Preface

This report is the **Final report** of my masters graduation thesis, at the Faculty of Civil Engineering and Geosciences; Delft University of Technology. The graduation research is carried out within the Section of Hydraulic Engineering.
The research lies within the framework of the faculty and the efforts in studying the feasibility of a floating port within a certain distance from land. Flexibility in configuration and the ability to fulfil the changing demands are considered to be important characteristics of the new innovation.
The reporting of the thesis is divided into:

Report 1	Literature study
Report 2	Preliminary study
Report 3	Work-plan
Report 4	Interim report
Report 5	Final report

The literature report was aimed to review the state-of-the art of similar technologies and to high lighten the important aspects of the research. The *Preliminary study* helped to confine the brood concept "floating port" and lead to the formulation a more specified problem proposition and objective of the study.
In this final report, many design aspects of the floating terminal are treated. More attention is given to the hydrodynamic research and the operability of the terminal.

My appreciation and thanks go to the supervisors who with no hesitance provided assistance during the course of this thesis.

Colophon

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Summary

Compared to land, rail and air, sea transport has proven to have the largest contribution to the transport of goods and is witnessing a continuous growth over the years. The existing ports are dealing with an increasing flow of goods and the transporting vessels, resulting in capacity problems. New innovations and technology are needed to encounter these problems and in a sustainable way.

One of the solutions proposed is to expand towards the sea. A floating port at a certain distance from land could reduce the pressure on these ports. The objective of this thesis is to examine feasibility of an offshore floating terminal for container transshipment with an annual throughput of 1 million TEU. Different locations around the world with high potential for the container transshipment have been proposed as possible locations for the floating terminal.

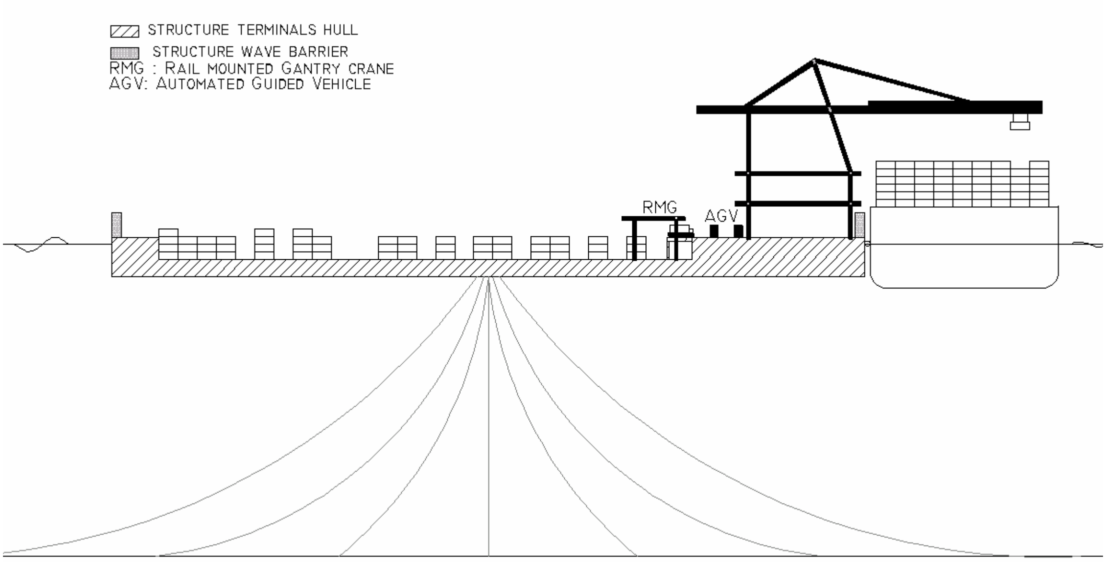
The first step was to design the terminal according to certain requirements. Except for accommodating a number of activities, the terminal has also the function of creating protected waters for the vessels calling on it. Different floating concepts were examined for their eligibility and finally a pontoon-shaped structure was chosen for the form of the hull of the terminal.

The terminal has a rectangular- shaped layout with a length dimension of 1190m and a width of 240m. Berthing facilities and 11 quay cranes are provided at the lee side of the terminal for the loading and unloading operations of the containers. Automated guided vehicles (AGV) and Rail Mounted Gantry (RMG) cranes are to be used for the quay-yard transport of the containers and within the yard respectively.

The heart of the study was to draw conclusions about the operability of the designed system based on the results of a hydrodynamic research. Computer models such as DELFRAC and SEAWAY were used to calculate the responses of both the terminal and vessel, in different sea conditions. According to the criteria for container vessel motions during lifting operations and the response calculations, it was concluded that the (un)loading operations of the containers could proceed safely up to sea conditions with a significant wave height of 3m. This state represents the *Serviceability Limit State* (SLS) for the designed system and is of importance for determining the downtime of the terminal as result of the wind waves generated motions.

Station keeping of the terminal is necessary to prevent the terminal from being drifted away by the sea loads. After considering a number of alternatives to achieve this function, it is finally chosen for a combined DP thrusters- turret mooring system. The system will make it possible for the terminal to maintain a beam-on position to waves during operating conditions. This is to fulfil the function of a breakwater. During high seas, the terminal rotates till a bow-on position (heading) to waves. The last characteristic

of the system will result in reduction of the sea loads on the terminal and thus the mooring system during aggressive sea conditions.
The ULS (maximum survival conditions) is of importance for the structural design of the terminal and also the design of the mooring system. The mooring system was designed for a maximum sea state with H_s = 10.25m and a wind speed of 115 km/hr (Beaufort scale 12). The water depth at the location of the terminal is 100 meters.



The terminal is to be built from a number of elements connected to each at the terminals final location. The elements are to be built partially in a dry dock and the completed afloat. The total construction cost of the terminal including the necessary equipment is estimated for 448 million Euros.

The terminal revenues are represented in the transshipment fee that the shipping liners must pay when using the terminal. According to the results of the financial analyses, a minimum fee of 125 Euro per TEU (for a rate of interest of 6%) must be charged in order to make the terminal cost-effective.

List of contents

1 Introduction

Using sea and water areas to expand land activities has become a trend in many places around the world. This trend attracted the attention of many governments, research centers and institutes as it offered good solutions in many cases to the rapidly changing world and the life style of its inhabitants.
The progress in technology and the increase of knowledge in the last decennia are the drive motor behind the idea of constructing large floating structures that could accommodate different kinds of land activities. Several studies are already carried out to examine the feasibility of allocating these activities on floating structures. Some of the examples are; *The Floating City* (living), *Floating Green Houses* (cultivation) and the *Floating Airport* (transportation).
Studying similar applications could lead to the innovation of more solution alternatives to problems confronting the marine world. This is the aim of this thesis report. The general objective is to examine the feasibility of a "Floating Port". It is considered to be the ***first cycle*** of the design process towards the definitive design and final conclusions about the topic.

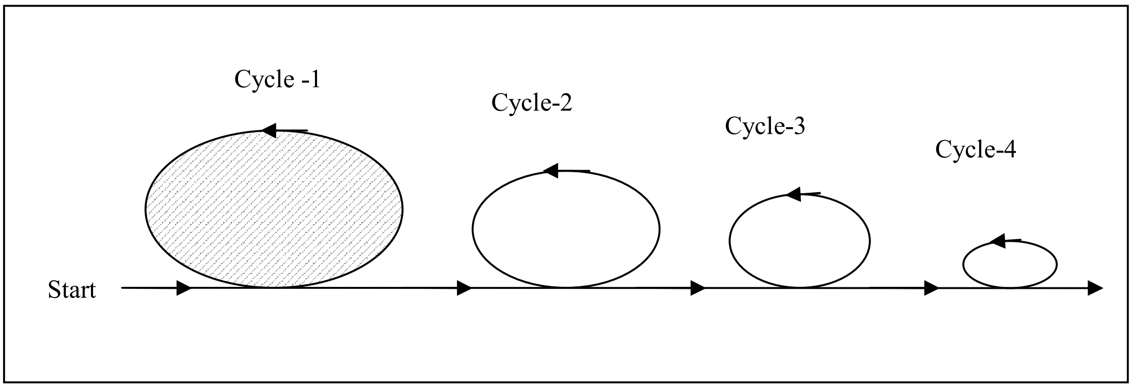
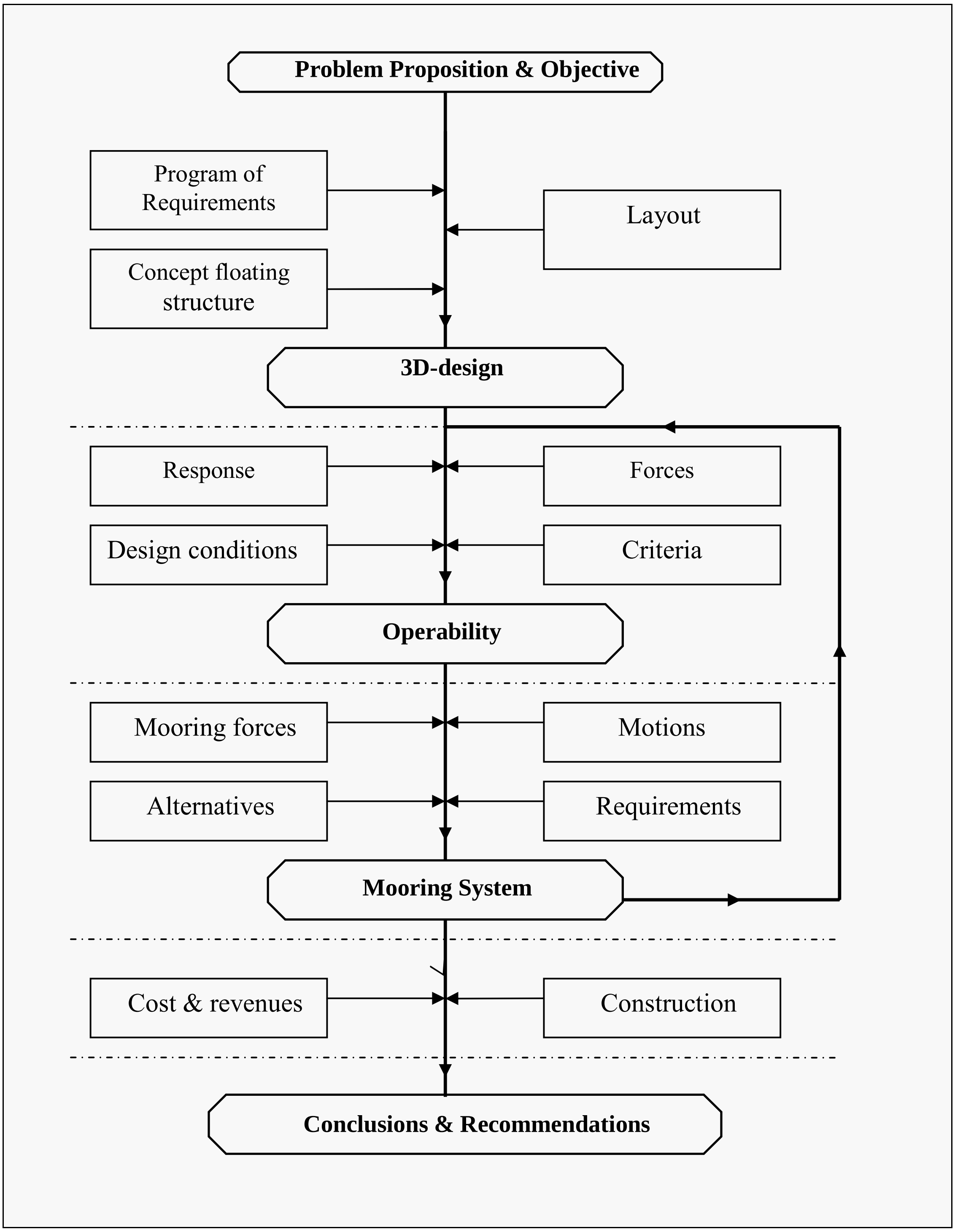


Figure 23-1: The design cycle

The first step of this study was to confine the broad concept, by drawing the borders around a more specific problem proposition and objective. This followed from the information collected in a ***literature Study*** and thereafter analyzed in a ***Preliminary Study*** to this report. Both reports could be seen as appendices at the end of this report.
The objective of this report is studying the feasibility of a floating terminal for container transshipment. There are four main study areas that will be treated. Based on the obtained results, conclusions will be drawn at the end of the report. The main study areas are:

- The design of the terminal.
- Hydrodynamics of the system.
- Station keeping of the terminal.
- Financial aspects.

The figure below illustrates the structure of this report and gives a general idea about what to be expected during the progress of this thesis study.



2 Problem Analysis

2.1 Problem description

It is expected that in the near future more than 80% of the world population will be living in metropolises around the world. The most of the metropolises are situated along the coastal regions. As result of the intensity of activities in these cities, people living there have to contend with problems like scarcity of space, air pollution, and other social problems.

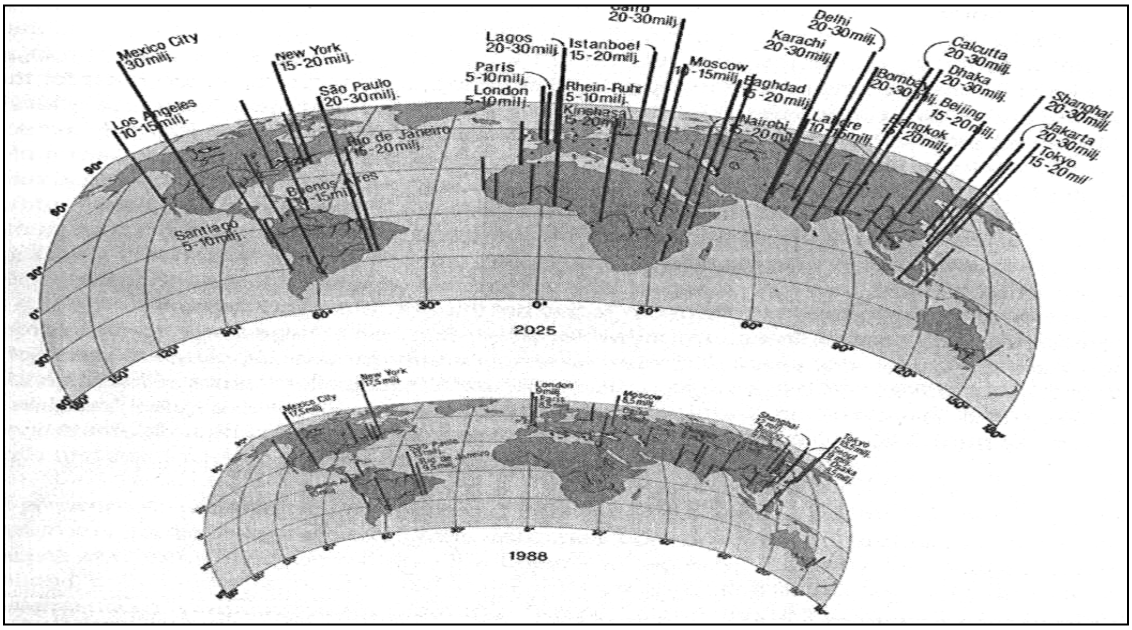


Figure 2.1: world population in 1986 and expected world population in 2025

In the marine world, the increasing cargo traffic makes the expansion of the existing ports imminent, especially the containerized cargo. The advantages of handling commodities per container have stimulated the transfer of many general cargo terminals into container terminals. Forecasts of container traffic predict a yearly growth of 5-10% for the coming years (see Literature [3-4] and [3-5]). This growth demands the establishment of new container terminals.

Moreover, the transporting vessels witnessed a continuous increase in their sizes. The introduction of the mega vessels created the need for deep water terminals that could accommodate these vessels. Other issue related to these large vessels, is that the shipping lines are trying to increase their utilization and shorten the turnaround time by reducing the number of port calls along the shipping route.

The increase in coastal activities and the need for new ports which are able to accommodate mega vessel, makes it necessary to innovate new solutions that cope with developments in the marine world.

2.2 Problem proposition

The container shipping industry has to contend with problems in the near future, related to the capacity of the existing ports, growth in traffic and steady increase in vessels size.

2.3 Objective

Examining the technical and economic feasibility of a commercial, offshore floating terminal for container transshipment.

3 System Definition and Functions

System definition: *the system consists of the floating terminal (FTCT) and the vessels calling on it.*

A variety of processes will take place at the system, so that it can function properly and fulfill the demands of both the users and operators. The processes and the components, which are required to achieve this, are listed below.

Functions	Sub-functions	(Possible) Components
Processing containers	- Loading/unloading. - Intern transport of containers. - Storage of containers. - Maintenance	- Cranes. - Chassis, fork lifts, AGV's, etc. - Storage yard, apron area and traffic lanes. - Maintenance workshop
Processing vessels	- Tugging vessels. - Mooring vessels. - Supplying vessels.	- Tug boats. - Mooring lines/fenders - Supply boats/systems
Processing Personnel	- Transport of personnel to/from fast land. - Hosting personnel	- Boat, helicopter, etc. - Offices, restaurants, hostels, etc.
Supplying terminal	- Electricity and light - Fuel supply - Food and drink water	- Light posts, generator station, electricity station. - Fuel tanks - Storage, supply boat
Protection of terminal and vessels	- Against waves, currents and wind	- Terminal (functioning as breakwater). - Additional facilities: floating breakwater, submerged breakwater, conventional breakwater, etc. - Horizontal fixation of the terminal

Table 3.1: Functions and system components

4 Restrictions

4.1 Boundary conditions

Technical boundary conditions;

- Loads
  - Waves
  - Currents
  - Wind.
  - resonance(long waves)
  - Loading/unloading operations.
  - Passing/berthing ships
- Sustainability.
- Stability (internal and external).

Geographic boundary conditions:
The terminal should not lead to:

- Hindering of existing sea infrastructure (shipping routes) or other activities.
- Interruption of the morphological balances.
- Damage or major disturbance of the marine life.

Operational boundary conditions:

- Loading/unloading operations will only continue if both the ship and terminal motions are within limiting boundaries.
- Berthing of vessels is only permitted is if the motions satisfy the safe mooring conditions.
- Safe operating conditions for the intern transport equipment.

Economic boundary condition:

- The terminal is commercial, and it is required to be economically feasible.

Legal boundary condition:

- Design according to the European norms and standards.

Functional boundary conditions:

- Efficient use of the terminal areas.

4.2 Starting points

Operational starting points:

- Minimum *service time* for the vessels must be guaranteed.
- Maximum *waiting time* for mainline vessels is 5% and for feeders is 10% of the service time.
- 50 operational weeks per year, 7 days per week, and 3 shifts per day and 8 hours per shift.

Technical starting points:

- Life span of the terminal is 30 years.
- Fixation of the terminal in the horizontal direction.

Functional starting points:

- A maximum stacking height of 5 containers in the storage yard with regard to the terminals operation.
- Maximum dwell time for both main line and feeder vessel containers is 7 days.[1]
- Average dwell time for both main line and feeder vessel containers is 3 days.

Geographic starting points:

- The terminal lies within a maximum travel distance of 1 hour from the departure point of the personnel on land (With regard to the transportation of the supplies and personnel to the terminal).

Economic starting points:

- Rate of discount of 8 % (interest + inflation).

4.3 Assumptions

- The ratio FEU/TEU is 1.
- Percentage of empty containers is 10%.
- Percentage of reefers is 5 %.
- Five regional ports will be served by feeder vessels.
- Two mainline shipping routes (inter-continental).[1]

5 Program of requirements

5.1 Throughput & Shipping traffic

The design throughput and the traffic flow as determined in section 5 of the Preliminary Study report.

1. Design throughput:
- A minimum throughput of 1 million TEU per year.

2. Traffic flow:

	Aver. Throughput per call (loaded + unloaded)	Vessel classification	No. calls per annum
Mega vessels	5000 TEU	4th generation – 15000 TEU vessels	100
Feeder vessels	1000 TEU	2nd– 4th generation	500

Table5-1: traffic flow FTCT

5.2 Functional requirements

1. Area requirements
- Storage yard (export, import, reefers and empties).
- Apron area.
- Intern transport infrastructure.

2. Berth facilities
- Quay.
- Mooring system.
- Fender system.

3. Facilities

I) Buildings

Main administration buildings:
- Terminal administration.
- Harbour master office & terminal control.
- Security offices.
- Shipping agents offices.

Others:
- Maintenance workshop, store and office.
- Fire station.
- Electricity & Drink water stations.
- Hostel

II) Utilities

- Fire fighting system.
- Waste disposal system.
- Electricity supply and water supply systems (only terminal).
- Lighting of terminal areas.

4. Equipment

- Loading/unloading equipment.
- Horizontal transport equipment.
- Supply boat, tugboats and other marine equipment.

5.3 Operational and technical requirements

- Motions [PIANC 5-7, Literature study] :

Limiting criteria for container vessels movements under working conditions (peak-peak values, except for sway zero-peak)

Efficiency %	**Surge (m)**	**Sway (m)**	**Heave (m)**	**Yaw (degr.)**	**Pitch (degr.)**	**Roll (degr.)**
100	1.0	0.6	0.8	1	1	3
50	2.0	1.2	1.2	1.5	2	6

Table 5-2: criteria for motion

- Accelerations (limiting criteria with regard to operation of equipment, cargo safety, personal safety and efficiency, [Faltinsen 5-5, Literature Study]

	Merchant ships
Vertical accelerations at forward Perpendicular (RMS-value)	0.275g (L≤100m) 0.05g (L≥300m)
Vertical accelerations at bridge(RMS-value)	0.15g
Lateral accelerations at bridge(RMS-value)	0.12g

Table 5-3: criteria for maximum accelerations

- Limiting H_s for safe tying up of tugboats is 1.5m.
- The floating structure must be statically and dynamically stable.
- The structure must be able to withstand all acting internal and external loads.

5.4 Economic requirements

- Full exploitation of the terminal, aiming to guarantee high revenues.
- A maximum transshipment charge of €100.00 per TEU (this is a total amount including all tariffs, dues and handling costs).
- Possibility for future expansion of the terminal must exist.

5.5 Site location requirements

- The waterdepth in the site location must be sufficient to accommodate the floating terminal, and all kinds of container vessels, without requiring further dredging activities.
- The Environmental conditions in the selected location must not lead to unacceptable downtime of the terminal.
- The chosen location must have economic potential for an FTCT.

6 Berths & Terminal Areas

In this begin phase of the design process, this section will deal with the following operational aspects of the FTCT

6.1 Number of berths
6.2 Quay length
6.3 Surface area

6.1 Number of berths

To satisfy the demand with regard to the maximum waiting time, a minimum number of berths should be available.

6.1.1 Container vessels berths

Approach method

At this phase, the queuing theory will be applied to determine the required number of berths. The queue-delay system is schematized as shown in the figure below:

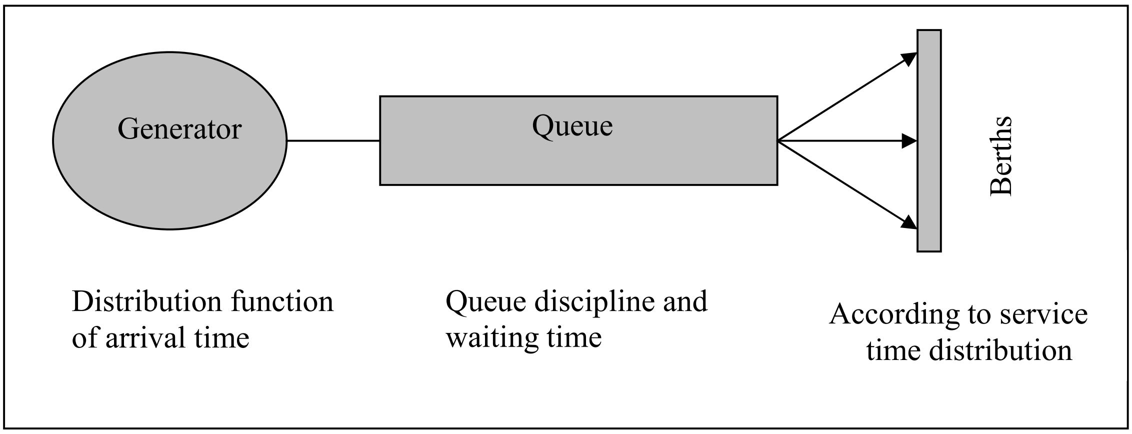


Figure 6.1: queue-delay system FTCT

Input parameters

There are four parameters of that have to be determined in order to obtain the results based on the queuing theory method. These parameters will be defined and determined in this paragraph.

1- Allowable maximum waiting time:

The waiting time of the vessels (as percentage of the service time) depends on the number of berths available and is required to be within the limits as given in the *Program of Requirements.*

Maximum waiting time for mega vessels: less than 5% of the service time.
Maximum waiting time for feeder vessels: less than 10% of the service time.

2- Queuing discipline
The First-in-first-out (FIFO) discipline, is the most suitable in the case of the FTCT because there will be no need to give privilege to vessels of the same type (feeder/mainline). It is chosen for the FIFO queuing discipline.

3- Production per berth
The production per berth depends on the *number of cranes* (portainers) per berth and the *net production* of the crane per hour.

- Crane productivity: Portainers (see figure below), have average productivity in the range between 20-30 moves/hour. Recently designed cranes have larger average productivity. By the calculations of the berth productivity, an average crane production of 30 moves per hour will be assumed in the case of the FTCT.

Figure 6.2: Quay-vessel cranes, Portainers (source: internet)

- Number of cranes: The maximum number of cranes, operating per vessel is limited by the vessel size (length). Furthermore, the berth configuration plays a role when determining the number of cranes designated per berth. Indented berth makes it possible to load/unload vessels from both sides.

By the calculations, this parameter will be set as variable. A number of alternatives will be examined with regard to the number of cranes operating per vessel. The starting points are.

- Marginal berths.
- A maximum of 6 cranes per mega vessel.
- A maximum of 3 cranes per feeder vessel.

4- Distribution functions
The statistical distribution describing the inter arrival and service time of the vessels. Below are three of the most often used distribution functions of the queuing theory.

I. The deterministic distribution function (D): With a constant value and standard deviation.

II. The negative exponential distribution function: Applying the function requires a mean value (λ) of the data. Its standard deviation (σ) is equal to the mean value.

III. The Erlang distribution function: The function requires a mean value (λ) and standard deviation value (σ).A special case is the Erlang-2 distribution function. The Erlang- 2 assumes that the mean value squared is twice the standard deviation squared.

The first two functions are to be considered as extremes of variability. Conservative results of the waiting time are to be expected from both functions. The Erlang 2 distribution function gives less conservative results of the expected the waiting time compared to the first two functions mentioned above.

Results

Using the input parameters determined above, calculations have been carried out using the queuing theory. The average waiting time of the vessels (as percentage of the service time) is calculated for a number of scenarios. In each case, different input is used with regard to the number of portainers per vessel, number of berth and the distribution function. Calculations are made, using Excel spreadsheet [appendices 6 A-D] and the tables of appendix- 6E. The results obtained are shown in the tables below.

Definitions:

XX/YY/n: The Kendall-notation of the system. The first (XX) and the second (YY) notations indicate the type of distribution function used to define the inter arrival time and the service time respectively, while **n** is the number of berth.

u: average berth utilization.

Feeder vessels				$(M/E_2/n)$	$(E_2/E_2/n)$
n	Number of cranes	Average Service time(hr)	utilization	Waiting time (% of service time)	Waiting time (% of service time)
1 berth	2	12.6	0.75	223	145.8
	3	8.9	0.53	84.7	46.3
2 berths	2	12.6	0.38	13	4.9
	3	8.9	0.27	5.9	1.8

Table 6.2: average waiting time feeder vessels

Mega vessels				$(M/E_2/n)$	$(E_2/E_2/n)$
n	Number of cranes	Average Service time(hr)	utilization	Waiting time (%)	Waiting time (%)
1 berth	5	24.2	0.29	30.4	12.3
	6	20.5	0.24	24.3	9.2

2 berths	5	24.2	0.19	1.9	0.3
	6	20.5	0.12	1.4	0.2

Table 6.3: average waiting time mega vessels

Evaluation

The arrival time:

The arrival of the feeder vessels is expected to have a random character. Assuming a negative exponential distribution instead of an Erlang-2 distribution for the inter arrival time seems more logic. In the contrary to the feeder vessels, the mega vessels are expected to have a more scheduled arrival program. An Erlang-2 distribution for the interarrival time is more suitable than the negative exponential distribution

The Service time:

Less conservative results will be obtained when assuming an Erlang-2 distribution function for the service time of the vessels. By large variation from the average value assumed for the service time of the vessels (derived from the average throughput per vessel), the service time will increase and thus the tolerated waiting time (percentage of the service time). For this reason, it is expected that an Erlang-2 distribution function-less conservative- could lead to more practical results and will be applied for the service time of both types of vessels.

The feeder vessels:

A minimum of two berths will be required. The results given in table [6.2] show that when choosing for 2 berths with 5 and 6 portainers each, the expected waiting time is 13% and 5.9% respectively. Although the waiting time to be expected by the berth with 5 portainers exceeds the limit of 10% slightly, however a very small waiting time is expected by the other berth. The later can compensate for the first.

The mega vessels:

. When choosing for 1 berth with 6 containers, the average waiting time is 9.2%. It exceeds the 5% limit. However, when considering the length of the quay and the cranes needed for an extra berth, it is decided to accept a longer waiting time of the vessels.

Conclusions:

1. Feeders ($M/E_2/n$):
   - 2 berths: one berth has 3 portainers while the other berth has only 2 portainers.

2. Mega vessels ($E_2/E_2/n$):
   - 1 berth with 6 portainers.
   - The average waiting time is 9.2% and berth utilization is 24%.

6.1.2 Tug and personnel transfer boats

Tugboats

Tugboats are required to provide assistance during the berthing and deberthing operation to counteract wind and current forces. Vessels with deadweight over 15,000 DWT will not be allowed to (de)berth under own power to avoid the lack of course control during the (de)berthing maneuver.

The number of tugboats follows from minimum bollard pull (T_B) capacity to be delivered by the boats.

$$T_B = (\Delta/100{,}000)\cdot 60 + 40 \text{ (ton)}, \qquad [6.1]$$

Where,

Δ = ship displacement (ton)

Offshore tugboats which can operate in exposed waters have horsepower which varies between 2000-5000 HP. Their sizes are in the range of 25-40m length. The power (in HP) is approximately **8 to 10** times the actual tugboat bollard pull in kN.

Number of tugboats

By the calculations of the number of tugboats at the FTCT, a jumbo vessel will be accounted for. Enough number of boats must be always available that can provide sufficient bollard pull to assist vessels up to jumbo ship (LOA = 299m, B= 42.8m and D=13.5m).

In case of larger vessels that require more than three tugboats to be processed, there are 2 possible solutions. The first is to hire extra tugboats from the nearby port. The other solution is that it may become possible to activate the bow thrusters of these vessels to provide the needed extra bollard pull capacity.

Economically, it is much favorable when the number of tugboats is minimized. Not only the purchase and operating costs are reduced, but also the needed quay length.

Assuming C_B jumbo ship is 0.75 and 1.025 ton/m^3 water, then is

$$\Delta \text{ (Jumbo ship)} = 299\times 42.8\times 13.5\times 0.75 = 133\times 10^3 \text{ ton}$$

The needed bollard pull, follows from equation [6.1], and is equal to

$$T_{B;jumbo} = (133{,}000/100{,}000)\cdot 60 + 40 = \quad 120 \text{ ton (1200 kN)}$$

Total power required = 1200 (kN) * 10 = 12000 Hp

This bollard pull capacity could be provided by a minimum of **three** tugboats. Therefore, the number of tugboats at the FTCT is 3 with a total power of 12000 HP

Personnel transfer boat

In the offshore world, helicopters are more often used for quick and safe transfer of personnel. However, supply vessels are still used to transfer personnel for short distances.

Figure 6.3: Offshore personnel vessel (32m 7,3m; source Internet)*

The personnel of the FTCT are to be transferred from and to land using personnel transfer vessel instead of helicopters, for the following reasons:

1. Relatively shorter distance to the land, in comparison to offshore units for which helicopters are used.
2. It is expected that the number of personnel in the FTCT much higher compared to offshore units.
3. In addition to personnel, supplies could also be transferred using the same boat.

The personnel boat is to make frequent trips bringing the personnel onshore. A two way trip at the beginning of each shift results in is minimum number of 3 trips per day. Considering the short distance to land (5 km) and the fact that large vessels call only twice per week at the FTCT, it is expected that the personnel boat will have a low utilization. This could bring another advantage of personnel vessels with respect to helicopters when,

4. A personnel transfer boat could be fitted in a way that it could also serve as a tugboat. Therefore, instead of 3 tugboats, 2 tugboats each with an engine power of 5000 HP plus the personnel boat could provide the required bollard pull capacity. Not only will the costs be reduced, but also the required quay length.

6.2 Quay length

The required quay length (L_q) follows from the number of berths and the average vessel size ($L_{s;\,av}$) in the case of multiple berths and the maximum vessel length ($L_{s;\,max}$) in the case of single berth.

For multiple (n) berths, and

$$Lq = 1.1 \cdot n \cdot (L_{q;av} + 15) + 15 \qquad [6.2]$$

And for a single berth,

$$Lq = L_{s;\max} + 15 \times 2 \qquad [6.3]$$

The 15m is the berthing gap- with regard to the mooring lines- between the container vessels and the ends. For the tugboats, these marginal distances will be reduced to 5m.
In the case of feeder vessels, the *average vessel size* follows from the container vessels classification. According to the *program of requirements*, the feeder vessels are classified from the 2nd to the 4th generation.

Container vessel	Length(m)	Breadth(m)	Draft(m)
2nd generation	225-240	30	10.5
4th generation	290-310	32.3	12.5

Table 6.3: feeder vessels

The average length feeder vessels = (225+300)/2 = 262.5m
In the case of mega vessels it will be accounted for a Post Panamax vessel with a maximum length of 400m.

Needed quay length:

Feeder vessels berth	=	$1.1 \times 2 \times (262.5 + 15) + 15$	= 626 m
Mega vessels berth	=	$400 + 2\times15$	= 430 m
Tugboats + personnel boat	=	$40\times2 + 32 + (4\times5)$	= 132 m
Total			**= 1188 m**

6.3 Terminal Areas

This section deals with the calculations of the surface area of the different terminal elements. As stated in the program of requirements, the FTCT consists of:

1. Container storage yards
2. Buildings and facilities
3. Apron area
4. Intern transport infrastructure

6.3.1 The Container storage yard

The container storage yard is divided into:

Export yard: for the storage of mega vessels containers (425,000 TEU/year)
Import yard: for the storage of feeder vessels containers (425,000 TEU/year)
Reefers yard: storage of reefer container (50,000 TEU/year)
Empties yard: storage of empty containers (100,000 TEU/year)

The surface area of the container yards could be calculated with equation 6.4.

$$O = \frac{C_i \cdot \bar{t}_d \cdot F}{r \cdot 365 \cdot m_i} \qquad [6.4]$$

Where,

O area required in m²
C_i number of TEU's per year.

$\bar{t}_d$	Average dwell time in days
F	required area per TEU inclusive op equipment traveling lanes (m^2/TEU)
r	average stacking height/nominal stacking height (0.6- 0.9)
m_i	acceptable average occupancy rate of the yard (0.6-0.7)

The average dwell time ($\bar{t}_d$)
The average dwell time has already been determined in the preliminary study. For import, export and reefers, it is 3 days. The empties have an average dwell time of 7 days.
Area per TEU
The factor F depends on the nominal stacking height of the containers and the handling equipment [see table below]. A number of options will be considered for the nominal stacking height ranging between 2 and 5 containers.
Stacking height
The factor r (0.6 < r < 0.9) is due to the fact that the sequence in which the containers leave the stack is unknown. r is in the range between 0.6 and 0.9. It is chosen for a relatively higher r by higher stacking height.

Results:
Import yard + export yard (each equal to the half of the total area given below):

Stacking height	C_i	t_d	F	r	m_i	O(m2)	O(ha)
2	850,000	3	18	0.9	0.7	199,609	19.96
3	850,000	3	12	0.8	0.7	149,706	14.97
4	**850,000**	**3**	**9**	**0.7**	**0.7**	**128,320**	**12.83**
5	850,000	3	7	0.6	0.7	116,438	11.64

Reefers:

Stacking height	C_i	t_d	F	r	m_i	O(m2)	O(ha)
2	**50,000**	**3**	**18**	**0.9**	**0.7**	**11,742**	**1.17**
3	50,000	3	12	0.8	0.7	8806	0.88

Empties:

Stacking height	C_i	t_d	F	r	m_i	O(m2)	O(ha)
	100,000	7	18	0.9	0.7	54,795	5.48
3	100,000	7	12	0.8	0.7	41,096	4.11
4	100,000	7	9	0.7	0.7	35,225	3.52
5	**100,000**	**7**	**7**	**0.6**	**0.7**	**31,963**	**3.20**

Table 6.4: Surface area of the storage yard

Evaluation

- The results obtained, show that the area of the floating structure, will be mainly affected by the stacking height of the containers. Delays and longer cycle time are expected for the horizontal transport equipment when the stacking height becomes more than 5 containers. This leads also to a longer service time of the vessels. For this reason it is chosen for a nominal stacking height of 4 containers on both the import and export yards of the FTCT, which is the case for the most of the container terminals around the world. This will guarantee a quality of service not less than those of land terminals.

- The reefers have to be connected to the electricity net to provide the cooling energy. A nominal stacking height of 2 containers is adopted within the reefers yard.
- The empties have long dwell time and need large surface area. For this reason, the area is calculated assuming the maximum nominal stacking of 5 containers.

6.3.2 Buildings and Facilities

The main building of the terminal consists of the administration offices, housing and personnel facilities. The building is to comprise three levels, with the control tower at the highest level. The technical service buildings and other facilities will be made up of one level.

Approach method
Each facility is assumed to be consisting of a number of units with a certain surface area per unit. Ground area factors are applied to calculate the total gross area.
The electric energy needed for operating the FTCT will be large and is expected to be very expensive if it is to be generated onboard the terminal. As the terminal will be within a maximum distance of 5 kilometers, it will be economically more favorable to obtain electricity from the land, transmitted to the terminal by underwater cables. Onboard the terminal only an electricity substation is to be built.
The table below shows the different components of the terminals buildings and facilities and the required surface area.

	No. of Units	Length (m)	Breadth (m)	No. of levels	Ground area factor	surface area (m^2)
1. Administration Building:						
Port administration offices	20	4	4	3	2	213
Harbour master offices	5	5	5	3	2	83
Control tower	1	10	10	3	2	67
Communication center	1	10	10	3	2	67
Other offices	5	4	4	3	2	53
Hostel(rooms)	10	4	4	3	2	107
Restaurant	1	20	20	3	2	267
supply storage	1	5	5	3	2	17
				subtotal		**873**
2. Technical Service Building						
Maintenance workshop,	1	50	50	1	1.2	3000
Offices	3	5	5	1	1.2	90
Yard	1	100	100	1	1.2	12000
				subtotal		**15090**

3. Other Facilities						
Water station	1	15	15	1	2	450
Electricity substation	1	15	15	1	2	450
Fire station.	1	10	10	1	2	200
Waste dump (disposal).	1	10	10	1	2	200
Helicopter platform	1	5	5	1	2	50
Fuel tanks	1	10	10	1	1.2	120
				subtotal		**1470**
Total surface area (in ha)						**1.74**

Table 6.7: surface area terminal facilities

Evaluation

- The required ground area for the above mentioned facilities on deck of the FTCT is found be 1.74 ha. During the preliminary design of conventional (fast) container terminals, an area of 5 -6 hectare is usually reserved for facilities such as buildings, technical facilities, container scan, customs, gates, and others related to road and rail transport. The absence of many of these facilities on deck of the FTCT resulted in a lower surface area requirement compared to the conventional terminals.
- The calculations of the required area of the buildings and facilities are based on rough assumptions. However, when comparing that area (1.74 ha) to for example the area of the storage yard (17.2 ha), it is obvious that the later is much larger. Therefore, the rough estimation of the area of the terminals *building* and *facilities* could be tolerable, as both represent less than 10% of the total area of the terminal.

6.3.3 The apron area

The apron area extends along the feeder and the mega vessel berths. In the transversal direction the apron area consists of the following:

- 5m wide service lane is between the coping and the front crane rail to provide access for the crew and supplies.
- A distance of 35m between crane legs (rails).
- A 15 m wide traffic lane for the straddle carriers, MTS or AGV's.

The total apron area = $(5m + 25m + 25m) \times (626m + 430m)$ = **5.81 ha**

6.3.4 Intern transport infrastructure

The surface area required for the intern transport corridors depend on the layout of the terminal and the type of system used. In general, it is estimated that area needed is about 10% of the total port area for conventional terminals. This area includes road, rail and intern traffic corridors (lanes). In the case of the FTCT, road and rail infrastructure are absent, that's why a lower percentage is estimated for the intern transport required area. 8% of the total terminal area is to be accounted for the intern transport corridors.

6.3.5 Terminals surface area

Terminal Areas		Area (ha)
1. Container storage yard		17.2
2. Building and facilities		1.74
	Sub-total	18.94
3. Apron area		5.81
4. Intern transport infrastructure (8% of subtotal)		1.52
	Total	**26.27**

Table 6.8: total surface area terminal

Evaluation

- According to the calculations above, the FTCT has a throughput-area ratio of about 38,000 TEU/hectare. This ratio is relatively high compared to the most container terminals. However, higher ratios are to be found in Hong Kong [see Ligteringen 4-4, Literature Study]. Although, the stacking height of the containers is not very high however this high ratio is to be accredited for the short average dwell time of the containers.

6.4 Conclusions Berths & terminal areas

- The terminal will have 3 berths for the container vessels. One berth is designated for the mega vessels while the other two vessels accommodate the feeder vessels.
- The required length of the quay is 1190m. This includes the length of the quay necessary for berthing the personnel boat and the tugboats which is 132m.
- There is total number of 11 portainers (quay cranes).
- A personnel boat will transfer personnel and supplies to and from the terminal. 3 trips per day (2-way) at the beginning and end of each shift.
- 2 tugboats, each with an engine power of 5000 HP. The personnel boat is to be fitted in a way that it can provide an extra bollard pull capacity of up to 20 ton (2000 HP) during berthing of large vessels whenever it is needed.
- The total required surface area of the terminal is 26.27 hectares. 65% of the total area will be occupied by the containers storage yards

7 Concepts floating structure

In the previous section, it is calculated that the required surface area of the terminal is 26.27 hectares. This section comprises a number of alternative concepts for the floating structure of the terminal. For each concept, the dynamic characteristics and behavior is generally analyzed. At the end of the section, a concept will be selected based on the results of a Multi Criteria Analysis.

7.1 Alternatives floating concepts

ALT – I ***Semi-submerged structure***

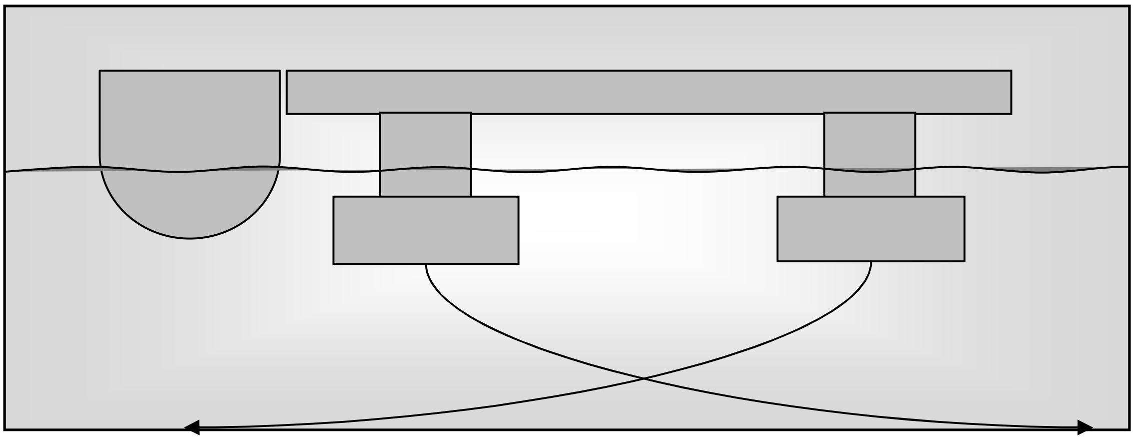


Figure 7.1: Semi-submersible

Concept definition :
The submerged (horizontal) pontoons provide the buoyancy for the whole structure. The deck of the structure is supported by columns connected to the submerged pontoons. The columns should be high enough to ensure that platform deck is elevated above wave crests.
Station keeping could be achieved by:

- chain/wire mooring systems,
- dynamic positioning systems(computer controlled thrusters which respond to motions and accelerations), or
- combination of both systems

Hydrodynamic characteristics
Semi-submersibles are characterized with large volume under water and a small water plane area. From a hydrodynamic point of view this could be favorable. For example, in the case of the heave motion, the small water plane area results in a relatively low natural frequency compared to the locally generated wind waves. This prevents the aggravation of the motion as result of resonance.

