination is presented in Table 66. The stability can be determined from the following ratio [3]:

\[ F_0 = \frac{\Sigma V}{\Sigma U} \]

In which:
\[ \Sigma V = \text{Sum of all loads directed downwards.} \]
\[ \Sigma U = \text{Sum of all loads directed upwards.} \]
\[ F_0 = \text{Safety factor against uplift} = 1,1. \]

Note: Loads from the reservoir filled with water, crane loads and the terminal load \( Q_{t1} \) are not considered as they result in forces directed downwards and do not contribute to the extreme load combination. The stability will be calculated per meter length.

Weight requirement for the highest design water level (HDWL)
The loads distribution is presented in Figure 107.

![Figure 107: Loads for uplift HDWL](image)

\[ \Sigma U = F_{SW} + F_{2W} = 1443,2kN + 14368,0kN = 15811,2kN \]
\[ \Sigma V = G \]
\[ F_0 = \frac{\Sigma V}{\Sigma U} = \frac{G}{15811,2kN} > 1,1 \]

Reservoir filled with oil:
\[ G_{oil} = F_{concrete} + F_{oil} > 17392,3kN \]

Empty reservoir:
\[ G_{empty} = F_{concrete} > 17392,3kN \]
Weight requirement for the lowest design water level (LDWL)
The loads distribution is presented in Figure 108.

\[ \Sigma U = F_{w1} + F_{w2} = 12006,4 \text{kN} + 1180,8 \text{kN} = 13187,2 \text{kN} \]
\[ \Sigma V = G \]

\[ F_0 = \frac{\Sigma V}{\Sigma U} = \frac{G}{13187,2 \text{kN}} > 1,1 \]

Reservoir filled with oil:
\[ G_{oil} = F_{concrete} + F_{oil} > 14505,9 \text{kN} \]

Empty reservoir:
\[ G_{empty} = F_{concrete} > 14505,9 \text{kN} \]
M.7 Horizontal sliding

General
The construction needs to have sufficient stability against horizontal sliding. The load combination is presented in Table 66. The stability can be determined from the following ratio [3]:

\[ F_{sl} = \frac{(\Sigma V - \Sigma U) \cdot f}{\Sigma H} \]

In which:
\[ \Sigma V = \text{Sum of all loads directed downwards.} \]
\[ \Sigma U = \text{Sum of all loads directed upwards.} \]
\[ \Sigma H = \text{Sum of all horizontal loads.} \]

\[ f = \text{Friction coefficient. For the lower limit } f = \tan \left( \frac{2}{3} \alpha \right) = 0.36 \text{ is used in which } \alpha = 30^\circ \text{ for sand.} \]

\[ F_{sl} = \text{Safety factor against horizontal sliding } = 1.25 \text{ for extreme loading.} \]

Note: Loads from the reservoir filled with water, crane loads and the terminal load \( Q_t \) are not considered as they result in forces directed downwards (partially horizontal) and do not contribute to the extreme load combination. For the crane load the clarification is left out from the report. The stability will be calculated per meter length.

Weight requirement for the highest design water level (HDWL)
\[ \Sigma H = F_1 - F_2H - F_{soilH1} - F_{soilH2} - F_{soilH3} - F_b = -1761.9 \text{kN} \]
\[ \Sigma U = F_3V + F_2V = 1443.2 + 14368.0 = 15811.2 \text{kN} \]
\[ \Sigma V = G \]

\[ F_{sl} = \frac{(G - \Sigma U) \cdot f}{\Sigma H} > 1.25 \]

Reservoir filled with oil:
\[ G_{oil} = F_{concrete} + F_{oil} > 21928.9 \text{kN} \]

Empty reservoir:
\[ G_{empty} = F_{concrete} > 21928.9 \text{kN} \]

Weight requirement for the lowest design water level (LDWL)
\[ \Sigma H = F_1 - F_2H - F_{soilH0} - F_{soilH1} - F_{soilH2} - F_{soilH3} - F_b = -3590.6 \text{kN} \]
\[ \Sigma U = F_3V + F_2V = 12006.4 + 1180.8 = 13187.2 \text{kN} \]
\[ \Sigma V = G \]

\[ F_{sl} = \frac{(G - \Sigma U) \cdot f}{\Sigma H} > 1.25 \]

Reservoir filled with oil:
\[ G_{oil} = F_{concrete} + F_{oil} > 25654.6 \text{kN} \]

Empty reservoir:
\[ G_{empty} = F_{concrete} > 25654.6 \text{kN} \]
M.8  Weight requirement for overall stability

The governing weight ($G$) per meter length to fulfil each stability requirement (see Appendix M.5 - M.7) is presented in red in Table 68.

<table>
<thead>
<tr>
<th>Water level</th>
<th>Stability</th>
<th>Uplift</th>
<th>Horizontal sliding</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDWL</td>
<td>$G \geq 24293.3\text{kN}$</td>
<td>$G \geq 17392.3\text{kN}$</td>
<td>$G \geq 21928.9\text{kN}$</td>
</tr>
<tr>
<td>LDWL</td>
<td>$G \geq 23494.2\text{kN}$</td>
<td>$G \geq 14505.9\text{kN}$</td>
<td>$G \geq 25654.6\text{kN}$</td>
</tr>
</tbody>
</table>

Table 68: Governing weight ($G$)

In order to comply with the overall stability, the weight of the tank should at least be

$$G_{\text{required}} \geq 25654.6 \frac{\text{kN}}{m} \cdot 6.4m = 1641894.4\text{kN}.$$  

For the tank design, which can possibly be set dry this result in the requirement:

$$G_{\text{required}} \geq 1641894.4\text{kN}$$

For the tank design, which is continuously filled this result in the requirement:

$$G_{\text{oil}} + F_{\text{concrete}} \geq 1641894.4\text{kN}$$
M.9 Concrete strength calculations (combination D)

M.9.1 General
The calculations considers two designs for the underground caisson alternative:
- Tank design, which can possibly be set dry.
- Tank design, which is continuously filled.

Concrete execution
Floor and walls: at the site
Roof: prefabricated prestressed concrete beams

---

**General data**

<table>
<thead>
<tr>
<th></th>
<th>B35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
</tr>
<tr>
<td>Reinforcement steel</td>
<td>FEB 500</td>
</tr>
<tr>
<td>Volumetric weight</td>
<td>$\gamma_{\text{concrete}} = 25 \text{kN/m}^3$</td>
</tr>
<tr>
<td>Volumetric weight ballast concrete</td>
<td>$\gamma_{\text{ballast}} = 23 \text{kN/m}^3$</td>
</tr>
<tr>
<td>Reinforcement percentage [22]</td>
<td>$\omega_{\text{min}} = 0.18$, $\omega_{\text{max}} = 1.94$, $\omega_{\text{economic}} = 0.91$</td>
</tr>
<tr>
<td>Concrete cover for hydraulic structures in seawater</td>
<td>$c = 70 \text{mm}$</td>
</tr>
<tr>
<td>Factor for variable loads</td>
<td>$\gamma = 1.5$</td>
</tr>
<tr>
<td>Concrete pressure strength [22]</td>
<td>$f_{b'} = 21 \frac{N}{\text{mm}^2}$</td>
</tr>
<tr>
<td>Concrete shear tension [22]</td>
<td>$\tau_1 = 0.56 \frac{N}{\text{mm}^2}$ (Without shear force reinforcement) $\tau_2 = 4.2 \frac{N}{\text{mm}^2}$ (With shear force reinforcement)</td>
</tr>
<tr>
<td>Effective beam thickness exclusive cover and reinforcement steel</td>
<td>$d$</td>
</tr>
<tr>
<td>Total beam thickness</td>
<td>$h$</td>
</tr>
<tr>
<td>Beam width</td>
<td>$b$</td>
</tr>
</tbody>
</table>

Table 69: Concrete properties
M.9.2 Roof

The roof span is 8m (see Figure 101 in Appendix M.1) and needs to deal with a variable terminal load of 50kN/m² (see Appendix L.2).

According to Figure 110 the SJP350 profile [52] is appropriate. The profile is presented in Figure 109 the properties in Table 71.

![Figure 109: SJP350 profile [52]](image-url)

### Table 70: Reinforcement percentages [22]

<table>
<thead>
<tr>
<th>$M_d$</th>
<th>$\phi$</th>
<th>$X_d$</th>
<th>$Z_d$</th>
<th>$\omega_1$ (%)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td>B25</td>
</tr>
<tr>
<td>10</td>
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<td>0.013</td>
<td>0.99</td>
<td>0.02</td>
</tr>
<tr>
<td>20</td>
<td>0.020</td>
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<td>0.99</td>
<td>0.07</td>
</tr>
<tr>
<td>30</td>
<td>0.030</td>
<td>0.240</td>
<td>0.98</td>
<td>0.10</td>
</tr>
<tr>
<td>40</td>
<td>0.041</td>
<td>0.055</td>
<td>0.98</td>
<td>0.14</td>
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<td>50</td>
<td>0.051</td>
<td>0.068</td>
<td>0.97</td>
<td>0.16</td>
</tr>
<tr>
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<td>0.97</td>
<td>0.21</td>
</tr>
<tr>
<td>70</td>
<td>0.073</td>
<td>0.097</td>
<td>0.96</td>
<td>0.25</td>
</tr>
<tr>
<td>80</td>
<td>0.084</td>
<td>0.112</td>
<td>0.96</td>
<td>0.29</td>
</tr>
<tr>
<td>90</td>
<td>0.095</td>
<td>0.127</td>
<td>0.95</td>
<td>0.33</td>
</tr>
<tr>
<td>100</td>
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<td>0.141</td>
<td>0.94</td>
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</tr>
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<td>110</td>
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<td>0.156</td>
<td>0.94</td>
<td>0.40</td>
</tr>
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<td>0.172</td>
<td>0.93</td>
<td>0.44</td>
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<td>130</td>
<td>0.140</td>
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<td>0.433</td>
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<td>320</td>
<td>0.406</td>
<td>0.540</td>
<td>0.79</td>
<td>1.40</td>
</tr>
</tbody>
</table>

$M_d$ in kNm, $d$ in m, $R_b$ in N/mm², $\psi = \omega_{f_b}$. 

Figure 109: SJP350 profile [52]
Next Generation Storage Tanks
A potential alternative for crude oil storage tanks
M.9.3 Concrete dimensions for the possibility to set the tank dry

External walls

<table>
<thead>
<tr>
<th>Construction detail</th>
<th>Phase</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>Operational phase</td>
<td>Empty tank</td>
</tr>
</tbody>
</table>

Table 72: Extreme load for external walls

Load schematisation according to the envelope method [29] (see Figure 111).

Figure 111: External wall schematisation

\[
\alpha = 45^\circ, \ h = 4 \text{m}, \ l = 8 \text{m}
\]

\[
\sigma_{\text{total}H_1} = 64,6 \frac{kN}{m^2}, \ \sigma_{\text{total}H_2} = 395,9 \frac{kN}{m^2} \quad \text{(See Appendix M.4)}
\]

\[
\sigma_q = q = 344,9 \frac{kN}{m^2}
\]

Bending [22]:
Cross section A-B

\[
M_s = \frac{1}{10} \cdot q \cdot l^2 = \frac{1}{10} \cdot 344,9 \frac{kN}{m^2} \cdot 8^2 = 2207,4 kNm
\]

\[
M_d = M_s \cdot \gamma = 3311,0 kNm
\]
\[
\frac{M_d}{b \cdot d^2 \cdot f'_{b}} \leq 170 \quad \text{According to Table 70.}
\]

\[
b = 1m
\]

\[
d = \sqrt{\frac{M_d}{170 \cdot b \cdot f'_{b}}} = 0,96m
\]

\[h = d + c = 0,96m + 0,07m = 1,0m\]

Shear [22]:

\[
V_d \leq \tau \cdot b \cdot d
\]

\[
V_d = q \cdot l \cdot 1m = 2759,2kN \quad (\text{Maximum shear force})
\]

\[
\tau_1 \cdot b \cdot d = 537,6kN
\]

\[
V_d \geq \tau_1 \cdot b \cdot d \quad (\text{Shear force reinforcement is required})
\]

\[
\tau_2 \cdot b \cdot d = 4032kN
\]

\[
V_d \leq \tau_2 \cdot b \cdot d \quad (\text{Satisfies})
\]

\[h = 1,0m \quad \text{The dimension will be applied for all external walls.}\]

**Internal walls**

<table>
<thead>
<tr>
<th>Construction detail</th>
<th>Phase</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal walls</td>
<td>Operational phase</td>
<td>Partially empty tank</td>
</tr>
</tbody>
</table>

**Table 73: Extreme load for internal walls**

Load schematisation according to the envelope method [29] (see Figure 112).

\[
\alpha = 45^\circ, \quad h = 4m, \quad l = 8m
\]

\[
\sigma_q = q = \gamma_w \cdot H = 10,25 \frac{kN}{m^3} \cdot (26m - 4m) = 225,5 \frac{kN}{m^2}
\]
Next Generation Storage Tanks
A potential alternative for crude oil storage tanks

Bending [22]:
\[ M_s = \frac{1}{10} \cdot q \cdot l^2 = 1443,2 \text{kNm} \]
\[ M_d = M_s \cdot \gamma = 2164,8 \text{kNm} \]
\[ d = \frac{M_d}{170 \cdot b \cdot f_b^\prime} = 0,78m \]
\[ h = d + c \]
\[ h = 0,85m \]

Shear [22]:
\[ V_d \leq \tau \cdot b \cdot d \]
\[ V_d = q \cdot l \cdot m = 1804,0 \text{kN} \text{ (Maximum shear force)} \]
\[ \tau_1 \cdot b \cdot d = 436,8 \text{kN} \]
\[ V_d \geq \tau_1 \cdot b \cdot d \text{ (Shear force reinforcement is required)} \]
\[ \tau_2 \cdot b \cdot d = 3276,0 \text{kN} \]
\[ V_d \leq \tau_2 \cdot b \cdot d \text{ (Satisfies)} \]

\[ h = 0,85m \] The dimension will be applied for all internal walls.