Hydrodynamic behavior

- First order wave forces: Relatively small motions are to be expected as result of first order wave forces, i.e. in the wave frequency region.
- Low-frequency wave drift forces: Surge, sway and yaw motions of the floating system will depend on the stiffness of the mooring lines
- mean wave drift forces: as result of the small water plane area, much less wave mean drift forces will be exerted on the floating structure compared to a barge shaped structure. This is of significance for the mooring system of the structure. The same applies for current loads on the structure.

ALT –II A ***Pontoon-shaped structure***

Figure 7-2: pontoon- shaped structure

Concept definition:

The floating structure has a rectangular hull with a certain draft. Wave energy will be partially transmitted under the structure, providing protection for the vessels moored at the berths side.

Station keeping could be achieved by:

- chain/wire mooring systems,
- dynamic positioning systems (computer controlled thrusters which respond to motions and accelerations), or
- combination of both systems

Hydrodynamic characteristics

The pontoon shaped structure is characterized with a large surface plane area resulting on relatively large heave, roll and pitch spring terms and thus large natural frequencies for these modes of motion. Surge, sway and yaw responses depend on the characteristics of the mooring system.

Hydrodynamic behavior

The floating structure of the FTCT with its large dimensions, is expected to perform very small oscillatory motions in short waves. However, the structure will tempt to disperse energy by generating waves (only heave, pitch and roll) which in its turn could cause motions of the moored vessel. Despite the large dimensions, the terminal could behave like a sea gull in long waves, depending on the wave period and its dimensions.

ALT - II B ***Mega Floats***

Another variant of the pontoon alternative mentioned above is the mega floats system. A mega float is a pontoon shaped floating structure supported by mooring dolphins

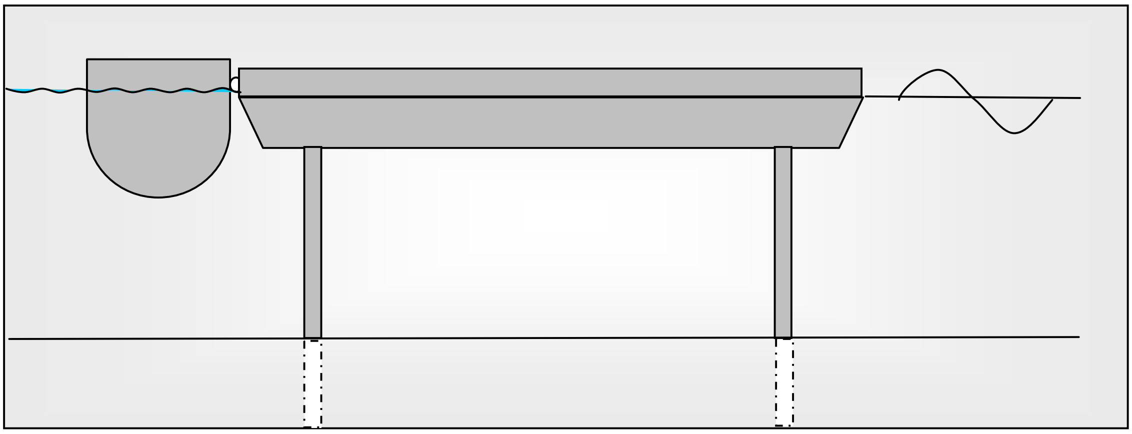


Figure7.3: Mega float

Hydrodynamic behavior:

The dolphins allow the vertical motions of the structure while the horizontal motions are restricted to certain extend depending on the stiffness of the dolphins and the fenders. The structure will heave freely and is comparable to the pontoon structure for that mode of motion.

Hydrodynamic loads:

Although the motions are limited, however the loads on the dolphins and also the floats are gigantic because of the relatively large stiffness of the mooring dolphins compared to for example a chain/wire mooring system as it is the case in ALT-II A.

ALT -III ***Tension leg floating structure***

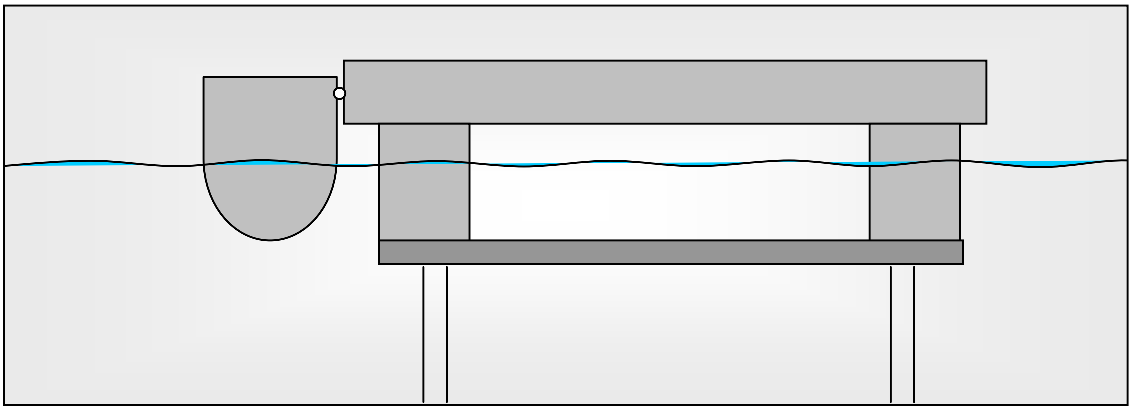


Figure 7-4: Tension leg Platform

Concept definition:
A TLP consists of a semi-submersible type hull with 4 or more vertical piercing columns Supporting the deck and standing on underwater columns.
Station keeping:
Tethers extend vertically downwards to foundation templates which are piled on the sea bed.
Hydrodynamic characteristics:
The tether should be designed in a way that the natural periods in heave, pitch and roll below the wave periods and those in surge, sway and yaw well above the wave period range
Hydrodynamic behavior
The pretensioned tethers of the system while allowing surge, sway and yaw limit the other modes of motion, i.e. heave, roll and pitch.

7.2 Selection floating concept

Selection criteria:

1- *Hydrodynamic behavior of the terminal*: based on a general analysis of the dynamic response of each concept mentioned above. Large water plane area results in high energy transfer to the structure and thus large motions (and the mooring forces) especially in the vicinity of the natural period of the structure.

Ranking	Floating concept	argumentation
1	Tension leg	- Restricted vertical motions - Small water plane area.
2	Semi- submersible	- small water plane area
3	Mega- float	- restricted horizontal motions - large water plane area
4	pontoon	- all modes of motion are not restricted - large water plane area

2- *Vessel protection*: the level in which the terminal's structure is functioning as a breakwater and protecting the moored vessels from open sea loads. It is at the end, both the motions of the vessel and the terminal that determine the level of workability of the FTCT. Some alternatives do not offer this protection and other facilities such as a breakwater will be necessary.

Ranking	Floating concept	argumentation
1	Mega- float	- functioning as horizontally fixed floating breakwater
2	Pontoon	- functioning as floating breakwater - system will respond to low frequency wave forces, resulting in horizontal motions
3	Tension leg	- offering no protection against waves for the vessels
4	Semi- submersible	- offering no protection against the waves and terminal is performing unrestricted motions

3- *Stability & deck load capacity:* stability is the ability of the structure to maintain its floating condition during severe sea conditions. With deck load capacity is meant the ability of the structure to accommodate as much activities as possible without sinking.

Ranking	Floating concept	argumentation
1	Mega- float	- supported by dolphins (restricted motions, thus more stable) - high deck loads capacity
2	pontoons	- high deck load capacity
3	Tension leg	- vertical fixation providing more stability - non- substantial deck load capacity
4	Semi- submersible	- non- substantial deck load capacity - exposed to all modes of motion

4- *Flexibility:* water depth restriction.

Ranking	Floating concept	argumentation
1	Semi- submersible	- most suitable for deepwater - low mooring line forces
2	Pontoon	- suitable for deep water
3	Tension leg	- less suitable for deep water
4	Mega- float	- not suitable for deep water

5- Financial aspects: construction, maintenance and relocation costs.

Ranking	Floating concept	argumentation
1	Pontoon	- simple structure - relatively less expensive
2	Semi- submersible	- long scheduled building times
3	Tension leg structure	- foundation for vertical tethers is required - relatively long building time
4	Mega- float	- costly dolphin structure

<u>Scoring method</u>

Each criterion will be attributed with a total of 10 plusses. The number of plusses per alternative depends on the ranking as shown in the tables above. The first ranking weighs 4 plusses, 2nd ranking 3 plusses, 3rd ranking 2 plusses and the last alternative only 1 plus.

Scores table

	Criterion	Semi-submersible	Pontoon shaped structure	Mega - float	Tension leg structure
1	hydrodynamic behavior	3+	1+	2 +	4 +
2	Vessel protection	1+	3+	4+	2 +
3	Stability	1+	3+	4 +	2 +
4	Flexibility	4+	3+	1+	2+
5	Financial aspects	3+	4+	1+	2+
	Score	**12+**	**14+**	**12+**	**12+**

Table 7.1: scores table

Weighing criteria

The scores table shows that the pontoon shaped structure has the largest score according to the method used. However, different results may emerge when applying weighing factors to the criteria. These weighing factors are to be used to express the significance of each criterion with respect to the others. The order in which the criteria are given below indicates the weight of the criteria, beginning by the ones weighing most heavy.

The workability (ability to load/unload) is considered to be the most important aspect. As already mentioned above, this will be determined by both the motions of the vessel and the terminal. The first is expressed by the 2nd criterion (see above) while the later is the dynamic behavior of the terminal itself (1st criterion). For this reason, these two criteria will be set to weigh heavy in the MCA. The terminals motions are expected to be much less than those of the vessels because of its large size. For this reason, the *vessel protection* (criterion 2) will be set to come at the first place (weighs heavier). Therefore, the ranking order of the criterion is

i. The vessel protection
ii. The hydrodynamic behavior

The financial aspects are of importance to the economic feasibility. The terminal is commercial and is required to be cost-effective. The financial aspect criterion is to have the third ranking order.

iii. Financial aspects

The remaining last two criteria are the *stability* and *flexibility*. The later is regarded to be of less significance as there will be always the possibility of choosing a suitable location according to the design requirements. Therefore, it follows

iv. Stability
v. Flexibility

The weights (to the criteria) will be attributed in the same way as the in the scoring method. The sum of the weights is 10. The weights are 3, 2.5, 2, 1.5, and 1 according to the ranking of the criteria given above.

Score table (including weights)

Criterion		Semi-submersible	Pontoon shaped structure	Mega-float	Tension leg structure
hydrodynamic behavior	2.5	3+	1+	2 +	4 +
Vessel protection	3.0	1+	3+	4+	2 +
Stability	1.5	1+	3+	4 +	2 +
Flexibility	1.0	4+	3+	1+	2+
Financial aspects	2.0	3+	4+	1+	2+
Score (excluding weights)		**12+**	**14+**	**12+**	**12+**
Score (including weights)		**22+**	**27+**	**26+**	**25+**

Table 7.2: scores including weighs

Conclusion
The results of the multi criteria analysis shows that the high score is gained by the concept II- A, *the pontoon shaped structure*. The difference in score is not large, however even without attributing weights to the criteria the same alternative remains the most favorable. Therefore, it will be chosen for a pontoon-shaped floating structure for the FTCT.

8 Layout Alternatives

Introduction

The workability of the floating system is determined by the **relative motions** between the terminal and the vessel. The serviceability limit state (SLS) is defined as environmental conditions within which the (un)load operations could proceed safely. The Ultimate limit state (ULS) is determined by the **loads** on the structure and the mooring system.

Both should be capable to withstand the forces up to a certain limit of the environmental conditions (e.g. $H_{s:ULS}$).

Regarding the terminal-vessel relative motions, different design aspects and their interrelations are given in figure 8-1. The significance of the *terminals layout* to the total behavior of the system appears from the number of interrelations with other aspects. The *layout* has the largest number of outputs (indicated by arrows) on other design aspects, and thus the whole workability of the system.

In this section a number of alternatives for the terminals layout will be presented. Comparison between the different designs and the advantages and disadvantage for each will be discussed.

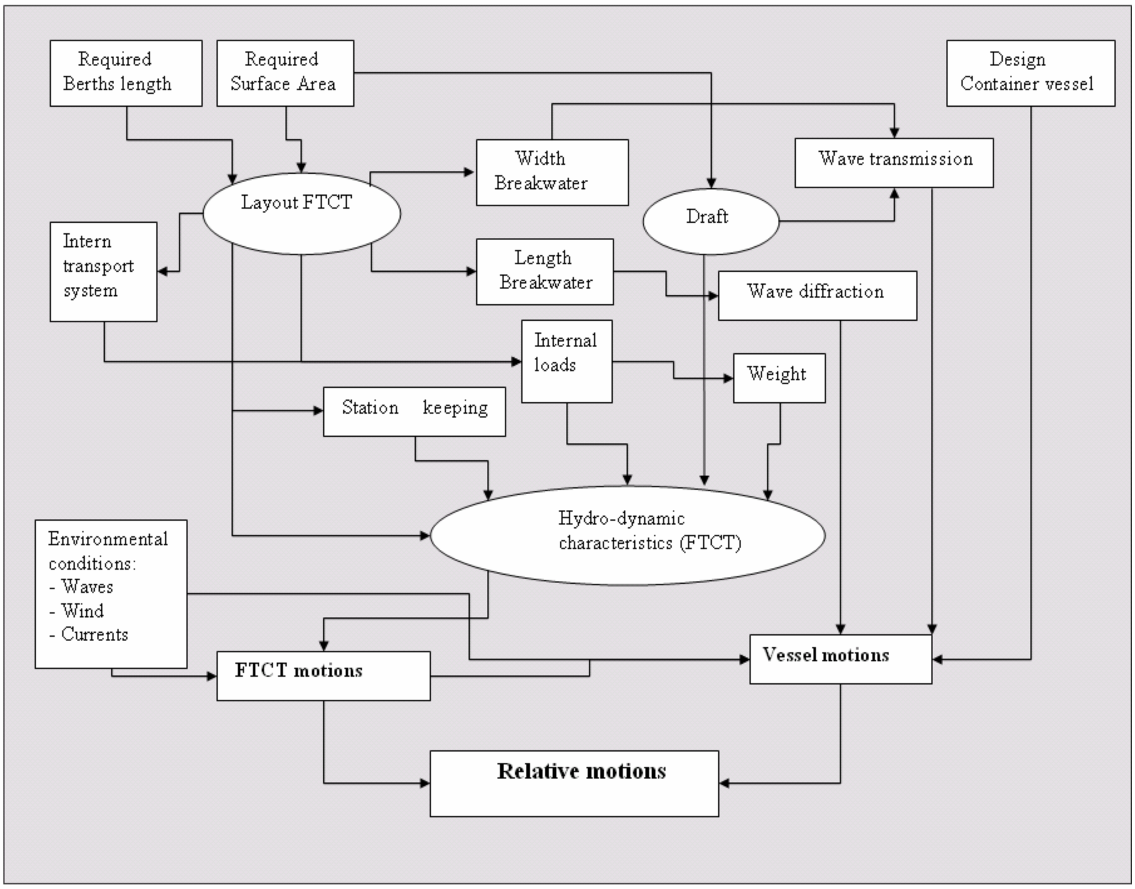


Figure 8.1: design model relative motions terminal-vessel

8.1 Alternative 1 - Marginal berths system

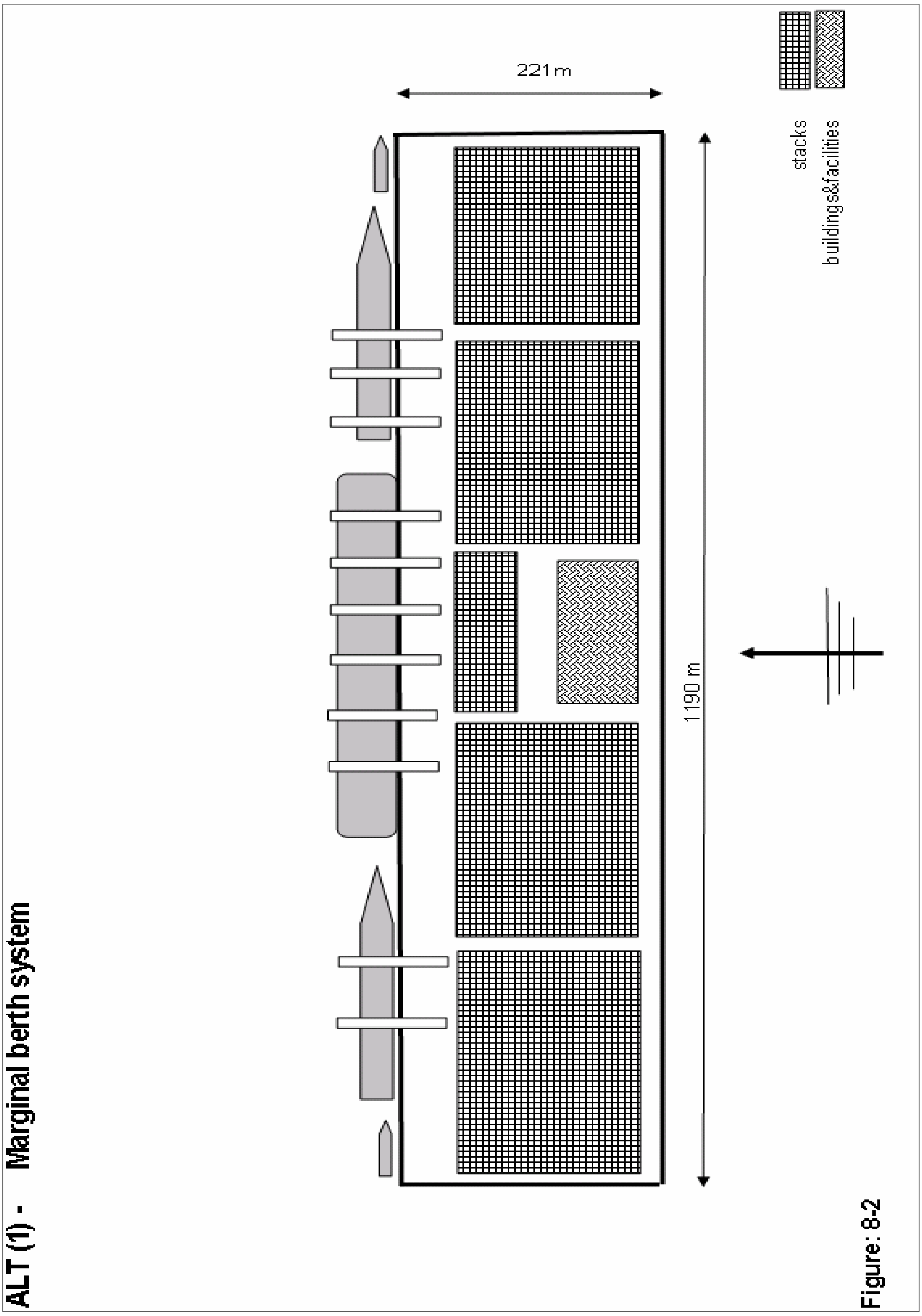
The first alternative of the layout is a rectangular shaped terminal with the vessels moored at marginal berths. The berths are located at the sheltered side of the terminal as shown in figure 8-2. The length of the berths is already determined in section 6 and is equal to 1190m. The minimum width of the rectangular terminal follows from surface area requirement which is 26.27 ha.

Length = 1190m
Width = 221m

This layout represents the simplest form of the terminal and therefore more favorable from a structural point of view. Furthermore, the rectangular shape and the linear berth and the configuration of the stacks will help to create a simple traffic net between the quay and the storage yards. The rectangular shaped stacks are also favorable, with regard to the transportation of the containers within them.

However there are restrictions when applying this form for the FTCT. It would be only suitable in the following cases.

- Waves from one direction:
  In the location of the terminal the waves are mainly (during most of the time) coming from one direction. If the waves are coming from the direction as given in figure 8.2, sheltering is provided at the berths. However if the waves change in direction, for example in the longitudinal direction, the terminal will provide no shelter to the vessels as the waves will pass along the berths side undisturbed resulting in (pitch, heave and surge) motions of the moored vessels
- Waves are coming from different directions. However, the terminal is capable to **weathervane**. With weathervane it is meant that the terminal will obtain a position beam-on to waves (the same as in the figure below), and thus providing a from waves sheltered environment at the berths side.


ALT (1) - Marginal berth system
221m
1190 m
stacks
buildings&facilities
Figure: 8-2

8.2 Alternative 2 - Modified marginal berths system

The layout of this alternative originates from that of traditional barge shape as proposed in the previous alternative. Modifications are made to create more sheltering to the moored vessels in case that the terminal is not able to weathervane (beam-on to waves). Figure 8-3 gives a sketch with of the proposed layout.

Length = 1000m
Width = 420m
Surface area = 27.48ha

Compared to the first alternative, this alternative has the following advantages:

1. Functioning as breakwater:
   - reduced wave transmission as result of the larger structure width
   - Reduction of the wave diffraction around the floating terminal.
   - offering more shelter from waves coming from different directions, for example the longitudinal direction. In many places (within certain distance from land) waves has a spreading in direction of around 120 degrees. In that case, this layout could represent an attractive alternative

2. Dynamic and static behavior:
   - The larger the structure width, the larger the radius of gyration and lever arm of stability. Dynamic roll motions and the static heel are relatively smaller.

Disadvantages in comparison to ALT-1:

1. Operational aspects:
   - The nonlinear quay results in less flexibility along the quay.
   - Complications and safety problems could occur with regard to the horizontal transport of containers onboard the terminal as result of the irregular configuration of the storage stacks.

2. Structural aspects:
   - The nods at the berths side and the irregular form result in a less favorable (internal) load distribution in the structure. Therefore, this alternative is less favorable from a structural point of view.

3. Costs:
   - Relatively higher construction costs.
   - Surface area 1.21 ha larger than ALT-1

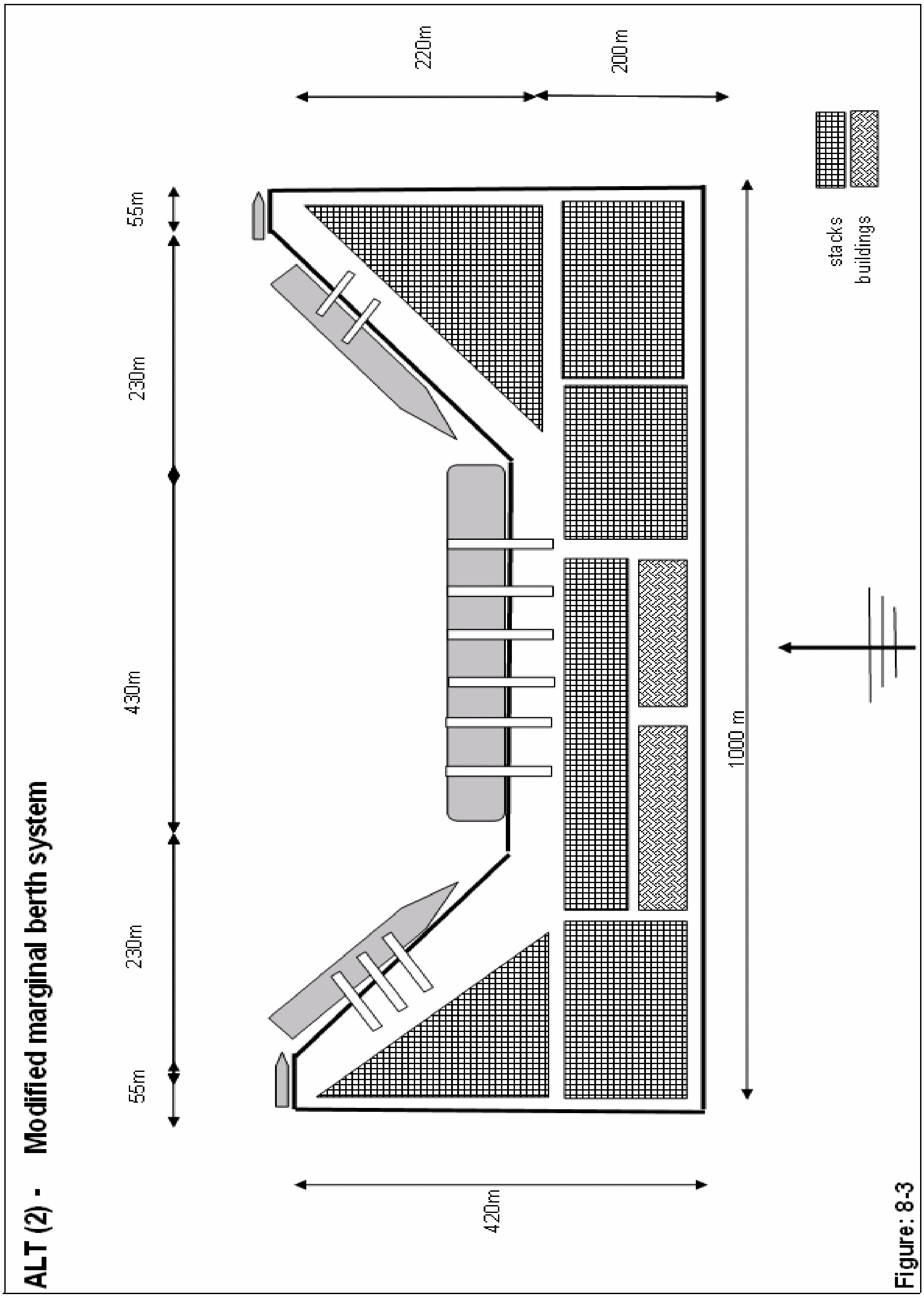

ALT (2) - Modified marginal berth system
55m
230m
430m
230m
55m
220m
200m
420m
1000 m
stacks
buildings

Figure: 8-3

8.3 Alternative 3 – Indented berth system

A sketch of this layout alternative is shown in figure 8-4. It is provided with an indented berth which will make it possible to reduce the service time of the (mega) vessels. Furthermore, the length of the structure is considerably reduced

Length = 760mm
Width = 422m
Surface area = 28.63 ha

Advantages of this alternative:

1. Station keeping:
   - The proposed alternative has smaller length and thus smaller attack area by waves and currents. Consequently, the loads on the mooring system as result of waves and currents are also reduced.

2. Operational aspects:
   - The indented berth will make it possible to deploy more cranes per vessel. This will improve the competitive status of the terminal and reduce the service time of the vessels.

3. Functioning as breakwater:
   - Vessels moored at the indented berth will have the ultimate protection as it is surrounded from 3 sides. Feeder berths are only protected in one direction.

Disadvantages:

1. Costs:
   - Relatively larger surface area.
   - The increased number of cranes brings extra costs

2. Structural aspects
   - Complex structure.

3. Operational aspects:
   - Risk of collision of the vessel with the terminal as the large vessels approach the indented berth. The waters in front of the berth are not protected and the berth basin is narrow which requires high precision.
   - Also the nonlinear quay results in less flexibility along the quay. Cranes cannot be exchanged between the berths.

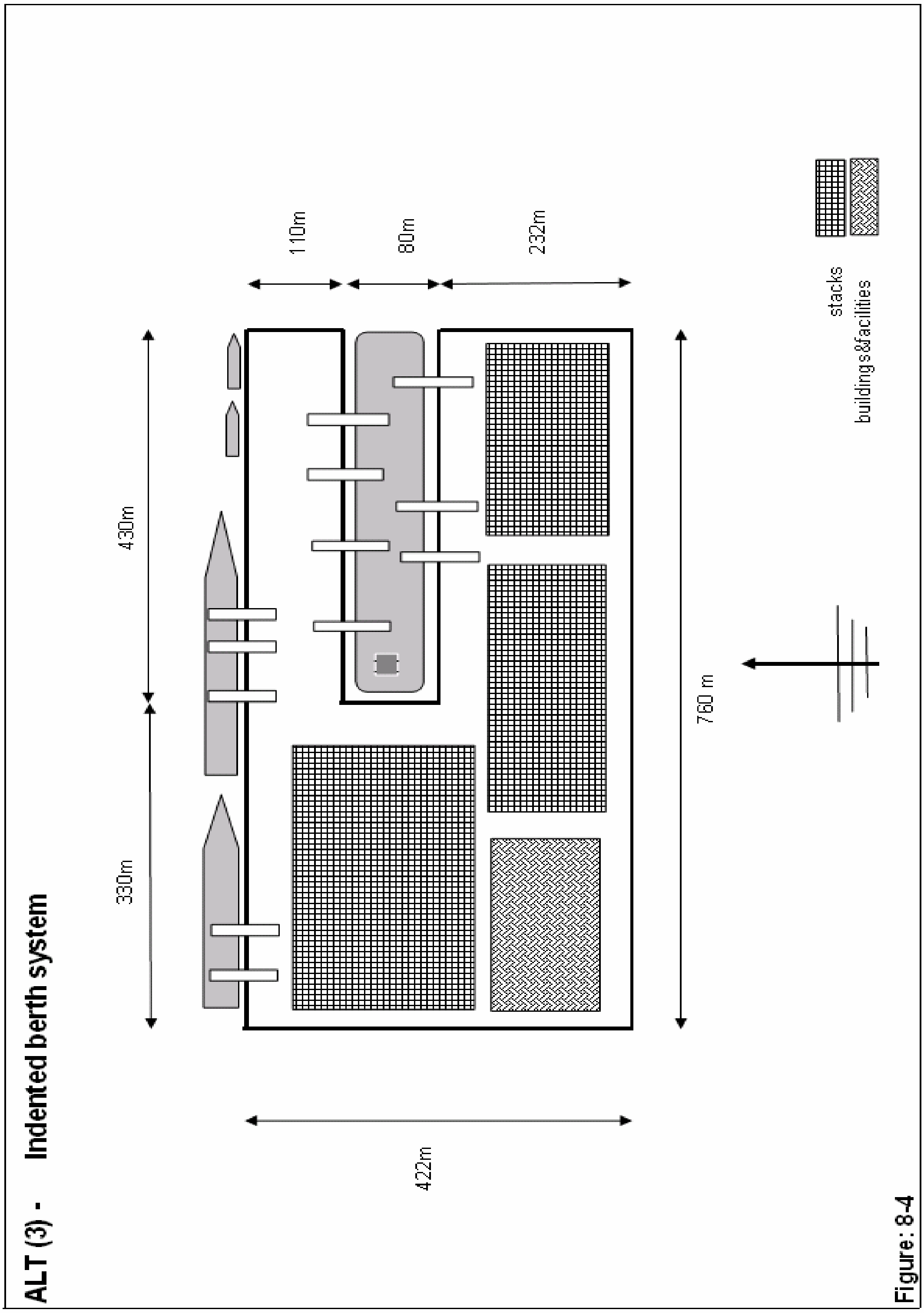

ALT (3) - Indented berth system
110m
80m
232m
430m
330m
760 m
422m
stacks
buildings&facilities

Figure: 8-4

8.4 Alternative 4 – Multiple berths system

The sketch in figure 8.5 shows the primary form of the 4th layout alternative. This main idea behind this layout is provide all-directional protection, i.e. providing sheltered waters for waves coming from every direction. Berths and berthing facilities are to be provided at all sides of the terminal. The idea behind this alternative originates from a square shaped terminal as given in the figure below.

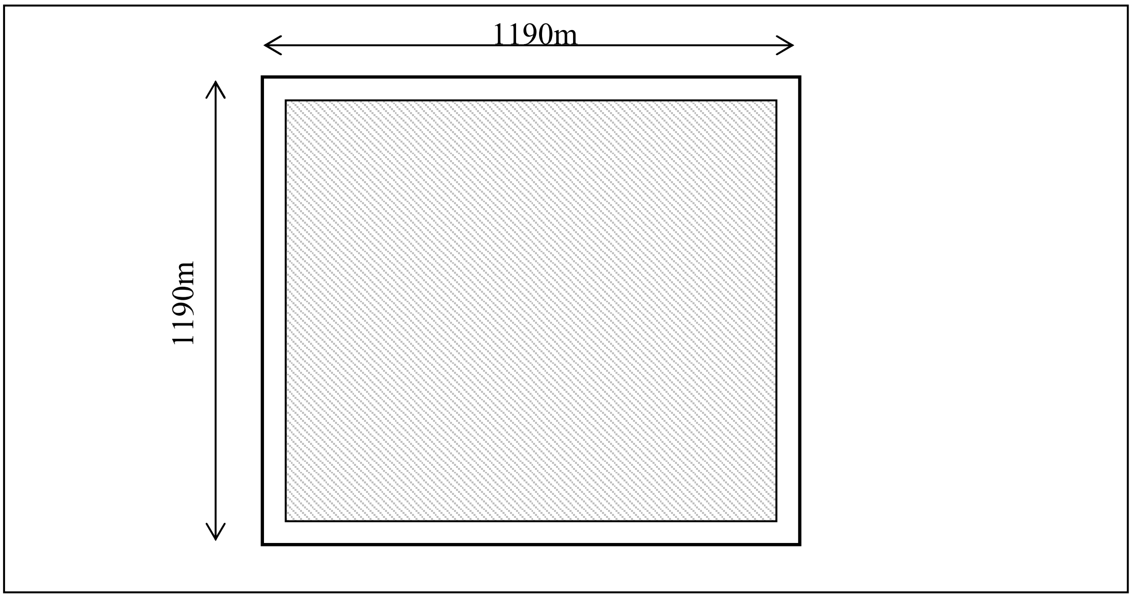


Figure 8.5: basic form alternative(4)

However, the above layout leads to unnecessary large surface area. For this reason modifications are made to create a layout alternative as shown in **figure 8.5**. The area is significantly reduced and the all-directional protection characteristic is preserved

Length = 845m
Width = 845m
Surface area = 35.40ha

Advantages of ALT- 4with respect to the first alternative:

1. Functioning as breakwater:
   - There is always one side at least, which is protected against waves. . For this alternative it will not be necessary that the terminal be able to weathervane.
2. Station keeping:
   - Relatively smaller wave attack area.

Disadvantages:

1. Structural aspects:
   - Complex structure.
2. Costs:

- The needed surface area is 9.13 ha larger than the area of ALT-1.
- The berthing facilities (e.g. cranes) at all side of the terminal will result in high construction and operating costs.

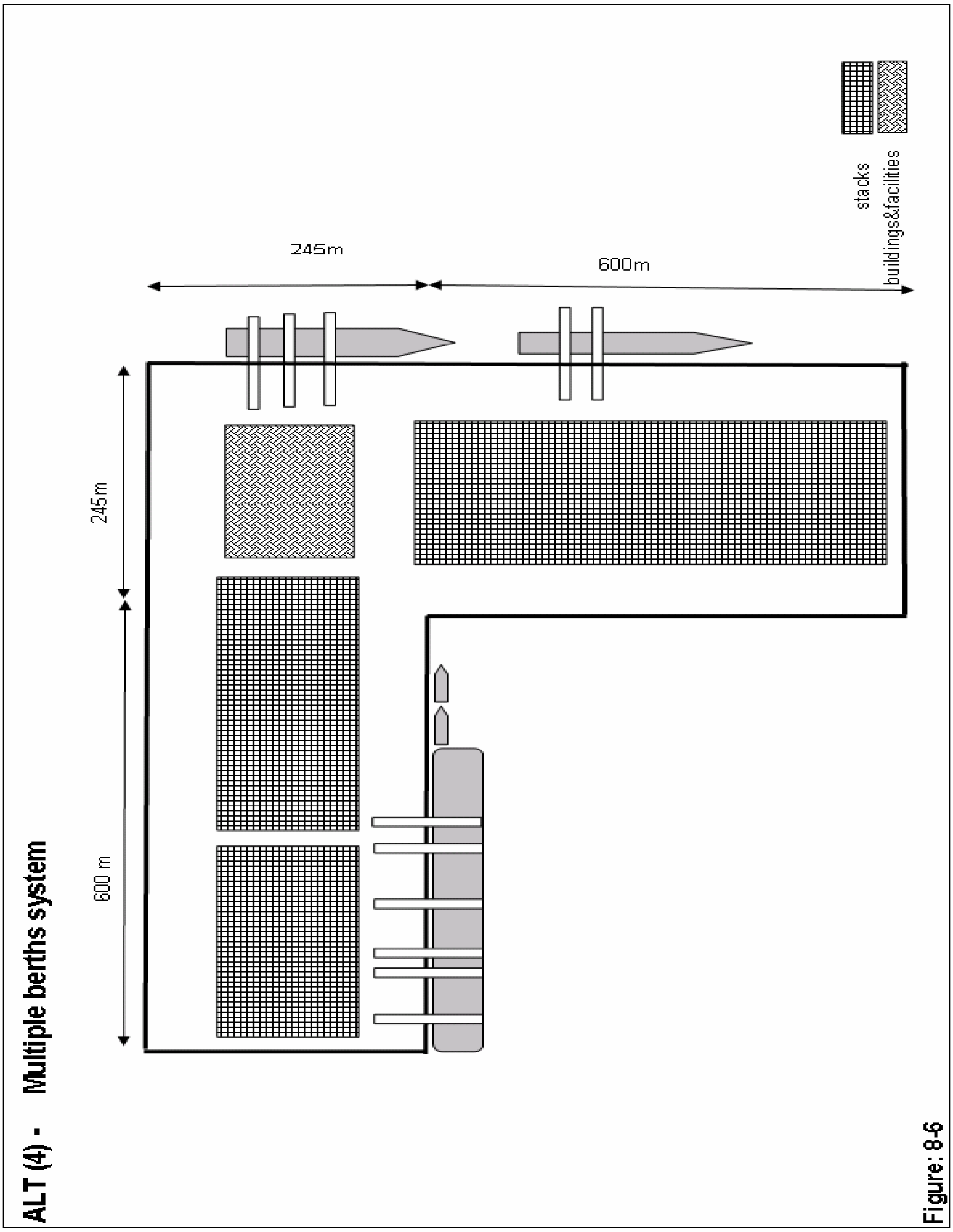


Figure: 8-6

8.5 Selected Alternative

Each of the above mentioned alternatives could be a possible solution for the floating terminal. However, the environmental conditions and the limits for which it could operate (e.g. $H_{s;SLS}$) or survive(e.g. $H_{s;ULS}$) and the wave directions is different from one to the other.
Except for the last alternative, protection is restricted for waves coming from specific directions. In a place where the waves are mainly generated by local winds, the prevailing wind direction will change from time to time. Therefore, in each case a certain downtime is to be expected.
The last alternative provides an all-directional protection, however the structure is economically not attractive. The surface area is 9.31 ha (more than 35% of the total area) larger by the first alternative, the *marginal berth*
The above analysis shows the importance of the ability of the terminal to weathervane in order to provide the required protection against the local wind generated waves with random direction.
For this reason, it is concluded that it would be logical to begin with examining the behavior of the most simple and economically attractive alternative, i.e. the marginal berth system given as ALT-1.
The possibility of the terminal to weathervane and the station keeping system, the operational limiting conditions, the survival limiting conditions and other design aspects will be treated in the following sections of this study.

9 Definitive Layout & Draught Calculations

Introduction

This chapter comprehends further treatment of the rectangular shaped alternative of the FTCT, referred to as alternative [1] in the previous section. This is the first cycle of the design process.

The first step to determine the definitive layout of the terminal is to define the intern transport processes and system on the FTCT. The number of equipment/vehicles will be deterministically calculated. Furthermore, the orientation of the stacks must be compatible with the selected transport systems. Finally other terminal elements will be allocated and the definitive surface area is to be determined.

At that stage, all terminal activities and the used equipment becomes known. Weight and draught calculations could then be carried out. This will be the theme of section 9.4.

9.1 Intern transport

With the intern transport, it is meant the transport of containers within the terminal from the moment they arrive until they are once again unloaded into the vessels.

The transport process of the containers could be divided into three sub-processes.

1- Vessel- quay transport of containers.
2- Quay-yard transport of containers.
3- Transport within the storage yard.

The first process will be carried out by 11 portainer cranes as already determined previously. The equipment used to perform the last two activities could also be classified into two different types

1- equipment suitable only for quay-yard transport, **or** within the storage yard(2nd or 3rd processes respectively)
2- Equipment which could perform **both** tasks, i.e. between the quay and the storage yard quay-yard transport and within the storage yard.

As this is considered to be the first cycle of the design process, the selection of the transport systems will be based on the general characteristics of these systems and a number of basic requirements with regard to the floating terminal. the calculations of the number of equipment required are more considered to be estimations and are necessary for the calculations of the weight of the terminal.

Important requirements with regard of the intern transport system of the FTCT:

1. Minimizing the number of manpower in the terminal. The fact that terminal is offshore and at a distance from land could result in relatively higher labour costs compared to land terminals.
2. The fact that the terminal is made of a floating structure made it necessary to minimize the surface area required. The calculated area of the storage yard is based on an area factor (F) of 9m^2/TEU. This makes that certain type of

equipment ineligible as they require larger space in the container yard. Examples of these equipment are the Forklift trucks, Reach Stackers and Chassis.

3. the terminal must guarantee short delay times of the vessels and the containers as result of the transshipment process. Therefore, the system chosen must always make it possible that the portainers operate at full capacity and does not lead to extra delays

9.1.1 Quay-yard transport of containers (2nd process)

Options for the type of equipment for the transport of containers between the quay and the storage on the FTCT are:

1. Straddle carriers: this types of equipment could perform both processes (2nd and 3rd) mentioned above. However, they are labour intensive and are considered to be complicated.
2. Multi trailer system (MTS): this system could be only used for the transportation of the containers from the quay to the stacks and vise verse. Each unit consists of a number of up to 5 trailers pulled by one tractor. They have de advantage of high throughput capacity and the disadvantage that they are relatively less flexible in operation.
3. Automated Guided Vehicles (AGV's): these vehicles are remotely controlled from a central control station and do not require drivers. Such a system reduces the number of manpower needed considerably. Moreover, they have high throughput capacity. However they can serve only for the transportation of containers to and from the stacks and not within.

Selection:

Considering the first two requirements with regard to the intern transport system mentioned above, the first option (straddle carriers) is less favorable than the MTS and the AGV's.

The remaining two options almost share the same characteristics. They can only serve the 2nd process. However, on high capacity terminals are usually separated to improve the service of the terminal.

From an economic of point of view The AGV's require less manpower, but they are considered to have high investment and maintenance costs. Form an economical point of view, they will be considered to score equally.

From an operational point of view, an MTS is less flexible during operation, while AGV's showed that they can position themselves very quickly and accurately under the hoisting equipment. Therefore, in that aspect the AGV's are more favorable than a MTS.

At this stage, the Automated Guided Vehicle (AGV) is selected as quay-stack transport system of containers.

Figure 9.1: AGV (Automatic Guided Vehicle)

9.1.2 Container transport inside the container yard (3rd process)

Both the facts that it is chosen for AGV's for quay- stacks transport and the area factor is as indicated in the second requirement, makes the choice for a crane type system within the container stacks unavoidable. A crane system will also have the advantage that it could guarantee high productivity. Possible crane systems are:

1. Rubber Tyred Gantry (RTG)
2. Rail Mounted Gantry (RMG)
3. Automated stacking crane (ASC)

RTG's have high productivity. However a nominal stacking height of 4 containers- as in the case of the FTCT- is too high for an RTG system.
The RMG has the advantage that they have a large width span (up to 25 meters) and good space utilization. The rails do not need to be at groundlevel. Moreover, there is a possibility of automation.
The last option, the ASC's are automated and leads to reduction of the manpower in the terminal. Nevertheless, it is a high cost system and its maintenance is relatively more expensive. Furthermore, the existing systems can operate only 1(container) over 2 high

Selection:
The first option drops with respect to the nominal stacking height in the FTCT. The same aspect may raise uncertainty about the operability of the ASC's. Compared to the AGV's, the later consists of much more number of units than the ASC's. Thus, the automation is more cost efficient in the case of the quay-yard transport.
Although the second option (RMG's) requires more manpower compared to the ASC's however the system is found to be more reliable and of low maintenance costs. Also it is liable for automation if needed.
For these reasons it will be chosen for an (un-automated) RMG system for the transport of the containers within the stacks.

Figure 9.2: Rail Mounted Gantry (source: http://www.ect.nl)

9.1.3 Number of intern transport units

For an accurate calculation of the number of units needed for both logistical processes, simulation models or the Queuing Theory – as applied previously - could be used. At this stage the calculations will be carried out based on deterministic data and a number of starting points.

RMG's:

- Maximum travel speed of RMG (Siemens cranes) = 2.5 m/s
- Maximum travel time RMG (to or fro) = length stack/max travel speed =170/2.5 = 68 s
- Average travel time RMG (to or fro) = 68/2 = 34 s
- Average cycle time RMG = 2* 34(to + fro) + 2*30(loading + unloading) = 128 s

Assuming loss of 20% of the time during maneuvering between the stacks, then it follows,

- Production per crane per hour = 0.8*3600/128 = 22.5 cont/hr

11 portainers (quay cranes), 30 containers per portainer;

- Needed number of RMG's = 11*30 / 22.5 = ***15 RMG's***

AGV's:

Average travel distance (to or fro) = max travel distance/ 2 = 1000/2 = 500m
Assuming an average speed of 15km/hr (4.2m/s), then is the
Average travel time (to+ fro) = 500 * 2 / 4.2 = 4min
Assuming 2 minutes for loading + unloading, and 2 minutes waiting time, then
The average cycle time per vehicle = 2 + 2 + 4 = 8 min
Production/vehicle /hr = 60/8 = = 7.5 cont/hr
Needed number of vehicles/RMG = 22.5/ 7.5 = = 3 vehicles
Total number of vehicles = 3*15 = = **45 vehicles**

9.2 Concepts terminal cross-section

The draught of the terminal will be determined by the total weight of the terminal. The amount of construction material and thus the structural weight will depend on the cross section of the terminal. There are two significant contradicting requirements with regard to the draught in the case of the FTCT.