Floor

Depth during floating transport (without weight of the floor):
\[ F_{\text{concrete}} = \text{roof} + 4 \cdot \text{walls(external)} + 14 \cdot \text{walls(internal)} = \]
\[ 64m \cdot 64m \cdot 10,49 \text{kN} \frac{m^3}{m^3} + 4 \cdot 25 \text{kN} \frac{m^3}{m^3} (1m \cdot 26m \cdot 64m) + 14 \cdot 25 \text{kN} \frac{m^3}{m^3} (0,85m \cdot 26m \cdot 64m) \]
\[ F_{\text{concrete}} = 704407,0 \text{kN} \]
\[ (l \cdot b \cdot h) \gamma_{\text{water}} = F_{\text{concrete}} \]
\[ (64m \cdot 64m \cdot h) 10,25 \text{kN} \frac{m^3}{m^3} = 704407,0 \text{kN} \rightarrow h = 16,8m \]

Inclusive 10% keel clearance the navigation depth will be 18,5m. Considering Table 59 in Appendix J.3 the navigation depth is too large for transport and measures need to be considered in order to reduce the depth, like for example:
- Extension of the construction phase for the roof and/or walls.
- Extra buoyancy due to the application of pontoons.
- No transport due to construction at the site in dry conditions (see Appendix L.4).

Construction at the site will be considered for the determination of the floor dimensions.

Weight requirement according to Appendix M.8 for overall stability
\[ G_{\text{required}} > 25654,6 \text{kN} \frac{m}{m} \]
\[ G_{\text{required}} > 25654,6 \text{kN} \frac{m}{m} \cdot 64m = 1641894,4 \text{kN} \]
Next Generation Storage Tanks
A potential alternative for crude oil storage tanks
The HDWL is not considered as it contains a higher water pressure directed upwards (compared to the LDWL) resulting in a smaller foundation pressure.

<table>
<thead>
<tr>
<th>Construction detail</th>
<th>Phase</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>After construction</td>
<td>Operation</td>
</tr>
</tbody>
</table>

Table 74: Extreme load for the floor

Load contribution in two directions (see Table 75 and Figure 114).

Table 75: Floor schematisation and governing moments [23]

Figure 114: Floor schematisation

Bending: The largest moment occurs in the cells with floor dimensions:

\[ l_x = 8m, \ l_y = 8m, \ \frac{l_y}{l_x} = 1 \]
Considering fixed connections around the plate the largest moment will be (according to Table 75):

\[ q = 400.8 \frac{kN}{m^2} \]

\[ M_{ss} = 0.001 \cdot q \cdot l^2 \cdot 51 = 1308.2 kNm \] According to Table 75.

\[ M_d = M_{ss} \cdot \gamma = 1308.2 kNm \cdot 1.5 = 1962.3 kNm \]

\[ d = \sqrt{\frac{M_d}{170 \cdot b \cdot f_b}} = 0.74m \]

\[ h = 0.07m + 0.74m = 0.81m \]

Shear [22]:
\[ V_d \leq \tau_b d \]
\[ V_d = q \cdot l \cdot 1m = 3206.4 kN \] (Maximum shear force)
\[ \tau_1 b d = 414.4 kN \]
\[ V_d \geq \tau_1 b d \] (Shear force reinforcement is required)
\[ \tau_2 b d = 3108.0 kN \]
\[ V_d \geq \tau_2 b d \] (Does not satisfies)

\[ d = \frac{V_d}{\tau_2 b} = 763.4 mm = 0.76m \]

\[ h = 0.07m + 0.76m = 0.83m \] The dimension will be applied for the complete floor.

Note: After the application of ballast concrete the height of the floor in total will increase and the floor properties will change.
M.9.4 Concrete dimensions for tank continuously filled

External walls

<table>
<thead>
<tr>
<th>Construction detail</th>
<th>Phase</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>Operational phase</td>
<td>Continuously filled tank</td>
</tr>
</tbody>
</table>

Table 76: Extreme load for external walls

Load schematisation according to the envelope method [29] (see Figure 115).

\[ \alpha = 45^\circ, \ h = 4\ m, \ l = 8\ m \]
\[ \sigma_{\text{total}1} = 64,6 \frac{kN}{m^2}, \ \sigma_{\text{total}2} = 395,9 \frac{kN}{m^2}, \ \sigma_q = q = 344,9 \frac{kN}{m^2} \] (See Appendix M.4)
\[ \sigma_{\text{olie}} = \gamma_{\text{olie}} \cdot h = 8,5 \frac{kN}{m^3} \cdot (26\ m - 4\ m) = 187,0 \frac{kN}{m^2}, \ q = \sigma_q - \sigma_{\text{olie}} = 157,9 \frac{kN}{m^2} \]

Bending [22]:
\[ M_s = \frac{1}{10} \cdot q \cdot l^2 = 1010,6\ kNm \]
\[ M_d = M_s \cdot \gamma, \ M_d = 1515,8\ kNm \]
\[ d = \sqrt{\frac{M_d}{170 \cdot b \cdot f_b'}} = 0,65m \]
\[ h = 0,65m + 0,07m = 0,72m \]

Shear [22]:
\[ V_d = q \cdot l \cdot 1m = 1263,2\ kN \]
\[ \tau_1 \cdot b \cdot d = 364,0 \text{kN} \]
\[ V_d \geq \tau_1 \cdot b \cdot d \text{ (Shear force reinforcement is required)} \]
\[ V_d \leq \tau_2 \cdot b \cdot d \text{ (Satisfies)} \]

\[ h = 0,72 \text{m} \text{ The dimension will be applied for all external walls.} \]

**Internal walls**

<table>
<thead>
<tr>
<th>Construction detail</th>
<th>Phase</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal walls</td>
<td>Operational phase</td>
<td>Tank filled with oil and water</td>
</tr>
</tbody>
</table>

Table 77: Extreme load for internal walls

Load schematisation according to the envelope method [29] (see Figure 116).

\[ \alpha = 45^\circ, \quad h = 4 \text{m}, \quad l = 8 \text{m} \]
\[ \sigma_q = q = \gamma_{\text{oil}} \cdot H = 10,25 \frac{\text{kN}}{\text{m}^3} \cdot (26 \text{m} - 4 \text{m}) = 225,5 \frac{\text{kN}}{\text{m}^2} \]
\[ \sigma_{\text{oil}} = \gamma_{\text{oil}} \cdot h = 8,5 \frac{\text{kN}}{\text{m}^3} \cdot (26 \text{m} - 4 \text{m}) = 187,0 \frac{\text{kN}}{\text{m}^2} \]
\[ q = \sigma_{\text{water}} - \sigma_{\text{oil}} = 225,5 \frac{\text{kN}}{\text{m}^2} - 187,0 \frac{\text{kN}}{\text{m}^2} = 38,5 \frac{\text{kN}}{\text{m}^2} \]

Bending [22]:
\[ M_s = 246,4 \text{ kNm} \]
\[ M_d = M_s \cdot \gamma = 369,6 \text{ kNm} \]
\[ d = \sqrt{\frac{M_d}{170 \cdot b \cdot f_b'}} = 0,32 \text{m} \]
\[ h = 0,32 \text{m} + 0,07 \text{m} = 0,39 \text{m} \]
Shear [22]:
\[ V_d \leq \tau \cdot b \cdot d \]
\[ V_d = q \cdot l \cdot 1m = 308,0kN \text{ (Maximum shear force)} \]
\[ \tau_1 \cdot b \cdot d = 179,2kN \]
\[ V_d \geq \tau_2 \cdot b \cdot d \text{ (Shear force reinforcement is required)} \]
\[ \tau_2 \cdot b \cdot d = 1344,0kN \]
\[ V_d \leq \tau_2 \cdot b \cdot d \text{ (Satisfies)} \]

\[ h = 0,39m \text{ The dimension will be applied for all internal walls.} \]

**Floor**

Depth during floating transport:

\[ F_{\text{concrete}} = 64m \cdot 64m \cdot 10,49 \frac{kN}{m^2} + 4 \cdot 25 \frac{kN}{m^3} (0,72m \cdot 26m \cdot 64m) + 14 \cdot 25 \frac{kN}{m^3} (0,39m \cdot 26m \cdot 64m) \]

\[ F_{\text{concrete}} = 389911,0kN \text{ (Exclusive weight of the floor)} \]

\[ (l \cdot b \cdot h) \gamma_{\text{water}} = F_{\text{concrete}} \]

\[ (64m \cdot 64m \cdot h)10,25 \frac{kN}{m^3} = 389911,0kN \rightarrow h = 9,3m \]

Including 10% keel clearance the navigation depth will be 10,2m and floating transport is possible according to Table 59 in Appendix J.3. Floating transport is further treated in Appendix M.11.

Weight requirement according to Appendix M.8 for overall stability

\[ G_{\text{required}} > 25654,6 \frac{kN}{m} \]

\[ G_{\text{required}} > 25654,6 \frac{kN}{m} \cdot 64m = 1641894,4kN \]

Requirement \( G_{\text{oil}} + F_{\text{concrete}} \geq G_{\text{required}} \)

\[ V_{\text{concrete}} = 64m \cdot 64m \cdot 0,35m + 4 \cdot (0,72m \cdot 26m \cdot 64m) + 14 \cdot (0,39m \cdot 26m \cdot 64m) = 15311,4m^3 \]

\[ V_{\text{oil/water}} = V_{\text{total}} - V_{\text{concrete}} = (64m \cdot 64m \cdot 26m) - 15311,4m^3 = 91184,6m^3 \]

\[ G_{\text{oil}} = V_{\text{oil/water}} \cdot \gamma_{\text{oil}} = 91184,6m^3 \cdot 8,5 \frac{kN}{m^3} = 775069,4kN \]

\[ 1164980,4kN < G_{\text{required}} \text{ Not sufficient so ballast is required.} \]

\[ G_{\text{required}} = F_{\text{concrete}} + G_{\text{oil}} + G_{\text{ballast}} \]

\[ G_{\text{oil}} + G_{\text{ballast}} = V_{\text{oil/water}} \cdot \gamma_{\text{oil}} + V_{\text{ballast}} \cdot \gamma_{\text{ballast}} \]

\[ V = V_{\text{oil/water}} + V_{\text{ballast}} \rightarrow V_{\text{oil/water}} = V - V_{\text{ballast}} \]

\[ G_{\text{required}} = F_{\text{concrete}} + V_{\text{oil/water}} \cdot \gamma_{\text{oil}} + V_{\text{ballast}} \cdot \gamma_{\text{ballast}} \]

\[ G_{\text{required}} = F_{\text{concrete}} + (V - V_{\text{ballast}}) \cdot \gamma_{\text{oil}} + V_{\text{ballast}} \cdot \gamma_{\text{ballast}} \]
\[ V = V_{\text{total}} - V_{\text{concrete}} = 91184,6 \text{ m}^3 \]
\[ V_{\text{ballast}} = \frac{G_{\text{required}} - F_{\text{concrete}} - V \cdot \gamma_{\text{oil}}}{(-\gamma_{\text{oil}} + \gamma_{\text{ballast}})} = 32890,6 \text{ m}^3 \]
\[ G_{\text{ballast}} = V_{\text{ballast}} \cdot \gamma_{\text{ballast}} = 32890,6 \text{ m}^3 \cdot 23 \frac{kN}{m^3} = 756483,8 kN \]
\[ V_{\text{oil/water}} = V - V_{\text{ballast}} = 58293,9 \text{ m}^3 \]
\[ \frac{V_{\text{ballast}} + V_{\text{concrete}}}{V_{\text{total}}} = 0,45 = 45\% \text{ concrete and 55\% storage.} \]

Floor load after construction in ship dock:
\[ q = \frac{F_{\text{concrete}}}{A} = \frac{389911,0 kN}{64m \cdot 64m} = 95,2 \frac{kN}{m^2} \]

Floor load during floating transport (see Figure 117):

Figure 117: Water pressure distribution during floating transport

\[ q = \sigma_{\text{water}} = h \cdot \gamma_{\text{water}} = 9,3 m \cdot 10,25 \frac{kN}{m^3} = 95,3 \frac{kN}{m^2} \text{ (Exclusive current pressure and wave run-up)} \]

Floor load for operational phase and LDWL (see Figure 118):

Figure 118: Loads for LDWL for operational phase
The HDWL is not considered as it contains a higher water pressure directed upwards (compared to the LDWL) resulting in a smaller foundation pressure.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction detail</td>
<td>After construction</td>
</tr>
<tr>
<td>Floor</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 78: Extreme load for the floor

Load contribution in two directions (see Table 75 and Figure 114).