1. Operational aspect: the larger the draught, the better the functioning of the terminal as a breakwater. The wave energy transmission to the berths side will be reduced resulting in a more favorable wave conditions to the moored vessels.
2. Economic aspect: Considering the large dimensions of the terminal, the structure height and thus the construction material must be minimized. This serves the economic feasibility.

The largest variable load contributing to the total weight (and thus the draught) of the terminal will be caused by the containers loads. Nevertheless, it is expected that the draught created by container loads is not large when considering the large water plane area of the pontoon shaped structure.
A TEU has an average payload of 12 ton. Assuming an average empty container (TEU) weighs 3 ton then is the average total container weight is 15 ton. It follows that:

Load per m^2 = 15ton*10/ (6.10*2.44) m2 = 10.1 kN/m^2

Assuming that the terminal is totally filled with containers then is the draught variation caused by the variable containers loads is between 0 en 4 meters (4 containers high).

Concepts:
Considering the above two mentioned criteria with regard to the cross-section of the terminal, two options are sketched below for the cross-section of the terminal. Each serves one of the two requirements.
It is assumed that the terminal in the transversal direction is built up of three caissons, caisson A is 55m, B is 170m and C is 15m. This should not give an indication about the construction method nor the material of the terminal.

Cross-section 1
The first alternative (see figure 9.3) is more favorable when considering the second requirement because of its smaller structural height. The draught of the terminal will vary with changing container loads. The variation of the draught has a maximum of 4 meters as calculated above.
To estimate D_1, the following assumptions are made:

- The permanent loads (structural and others) contribution to the total draught of the terminal is **6 meters**.
- 4 containers high and only 25% of the total surface area filled with containers.

Then it follows,

$$7m < D_1 < 10m$$

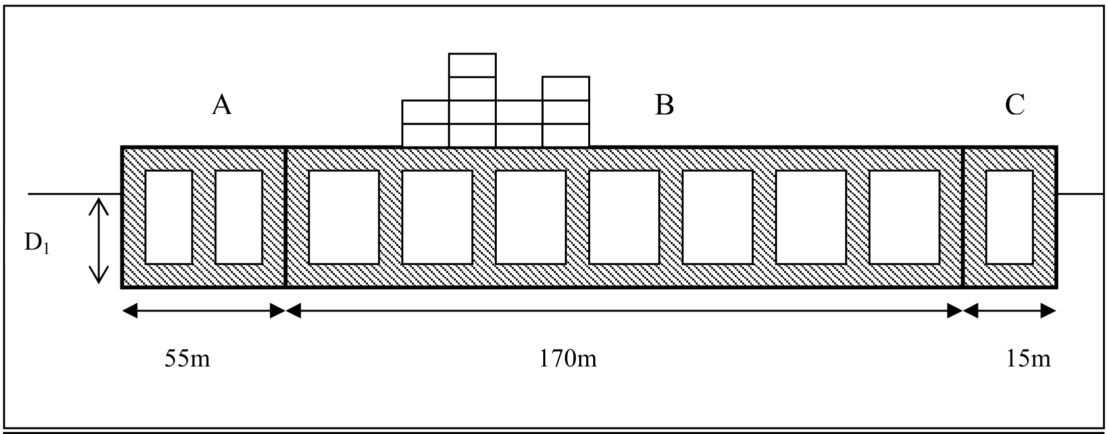


Figure 9.3: cross- section (1)

Cross-section 2

The second alternative for the cross-section of the terminal could be seen in figure…..
This alternative serves the first requirement better than the first alternative. The structure will have a constant draught. This is to be provided by using ballast tanks built inside the structure. The ballast weight is to compensate for the missing container loads. Considering the same assumptions made by the previous alternative then is:

D_2 = constant = 6m → as result of permanent loads

D_3 = constant = 4m → ballast + container loads

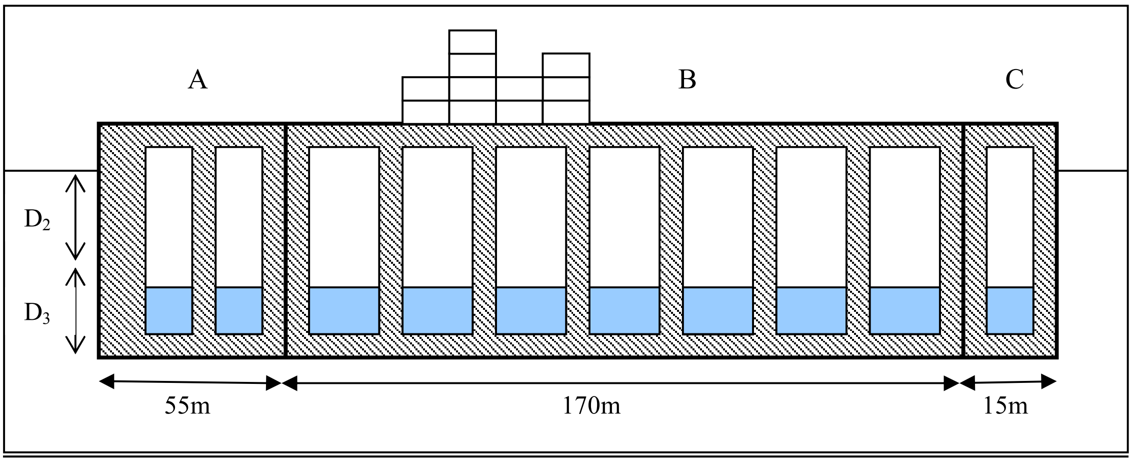


Figure 9.4: cross-section (2)

Another alternative which could be generated from both the above mentioned concepts is the ***deep stacks*** alternative, see figure 9.4. This alternative fulfills both requirements to a certain extend.

Caisson B, which has relatively large dimensions will remain unchanged in size, while A and C become deeper. Thus, the *deep stacks* alternative makes it possible to create an extra draught using a relatively smaller extra construction material compared to the 2nd alternative.

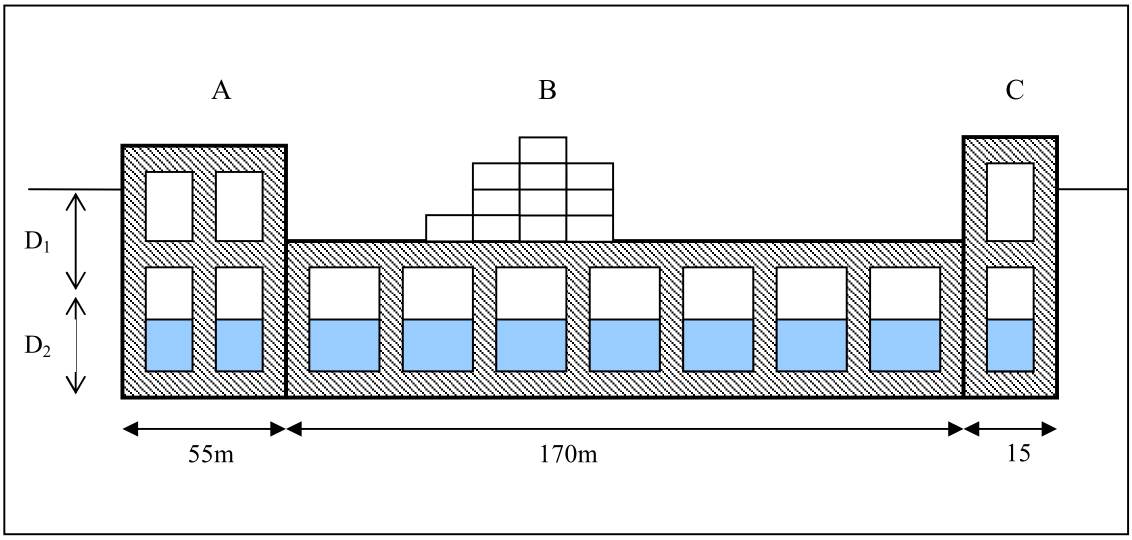


Figure 9.5: cross- section (3), deep stacks

The advantages of *deep stacks* alternative in its totality:

1. Flexibility: the use of ballast water will makes possible to adjust the draught of the terminal according to the prevailing conditions. Large draught during operation conditions provides more protection while an extra freeboard could be created during survival conditions by pumping the ballast out (over-draught).
2. Also the ballast system (flexible draught), makes it possible that the terminal could accommodate more containers, and thus larger throughput. This could be achieved by increasing the stacking height if this does nay contradict with the operational requirements
3. If after construction it is found that the draught smaller is than calculated, it is always possible to increase the draught by the use of ballast water, while the opposite is not possible.
4. Reducing the windage area of the containers and the risk of being blown away by wind during a storm.

Disadvantages of the *deep stacks* system:

1. The terminal will have two different ground levels. It will be impossible Quay-stacks transport units to operate in the storage yard floor. However the system chosen already separates between the two processes of container transport. Therefore, this restriction will only be applicable if it is to be chosen for other type of equipment in the future.
2. The drainage system must be reliable and capable of preventing water accumulation in the stacks during heavy rainfall and storms(wave overtopping)
3. From a structural point of view, the non-homogenous form of the cross-section may lead to less favorable distribution of the internal loads in the structure.

The **deep stacks** alternative is found to offer an attractive solution and will be adopted for the design of the FTCT.

9.2.2 Freeboard of the terminal

The terminal will follow the slowly varying tidal wave. In the case of beam waves, the waves will be reflected at the breakwater side, pass undisturbed along the bow and the stern and reduced at the breakwater side.
The floating terminal must have sufficient freeboard to prevent or minimize the chance of wave overtopping. This so called *shipping water* could result in material damage and unsafe conditions for the personnel. The required freeboard follows relative absolute vertical motion of the terminal with respect to the incident wave. The Rayleigh distribution method could then be used to calculate the probability of shipping water. At this stage, the motions are still unknown. To deal with this the freeboard will be estimated, and in a later phase this will treated more accurately.
In the maritime world, a first estimation of the freeboard is obtained by setting the freeboard of the structure equal to its draught. When applying the same to get a first estimation of the needed freeboard of the FTCT, then is freeboard equals to the above estimated draught of 10m.
To provide the 10m freeboard, there are two possible options:
The first option is to choose for high *deck level* as shown in the figure below. The deck level is the level where the portainers, quay-yard transport traffic lanes, buildings, etc. are found. In that case is the freeboard equals to F_1 and is estimated for 10m.

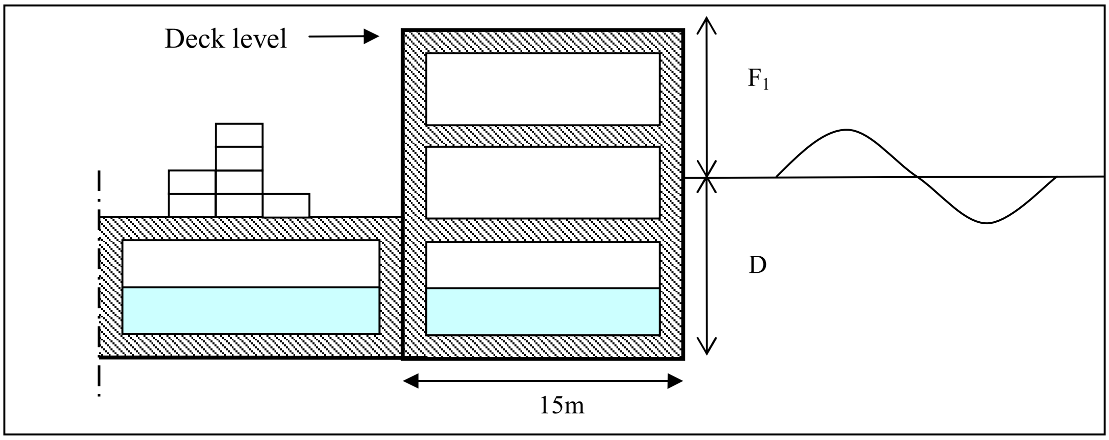


Figure 9-6: Freeboard of the terminal

Another solution which leads to the reduction of the construction material is to construct a ***wave barrier.*** The wave *barrier* is comparable to the steel (barrier) structure at the ends of ships. The proposed wave barrier is sketched in the figure below. The structure could be constructed of concrete caissons placed all around the terminal.
If the waves always attack at the same side (breakwater, berths, bow or stern) the height of the structure does not need to be equal at all 4 sides. This will depend on the mooring system of the terminal and will be determined in a later phase of this report. The width of the barriers caisson follows from structural analysis calculations. A first estimation of the width of the caisson is 3-5 meter. The barrier is to be provided with stairs allowing the transfer of the vessels crew from the top of the barrier to the deck of the terminal.

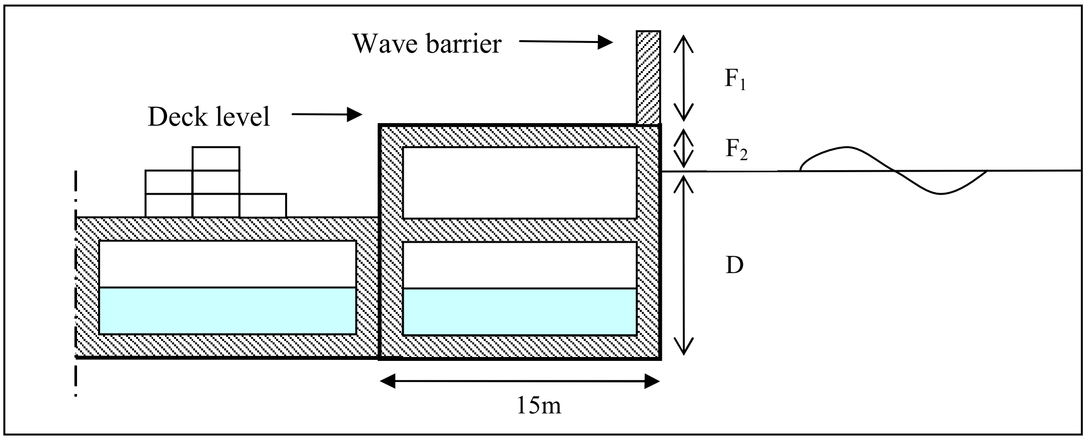


Figure 9-7: wave barrier

In the second case, the total freeboard is then the sum of the height of the deck level (F_2) above the still water level (SWL) and the height of the wave barrier (F_1).
It is chosen for the wave barrier system. This option becomes appealing when considering the large surface area of the terminal and the reduction of construction material it facilitate.
For the draught calculations, the deck level will be taken as 2m above (SWL), which is comparable to conventional terminals. The height of the barrier will be determined in a later stage. The contribution of the barriers weight to the total weight of the terminal is very small and therefore will be neglected by the draught calculations.

9.3 Weight and draught calculations

The total weight of the terminal is divided into lightweight and deadweight. The lightweight of the terminal includes the hull, machinery, outfit items, buildings, mooring system and equipment. The deadweight is the weight of the containers, fuel, ballast water, personnel and their effects.

Construction material
Draught calculations will be carried out for two construction materials, i.e. concrete and steel/iron structures.

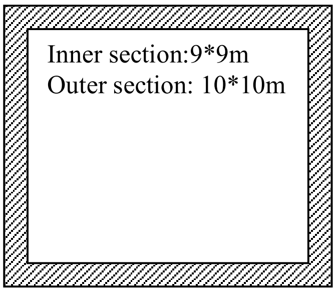
Lightweight:
1. *Structural weight:*

- Steel/iron structure: The Centre for Marine and Petroleum Technology (CMPT) recommends a method to estimate the *structural weight* at a preliminary stage of the design. The *structural weight* is given as the ratio of the total displacement for various types of offshore structures, see table 9.1. The FTCT will be compared to an FPSO and the ratio structural weight/displacement is taken as 0.2.
  By the calculations, extra larger weight is accounted for as the activities onboard the terminal will require road infrastructure for the intern transport of the cargo and

personnel.

	TLP	Semi-submersible	FPSO(ship)
Payload/Displacement	0.25	0.15	0.7
Payload(incl. storage)/structural weight	0.45	0.35	3.5
Structural weight/Displacement	0.6	0.40	0.2
Mooring load/ Displacement	0.2	0.05	0.1
Storage(ballast)/ displacement		0.4	0.6

Table 9.1: Weight ratios (source: Floating structures: a guide for design and analysis: CMPT 1998)



- Concrete structure: it is assumed that the structure is built up of prestressed concrete elements of 10*10m, and that the inner cross-section is 9*9m. Therefore, 20% solid structure, filled with material 2.6ton/m^3. The structural weight is calculated as function of the draught (D) and with an iteration process total the
- draught (and thus the weight) can be calculated.

2. Mooring loads: 0.1 of the total displacement as given in the table above.
3. Buildings and facilities: assumed as 0.2 of the total weight
4. Equipment:
   a. Portainers 1000 ton/unit
   b. RMG 500 ton/unit
   c. Quay-stack vehicles 50 ton/unit

Deadweight:

-Ballast water

Functions of the ballast water:

1 To maintain even keel by the removal of addition of a weight.
2 To maintain a constant draught. Mainly the containers loads will cause the largest draught variations.
3 to compensate for the weight of the portainers at the berths side of the terminal.
4 To create an extra freeboard during high seas by pumping out the ballast.

It is put as condition that the capacity of the ballast storage must be adequate to compensate for 80% of the maximum containers weight, thus only 20% of the containers are onboard.

- Containers:

A TEU has a maximum payload of 22 ton and an average payload of 12 ton. Assuming an average empty container (TEU) weighs 3 ton, then is the average total container weight is 15 ton

Number of containers:
For an estimation of the containers loads, the worst case will be assumed that the storage stacks are totally filled with containers, 4 high. This might lead to conservative results, however it will always be possible to use ballast to obtain that draught when there are less containers onboard. As already mentioned, the capacity of the ballast tanks must be adequate to obtain this
The total area of the stacks is divided by the area per TEU (6.10m×2.44m)

$$\textit{Load per } m^2 = 4\times 15ton\times 10/(6.10\times 2.44)m^2 = 40.3\ kN/m^2$$

During the design of conventional container terminals, a distributed vertical variable load of 40 kN/m^2 is usually accounted. This shows similarity with the assumption made above.

Safety factors:
In addition to the above mentioned components contributing to the total weight of the terminal, safety factors will be also applied as a margin compensating for weights not accounted for or underestimated.

- variable loads: safety factor of 1.5
- permanent loads: safety factor of 1.2

Results:
Appendices 9-1 and 9-2 comprise the draught calculations for both cases construction materials. As the (displacement) draught is given as a ratio of the structures weight, the equation is solved iteratively in the spread sheet. The following results were obtained.

	Steel/iron structure	Concrete structure
Draught (m)	6.9	10.3
Weight (ton*10^6)	1.97	2.94

Table 9-2: Draught FTCT

Evaluation:
- Concrete of steel?
The choice for the construction material should follow after a structural analysis, which is beyond the scope of this thesis. However, a selection will be made based on a qualitative assessment to determine the dimensions (draught) of the structure.

- Although a steel/iron structure has smaller draught than the concrete structure and thus less material is needed, however the material itself is much expensive in comparison to concrete.
- Concrete structure will result in a larger draught and thus more favorable operating conditions for the vessels moored at the berth side.
- A concrete structure of the terminal (build up of a number of units) will behave more rigid than an iron/steel structure.
- From a structural point of view, concrete is more favorable for the floating structure. The material scores better with regard to life span of the structure,

maintenance and corrosion processes compared to the iron/ steel structure.
Based on the above, it is chosen to examine different aspects of a concrete made FTCT, in the coming sections.

9.4 Definitive Layout of the terminal

In this section the definitive layout of the terminal will be determined. Terminal elements will be allocated according to the area and operational and area requirements treated previously. The main terminal elements are:

1. Container storage yards
2. Buildings and facilities
3. Apron area
4. Intern transport infrastructure

The storage yard

The storage yard is to be divided into 8 stacks as shown in figure 9.10. Different stacks are separated from each other only by markings. This is to prevent that equipment are hindered from moving between the stacks, when it becomes necessary. The stacks are classified as following:

- 5 stacks for the storage of the import/export containers; each 170m long and 140m wide. An additional stack of 170*50 m will make a total area of 12.8 hectare (as required).
- 2 stacks for the storage of empties and reefers. Each stack is 170m long and 140m wide, with the reefers stack partially used for the storage of empties.

The orientation of the container stacks is chosen in the transversal direction, with the containers heading towards the berths with their longest side. This will create a simple traffic net and thus short cycle time of the vehicles bringing containers to and from the stacks.

At the head of the stacks, a marshalling yard is to be reserved for the AGV's where they are to be loaded and unloaded. The marshalling areas are bridge like structures with their deck at the same level as that of the apron area. The deck is supported with columns or vertical walls built inside the stacks. Each marshalling area is 25 meter wide. A distance of two meters wide is kept between every two marshalling areas. This is necessary so that the RMG cranes can move over the AGV's and load or lift the containers.
(See figure 9.10).

The rail mounted gantry cranes move in the longitudinal direction of the stacks during the lifting operations of the containers. However, the cranes must be also able to move in transversal direction so that they can move between the stacks. This could be achieved by providing rails system (in the longitudinal direction of the terminal) at the back side of the stacks.

In appendix 9-B, it has been calculated that the required minimum height of the ballast tanks is 2.95m (over 80% of the water plane area of the terminal). For the total height of the concrete elements (floor slabs + deck) under the container stacks, it is estimated that the (pre-stressed) concrete elements have a total height of 2.5m.

The height difference between the floor levels of stacks and the other terminal areas is

then 6.8 meters (figure 9.10). That means, when stacking 4 containers high (9.8m), the containers will tower only 3 meters above the terminals deck level.
Stairs are to be built various locations in order to provide accessibility for the personnel to and from the container stacks. Maintenance operations or other kind of activities may require that some equipment have to be transported between the stacks and other terminal areas. To make this possible, a slip way (with a certain inclination) is to be built to bridge over the 6.8 meter difference in floor levels.

Apron Area

The apron area is 55 meters wide and extends along the whole berths side of the terminal (1190m). It includes:

- The space required for the wave barriers already proposed ac a concrete structure with 3-5m wide. Depending on the design of barriers structure, the possibility of providing a service traffic lane within the barriers structure (at deck level) must be tested. This is to ensure accessibility for equipment and people to that part of the terminal.
- The rails of the portainers extend along the whole berths side, with a distance of 35 meters between the front and back rails.
- The remaining 15 meters (in the transversal direction) are to be reserved for traffic lanes of the AGV's. The traffic lanes are only to be used by the moving automated vehicles. The space between the portainers legs is to be used for vehicles which are being loaded or unloaded as shown in the figure below.

Figure 9.8: AGV's loaded/unloaded between crane legs

Buildings & Facilities

The terminals administration building and facilities are to be located within a close distance to the berth of the personnel boat. This is to minimize the distance between the offices and the arrival/departure point, and at the same time reduce the human activities in the apron area.

- The administration building has a surface area of 900m^2. The building is 3 levels high and each level is 3m. at the top of building, The control tower is to be built on the top of the building .

- The *Technical service building* and the other *Facilities* are to be located near to the administration building, all together in a sort of compound. The total area of that compound is 1.7 hectares (100*170m).
- Accessibility to the various terminal areas is to be provided by pavements and traffic lanes along the stern, bow, and breakwater side of the terminal. This is necessary for the movements of personnel and equipment within the terminal areas.

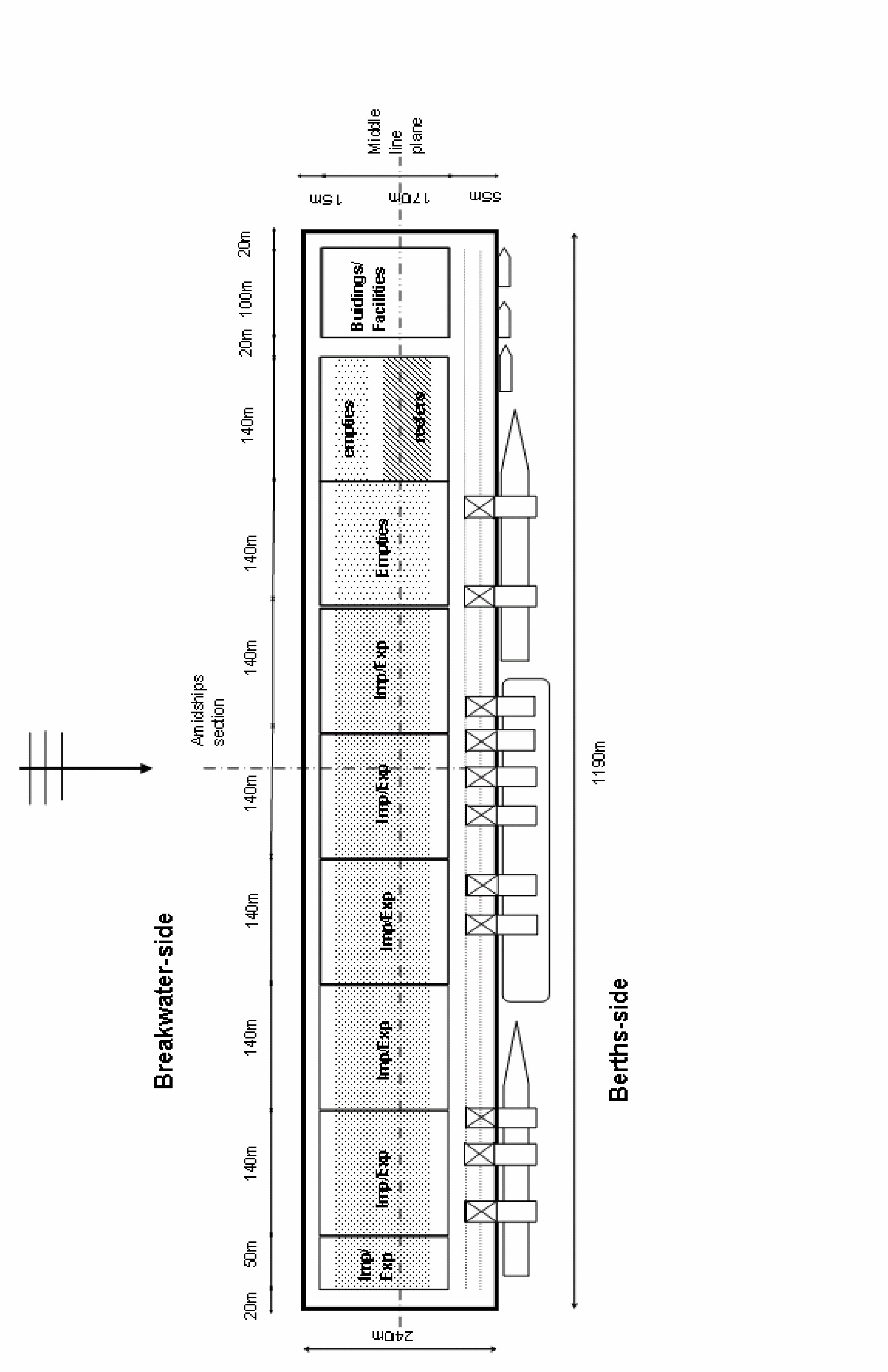


Figure 9.9: Definitive layout FTCT

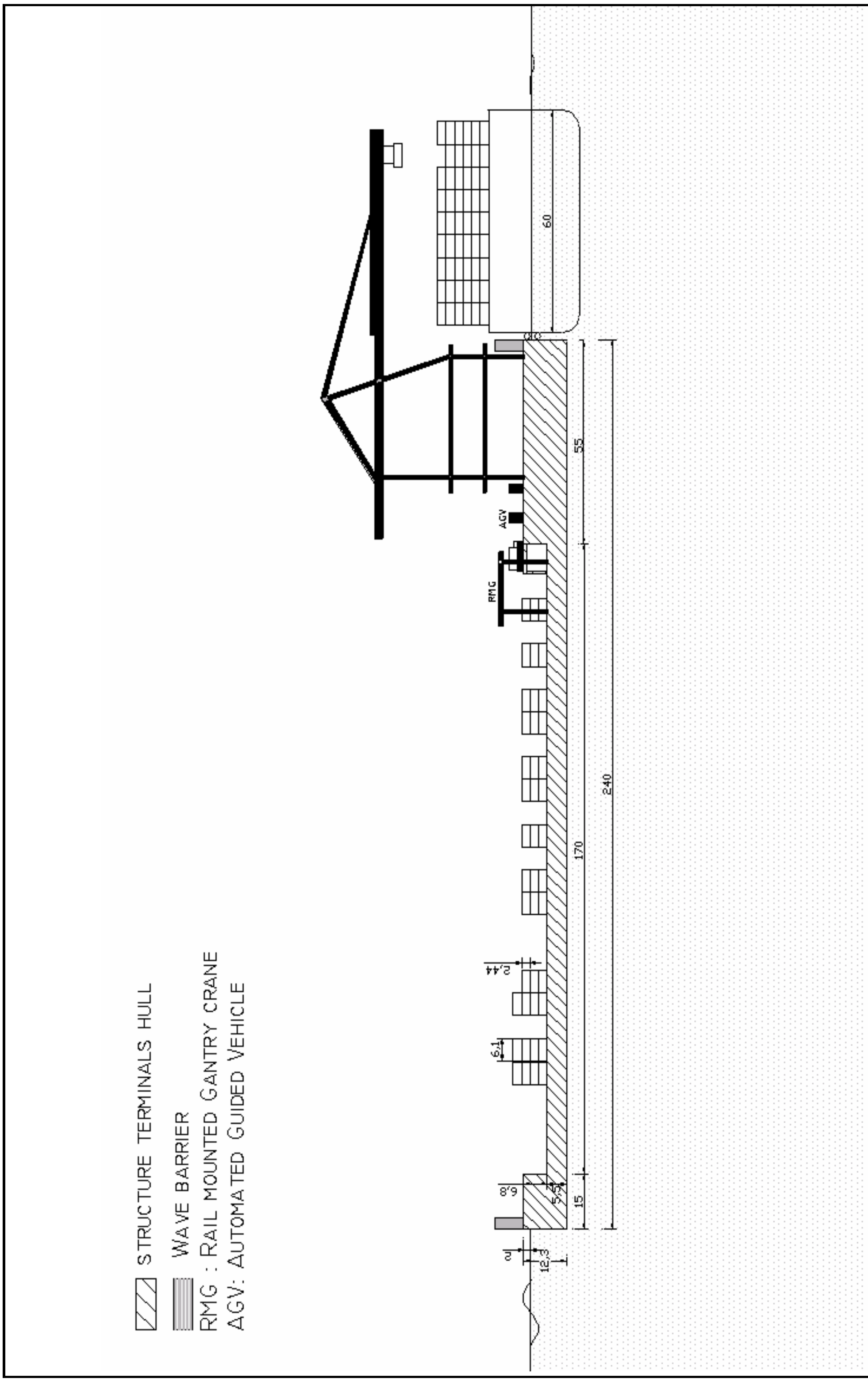


Figure 9.10: terminals cross-section

9.5 Conclusions

- The FTCT is 1190m long, 240m wide. the definitive total surface area of the terminal is **28.56 hectares**
- The draught calculations were carried out for two construction materials, i.e. concrete and steel/iron structures. It is chosen for a concrete structure for the FTCT and the corresponding draught of the terminal is **10.3m**.
- Required minimum height of the ballast tanks (over 80% of the water plane area) is 2.95m. The ballast tanks should have a height of 3m.
- Height of the deck level is 2m. The total freeboard will be follow from the height of the wave barrier.
- Figures 9.9 and 9.10, show drawings of the layout and a cross-section of the terminal respectively.

10 Terminal Hydrostatics

Introduction
This section treats the static properties of the structure. The addition, removal or shift of masses will cause heel or/and trim. The heel and trim are the rotations about the structure's longitudinal and transverse horizontal axis (through CoG). It is assumed that the processes causing these rotations will be brought about so slowly that all dynamic effects can be ignored. The maximum sinking and draught reduction as result of heel and trim will be calculated at one of the corners of the terminal.

10.1 Calculations static behavior

There are two processes onboard the terminal that may lead to major shift, removal or addition of masses onboard the terminal.

1- containers: The change/shift in mass as result of the containers
2- Quay/stacks cranes: the portainers and RMG's motions onboard the terminal will cause also trim and heel of the structure.

By the calculations of heel and trim, only the second process will be considered. The shift/change of masses as result of (a large number of) containers occurs slowly and will be compensated for by using ballast water in order to maintain an even keel position of the terminal. The cranes move relatively fast, and the use of ballast to compensate for mass shift would not be possible.

The maximum sinking and freeboard reduction will be calculated at point A as shown in the figure below.

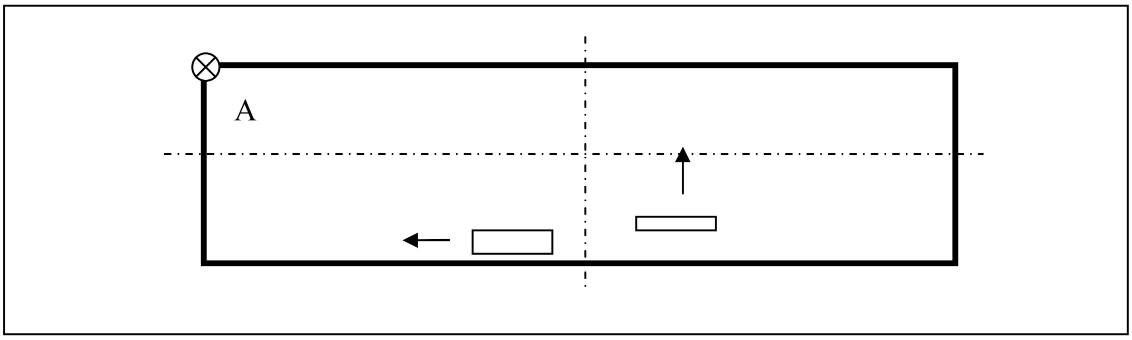


Figure 10.1: cranes motions with regard to static behavior

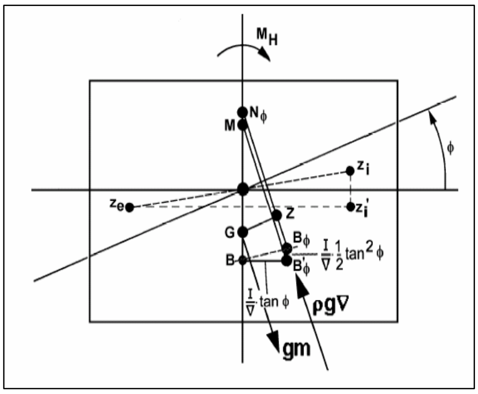
Other starting points:
-The terminal is floating at even keel. Because of the rotational equilibrium, the center of gravity G is positioned in a vertical line through the center of buoyancy B.
- At a certain moment, 10 of the yard cranes (500 ton each) will move simultaneously a distance of 150 meter (length of the yard) in the lateral direction towards point A causing

a heeling moment M_H and thus sinking of that point.
- At the same time, 10 of the quay cranes (1000 ton each) will move 50 m in the longitudinal direction towards point A, causing a trimming moment M_T.

Position center of gravity:
To estimate the position of the center of gravity, assumptions were made in a way that highest possible position of the CoG from the keel is obtained, thus the worst case.

- Container yards completely filled with containers.
- Homogenous mass distribution, for both the terminals and containers cross-section.
- In the longitudinal direction, CoG lies at half the length of the terminal.

Equations
As result of the shifting masses, the Center of Gravity will shift only in the horizontal direction. The angle of heel follows from the equation for the righting stability moment M_H by iteration. The same applies for trim.



$M_s = M_H$

$$M_s = \rho g \nabla \cdot \overline{GZ}$$

$$M_s = \rho g \nabla \cdot \overline{GN_\phi} \sin\phi$$

Where,
$\overline{GZ}$ is the lever arm of stabilty
∇ is the volume of water displaced

$$\overline{GN_\phi} = \overline{KB} + \overline{BN_\phi} - \overline{KG}$$

$$\overline{BN_\phi} = \frac{I_T}{\nabla}(1 + \frac{1}{2}\tan^2\phi) \rightarrow \text{Scribanti Formula}$$

Results:
The calculations are executed in an Excel spread sheet [appendix 10-1 and 10-2]

1- Location CoG:
- vertical position: 7.07m above keel
- lateral position: 123 from the breakwater side

2- Heel angle = $5.26*10^{-3}$ ⟶ Vertical displacement point A = 0.65m
3- Trim angle = $0.14*10^{-3}$ ⟶ Vertical displacement point A = 0.08m

4- Total Vertical displacement point A as result of heel and trim = 0.73m

Evaluation
- static stability: Considering the small angles of heel and trim calculated above, and the large metacentric height GM (464m and 11455m for heel and trim respectively,

see appendix 10-1), it could be concluded that the terminal is statically stable and is capable of obtaining its equilibrium position –thus not capsizing- as result of activities onboard. The large widths and lengths resulted in very large moments of inertia of the terminal.

- By the calculations of the terminals freeboard, a static vertical displacement of 0.73m has to be accounted for
- As the sizes and the water depths of the ballast chambers are still unknown (follow from structural design), the effect of free surface liquids inside the floating structure is not accounted for. However, there effect can be kept low by choosing for multiple tanks with small widths.

11 Approach method system hydrodynamics

Introduction
Studying the hydrodynamics of the designed system represents an important part of the research as conclusions could be drawn about the *operability* of the designed system. The operability represents a part of the *technical feasibility* which is one of the objectives of the study. The *operability* is defined as the limits to which the designed system would be able to allow safe terminal operations according to the criteria. These limits could be expressed in terms of the maximum significant height of the incoming wave or the commonly used Beaufort scale.
This section comprises the first step of the hydrodynamic research. It is aimed to give a clear picture about the approach method and the steps required to be taken in the following sections to reach a final conclusion with regard to the terminals operability.

11.1 Terminal motions

The different loads on the floating body result in different modes of motion. These motions and the different paths that could be taken to calculate them are demonstrated in the figure below. The shading in the figure could be temporarily ignored.
The oscillatory motions are mainly caused by the wave forces on the terminals body. These forces could be divided into forces with frequencies equal to that of the incoming wave frequency and. Forces with low frequencies, the so called *low frequency wave drift forces.* In general, each of the two forces could result in all 6 dynamic modes of motion (surge, sway, heave, roll, pitch and yaw). For the definition of the six modes of motion see literature study [Lit 5-1] at the end of this report. However, when considering the frequencies of these forces and the resulting motions, some motions are of less significance with regard to the *operability* of the terminal.
Its is more probable that systems natural frequencies for heave, roll and pitch lie within the range of frequencies of the *wave frequency forces* than that of *low wave drift forces*. The opposite could applicable in the cases of surge, sway and yaw, depending on the stiffness of the mooring system.

<u>*Beam waves*</u>
As previously mentioned, in order to create sheltered waters for the moored vessels the orientation of the designed terminal should be beam-on to waves. This will only be necessary during the container vessels processing (loading, unloading, berthing or deberthing). There are two possibilities to achieve this:

1- The terminal is able to w*eathervane*. With *weathervane* it is meant that the terminal will have the ability to position itself beam-on to waves.

2- The terminal will not be able to weathervane. Consequently, by the location choice, the terminal location is to be restricted to places where the waves are mainly (for example during 80% of the time) coming from one direction. The terminal will have one fixed orientation and should be beam-on to that prevailing direction

Whether the terminal will have the ability to weathervane or not, will be examined later (section station keeping). However, at this stage it will be assumed that the terminal will always be beam-on to waves during the operation of the terminal

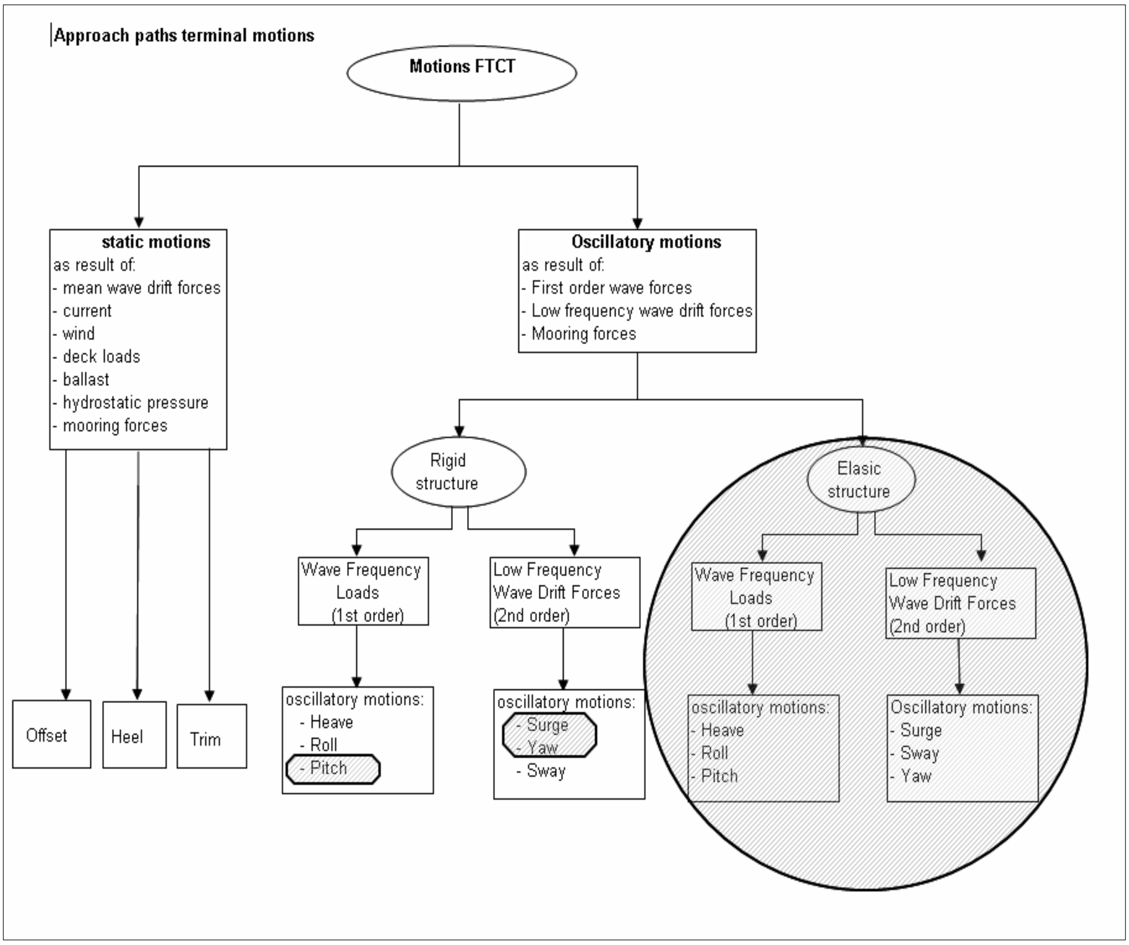


Figure 11-1: approach to terminal motions

The importance of the assumption that the terminal remains beam-on to waves, is of importance- at this stage- for the possible motions. The terminal will perform neither pitch and yaw rotations nor surge translations in the case of beam waves. Therefore the assumption of beam waves reduces the possible motions to heave, roll and sway. This has indicated by 2 small shadings in figure 11.1.

11.2 Elasticity effects

The structural elasticity also plays a role in the hydrodynamic behavior of the system. The first effect is that the structures elasticity will result in extra motions when the structure is subjected to sea loads. Furthermore, the wave transmission to the berths side will be larger in the case of an elastic structure compared to a totally rigid structure.
At this stage it will be assumed that the FTCT structure is totally rigid and will behave as one rigid element floating in waves, which is less probable when considering the large

dimensions of the terminal. However, the elasticity of the structure follows from the structural design which is beyond the scope of this study. In a later phase of this report, this aspect will be treated once again and evaluated.
With the later assumption over the terminals elasticity, the motions will be reduced to the not shaded motions in figure 11.1.

11.3 Criteria for moored container vessels

During the loading/unloading operations of the containers, problems could occur whenever vessel motions exceed a certain limit. These problems could occur in the form of:

- A container could get stuck inside its cell guide during loading/unloading, causing vessel delays and/or possible damage.
- The motions make it difficult for the crane operator to position the cranes spreader just above the container or to lower the containers exactly into the cell guides. Waiting for the right moment to do these actions is based on the judgment and experience of the crane operator. However, this creates a stressing working sphere for the operators.
- Reduction of the portainers productivity per hour.

The aim of this section is to discus a number of criteria defining the limits of motions for safe and efficient lifting operations of the containers.

1- An extensive research program was carried out by the Joint Nordic Group (involving Denmark, Finland, Sweden, Norway, etc). The group, in its report "*Ship Movements in Harbours*" concluded the following about the limits of motion for safe operation conditions of the container vessels. [See literature study 5-7].

Efficiency	Surge(m)	Sway(m)	Heave(m)	Yaw(^{o})	Pitch(^{o})	Roll(^{o})
100%	1.0	0.6	0.8	1	1	3
50%	2.0	1.2	1.2	1.5	2	6

Table 11-1: criteria for safe operating conditions

Motions are peak-peak, except for sway zero-peak.
Furthermore, it is demanded that occurrence frequency of the critical ship movements should be less than 1 week per year (2% of the time) in order to obtain the mentioned efficiency percentages.

2- The criterion given in the lecture notes of Ligteringen, H., "Ports and Terminals, 2000" requires maximum motion *amplitude* of **0.3 meter** for the heave motion, which is smaller than the limit given in the table above.

3- Goedhart, B., in his thesis research “Criteria for (un)-loading container ships” concluded that the limits of motion shown in table 8.1 (also published in PIANC’s bulletin no.88) are not strict enough. The conclusions are only drawn for Sway and Surge. The writer didn’t draw conclusions about heave and roll, which are more relevant in the case of the FTCT.

Analysis:
The criteria given above are expressed for the six modes of motion separately. It would be more logic to think that for the crane operator, the vertical, longitudinal and the lateral displacements (or velocities) at the location of the container is of relevance. However, these displacements are expressed in terms of the amplitudes of the different modes of motion. For example, the *vertical* displacement z_p at point P(x, y, z) from the center of gravity of the vessel could be calculated with formula:

$$z_p = z - x \cdot \theta + y \cdot \phi \qquad [11\text{-}1]$$

Where z is the heave motion, while θ and ϕ are pitch and roll rotations respectively about the center of gravity (CoG).
Therefore, although the criteria do not provide explicit limits for the amplitudes of the absolute (vertical, longitudinal and lateral) displacements, however the limits are expressed in the amplitudes of the different modes of motion (heave, roll, pitch, sway, surge and yaw).
When applying the given criteria in combination with the formula 11-1, it could be noticed that the criteria tolerates larger vertical displacement z_p for the larger vessels (larger *x and y*).
This might be logic, as the periods of motion of the larger vessels are larger than that of the smaller ones. Thus, although the amplitude of motion is larger, however the motions period is smaller.

Evaluation:
It has already been concluded that for the designed system, only heave, roll and sway are of importance with regard to the o*perability*. Its will also be shown in later stage of this report, that the heave motions are decisive for the determination of the maximum wave conditions for which container lifting operations could safely proceed.
- Heave motions:
When combining the facts that the criteria given by the Joint Nordic Group criteria (also published by PIANC) are found not to be strict enough and that in the lecture notes Ports and terminals a smaller maximum amplitude of motion is require, it will be chosen for a maximum amplitude of heave motion of **0.3m** (as given in the lecture notes).
- Sway motions:
Both the lecture notes “Ports and Terminals” and the PIANC criteria for sway motions are similar. In the case of the FTCT, the criteria will be required as given in table 11-1.

- Roll motions:
The only obtained criteria with regard to the roll motions are published in the PIANC's bulletin (determined by the Joint Nordic Group). These are also given in table 11-1.
- Efficiency:
The criteria given above are for 100% crane efficiency. This is of significance to the already made starting point (by the calculations of the number of needed berths) that the portainers have an average productivity of 30 containers per hour. To obtain this efficiency, according to the criteria it is demanded that occurrence frequency of the critical ship movements should be less than 1 week per year (2% of the time).

11.4 Approach method to calculate systems relative motions

The criteria mentioned above are set for container vessels moored to fixed quays. In the case of the FTCT, both the vessels and the cranes are in motion. For this reason the limits of motions have to be interpreted as the limits of relative motions between the vessel and the terminal (at the crane spreader).

Two possible approaches could be taken to calculate the relative terminal-vessel motions:

1. *Advanced approach*:
Diffraction models (based on the panel method) could be used to simulate both the motions of the terminal and the moored vessels. The properties of the mooring system vessel-terminal are required to calculate the relative motions. The models make it also possible to determine the wave conditions at the berths side for a certain incoming wave.

2. *Simplified approach:*
A more simple approach is to consider the vessel and the terminal as two independent floating bodies. This will only apply for the heave, roll and pitch motions. For these three modes of motion it is assumed that neither the vessel moorings nor the terminals motions will affect the vessels motion.
The *terminal* will respond to the incoming wave at the breakwater side. The wave conditions at the *berths side* will follow from the wave transmission, diffraction and the dynamic swell-up (will be explained later). The *vessels* response (as free floating body) for the above three mentioned modes of motion could then be calculated.
The disadvantage of this approach compared the *advanced*, is that the phase lag between each of the two bodies motions and the *incoming* wave could be only calculated for the terminal and not the vessel. This is for the reason that the wave conditions at the berth side could not be calculated in the time domain. Therefore, the phase difference between the incoming wave - thus also the terminals motions- and the vessels motions remains unknown.
To deal with this, the worst case will be assumed by regarding that the terminal and the vessel are always moving in the opposite direction (180 degree phase lag). Thus, the *amplitude of the relative motion* is equal to the summation of the amplitudes of terminals and vessels motions.

It is obvious the *advanced approach* by using diffraction models leads to more accurate hydrodynamic results and thus conclusions about the operability of the system, while the *simplified approach* overestimates the results of the relative motions. However, it is considered that the design process is at its early stage and that the advanced approach demands a deeper research that is beyond the scope of this thesis. Therefore, the simplified approach will be adopted to draw conclusions about the *operability* of the system. Nevertheless, the results obtained from the *simplified* approach will be evaluated with respect to that issue (assumption) in a later phase.

11.5 Design conditions

No particular location has been selected for the FTCT. This approach was chosen to generalize the concept of the floating port and finally draw the conclusions about the *operation* and *survival* conditions of the designed system.
However the environmental conditions will be needed to simulate the response and finally reach a conclusion. To deal with the following approach has been taken.

The waterdepth:
When using mooring lines for the station keeping of the terminal, the water depth is significant for the calculations of the (stiffness) of the mooring system. Furthermore, the water depth could affect the response of the terminal when it is not located in deep water (trajectories of water particles under the waves in different depths).
One of the *starting points* was that the terminal will be floating within a certain distance from the fast land. This is with regard to the transport of personnel and supplies to and from the terminal.
Keeping the terminal at a distance of 5 kilometer from the coast, will guarantee in the most cases less impediment to the existing sea infrastructure (shipping traffic routes, pipelines, etc) and other (recreational) sea activities. Assuming a coast with a steepness of 1:50 and that the terminal floats at a distance of 5 kilometers from the coast, then is the water depth at the site location is **100 meters**.

Waves:
By the response calculations, the wave conditions around the system (terminal and vessels) will classified as following:

- Incoming waves: waves at the breakwater side of the terminal.
- Berths side waves: waves at the berths side (lee side) of the terminal.
- Dynamic swell-up: Waves generated by the motions of the floating bodies, mainly the terminal.
- Free surface waves generated in fluids in partially filled (ballast) tanks.

The free surface generated wave will not be accounted for as this will depend on the structural design of the terminal.

- ***Incoming waves***

Possible types of waves at the location of the FTCT are:

- Wind waves: wind generated waves are **irregular** and are considered to be short waves. The two types of wind generated waves are the so called Sea and Swell waves. A Sea is a train of waves driven by the prevailing **local** wind while the (relatively long period). Swell waves which have propagated out of the area and local wind in which they were generated.
- Tides generated by the astronomical forces.
- Waves generated by earthquakes or submarine landslides: Tsunamis

Waves to be considered during the response calculations:
It will be assumed that Tsunamis do not occur in the location of the floating terminal. This assumption is to be translated into a *requirement* by the choice of the location of the designed FTCT.
Both the vessel and the terminal will follow the variation of the water surface elevation as result of the long **tidal** waves. The bodies will be regarded as one system and the relative motions are negligible.
Therefore, the *terminals* response calculations will follow mainly from the behavior of the body in wind waves.
The energy in irregular wind waves causing the system motions could be quantified using the wave spectra. Determined using wind waves could be Wave spectra will be used to determine the energy of the incoming waves (at the breakwater side of the terminal).
Three popular methods to generate wave spectra in the offshore world are:

1. Pierson- Moskowitz wave spectrum: the spectral density $S_\varsigma(w)$ as function of the wind speed.
2. Bretschneider wave spectrum: spectral density as function of the H_s and T_1
3. JONSWAP wave spectrum: the spectral formulation is based upon measurements carried out along a line extending over **100 miles** into the North Sea.

The first method is used in the case of fully developed seas while the second method is suited for open sea areas. The JONSWAP remains the most suitable method for the near to the coast floating terminal. The JONSWAP spectrum is expressed by the formula:

$$S_\varsigma(w) = \frac{320 H_{1/3}^2}{t_1^4} w^{-5} \exp\left\{\frac{-1950 w^{-4}}{t_1^4}\right\}\gamma^A \qquad [11\text{-}1]$$

$$\gamma = 3.3, \qquad A = exp\left\{-\left(\frac{\frac{w}{w_p}-1}{\sigma\sqrt{2}}\right)^2\right\}, \qquad w_p = \frac{2\pi}{T_p}$$

And
$\sigma = 0.07 \; for \; \mathrm{w} < \mathrm{w_p}$ and 0.09 for $\mathrm{w} > \mathrm{w_p}$
See the notation list [appendix-1] for the definition of the terms given above.

<u>*Relation wind speed, wave height and Beaufort Scale*</u>

The extensive wave measurement program carried out by the Joint North Sea Wave Project (JONSWAP) yielded also a relation between the Beaufort Scale(or the associated wind speed at 19.5m above sea, significant wave height and the mean wave periods for two types of areas. This is shown in the table below.

Wave Spectrum Parameter Estimates								
Scale of Beaufort	Wind Speed at 19.5 m above sea	Open Ocean Areas (Bretschneider)			North Sea Areas (JONSWAP)			
	(kn)	$H_{1/3}$ (m)	T_1 (s)	T_2 (s)	$H_{1/3}$ (m)	T_1 (s)	T_2 (s)	γ (-)
1	2.0	1.10	5.80	5.35	0.50	3.50	3.25	3.3
2	5.0	1.20	5.90	5.45	0.65	3.80	3.55	3.3
3	8.5	1.40	6.00	5.55	0.80	4.20	3.90	3.3
4	13.5	1.70	6.10	5.60	1.10	4.60	4.30	3.3
5	19.0	2.15	6.50	6.00	1.65	5.10	4.75	3.3
6	24.5	2.90	7.20	6.65	2.50	5.70	5.30	3.3
7	30.5	3.75	7.80	7.20	3.60	6.70	6.25	3.3
8	37.0	4.90	8.40	7.75	4.85	7.90	7.35	3.3
9	44.0	6.10	9.00	8.30	6.10	8.80	8.20	3.3
10	51.5	7.45	9.60	8.80	7.45	9.50	8.85	3.3
11	59.5	8.70	10.10	9.30	8.70	10.00	9.30	3.3
12	$>$64.0	10.25	10.50	9.65	10.25	10.50	9.80	3.3

Table11-2: wave conditions in open ocean areas and North Sea areas (source: Journee,J. and Massie,W. ;Lecture notes: Offshore Hydromechanics, TU-Delft,2001)

In the case of the FTCT, the relations for the North Sea areas will be used. This is more probable, as the terminal will be floating within a certain distance from the fast land.

- ***Waves at the berths side:***

Three physical phenomena will be accounted for when determining the wave conditions at the berths side (lee side) of the terminal.

1- Wave transmission under the terminal.
2- Wave diffraction around the structure.
3- Dynamic swell-up.

<u>1- Wave transmission</u>

The waves attacking the structure at the berth side will be partially reflected while a part of the energy will be transmitted under the structure to the other side. PIANC, in its report *Floating Breakwaters: A Practical Guide for Design and Construction* of 1994 presented a method to calculate an acceptable first approximation of the transmission coefficient of the incoming wave height for rectangular surface floating barriers (see appendix 11-1). The method is introduced by Thompson (1989) where he expressed the transmission coefficient as function of the water depth, the width and the draft of the breakwater and the length of the incoming wave.

2- Wave diffraction

The wave diffraction could also be expressed in terms of diffraction coefficient of the incoming wave height. Battjes, J.A, in his lecture notes *Korte Golven* (short waves) of 2001 explains a method to calculate the diffraction coefficient using the Cornu graph. The method is applicable for both permeable and impermeable breakwaters. The first case is suitable for the calculations of the FTCT as only the transmission coefficient is required to calculate the wave height at a certain point behind the breakwater

3- Dynamic swell-up

The oscillating terminal will produce waves which will in its turn affect the motion of the moored vessels. The contribution of the dynamic swell-up is non-negligible when considering the dimensions of the large terminal.

For the heave motion and zero forward speed, the ratio of the amplitude of the produced wave to that of the incoming wave can be calculated with equation 11-4 *(source: Journee,J and Massie,W;Lecture notes: Offshore Hydromechanics, TU-Delft,2001)*

It is for heave and for motions in the vicinity of the natural frequency.

$$\frac{\Delta\zeta_a}{\zeta_a} = \frac{x_a}{\zeta_a} w \sqrt{\frac{b'}{\rho g c_w}} \text{ or } \Delta\zeta_a = x_a w \sqrt{\frac{b'}{\rho g c_w}} \qquad [11\text{-}4]$$

The Wave spectrum at the berth side

- The wave height:

The transmitted and diffracted wave height to the berth side will be calculated as a mentioned above. The incoming H_s will cause a motion of the terminal with amplitude x_a. Equation 11-4 will be used to calculate $\Delta\zeta_a$ as result of dynamic swell-up. This is only applicable for the heave motion. Superposition of all three wave heights gives the total wave height of the at the berth side.

- The wave period:

The wave period of the transmitted will be assumed to equal the period of the incoming wave. The (wave) energy flux is regarded to be related to the wave period. As the energy is partially transmitted to the berths side, however the energy flux will remain unchanged.

Currents:

It is assumed that the current velocity at the terminals location:

- 1 m/s, in the SLS
- 2 m/s, in the ULS

11.6 Conclusions

Wave and wave conditions:

- The irregular wind short waves will mainly determine the response of the **terminal**. The JONSWAP method is selected to quantify the wave energy (spectrum) at the location of the FTCT.

- A spectrum is to be generated describing the wave conditions at the berth side and thus the motions of the **vessels**.

Response:

- Except for the steady motions (heel, trim and offset), oscillatory motions of the system will be caused by the wave frequency (1st order) forces and the low frequency (2nd order) wave forces.
- During the operation of the terminal (vessels processing), the terminal is required to have a beam-on position to waves. The motions determining the operability are reduced to:

  Heave and roll (as result of the Wave frequency forces)
  Sway (as result of the Low frequency wave forces)
- The *relative motion* (for heave and roll) will be calculated as the sum of the amplitudes of the motions of both the vessel and the terminal (portainers).

Maximum operating conditions:

- Maximum amplitude relative heave motion = 0.3 meter (peak-peak 0.6m).
- Maximum amplitude roll motion = 1.5 m.
- The frequency of occurrence should be less than 0.02.

Elasticity effects:

- Both the terminal and the vessels will be assumed as rigid bodies.

12 Heave & roll motions

Introduction

This section represents the first calculations of the hydrodynamic response of both the terminal and the vessels in **irregular wind waves**. The calculations will be carried out according to the approach method and the assumptions as discussed in the previous section.
The calculations in this section are limited to the motions as result of the 1st order wave frequency forces. Furthermore at this stage, the motions are limited to heave and roll for the beam-on to waves terminal.
At the end of the section conclusions will be drawn about the operability of the
As already mentioned, the operability of the beam-on to waves terminal Only the motions as result of the wave frequency forces (1st order) will be considered.
Therefore, this section is dealing with forces and motions only during operation of the terminal

12.1 Response calculation method

The amplitude of the motions in irregular waves could be driven from the response spectrum. The later in its turn is a function of the wave spectrum and the response amplitude operator (RAO) as given in the equation below.
The response spectrum (of the motion r) can be found from the transfer (RAO) function of the motion and the wave spectrum using the equation:

$$S_r(w) = \left| \frac{r_a}{\zeta_a}(w_e) \right|^2 .S_\zeta(w_e) \qquad [12\text{-}1]$$

Where,

$S_r(w)$	The response spectrum
$\left\| \frac{r_a}{\zeta_a}(w_e) \right\|$	RAO-function
$S_\zeta(w_e)$	Wave spectrum
w_e	Wave frequency of encounter = w for zero speed

Using the Rayleigh distribution function, the significant amplitude of the motion $r_{a1/3}$ could be calculated with equation 12-2:

$$r_{a1/3} = 2\sqrt{m_0} = 2.RMS \qquad [12\text{-}2]$$

The amplitude of the motion that will be exceeded by 2% of the time (as required) is:

$$0.02 = \exp\left\{ -\frac{r_{0.02}^2}{2m_{0r}} \right\}$$

$$r_{a0.02} = 2.79\sqrt{m_{0r}}$$

The zero moment m_0 is the zero moment of the motion spectrum and is equal to the area under the graph. The area under the graph will be calculated using the *Trapezoidal rule*
Therefore, the Peak –to-peak motion = $2 \cdot r_{a0.02}$
The mean centric period t_{1r} and the zero crossing period t_{2r} of the motions are respectively:

$$t_{1r} = 2\pi \frac{m_{0r}}{m_{1r}} \qquad t_{2r} = 2\pi \sqrt{\frac{m_{0r}}{m_{2r}}} \qquad [12\text{-}3]$$

In the following paragraphs, each of the unknowns given above will be calculated in both the cases of heave and roll motions and for the terminal and the design container vessel separately.

12.2 Terminal motions

The following steps will be taken:

Step 1- Finding the Response Amplitude Operator (RAO) for heave and roll of the floating terminal as function of the wave frequency (w)
Step 2- Generating a number of wave spectra for the incoming wave as function of the wave frequency. The JONSWAP method and the relations between wind speed (Beaufort scale) and the wave conditions as given in section 11.5 will be used.
Step3- The amplitude of the motion as function of the Beaufort scale value (also H_s and T_2) could be calculated by using the filling the results of the first two steps in equation 12-1.

12.2.1 The terminals response amplitude operator – RAO

Two methods were used to calculate the RAO- functions of the terminal. This section comprises a description, results, comparison and analysis of these methods.
A method which gives an estimation of RAO-functions is introduced by the CMPT (center of maritime and petroleum technology) in it book *Offshore structures: Guidelines for the design of floating structures, 1998, appendix 5B of the reference*). The RAO-functions of the terminal are also obtained using the simulation model DELFRAC.
The aim behind applying two methods is that the first method is much simple compared to the second. Using a simple spread sheet program, it will be much easier to obtain the RAO-functions for a pontoon structure of different sizes just by changing its dimensions. DELFRAC requires relatively more time and effort to perform the same calculations.
The results found using the CMPT-method will then be compared to these of DELFRAC and thus verified for its accuracy.

<u>CMPT–method:</u>
The floating terminal is to be considered as mass-spring-system. The uncoupled equation

of motion for all modes of motion is:

$$(m+a)\ddot{x}+b\dot{x}+cx=F(w) \qquad [12\text{-}4]$$

Where,

m mass of object (kg)

$a(w)$ hydrodynamic mass coefficient(added mass) in kg

$b(w)$ hydrodynamic damping coefficient(Ns/m)

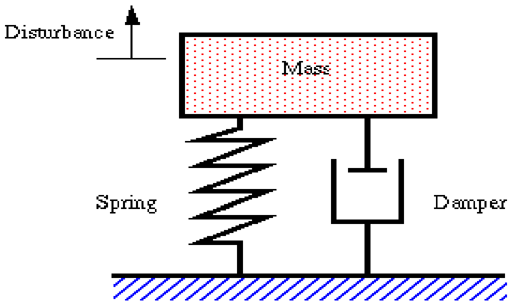
c restoring spring coefficient(N/m)

x displacement

$F(w)$ Force

The amplitude $\bar{x}(w)$ of the displacement follows from:

$$\bar{x}(w)=\frac{\bar{F}}{\left\{(c-w^2M)^2+(bw)^2\right\}^{1/2}} \qquad [12\text{-}5]$$



Forces acting on the floating body:

1. The Froude-Krylov pressure: this pressure is additional to the hydrostatic pressure that acts on the in waves floating bodies. The pressure gradients will cause them to accelerate.
2. The added mass force: This force is caused by the accelerations that are given to the water particles near the body.

HEAVE:

The total heave force is:

$$F_H=F_{FK}+F_A \qquad [12\text{-}6]$$

where,

F_{FKH} Froude-Krylov heave force

F_A Added mass force

The Froude-Krylov force for **heave in beam waves** is:

$$F_{FK}=L\rho g\frac{H}{2}e^{-kT}\int_{-B/2}^{B/2}\cos(kx)dx \qquad [12\text{-}7]$$

The added mass force for **heave in beam waves** is:

$$F_A=-C_a\frac{\pi}{2}(L/2)^2\rho\frac{2\pi^2H}{t^2}e^{-kT}\int_{-B/2}^{B/2}\cos(kx)dx \qquad [12\text{-}8]$$

ROLL:

The total **roll force (moments about roll center) in beam waves**:

$$F_R = F_{FKS} + F_{FKB} + F_{AMS} + F_{AMB} \quad [12\text{-}9]$$

Where,

F_{FKS} Froude-krylov moments on side shells

F_{FKB} Froude-krylov moments on bottom

F_{AMS} added mass moment on side shells

F_{AMB} added mass moment on bottom

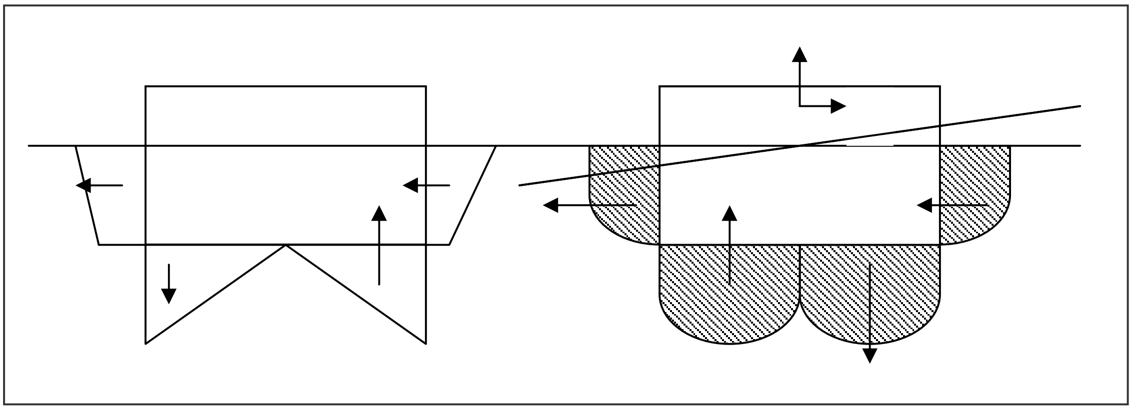


Figure12-1: Roll forces acting on the hull on beam waves

Where,

$$F_{FKS} = 2\rho g \frac{H}{2} L \int_{-T}^{0} e^{kz}(z-r)dz \sin(\frac{kB}{2}) \quad [12\text{-}9]$$

$$F_{FKB} = \rho g \frac{H}{2} L e^{-kT} \int_{-B/2}^{B/2} \sin(ky)y dy \quad [12\text{-}10]$$

$$F_{AMS} = \frac{1}{2}\rho p T^2 L\left(\frac{2p^2 H}{t^2}\right) e^{-k\frac{T}{2}}\left(\frac{T}{2}+r\right)\sin\left(\frac{kB}{2}\right) \quad [12\text{-}11]$$

$$F_{AMB} = \frac{1}{2}\rho p\left(\frac{B}{4}\right)^2 .\frac{5}{4}.\frac{B}{2}.L\left(\frac{2p^2 H}{t^2}\right) e^{-kT}\sin\left(\frac{kB}{2}\right) \quad [12\text{-}12]$$

<u>Added mass, damping coefficients and the spring terms</u>

The added mass and damping coefficients are both frequency dependant. However, they will be considered as constants as the method allows.

The heave added mass could be calculated with the formula:

$$a_{33} = L\frac{1}{2}\rho\pi(B/2)^2 \quad [12\text{-}13]$$

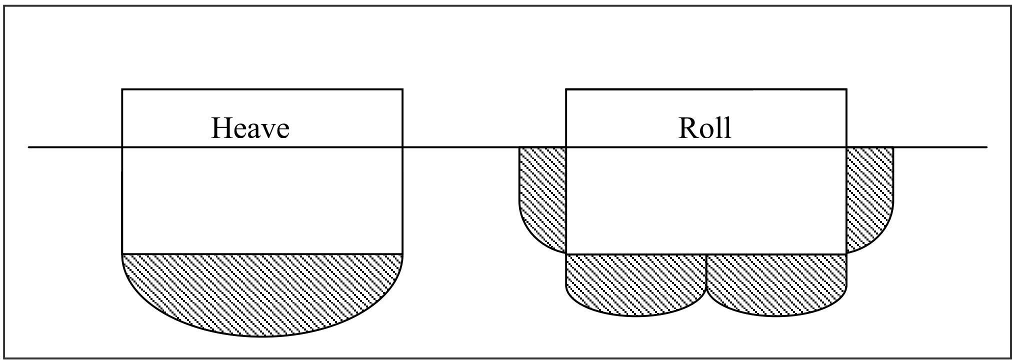


Figure12-2: added mass heave and roll

The roll added mass could be calculated with the formula:

$$a_{44} = L\rho\pi\left[(B/4)^4 + (T/2)^2(\frac{T}{2}+r)^2\right] \qquad [12\text{-}14]$$

Heave spring term:

$$c_{33} = \rho g A_w \qquad [12\text{-}15]$$

Roll spring term:

$$c_{44} = c_{hydrostatic} + c_{geometric}$$

$$c_{hydrostatic} = \rho g L\frac{B^3}{12} \qquad [12\text{-}16]$$

$$c_{geometric} = \rho g LBT(\frac{T}{2} - T_1)$$

Damping coefficient (roll and heave) [12-17]

$$b = 2\zeta\sqrt{Mc}$$

ζ is taken as 10% in the case of heave. this is a typical value for vessels

<u>Results</u>:

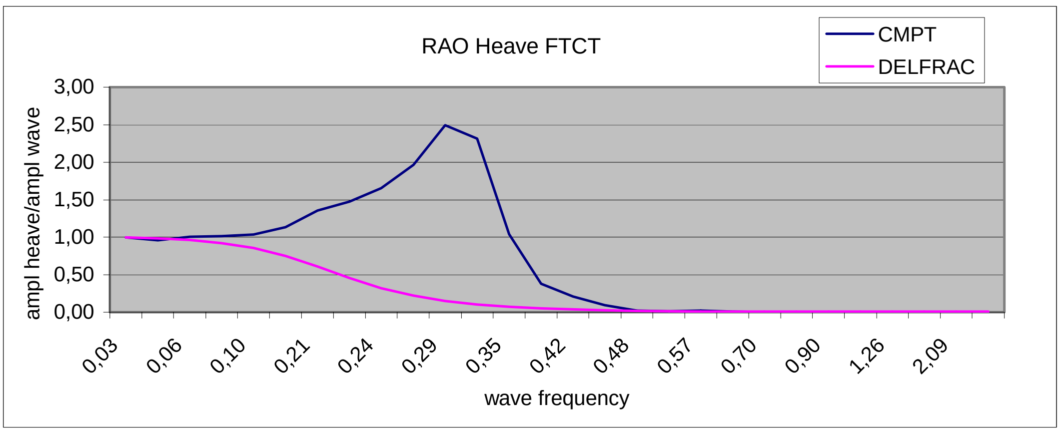


Figure 12-3: RAO FTCT heave motion, beam waves

The results obtained by the CMPT method and DELFRAC for the RAO-functions of the heave motions of the terminal on beam waves are shown in the figure 12-4. The calculations could be seen in appendix 12-2 and 12-3 respectively).
It is obvious from figure 11-3 that the CMPT method gives an overestimation of the response of the terminal. The graph has a peak –value of 2.5 near its natural frequency while the DELFRAC shows no peaks implying that the terminals damping is too large preventing such peaks.

Comparison added mass and damping coefficients:

- The added mass: the figure below shows that equation 11.13 (CMPT) for the added mass below gives acceptable results for a wide range of frequencies, actually the range which is of significance to the response calculations.

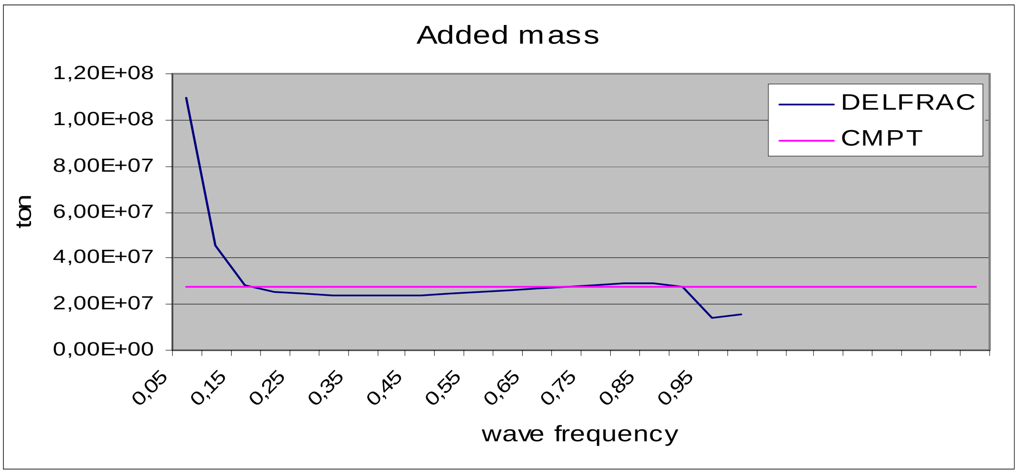


Figure 12-4: heave motion added mass FTCT

- In the contrary to the added mass, the damping coefficient calculated according to the CMPT method is considerably smaller than that of DELFRAC. This is graphically demonstrated in the figure below.

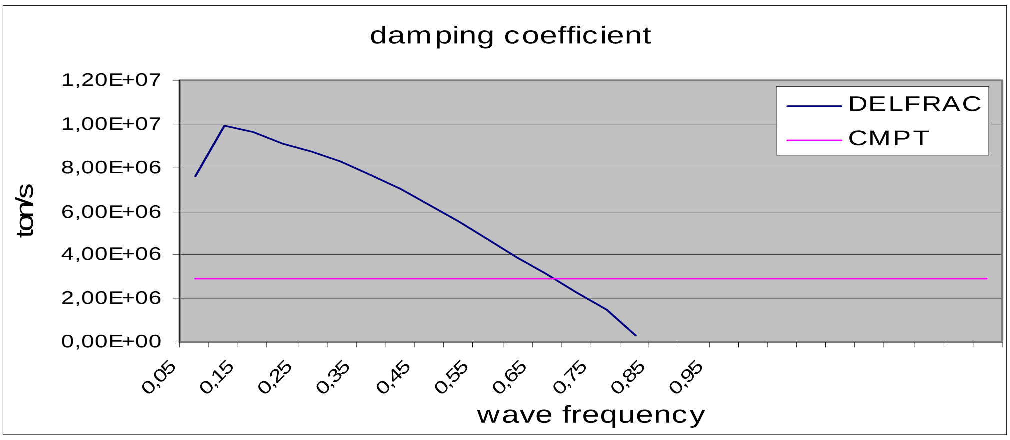


Figure 12-5: FTCT heave motion damping coefficient

The damping coefficient is dependant of the damping ratio ζ as given in equation 8.16. The assumed ratio of 0.1 is a typical ratio for vessels. When choosing for ζ = 1, for the pontoon-shaped FTCT a different result will be obtained for the RAO- function using the same (CMPT) method, as shown in figure below.

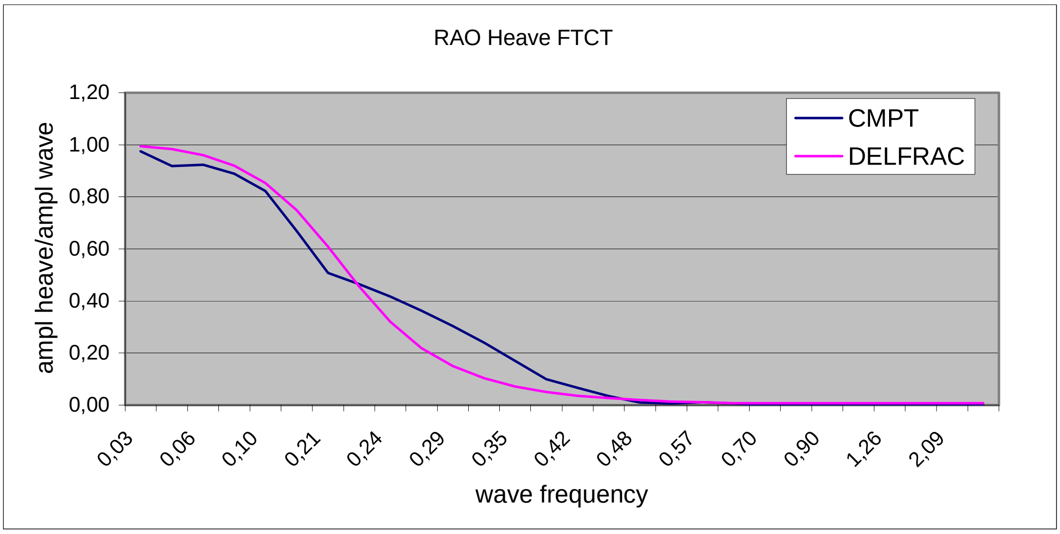
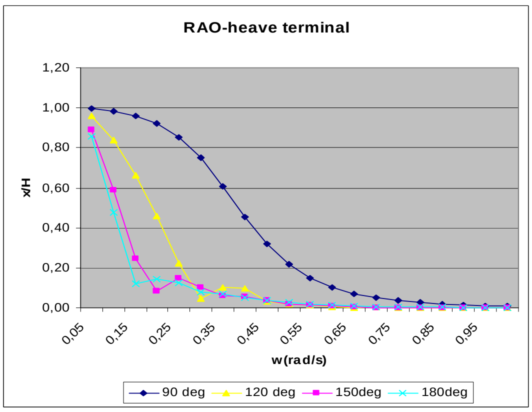


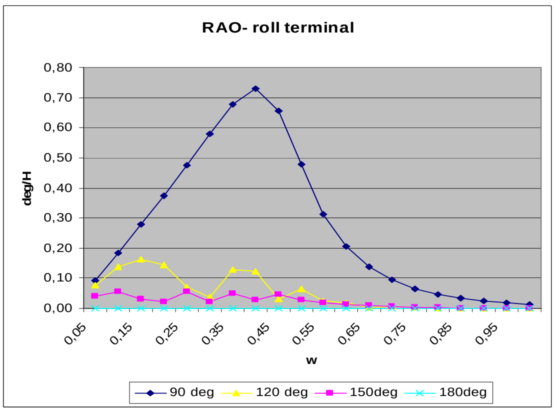
Figure 12-6: RAO heave motion FTCT, beam waves (ζ = 1)

<u>Evaluation</u>

Better results for the heave RAO-function are obtained for a damping ratio equals to 1. However, this could not be verified for a terminal with different dimensions (L, B or D). Therefore, the method introduced by the CMPT will not be further used and henceforth the DELFRAC results will be used as they are more reliable.

Below are RAO-functions of the **FTCT** obtained using DELFRAC for all six modes of motion and for waves from 4 different directions. H, x and degrees are amplitudes of the wave, translations and rotations respectively.





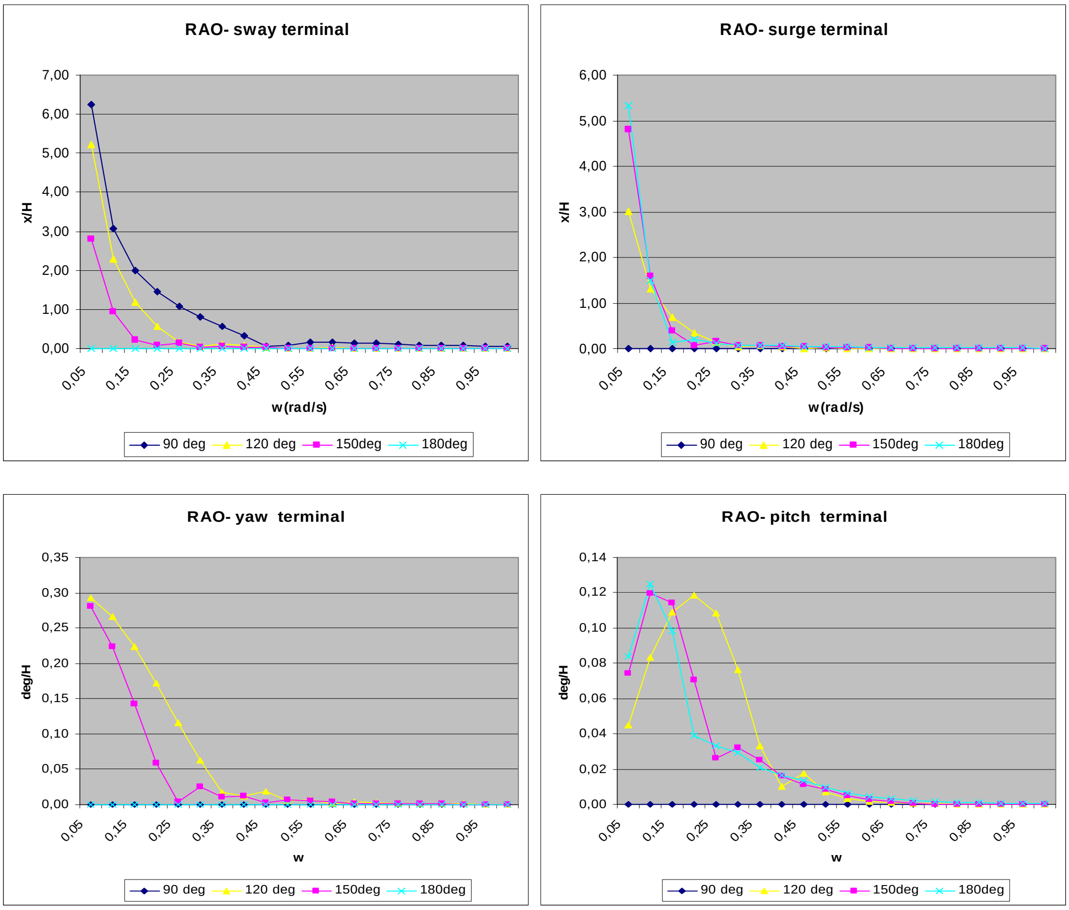


Figure 12-7: Terminals RAO-functions heave motion (DELFRAC)

Remarks:

- As already stated in the previous section, the pitch, yaw and surge motions are negligible in the case of beam waves (90 degrees).
- It becomes also obvious from the RAO-function, that the sway motions will be aggravated for waves with small frequencies in the case of beam waves.

12.2.2 The terminal heave motions

The wave spectra shown below are generated as described in section 11.5. the spectra are for two Beaufort scales, i.e. 6 and 7 . According to JONSWAP, scale 7 corresponds with a H_s of 3.6m and a T_2 of 6.25 s, while scale 6 has a H_s of 2.5m and a T_2 of 5.30s in the North SEA area

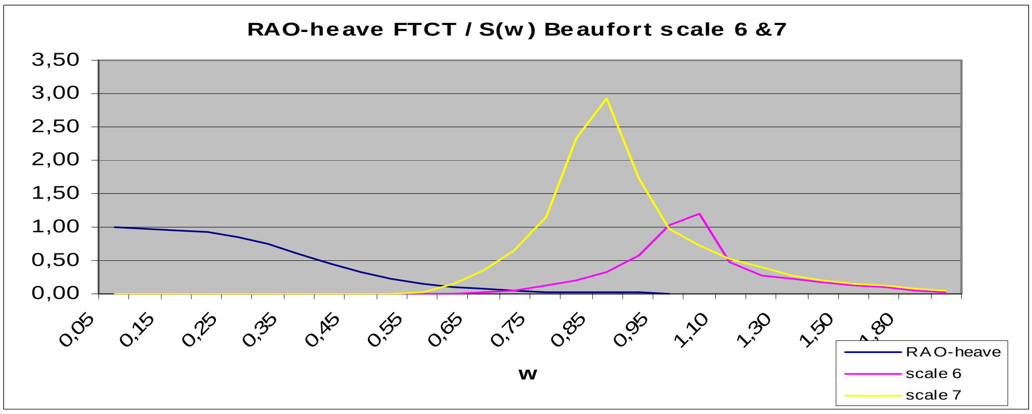


Figure 12-8: RAO heave motion-wave spectrum

Applying equation 12-1, the heave motion spectrum for scale 7 is as given below.[also appendix 12-4a and 12-4b).

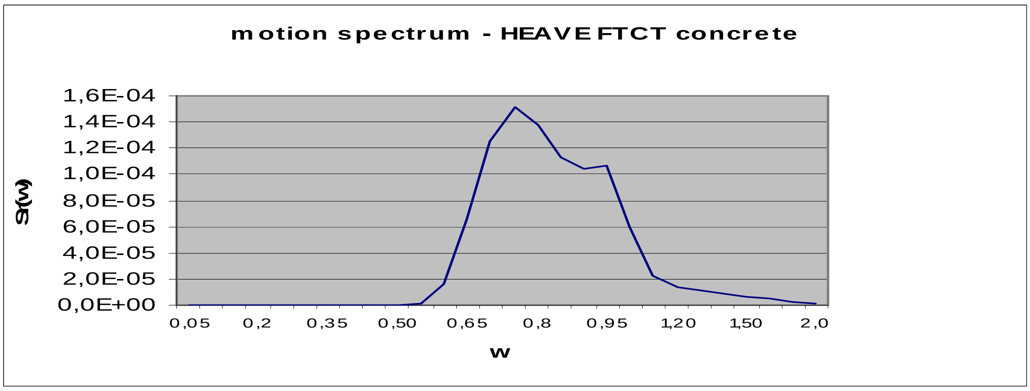


Figure 12-9: heave motion spectrum FTCT

The same steps were repeated for different sea states and the peak-to- peak amplitudes ($2 \cdot r_{a0.02}$) of the heave motion of the FTCT are calculated. The results are plotted below.

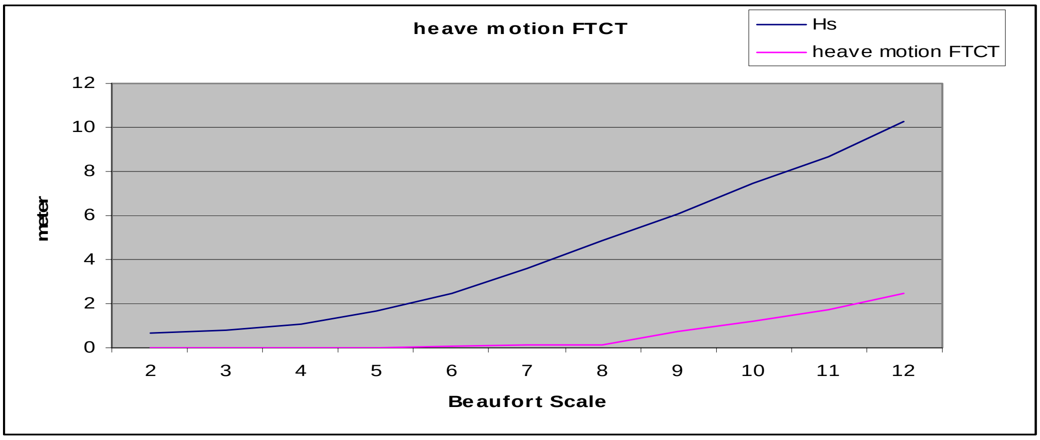


Figure 12-10: Heave motion FTCT

12.2.3 The terminal roll motions

The same approach taken in the case of the heave motions has been applied to calculate the peak-to- peak amplitude (in degrees) of the terminals roll motions. In Figure 12-11, the values are plotted for different sea states.

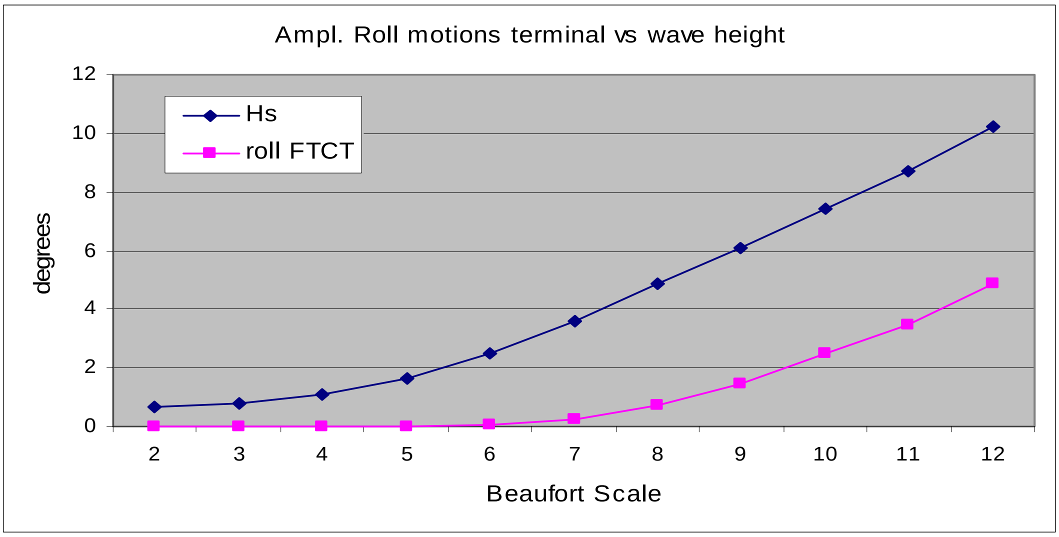


Figure 12-11: Terminal roll motions

12.3 Container vessel motions

In this section the heave and roll motions of the container will be treated.
Design vessel:
With the design vessel it is meant the type and size of vessel which will be used by the calculations of the motions and thus the final conclusion about the systems operability. It is chosen for an average sized feeder vessel. The large mega vessels perform relatively calmer motions and are not decisive. An average feeder vessel has the following characteristics:

LOA=	260m
B=	32m
D =	11m
C_B=	0.7
GM (transverse) =	1.0 m

12.3.1 RAO- function container vessel

The RAO-functions for heave and roll motions of the feeder vessel, are calculated with the computer model SEAWAY.