Bending:
The largest moment occurs in the cells with floor dimensions:

\[ l_x = 8\, m, \quad l_y = 8\, m, \quad \frac{l_y}{l_x} = 1 \]

Considering fixed connections around the plate the largest moment will be (according to Table 75):

\[ q = 320,1 \, \frac{kN}{m^2} \]
\[ M_{xx} = 0,001 \cdot q \cdot l_x^2 \cdot 51 = 1044,8\, kNm \quad \text{According to table} \]
\[ M_d = M_{xx} \cdot \gamma = 1044,8\, kNm \cdot 1,5 = 1567,2\, kNm \]
\[ d = \sqrt{\frac{M_d}{170 \cdot b \cdot f_{b}}} = 0,66m \]
\[ h = 0,07m + 0,66m = 0,73m \]

Shear [22]:

\[ V_d \leq \tau \cdot b \cdot d \]
\[ V_d = q \cdot l \cdot 1m = 2560,8\, kN \quad \text{(Maximum shear force)} \]
\[ \tau_1 \cdot b \cdot d = 369,6\, kN \]
\[ V_d \geq \tau_1 \cdot b \cdot d \quad \text{(Shear force reinforcement is required)} \]
\[ \tau_2 \cdot b \cdot d = 2772,0\, kN \]
\[ V_d \leq \tau_2 \cdot b \cdot d \] (Satisfies)

\[ h = 0.73m \] The dimension will be applied for the complete floor.

Note: After the application of ballast concrete the height of the floor in total will increase and the floor properties will change.

**M.9.5 Design optimisation**

The previous design is based on general pre-design concrete calculations and can possibly be optimised. This may result in a reduction of the construction costs. A possible concept is presented in Figure 119.

![Figure 119: Design optimisation](image)

**Concept properties:**
- Double walls with internal walls for more evenly distribution of the loads.
- Larger span resulting in fewer cells.
M.10 Foundation and settlements (combination E)

The tanks will be placed directly on the harbour bottom, which is considered to exist of sand with properties presented in Table 65 in Appendix M.2.

Foundation bearing capacity [25]
According to Terzaghi [25] the foundation can be considered shallow, as the depth is smaller or equal to the width of the foundation:

\[ H \leq B \rightarrow 26m \leq 64m \quad \text{(Satisfies)} \]

For shallow square foundations under the water table the bearing capacity can be calculated from:

\[ q_u = 1.3c'N_c + qN_q + 0.4\gamma'BN_y \]

In which:

- \( c' \) - Soil cohesion, is considered to be 0 for sand.
- \( N_c, N_q, N_y \) - Bearing capacity factors which are a function of the soil friction (\( \phi' \)) (see Table 79).
- \( q \) - Surcharge, is considered to be 0

\[ \gamma' = \gamma_{wet} - \gamma_{water} = 20 \frac{kN}{m^3} - 10,25 \frac{kN}{m^3} = 9.75 \frac{kN}{m^3} \]

\[ B = 64m \]

<table>
<thead>
<tr>
<th>( \phi' )</th>
<th>( N_c )</th>
<th>( N_q )</th>
<th>( N_y )</th>
<th>( \phi' )</th>
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<th>( N_y )</th>
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</table>

Table 79: Terzaghi’s bearing capacity factors [25]

\[ q_u = 0.4\gamma'BN_y = 4774.8 \frac{kN}{m^2} \]

\[ q_{allowable} = \frac{q_u}{FS} = \frac{4774.8 \frac{kN}{m^2}}{3} = 1591.6 \frac{kN}{m^2} \]
Maximum foundation pressure for the tank, which can possibly set dry
The load combination is presented in Table 66.
The maximum pressure can be calculated from [3]:
\[ \sigma_{\text{max}} = \frac{\Sigma V - \Sigma U}{b} \left( 1 + \frac{6e}{b} \right) \]
In which:
\[ e = \frac{1}{2} \cdot b - e_1 \]
\[ b = 64m \]
\[ e_1 = \frac{\Sigma M}{\Sigma V - \Sigma U} \]

According to Appendix M.5 and M.9.3:
\[ \Sigma M_0 = 508190,0\, \text{kNm} \]
\[ G_{\text{total}} = G_{\text{ballast}} + F_{\text{concrete}} + V_{\text{oil/water}} \cdot \gamma_{\text{water}} = 2112744,5\, \text{kN} \] (Inclusive weight of the floor)
\[ G = \frac{G_{\text{total}}}{64m} \cdot 1m = 33011,6\, \text{kN} \]
\[ \Sigma M = \frac{1}{2} \cdot G \cdot B + \frac{1}{3} \cdot h_1 \cdot F_{\text{ballast}} = 1066841,9\, \text{kNm} \]
\[ \Sigma M = \Sigma M_0 - 558651,9\, \text{kNm} \]

According to Appendix M.6:
\[ \Sigma U = F_{\text{dow}} + F_{\text{wall}} = 123006,4\, \text{kN} + 1180,8\, \text{kN} = 13187,2\, \text{kN} \]
\[ \Sigma V = G = 33011,6\, \text{kN} \]
\[ \Sigma V - \Sigma U = 19824,4\, \text{kN} \]
Next Generation Storage Tanks
A potential alternative for crude oil storage tanks

Maximum foundation pressure for the tank, which is continuously filled
According to Appendix M.5 and M.9.4:

\[ \Sigma M_0 = 508190,0 \text{kNm} \]

\[ G_{\text{total}} = G_{\text{ballast}} + F_{\text{concrete}} + V_{\text{oil/water}} \cdot \gamma_{\text{water}} = 1818659,3 \text{kN} \] (Inclusive weight of the floor)

\[ G = \frac{G_{\text{total}}}{64m} \cdot 1m = 28416,6 \text{kN} \]

\[ \Sigma M_1 = G \cdot \frac{1}{2} \cdot B + F_{\text{hu}} \cdot \frac{1}{3} \cdot h_i = 940409,3 \text{kNm} \]

\[ \Sigma M = 432219,3 \text{kNm} \]

According to Appendix M.6:

\[ \Sigma U = F_{1w} + F_{3w} = 12006,4 \text{kN} + 1180,8 \text{kN} = 13187,2 \text{kN} \]

\[ \Sigma V = G = 28416,6 \text{kN} \]

\[ \Sigma V - \Sigma U = 15229,4 \text{kN} \]

\[ e_1 = 28,4m \text{ And } e = 3,6m \]

\[ e \leq \frac{b}{6} \rightarrow 3,6 < 10,7 \text{ (Satisfies)} \]

\[ \sigma_{\text{max}} = 318,7 \text{kN/m}^2 \]

\[ \sigma_{\text{max}} < q_{\text{allowable}} \text{ (Satisfies)} \]

Note: The HDWL situation is not considered as \( q_{\text{allowable}} \) is sufficiently large.

Settlements [26]
Depending on the local conditions foundation settlements may be expected.
According to conservative method of Meyerhof [26] the settlements on sand can be calculated directly from a CPT scan by:

\[ s = \frac{\Delta p \cdot B}{2 \cdot q_c} \]

In which:

\( \Delta p = \) Net foundation pressure.

\[ \overline{q_c} = 31,6MPa = 31600 \text{kN/m}^2 \] Cone resistance taken as average over a depth equal to the width of the foundation (B) (See Figure 83 and Figure 84 in Appendix J.4).

\[ B = 64m \]
Settlements for the tank, which can possibly be set dry

\[ \sigma_{\text{max}} = \Delta p = 420,0 \frac{kN}{m^2} \]
\[ s = 0,42m \]

Settlements for the tank, which is continuously filled

\[ \sigma_{\text{max}} = \Delta p = 318,7 \frac{kN}{m^2} \]
\[ s = 0,32m \]
M.11 Floating transport and installation (combination F)

As mentioned in Appendix M.9.4 the construction of the continuously filled tank may elapse at a different location. After the construction the tank needs to be transported floated to the destination.

Water level during transport

An average low water level of 0,63-NAP (meter) is assumed during transport (see Figure 121 and Appendix J.5). Considering this water level results in enough time span with sufficient water depth to transport the caisson.

**Figure 121: Average water level [53, 56]**

**Navigation depth during floating transport**

\[ F_{\text{concrete}} = \text{roof} + \text{externalwalls} + \text{internalwalls} + \text{floor} = \]
\[ 64m \cdot 64m \cdot 10,49 \frac{kN}{m^2} + 4 \cdot 25 \frac{kN}{m^3} (0,72m \cdot 26m \cdot 64m) + \]
\[ 14 \cdot 25 \frac{kN}{m^3} (0,39m \cdot 26m \cdot 64m) + 25 \frac{kN}{m^3} (64m \cdot 64m \cdot 0,73m) \]

\[ F_{\text{concrete}} = 464663,0kN \] (Inclusive weight of the floor)

\[ (1 \cdot b \cdot h) \gamma_{\text{water}} = F_{\text{concrete}} \]

\[ (64m \cdot 64m \cdot h) 10,25 \frac{kN}{m^3} = 464663,0kN \rightarrow h = 11,1m \]

Including 10% keel clearance the navigation depth will be 12,2m. According to the average low water level transport requires a channel depth of 12,83-Nap (meter).

The caisson can be fabricated in the ship dock no. 7 of Keppel Verolme located in the Port of Rotterdam (see Table 80). The dock has sufficient capacity to lodge 2 caissons at the time.

<table>
<thead>
<tr>
<th>Dock no. 7 properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length (m)</strong></td>
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<tr>
<td>405</td>
</tr>
</tbody>
</table>

Table 80: Keppel Verolme dock no. 7 properties
Other dock information:
- Water depth at waterfront (low tide): 9.50/10.50 metres.
- Water depth at waterfront (high tide): 11.00/12.50 metres.
- Water depth in channel to open water ("New Waterway") (low tide): 15.00 metres.
- Distance from yard to North Sea: 11.00 miles.
- There are no restrictions between the yard and open water for vessels or offshore units regarding height, or width at/or above the water line.

**Stability during transport [20]**
The caisson needs to have sufficient static stability during transport. Dynamic stability is not considered.

The stability depends on (see Figure 122):
- The pressure point (P). Point P is the mass-gravity point from the displaced amount of water. Point P is located halfway the water level and the underside of the caisson.
- The weight point (G). This is the location of the mass-gravity point of the caisson. Point (G) is located in the centre of the caisson.
- The meta-centre (M). This is the point of intersection between the upward force and the symmetrical vertical axis.
- The meta-centre height ($h_m$). The length of the line, which connects point G and M.

If $h_m$ is positive a correcting moment will force the caisson back to its equilibrium position. If $h_m$ is negative the caisson will be instable and will eventually turn over completely.

For a first approximation $h_m > 0.5$ m is considered.

![Figure 122: Stability during floating transport](image-url)
Point P
d_{p} = \frac{1}{2} \cdot h = \frac{1}{2} \cdot 11,1m = 5,6m.

Point G
Depends on the concrete distribution and is considered to be located at:
d_{G} = \frac{1}{2} \cdot H = \frac{1}{2} \cdot 26m = 13m

The position of point M can be calculated from:
d_{PM} = \frac{I}{V}
I = \frac{1}{12} \cdot l \cdot b^3
l = 64m
b = 64m
I = \frac{1}{12} \cdot l \cdot b^3 = \frac{1}{12} \cdot 64m \cdot (64m)^3 = 1398101,3m^4
V_{displacement} = B \cdot h \cdot l = 64m \cdot 11,1m \cdot 64m = 45465,6m^3
\frac{d_{PM}}{V} = \frac{I}{V} = \frac{1398101,3m^4}{45465,6m^3} = 30,7m
h_{m} = d_{PM} - (d_{G} - d_{p}) = 23,3m
h_{m} \gg 0,5m \text{ (satisfies, sufficient stability)}

Stability during installation/sinking down [20]
The installation process contains the following phases:
• Sinking down by filling the tank with ballast water.
• After positioning at the harbour bottom the tank will be filled partially with underwater ballast concrete \( V_{ballast} = 32890,6m^3 \) (See Appendix M.9.4).