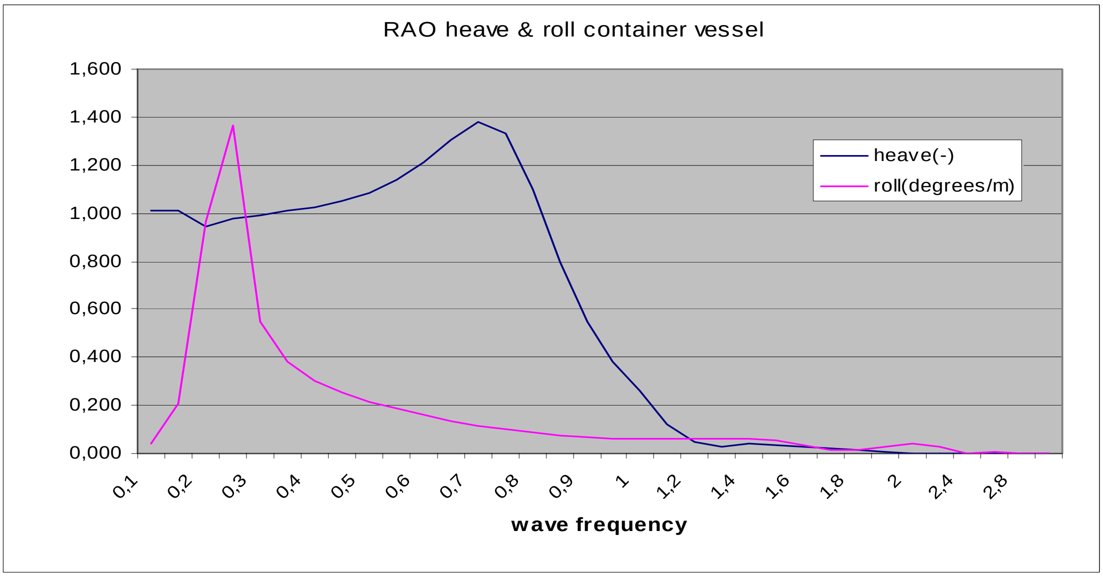


Figure 12-12: RAO heave and roll container vessels

12.3.2 Wave conditions at the berth side

The method to generate a wave spectrum at the berth side has already been explained in section 11.5. The first step is to calculate wave height at the berths side. This will follow from the transmission, diffraction and the dynamic swell-up.

- *Transmission factor (C_T):*
The calculation method is explained in paragraph 11.5. Two types of wind waves were examined to determine the transmission factor to the berths side of the incoming wave.

1. *Sea*, (locally generated waves) Beaufort scale 8 with H_s= 4.8 m and T_2 = 7.3s and T_p=9.4s
2. *Swell*, with a period of 13s.

The results could be seen in Appendix 12-5. In the first case, the C_T is found to be smaller (=0.15) than in the second case (=0.25). However, swell has often smaller wave heights compared to sea waves. Most of the swell waves in the North Sea areas have a wave height smaller than 2m. Therefore it could be concluded that the wave height transmitted in the first case is larger (0.15*4.8 = 0.72m) than in the second case (0.25*2= 0.5m).
For the motion calculations the transmission factor will be kept constant an equals to **0.15** as in the first case, unless it appears in a later phase that the lifting operations can proceed for a scale higher than Beaufort scale 8.

- *Wave diffraction:*
Using the transmission value C_T found above and the *Cornu Spiral* (section 11.5), it is possible to calculate the wave height at a certain point at the berth side as result of both transmission and diffraction. The point (at the berths side) is chosen at a distance of 75

meter in the longitudinal direction and 50 meter from the terminal in the lateral direction. The calculations are carried out in appendices 12-6a and 12-6b.

$$R = \left|(-\infty, T_{L)} + C_T(T_L, T_R) + (T_R, +\infty)\right| \quad [12\text{-}18]$$

$= 33$

It follows,

$C_{T+D} = 33/200 = 0.17$

- Dynamic swell-up:

Dynamic swell-up resulting from the heaving terminal is calculated using [11-4]. The increase of the wave height $2^*\Delta\zeta_a$ is found to be equals to **0.04m** and **0.1m** for Beaufort scale 7 and 8 respectively. The contribution of this phenomena is relatively small for the given wave conditions as result of the small amplitude of the FTCT's heave motion.

Evaluation

- using the above approach and in the case of an incoming wave of 4.8m (at the breakwater side), the wave height at the berth side of the terminal is 0.916 meter (0.17*4.8m +0.1m).
- Comparing the contribution of all three phenomena to the wave height at the berth side, it could be concluded that the wave transmission (under the structure) is much dominant than both the dynamic swell-up and the wave diffraction (in the chosen point). The contributions of the 0.92m calculated wave at the berth side, is divided as following.

- Wave transmission = 0.72/0.92 = 78.5 %
- Wave diffraction = 0.096/0.92 = 10.6 %
- Dynamic swell-up = 0.1/0.92 = 10.9%

Wave spectrum at the berth side

Using the above approach, calculations are carried out to obtain the wave spectrum at the berth side of the terminal. The wave spectrum is shown below for Beaufort scale 6 at the breakwater side. The incoming wave has a H_s of 2.5m and a T_2 of 5.3 s. The calculated H_s at the berth side is equal to 0.44 meter. The wave period is kept equal to that of the incoming wave, i.e. 5.3 seconds.

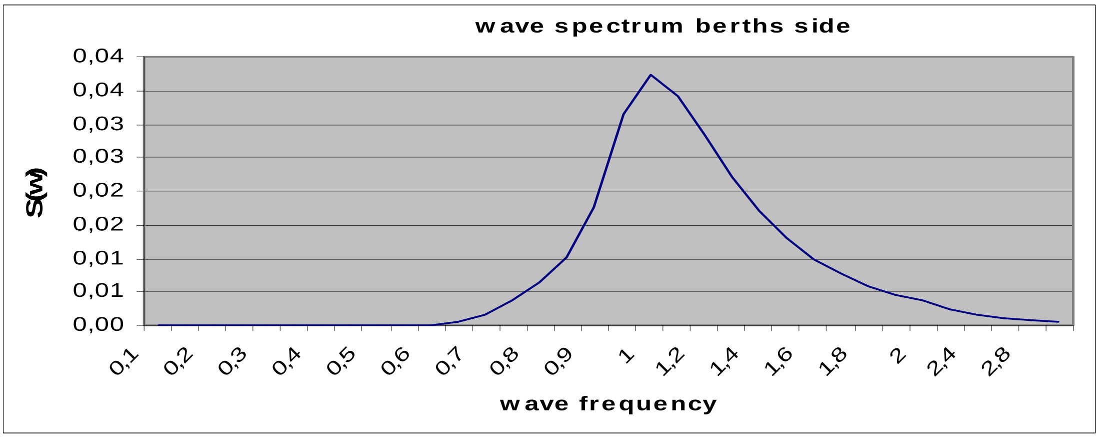


Figure 12-13: Wave spectrum berth side

12.3.3 Feeder vessel motions

The peak-to- peak amplitudes of the heave and roll motions of the feeder vessel follow from the generated wave spectrum at the berth side and the RAO- function for beam waves (equation 12-1). The peak-to-peak amplitudes ($2 \cdot r_{a0.02}$) of this motion were calculated for different sea states. In the figure below, the results are plotted for the heave motion. It should be emphasized that the H_s in the figure below is for the incoming wave at the breakwater side, while the amplitudes of the motions are those of the in the protected waters (berths side) floating vessel.

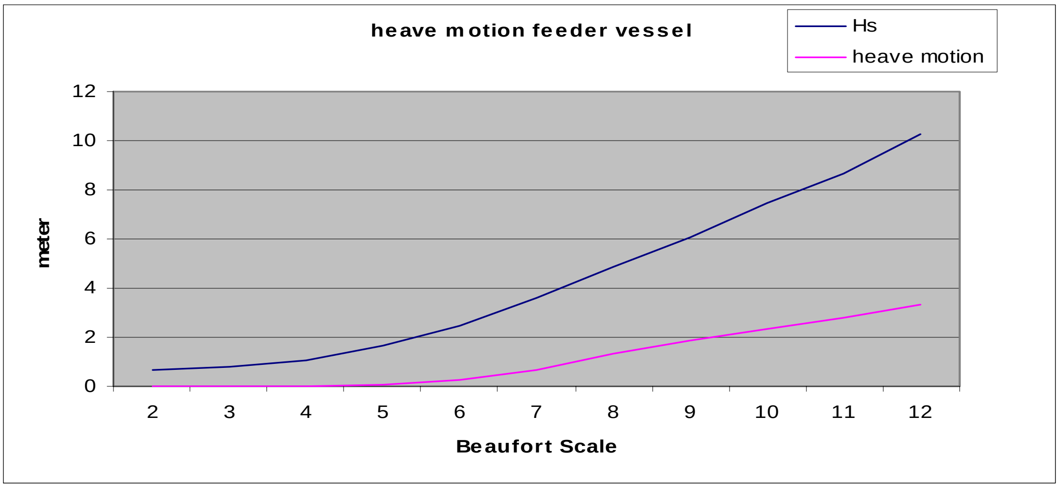


Figure 12-14: peak- to-peak heave motion feeder vessel

12.4 Relative heave and roll motions

It would have been possible to obtain a spectrum of the relative heave motion between the vessel and the crane (spreader) using superposition principle. In order to achieve this, the phase difference with respect to the incoming wave of both heaving bodies must be known (as function the wave frequency w). Unfortunately, in the case of the vessel, the phase difference between the incoming wave and the heave motion remains unknown. This is because of the fact that motions are induced by a locally (at the berth-side) generated wave spectrum.
As already described in the approach method (section 11.4), the amplitude of the relative motions (heave and roll) will be set equal to the sum of the amplitudes of both the terminal and the vessel motions.

Relative heave & roll motions

Figure 12-15 and 12-16 show the peak-to-peak amplitudes ($2 \cdot r_{a0.02}$) of the relative heave and roll motions (terminal and the feeder vessel) respectively. Furthermore, the maximum operating condition for each mode of motion is plotted.

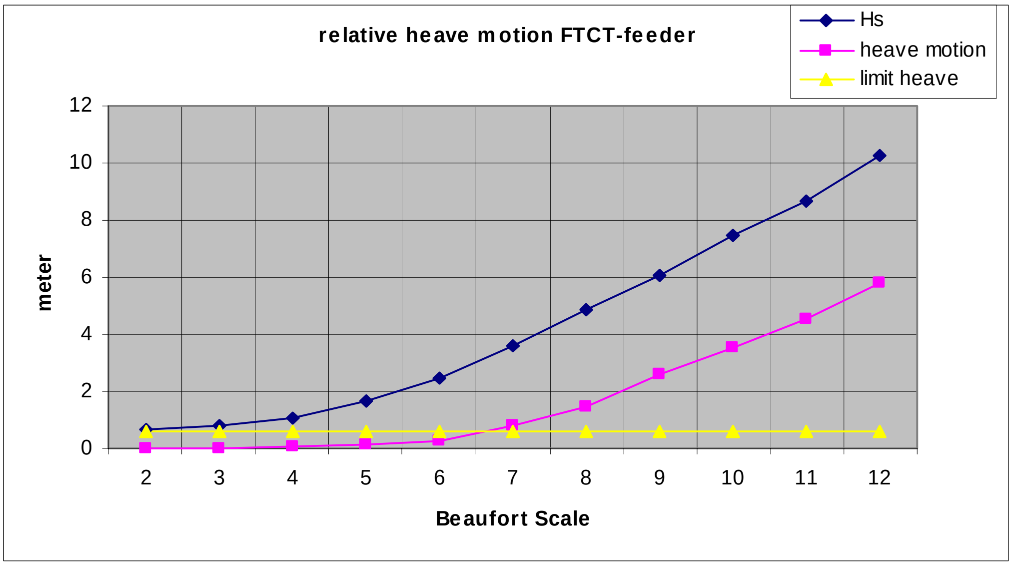


Figure 12-15: relative heave motion

In the case of roll motions, the dynamic swell-up was not accounted for. Equation 11-4 used to calculate $\Delta\zeta_a$ as result of the heaving terminal is only applicable for the heave motion. The negligence of the dynamic swell-up will be later evaluated.

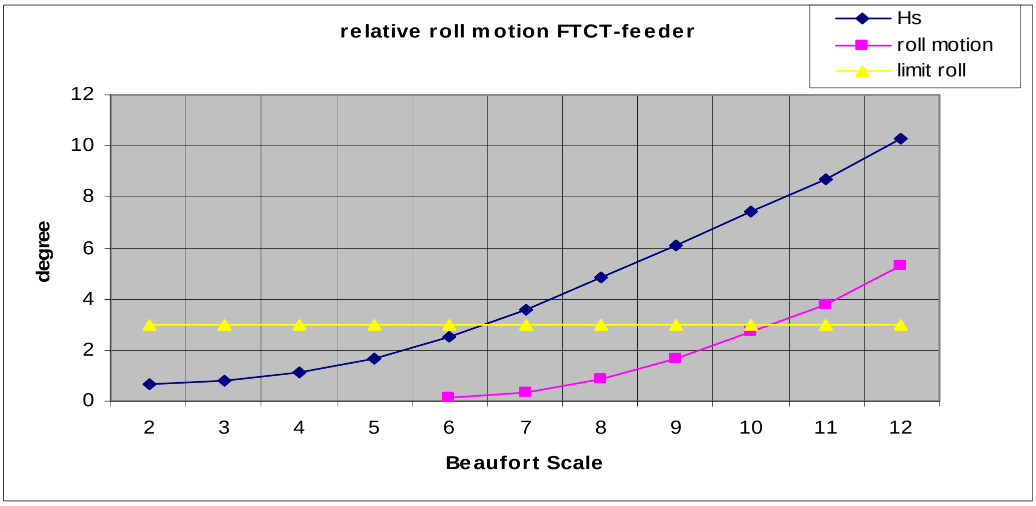


Figure 12-16: relative heave motion

12.5 The (absolute) vertical displacement

In the previous paragraphs of section 12, the calculations where mainly made for separate modes of motion. In this paragraph, the vertical absolute displacement of the motion at the crane (spreader) will be calculated. According to the approach adopted, conclusions

could not be drawn about the systems operability based on the absolute motions. However, the calculation are carried out so that a comparison could be made between a fast quay portainer (not moving) and the on the floating terminal mounted portainer.
Equation 11-1 gives an expression for the vertical displacement at any point in the terminal. The largest motion will be encountered when the spreader is at the outermost point of the boom, thus 50 m from the quay (170m from the CoG of the terminal). The pitch contribution is very small on beam waves and will be neglected. Equation 11-1 then reduces to:

$$z_p = z + y \cdot \phi \qquad [12\text{-}19]$$

Where z is the heave motion and ϕ is the roll rotation at the CoG in radians. y = +170m.
This equation could also be written as following:

$$\begin{aligned} h(w,t) &= z + y_b\phi \\ &= z_a \cos(wt + \varepsilon_{z\zeta}) + y_b\phi_a \cos(wt + \varepsilon_{\phi\zeta}) \end{aligned} \qquad [12\text{-}20]$$

Applying the sum rule[1], gives the in and out of phase terms

$$\begin{aligned} &= \left\{ +z_a \cos\varepsilon_{z\zeta} + y_b\phi_a \cos\varepsilon_{\phi\zeta} \right\} \cdot \cos(wt) - \\ &\quad \left\{ +z_a \sin\varepsilon_{z\zeta} + y_b\phi_a \sin\varepsilon_{\phi\zeta} \right\} \cdot \sin(wt) \end{aligned} \qquad [12\text{-}21]$$

Also,

$$\begin{aligned} h(w,t) &= h_a \cos(wt + \varepsilon_{h\zeta}) \\ &= \left\{ h_a \cos\varepsilon_{h\zeta} \right\} \cdot \cos(wt) - \left\{ h_a \sin\varepsilon_{h\zeta} \right\} \cdot \sin(wt) \end{aligned} \qquad [12\text{-}22]$$

From equations 12-21 and 12-22, it follows that

$$\begin{aligned} h_a \cos\varepsilon_{h\zeta} &= +z_a \cos\varepsilon_{z\zeta} + y_b\phi_a \cos\varepsilon_{\phi\zeta} \\ h_a \sin\varepsilon_{h\zeta} &= +z_a \sin\varepsilon_{z\zeta} + y_b\phi_a \sin\varepsilon_{\phi\zeta} \end{aligned} \qquad [12\text{-}23]$$

And thus,

$$\begin{aligned} h_a &= \sqrt{\left(h_a \sin\varepsilon_{h\zeta}\right)^2 + \left(h_a \cos\varepsilon_{h\zeta}\right)^2}, and \\ \varepsilon_{h\zeta} &= \arctan\left\{ \frac{h_a \sin\varepsilon_{h\zeta}}{h_a \cos\varepsilon_{h\zeta}} \right\} \end{aligned} \qquad [12\text{-}24]$$

For a H_s of 3m and a T_2 = 6 sec (beam waves) is z_a = 0.035m, $\varepsilon_{z\zeta}$ = 165 degrees, ϕ = 0.065 degrees ($1.13 \cdot 10^{-3}$ radians) and $\varepsilon_{\phi\zeta}$ = 355 degrees.
The corresponding amplitude of the vertical motion at point P is 0.157m.

[1] Sum rule: cos(a+b) = cos(a)cos(b)+sin(a)sin(b)

12.6 Evaluation

- The limit for the amplitude of the (relative) heave motion during the operation of the terminal is 0.6m. From 12-15 it could be seen, that this limit lies between Beaufort scale 6 (H_s =2.5m, T_2=5.3) and scale 7 (H_s = 3.6m and T_2=6.25m). For a H_s of 3 m and T_2=6.0s, the heave relative motion is 0.59m, thus just below the limit.

- In the case of roll, it is found that motion limit is exceeded only if the wave conditions at the breakwater side are beyond scale 10 (figure 11-15).

- Therefore, it could be concluded that heave is decisive when determining the limiting wave conditions under which operations could continue (SLS).

- The facts that the contribution of the dynamic swell-up to the wave height at the berth side is small (see 12.3.2) and that the heave motion found to be decisive, makes its negligence in the case of roll has no effect on the final conclusion.

- The wind speed which corresponds with Beaufort scale 6 is 24.5 knots (44 km/hr). By this wind speed the lifting operations will be hindered by the wind loads on the container itself. Thus, even for a fixed berth, problems will be encountered during sea conditions beyond scale 6 as result of the wind.

- As already mentioned, the aim of the calculations of the amplitude of the vertical motion (11.4.3) is to give an indication about magnitude of that motion at the tip of crane. It can not be coupled to the (PIANC) criteria for motion, as the later treats different modes of motion separately. It could only be used to compare between an FTCT mounted crane and a fast quay crane.

- Terminals acceleration:
  According to the program of requirement, the maximum accelerations limit (with regard to operation of equipment, cargo safety, etc), is 0.12g. The vertical acceleration of the terminal as result of heave during sea state (Beaufort scale) 7 is found to be equal to 0.042g. This acceleration is much less than the maximum limit.

13 Station keeping

Introduction
The floating terminal is exposed to wave, current and wind loads. To prevent it from being drifted away, a mooring system and/or DPS (Dynamic Positioning System) is needed. The mooring system should be capable of resisting the horizontal forces and allow the terminal to move freely in the vertical direction.
In this section, a number of alternatives will be studied and finally one will be selected to station keep the floating terminal.

13.1 Approach method

Environmental loads on the terminal will cause horizontal motions of the terminal. These motions will result in deflection of the mooring lines. The later will exert a reaction force on the floating terminal and restricts its motion. The stiffness of the mooring system will determine its deflection. While the reaction force will also follow from stiffness of the mooring system. Thus, the design process has an iteration character.
To deal with this, the following approach will be taken:
Step-1
The on the mooring system acting forces acting in the mooring system will be roughly calculated and in some cases estimated. This will give an indication of the magnitude of the total mooring force.
Step- 2
Based on the results of the previous step, different alternatives of mooring systems will be examined for there eligibility. Finally a system is to be chosen for the station keeping of the terminal
Step-3
Once the system and is determined based, calculations providing accurate results of the acting forces will be carried out in the next two section. At the end, it will be checked if the estimated design force was not underestimated and that the final design satisfies.

13.2 Serviceability and Ultimate limit states

In this paragraph distinguish both the *Serviceability Limit State* (SLS) *the Ultimate Limit State* (ULS) will be defined.

Serviceability Limit State (SLS)
The serviceability limit state is defined as the environmental conditions within which the load and unload operations could proceed. This was the theme of the previous section and it was found to be between Beaufort scales 6 and 7.

- $H_{s;\,SLS}$ = 3.6m (Beaufort scale 7)
- Wind speed = 15.3 m/s (Beaufort force 7)
- Current speed = 1m/s (see section 11.5)

Ultimate Limit State (ULS)

The ultimate limit state is determined by the sea conditions in that particular location. In the case of the FTCT, the ULS is of significance to the *structural design* and the *mooring system*. For example, the structure or the mooring system should be capable of resisting loads of waves with a certain frequency of occurrence or returning period.
As no particular location is yet chosen for the floating terminal, other approach will be taken. The mooring system will be designed for sea conditions up to Beaufort Scale 12. The corresponding significant wave height is 10.25m. This will be evaluated in section 18 of this report.
The Ultimate limit state (will be called survival conditions further on) of the terminal are:

- H_s = 10.25 (Beaufort force 12)
- Wind speed = 32 m/s (Beaufort force 12)
- Current speed = 2m/s (assumed, in deep water)

13.3 Estimation mooring forces

The on the system acting forces are:

1. steady forces as result of
   - Current,
   - Wind,
   - And mean wave drift forces.
2. As result of the (oscillatory) motions due to:
   - Wave frequency forces (1st order),
   - And low frequency wave forces (2nd order).

The Steady forces

Mean wave drift forces :

$$F^{(2)} = L \frac{1}{16} \rho_{water} g \left[(1\text{-}C_T)\, H_{s;inc} \right]^2 \qquad [13\text{-}1]$$

Currents forces :

$$Fc = \frac{1}{2} \rho_{water}\ C_s A\ v^2$$

[13-2]

Wind forces:

$$Fw = \frac{1}{2} \rho_{air}\ C_s A\ v^2$$

Where,

C_T	wave height transmission coefficient (= 0.15 as calculated in section 8)
L	length of the terminal (= 1190m, in case of beam waves)
ρ_{water}	Density water (1.025 ton/m^3)
$Hs;_{inc}$	significant wave height of the incoming wave.
ρ_{air}	Density air (1.25kg/m^3)

A	Wind age area /current area
v	current/wind speed
C_s	shape coefficient (= 1 for rectangular barges)

2. Oscillatory motion induced mooring forces

Considering the large size of the terminal, it is expected that **motions** induced by the 1st order wave forces and therefore the mooring forces to be relatively smaller compared to the sum of the steady forces.
The low frequency (2nd order) wave forces and the resulting induced motions depend on the characteristics (stiffness)of the mooring system. Usually, the mooring system has small stiffness and thus low natural frequency. Although, these forces have small amplitudes but resonance could aggravate the motions and thus the forces in the mooring lines.
The magnitude of both of these mooring forces depends on the response of the terminal which is in its turn also depending on the (stiffness) mooring system.
To deal with this, it is estimated that the sum of the oscillatory forces is equal to ½ the sum of the steady forces.

Results:
- Assuming all forces acting at the same direction (worst case), the total of the steady forces is calculated in appendix 13-1. The results are shown in the table below

	Force	SLS (MN)	ULS (MN)
1	$F_{current}$	6.28	25.13
2	F_{wind}	1.74	7.62
3	$F^{(2)}$	7.00	56.77
	TOTAL	15.03	89.51

Table 13-1: steady forces

- Total acting force (ULS) = 1.5 * total steady force = **134 MN**
- Total acting force (SLS) = 1.5 * total steady force = **23 MN**

As can be seen from the previous estimation, the mean wave drift force has the largest contribution, in both the ULS and SLS.

13.4 Alternative solutions

This section treats a number of alternatives with regard to the station keeping of the terminal

1. Spread Moorings:

- Mooring lines are directly connected to both the stern and the bow of the floating structure.

- Fixed orientation towards load.
- Generally used in mild environments.
- Mooring lines are made of chains, wires or synthetic fiber ropes

2- Dynamic Positioning System (DPS):

- Thrusters of the DP system below the water, counteract for environmental forces.
- Thrusters may be controlled either manually (joystick control) or automatically (computer).
- High energy consumption.
- Currents produced by thrusters may cause hindrance for the mooring vessels
- Risk of Coanda Effect (thruster slip stream will be attracted by the hull, reducing the efficiency of the thruster)
- Could also be used to resist motions induced by wave low frequency forces.

3- Single Point Mooring (SPM)

The SPM systems have the advantage that it allows the terminal to weathervane and obtain an optimal orientation (beam waves) according to the prevailing wave direction.
As disadvantage, an SPM with large forces could be unfavorable from a structural point of view, as all these forces are concentrated within small area of the structure

Two of the most common types of SPM's are:

3a. Turret mooring:

a. This type of mooring is generally used in harsh environments.
b. Multiple mooring lines come together at the turntable of the floating structure.
c. Mooring lines are terminated at the seabed using anchors or piles.

Figure 13-1: Turret mooring

3b. CALM buoy:

d. Buoy is moored by means of four or more mooring lines at equal spaced angles.
e. The floating structure is connected to the buoy with a single line and free to weathervane around the buoy.

F

Figure13-2: CALM buoy

13.5 Selection

-Technical aspects:

The mooring should be reliable and able to resist the environmental forces in both the ULS and SLS.

- Freedom to weathervane.

With the freedom to *weathervane*, it is meant that the terminal will be able to have an orientation always beam-on to waves. In General, a **free** floating body (with no thrusters' action) in waves will weathervane (maintain a position with its long side perpendicular to wave). However, when using a mooring system to prevent it from being drifted away this characteristic could disappear.

- Financial aspects.

Operating and construction costs should not be too high.

Selection:

- Although the spread mooring system resembles a reliable and relatively inexpensive alternative, it has the disadvantage that it does not allow the terminal to weathervane. Therefore, it imposes the restriction about the wave direction and the location of the terminal. The waves have to come from one direction (during the most time) so that the terminal could operate.
- In the contrary, DP thrusters retain the characteristic of the terminal to weathervane. However, because of the large dimensions of the terminal, the system is less reliable and also economically unattractive solution.
- The single point mooring appears to be the most suitable mooring system for the FTCT. Especially the turret mooring which is usually used in harsh environments.

13.6 Combined DP-turret mooring system

The turret mooring system is the best alternative that serves the operability of floating terminal. However, to fulfill the main function-station keeping- the system must be able to deliver the required resisting force.
To examine this, the minimum number of chains required is roughly calculated below.
Choosing for the largest used mooring chains with a diameter of 185mm (source: Vryhof, anchor manuals 2000), then it follows:

- Break load of chain (CBS) = 21 MN
- Design strength of the chain = 1/3 CBS = 7 MN
- Needed number of chains = 134/7 = 20 chains

Only the active (tensioned) chains deliver the resisting force. Therefore, whenever the loads have spreading in direction- which is the case of the FTCT- the number of the chains in the turret has to be doubled. It follows that,

- Minimum number of chains in the turret = 40 lines

Actually a larger number of chains will be needed than the above calculated. This is

because of the fact that mooring lines making an angle with the resultant of the loads, deliver smaller force than the ones parallel to the resultant force.
Mounting that number of chains could be technically challenging. A too large turret will be needed. Furthermore, during rough sea conditions the lines will exert gigantic concentrated forces that will be transferred to the structure (hull) of the terminal.

A more attractive solution is the *combined DP-turret mooring system*. It consists of a turret mooring and DP thrusters.
The idea behind the combined DP-turret system emerges from the following two facts:
1- The large resulting force which the turret has to resist is mainly caused by the large length dimension of the terminal, in its beam-on position.
2- During survival conditions, the terminal does not need to maintain this position. The lifting operations should have stopped long time before and the vessels are expected to have already left the terminal.

If it is possible, that the terminal maintains a position heading to waves (bow-on) during the survival conditions, the waves attack area will be considerably reduced. The acting force will also be reduced by a factor of 4.95 (1190/240). **The mooring force in the ULS will then be 27.1 MN and in the SLS will remain unchanged (23 MN).** The ULS is then the decisive case.

In order to achieve this, it could be chosen for one of the two proposed variants of the combined DP-turret mooring system discussed below:

Variant -1
Figure 13-3 shows a mooring system with the turret mounted in the intersection point of amidships section and middle line plane. Without the action (moments) of the thrusters the terminal will always maintain beam-on position. When the significant wave height H_s exceeds the 3m, the vessels should begin to leave the terminal. Once the vessels are in a safe distance from the terminal, thrusters could be used to create rotating moment bringing the terminal into a bow-on position.

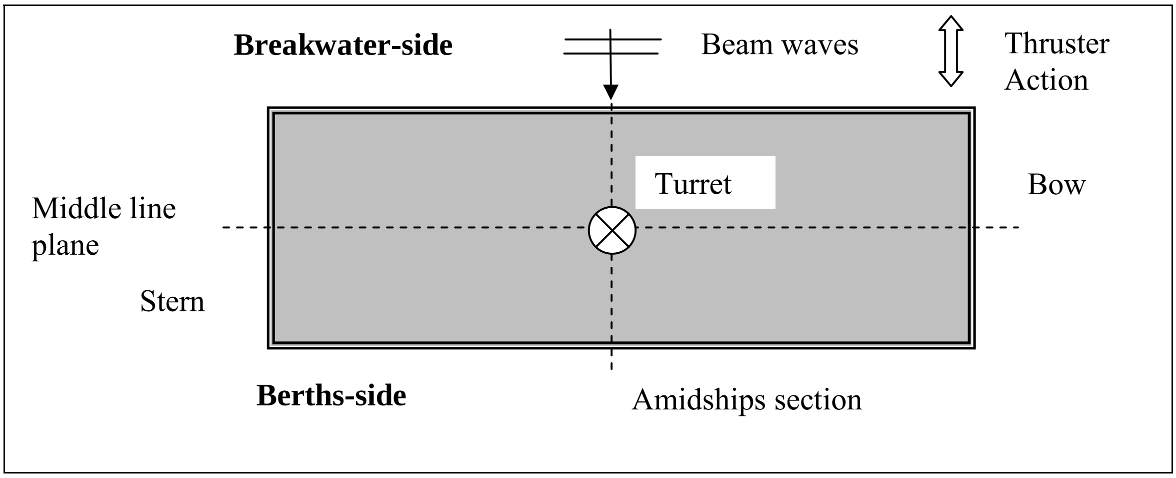


Figure 13-3: variant (1) - Centric turret

Variant -2

Figure 2 shows a system where the turret is mounted along the middle line plane with some eccentricity from the amidships section. The thruster action will be needed continuously to maintain beam waves position during the operation of the terminal. During storm conditions the vessels should leave the terminal. The DP thrusters are to be deactivated and the terminal will then weathervane towards heading seas (bow-on).

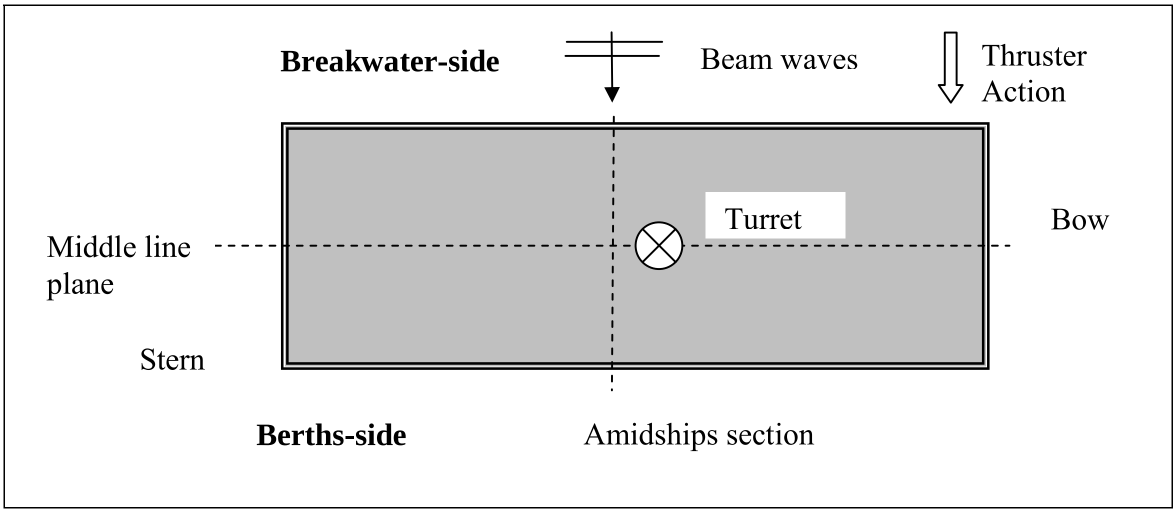


Figure 13-4: variant (2) - Eccentric turret

Selection:

- The first variant is financially more attractive as the thrusters only operate during ULS conditions. While the second variant requires that the thrusters must always be active during the operation of the terminal
- By the first alternative, the terminal will be in a state of **unstable equilibrium**. It tends to return to its beam-on position by the absence of the thrusters action. Thus, the failure of the DP system means the failure of the whole mooring system as the turret chains are not designed for beam-on sea loads during survival conditions.

The selection should be based on a *Risk Assessment Analysis*. The risk (damage* probability) versus the operating costs of each variant have to be determined.

However, at this stage it is chosen for the second alternative as it is considered to be more reliable. Not only the damage of the mooring system as result of the failure of the DP thrusters is possible, but also collisions with vessels or other structures in the vicinity of the freely floating terminal could take place.

13.7 Preliminary design of the combined DP-turret mooring system

The aim of this section is to make a preliminary design of the mooring system and to calculate its stiffness (K). The equation of motion could be written in the form:

$$M\frac{d^2x}{dt^2}+b\frac{dx}{dt}+Kx=F_{static}+F_{wavefrequency}+F_{slowdruft}+F_{mooring} \qquad [13\text{-}3]$$

13.7.1 The mooring lines

The CMPT (Centre for Marine and Petroleum Technology) gives a method to calculate the chain size, number of mooring lines needed and the stiffness in a preliminary stage of the design. Appendix 13-2 explains the method as given in the reference [*Floating structures: a guide for design and analysis, CMPT 1998]*

Starting points:

- Catenary chain mooring lines.
- The lines are to be mounted at even distances around the turret. This is to make sure that for horizontal loads from every direction; an equal number of lines will be active (tensioned).
- Linear characteristics of the catenary lines
- There is no requirement with regard to the maximum deflection of the terminal. The lower the stiffness, the larger the deflection becomes. Low stiffness also leads to smaller mooring forces. However, problems could occur with the anchorage of the non-tensioned lines if they move from one side to the other over there anchorage. Considering a water depth of 100m and a maximum inclination of the lines of 1:1 to touch down point (at sea bed), then the maximum deflection becomes 100m (including offset deflection).

Number of chains

$$H = \frac{1}{3} CBS \qquad [13\text{-}4]$$

$$CBS = N_{chain} \cdot c(44 - 0.08D) \cdot D^2$$

Where,

H design strength (N)
CBS catalogue break strength (N)
c chain grade factor (= 27.4 N/m^3, grade 4)
D diameter chain (mm)
N_{chain} number of (active) chains

Calculations are shown in appendix 13-3. For a chain diameter of 180mm and N_{chain} equals to 4, the design strength is **35.04 MN**. This satisfies the minimum required strength of **27.04 MN**

Number of mooring lines

The lines contribute unequally to the total mooring force delivered, as result of the unequal displacements. For a chain making an angle θ to the direction of the motion, the applied deflection and the restoring force are both reduced by cosθ. For linear system, each chain contributes to the stiffness by $\cos^2\theta$.

The figure below shows the chosen plan for the catenary lines. The angle between the mooring lines is 45 degrees. Only 3 lines will contribute to the restoring force per direction.

Each line consists of two chains, thus making a total of six.

N_{chain} = 2*cos(0) + 2*cos(45)+2*cos(45) = 4.8 > 4,thus satisfies

Stiffness = 2*cos(0) + 2*$\cos^2$(45)+2*$\cos^2$(45) = 4 > 4, also satisfies

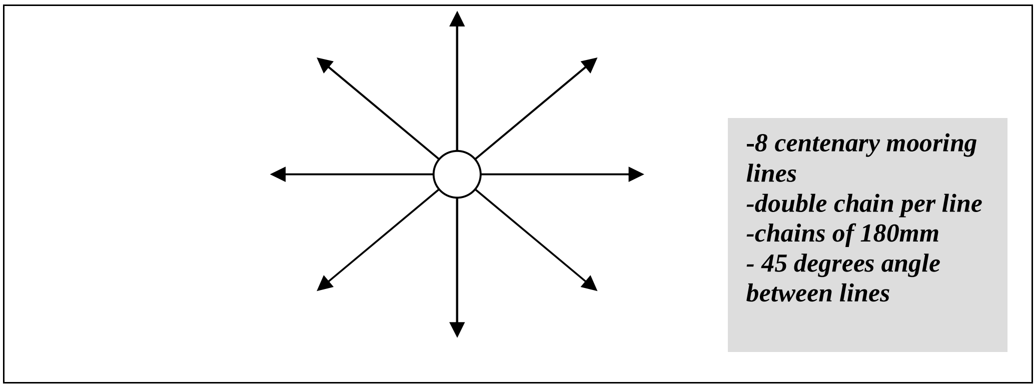


Figure 13-5: Spreading plan mooring lines

<u>Stiffness of the mooring system</u>

The stiffness is inversely proportional to the natural period of the mooring system. To prevent large wave frequency forces, the natural period of the mooring lines must be much longer than that of the wave.

- *Upper limit of the stiffness:*

To avoid dynamic amplification of the wave frequency loading response (at periods up to 20 seconds), a lower limit of 100 seconds for the natural period is considered. The maximum stiffness could be calculated.

$K < 4\pi M/T2$

Thus the upper limit of the stiffness (K) is 11.6 MN/m

The stiffness calculations were carried out according to the CMPT method as shown in appendix-13-3. The results are given below.

- The Elastic stiffness = 117 MN/m
- Horizontal stiffness = 484 kN/m
- Total stiffness = 482 kN/m
- Design stiffness = 386 kN/m

13.7.2 Dynamic Positioning system

Diesel and electric drives are both possible applications. In the offshore world, the electric drive is very common will be used also in the FTCT.

Additional requirements with regard to the DP system:

- The thruster jet stream must flow in the opposite direction of the berths.
- The thrusters should be located as far as possible from the container vessel berths parallel to the amidships section.

<u>DP system Thruster forces</u>

The thrusters are to be fixed to the hull of the terminal in a line parallel to the middle line

plane. The resultant of the thruster forces is regarded to be acting at a distance of 560m in the positive x-axis (35m from the bow end). This will maximize the turning moments delivered by the thruster on the terminal and at the same time guarantees enough space for the thrusters to be mounted.
The larger the eccentricity, the larger the thruster force must be. At the other hand, a large eccentricity will shortens the time needed for the terminal to rotate.
The turret's center is to be mounted at the (0, +10m) from the center of buoyancy (intersection amidships with the middle line plane in the case of the FTCT).

Moment (M) = eccentricity turret * total mooring force
$M_{max;SLS}$ = 23 MN*10m = 230 MNm
Maximum required thruster force = 230/ (595-10-35) = 0.42 MN

Evaluation:
The relation between thrusters power depends on the type of thruster used. A conventional *steerable thruster* typically provides between 100 and 150 N/hp (source: Floating structures: a guide for design and analysis, CMPT 1998). Therefore, the needed Total thruster power: 420000/100 = 4200 hp
Motors used in middle size tugboats have a power of 1000-2000 hp. Accordingly it could be concluded that the required thruster power is obtainable. Two thrusters, each 2200 hp will provide the required thruster power for the FTCT

14 Mean wave drift forces & response

Introduction

In the previous section, it is roughly calculated that the steady mean wave drift force has the largest contribution to the total mooring force. The theme of this section is to calculate the exact magnitude of these forces.
The mean drift force is non-oscillating and results in an ***offset*** (steady deflection)of the terminal.

14.1 Approach method

The resultant of the mean drift force will be calculated in 4 different orientations of the terminal with respect to the incoming wave (or vice verse). During the rotation of the terminal the forces change. It is important to calculate these forces at different stages and find out what the largest (decisive) force is. The 4 situations are

- during operation (90 deg.) : Sway only
- during rotation (120 deg.): Pitch and Sway
- during rotation (150 deg.): Pitch and Sway
- during survival conditions (180 deg): Pitch only

Calculation method and equations:

$$F^{(2)}_{1_{mean}} = \sum_{i}^{N} \zeta_i^{(1)^2} \cdot P_{ii}$$

and,

$$\zeta_i^{(1)^2} = 2 \cdot S_\zeta(w) \cdot dw_i$$

therefore, [14-1]

$$F^{(2)}_{1_{mean}} = 2\int_0^\infty S_\zeta(w) \cdot P(w,w)$$

where,

$P(w,w)$ is the mean drift force in regular waves

- The P(w,w) values for Sway, Surge and Yaw has been obtained from the computer program DELFRAC.[see appendices 14-1a and 14-1b]
- The wave spectrum $S_\zeta(w)$ will be calculated as in the previous sections, using the JONSWAP method for the North sea areas.
- The integral of equation 14-1 is calculated with the trapezoidal rule.

14.2 Magnitude of the forces

The calculations are carried out for the 4 cases. The results are shown graphically below. Appendices 14-2a and 14-2b show the calculations for the case of beam waves, thus sway only.

- During operation (beam-on)

The calculations were repeated for different sea conditions and the results are plotted below as function of the Beaufort scale.

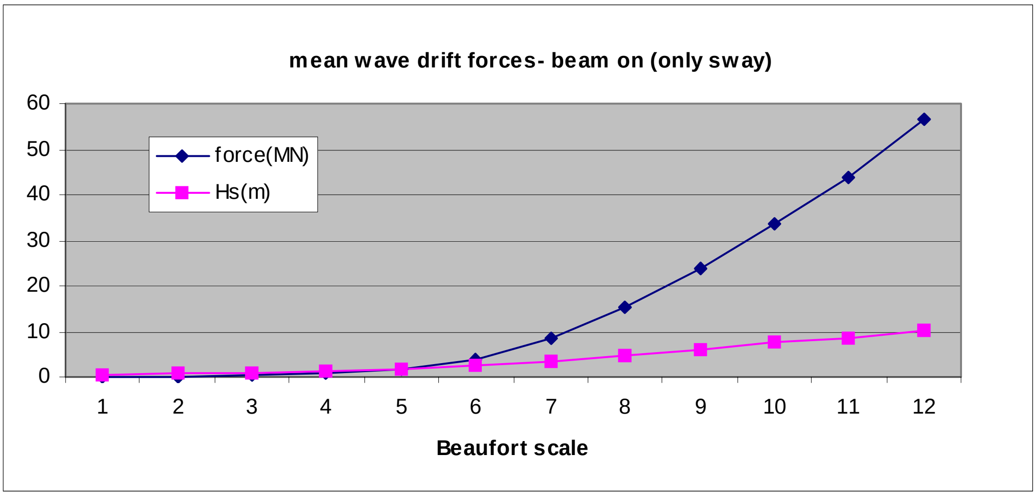


Figure 14-1: mean wave drift forces, beam waves

- During the rotation

Similar steps were taken to calculate the resultant of the forces for two different orientations. In this case, the resultant of force is consists of the sway and surge forces.

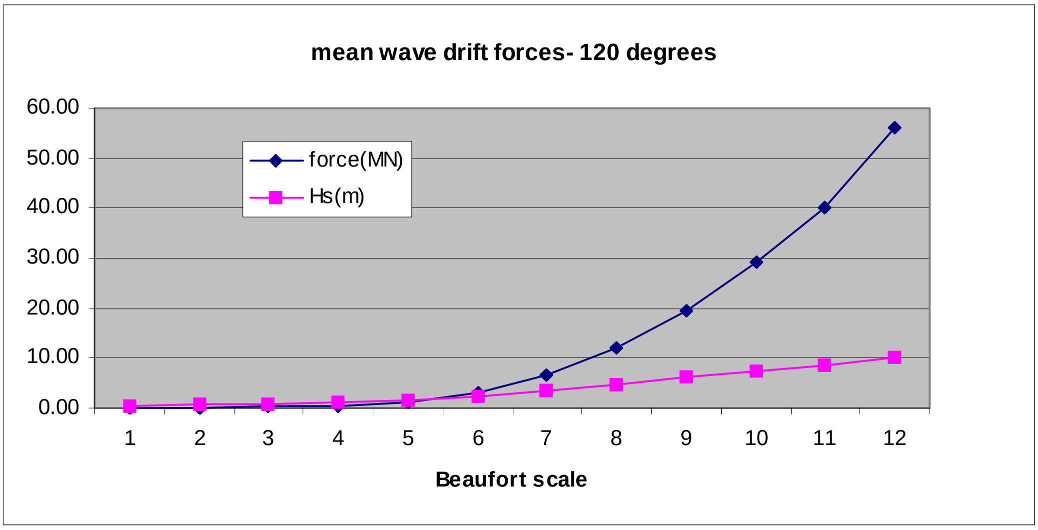


Figure 14-2: mean wave drift forces, waves 120 degrees

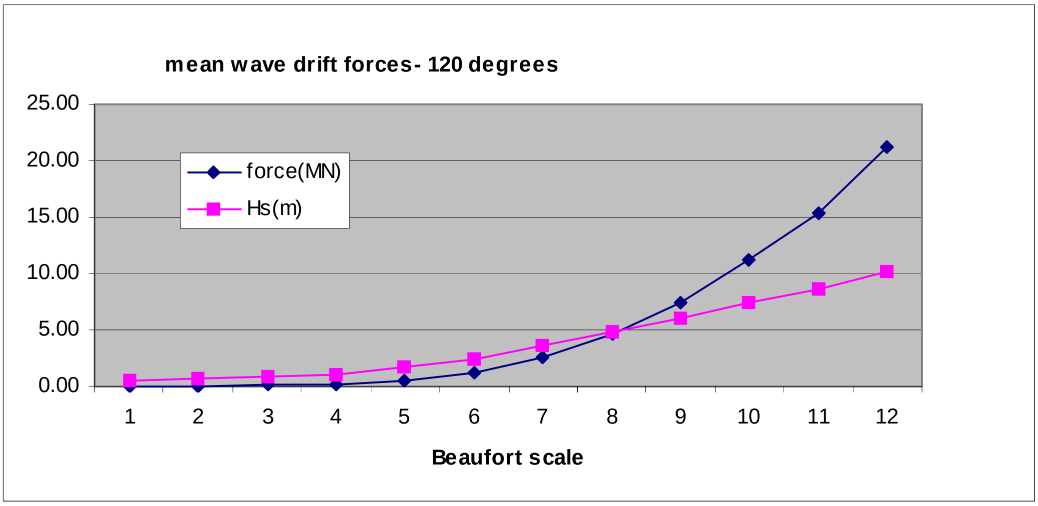


Figure 14-3: mean wave drift forces, waves 150 degrees

<u>- During survival conditions (bow-on)</u>

Only the surge drift forces are considered by the calculation of the resultant force.

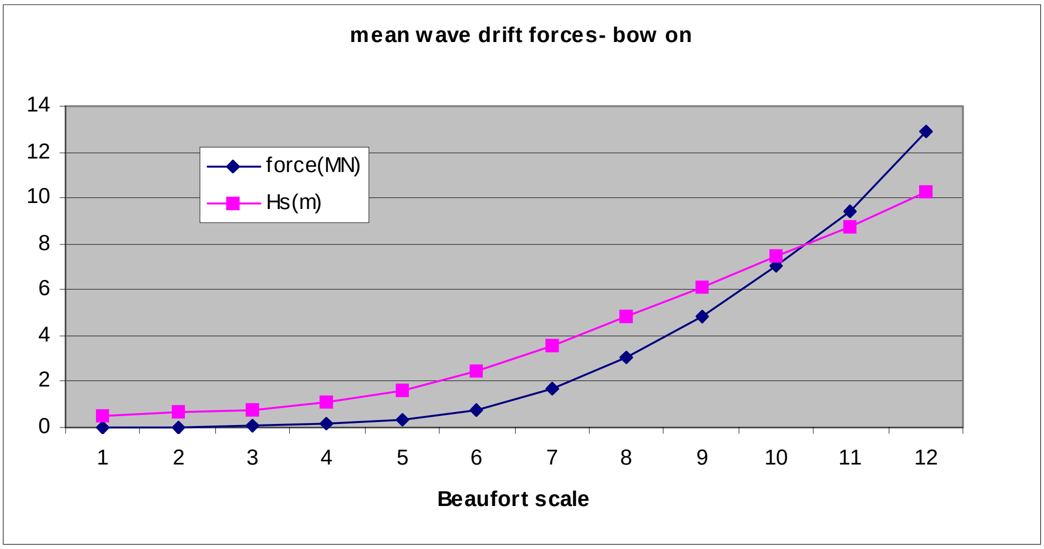
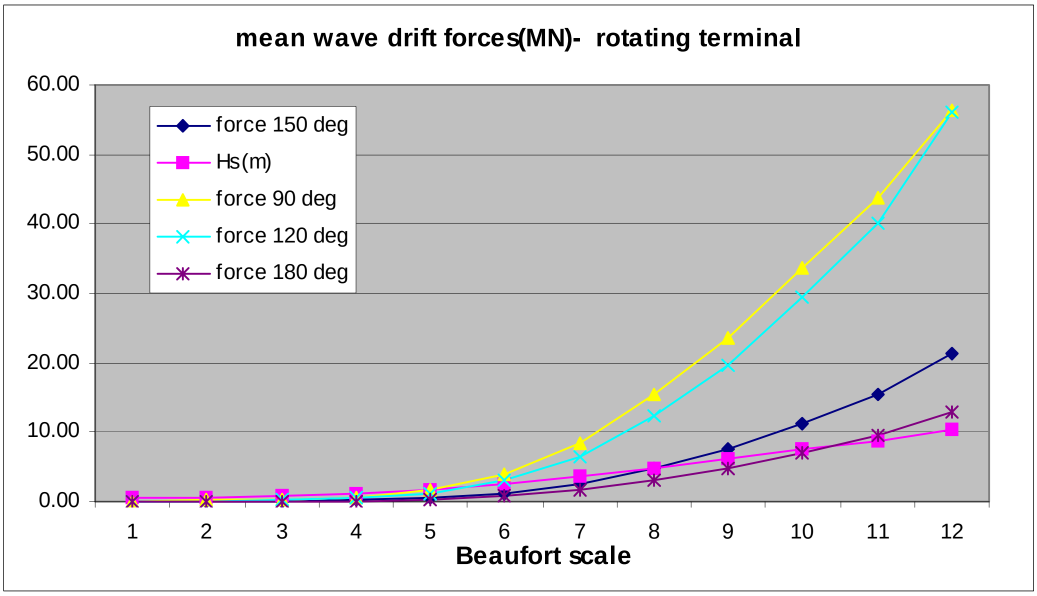


Figure 14-4: mean wave drift forces, bow waves

14.3 Evaluation

- Up to a H_s of 3m, the lifting operations will continue. As the storm further develops the vessels have to leave the terminal. Once all vessels have deberthed, the thrusters will be deactivated. It is required that the terminal will begin to rotate from its beam-on position towards a bow-on position by a H_s of 3.6m (scale 7).

- The forces in the 4 directions are shown in the figure below. The beam-on position results in largest forces. However, it could be seen from the figure below that a larger force will be encountered during survival conditions (Beaufort scale 12). In that last case the mean wave drift force is equals to **12.88 MN** and is the decisive.



- The 12.88 MN force is larger than the force accounted for by the design of the mooring system, which is 11.47 MN (56.77/4.95 MN). This will be later reviewed, when all the force acting on the mooring system are finally calculated.
- The Yaw mean drift moments are also calculated for Beaufort scale 7. This is of significance to the determination of the power of the DP thrusters. However, yaw moments were found to be equal to 0.681 kNm and thus much smaller when compared to the in section 10 calculated 0.42 MNm as result of the eccentricity of the turret. It is logic that the yaw moments are small when the terminal is beam-on to waves.
- assuming that the catenary lines have linear character- which is most probable as result of their low stiffness- the *offset* caused by the mean wave drift force is then:
  - In the SLS = $8.5*10^3/ 386 = 22.9$m
  - In the ULS = $12.88*10^3 /386 = 33.4$m

15 Low frequency wave drift forces and motions

Introduction

The previous section dealt with the steady part of the of the second order wave drift force. This will cause an offset position. The oscillating part of the second order wave drift force, i.e. low frequency wave drift force (2nd order) will cause an oscillating motion of the terminal.
Low frequency wave forces have frequencies corresponding to the frequencies of the wave groups present in irregular waves. Although the forces have small amplitudes, however resonance may occur when the wave groups have a period in the vicinity of the natural period of the mooring system, resulting in large amplitudes of motions. Thus, they are of significance in the case of sway, surge and yaw motions. For these motions, the terminal has small spring and damping terms.
The aim of this section is to calculate the magnitude of these forces and the amplitudes of the motions they cause during *operating conditions* (terminal beam-on and only sway motions) and also during *survival conditions* (terminal bow-on and only surge motions)

15.1 Calculations of the low frequency drift force

The low frequency wave drift force (in- phase part) can be expressed with the formula:

$$F^{(2)}(t) = \sum_{i=1}^{n}\sum_{j=1}^{n} \zeta_i \zeta_j P_{ij} \cos\left\{(w_i - w_j)t + \varepsilon_i + \varepsilon_j\right\} \qquad [15\text{-}1]$$

The amplitude of the force $\hat{F}^{(2)}$ is equal to:

$$\hat{F}^{(2)}(t) = \sum_{i=1}^{n}\sum_{j=1}^{n} \zeta_i \zeta_j P_{ij}$$

$$and, \qquad [15\text{-}2]$$

$$\hat{F}_{ij}^{(2)} = \zeta_i \zeta_j P_{ij}$$

ζ_i and ζ_j are the wave amplitudes corresponding to the wave frequencies w_i and w_j respectively.

Approach:
The following approach applies for both the surge and sway motions

Step-1: Determining (n)

As already mentioned, the horizontal motions are aggravated when the frequencies of these forces is in the vicinity of the natural frequency .The designed mooring system has a natural frequency of **0.011** rad/s. The number of ζ_i's and ζ_j's (n) follows from the frequency range of the wave spectrum divided by a 0.01. The frequency range of the spectrum is chosen to between 0 and 2 rad/s and therefore is n **= 200**.

Step-2: Determining (Δw)

$$\Delta w = w_j - w_i \qquad [15\text{-}3]$$

Δw represents the frequency of the low frequency force. Its value should be chosen somewhere near to natural frequency of the system, i.e. **0.011** rad/s. However this might lead to an overestimation of the motions as it will be considered that the terminal is always performing resonance motions. To avoid this, Δw will be **randomly generated** in the range between **0.006 and 0.015** using the random generator provided in the program Excel.

Step-3: Finding ζ_i, ζ_j and $\zeta_i \cdot \zeta_j$ generating wave spectrum

The ζ_i and ζ_j could be extracted the (JONSWAP) wave spectrum for i =j = n.

$$\zeta_i = \zeta_j = \sqrt{\left(2 \cdot S_\zeta(w) \cdot \Delta w\right)} \qquad [15\text{-}4]$$

$$\left[\zeta_i \zeta_j\right] = \begin{bmatrix} 1.....n \\ n \end{bmatrix} = \left[\zeta_{i=1} ....\zeta_n\right] \cdot \begin{bmatrix} \zeta_{j=1} \\ \\ \zeta_{j=n} \end{bmatrix}$$

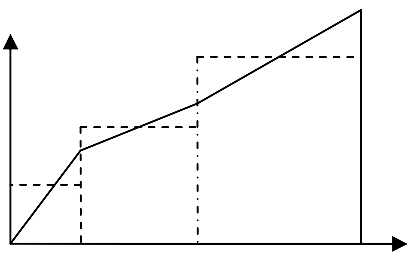
Step-4: Finding P_{ij}.

$$P_{ij} = \frac{P_{ii} + P_{jj}}{2} \qquad [15\text{-}5]$$

where,

P_{ii} is the mean wave drift force in regular waves for w_i

These forces are obtained from DELFRAC for frequencies multiple of 0.05 rad/s. It will be considered that the P_{ij} value is constant between every two steps and equals to the average of the corresponding P_{ij}'s. [see next figure]



Results:

The calculations are carried out in an Excel spread sheet. For each of the variables mentioned above, a 200 ×200 matrix (i=200 and j =200) is made in the spreadsheet. Because of the large size of the Excel spread sheet, the calculations are not shown in the appendices. However parts of these matrices are given below to give an indication about the magnitudes of each variable.

- the table below shows some of the values of Δw's generated by the Excel random generator

	i			
J	197	198	199	200
197	0,05155	0,05092	0,05031	0,05031
198	0,05092	0,0503	0,04969	0,04969
199	0,0503	0,04969	0,04909	0,04909
200	0,04969	0,04909	0,0485	0,0485

- The same could be seen here next for the amplitude of the force $\hat{F}_{ij}^{(2)}$ in kN, beam-on terminal and Hs = 3.6m

	i			
J	1	2	3	4
1	0,0110263	0,0125015	0,0144398	0,0067286
2	0,0068417	0,0070731	0,0098992	0,0066122
3	0,0111652	0,0076395	0,0094512	0,011696
4	0,0082069	0,0134098	0,0062155	0,0069803

- The significant amplitude of the total acting low frequency drift force $\hat{F}^{(2)}$ is:

  Terminal beam-on and H_s = 3.6m ⟶ $\hat{F}^{(2)}(t) = \sum\sum \hat{F}_{ij}^{(2)}$ = **9.36 MN**

  Terminal bow-on and H_s = 10.25m ⟶ $\hat{F}^{(2)}(t) = \sum\sum \hat{F}_{ij}^{(2)}$ = **11.62 MN**

15.2 Response to low frequency wave forces

It is regarded that each component $\hat{F}_{ij}^{(2)}$ of the total force $\hat{F}^{(2)}$ will cause a motion with amplitude $\hat{x}_{ij}$.

The later could be calculated from the equation of motion:

$$\hat{F}^{(2)}\cos(\Delta wt + \varepsilon) = (m+a)\ddot{x} + b\dot{x} + cx$$

then,

$$\hat{x}_{ij} = \frac{\hat{F}_{ij}^{(2)}}{\sqrt{\left(\left(c-(m+a)\Delta w^2\right)+(b\cdot\Delta w)\right)^2}}$$

and

$$\hat{x}_{RMS} = \sqrt{\sum_i\sum_j \hat{x}_{ij}^2}$$

$$\hat{x}_{1/3} = 2\cdot\hat{x}_{RMS}$$

$$m_0 = \hat{x}^2_{RMS}$$
$$m_2 = \sqrt{\sum_i \sum_j (\Delta w^2 \cdot \hat{x}_{ij}{}^2)}$$

Results:

- The $\hat{x}_{ij}$'s for i and j between 197 and 200 could be seen below, beam-on terminal and H_s = 3.6m

	i			
J	197	198	199	200
197	1,295E-06	1,604E-08	1,371E-05	4,909E-08
198	5,187E-08	2,101E-06	6,162E-07	6,799E-07
199	7,122E-08	1,082E-07	5,6E-08	5,873E-08
200	4,147E-08	2,313E-08	2,674E-08	1,074E-08

- The significant amplitude of the motion $\hat{x}_{1/3}$:

Terminal beam-on and H_s = 3.6m ⟶ $\hat{x}_{1/3}$ = **6.49 meter**

Terminal bow-on and H_s = 10.25m ⟶ $\hat{x}_{1/3}$ = **10.12 meter**

- The mean period of the motion T_2 follows from m_0 and m_2 as given in equation [12-3]:

T_2 = **632 seconds**

16 Horizontal motions of the terminal

Introduction

In section 12, calculations were carried out for the forces and motions as result of the 1st order wave frequency forces. Only the heave and roll motions are considered as the characteristics of the mooring system were unknown at that stage. In this section, the same calculations will be carried out for two other modes of motion, i.e. **sway and surge.** Furthermore at the end of the section, the total forces acting on the turret mooring will reviewed to ensure that exact calculated mooring force –which is initially roughly calculated- is within the limits of the breaking load of the designed catenary chain turret mooring.

16.1 Forces and motions Calculations

Operating conditions

During the operation of the terminal (beam-on) the *longitudinal* motions of both the vessel and the terminal are relatively too small as appeared from the RAO-functions in section 11. The resultant of the lateral horizontal forces is dominated by sway. The acting sway wave forces are:

- mean wave drift force (2nd order)
- Low frequency drift forces(2nd order)
- wave frequency forces (1st order)

Forces:

In the previous two sections, it was found that mean wave drift force has a maximum of **8.50 MN** while the low frequency drift force has significant amplitude of **9.36 MN** during operating conditions.

Calculations are also carried out for the sway 1st order wave frequency forces in t he same way as in the case of heave and roll (see section 12). The calculations resulted in a huge force acting on the structure (thus not the mooring lines). For the sea state Beaufort scale 7 with H_s equals to 3.6m, the significant amplitude of the force is equal to **299 MN**. However, the forces acting on the mooring lines are related to the motions, thus not the wave forces. Although the force is very large, the response of the terminal is small.

Motions:

The maximum offset caused by the mean wave drift force was found to be **33.4m**, while the maximum calculated significant amplitude of the motion as result the low frequency drift forces is **10.12m**.

The response to 1st order wave frequency force has significant amplitude of the sway motion of 0.15m (T_2 = 7.77 seconds) by sea state 7 (H_s = 3.6m).

The amplitude of the force acting on the mooring lines as result of the 1st order wave sway motions (assuming linear characteristic of the mooring lines) is then:

$$\hat{F}_{1/3} = Ku = 378\text{kNm}*0.15\text{m} = \mathbf{53.67*10^{-2}\ MN}$$

Compared to other acting forces (2nd order), this force is very small. This actually shows the advantage of the low stiffness and that the terminal is free to make certain excursion (deflection). The mooring lines with their low stiffness escape the largest acting wave force (299 MN) by not resisting the motions as result of the 1st order wave frequency forces.

Operability:
The limit for the sway motions according to the criteria is 0.6m. However, unlike the heave and roll motions, the relative sway motions (vessel-terminal) could not be considered as the sum of both bodies motions. In that case the relative lateral motion between the vessel and the terminal depends on the characteristics of the vessels mooring lines and the fenders. The deflection of the fender (mooring lines) will determine the relative motion. This will be further treated in the next section

Survival conditions:
During the operation of the terminal (bow-on) the *longitudinal* motions of both the vessel and the terminal are of significance. The resultant of the lateral horizontal forces is dominated by surge.
1st order wave frequency forces in the ULS:

- Significant amplitude of the surge motion of the terminal by H_s = 10.25m is **0.19m** (T_2 = 12.12 seconds).
- The force acting on the mooring lines when assuming linear characteristics, is **7.18*10^{-2} MN** (= 378kNm*0.19m). Compared to other acting forces, the later is negligible.

In the previous two sections, it was found that mean wave drift force has a maximum of **12.88 MN** while the low frequency drift force has significant amplitude of **11.62 MN** during survival conditions

16.2 Review designed mooring system

The mooring lines of the turret as given in section 13 were designed for a maximum horizontal force of **35.04 MN.** The table below summarizes the exactly calculated horizontal mooring forces, in both the SLS and ULS

Force (MN)	**SLS (H_s = 3.6m, beam-on)**	**ULS (H_s = 10.25m, bow-on)**
Wind	1.74	1.54
Current	6.28	5.08
Wave frequency	53.67*10^{-2}	7.18*10^{-2}
Mean drift	8.50	12.88
Low frequency drift	9.36	11.62
Total	**25.88**	**31.12**

Therefore, it could be concluded that for both limit states, the designed mooring system **satisfies** the requirements with regard to its resisting force capacity.

The later does not apply in the case of the DP thrusters. The initially estimated moment (23MN) is smaller than that of the last results (25.88 MN). Therefore modifications should be made with regard to the required thruster force of the DP-thrusters.

The calculations were already explained in section 13.6:

Moment (M) = eccentricity turret * total mooring force

$M_{max;\ SLS}$ = 25.88 MN*10m = 258.8 MNm

Maximum required thruster force = 230/ (595-10-35) = 0.47 MN

Thus the,

Total thruster power: 470000/100 = **4700 hp**

The above calculated required thrusters power is also obtainable (see section 13.6)

17 Vertical relative displacement & deck wetness

Introduction

The relative vertical motion plays a role in shipping water phenomena. Deck wetness caused by shipping water or wave overtopping could cause certain damage.
In the first part of this section, the number of times per hour that green water will be shipped in certain sea state will be determined as function of the freeboard f . Finally, the water discharge will be calculated.

17.1 Relative vertical displacement

Calculations of the harmonic relative displacements with respect to the undisturbed wave height will be carried out at point x_b = -595. Thus at the end of the floating structure where generally the relative vertical displacements are largest

Formulas:

$$s_p = \zeta_p - z + x_b \cdot \theta - y_b \cdot \phi \qquad [17\text{-}1]$$

Where,

s_p	Relative vertical displacement
ζ_p	Undisturbed wave height at point P(x_b,y_b,z_b).
z	Amplitude heave motion
θ	Amplitude pitch rotation (in radians)
ϕ	Amplitude roll rotation (in radians)

The terminal with its bow-on position in the given state, the roll could be neglected (Response amplitude operator, a factor of 10^{-5} smaller than pitch). The equation reduces to:

$$\begin{aligned} s_p &= \zeta_p - z + x_b \cdot \theta \\ &= s_{p_a} \cdot \cos(wt + \varepsilon_{s_p\zeta}) \end{aligned} \qquad [17\text{-}2]$$

Also,

$$\zeta_p = \zeta_a \cos(wt - kx_b \cos\mu - ky_b \sin\mu)$$

μ =180^{o}

Applying the sum rule, and equating the in and out of phase terms in the equation of the relative vertical motion, gives:

$$\begin{aligned} s_p \cos(\varepsilon_{s\zeta}) &= +\zeta_a \cos(kx_b) - z_a \cos(\varepsilon_{z\zeta}) + x_b\theta_a \cos(\varepsilon_{\theta\zeta}) \\ s_p \sin(\varepsilon_{s\zeta}) &= +\zeta_a \sin(kx_b) - z_a \sin(\varepsilon_{z\zeta}) + x_b\theta_a \sin(\varepsilon_{\theta\zeta}) \end{aligned} \qquad [17\text{-}3]$$

The amplitude of the vertical relative displacement s_{p_a} becomes then:

$$s_{p_a} = \sqrt{(s_p \cos(\varepsilon_{s\zeta}))^2 + (s_p \sin(\varepsilon_{s\zeta}))^2} \qquad [17\text{-}4]$$

To calculate the contribution of the dynamic swell-up to the vertical relative motion $\Delta\zeta_a$, equation 8.2 will be used.

The **actual** amplitude of the vertical displacement $s^*_{p_a}$ becomes:

$$s^*_{p_a} = s_{pa} + \Delta\zeta_a \qquad [17\text{-}5]$$

The transfer function of the relative vertical displacements s_{p_a} / ζ_a , could be obtained by dividing EQ [17-3] by ζ_a and filling in EQ [17-4]

$$s_p \cos(\varepsilon_{s\zeta}) = \cos(kx_b) - \frac{z_a}{\zeta_a}\cos(\varepsilon_{z\zeta}) + x_b \frac{\theta_a}{\zeta_a}\cos(\varepsilon_{\theta\zeta})$$

$$s_p \sin(\varepsilon_{s\zeta}) = \sin(kx_b) - \frac{z_a}{\zeta_a}\sin(\varepsilon_{z\zeta}) + x_b \frac{\theta_a}{\zeta_a}\sin(\varepsilon_{\theta\zeta}) \qquad [17\text{-}6]$$

The transfer function of the relative vertical displacement $s^*_{p_a} / \zeta_a$ becomes,

$$\frac{s^*_{p_a}}{\zeta_a} = \frac{s_{pa}}{\zeta_a} + \frac{\Delta\zeta_a}{\zeta_a} \qquad [17\text{-}7]$$

The spectral density of the vertical relative displacement,

$$S_{s^*}(w) = (\frac{s^*_a}{\zeta_a})^2 \cdot S_\zeta(w) \qquad [17\text{-}8]$$

Using the Rayleigh distribution, the short term probability of shipping water in a given storm condition is:

$$P\{s^*_a > f\} = \exp\left(\frac{-f^2}{2m_{0s^*}}\right) \qquad [17\text{-}9]$$

The number times per hour that green water will be shipped in certain sea state as function of the freeboard f is:

$$N_{shipping/hour} = \frac{3600}{T_{2s*}} \cdot p\{s^*_a > f\} \qquad [17\text{-}10]$$

In which T_{2s*} is the average zero crossing period of the motion.

- The calculations are carried out for (Beaufort) sea state 12. H_s = 10.25m (ζ_a = 5.125m) and T_2 = 10.5. The terminal is bow-on to waves.
- JONSWAP wave spectrum ($S_\zeta(w)$)
- The transfer function of the relative vertical displacement $s^*_{p_a} / \zeta_a$ is then calculated using the RAO- functions by DELFRAC and the formulas above.
- The spectral density of the **actual** relative motion $S_{s^*}(w)$ was calculated using EQ17-8.

See the figure below

Results:

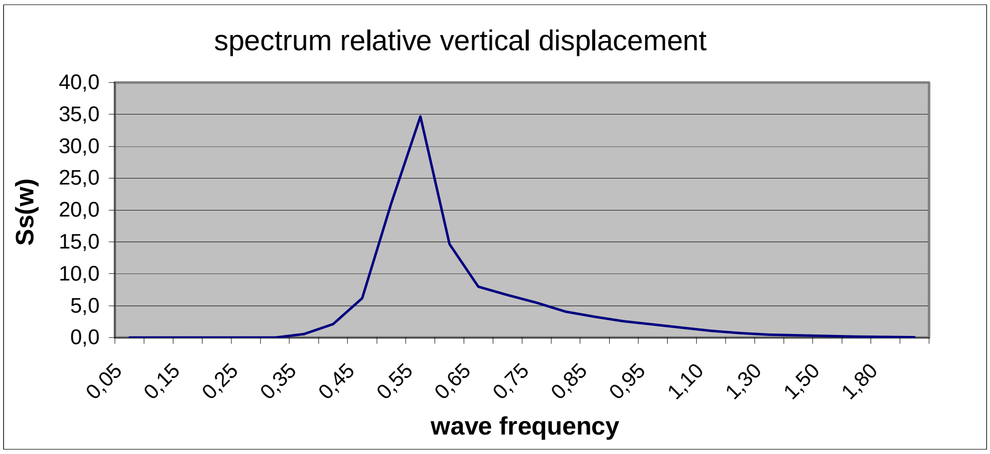


Figure 17-1: Spectrum relative vertical displacement

- The table below shows the number of shipping waves per hour for the given sea state (Beaufort 12) as function of the *freeboard.*

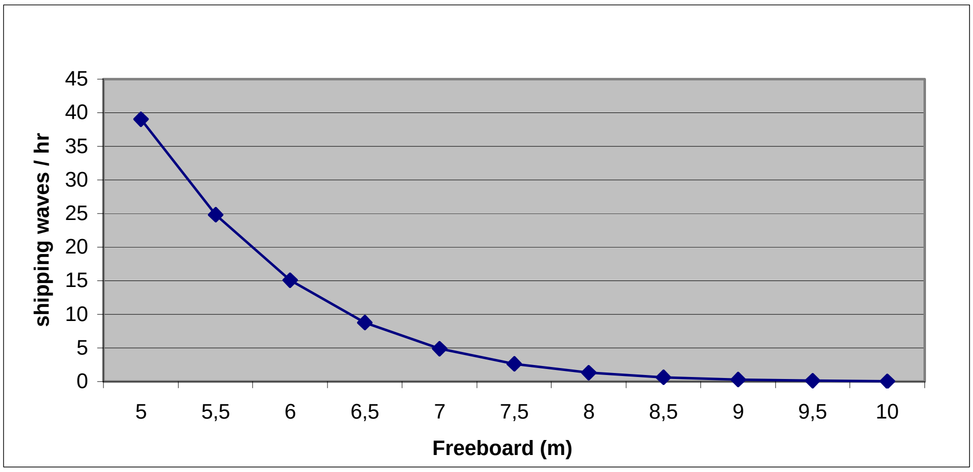


Figure 17-2: shipping water

17.2 Wave overtopping

Wave overtopping for vertical walls has been investigated by Franco, L. and Meer, J.W. van der [source: d'Angremond, K. and Roode, F.C. van ; Breakwaters and closure dams,2001]. They describe the unit discharge q as:

$$\frac{q}{\sqrt{gH_s^3}} = a\exp\left(-b\frac{R_c}{\gamma H_s}\right) \qquad [17\text{-}11]$$

In which,
R_c = crest freeboard relative to SWL (m)
q = unit discaharge ($m^3/m/s$)
a,b = experimentalcoefficients
γ = geometrical parameter

For a rectangular shape:

a = 0.192
b = 4.3
γ = 1

Results:
The calculations are carried out in appendix 17-1

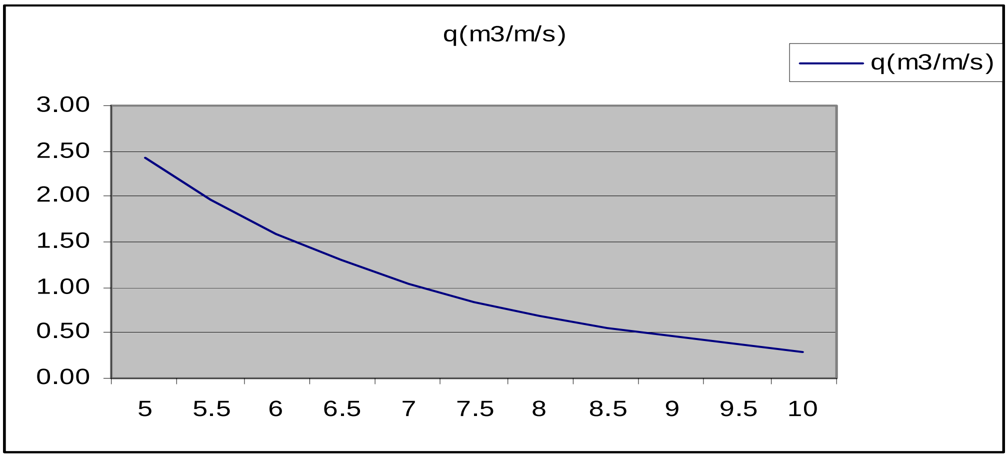


Figure 17-3: discharge wave overtopping

Evaluation:
- The formula used does not account for the spray. A vertical wall usually causes lot of spray when the waves hit the wall. At the other hand, it is more suitable for fixed walls than for floating breakwaters. The later allows certain energy transmission under the structure and thus less wave overtopping and spray.
- As the method is usually used for fixed breakwaters, figure 12-3 should only give an indication about the fall of the discharge graph by an increasing freeboard.

17.3 Determining the freeboard of the terminal

The water discharge or number of shipping waves to be tolerated during storm conditions depend on the capacity of the drainage system. The definitive freeboard of the terminal is to be determined based on a risk assessment analysis. However, from the above results it could be concluded that for the initially adopted freeboard of 10m that the expected number of shipping water per hour during storm conditions is small and equals to 0.06.

18 Evaluation system operation

Introduction

In this section, results found previously will be used to sketch a more complete picture of terminals operation. The following processes and aspects will be considered:

- Loading /unloading vessels.
- Berthing process
- Fender system
- Downtime of the terminal.

18.1 limit states

It has already been concluded that the lifting operations could proceed up to a significant wave height up to 3.0m (T_2 = 6s). It is also required that also required that the terminal will begin to rotate towards bow-on position to waves by a H_s of 3.6m. Wave measurement buoys at a distance from the terminal could be used to forecast the height of the waves approaching the terminal. This will give more time to the vessels to leave the terminal

In addition, it is put as condition that the vessels should not be allowed to berth by a H_s larger than 2.5m (Beaufort scale 6). By higher sea conditions it was found that the sway motions and velocities of the terminal increase sharply and thus also the berthing energy and forces. For Example, the amplitude of the sway velocity increases by a factor 2 by a sea state 7 (Beaufort scale). The berthing energy will then be 4 times larger than that during sea state 6.

The mooring system sets the condition for the maximum survival conditions (ULS). The system is designed for sea conditions up to Beaufort Scale 12. The corresponding significant wave height is 10.25m.

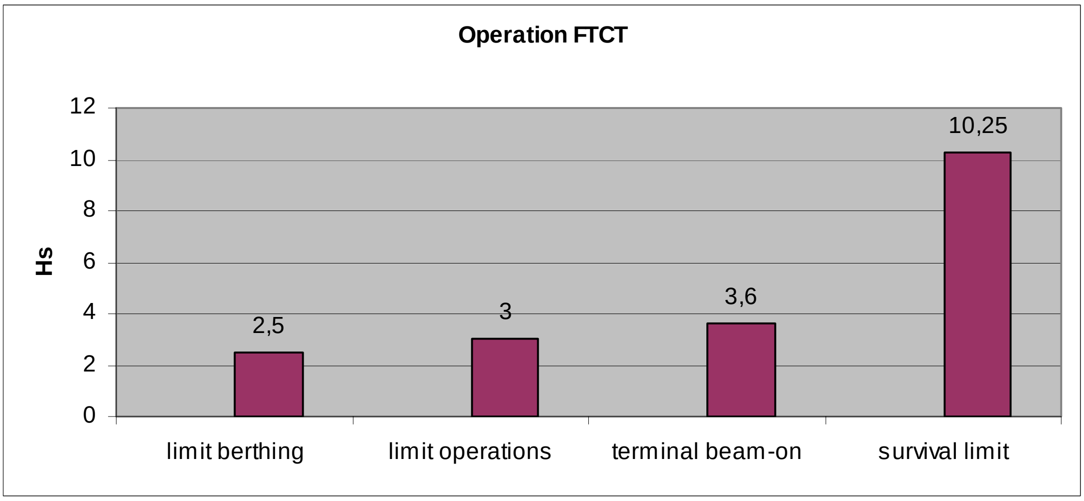


Figure 18.1: limiting wave conditions

18.2 Berthing vessels

Berthing process

The berthing process of the vessels to the swaying terminal will require more precision and cautiousness than in the case of a fixed berth. The amplitude of the sway motion of the terminal by a H_s of 2.5 as result of the low frequency drift forces is **2.75m** and the motions period is **554s** (9.2 minutes). The amplitude of the motions velocity is equal to **0.03m/s** (frequency * ampl. motion).

To prevent collision with other berthed vessels during berthing process, the vessel must first be brought parallel to its berth at a minimum distance of 72 meter (69m width of the largest vessel + 2.75m amplitude sway). This could be done with assistance of the tugboats or own thrusters. Once it is exactly within the front of the berth, it could then be pushed towards the berth (see figure below).

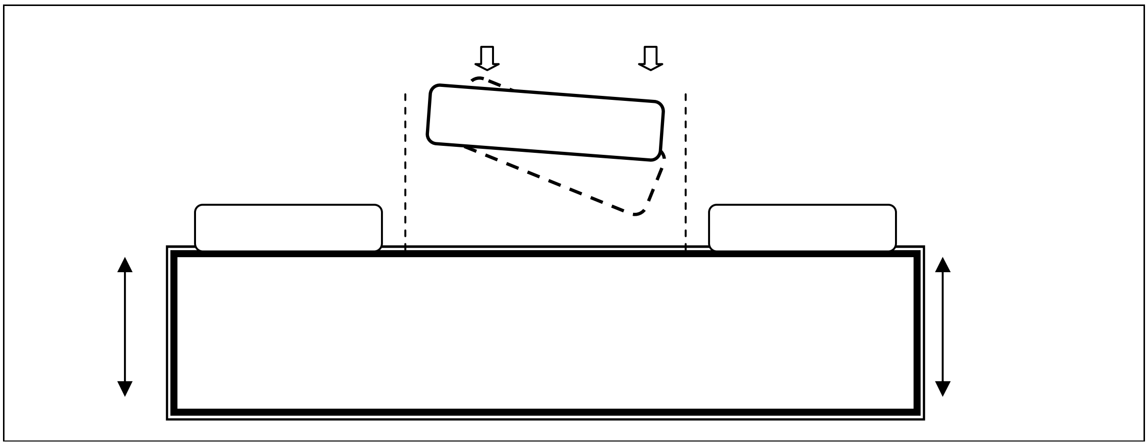


Figure 18.2: Berthing process

Fenders

During the berthing process, fenders should be capable of absorbing the berthing (kinetic) impact energy. Hard fenders are needed to absorb the large berthing energy.

During mooring conditions and once the vessel is moored, it will follow the terminal in its motion.

When assuming (relatively) rigid terminal and vessel structures, the deflection of the fender will actually represent the relative lateral motion between the two. The criteria for vessels motion during operation, demands maximum amplitude of 0.6m for the sway motion.

Although hard (large stiffness) fenders cause will large reaction (berthing) forces on the structures, however in the case of the FTCT hard fenders will be needed for two reasons:

1- absorb the impact berthing energy of the two colliding bodies
2- The deflection of the fender represents the relative sway motion terminal-vessel during operation.

A rough estimate of the kinetic energy can be calculated with the formula:

$E_{kin} = ½\ M·C_b·v^2$

M displacement ship (in tons)
V approach velocity of ship's centre of gravity
C_b coefficient representing four effects and is equal to 0.7 .

Starting pointes by the calculation of the largest possible berthing energy (worst scenario) are:

- Vessels berthing velocity (unfavorable conditions) = 0.15m/s.
- Amplitude sway velocity terminal (H_s =2.5m) = 0.03m/s.
- The moment of impact, terminal and vessels moving in opposite direction

It follows that for the design mega vessel, the

$E_{kin:mega}$ = ½ *400*69*14*1.025*0.7*[0.15-(-0.03)]^2 = **4.49 MNm**

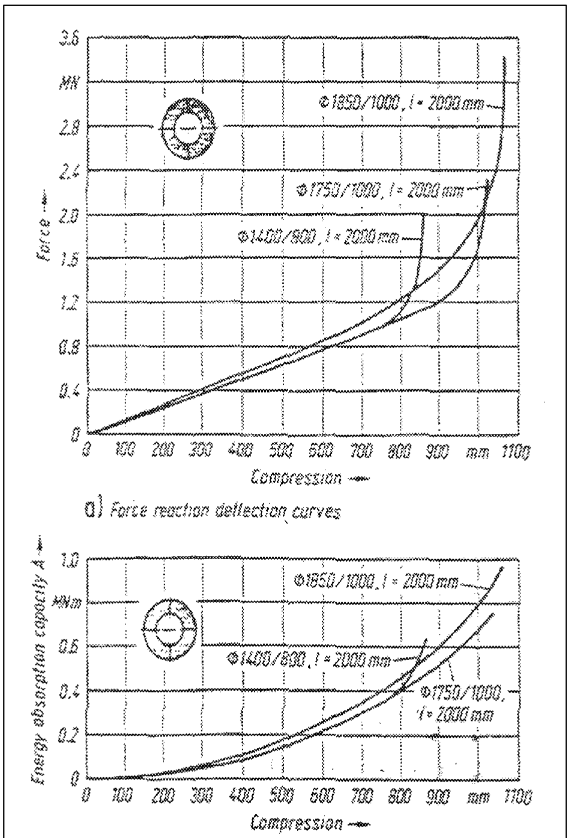
And the design feeder vessel,

$E_{kin;feeder}$ = ½ *300*32*11.5*1.025*0.7*[0.15-(-0.03)]^2 = **1.28 MNm**

The impact kinetic energy will be transferred into potential energy in the fenders and the terminals structure. the total absorbed energy is the area under the force-deflection graph. The berthing force (F) follows from:

$$E = \frac{1}{2} F \cdot y_t + \int F \cdot y_f \cdot dy$$

y_t Deflection terminal structure
y_f Deflection fender



a) Force reaction deflection curves

b) Energy absorption capacity - deflection curves

By the structural design of the terminal structure an additional lateral force equals to 0.5F must be accounted for. This lateral force is caused by the friction between the terminal structure and the fender surface.
The contribution to the energy absorption by the terminals structure is very small compared to that that of the fender as results of the larger stiffness of the first. Assuming that the whole energy will be absorbed by the fenders, the berthing force F could be calculated.
The Cylindrical fender as shown in the figure aside has high energy absorption capacity. However, each fender can absorb

maximum impact energy of about 1 MN. From the upper graph in the same figure, it follows that the berthing force (F) is then around 3.6 MN per fender.
Double fender systems could be used at the feeder berths. The fenders will have the capacity to absorb the berthing energy which will then be divided over the fenders.

In the case of the mega vessels berth, the berthing energy is too large and other solutions must found. Possible solutions are:
1- Design of special type of non-traditional fender with large energy absorption capacity, such as pneumatic fenders.
2- Reducing the maximum allowable approach velocity of the mega vessels. by a maximum berthing energy of 2 MN (2 cylindrical fenders), it follow that the maximum velocity of the (design mega vessel + terminal) is 0.12 m/s. A possible solution is to restrict the berthing of these mega vessels to a certain sea conditions where the vessels could berth at low approach velocities. The Mega vessels call only twice per week on the FTCT.

18.3 Downtime of the terminal

Downtime as results of wave conditions:
The National Institute for Coastal and Marine management (RIKZ) in The Netherlands provides in its website "www.golfklimaat.nl" updated information about the wave conditions in a number of deepwater locations along the Dutch coast (southern North Sea). The information is based on data collected during the last 23 years.
At the location Euro platform (about 50km from the coastal line), the wave height frequency of exceeding is shown below as obtained from the website.
A H_s of 3 meter will be exceeded during 3.2% of the time (year) at that location. Whenever this location is to be chosen for the FTCT, this will imply that the downtime of the terminal resulting from the wind waves generated motion is 3.2%. This percentage could be very much acceptable.

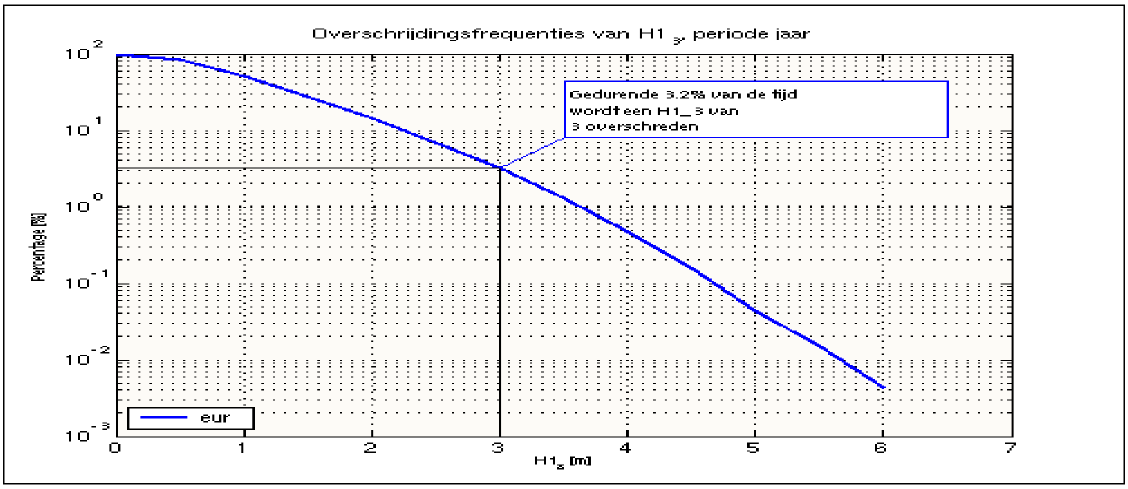


Figure 18.3: wave freq. of exceeding Euro Platform, Dutch coast (source: www.golfklimaat.nl)

Downtime as result of berthing vessels:

Vessels approaching the terminal will generate waves- either by own thruster or that of the tugboats- at the berth side. In that case, the floating terminal will provide no protection. These waves cause extra motions of the berthed vessels and could affect the efficiency of the container lifting operations. The number of vessel calls per year is 600 (100 mega vessels + 500 feeders). Assuming a (de)berthing time of 15 minutes per vessel gives a total of 300 hours per annum (berthing + deberthing). If it is assumed that the operations will be totally interrupted during that time, then is the resulting downtime is **3.6%** of the total operation time of the terminal (50 weeks, 7 days and 24 hours).
However, the same applies for fixed berths.

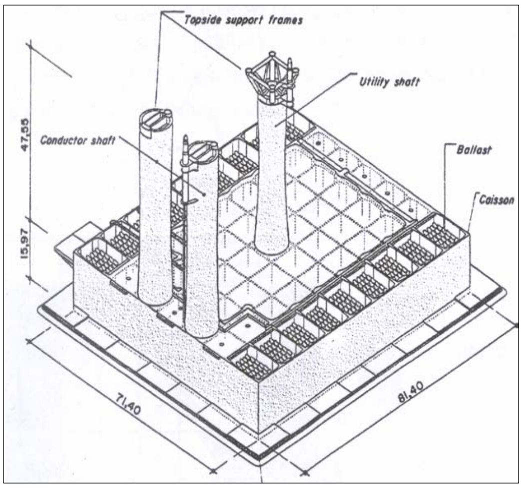
19 Structural & construction aspects

Introduction

Attention was focused so far on the external loads and response of the floating terminal caused by the surrounding sea loads. Furthermore, conclusions were drawn about the operability of the designed system. The first paragraph of this section discusses the important aspects about the modular construction of the terminal. Moreover, a method will be introduced for the construction of the terminal and finally the loads acting on the terminals sections will be qualitatively formulated.