The use of ballast water reduces the stability as it results in a moment enlarging a possible deviation.

Figure 123: Ballast water influence at stability
\[ d_{\text{internal}} = 0,39m \]
\[ d_{\text{external}} = 0,72m \]
\[ B = 64m \]
\[ l = 1m \]
\[ I_u = \frac{1}{12} \cdot l \cdot B^3 = 21845,3m^4 \]
\[ b = \frac{B - 7 \cdot d_{\text{internal}} - 2 \cdot d_{\text{external}}}{8} = 7,5m \] (See Figure 123)
\[ \Sigma I_i = 7 \left( \frac{1}{12} \cdot l \cdot b^3 \right) = 246,0m^4 \]
\[ I = I_u - \Sigma I_i = 21601,3m^4 \]
\[ h = 20,8 \text{NAP}(m) + 1,11 \text{NAP}(m) = 21,9m \]
\[ V_{\text{displacement}} = B \cdot h \cdot l = 64m \cdot 21,9m \cdot 1m = 1401,6m^3 \]

Point M
\[ d_{PM} = \frac{l}{V} = 15,4m \]

Point P
\[ d_p = \frac{1}{2} \cdot h = \frac{1}{2} \cdot 21,9m = 10,9m . \]

Point G
Depends on the concrete distribution and the amount of ballast water.

\[ V_{\text{ballast}} \cdot \gamma_{\text{water}} + F_{\text{concrete}} = V_{\text{displacement}} \cdot \gamma_{\text{water}} \]
\[ F_{\text{concrete}} = 464663,0kN = \frac{464663,0kN}{64m} = 7260,4 \frac{kN}{m} \]
\[ V_{\text{ballast}} = \left( \frac{V_{\text{displacement}} \cdot \gamma_{\text{water}} - (F_{\text{concrete}} \cdot l)}{\gamma_{\text{water}}} \right) = 693,3m^3 \]
According to Appendix M.9.4 the storage volume (exclusive ballast concrete) is:

\[ V_{\text{oil/water}} = V_{\text{total}} - V_{\text{concrete}} = (64m \cdot 64m \cdot 26m) - 15311,4m^3 = 91184,6m^3 \]

\[ V_{\text{oil/water}} = \frac{91184,6m^3}{64m} = 1424,8m^3 \]

\[ \frac{V_{\text{ballast}}}{V_{\text{water/oil}}} = 0,5 \]  The tank needs to be filled up to 50% with ballast water in order to sink to the harbour bottom (see Figure 124).

\[ d_{\text{concrete}} = \frac{1}{2} \cdot H = \frac{1}{2} \cdot 26m = 13m \]

\[ d_{\text{water}} = \frac{1}{4} \cdot H = \frac{1}{4} \cdot 26m = 6,5m \]

\[ d_{\text{concrete}} \cdot F_{\text{concrete}} + d_{\text{water}} \cdot F_{\text{water}} = d_g \cdot (F_{\text{concrete}} + F_{\text{water}}) \]

\[ F_{\text{water}} = V_{\text{ballast}} \cdot \gamma_{\text{water}} = 7106,3kN \]

\[ d_g = 9,8m \]

Figure 125: Stability during installation/sinking down

\[ h_m = d_{PM} = 15,4m \]

\[ h_m >> 0,5m \] (satisfies, sufficient stability)
M.12 Piping (combination G)

Due to the differences between the groundwater level on the landside of the caisson and the water level on the harbour side, ground water flow or percolation water flow may occur underneath or beside the caisson (see Figure 126).

![Diagram of piping](image)

**Figure 126: Situation considering piping for LDWL**

This may lead to piping, which may lead to instability of the construction. Piping is the flow of water through a tube shaped canal, which is formed by internal erosion of the soil or foundation material. Maximum flow may develop when the differences between the water levels ($\Delta H$) is at its maximum. This occurs for the lowest design water level (LDWL) at the harbour side and the highest groundwater level (HGWL) at the landside.

The stability against piping for the underside of the caisson depends on the percolation length according to Bligh and Lane [22].

According to Bligh’s formula the safe percolation length ($L$) must be $L_{\text{percolation}} \geq C_B \cdot \Delta H$.

In which:
- $C_B = 12$ Bligh’s factor for coarse sand
- $\Delta H =$ Water level drop $= 3.6\, m$
- $L_{\text{percolation}} \geq 43.2\, m$

According to Bligh the actual percolation length is:
- $L = \text{Actual total percolation length}$
- $L = \Sigma L_{\text{vertical}} + \Sigma L_{\text{horizontal}}$
- $\Sigma L_{\text{vertical}} = 0$
- $\Sigma L_{\text{horizontal}} = B = L_n = 64\, m$
- $L = 64\, m \geq L_{\text{percolation}} \text{ (Satisfies)}$
According to Lane’s formula the safe percolation length is \( L_{\text{percolation}} \geq C_L \cdot \Delta H \).

In which:

\( C_L = 5,0 \)  Lane’s factor for coarse sand
\( \Delta H = \) Water level drop = 3.6m
\( L_{\text{percolation}} \geq 18m \)

According to Lane the actual percolation length is:

\( L = \) Actual total percolation length
\( L = \sum L_{\text{vertical}} + \sum \frac{1}{3} \cdot L_{\text{horizontal}} \)

\( \sum L_{\text{vertical}} = 0 \)
\( L_{\text{horizontal}} = \frac{1}{3} \cdot 64m = 21,3m \)
\( L = 21,3m \geq L_{\text{percolation}} \) (Satisfies)

L is sufficiently large according to Bligh and Lane and piping is considered to be not an issue.

Possibly the caissons will not be placed closely adjacent to each other. Depending on the closure of this space the stability against piping around the caisson needs extra attention. A drainage system around the caissons is a possible solution.
M.13 Scour (combination H)

The bottom of harbours may erode by the action of tides, river flow, the wash from jet propellers, etc or a combination of these factors.

The extent of bottom erosion depends on current velocity, turbulence, time span of the scour process, and resistance of the bottom material against scouring and the supply of new sediment to the scour hole.

Bottom scour often occurs near berthing locations where vessels use their propeller capacity (partially or completely) to manoeuvre. Prevailing scour could eventually lead to instability of the quay wall.

As the tidal currents are assumed to be negligible only scour due to propeller wash will be considered.

Scour caused by the stern screw

The jet velocity caused by the rotating screw can be calculated from [3]:

\[ V_0 = C_p \left( \frac{p}{\rho_0 \cdot D^3} \right)^{\frac{1}{3}} \]

In which:
- \( p = \) Screw output = 100.000 kW
- \( \rho_0 = 1.025 \text{ton/m}^3 = \) Density of the water (1025kg/m³)
- \( C_p = 1.48 \) for free screw (without nozzle) or 1.17 for screw in a nozzle. \( C_p = 1.48 \) is assumed
- \( D = 10m = \) Diameter of the propeller

For pre design calculations 75% of the maximum screw output is advised [3] resulting in:

\[ V_0 = 1.48 \left( \frac{100.000 \text{kW} \cdot 75\%}{1.025 \text{ton/m}^3 \cdot (10m)^3} \right)^{\frac{1}{3}} = 13.3 \frac{m}{s} \]

Due to the attendance of tugboats in practise usually 10% of the maximum screw output will be used resulting in:

\[ V_0 = 1.48 \left( \frac{100.000 \text{kW} \cdot 10\%}{1.025 \text{ton/m}^3 \cdot (10m)^3} \right)^{\frac{1}{3}} = 6.81 \frac{m}{s} \]

As the current progresses further, the jet expands and losses speed with the increasing length due to the exchange of turbulence. The maximum speed near the bottom which causes scour can be calculated from:

\[ V_{bottom/bottom} = V_0 \cdot E \left( \frac{h_p}{D} \right)^a \]
In which:

\[ V_0 = C_p \left( \frac{p}{\rho_0 \cdot D_B^2} \right)^{\frac{1}{3}} \]

\[ E = 0.71 \] is assumed for single screw vessels with central rudder
\[ a = -1.00 \] is assumed for single screw vessels
\[ h_p = z + (h - T) = \text{Height of the screw shaft above the bottom} \]
\[ z = \left( \frac{D}{2} \right) + 0.15 = \left( \frac{10m}{2} \right) + 0.15 = 5.15m \]
\[ h = \text{Water depth = according to average low water = 20.2-NAP (m)} \]
\[ T = \text{Draught = 15.7m} \]
\[ h_p = z + (h - T) = 5.15m + (20.2m - 15.7m) = 9.65m \]

As this will result in

\[ V_{\text{bottom/max}} = C_p \left( \frac{p}{\rho_0 \cdot D_B^2} \right)^{\frac{1}{3}} \cdot E \cdot \left( \frac{h_p}{D} \right)^{\frac{a}{2}} = 9.8 \text{ m s}^{-1} \]

Considering 75% of the max screw output.

\[ V_{\text{bottom/max}} = C_p \left( \frac{p}{\rho_0 \cdot D_B^2} \right)^{\frac{1}{3}} \cdot E \cdot \left( \frac{h_p}{D} \right)^{\frac{a}{2}} = 5.0 \text{ m s}^{-1} \]

Considering 10% of the max screw output.

**Scour caused by the bow thrusters**

The velocity at the bow thruster outlet can be calculated from [3]:

\[ V_0 = 1.04 \left( \frac{p}{\rho_0 \cdot D_B^2} \right)^{\frac{1}{3}} \]

In which:
\[ p = 5000kW = \text{Assumed 100% output of the bow thrusters} \]
\[ D_B = \text{Inner diameter of the bow thrusters opening = assumed to be } D_{\text{screw}} \]
\[ D_{\text{screw}} = 4m = \text{Diameter bow propeller} \]
\[ \rho_0 = 1.025 \text{ ton m}^{-3} = \text{Density of the water (1025kg/m}^3) \]

\[ V_0 = 1.04 \left( \frac{p}{\rho_0 \cdot D_B^2} \right)^{\frac{1}{3}} = 1.04 \left( \frac{5000kW \cdot 100\%}{1.025 \text{ ton m}^{-1} \cdot (4m)^2} \right)^{\frac{1}{3}} = 7.0 \text{ m s}^{-1} \]

The velocity at the bottom, which is responsible for erosion, can be calculated as follows:

\[ V_{\text{bottom/max}} = 2.0 \left( \frac{L}{D_B} \right)^{-1} \cdot V_0 \]

In which:
\[ L = \text{Distance between opening of the bow thrusters and the quay wall, assuming to be } B \]
\[ \frac{B}{2} = 60m \]
\[ \frac{B}{2} = 30m \]

In which B is the width of the ship.
As \( V_0 = 1,04 \left( \frac{p}{\rho_0 \cdot D_B} \right)^{\frac{1}{3}} \) this will result in:

\[
V_{\text{bottom}}/\text{max} = 2,0 \left( \frac{L}{D_B} \right)^{-1} \cdot 1,04 \left( \frac{p}{\rho_0 \cdot D_B^2} \right)^{\frac{1}{3}} = 1,9 \frac{m}{s}
\]

**Scour protection**

The required diameter of the scour protection can be calculated from [3]:

\[
d_{\text{required}} \geq \frac{V_{\text{bottom}}^2}{B^2 \cdot g \cdot \Delta}
\]

In which:

- \( d_{\text{required}} \) = Required diameter of the stones (m).
- \( V_{\text{bottom}} \) = Bottom velocity due to stern screw or bow thrusters.
- \( B \) = Stability coefficient = 1,25 for ships with central rudder and stern screw or 1,20 for bow thrusters.
- \( g = 9,81 \frac{m}{s^2} \) = Earth acceleration

\[
\Delta = \left( \frac{\rho_s - \rho_0}{\rho_0} \right) = \text{Relative density of the stone material under uplift (ton/m}^3\text{)}
\]

\[
\rho_s = 2,65 \frac{\text{ton}}{\text{m}^3} = \text{Density of stone material (2650kg/m}^3\text{)}
\]

\[
\rho_0 = 1,025 \frac{\text{ton}}{\text{m}^3} = \text{Density of the water (1025kg/m}^3\text{)}
\]

\[
\Delta = \left( \frac{\rho_s - \rho_0}{\rho_0} \right) = \frac{\left( 2,65 \frac{\text{ton}}{\text{m}^3} - 1,025 \frac{\text{ton}}{\text{m}^3} \right)}{1,025 \frac{\text{ton}}{\text{m}^3}} = 1,59
\]

The bottom velocity created by the stern screw requires a scour protection with a minimal stone diameter of:

\[
d_{\text{required}} \geq \frac{\left( 9,8 \frac{m}{s} \right)^2}{1,25^2 \cdot 9,81 \frac{m}{s^2} \cdot 1,59} = 3,9 m \text{ Considering 75% of the max screw output.}
\]

The required diameter is not deliverable according to Figure 127.

\[
d_{\text{required}} \geq \frac{\left( 5,0 \frac{m}{s} \right)^2}{1,25^2 \cdot 9,81 \frac{m}{s^2} \cdot 1,59} = 1,0 m \text{ Considering 10% of the max screw output.}
\]

According to Figure 127 the required diameter calls for a stone grading of 1000-3000kg.
The bottom velocity created by the bow thrusters requires a scour protection with a minimal stone diameter of:

$$d_{\text{required}} \geq \frac{\left(\frac{1,9\ m}{s}\right)^2}{1,20^2 \cdot 9,81 \frac{m}{s^2} \cdot 1,59} = 0,16 m$$

According to Figure 128 the required diameter calls for a stone grading of 0,08-0,2m.
The governing diameter is 1.0m with a grading of 1000-3000kg.

The dimensions of the scour protection (the thickness and the build up of the layer) need to be studied. As 10% of the stern screw power is considered, additional bottom survey is needed every year to check the thickness and location of the bottom material.
Appendix N. Cost estimation

The cost estimation for the concept, which is continuously filled, is presented in Table 81. The estimation is based on benchmarking. Information is obtained from a recorded Shell project, which also consisted of the construction, floating transport and installation of a caisson.

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Unit rate</th>
<th>Costs 1 (euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship dock rent</td>
<td>16 weeks/caisson (2 caissons)</td>
<td>110.000 euro/week</td>
<td>900.000</td>
</tr>
<tr>
<td>Oil movement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piping and valves</td>
<td></td>
<td></td>
<td>1.000.000</td>
</tr>
<tr>
<td>Level alarms</td>
<td></td>
<td></td>
<td>15.000</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td>40.000</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td></td>
<td>1.955.000</td>
</tr>
<tr>
<td>Marine operations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tow out to destination</td>
<td></td>
<td></td>
<td>15.000</td>
</tr>
<tr>
<td>Ballast operation</td>
<td></td>
<td></td>
<td>750.000</td>
</tr>
<tr>
<td>Installation</td>
<td></td>
<td></td>
<td>15.000</td>
</tr>
<tr>
<td>Gap closing and connection</td>
<td></td>
<td></td>
<td>100.000</td>
</tr>
<tr>
<td>Scour protection</td>
<td></td>
<td></td>
<td>960.000</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td></td>
<td>1.840.000</td>
</tr>
<tr>
<td>Civil operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete for hull</td>
<td>15.000m³</td>
<td>85 euro/m³</td>
<td>1.300.000</td>
</tr>
<tr>
<td>Form work</td>
<td></td>
<td></td>
<td>3.000.000</td>
</tr>
<tr>
<td>Reinforcement steel</td>
<td></td>
<td></td>
<td>3.000.000</td>
</tr>
<tr>
<td>Post tensioned roof</td>
<td></td>
<td></td>
<td>880.000</td>
</tr>
<tr>
<td>Ballast concrete</td>
<td></td>
<td></td>
<td>800.000</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td></td>
<td>8.980.000</td>
</tr>
<tr>
<td>Total construction costs</td>
<td></td>
<td></td>
<td>12.775.000</td>
</tr>
<tr>
<td>Contingencies (10%)</td>
<td></td>
<td></td>
<td>1.277.500</td>
</tr>
<tr>
<td>Design and construct (25%)</td>
<td></td>
<td></td>
<td>3.193.750</td>
</tr>
<tr>
<td>Clients (10%)</td>
<td></td>
<td></td>
<td>1.277.500</td>
</tr>
<tr>
<td>TOTAL COSTS 5/6</td>
<td></td>
<td></td>
<td>19.000.000</td>
</tr>
</tbody>
</table>

Table 81: Cost estimation for tank design continuously filled

Notes:

1. The costs are:
   - Related to 1 caisson.
   - Based on Greenfield conditions.
   - Based on normal project execution and duration.
• Location and site specific.

2 Keppel Verolme dock located in the Port of Rotterdam. Considering 2 caissons per dock cycle.

3 Exclusive water treatment and pump installations.

4 Exclusive mooring facilities, container terminal facilities and repetition.

5 The total costs are including:
   • Project contingencies.
   • Subcontractor overheads and profits.
   • Subcontractor supervision during construction.
   • Subcontractor design and engineering.
   • Development allowance.

6 The total costs are excluding:
   • Taxes, customs and related duties.
   • Cost related to soil and groundwater contamination.
   • Insurance.
   • Escalation.
Appendix O. Legislation developments

O.1 VOTOB

VOTOB [55] is the Dutch association of six independent tank storage companies (Koole Tank storage Pernis B.V., LBC Rotterdam B.V., Odfjell Terminals Rotterdam B.V., Oiltanking, Petroplus International N.V., Royal Vopak, Europoint Terminals Netherlands B.V.).

The notion independent stands for providing logistic services to customers, without having ownership of the products in custody. VOTOB’s goal is to defend the common interests of their members by providing technical and operational information to regional and or national authorities on relevant issues. All these issues have in common that they relate to the interaction with society. In this manner VOTOB and its members aim to enhance the overall reputation of the tank storage sector. VOTOB deals exclusively with matters concerning the environment, occupational and external safety, the use of energy, technical standards and procedures like those related to customs declarations and other general aspects that may interfere with tank storage sector as a whole. The result of these efforts is brought forward into debates pertaining to new or internationally agreed regulation or law with authorities and other interested third parties.

O.2 Dutch emission figures

The fight against emissions to the atmosphere has a big priority. The issue here is the reduction of emission from Volatile Organically Compounds (VOC). According to the European guidelines for excessive rates for emission (NEC guidelines 2001/81/EG) The Netherlands have accepted a maximum total VOC emission of 185 kton in the year 2010. This compulsory result accounts for a reduction of 20% according to the year 2000. See Figure 129 for the emission trend lines for the different contributors [41].

![Dutch VOC emission trend lines](image-url)

Figure 129: Dutch VOC emission trend lines [41]
For an indication of the different sectors and their contribution to VOC emission in the year 2004, 1990 and 2010 see Figure 130 and Figure 131.

Figure 130: VOC emission per contributor in The Netherlands in the year 2004 [41]

Figure 131: VOC emission per contributor in The Netherlands in the year 1990 and 2010 [41]

O.3 Environmental agreement

IMKO-2 [55] (integral environmental frame for storage and transhipment companies) is an agreement for the period till 2020 between the three Dutch provinces that are qualified for establishment of storage and transhipment companies (North Holland, Zeeland and South Holland) and the Dutch ministries of public housing department, spatial arrangement & environmental hygiene (VROM) and the participating companies from the association of independent tank storage companies (VOTOB). The IMKO-2 agreement is based on the implementation of the best available technology.

A head of the signature of this agreement, planned for the fall of the year 2006, the negotiation results until 8th of February 2006 were presented in the “tank storage companies framework for the realised plan for the years 2006-2010”.

Next Generation Storage Tanks
A potential alternative for crude oil storage tanks
Tank storage companies can use this framework in order to set up its environmental plan for the period 2006-2010, which is compulsory. It gives a good indication concerning the future developments in the business.

For more information concerning the agreement see [www.votob.org](http://www.votob.org).
Appendix P. Concepts

P.1 General

According to the requirements and premises stated in Chapter 5.1, several “out of the box” concepts have been generated and gathered. The concepts are divided into the following classifications:

- Aboveground.
- Underground.
- Floating.
- Submerged.

Each concept is described conform:
- Impressions.
- Specific properties.
- Structural design.
- Operation.
- Inspection and maintenance.
- Fire safety.
- Spatial use.
- Fulfilment of the technical requirements.

To indicate the fulfilment of the technical requirements, at the end of each concept description a multi criteria analysis is performed conform Table 82 and Table 83. The results are again presented in a table. Note: each concept is compared to The Base Case (traditional tank design incl. expected design enhancements for the future, see Chapter 3.7).

<table>
<thead>
<tr>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less sensitive for degradation</td>
</tr>
<tr>
<td>Less failure modes</td>
</tr>
<tr>
<td>Integrated sludge removal system</td>
</tr>
<tr>
<td>No emission</td>
</tr>
<tr>
<td>Intensification of space utilisation</td>
</tr>
</tbody>
</table>

Table 82: Multi criteria analysis parameters

<table>
<thead>
<tr>
<th>Score</th>
<th>Technical requirements fulfilment</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>Worse</td>
</tr>
<tr>
<td>-</td>
<td>Bad</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>+</td>
<td>Good</td>
</tr>
<tr>
<td>++</td>
<td>Best</td>
</tr>
</tbody>
</table>

Table 83: Multi criteria analysis scores
Some of the concepts are partially based on the oil and water exchange principle. When oil is pumped out water will be pumped in resulting in a continuously filled tank. Because of the fact that oil is lighter than water, the oil will be floating on top of the water inside the tank.

P.2 Aboveground

Concept A-A:
The concept is generated as a non-flexible concrete tank with an integrated sludge collecting and removal system (see Figure 132).

![Concept A-A non-flexible concrete tank with integrated sludge removal system](image)

Figure 132: Concept A-A non-flexible concrete tank with integrated sludge removal system

Properties:
The concept properties are presented in Table 84.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 84: Properties concept A-A

Structural design:
The non-flexible tank is positioned on top of an impermeable layer. The topside of the tank is closed. The tank is continuously filled with oil and/or water. The tank can possibly be set dry. The internal floating structure separates the oil from the water. The floating structure is kept in balance by inflatable floaters and contains a sludge-collecting compartment in the middle.

Operation:
The filling and emptying of the tank is based on the oil and water exchange principle. When oil is pumped out water will be pumped in resulting in a continuously filled tank. The sludge will accumulate on top of the floating structure. During filling of the reservoir with oil the water will be discharged. If the water is contaminated it needs to be treated.

Inspection and maintenance:
After the oil product has been pumped out and the tanks are completely filled with water divers can inspect the tank. In order to remove the sludge, the oil is pumped out and the floating structure floats to the top. The oil suction pipe fits in the sludge-collecting compartment and the sludge can be sucked out as well. Due to non-corrosive sensitive concrete the tanks need less inspection and maintenance.
Fire safety:
There is no vapour space due to the fact that the tank is continuously filled. According to this the fire risks will be smaller.

Spatial profits:
Due to the smaller fire risks because of no presence of vapour space the inter tank distances may possibly be reduced and the bund area may be excluded (with the necessity that the integrity of the outer wall is guaranteed). This will result in some spatial gain. The storage of water in case of contamination requires some additional space.

Environmental issues:
There will be no emissions to the atmosphere and less failure modes. The impermeable layer below the tanks will function as a secondary protection.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 85.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 85: Fulfilment technical requirements concept A-A

Concept A-B:
The concept is generated as a non-flexible concrete tank (see Figure 133).

![Figure 133: Concept A-B non-flexible concrete tank](image)

Properties:
The concept properties are presented in Table 86.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 86: Properties concepts A-B
Structural design:
The concrete tank is positioned on top of the impermeable layer at the ground level and supplemented with sand or some other material, for example garbage or contaminated harbour silt covered with an impermeable layer. The topside of the tank is closed. The tanks are continuously filled, with the possibility to set dry. The structure consists of non-corrosive concrete.

Operation:
The filling and emptying of the tanks is based on the oil and water exchange principle. During filling of the reservoir with oil the water will be discharged. If the water is contaminated it needs to be treated. The sludge will sink to the bottom of the tank.

Inspection and maintenance:
After the oil product has been pumped out and the tanks are completely filled with water, divers can inspect the tank and the sludge can be removed from the bottom. The outer side of the tank is difficult to inspect. Due to non-corrosive sensitive concrete the tanks need less inspection and maintenance.

Fire safety:
There is no vapour space due to the fact that the tanks are continuously filled. According to this the fire risks will be smaller. The tanks are protected against extreme wind loads by the supplement.

Spatial profits:
Due to the smaller fire risks because of no presence of vapour space the inter tank distances may possibly be reduced and the bund area may be excluded (with the necessity that the integrity of the outer wall is guaranteed). This will result in some spatial gain. The storage of water in case of contamination requires some additional space.