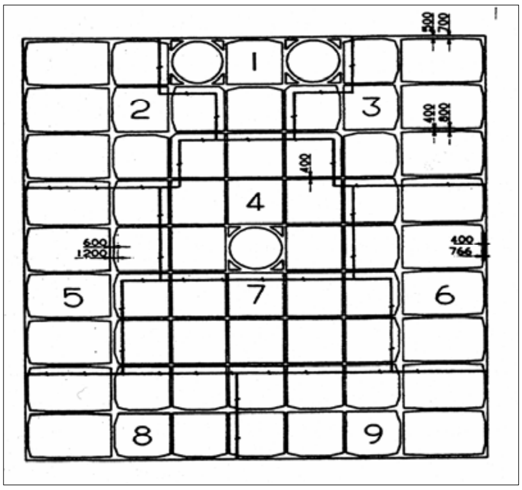
19.1 Terminal modules

Because of the large dimensions (width and length) of the designed terminal, it will be necessary that the terminal must be built of a number of modules (elements). Each module is to be constructed separately and afterwards the modules are to be connected to each other at the final location of the terminal.



The figures aside, show the detail design of an offshore concrete base platform in the Dutch Sector of the North Sea. The caisson base structure is divided into cells for the storage of gas and oil.
Except for the dimensions, similar structural concept could be used for the design of the pre-stressed concrete (modules) hull of the terminal. In the case of the FTCT, the cells will be needed for the storage of the ballast water.

Size of modules
If chosen for a standard size for all the modules, the number of modules follows then from the total surface area of the terminal (28.56 ha) divided by the size of the modules. There are a number of factors which play a role by determining of the size of the modules. These factors are:



1- The dry dock:
The modules are to be built onshore on a dry dock. Depending on the location of the terminal, dry docks are sometimes already available within an acceptable distance to the final location of the terminal. If this is not the case, it might be economically more attractive to construct a dry

dock for the building of the terminals modules.
In each case, one of the *boundary conditions* of the (maximum) dimensions of the terminal modules will emerge from the size of the dry dock. The sizes of the docks could vary from large ones such as the dock construction of the semi-floating breakwater in Monaco. The breakwater is 352m ×28m [see literature study 2-7] and was constructed as one element. Average sized dry docks have sizes usually suitable for the construction of tunnel elements (± 100m long, ± 10m wide) for example.

2- Transport

After construction, the modules are to be transported to final location of the terminal. Another boundary condition to the design and size of the modules is the *floating stability*. The modules have to be design in a way that their stability is guaranteed during their transportation.

3- Elasticity

The response calculations carried out in the previous sections were based on the assumption that the terminal is totally rigid. However, the terminal will behave elastically to certain extend depending on the:

- The structural design of the modules and the material used.
- Moreover, the number of modules and the type of connections used to joint the modules together. The structure will behave more rigid for s smaller number of modules.

19.2 Construction method

In this paragraph a method will be introduced for the construction of the concrete terminal. The terminal elements could be either *partially* constructed in a dry dock and further completed afloat or *completely* in the dock.
The first option is found to be more attractive in the case of the FTCT for the following reasons:

1. The dock(s) will be more efficiently used when the elements are to be partially built inside it, and thereafter completed afloat outside the dock.
2. Relatively smaller water depth and thus dock depth is needed to get the elements afloat when they are partially built. Therefore, less (excavation) work and costs of the dry dock.

Construction sequence:

In this paragraph a method is proposed for the construction sequence of each of the elements of the terminal. The method is suitable when choosing for partially constructed elements in a dock.

1. A dry dock is prepared by excavating below the mean sea level at a coastal site.
2. Construction of the bottom slab and the outer walls partially inside the dock. (see figure19.1).

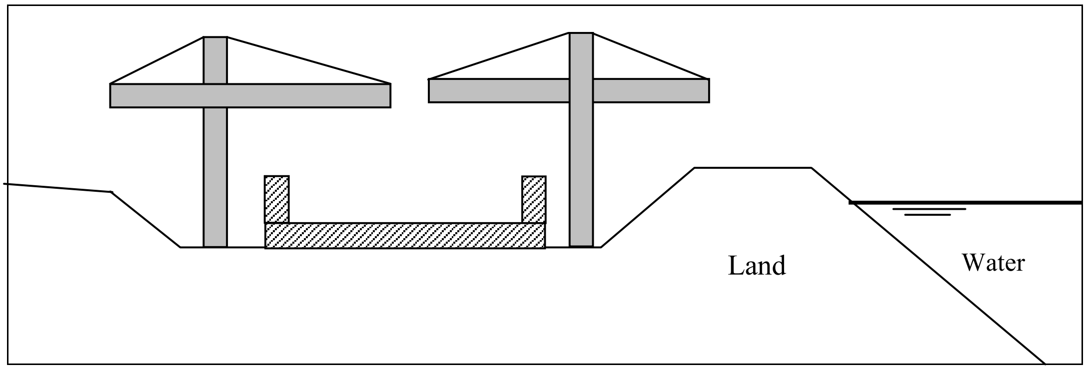


Figure 19.1: terminals element built partially inside the dry dock

3. The sea wall must be removed and the constructed part be tugged out of the dock.
4. Further construction of the elements on sea with the assistance of barges and floating cranes. (figure19.2).

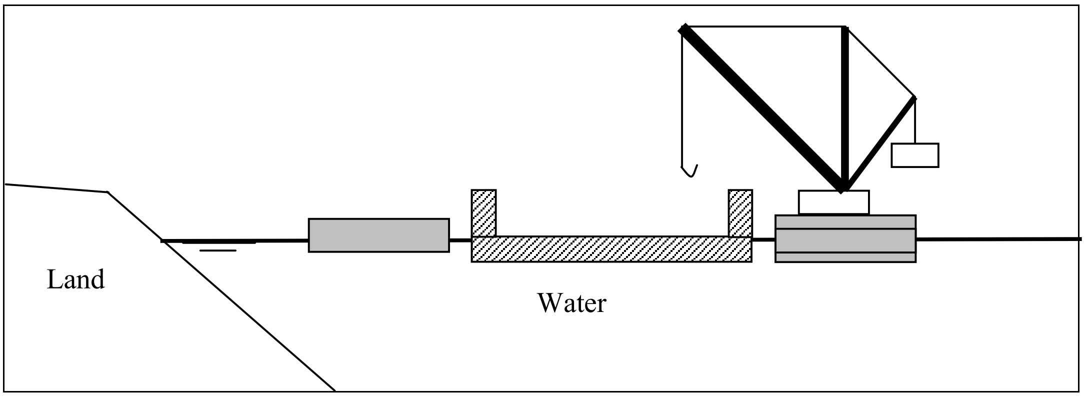


Figure 19.2: Completion terminal elements (afloat)

5. The element with the turret should be built initially. The turret is mounted inside the element. Once it is totally constructed, it could be towed to the final location of the terminal. The centenary chains are to be installed and terminated at the sea bed.
6. The construction of the other elements will meanwhile proceed and every completed element is to be immediately connected to the already fixed elements.
7. After that all the terminal elements are brought together, Load-on Load-off vessels could be used for the transport of the quay cranes and other equipment to the terminal.

19.3 Structural aspects

By the dimensioning of the terminals elements, it is required that each element must be able to resist the shear stresses and the bending moments acting on it. The first step towards the detail design is to divide each module into components as given below.

- **Components**
  - bottom slab
  - outer walls
  - inner walls
  - deck (or roof)

- **Loads:**

Three important aspects:

- Distinguish between the loads in the SLS and ULS
- different types of acting loads
- Another distinguish is the varying loads during different phases of the construction.

	Phase	Conditions	Acting loads (stresses)
1	**Inside the dock**	- Elements still inside the dock and the dock is dry	- dead loads - prestressing
2	***Elements outside the dock***	- Elements during completion afloat (probably in protected waters)	- dead load - Prestressing - hydrostatic water pressure
3	***During sea transport***	- Elements towed to final destination	- dead load - prestressing - hydrostatic pressure - towing loads - waves (dynamic loads)
4	***During operation***	-Elements are connected to each other and the terminal - Mooring lines are mounted in the turret - Cranes, intern transport and other equipment installed. - Vessels call at the terminal	*Static*: - dead load - prestressing - dead weight cranes and other equipment - hydrostatic pressure *Quasi-static*: - ballast water - currents and wind loads - container loads *Dynamic:* - wave loads - turret moorings - fender and bollard loads - mobile loads cranes and equipment

20 Financial Feasibility

Introduction

This section treats the financial aspects of the FTCT. The construction costs, operating costs, revenues of the terminal will be calculated. The main objective is to draw conclusions about the conditions that make the FTCT cost-effective. These conditions will be expressed in the in the required transshipment fee per TEU. For the commercial FTCT, economical benefits such the creation of new job opportunities and positive environmental impacts (transfer of coastal activities offshore) will not be considered. The All prices and amounts are at 2004 cost level and are given in Euros.

20.1 Construction costs

C1- Construction costs terminal modules

The quantity of material used for the construction of the prestressed concrete terminal has already been estimated by the calculations of the terminals weight. It is estimated that 20% of the cross-section is filled with material. Therefore, it follows (Figure 9.10, terminals cross-section):

- Quantity material/ meter length = [(5.5×170)+(55×12.3)+(15×12.3)] × 0.2 = 359.2 m^3
- Total material quantity (excl. wave barrier) = 1190×359.2 = 427448 m^3
- Wave barrier (8m high, 3m wide) = [(1190×240)- (1184×234)] ×8×20% = 13760 m^3

Total quantity material = 0.441×10^6 m^3

The Dutch Bouwmaat Nederland B.V. recommends in its catalogues 2 of the year 1995 a calculation cost of 500-1000 Florin (450-225 Euro) per m^3 prestressed concrete (inclusive). Also the lecture notes of Wagemans,L.A. (Infomap Algemene Constructieleer; TU-Delft, 1998) recommends a cost calculation value of 1000 Florin per m^3 prestressed concrete.

Although it is usually that whenever the (material) quantity becomes high, this leads to a decrease in the price per unit. This is for example is the case in the dredging world. In the case of the FTCT, the quantity of material used is very high compared to for example to a building or tunnel elements. However by the cost calculations, the highest value of **450.00 Euro per m^3** will be accounted for. This is for the reason that the calculated quantity of material is based on the assumption that the quantity of material used is 20% of the volume of the structure. if it happened (after the detailed design) that this ratio is found to be smaller after the actual one, there will still be a cost margin represented in the high cost per unit used in the calculations.

The Price per cubic meter reinforced/perstressed concrete includes only fabrication plus the costs of the dry dock. Transport and assembly are excluded and will be calculated later.

Total cost terminal structure: 450.00Euro× $0.441\times10^6 m^3$ 198.5 million

C2- Transport & assembly

The costs for the transportation and assembly of the terminal modules will depend on the location of the dry dock with respect to the final destination of the elements. However, it will be estimated that these costs are 20% of the construction costs given in C1.

Total = 39.7 million

C3- Equipment

Type	no. of units	price per unit (ml)	cost(ml)
- Portainers	11	5	55
- RMG's	15	3	45
- Personnel boat	1	5	5
- Tugboats	2	5	10
- AGV's:	45	0.3	13.5
Total			***128.5 million***

C4- Turret mooring

In the offshore world, the following cost prices are often used for the fabrication and installation costs of a turret mooring system.

- 10 million Euros for the turret structure.
- 1.5 million Euros per line (including anchors). 8 lines in the case of the FTCT

Total = 22 million

C5- building & workshop

The building and maintenance workshop onboard the terminal are to build afloat. Costs are estimated as following:

- Administration building: a total budget of 20 million is to be reserved for this facility. This amount includes the control tower and all necessary equipment.
- Technical service facilities: a total amount of 10 million.

Total = 30 million

C6- Facilities

Water station:	1 million
Electricity substation:	2 million
Fire station:	1 million
Waste disposal & drainage system:	2 million
Helicopter platform:	1 million
Fuel tanks:	1 million
Light posts:(per post1000m^2 , thus 285 posts, 5000 Euro/ post)	1.4 million
Total =	***9.4 million***

C7- Ballast system

Fabrication and Installation of the tanks, pump and other necessary equipment are estimated for 10 million Euro

Total = 10 million

C8- DP thrusters

A total amount of 10 million Euros will be reserved for the purchase and installation of the DP- thrusters with a total engine power of 4700 Hp. This amount includes control system and necessary equipment.

Total = ***10 million***

The items given above and their contribution to the total construction costs are shown in the table below.

	Cost (in millions)	%
Terminal modules	198.5	44.3
Transport & assembly	39.7	8.9
Equipment	128.5	28.7
Turret mooring	22	4.9
Building & workshop	30	6.7
Facilities	9.4	2.1
Ballast system	10	2.2
DP-thrusters	10	2.2
Total	**448.1**	

Table 20-1: construction costs FTCT

The total construction costs of the FTCT (Euro) = ***448.1 million***

20.2 Operating running costs

O1- Personnel Salaries

- Number of employees per shift:

  RMG's and Portainers machinists (26 units) 26 employees.
  Boats; 2 per boat (2 tugboats + 1 personnel boat): 6 employees
  Administration 20 employees
  Maintenance 5 employees
  Others (tasks not accounted for) 3 employees
  Total number of employees per shift = 60 employees

- The terminal operates 168 hour per week (24 hours/day and 7 days/week). Assuming that every employer works a 42 hour per week, that will require that 4 (=168/42) teams must be employed at the FTCT.
- Therefore, the total number of employees on the FTCT
  = 4 teams×60 employees per team = 240 employees
- It is also assumed that the average salary of an FTCT employee (amount paid by the employer) is 6000.00 Euro per month.

Total salaries FTCT employees per year (Euros) = 240×6000×12 = 17.28 million

O2- Energy cost

- ***Electricity***

The electrical energy needed will be transmitted to the terminal at the substation from the onshore through cables (at the seabed). The energy consumption is measured in KWh.

Cost per KWh:

The cost per unit varies depending on the country or company which delivers the energy. In the Netherlands, the average price per KWh is 0.20 Euro for consumptions more than 50.000 KWh per year. (Source: internet)

Consumption Portainers:

The electricity consumption of a quay crane is 5-6 KWh per move. (Source: report "Onderzoek energiebesparing bij stuwadoorsbedrijven"; DWA installatie- en energieadvies, 2003).The total number op crane moves on the FTCT is 0.67 million moves (FEU/TEU ratio = 1). This will result in,

Annual electricity consumption Portainers $= 6 \times 0.67\times10^6 \quad = 4.02\times10^6$ *KWh*

Consumption RMG cranes:

The same report indicates that the measured consumption for a rail crane is about 5 KWh. This will apply for the

Annual electricity consumption RMG's $= 5 \times 0.67\times10^6 \quad = 3.35\times10^6$ *KWh*

Consumption facilities

The terminal is lightened with 285 posts and assuming a consumption of 0.2 KWh (200 W lamps) per post, it follows:

Annual electricity consumption lighting $= 285[0.2\times 24 \times 365] = 0.5\times10^6$ KWh

For other facilities such as the administration building and maintenance workshop the same annual consumption as that of the terminals lighting will be assumed, thus:

Annual electricity consumption facilities $=2\times 0.5\times10^6$ *KWh* $= 1.0\times10^6$ *KWh*

- ***Fuel***

The price per liter diesel also varies per location or country. In the Netherlands where the prices of fuel are relatively very expensive, the price per diesel liter is around 1.00 Euro.

Automated guided vehicles:

AGV's have diesel driven motors. No data is found about their fuel consumption. However, a 400 hp truck drives on average 2km/liter diesel. The same will be assumed for the AGV's. In section 9.3.1, it has been calculated that the average travel distance per move is 1 km. Therefore the consumption per move is 0.5 liter.

Annual diesel consumption AGV's $= 0.5 \times 0.67\times10^6 \quad = 0.335\times10^6$ *liters*

Tugboats:

A tugboat with a bollard pull of 50 ton, burns about 50 gallons/hr Source: www.epa.gov/ttn/chief/conference/ei11/poster/agyei.pdf). The number of towing hours per year per tug follows from the number of vessel calls (600 as given in the program of requirements) and the operation time (towing time + travel time) of the tugboat per vessel call. The operation time per hour is assumed to be 1 hour per. 30 minutes for (de)berthing processes and 30 minutes for maneuvering. It is also given that 1 (US) gallon equals to 4.5 liter of diesel. Based on the above, it could be concluded that:

Annual diesel consumption tugboats =

2boats×600calls × 1hr/call × 5gallons/hr/boat×4.5liter/gallon = 0.456×10⁶ liters

Personnel boat:

The same will apply for the personnel boat as in the case of the tugboats, however the personnel boat will have longer operation time, making 6 trips per day (to and fro) and 30 minutes per trip. Furthermore, the personnel boat will provide extra bollard pull by the (de)berthing of the mega vessels (100 calls per year)

Number of operation hours = [6 trips/day × 365 days/year ×0.5hr/trip] + [100 calls/year × 1 hr/call]

Annual diesel consumption personnel boat =

1195 hrs/year ×85 gallons/hr × 4.5 liter/gallon= 0.457×10^6 liter

DP-thrusters:

The Dynamic positioning thrusters are required to have an engine power of 4700 HP (see section ……). The survey vessel SEAWORKER (dynamically positioning system) with a total engine power of 1300 HP (engine and bow thrusters) consumes maximally 1500 liters of fuel per day (source: www.seaworks.co.nz/Text/seaworker.htm). Using the later, the fuel consumption of the DP-thrusters will be estimated for:

Annual diesel consumption DP-thrusters =

(4700/1300) ×1500liter/day ×365 days= 1.98×10^6 liters

- ***Total annual energy costs***

	Number of units	Price per unit (€)	Cost (million €)
Portainers	*4.02*10^6 KWh*	0.20	0.804
RMG cranes	*3.35*10^6 KWh*	0.20	0.67
Facilities	*1.0*10^6 KWh*	0.20	0.2
AGV's	*0.335*10^6 liters*	1.00	0.335
Tugboats	*0.456*10^6 liters*	1.00	0.456
Personnel boat	*0.457*10^6 liter*	1.00	0.457
DP-thrusters	*1.98*10^6 liters*	1.00	1.98
Total (per year)			**4.90**

Table 20-21: annual energy costs FTCT

O3 - Maintenance & insurances

- The maintenance of the terminal areas, facilities and equipment will be estimated for 1% of the total terminal construction costs.
- The premium of the marine insurance depends on the type of the marine structure, number of crew and the area of operation. Furthermore, there are different kinds of

insurances such as hull, ocean cargo, etc. Except for the terminal, the insurance should cover the tug and personnel boats. For the insurance bill, also a percentage of 1% of the total construction costs will be accounted for.

Annual maintenance & insurance costs = 0.02× 448.1 = 8.96 million

O4 - Memory costs

Memory costs are meant to compensate for costs not accounted for. A 5% of the total operating costs will be reserved for memory costs

Annual memory costs = 5 (17.28+4.90+8.96)/100 = 1.56 million

- ***Total Annual operating cost FTCT = 17.28+4.90+8.96+1.56 = 32.70 million***

20.3 Exploitation

Revenues:

- The primary revenues will mainly be brought by the transshipment fee paid by the shipping liners. The throughput of the terminal is 1 million TEU per year while the number of TEU's transshipped per year is 0.5 million.
- Other secondary cash resources such as supplying vessels with water and fuel will not be accounted for
- The rest value of the terminal including cranes, boats and other equipment is assumed to be zero

Exploitation span:

The life span of the terminal is already determined in the program of requirements to be 50 years. This begins from the day the terminal is completed and is ready to operate

20.4 Financial Analysis

Construction time:

The construction time of the terminal will depend on the structural details of the design. However, in this financial analysis it will be assumed that the construction duration is 3 years. After that time the terminal the terminal will be able to receive vessels. The total construction costs will de divided equally over the 3 years.

Financial parameters:

- The ***Net Cash Value (NCV)*** is the sum of the annual profits (revenues– costs) over the whole exploitation period discounted in the time.

$$NCV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+i)^t} \quad [20\text{-}1]$$

where,

R_t revenues at year t

C_t costs at year t

n total number of years

i rate of interest

- The ***Benefit-Cost Ratio (BCR)*** is the ratio between the sum of the revenues (in other words, the benefits) and the sum of the costs, both discounted in the time as given in formula 20-2.

$$BCR = \frac{\sum_{t=1}^{n} \frac{R_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+i)^t}} \qquad [20\text{-}2]$$

In the table below, both NCV and BCR values have been calculated for variable transshipment fees. The transshipment fee is per TEU and includes both unloading and reloading. The rate of interest i is kept constant and equals to 6%. The calculations could be seen in appendix 20-A.

Transshipment Fee / TEU	***Net cash value (*10^6 €)***	***Benefit-Cost ratio***
80	-299.9	0.64
100	-167.5	0.80
120	-35.2	0.96
140	97.1	1.12
160	229.5	1.28
180	361.8	1.44
200	494.2	1.60

Table 20-3: NCV & BCR FTCT (6% interest)

- The ***Internal Rate of Return (IRR)*** is by definition the rate of interest i for which the sum of the revenues minus the sum of the costs (both discounted in the time) is exactly equal to zero. When calculation the IRR the following formula applies:

$$\sum_{t=1}^{n} \frac{R_t - C_t}{(1+i)^t} = 0 \qquad [20\text{-}3]$$

  The IRR is mostly used by governmental institutions during decision making. (Infrastructural) projects with expected high IRR should have priority above those with low rates. It expresses the rate of interest that the government or institution will obtain when investing money in a certain project

With iteration, the value for i (rate of interest) could be calculated using equation 20-3. This will then be equal to the IRR. In the same manner as previously, for variable transshipment fees, the IRR values are calculated. The results are shown in the figure below.

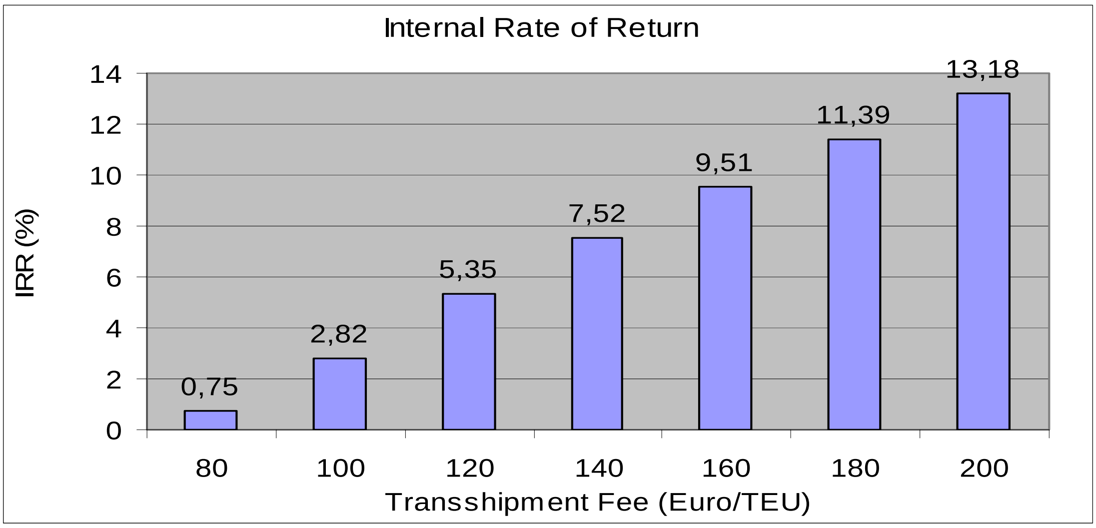


Figure 20-1: Internal Rate of Return FTCT

20.5 Evaluation

- ***Transshipment Fee***
  According to the calculations made above, it is clear that the terminal is financially unfeasible starting from a commercial interest rate of 6% per year and a transshipment fee of 100 Euros per TEU.
  The minimum transshipment fee for which the FTCT is cost-effective (NCV is equal to zero), by a rate of interest of 6% is **125 Euro per TEU**.
- ***The average transshipment fee***
  The average transshipment fee is in the range between 100-150 USD (85-125 Euros) per TEU. However, the readiness of the shipping liners to pay higher transshipment fee could be enhanced when in the location of the FTCT, no deep water container terminals are available.
- ***Finance and sponsoring***
  An economic feasibility study will probably result in much higher revenues when considering other advantages of the floating terminal not accounted for. In addition to the new job opportunities that will be created, the floating terminal has a relatively more favorable environmental impact compared to land terminals. The later could qualify the FTCT for possible governmental or organizational subsidies.

22 Environmental Aspects

Environmental considerations play an important role by the design of new ports or port extensions. An *Environmental Impact Assessment* (EIA) represents an important part of the decision making procedure between different alternative solutions.
In this section, possible negative effects on the environment caused by a traditional land terminal will be compared to those of the FTCT. For different aspects (of an EIA analysis), a "+" or "-" sign will be given to either alterative, indicating in a relative manner what the effects to the environment are. A "+" sign means that the alternative scores better compared to the other.

Aspect	*FTCT*	*Land terminal*	*Argumentation*
land use	+	-	Areas to be reserved for the building of land terminal comes in cost of urban and coastal areas
dredging	+	-	All three C*apital, Maintenance and Environmental dredging* activities will be unnecessary in the case of the FTCT where the water is naturally deep
Nature areas	+	-	Less effect by the FTCT to Wetlands, recreation and fishery grounds
Coastal morphology	+	-	Disturbance of sediment transport balance and coastal erosions could occur when land terminals (breakwaters) are built in soft soil coasts.
Ecology and sea habitats	+	-	The in deep water (100m) floating terminal will have less (if at all) impact on the sea life. A land terminal attracts vessel traffic into shallow water rich with sea life
Ballast water	+	-	Disposal of ballast ships water of different quality (oily, salinity) causing harbour pollution in the case of (in)land terminals.
Energy consumption	-	+	More electric energy consumption in the case of the FTCT needed for the operation of the DP-thrusters.
Use of resources	-	+	The large quantity of material needed for the construction of the concrete terminal does not enhance the efforts for an economic use of the natural resources.
Socio-cultural	+	-	Relocations and other social, political and cultural impacts could introduce problems in the case of land terminals
Health	+	-	Vessels and equipments emissions (smoke) and traffic kept at a distance from urban and populated areas in the case of the FTCT.
Safety	+	-	Less chance of vessel accidents, as the floating terminal gives the freedom to be situated in locations with low traffic intensity

22 Evaluation & visualization

The results found in each section were always evaluated at its end. As at this phase, the whole picture has become more clear, the general approach used from which the final conclusions were drawn will be evaluated. This will be done by judging on different aspects of the study, such as the design and some important choices and assumptions made. At the end of the section, a number of drawings are shown giving a total visualization of the designed system. It must be emphasized that no details are shown for the design of the hull of the terminal as this should follow from the structural (detail) design study.

- The choice for container terminal

The *general* objective of the thesis was to study the feasibility of a “floating port”. At a certain stage of the study (Preliminary study), it was chosen for a terminal for container transhipment. The conclusions were drawn about the limiting sea conditions for the operations of the terminal such as $H_{s;max}$ is 3m. However it is expected that for many other types of goods, these limits are larger and as the container lifting operations require more accuracy and thus more restricted motions compared to other sorts of cargo, such as dry and liquid bulks for example.

- The terminal layout

It has been chosen for the simplest form (rectangular shaped and marginal berths) of the terminals layout. The layout has the largest length dimension and the smallest width compared to the other alternatives. The fact that the width is relatively smaller, affects the operability of the terminal (SLS) in a negative way, because of the relatively larger wave transmission into the berths side. However, for the designed terminal –which rotates bow on to waves during high sea- the small width has the advantage that the horizontal forces in the ULS are much lower compared to the other alternatives. This is in addition to the advantages with regard to the structural aspects.

- Draught calculation & quantity construction material

By the calculations of the terminal draught, it was assumed that the quantity of material used to construct the terminal is 20% of the total volume. This is a rough assumption and there is a chance that the calculated draught (10.3m) of the terminal is underestimated. Clearly, it very difficult to calculate the exact weight of the terminal is such early stage of the design. Especially in the case of the FTCT, as there are no similar terminal existing that could be used as references. The exact draught could be once the structural detail design study is carried out. However, the larger the draught, the more the protection provided to the vessels (less wave transmission). Therefore, the conclusions about the systems operability could be only effected in positive way by larger draughts.

- Design conditions

Ultimate limit state:

The ULS is of significance to the *structural design* and the *mooring system* of the terminal. It follows from the sea conditions in a particular location. As no specific location is yet chosen for the floating terminal, other approach will be taken. The terminal mooring lines were designed for sea conditions up to Beaufort Scale 12. This corresponds to a significant wave height is 10.25m.

However, these conditions could be too aggressive or too mild in other places around the world. For example in the west coast of Africa (where there is a need for deep water terminals) or the Gulf of Mexico, H_{max} is about 5m and the occurrence of waves 10m high is almost not probable. In the southern part of the North Sea, for example in the location of the Euro Platform (about 50 kilometres from the Dutch coast,) an extreme wave height (H_{m0}) of 9.32m has a returning period of 10.000 years. While in the Northern part of the North Sea, the sea conditions are more aggressive and waves up to 20 meters high have been observed.

Waterdepth:

The design waterdepth is 100 meters. When considering the draught of both the vessels and the terminal, such large water depth may not be necessary. However there are two other factors that may resemble a restriction for the smallest waterdepth, and these are:

1- The turret mooring lines require a certain minimum length to provide the resisting force. For the designed system, the minimum waterdepth will be about 50 meters. For shallower waterdepths another system must be chosen for the station keeping of the terminal.

2- In relatively shallower waters, waves coming from deep areas could "feel" the sea bed resulting in elliptical trajectory motions of the water particles. This will result in larger motions of the system and thus less favourable operating conditions.

- Hydrodynamics

By the calculations of the relative motions (terminal-vessel) two assumptions were made. The first is that the terminal is totally rigid. As the terminal will have certain elasticity, this assumption leads to an underestimation of the terminals motions and thus the relative motions of the system. In the contrary, the second assumption leads to an overestimation of the relative motions. The assumption is that the terminal and the vessel always move in the opposite direction and that the amplitude of the relative (heave) motion is equal to the sum of those of the two bodies.

- Financial feasibility

The accuracy of the calculated construction and operating costs of the terminal, the accuracy varies from one item to another. For a number of items, concrete figures and prices were available. While in some cases, estimations were made based consultations with lecturers at the university of different disciplines (Offshore, Structural Hydraulics or Port Engineering) or information available on the worldwide web. Although, the most figures are considered to be reasonable, however some items must be revised to obtain more accurate results. An example of the later, are the maintenance and insurance costs as given in section 20.2.

23 Conclusions & recommendations

This section comprises the important conclusions which have been drawn during the course of this study. In addition, a number of recommendations will be formulated based on the experiences and extra knowledge gained during the progress of the thesis.

23.1 Conclusions

Terminals design

- The required surface area of the terminal is 28.56 hectare. The needed berth length is 1190 meter. The expected waiting time of the mega vessels is 9.2% of the service time and for the feeder vessel, the average waiting is 9.5% of the service time.
- The operability of the terminal is determined by the relative motions between the terminal and the vessels. It was found that *terminals layout* plays is a significant factor in the determination of these relative motions and thus the systems operability.
- The needed surface area and quay length are the two important boundary conditions when determining the terminals layout
- It is chosen for a pontoon-shaped rectangular design of the terminal. One of the important characteristics of such a structure is that it provides the berthed vessels with protection against sea loads.

Operability

- The lifting operations of the containers could proceed up to a sea state with a significant wave height of 3m. This is based on the calculated response of the designed system in wind wave conditions as those in areas of the North Sea.
- Heave and roll motions are the most significant modes of motion for the operability of the designed system. Furthermore, the heave motions are decisive for the determination of the maximum operating sea conditions. The terminal large width dimension resulted in a large radius of gyration and thus relatively smaller roll motions.
- From the results it could be concluded that the largest contribution to the systems relative motions follow from the vessels motions. The terminal with its large dimensions will barely respond to mild sea conditions.

Mooring system

- A single point mooring is found to be the most suitable mooring system for the terminal. This will make it possible that the terminal rotates and changes its orientation towards the varying wave directions. It is chosen for a combined DP-turret mooring system. (variant of the SPM)
- By the design of the mooring system, it was found that a low stiffness of the system has two advantages. The first is that the mooring system will not need to resist the large (299 MN) 1st order wave frequency forces. Secondly, during operating conditions, the sway motions induced by 2nd order low wave drift forces will have small frequencies and thus resulting in long period oscillatory motions. The later is

favorable with regard to the terminal operations

Financial aspects:

- The total construction costs of the terminal including necessary equipment are estimated for 448.1 million Euros. The total of the annual operating costs are 32.70 million Euros.
- From a cost-revenue analysis, it has been concluded that the minimum transshipment fee that the shipping liners must pay per TEU is 125 Euro. This applies for an interest rate of 6% and an exploitation time of 50 years.

23.2 Recommendations

This thesis is regarded to be the first step towards a complete study about the feasibility of the "Floating Port". It represents the first cycle of the design process. In this section, a number of recommendations and suggestions will be given which can be used during further treatment of the subject.

- Selection of a specific location
  Based on the conclusions drawn on this report about the operability of the designed system, a location(s) for the FTCT could be chosen. The downtime of the terminal as result of excessive motions will then follow from the probability of exceeding a H_s of 3 meters at that particular location(s). This approach will make it possible to draw the borders about a more specific problem during a second cycle of the design process.

- It is also recommended to use more updated criteria for the maximum vessel motions during the lifting operations of the terminal. A recent thesis research, "Criteria for un(loading) container ships" by Goedhart, B. treated the criteria for sway and surge motions only. However the model could be expanded to include all six modes of motion.

- With regard to the terminal design, it is recommended to examine the hydrodynamic behaviour and the operability of different layout alternatives, such as those mentioned in section 8 of this report. The requirements with regard to the station keeping of the terminal will vary per alternative.

- Simulation models could be used to obtain more accurate results about the required number of intern transport equipment for quay-yard yard transport of containers as well as within the storage yard.
- By the calculations of the relative vessel-terminal motions, the bodies were assumed to be always moving in the opposite direction. This is because of the fact that the phase difference between the motions of the two bodies is unknown. To avoid overestimating the relative motions, it is recommended to apply Diffraction computer models which can calculate the motions of both bodies with respect to the incoming wave.

- A structural analysis should follow for the detail design of the terminals structure. The structural analysis should include further treatment of the fender system and elasticity effects.

- To enhance the financial feasibility, the following is recommended:
  1- Annual throughput:
  Increasing the terminals throughput by allowing a maximum stacking height of 5 containers. This will lead to a less favourable level of service of the terminal (usually translated in the service time of the vessels). Nevertheless, the increase in the annual revenues will make it possible to reduce the transhipment fee per TEU, making the terminal more competitive.
  2- Automating:
  The labour costs at the FTCT represents 52% of the total operating costs of the terminal. For this reason, it is recommended to reduce of the number of labours by introducing automated (computer) guided equipment. This is for instance could be applied for the container transport equipment within the storage yard. Automated systems are since recently been introduced and are already in use.

List of contents

1 Introduction

Developing technologies could help to find non-traditional solutions to problems emerging as result of a fast changing world and increasing demands of the inhabitants. The possibility of expanding towards the sea, in the form of large scale floating structures was been examined in many places around the world. Floating cities, airports, factories and even green houses are examples of areas of research or application.

Chapter 2 of this report deals with literature about the state of the technology in the marine world. Updating information about a number of applications of large floating marine structures could be found in this chapter.

Literature about the trends in the marine industry and transport is the theme of chapter 3. Special attention is also given to one of the most fast growing sea-borne trade which is the container shipping. Chapter 4 comprises information about the design aspects, parameters and methods of container terminals.

Criteria for the operation of different types of terminals are collected from various sources. Limiting amplitudes of motions and acceleration within both the ultimate limit state and the serviceability limit state are illustrated in chapter 5 of this report

Finally, chapter 6 comprises information about different types of floating structures used worldwide. These structures or there concepts could represent eligible solution alternatives for the floating port.

2 State-of-the-Art

2.1 General

The possibility of using floating terminals to handle and store various types of commodities or to offer berthing facility has already been examined in many parts of the world. To satisfy certain kind of demands, many of these terminals are designed, and even in some cases already in operation. In this chapter information is collected over various types of offshore terminals and handling facilities. This gives a general picture about the state of the technology and the trends in the marine world.

2.2 Floating Liquefied Gas terminals

Gas energy is proven to have less damaging environmental impact compared to petroleum oil extracted fuel. However, the nature of the product demands high standard safety regulations during transport or storage. Proposals for handling of liquefied gas in offshore terminals are demonstrated below.

ABS [2-1] Concern over long-term US gas supplies, a large number of new supply projects, and lower LNG infrastructure costs are all contributors to the LNG growth spurt of recent years. The last five years have seen a doubling in the number of LNG export terminals, most of which have plans to expand further in the near future.
Advantages of offshore LNG terminals include: favorable construction locations, the ability to relocate floating terminals once a field becomes depleted, the manner in which they address safety and security concerns of the public, and the elimination of restrictive size and draft limitations for LNG ships.

Figure: offshore LNG terminal

These purpose-built offshore LNG terminals will have the ***capability to store up to 300,000 m3 of LNG***. They may be either floating or gravity-based structures with steel or concrete being the most likely material used in their construction.
***Industry forecasts estimate that at least five and possibly up to 20 terminals could be built for US offshore* installation in the next 10 years**. Other regions where offshore LNG terminals are currently being considered are Australia, Norway, Angola and

Italy.

BERGER/ABAM [2-2] ARCO's floating liquefied petroleum gas (LPG) facility in the Java Sea is located off the coast of Indonesia. The hull measures 461 by 136 feet with a depth of 57 feet; overall height of the hull and topside is 100 feet; and the displacement is 65,000 tons. Twelve insulated steel tanks provide 375,000 barrels of LPG storage.
The vessel supports a system of integrated tanks, product loading arms, a liquefaction facility, and crew accommodations for 50. It is designed to bring gas on board through a single-buoy mooring system, store liquefied gas for two weeks, and transfer gas to a LPG tanker moored alongside.

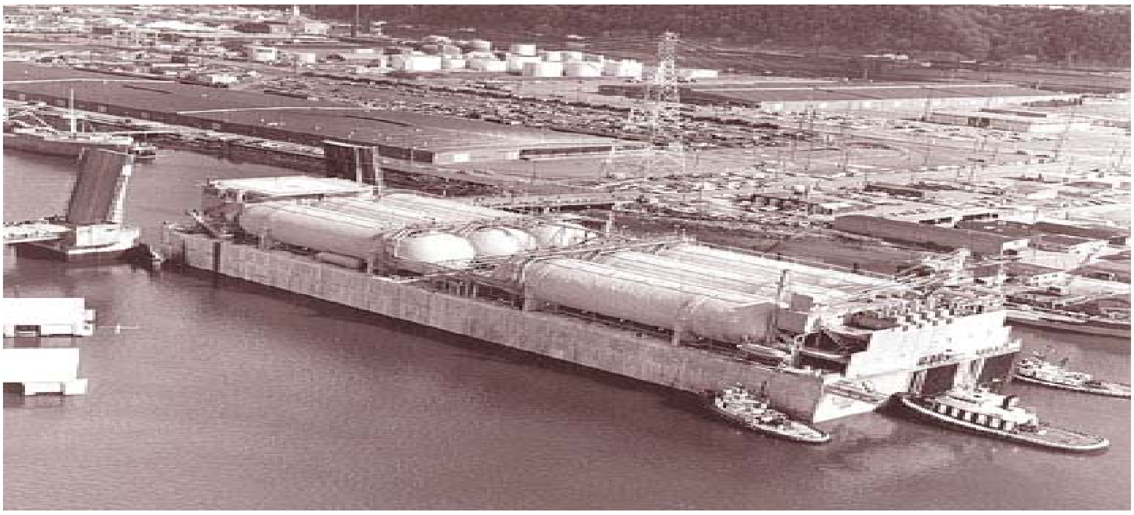


Figure2: ARCO Floating LPG Terminal, Indonesia

The safety aspect seems to be of great concern in the transportation process of flammable liquid bulk such as petroleum oil and liquefied gas. Strict safety measurements are to be taken to lower the risks of explosions or environmental damage

DoT [2-3] The Coast Guard is establishing temporary safety and security zones for Liquid Natural Gas Carrier (LNGC) vessels within the Boston Marine Inspection Zone and Captain of the Port Zone. These safety and security zones will temporarily close all waters within a 500-yard radius of all LNGC vessels anchored in Broad Sound and while moored at the Distrigas waterfront facility in the Mystic River, Everett Massachusetts.
These safety and security zones also temporarily close all navigable waters and internal waters of the United States within the Boston Marine Inspection Zone and Captain of the Port Zone, two miles ahead and one mile astern, and 1000-yards on each side of any LNGC vessel anytime a vessel is within the internal waters of the United States.

2.3 Floating Production, Storage and Off-loading Vessel (FPSO)

An FPSO is also an example of large offshore handling and storage facility. In general, these vessels operate in (unprotected) open sea. The sea conditions and the vessels design determine the level of workability of the vessel.

Journeé [2-4] A Floating Production, Storage and Off-loading vessel (FPSO) is generally based on the use of a tanker hull, which has been converted for the purpose. Such vessels have a large storage capacity and deck area to accommodate the production equipment and accommodation

Motion characteristics of such vessels are acceptable as long as the vessel can 'weathervane' with the predominant direction of the wind and the waves. This requires that a single point mooring system be used by means of which the vessel is effectively held at the bow or stern by the mooring system and allowed to rotate freely around that point. A complicating factor of the SPM system is the need to include fluid swivel systems in the oil transport system to and from the vessel.

In some sheltered locations it is not necessary to apply an SPM type mooring system. In such cases a spread mooring system which holds the vessel in a fixed mean heading direction is the preferred solution since no swivels are required in the oil transport lines to and from the vessel. Due to the wave induced motions of the FPSO, the oil transportation lines to the vessel have to be flexible

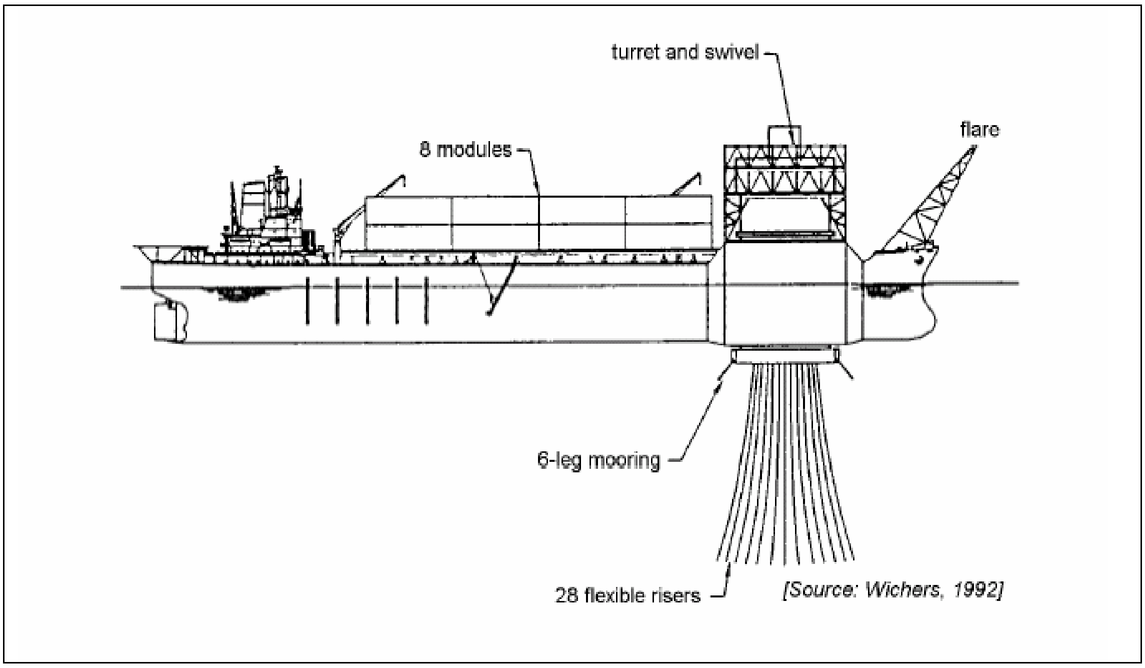


Figure: Floating production supply off-loading vessel

TIMES [2-5] LNG is becoming an increasingly important source of natural gas for North America as economic and environmental restrictions make it more difficult to extract remaining supplies from fields in the United States and Canada.

The push for increased LNG imports comes as federal government statistics project that demand is exceeding supply by 1.8 percent annually.
Shell has revealed details of a proposal by Shell Development (Australia) PTY Ltd (SDA) to use the world's first floating liquefied natural gas (FLNG) facility to develop the Greater Sunrise gas fields in the Timor Sea. The facility would be located offshore on a barge, close to the proposed Sunrise drilling platform.
The company said that the FLMG facility would make use of technology developed by the company in Floating Production Storage and Offloading (FPSO) vessels.

2.4 Floating dry-bulk terminals

Offshore handling and storage facilities are mainly common in the transport of liquid bulk. However, as the technology has delivered many advantages, the same technology may be applied for other kinds of commodities. This paragraph shows an example of an offshore transshipment dry bulk terminal.

Terenzi [2-6] the Genoa based Coe Clerici Logistics has developed a technically advanced facility, identified and patented as the Floating Transfer Station (FTS). This concept can be considered as the next generation of floating terminals and encompasses the latest technology associated with the off shore transshipment.