Environmental issues:
There will be no emissions to the atmosphere and less failure modes. The impermeable layer below the tanks will function as a secondary protection. Leakage is difficult to monitor.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 87.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 87: Fulfilment technical requirements concept A-B
Concept A-C:
The concept is generated as a non-flexible concrete tank with an integrated sludge removal system in the bottom and no inter-tank distances (see Figure 134).

![Non-flexible concrete tank with integrated sludge removal system](image)

Figure 134: Concept A-C non-flexible concrete tank with integrated sludge removal system

Properties:
The concept properties are presented in Table 88.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 88: Properties concept A-C

Structural design:
The non-corrosive and non-flexible tank is positioned on top of an impermeable layer. The topside of the tank is closed. During operation the tank is continuously filled.

Operation:
The filling and emptying of the tanks is based on the oil and water exchange principle. During filling of the reservoir with oil the water will be discharged. If the water is contaminated it needs to be treated. The sludge will accumulate in the collecting compartment at the bottom of the tank and will be pumped out with the water. The sludge needs to be removed from the water.

Inspection and maintenance:
After the oil product has been pumped out and the tanks are completely filled with water divers can inspect the tank. The tank can also possibly set dry. Due to non-corrosive sensitive concrete the tanks need less inspection and maintenance. There is no need for personnel entering the tank for the removal of sludge due to the integrated system.

Fire safety:
There is no vapour space due to the fact that the tank is continuously filled. According to this the fire risks will be smaller and the inter tank distances and the bund area may possibly be excluded (with the necessity that the integrity of the outer wall is guaranteed). This will result in spatial gain. The storage of water in case of contamination requires some additional space.
Spatial profits:
The spatial profits will be large due to the fact that the tanks will be positioned directly against each other.

Environmental issues:
There will be no emissions to the atmosphere and less failure modes. The impermeable layer below the tanks will function as a secondary protection. Leakage is difficult to monitor.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 89.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 89: Fulfilment technical requirements concept A-C

Concept A-D:
The concept is generated as elevated concrete tanks with an integrated sludge removal system and no inter-tank distances (Figure 135).

Properties:
The concept properties are presented in Table 90.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 90: Properties concept A-D

Structural design:
The non-corrosive tanks are positioned on a pile foundation above an impermeable layer. The topside of the tank is closed. During operation the tank is continuously filled. The tank can possibly be set dry.
Operation:
The filling and emptying of the tanks is based on the oil and water exchange principle. During filling of the reservoir with oil the water will be discharged. If the water is contaminated it needs to be treated. The sludge will accumulate in the collecting compartment at the bottom of the tank and will be pumped out with the water. The sludge needs to be removed from the water.

Inspection and maintenance:
After the oil product has been pumped out and the tanks are completely filled with water divers can inspect the tank. The tank can also possibly be set dry. The bottom outer side of the tanks are easily accessible for inspection and maintenance work. Due to non-corrosive sensitive concrete the tanks need less inspection and maintenance. There is no need for personnel entering the tank for removing sludge due to the integrated system.

Fire safety:
There is no vapour space due to the fact that the tank is continuously filled. According to this the fire risks will be smaller and the inter tank distances and the bund area may possibly be excluded (with the necessity that the integrity of the outer wall is guaranteed). This will result in spatial gain. The storage of water in case of contamination requires some additional space.

Spatial profits:
The spatial profits will be large due to the fact that the tanks will be positioned directly against each other.

Environmental issues:
There will be no emissions to the atmosphere and less failure modes. The impermeable layer below the tanks will function as a secondary protection. Leakage is easy to monitor.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 91.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 91: Fulfilment technical requirements concept A-D
Concept “The Base Case”:
The concept is generated as a traditional tank design (see Appendix C) with expectable adjustment for the coming 20 years (see Chapter 3.7).

Properties:
The concept properties are presented in Table 92.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 92: Properties concept “The Base Case”

Technical requirements:
The fulfilment of the technical requirements is presented in Table 93.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 93: Fulfilment technical requirements concept “The Base Case”
P.3 Underground

Existing concept designs:
In 1998 a consortium developed potential concepts for underground crude oil storage. The consortium consisted of The Port of Rotterdam, Dutch Concrete Group (HBG, nowadays also known as BAM), Volker Wessels Stevin Concrete- and Hydraulic Engineering (VWSB), Shell Global Solutions and The Weger architects- and engineering agency (at present also known as Royal Haskoning) [17].

The technological basis for the development was formed by 3 options for the separation between the crude oil and the water:

- No separation; oil floating on top of the water.
- Separation by an intermediate membrane.
- Separation by bags.

Concept U-A:
The concept has been developed by Shell. It gives an alternative for relatively small amounts of crude oil in tanks with a capacity of 50000m³ (see Figure 136).

Figure 136: Concept U-A underground crude oil storage by Shell

Properties:
The concept properties are presented in Table 94.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location than aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 94: Properties concepts U-A
Structural design:
Diaphragm walls\(^{18}\) or combi-/sheet walls form the underground cylindrical structure. The reservoir is continuously filled with water. At the bottom side it will be closed from the surrounding by an underwater concrete floor. The reservoir can’t be set dry as the water stabilizes the vertical and horizontal forces. The oil in the reservoir will be stored in a steel lining with the appearance of “a reversed or upside-down glass”.

Operation:
The oil will be floating on the water inside the reverse glass. The filling and emptying of the tank develops on the exchange principle between oil and water. A water basin at ground level surrounding the tanks will provide the water for the exchange principle. During the filling of the tank with oil the ballast water is stored in this basin in order to be reused during the emptying of the tank. The sludge will accumulate at the bottom of the tank.

Inspection and maintenance:
Tank inspection and maintenance is feasible by divers when the tank is empty that is when the tank is filled with ballast water. The steel lining can be lifted out of the water after which inspection and maintenance can take place. During the inspection of the steel lining possible inspection of the underground structure can take place and/or the sludge may be removed from the bottom.

Fire safety:
The concept doesn’t contain any vapour space, so the hazard for fire is minor.

Spatial profits:
Per tank a surface of 75x75 m\(^2\) (inclusive the water basin) is needed. In comparison with the conventional storage method this will result in a spatial saving of 70% (according to the consortium). Depending on the required storage capacity, one or more tanks can be constructed. The spatial use depends on the required amount of ballast water that needs to be stored when a complete load of oil is being loaded.

Environmental issues:
The concept doesn’t include a double lining due to the open bottom side of the steel lining. During a calamity the underground structure may function as protection. The ballast water makes contact with the sludge and may be contaminated. When a leak occurs in the outer walls groundwater contamination can be prevented by keeping the ground water level outside the tank higher than the tank level itself. In this case the resulting water pressure is directed inwards and contamination can’t flow outwards.

\(^{18}\) Diaphragm walls have the reputation not to be completely impermeable. The application requires extra attention.
Technical requirements:
The fulfilment of the technical requirements is presented in Table 95.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score: 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td></td>
</tr>
</tbody>
</table>

Table 95: Fulfilment technical requirements concept U-A

The concept has already been applied in Brazil by Shell for fuel storage (see Figure 137).

Figure 137: Application of concept U-A in Brazil by Shell

In order to prevent mixing from gasoline and water, which reduces the quality of the product, an intermediate membrane was applied. The integrity of the membrane needed much inspection and maintenance effort, which finally resulted in the termination of the application. From the product quality point of view this is not considered to be an issue for this study as crude oil originally contains water.
Concept U-B:
The Weger has developed the concept. It gives an alternative for the storage of large amounts of crude oil in tanks with the storage capacity of 400,000m$^3$. The underground tank storage capacity is 300,000m$^3$. The resulting 100,000m$^3$ is stored on top, above the ground level (see Figure 138).

![Figure 138: Concept U-B underground oil storage by The Weger](image)

Properties:
The concept properties are presented in Table 96.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 96: Properties concept U-B

Structural design:
A ring of diaphragm walls forms the underground cylindrical structure. Within the cylindrical structure the crude oil is stored in a fluid tight synthetic membrane. Above the ground a traditional tank is placed. The filling and emptying of the reservoir happens according to the exchange principle between water and oil. The reservoir can’t be set dry as the water stabilizes the vertical and horizontal forces. A submerged/floating membrane will separate the oil and water from each other. The membrane needs to have a density higher than oil and lower than water (850 kg/m$^3$ < \( \rho < 1000 \) kg/m$^3$).

Operation:
Filling and emptying of the reservoir is possible due to the exchange principle between oil and water. In this concept the ballast water will not be contaminated with oil and can possibly be discharged.

---

\(^{19}\) Diaphragm walls have the reputation not to be completely impermeable. The application requires extra attention.
**Inspection and maintenance:**
Tank inspection and maintenance is feasible by divers when the tank is empty, which is when the tank is filled with ballast water. During the inspection the sludge can be removed from the submerged/floating membrane. The strength and durability of the synthetic membrane and the design of the submerged floating membrane needs extra attention.

**Fire safety:**
The fire safety of the aboveground tank is comparable with the conventional tank.

**Spatial profits:**
Per tank a surface of 200x200 m$^2$ is needed. In comparison with the conventional storage method this will result in a spatial saving of 75% (according to the consortium). The spatial use does not depend on the amount of ballast water due to the fact that the water is not contaminated.

**Environmental issues:**
The storage in principle is double walled. In case of a calamity the content of the aboveground storage will be contained within the bund area surrounding the tank. The ballast water can be drained away and is not or little contaminated with oil. When a leak occurs in the outer walls groundwater contamination can be prevented by keeping the ground water level outside the tank higher than the tank level itself. In this case the resulting water pressure is directed inwards and contamination can’t flow outwards. There will be emission to the atmosphere true the aboveground conventional tank.

**Technical requirements:**
The fulfilment of the technical requirements is presented in Table 97.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score: 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td></td>
</tr>
</tbody>
</table>

Table 97: Fulfilment technical requirements concept U-B
Concept U-C:
The concept (see Figure 139) is formed by a concrete reservoir with a membrane.

![Figure 139: Concept U-C reservoir with a membrane](image)

**Properties:**
The concept properties are presented in Table 98.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 98: Properties concept U-C

**Structural design:**
The circular underground structure consists of diaphragm walls or a caisson. The membrane with folding conductors serves as an oil water separation system. The reservoir is covered with a floating roof. The reservoir can’t be set dry as the water stabilizes the vertical and horizontal forces.

**Operation:**
Filling and emptying of the reservoir is based on the exchange principle between oil and water. In this concept the ballast water will not be contaminated with oil and can possibly be discharged.

**Inspection and maintenance:**
Reservoir inspection and maintenance is feasible by divers. The sludge drops down between the membrane and the construction walls due to the movement of the membrane. The sludge is difficult to remove and the membrane is subjected to folding. So the strength and durability of the membrane needs extra attention.

**Fire safety:**
There is no vapour space.

**Spatial profits:**
The spatial profit is big. The water in this system doesn’t make contact with the oil. So there is no spatial use needed for contaminated water.

---

20 Diaphragm walls have the reputation not to be completely impermeable. The application requires extra attention.
Environmental issues:
The emission to the soil and the ground water is hindered by a single protection. When a leak occurs in the outer walls groundwater contamination can be prevented by keeping the ground water level outside the tank higher than the tank level itself. In this case the resulting water pressure is directed inwards and contamination can’t flow outwards. Emission to the atmosphere is comparable with the conventional tank.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 99.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>0</td>
<td>++</td>
</tr>
</tbody>
</table>

Table 99: Fulfilment technical requirements concept U-C

Concept U-D:
The concept is formed by a reservoir with a submerged oil mattress (see Figure 140).

Figure 140: Concept U-D submerged oil mattress

Properties:
The concept properties are presented in Table 100.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 100: Properties concept U-D

Structural design:
Oil will be stored in a mattress that consists of a membrane. The membrane is situated at the bottom of the reservoir. A ground forcing structure is not necessary. The membrane functions as a separation system between oil and water. The reservoir is covered with a floating roof in order to cover incidental releases. Chains will compensate the up forcing force of the oil.
Operation:
Filling and emptying of the reservoir is based on the exchange principle between oil and water.

Inspection and maintenance:
Reservoir inspection and maintenance is feasible by divers. The sludge will sink to the bottom and accumulates in the mattress, which makes it hard to remove. The strength and durability of the membrane needs extra attention.

Fire safety:
There is no vapour space.

Spatial profits:
The spatial profit depends on the dimensions of the mattress.

Environmental issues:
The emission to the soil and the ground water is hindered by a single membrane protection. There is no emission to the atmosphere.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 101.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score: 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Table 101: Fulfilment technical requirements concept U-D
Concept U-E:
The concept is formed by a reservoir with a floating roof and a floating membrane (see Figure 141).

![Diagram of Concept U-E](image)

**Figure 141: Concept U-E floating roof and floating structure**

**Properties:**
The concept properties are presented in Table 102.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 102: Properties concept U-E

**Structural design:**
The reservoir consists of an underground concrete smooth structure. The floating structure separates the oil from the water. The structure needs to have a density higher than oil and lower than water (850 kg/m$^3$ < $\rho$ < 1000 kg/m$^3$). The reservoir is covered with a floating roof. The bottom side of the reservoir is closed. The reservoir can’t be set dry as the water stabilizes the vertical and horizontal forces.

**Operation:**
Filling and emptying of the reservoir is based on the exchange principle between oil and water.

**Inspection and maintenance:**
Reservoir inspection and maintenance is feasible by divers. The floating structure can be emerged to the surface. The sludge will accumulate on top of the floating structure.

**Fire safety:**
There is no vapour space.

**Spatial profits:**
The spatial profit is big. The water does not come into contact with the oil. So there is no spatial use from contaminated water storage.
Environmental issues:
A single concrete layer forms the separation between the oil and the groundwater. When a leak occurs in the outer walls, groundwater contamination can be prevented by keeping the groundwater level outside the tank higher than the tank level itself. In this case, the resulting water pressure is directed inwards and contamination can’t flow outwards. The amount of emission to the atmosphere is comparable with the conventional tanks. The floating structure prevents contamination of the water.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 103.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
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<td>++</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 103: Fulfilment technical requirements concept U-E

Concept U-G:
This concept is formed by a drilled reservoir (see Figure 142).

Figure 142: Concept U-G drilled reservoir

Properties:
The concept properties are presented in Table 104.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 104: Properties concept U-G

Structural design:
The reservoir consists of a drilled tunnel fabricated of concrete below the ground surface. The shafts are dry and give excess to the tunnel and create space for pipe work.
Operation:
Filling and emptying of the reservoir is based on the exchange principle between oil and water. The sludge will sink to the bottom and is difficult to remove.

Inspection and maintenance:
The reservoir needs to be emptied before it can be inspected visually. Another possibility is inspection by divers when the reservoir is filled with water.

Fire safety:
There is no vapour space.

Spatial profits:
The spatial profit will be big. The aboveground area can be used for example for container storage.

Environmental issues:
The drilled tunnel will be stable and can be pumped dry. The groundwater pressure surrounding the reservoir will be higher than the pressure inside the reservoir. So during a leakage the oil will not flow outwards into the surrounding soil. There is no emission to the atmosphere.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 105.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score: 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 105: Fulfilment technical requirements concept U-G
Concept U-I:
Concept U-I consists of prefabricated caissons (see Figure 143).

![Concept U-I](image)

Figure 143: Concept U-I caisson

Properties:
The concept properties are presented in Table 106.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 106: Properties concept U-I

Structural design:
The reservoir consists of concrete caissons, which are divided into smaller units. Caissons give preference to diaphragm walls due to the possible permeability of diaphragm walls. The filling and emptying of the reservoir happens according to the exchange principle between water and oil. The reservoir can’t be set dry as the water stabilizes the vertical and horizontal forces.

Operation:
The filling and emptying of the units is based on the oil and water exchange principle. The ballast water needs to be treated depending on the amount contamination.

Inspection and maintenance:
Divers can carry out inspection and maintenance when the reservoir is filled with water. Another possibility could occur when one unit has been set dry.

Fire safety:
There are no fire safety issues to be expected due to the absent of emission and vapour space.

Spatial profits:
The spatial profits will be big. The caisson can be part of the quay construction. The aboveground space may be used for different purposes.

Environmental issues:
There is no emission to the atmosphere. The walls form a single leak protection.
Technical requirements:
The fulfilment of the technical requirements is presented in Table 107:

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 107: Fulfilment technical requirements concept U-I

Concept U-J:
The concept has the appearance of a reservoir in a reservoir (see Figure 144)

![Concept U-J reservoir in reservoir](image)

Figure 144: Concept U-J reservoir in reservoir

Properties:
The concept properties are presented in Table 108:

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 108: Properties concept U-J

Structural design:
The design consists of a large water basin constructed with diaphragm walls. The basin is divided into several smaller units. The storage takes place in double walled synthetic bags. The reservoir can't be set dry as the water stabilizes the vertical and horizontal forces.

---

21 Diaphragm walls have the reputation not to be completely impermeable. The application requires extra attention.
Operation:
The synthetic bags can be filled and emptied with oil. The outer bag will be put under pressure so the inner bag, containing oil, can be emptied. The sludge accumulates at the bottom and can’t be removed. Another possibility is to remove the bag in total, just as with the bag changing in a pedal bin. There is no contact between oil and water so the water does not require treatment and can safely be discharged.

Inspection and maintenance:
Inspection and maintenance is difficult to carry out. The strength and durability of the bags needs extra attention.

Fire safety:
There are no fire safety issues to be expected due to the absent of emission and vapour space.

Spatial profits:
The spatial profits depend on the dimensions of the bags.

Environmental issues:
There are no environmental issues to be expected due to the triple safety system: inner bag, outer bag and the higher water table outside the basin with respect to the water table inside. The groundwater pressure surrounding the reservoir will be higher than the pressure inside the reservoir. So during a leakage the oil will not flow outwards into the surrounding soil.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 109:

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>++</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 109: Fulfilment technical requirements concept U-J
Concept U-K:
The concept (see Figure 145) is the further elaborated version of concept U-A (see Figure 136).

![Figure 145: Concept U-K underground oil storage](image)

Properties:
The concept properties are presented in Table 110:

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>0</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 110: Properties concept U-K

Structural design:
The steel tank or “reversed glass” will be placed inside the reservoir. The underground structure consists of diaphragm walls\(^{22}\) or sheet piles. A concrete floor closes the bottom side of the reservoir. The reservoir can’t be set dry as the water stabilizes the vertical and horizontal forces.

Operation:
The filling and emptying of the “reversed glass” is based on the oil and water exchange principle. The sludge will accumulate at the bottom of the reservoir. The water from the exchange system will be stored internal or external. Depending on an open or closed system the water needs to be treated.

Inspection and maintenance:
The steel tank or “reversed glass” can be lifted. The sludge can be removed from the bottom.

Fire safety:
There are no fire safety issues to be expected due to the absent of emission and vapour space.

---

\(^{22}\) Diaphragm walls have the reputation not to be completely impermeable. The application requires extra attention.
Spatial profits:
The spatial profits will be large. The storage of the ballast water possibly requires space.

Environmental issues:
The oil will be separated from the groundwater by the steel tank and the underground concrete reservoir. The ballast water comes into contact with the oil or sludge. When a leak occurs in the outer walls groundwater contamination can be prevented by keeping the ground water level outside the tank higher than the tank level itself. In this case the resulting water pressure is directed inwards and contamination can’t flow outwards.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 111:

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

Table 111: Fulfilment technical requirements concept U-K

Concept U-O:
The concept is formed by oil storage in rock formations and is limited for countries with rock formations. The concept is already applied in some places in the world (see Figure 146).

Figure 146: Concept U-O storage in rock formations

Properties:
The concept properties are presented in Table 112:

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 112: Properties concept U-O
Structural design:
The oil is stored in artificial caves in rock formations. The oil is stored on top of a water layer, which is kept constant.

Operations:
In order to reduce the amount of sludge formation the oil is pumped in on one side and pumped out on the other side.

Inspection and maintenance:
The reservoir can be set dry and is accessible through the shaft.

Fire safety:
The reservoir contains a vapour space above the oil level. This space is ventilated and during pumping filled with inert gas to reduce evaporation. The shaft is closed with a concrete block, which can take up an explosion.

Spatial profits:
The spatial profits are big en the aboveground surface may be used as well.

Environmental issues:
The water layer and the rock form a dual protection against leakage. The water pressure surrounding the reservoir needs to be higher then the pressure inside the reservoir. So during a leakage the oil will not flow outwards into the surrounding rock formations.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 113:

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>0</td>
<td>++</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 113: Fulfilment technical requirements concept U-O
Concept U-P [42]:
The concept consists of oil storage in salt caverns (see Figure 147).

1. Product in/out
2. Brine in/out
3. Product
4. Brine

Figure 147: Concept U-P salt caverns

Properties:
The concept properties are presented in Table 114:

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 114: Properties concept U-P

Structural design:
Salt caverns are man-made features constructed within thick beds of salt in the subsurface. Drilling through the overlying strata down into the salt formation to the calculated cavern location, and washing the cavern to the appropriate size results in reservoirs. The wall of the completed cavern is insolvable (according to the information source) in hydrocarbons and therefore prevents leakages.

Operation:
The filling and emptying of the reservoir is based on the oil and brine (fluid containing salt) exchange principle.

Inspection and maintenance:
The state of the salt cavern needs to be monitored by for example sound waves. Sludge will sink to the bottom and is difficult to remove.
Fire safety:
There is no vapour space and no emission

Spatial profits:
The spatial profits are big and the aboveground surface may be used as well.

Environmental issue:
The brine may be contaminated with oil. The sludge is difficult to remove and will possibly stay at the bottom.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 115:

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>++</td>
<td>++</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 115: Fulfilment technical requirements concept U-P
P.4 Floating

Concept F-A [24]:
The first thoughts resulted in a floating structure like the Shirishima Floating Oil Storage Base in Japan and the Kamigoto Floating Oil Storage Base, Nagasaki Prefecture in Japan. These concepts are also known as Very Large Floating Structure (VLFS) (see Figure 148 and Figure 149). The structure is protected from seismic shocks since the sea dissipates the energy.

![Figure 148: Concept F-A Shirishima floating oil storage base concept in Japan [24]](image)

![Figure 149: Concept F-A Kamigoto floating oil storage base concept, Nagasaki Prefecture in Japan [24]](image)

VLFS’s can be classified into the pontoon-type and the semi-submersible type. In open sea, where the wave heights are relatively large, it is necessary to use the semi-submersible type to minimize the effects of waves. VLFS’s of the semi-submersible type are used for oil or gas exploration in sea and other purposes. They are fixed in place by column tubes, piles, or other bracing systems.
Properties:
The concept properties are presented in Table 116:

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 116: Properties concept F-A

Structural design:
The Shirishima project, for example, required 60 hectare mooring basin for eight storage barges, a 14 hectare ground operation yard including a power plant, fire extinguishing pumps, fire extinguishing foam tanks, inert gas generator, crude oil gas treatment facilities, instrument control room, oil drainage treatment facility and an industrial water generator. Also a sea berth connected by an 840-meter long pipe trestle assembly was constructed and four breakwaters, 2,350 meters in length, surrounding the barge-mooring basin. The construction is fast to construct (components may be made at shipyards and then be transported to and assembled at the site), thus, the sea space can be quickly exploited. The VLFS’s can easily be transported or expanded (see Figure 150). To reduce the impact of waves on pontoon-type VLFS breakwaters are usually constructed nearby. Also special anti-motion devices, anchoring or mooring systems can be used to stabilize the behaviour.

Figure 150: Concept F-A Shirishima floating oil storage transportation [24]

Each barge has a 700,000 m$^3$ capacity, has a rectangular shape is 397 meters in length, 82 meters wide and 25.4 meters in depth. The barge consists of seven tanks each with a 100,000 m$^3$ capacity, 28 water ballast tanks, a pump room, a motor room, a switchboard room, a control room etc. The barges do not have propulsion. The oil storage barge has a double hull structure where in seawater in the double hull serves to prevent oil leakage from the barge. Each oil storage barge is enclosed in a primary oil dike made of steel floats designed to localize oil diffusion in the basin should any oil leakage occur. The interior of the VLFS is divided into many buoyancy air chambers; hence, even if water leaks into one or two chambers, the neighbouring chambers will provide sufficient buoyancy for the complete structure.
Operation:
The storage capacity may be in the order of 560,000 m$^3$ as is the case in the Shirishima project.

Inspection and maintenance:
The lifetime of floating structures of the proposed concepts is approximately 100 years (at least 50 years), so the structure can be used for a very long time (including maintenance if any is needed).

Fire safety:
The barges contain; pressure relieving devices, remotely controlled on deck foam fire extinguishing systems, in tank foam injectors, water spray systems for prevention of fire propagation. And an inert gas can be injected into the oil tank as well.

Figure 151: Concept F-A Shirishima floating oil storage base in Japan [24]

Spatial profits:
If are of water is provided the spatial profits are large.

Environmental issues:
The structure is environmentally friendly, as it does not damage the marine ecological system, or silt up deep harbours or disrupt the ocean/sea currents. The oil storage barge has a double hull structure where in seawater in the double hull serves to prevent oil leakage from the barge. Each oil storage barge is enclosed in a primary oil dike made of steel floats designed to localize oil diffusion in the basin should any oil leakage occur. The surrounding breakwaters function as a secondary oil dike. Emissions will be treated in the crude oil gas treatment facility.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 117:

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score: 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td></td>
</tr>
</tbody>
</table>

Table 117: Fulfilment technical requirements concept F-A
Concept F-B:
The concept consists of double walled floating tanks (see Figure 152).

Properties:
The concept properties are presented in Table 118.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 118: Properties concept F-B

Structural design:
The design is based on the principle from concept U-A, “a reverse glass”. A floating barrel surrounds the “reversed glass” in a water basin. The construction material can be steel or concrete provided that the tanks float.

Operation:
The filling and emptying of the tank develops on the exchange principle between oil and water inside “the reversed glass”. Sludge will be collected inside the floating barrel. Water from the exchange process possibly needs to be treated external or can be stored in a closed system.

Inspection and maintenance:
Both tanks can be set dry in a dock. The floating barrel can be submerged and separated from the “reversed glass” in order to remove the sludge.

Fire safety:
The tanks do not contain vapour space and emission.
**Spatial profits:**
The spatial profits will be big.

**Environmental issues:**
There are no environmental issues to be expected because the oil is protected by dual tank containment. The concept does not contain emission to the atmosphere.

**Technical requirements:**
The fulfilment of the technical requirements is presented in Table 119.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 119: Fulfilment technical requirements concept F-B
P.5 Submerged

Concept S-A [32]:
An already existing concept for submerged storage is the Khazzan (Arabic word that translates into “keeping place of treasurers”) storage concept, which is located in the Arabian Gulf (see Figure 153).

Figure 153: Concept S-A Khazzan storage [32]

Khazzan Dubai No. 1, the first in a sequence of three, is a 500,000-barrel (79,500 m$^3$) underwater oil storage structure built for the Dubai Petroleum Company in 1969 by CB&I offshore structures. The structure is submerged in the Arabian Gulf 60 miles from Dubai.

Properties:
The concept properties are presented in Table 120.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 120: Properties concept S-A

Structural design:
The steel storage tanks were constructed on shore in a graving dock, which was flooded after which the tanks were towed to the location floating on a trapped bubble of air. At the location the tanks were submerged and anchored to the sea floor. Anodes protect the steel structure from corrosion.

Operation:
The tanks operate on the principle that oil and water do not mix. As crude oil flows in at the top, water flows out at the bottom. The pumping equipment is positioned on top of the structure.

Inspection and maintenance:
The structure needs frequent inspection, done by divers, of the anodes to reduce/overcome corrosion of the structure.
Fire safety:
There is possibly no vapour space and emission.

Spatial profits:
The spatial profits are large.

Environmental issues:
Sludge will accumulate at the bottom of the structure and may possibly lead leak into the sea.

Technical requirements:
The fulfilment of the technical requirements is presented in Table 121.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score: 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>-</td>
<td>+</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td></td>
</tr>
</tbody>
</table>

Table 121: Fulfilment technical requirements concept S-A

Concept S-B [44, 47]:
Another existing concept for submerged storage has been realised in the Norwegian part of the North Sea at the location of the Ekofisk oil field. A Gravity Based Structure (GBS) forms the storage tank (see Figure 154).

Figure 154: Concept S-B Ekofisk storage tank [62]

Properties:
The concept properties are presented in Table 122.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 122: Properties concept S-B
Technical requirements:
The fulfilment of the technical requirements is presented in Table 123.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>0</td>
<td>++</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 123: Fulfilment technical requirements concept S-B

Concept S-C:
This concept has been generated and consists of submerged spherical tanks (see Figure 155). The concept is based on the sunken tunnel principle.

![Concept S-C submerged spherical tanks](image)

Properties:
The concept properties are presented in Table 124.

<table>
<thead>
<tr>
<th>Concept properties</th>
<th>Non-corrosive materials</th>
<th>Rigid structure</th>
<th>Simple structure with fewer appendages</th>
<th>Integrated sludge removal system</th>
<th>Closed reservoir continuously filled</th>
<th>Multiple space utilisation</th>
<th>Other location then aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 124: Properties concept S-C

Structural design:
The tank consists of concrete and is spherical to effectively deal with the water pressure. Due to the fact that the tank is continuously filled the weight of the structure can be lighter, which results in a reduction of the dimensions.

Operation:
Filling and emptying of the reservoir is based on the exchange principle between oil and water. The sludge will accumulate at the bottom and can be pumped away during the filling of the tank with oil. The water will get contaminated with sludge and needs to be treated or stored.
**Inspection and maintenance:**
Divers can do inspection and maintenance work.

**Fire safety:**
There is no vapour space and emission.

**Spatial profits:**
The spatial profits are large.

**Environmental issues:**
There is no emission. The water pressure is directed inwards so during a leakage the product will not flow out.

**Technical requirements:**
The fulfilment of the technical requirements is presented in Table 125.

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Less sensitive for degradation</th>
<th>Less failure modes</th>
<th>Integrated sludge removal system</th>
<th>No emission</th>
<th>Intensification of space utilisation</th>
<th>Total score: 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>10</td>
</tr>
</tbody>
</table>

*Table 125: Fulfilment technical requirements concept S-C*
Appendix Q. Concept assessment

Q.1 General

The assessment process is based on two analyses:
• First a multi criteria analysis was performed to indicate the fulfilment of the technical requirements to discern potential concepts.
• Secondly these potential concepts were analysed with a more detailed multi criteria analysis.

Q.2 Multi criteria analysis

First analysis:
The overall results from the first analysis, as presented in Appendix P.1, are again presented in Table 126-Table 129. The potential concepts per classification are indicated in green.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 126: Fulfilment results technical requirements underground concept

<table>
<thead>
<tr>
<th>Concepts</th>
<th>A-A</th>
<th>A-B</th>
<th>A-C</th>
<th>A-D</th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>7</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 127: Fulfilment results technical requirements aboveground concepts

<table>
<thead>
<tr>
<th>Concepts</th>
<th>S-A</th>
<th>S-B</th>
<th>S-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 128: Fulfilment results technical requirements submerged concepts

<table>
<thead>
<tr>
<th>Concepts</th>
<th>F-A</th>
<th>F-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 129: Fulfilment results technical requirements floating concepts
**Second analysis:**
The potential concepts marked in green (see Table 130) have been analysed in a more detailed analysis.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Underground</th>
<th>Aboveground</th>
<th>Submerged</th>
<th>Floating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 130: Potential concepts

**Note:**
- Due to the fact that the underground concept U-A and U-K are almost similar and have equal scores it was decided to remove concept U-A from the analyses.
- Despite the low score of The Base Case (traditional tank design incl. expected design enhancements for the future, see Chapter 3.7), the concept was considered in the analysis for reference.

The analysis is based on a multi criteria analysis (see also Chapter 5.3). The following tank specialists with different business interests participated:
- Health, safety and environment consultant.
- Oil movement technologist.
- Tank engineer.
- Storage and integrity engineer.
- Structural tank engineer.

**Results:**
After rating the concepts, an average score and subsequently a normalised score have been calculated. The normalised score was then multiplied with the each parameter weight resulting in the parameter scores presented in Table 131.

Table 131: Final analysis results
Appendix R. Tank ballast water

Filling and emptying [21]
The reservoir will continuously be full with oil and/or water. Filling will elapse by pushing away the water with oil or by discharging the water. Emptying will elapse on the reverse procedure. The pumping speed depends on the capacities of the pumps located at the vessels and onshore. The typical crude oil vessel-unloading rate is approximately 2500 m$^3$/hour per manifold to the loading arm. Common total unloading rate is 5000 m$^3$/hour. According to this, completely filling or emptying a 100,000 m$^3$ tank will approximately take 1 day.

Water discharge [21]
The water may be clean or contaminated. After sampling the clean water can be discharged into the harbour. The contaminated water can have the following destination:

- The water can be cleaned directly, after which it can be discharged into the harbour.
- The water can be pumped to a central reservoir with sufficient capacity, from which it will be cleaned with a smaller flow rate. The storage capacity of the central reservoir and the capacity of the oil storage reservoir depend on the management of the tank farm. Figure 156 indicates the utilisation of storage capacity obtained from several storage sites. The figure shows that on average 50% of the capacity is in use. So possibly the central reservoir does not need to have a 100% storage capacity because the oil reservoirs can function as a buffer as well.

![Utilisation of Storage Capacity - Total](image)

Figure 156: Storage capacity utilisation

- The water can function as ballast water in the oil tanker vessel.
Water supply
The water may be obtained from the harbour.

Environmental aspects (the interaction between crude oil and water) [21]
Water, heavy elements and sediment from the crude oil will accumulate at the bottom of the storage reservoir. The intermediate layer between water and crude oil shall mainly contain salts and solvable hydrocarbons and may strongly vary in contents.

The grade of water contamination depends on:
• The sort of crude oil: the properties may vary strongly.
• The accommodation time of the crude in contact with water.
• The amount of mixing during filling and emptying of the tank.

The interaction between oil and water in the storage tanks can possibly have similarities with oil vessels containing ballast water (present oil vessels contain also separated ballast tanks). The oil concentration in the ballast water is approximately 1600mg/l.

Oil-water separation [21]
When the crude oil floats on top of the water, a boundary layer between the two will develop with a mixture of oil and water. It is expected that the water column below the boundary layer will not be contaminated. The boundary layer can be detected nearby the location where the water is discharged. When during emptying of the tank the boundary layer is reached, the contaminated water can be discharged to a storage reservoir.

Discharging requirements [21]
The discharging requirements with respect to the Port of Rotterdam vary from 2 to 30mg/l depending on the location and the rate of discharge. As the rate of discharge increases the permitted oil concentration decreases. Companies like Shell, who approximately discharges 100.000m³/day, have a license for approximately 2mg/l. Depending on the amount of discharge from the storage site a discharge standard can be established.

Cleaning methods [21]
For the cleaning of contaminated water 3 alternatives can be considered:
• Primary treatment; removes the free oil.
• Secondary treatment; removes the emulsified oil.
• Biological treatment; removes the dissolved oil.

The choice depends mostly on the type of crude oil present in the water. If the magnitude of the drops increases, the cleaning process will be simpler due to the gravitational force. Based on this the oil occurs in the following matters:
• Free oil. The oil is formed by small drops with a diameter of 5 μm, which forms an area floating on the water surface. This layer can be removed with oil skimmers. Temperature, density of water and oil, retention time and the diameter of the oil drops influence the efficiency. The most common gravity separators are CPI’s (corrugated plate separators) and API’s (rotation basins). These systems can remove oil drops with a diameter of ≤ 60 μm respectively 150 μm. The expected quality after the procedure is approximately 30 to 50 mg/l.
• Emulsified oil. The oil drops have a diameter of < 5 µm and form a stable emulsion in the water, which can not me removed by a conventional flotation method like skimmers. Addition of chemicals (resulting in chemical waste material) and aerate can improve the flotation. Possible methods are FFU’s (flocculation/flotation units) or DAF units (diffused air flotation). DAF units contain a high removal percentage with a quality of approximately 5 to 10 mg/l.

• Dissolved oil. This is the fraction of petroleum, which on molecularly level dissolves in water. The oil cannot be removed by normal flotation and biological cleaning is necessary. The applicable systems are called RBC’s (rotating biological contactors) or bio filters or trickling filters.

The methods mentioned under points 2 and 3 require the highest investment costs and are usually applied to comply with strict discharge requirements. The estimated investment costs for the different methods are presented in Table 132.

<table>
<thead>
<tr>
<th>Method</th>
<th>Discharge rate 100,000 m$^3$/day</th>
<th>Discharge rate 10,000 m$^3$/day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Costs (k euro)</td>
<td>Required surface (m$^2$)</td>
</tr>
<tr>
<td>CPI</td>
<td>4.200</td>
<td>600</td>
</tr>
<tr>
<td>FFU</td>
<td>71,000</td>
<td>1000</td>
</tr>
<tr>
<td>RBC</td>
<td>42,000</td>
<td>15,000</td>
</tr>
</tbody>
</table>

Table 132: Investment costs for several contaminated water cleaning methods [21]

From the table it may be concluded that simple cleaning systems for a discharge rate of 100,000 m$^3$/day require significant surface and results in high costs. Moreover the discharge requirements for a discharge rate of 100,000 m$^3$/day will be approximately 2mg/l, which can be achieved when a combination of the different methods will be applied.

In case of a discharge rate of 10,000 m$^3$/day the costs will be lower and the required amount of space is less. Also in this case a combination of the different methods will result in a sufficient low grade of contamination.

---

23 The extra costs for the utilisation of space for a discharge rate of 10,000 m$^3$/day have not been taken into account
Appendix S. Bibliographic Information

This report has been classified as Confidential and is not subject to US Export Control regulations.

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Commercial Register, The Hague 27155370
Appendix T. Report distribution

Outside Shell Global Solutions

<table>
<thead>
<tr>
<th>Company name and address</th>
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