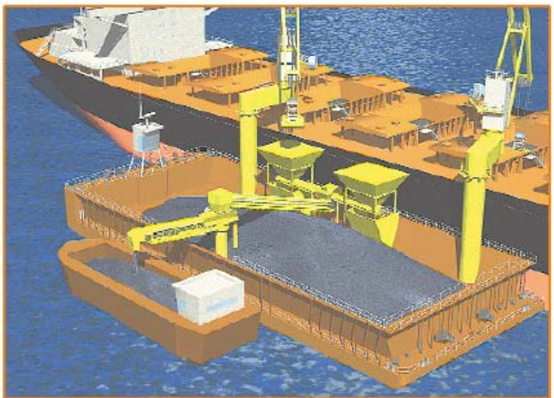


Figure 1. An artist's impression of the FTS while transferring dry bulks from a vessel to a barge

Figure 2. FTS Bulk Irony has proved an efficient and cost-effective solution to Piombino (Italy) Port bottlenecks for both raw material and steel product.

FTS – Main Advantages vis-à-vis Shore Terminal

- FTS can be positioned at the closest possible site to the mine or to the end users thus reducing transportation cost to the minimum.
- The FTS investment cost is definitely much lower compared to a dedicated shore berth facility.
- The FTS project implementation time of no more than 12–14 months is significantly less than the development time for a shore-based facility.
- The environmental impact of the FTS is very limited. The FTS does not require permanent civil works, dredging or land acquisition and as a consequence statutory permits are more easily accessible.
- Heavy investment is required to build and equip port infrastructure whereas only a service is paid in the case of the FTS.

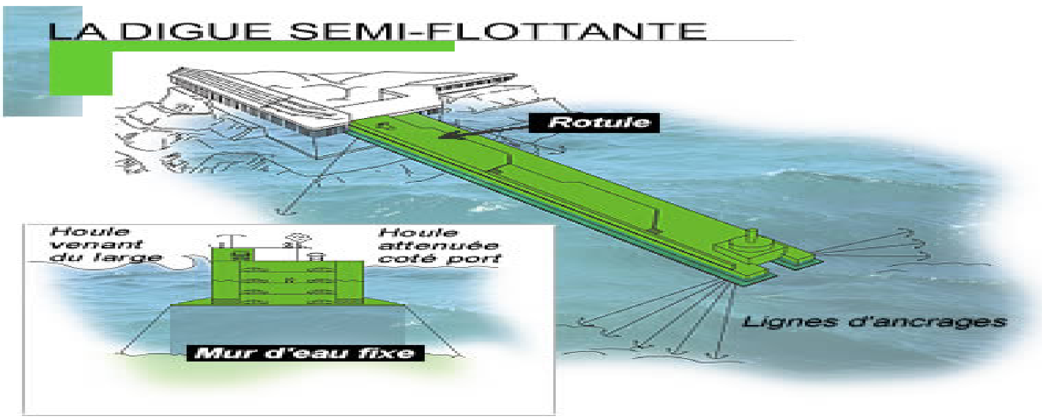
2.5 Floating marinas

Floating marinas are already common in many places around the world, especially in the United States. They are mainly located in lakes or protected waters and consist of floating elements with dimensions of few meters. An exceptional case is the semi-floating breakwater in Port Hercule (Principality of Monaco) which has a length of 352 meter and 28 meter wide. It functions as a breakwater and accommodating cruise ships at the same time.

Monaco [2-7] the principality of Monaco is equipping Port Hercule with new docking facilities to make of one of the largest yachting harbours on the Mediterranean.

Facilities on the breakwater:
- 360 parking spaces on 4 levels,
- 25 000 m3 of storage space on 2 levels inside the breakwater.
- Passenger boat terminal for cruise ship passengers and to meet company needs.
- Administrative and business premises.

Berthing: 3 cruise ships (including one on the offshore side when the weather is fine).



2.6 Conclusions

From the above collected literature the following could be concluded:

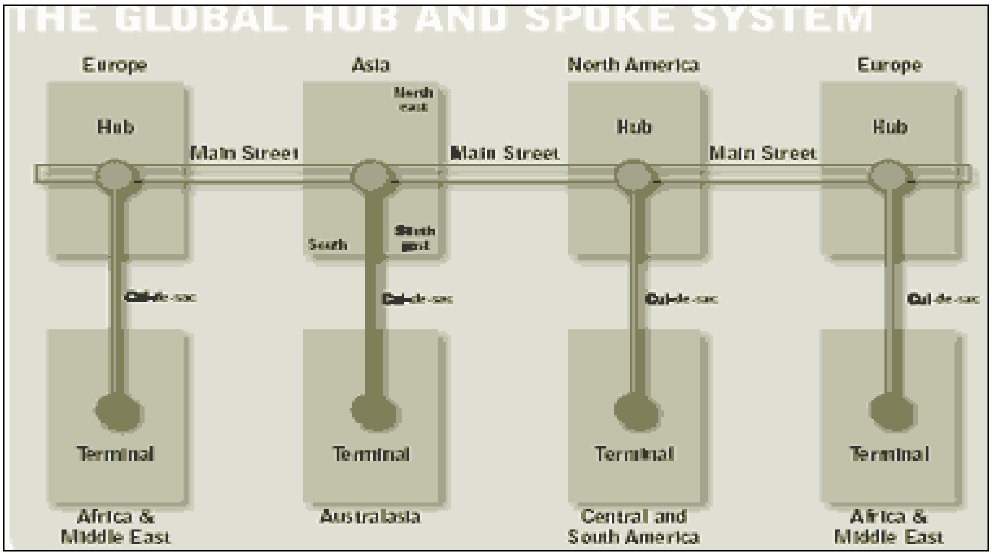
- There use of floating terminals or handling facilities has become a fact in many places around the world. It has many advantages and may offer a good solution.
- Forecasts show that there will be an increase in the sea-borne trade in the coming years and therefore the demand for more ports and terminals worldwide.
- The offshore liquid and dry bulk facilities mentioned above has the function of *transshipping* commodities. This may apply for the most offshore terminals for the reason that connecting offshore terminals to the fast land may become too expensive.

3 Trends in Maritime transport

The last chapter comprised literature about trends in the marine world where it is shown that there is a tendency to allocate some activities offshore. The theme of this chapter is the trends and developments in the logistical process associated to the industry.

3.1 Hub ports

The hub-and-spoke logistical system appears to have a wide application globally. Its application in the sea-borne transport and the major transport routes could be seen in the figure below



Damas [3-1] The hub-and-spoke system has spread from the airline passenger industry to the cargo shipping business, and is becoming a predominant method of routing cargoes for most secondary ports and trade routes. Last year, a new container terminal on Panama's Pacific Coast opened, bidding to become a major *transshipment hub for Latin America and the Caribbean.*
Panama Ports has invested $120 million in the 600,000-TEUs-a-year terminal. Balboa is one of the most strategic locations in Latin America providing transshipment services for the world's major carriers operating on transpacific routes.
The opening of the Panamanian hub allowed *Maersk Sealand to convert its direct U.S. East Coast/Panama/West Coast of South America service into transshipment.* Cargo is now relayed in Panama, using feeder ships sailing between Panama and the South American Ports.

Dongwoo [3-2] To provide member countries with a planning context for the development of shipping and port development strategies, the UNESCAP secretariat developed and utilized the Maritime Policy Planning Model (MPPM) to forecast trade flows, port throughputs, future shipping network and port capacity requirements.

- It has become increasingly clear that there are no insurmountable technical barriers to the future increase in ship size. Some analysts take the view that the search for economies of scale is inexorable, and will drive *vessel sizes up through 12,000 TEU* and even beyond within the next decade, despite the challenges in terminal handling that will need to be overcome.

- According to this view, the move to larger and larger ships will continue and, if anything, accelerate. The need to maximize the utilization of this large vessel will in turn drive a radical reduction in the number of port calls on major routes, and *feed the development of global mega-ports* served by fully integrated global networks.

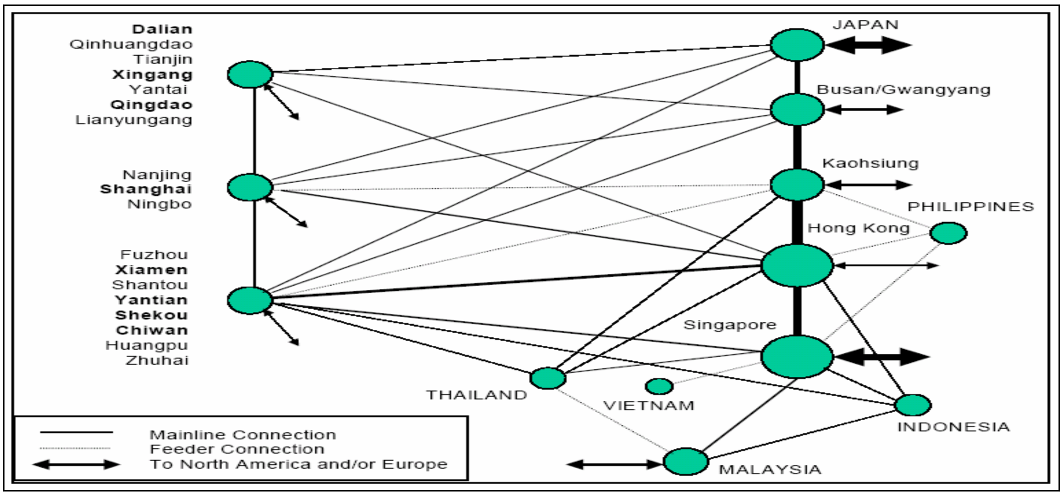


Figure: Asian hub and feeder network

The port of Singapore is a prior example of a hub- port. The most incoming cargo is transshipped to other regional ports making the percentage of sea-sea cargo very high for certain commodities. Compared to the Port of Rotterdam, this percentage is very high as the most cargo is sea-land or vice verse for the last.

KLEYWEGT [3-3] Singapore is located close to some of the world's major shipping lanes. Almost everything that travels between Europe and East Asia passes by Singapore through the Straits of Malacca [10]. Singapore is linked by more than 250 shipping lines to more than 600 ports in 123 countries. The port of Singapore has the second busiest container terminal in the world (after Hong Kong). It has developed into the world's largest transshipment center for containers and bulk oil products, as well as the world's largest bunkering port. *Approximately 80% of the containers that enter the port of Singapore are transshipped.*

Container terminal in the port of Singapore:

- Area: 339 hectare
- Draft: 9.6 to 15.0 meter
- Berths: 37 (21 main; 16 feeder)
- Quay cranes: 118
- Area: 339 hectare
- Throughput: 15.52 million TEU in 2001

Table: PSA Corp's Revenue & Profit Performance, 1996-2000 (S$ millions)					
	1996	**1997**	**1998**	**1999**	**2000**
Revenue	2,049	1,972	2,765	2,541	2,458
Profit	1,008	1,124	931	1,103	1,210
Source: PSA Corporation Annual Report					

3.2 Container traffic and transshipment

Increase of container shipping traffic and container vessels size lead to the introduction of new logistical system for intercontinental container traffic. Aiming to reduce the turnaroundtime of the large vessels (main line vessels), they are only to call on a few ports in there route. From there smaller vessels (Feeders) are used to bring the containers to the final destination.

Ligteringen [3-4] both the intercontinental and continental maritime transport volumes are increasing. The former due to the steady growth of the world trade, the latter also because sea transport is becoming more attractive. Containerization in particular represents a major factor in the growth of cargo volume and hence in the increase of port capacity required. The average growth rate of container terminal capacity in the period 1990-1997 was around 9% per year. This is to accommodate partly the growth of general cargo, partly also the shift of conventional general cargo to containerized cargo.

The world container traffic reached a volume of 160 million TEU in 1997, representing 1500 million tons of cargo (containerization International, 1998). The top 20 container ports handled, more than 50% of this traffic. Notwithstanding the Asia crisis the growth rate in 1998 remained around 5% and recent forecasts predict this growth to continue for the coming 5-10 years.

A number of studies have been carried out to examine the feasibility of establishing transshipment container terminals. Following is a summary of consultancy study undertaken by the TRI Maritime Transport Research Group at Napier. The study was jointly commissioned by Orkney Islands Council, Highlands and Islands Enterprise, and Halifax Port Authority in Nova Scotia.

TRI [3-5] this study was aimed at investigating the potential for the establishment of a container transshipment port in Scapa Flow, specifically in the context of a North Atlantic route between Orkney and Halifax, to cater for container traffic between North West Europe and the eastern seaboard of North America.

The heart of the study was the construction of a financial model to compare the costs of this alternative solution with existing arrangements. Whilst this summary touches on the overall conclusions drawn from the model, the model itself is commercially sensitive and is not being released in its entirety at this stage.

Demand for new container terminal capacity
To accommodate forecast increases in traffic, substantial new container terminal capacity will be required by 2005 and beyond. Additional capacity will need to be in the order of 100m TEU or, in other words, 100 additional container terminals each capable of handling 1m TEU a year.

Industry consolidation and increased ship size
An increase in ship size is necessary to accommodate constant trade growth, as well as to reduce carrier unit costs in the face of fierce competition. Maximum ship size is expected to increase further to over 10,000 TEU and to perhaps as high as 15,000-18,000 TEU.

Implications of ship upsizing for ports
Many traditional liner ports are unable to accommodate the mega ships. Key barriers to a port handling such ships include the need to dredge far deeper channels, lack of terminal land area, and local traffic bottlenecks.
Mega ships are more easily handled at specially built **offshore** transshipments terminals than depth-constrained and congested city ports. New offshore mega-hubs being built in a number of locations around the world have the natural benefit of deep water and therefore avoid high capital and maintenance dredging expense. Furthermore, as almost all containers are transshipped at such facilities, the port itself neither contributes to, nor suffers from, landside bottlenecks.

Benefits of offshore container hub terminal development
The primary benefits to be derived from diversion of mega ships to specially designed offshore hub terminals are as follows:

- Reduced pressure on existing constrained land areas at mature traditional mainports;
- Reduced costs from diversion of largest ships to cheaper offshore mega-hubs (e.g. heaper land, less dredging/towage/multiple calls);
- Reduced pressure on traditional mainports to act as transshipment centers, with all the implications this entails for additional land take/access; and,
- An offshore transshipment terminal allows ever increasing demand (for freight transport) to be distributed across more ports in any given region. It also permits growth to be managed more efficiently and effectively

Financial Model
The aim of the model was to derive costs relating to a container transshipment service using Orkney and Halifax as hub ports (hereafter referred to as a MEGASHIP service), and then to compare these costs with the alternative direct service options (i.e. MULTIPORTSHIP service). The main objectives are therefore:

- To estimate Total Shipping Costs per TEU for a MEGASHIP transshipment service, inclusive of FEEDERSHIP costs;

- To estimate Total Shipping Costs per TEU for a MULTIPORTSHIP direct service;
- To compare and evaluate Total Shipping Costs per TEU relating to a MEGASHIP + FEEDERSHIP transshipment service with a MULTIPORTSHIP service, and over a range of vessel sizes.

Container services modeled

Estimated Total Shipping Costs per TEU are therefore modeled for three specific types of container shipping service:
- MEGASHIP – vessels between 4,000-10,000 TEU capacities employed only on a trunk- haul between Orkney and Halifax transshipment hubs;
- FEEDERSHIP – smaller capacity vessels employed to connect the Orkney and Halifax transshipment hubs with key ports at each end of the trade (i.e. in North America and in Northern Europe), and;
- MULTIPORTSHIP – vessels between 4,000-10,000 TEU capacities serving by direct call a range of ports in North America and Northern Europe in an End-to-End service.

Methodology

For each service type, the model employed requires development of the following submodels:

(1) Daily Fixed Cost per TEU
(2) Cost per TEU-Mile
(3) Cost in Port per TEU
(4) Total Shipping Cost per TEU

Corresponding with suggestion made by the industry, the following MEGASHIP services were modeled and compared with alternative MULTIPORTSHIP services:
- Orkney-Halifax
- Orkney-Freeport (Bahamas)
- Orkney-Singapore

Modeled results

Total-Shipping-Cost-Per-TEU1 were modeled and estimated for each of the three deeps MEGASHIP services. Potential cost savings using Orkney as transshipment hub, based on optimal ship size for each route, was as follows:
- A reduction in Total-Shipping-Cost-Per-TEU of up to 23%;
- A reduction in one-off fleet capital costs of up to 7.5%
- A reduction in TEU-miles of up to 17%;
- A reduction in fuel consumption of up to 10%

Explanation for MEGASHIP economic and environmental benefits

The results of the detailed modeling exercise therefore indicates the potential for carriers to enjoy significant cost savings, and to generate major environmental benefits using transshipment via Orkney, compared with current direct call services.

Services and traffic flows

Based on modeled cost findings, and optimal vessel sizes, three separate levels of terminal utilization and associated terminal development scenarios were considered:
- Minimum (MIN) Scenario
  - Twice weekly North Atlantic MEGASHIP (4,000 TEU) service to Halifax hub
- Medium (MED) Scenario
  - Twice weekly North Atlantic MEGASHIP (4,000 TEU) service to Halifax hub
  - Twice weekly South Atlantic MEGASHIP (4,000 TEU) service to Freeport hub
- Maximum (MAX) Scenario
  - Twice weekly North Atlantic MEGASHIP (4,000 TEU) service to Halifax hub
  - Twice weekly South Atlantic MEGASHIP (4,000 TEU) service to Freeport hub
  - Twice weekly Europe-Asia MEGASHIP (6,000 TEU) service to Singapore hub

Table X.2: Terminal facilities and cost

	MIN	MED	MAX
TEU Per Annum	*1,120,560*	*2,241,120*	*3,921,680*
Cranes	*8*	*16*	*28*
Straddles	*24*	*48*	*84*
Quay length	*850m*	*1,701m*	*2,976m*
Terminal area	*297,649m²*	*595,298 m²*	1,041,696 *m²*
Total Cost	**$196.1m**	**$392.2m**	**$686.4m**

A further confidential financial model has been prepared in order to estimate terminal revenues, expense, and cash flows for developments corresponding with each of the three operating scenarios.

National and international significance of development

The Hub Port proposal is of such national significance that the application will almost certainly be ‘called in’ by the Scottish Executive for determination by the Minister rather than the Local Authority.
As there are currently no deep-sea container terminal facilities active in Scotland, a transshipment terminal in Orkney would have no displacement effect at the Scottish level.
Any adverse employment effects at other ports in the UK and on the Continent would be expected to be minimal as these ports would still be handling similar traffic volumes, albeit carried by FEEDERSHIPS.

3.3 Conclusions

- The steady increase in vessels size especially for container shipping created the need for deep water ports.
- Shipping lines tend to maximize the utilization of their vessels by reducing the number of port calls along the shipping route.
- Hub ports and cargo transshipment are becoming more familiar as result.
- Despite the fact that containers will be double handled the results of the financial model of the TRI study shows that the Total-Shipping-Cost-per-TEU will reduce up to 23%. Accordingly, potential for such kind of terminals should be very high.
- Ports accommodating those large vessels should not per se be connected to the hinterland land as the port serves a large region.

4 Design Aspects of Container Terminals

Literature with regard to the operational design of container terminal is the theme of this chapter. Different design methods and parameters are used to determine the required quay length, surface area and finally the layout of the terminal

4.1 Determining quay length

To determine the required quay length a number of approaches are mentioned below. The methodology varies from simple empirical formulas to a more detailed approach by using simulation models.

Groenveld [4-1] a very important item in the port operations is the ready availability of adequate *berth capacity*, when it is required. Too few berths will give rise to queues for ships and delay in cargo delivery. Berths that are too small, limit the maximum ship size, which in turn limits the throughput capacity.
In general there are four ways of determining some of the answers to the question of optimizing port capacity, these are:

1. Empirical 'rule of thumb'
2. Queuing theory
3. Simulation models.

Empirical 'rules of thumb'
For small ports with low traffic intensity it is possible to obtain good insight into the prevailing conditions without the use of any mathematical techniques whatsoever. Most small ports have, in fact been designed this way. However, when in case of *increasing traffic intensity interactions begin to play a more important role, even with a simple port system it is necessary to use the queuing theory to estimate the basic throughputs involved.*

Queuing theory
With this theory the port system has to be schematized such that it consists only of a queue (anchorage) and a discrete number of berths. In addition the inter arrival time distributions and service time distribution are expressed mathematically. *Assuming no tidal or meteo windows apply the arrivals, per unit time, are usually found to fit into a Poisson distribution while the service operation generally fits an Erlang-K distribution*

D.G. Kendall proposed a notation that covers a wide range of queuing situations. This caters for queuing systems at which customers require a single service before departure from the system. The factors determining the behavior of such a system are:

1. The customer's arrivals.
2. The service time of customers.
3. The service system.

In general, the arrival process of the ships is stochastic in character. *Very often the negative exponential distribution (N.E.D.) is used to model inter arrival times when arrivals are completely random.*
The time taken to serve ships along the quay obviously has an effect on the length of

the queue that may form. *A system with sufficient berths to meet the average rate of arrivals of ships will still have queue forming. In port engineering systems the total service time often consists of several different-stages and this also the nature of the Erlang-k distribution. The Erlang-k distribution may thought to be built up of k negative exponential distributions (N.E.D.). Ships of a wide range of sizes result in a negative exponential service time.*

The constant distribution has no variability and the variation of the negative exponential distribution is unity, while its standard deviation is equal to its mean. In making the models more general, the distribution functions have to be more flexible

Simulation techniques

Simulation techniques have to be used when it is no longer possible to create a simple system such as described above. This can occur, for example when:

- The sailing time from the anchorage to the quay cannot be neglected in relation to the servicing time,
- The number of berth is dependant on the length of the ships and
- *The tidal conditions affect the functioning of the system.*

Ligteringen [4-2] a *first approximation* of the number of berths and hence of the quay length is made on the basis of an estimated berth productivity.
For modern terminal receiving 4000-5000 TEU ships on regular basin and working 24 hours per day, 360 days per year, *the average ship size is assumed to be about* ***2000 TEU*** *with a length of 250m.* We would expect on average 3 cranes to be available per berth and rather low berth occupancy of 35%.

(i) *Berth occupancy of 0.35 is rather low*, but often encountered due to the stringent conditions posed by the shipping lines with respect to minimum waiting time.
(ii) A berth productivity of 340,000 TEU/yr is higher than the most terminals can achieve at present. However, on modern hub terminals the berth productivity can be as high as 500,000 TEU/yr, *due to high TEU factor.*

The second and more accurate method for determining quay length requires also more precise input in terms of *expected annual number of calls* and the *average parcel size*, i.e. the number of containers unloaded and loaded per call.

In practice most container ships sail on fixed routes and within tight schedules. Unless significant delays occur due to bad weathers or vessel repairs, the ships arrive within about 1 hour of their scheduled time of arrival this means the assumption of random arrivals is conservative. Most likely the *berth occupancy can be increased to 0.5-0.6 without significant waiting time* resulting for the majority of the ships.

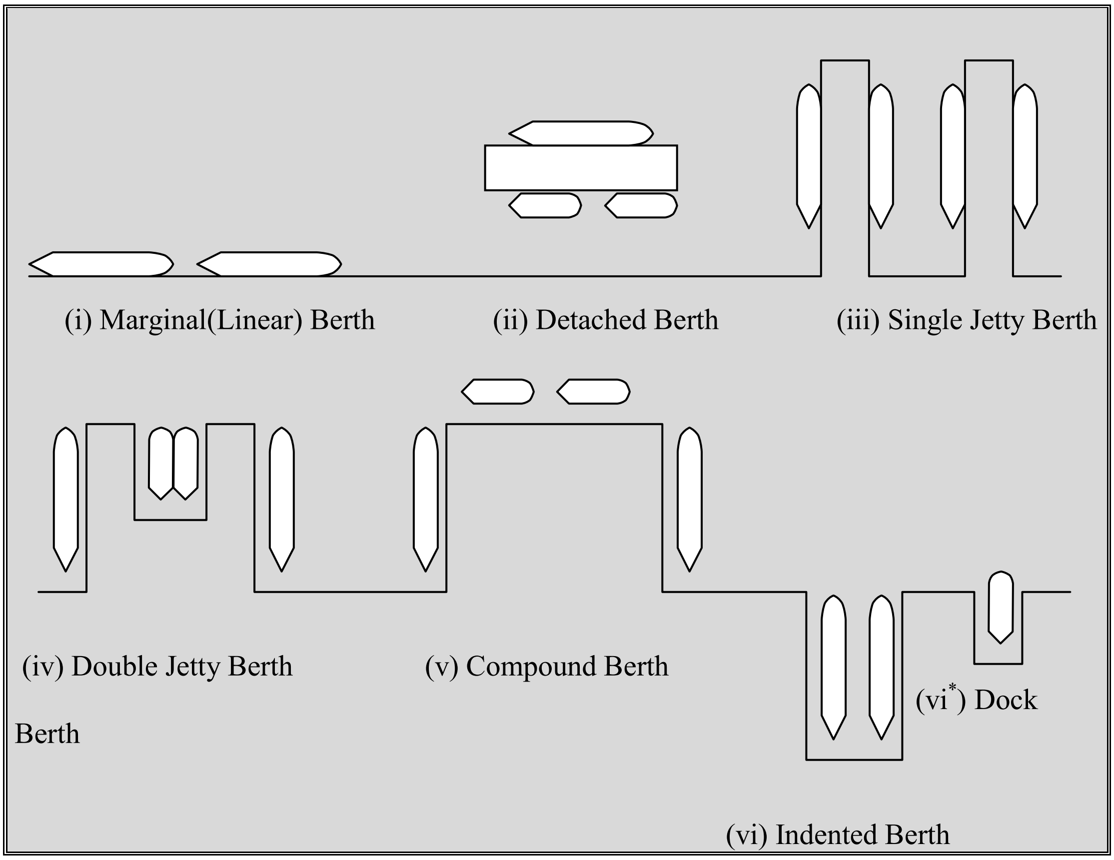
Another aspect of this service level is the maximum time spent in port, which is stipulated at 24 hours. The latest class of Post Panamax vessels with 6000 TEU and above *cannot be handled within this time period* when the parcel size exceeds 4400 TEU (assuming 1 hour for berthing and 1 hour for departure).
Solutions to this problem are sought in various directions, including improvement of the crane productivity by further automation and reduction of the cycle time. A very interesting solution is chosen for the new container terminal in Port of Amsterdam., the Ceres Paragon container terminal.

Figure: Ceres Paragon container Terminal, source: Internet

Annual capacity:	950,000 TEU.
Total area;	63 hectares (50 ha for open space).
Berths:	- 400× 50m "indented berth". - 650m "conventional berth".
Maximum vessel draft:	13.7m.
Cranes:	- 9 units super-post-Panamax (22m outreach) with twin lift, of which 5 cranes can be shifted between the conventional berth and the indented berth; total capacity 300 TEU per hour. - Expansion capacity up to 12 cranes.
Yard operation:	- Straddle carriers (39 units)

4.2 Berths layout

Different types for berth layout exist. After determining the needed quay length a specific layout has to be chosen which is compatible with the required functions at the berth.



Source; Inoue, Haruo, et. (1979). Introduction to port planning. Tokyo: Zennihon Kyokai.

Berth type	Major Characteristics
(i) Marginal (linear)	- Good for locations such as channel with small sea area in front or a river. - possible to construct huge yard behind
(ii) Detached Berth	- enables transfer of cargo between main vessel and barge
(iii) Single Jetty	- Suitable for locations with limited shore lines. - Difficult to construct huge yard.
(iv) Double Jetty	- enables accommodation of large vessels and small vessels at the same time. - enables easy transfer of cargo between large and small vessels.
(v) Compound	- Which combines the marginal type berth and the jetty type berth; to be applied when port is constructed by reclamation.
(vi) Indented (vi*) Dock	- difficult to maneuver vessels

Source; Inoue, Haruo, et.,(1979). Introduction to port planning. Tokyo: Zennihon Kyokai.

4.3 Intern transport equipment and processes

Ligteringen [4-3] *At the quay*: prior to arrival of a ship the containers to be loaded have been identified (and those to be loaded have been arranged in the export stack in such a way that they can be transferred to the ship in the right order. Typical properties of portainers (ship-to-ship gantry cranes for loading/unloading) are:

- Lifting capacity around 400 kN
- Boom length going up to 55m for hub terminals
- Rail gauge vary from 15m to 35m
- Width between legs min. 16m to allow oversized containers to pass
- Breadth outer bogeys < 2*40′ to allow cranes at every other bay
- Crane productivity peak 40-50 moves/hr. average 20-30 moves/hr.

Between quay and storage: for transport between the quay and the storage areas several options exist, depending on the size and the throughput of the terminal and on the preferences of its operator. In increasing order of sophistication these are:

- Forklift Truck(FLT)
- Reach Stacker
- Chasis
- Straddle Carrier(SC)

the above four types of equipment deal with the transport from quay to storage yard and within the yard. On high capacity terminal the two functions are often separated, the following two types only used for quay-yard and vice-verse, and dedicated cranes within the stack.

- Multi Trailer System (MTS).
- Automated Guide Vehicle (AGV).

Transport module	Advantages	Disadvantages
Fork lift / Reach stacker	- low investment equipment - simple/flexible in operation - mostly used for empties	- much storage space - labour intensive - handles only 20 feet containers.
Terminal chasis	- low investment pavement - low maintenance costs - simple/flexible in operation	- much storage space - large number of chasis needed - low throughput capacity - labour intensive
Straddle carrier	-high throughput capacity -one type for equipment for the entire terminal	- complicated equipment - high investment and maintenance costs - highly qualified personnel needed - labour intensive

Transport module	Advantages	disadvantages
Multi trailer system	- less labor needed - high throughput capacity - traffic peaks easily absorbed	- less flexible in operation
Automatic guided vehicles(AGV)	- minimum labor costs. - high throughput capacity	- high investment and maintenance costs - complicated and sensitive equipment

<u>Within the storage yard:</u> the MTS and AGV's deliver the containers outside the stacks and for further handling within the stack separate equipment is needed. Various types of gantry cranes are used.

- Rubber Tyred Gantry(RTG)
- Rail Mounted Gantry(RMG)
- Automated Stacking Crane

Transport module	Advantages	disadvantages
Rubber Tyred Gantry(RTG)	- good space utilization - flexible, high occupancy rate - high productivity	- high maintenance - needs good soil conditions - highly qualified personnel needed
Rail Mounted Gantry(RMG)	- good space utilization - reliable, low maintenance - automation possible	- high investment - inflexible
Automated Stacking Crane(ASC)	- minimum labour costs - high capacity	- high investment and maintenance costs

4.4 Surface areas

Ligteringen [4-4] for the lay-out of a container terminal the following the following elements have to be determined and qualified:

- Quay length and number of portainers.
- Apron area.
- Storage area
- Container transfer area (to truck and rail).
- Buildings (container freight station, office, gate and workshops).

The throughput-area(total gross surface area) for the major container terminals in Asia is given below:

Terminal	TEU/ha
Kaohsiung	15,400
Singapore	22,000
Hong Kong	40,000 – 50,000

This difference is to a large extent caused the efficient use of the storage yard, in particular by lowering the dwell time.

The storage yard is usually divided into stacks for export, import, reefers, hazardous cargo and empties. In addition one finds a Container Freight Station.

The *average dwell* (t_d) time of containers has to be considered separately for import export and empty containers. The *maximum dwell time* (e.g. the time within which 98% of the containers have left the terminal) for western Europe is 10 days and for the developing countries is 20–30 days.
Average dwell time (t_d) = (Maximum dwell time + 2)/3

The required area per TEU (F) inclusive op equipment traveling lanes is empirical and depends on the handling systems and the nominal; stacking height. Typical values are given below:

System	Nominal stacking height	F(m^2/TEU)
Chasis	1	50-60
Straddle carrier	2 3	12-20 10-13
Gantry crane(RMG/RTG)	2 3 4 5	15-20 10-13 7.5-10 6-8
Forklift truck	2	35-40
Reach stacker	3	25-30

5 Hydromechanics

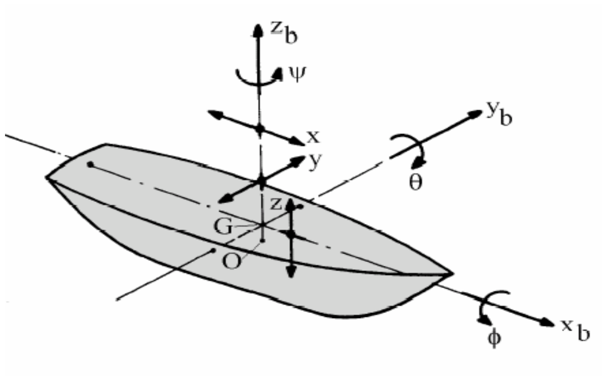
The dynamic and static behavior of a floating structure is dictated by loads acting on it. the medium on which the structure is floating will transfer energy causing a rotation or translation of the structure.

5.1 Definition of motions

Journée [5-1] any ship motion is build up from the below mentioned basic motions. For instance, the vertical motion of a bridge wing is mainly build up by heave, pitch and roll motions. Another important motion is the vertical relative motion, defined as the vertical wave elevation minus the local vertical motion of the ship. This is the motion that one observe when looking over thee rail downwards to the waves.
The six ship motions in the steadily translating system are defined by:

Three translations of the ship's center of gravity (CoG or G) in the direction of the x-, y- and z-axes:
- Surge in the longitudinal x-direction, positive forwards,
- Sway in the lateral y-direction, positive to port side, and
- Heave in the vertical z-direction, positive upwards.

Three rotations about these axes:
- Roll about the x-axis, positive right turning,
- Pitch about the y-axis, positive right turning, and
- Yaw about the z-axis, positive right turning.



5.2 Dynamic forces

The physical phenomena causing motion of the floating structure and the magnitude of the forces will be treated in this paragraph.

Pianc [5-2] *the wave* periods of storm and swell waves are far from the natural periods of surge, sway and yaw of medium and large ships. Therefore3, horizontal motions of significance are normally not occurring due to short waves. The natural periods of heave, pitch and roll of large ships are typically within the large the range of short wave periods and consequently these motion modes can be excited.

Long waves are in contrast more difficult to dissipate. Their periods are close to the natural periods of surge, sway and yaw for medium and large ships.

The wind effect can be decomposed into a static (constant wind or slow variation in intensity) and a dynamic action (gusty wind, intensity blusters and changing direction). For calculation of steady wind forces, methods such as British Ship Research Association or Oil Companies International Marine Forum can be used.

Current forces are caused by pressure drag. Under certain circumstances, a current can induce lateral oscillations due to 'flatter'. Flatter occurs when the arm of the moment exerted by the ensemble of external forces relative to the center of gravity of the ship, including the added mass, reaches a value close to radius of gyration.

The astronomical tide does not exert forces of importance on moored ship, but it causes vertical rise and fall of the vessel. The use of constant tension winches avoids manual adjustments of the moorings. Another aspect to be taken into account is the position of the ship relative to the fenders at different tide levels.

A *passing ship* generates a pressure pulse and a wave system. The pressure pulse is caused by the displacement of the water, which has to flow from the stem to the stern, resulting in a water level depression alongside the ship. The pressure ships may be inconvenience for moored ships as the ship may be set in motion.

The *loading and unloading* of vessel results in change of its draft if not compensated by a change in the volume of the water ballast. The effect is thus of similar nature as for varying tide levels and should be considered in the design

5.3 Dynamic behavior

In examining the dynamic behavior of a floating structure, two things are usually distinguished in the literature. Loads causing oscillatory motions are distinguished from those causing or affecting the oscillatory motions of the structure. Another distinction is the difference in the response between free floating structures and moored floating structures.

Faltinsen [5-3] *the natural or resonance periods, damping level and wave excitation* are important parameters in assessing the amplitudes of motion of a platform or vessel. Relatively large motions are likely t occur if the structures are excited with oscillation periods in the vicinity of the resonance period. However, if the damping is high or the excitations level relatively low due to cancellation effects it may be difficult distinguish the response at the resonance periods from the response at the other periods. For any unmoored structure there are no (uncoupled) resonance periods in surge, sway and yaw. For a typical moored structure the natural periods in surge, sway and yaw are of the order of magnitude of minutes and will therefore be long relative to wave periods occurring in the sea. However, non-linear effects may excite resonant oscillations at these long periods.

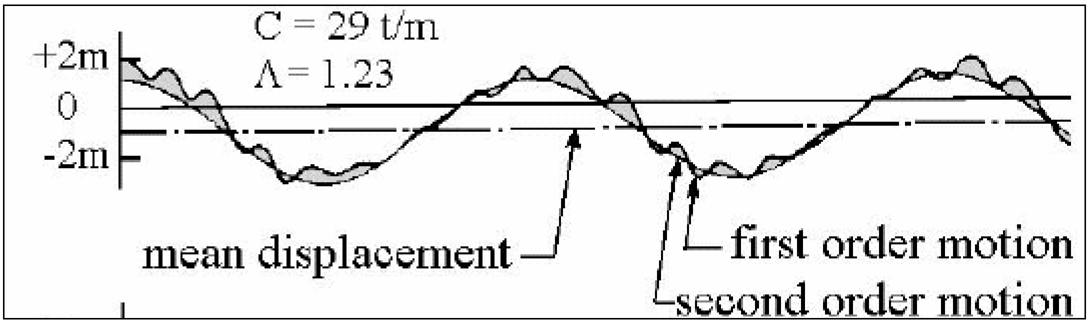
Linear wave theory, can to large extent, describe the wave-induced motions and loads on semi-submersibles, ships and other large-volume structures. However, non-linear effects are important in severe sea states and in describing horizontal motions of moored structures. Consider a structure in incident regular waves of amplitude ζ_a. the wave steepness is small, i.e. the waves are far from breaking. Linear theory means that the wave induced-motions ad load amplitudes are linearly proportional to ζ_a.

Journée [5-4] the *effects of second order wave forces* are most apparent in the behavior of *anchored or moored floating structures.* Analyses of the horizontal motions of moored or anchored floating structures in a seaway show that the responses of the structure on the irregular waves include three important components:

1. A mean displacement of the structure, resulting from a constant load component. Obvious sources of these loads are current and wind. In addition to these, there is also a so-called **mean wave drift force**. This drift force is caused by non-linear (Second order) wave potential effects. Together with the mooring system, these loads determine the new equilibrium position - possibly both a translation and (influenced by the mooring system) a yaw angle - of the structure in the earth-bound coordinate system. *This yaw is of importance for the determination of the wave attack angle.*

2. An oscillating displacement of the structure at frequencies corresponding to those of the waves; the wave-frequency region. These are linear motions with a harmonic character, caused by the **first order wave loads**. The time-averaged value of this wave load and the resulting motion component are zero.

3. An oscillating displacement of the structure at frequencies which are much lower than
those of the irregular waves; the low-frequency region. These motions are caused by non-linear elements in the wave loads, the **low-frequency wave drift forces**, in combination with spring characteristics of the mooring system. *Generally, a moored ship has a low natural frequency in its horizontal modes of motion as well as very little damping at such frequencies. Very large motion amplitudes can then result at resonance so that a major part of the ship's dynamic displacement (and resulting loads in the mooring system) can be caused by these low-frequency.*



The table below summarizes possible responses of a system (such as a moored vessel) to regular and irregular waves. Both linear and nonlinear mooring systems are included here; mooring systems can be designed to have nearly linear characteristics, but most are at least a bit nonlinear. The right hand side of the table below gives the motions which are possible via each of the 'paths' from left to right.

Wave	Excitation	System	Response
Regular	First order	Linear	First order (single frequency)
Regular	First order	Nonlinear	Subharmonic (single low frequen
Regular	Higher order	Linear	Time-independent drift
Regular	Higher order	Nonlinear	Time-independent drift
Irregular	First order	Linear	First order (wave frequencies)
Irregular	First order	Nonlinear	Subharmonic (uncertain)
Irregular	Higher order	Linear	Time-dependent drift
Irregular	Higher order	Nonlinear	Time-dependent drift

5.4 Operating criteria

As the motions of a floating body are not to be prevented, researches have been done to examine the limits of the motions in which different operations on board could continue safely. ***Relative motions*** are of significance when determining the level of workability during the load and unload processes, while ***accelerations*** of the floating structure are important for activities on deck and seasickness of the crew.

Faltinsen [5-5] vertical accelerations and relative vertical motions between the ship and the waves are important responses. Accelerations determine loads on cargo and equipment and are an important reason for seasickness. The relative vertical motions can be used to evaluate the possibility and damage to slamming and water on deck.

Rolling may be a problem from an operational point of view of fishing vessels, crane vessels, passenger ships and naval vessels. Means to reduce the rolling of ship are therefore of interest. Examples are bilge keels, anti-roll tanks and active fins.

For large ships, wave induced bending moments, shear stress and torsional moments are important. More specific problems are *whipping* and *springing.* Whipping is transient elastic vibration of the ship hull girder caused by instance slamming. Springing is due to linear and non-linear excitation mechanisms.

Criteria for acceptable levels of ship motions have been discussed in the Nordic cooperative project 'seakeeping performance of ships' **(NORDFORSK, 1987)**. Considerations have been given to hull safety, operation of equipment, cargo safety, personal safety and efficiency. General operability limiting criteria for ships are given in table below.

	Merchant ships	Naval vessels	Fast small craft
Vertical accelerations at forward Perpendicular (RMS-value)	0.275g(L≤100m) 0.05g(L≥300m)[a]	0.275g	0.65g
Vertical accelerations at bridge (RMS-value)	0.15g	0.2g	0.275g
Lateral accelerations at bridge (RMS-value)	0.12g	0.1g	0.1g
Roll (RMS-value)	6.0 deg	4.0 deg	4.0 deg
Slamming criteria (probability)	0.03(L≤100m) 0.01(L≥300m)[a]	0.03	0.03
Deck wetness criteria(probability)	0.05	0.05	0.05

[a] *The limiting criterion for lengths between 100 and 330 m varies almost linearly between the values L= 100 m and 330m.*

Rolling is an important motion mode to evaluate, for example for operation of crane vessels or for transportation of jackets and semi-submersibles on ship barges. Rolling pitching and accelerations may represent limiting factors for the operation of process equipment on board a floating production platform.

Ligteringen [5-6] the criteria for allowable wave heights during loading/unloading at various berth locations are shown in the table below.

Vessel type	DWT	Limiting H_s 0° (head or stern)	Limiting H_s 45°-90°(beam)
General cargo		1.0	0.8
Container, RO/RO ship		0.5	
Dry bulk	30,000-100,000 (loading) 30,000-100,000 (unloading)	1.5 1.0	1.0 0.8 - 1.0
Tankers	30,000 30,000 – 200,000 > 200,000	1.5 1.5 - 2.5 2.5 - 3.0	 1.0 - 1.2 1.0 - 1.5

For wave heights above the operational limit the (un)loading of the ship is interrupted, but the ship remains berthed till limit state conditions are reached. A limit state condition is determined as a trade-off between costs for breakwaters and shipping costs related to loss of time. In the case of an offshore berth the limit state may be chosen at 1/yr wave condition, while in case of an enclosed harbour basin a 1/10 yr sea state may be appropriate. In both cases forces in the mooring lines and fenders has to be within the allowable limits.

Pianc [5-7] recommended motion criteria for safe working conditions are shown below. Motions refer to peak-peak values (except for sway, zero peaks).

Ship type	Cargo handling equipment	Surge (m)	Sway (m)	Heave (m)	Yaw (°)	Pitch (°)	Roll (°)
Fishing vessels	Elevator crane LO-LO Suction pump	0.15 1.0 2.0	0.15 1.0 1.0	0.4	3	3	3
Freighters, Coasters	Ship's gear Quarry cranes	1.0 1.0	1.2 1.2	0.6 0.8	1 2	1 1	2 3
Ferries, RO-RO General cargo	Side ramp Dew/storm ramp link span Rail ramp	0.6 0.8 0.4 0.1 2.0	0.6 0.6 0.6 0.1 1.5	0.6 0.8 0.8 0.4 3	1 1 3 - 2	1 1 2 1 2	2 4 4 1 5
Container Vessels	100% efficiency 50% efficiency	1.0 2.0	0.6 1.2	0.8 1.2	1 1.5	1 2	3 6
Bulk carriers	Cranes Elevators / Bucket-wheel Conveyor belt	2.0 1.0 5.0	1.0 0.5 2.5	1.0 1.0	2 2 3	2 2	6 2
Oil Tankers	Loading arms	3.0	3.0				
Gas Tankers	Loading arms	2.0	2.0		2	2	2

Requirements for safe mooring conditions are rather high. The recommended criteria comprise ship motions as well as velocities and are presented in the table below. Velocities and sizes represent the dynamic impact of moored ship on a berth and are considered adequate parameters regarding safe mooring conditions.

Ship size (DWT)	Surge (m)	Sway (m)	Heave (m)	Yaw (o)	Pitch (o)	Roll (o)
1,000	0.6	0.6	-	2.0	-	2.0
2,000	0.4	0.4	-	1.5	-	1.5
3,000	0.3	0.3	-	1.0	-	1.0

Faltinsen [5-8] the maximum ship movements for working conditions should not be higher than shown in the table below. The figures assume that the occurrence frequency of critical ship movements for fishing boats, coasters and container vessels should be less than 1 week per year (2% of the time), and for ferries less than 3 hours per year (0.3 % of the time).

Ship type		Surge (m)	Sway (m)	Heave (m)	Yaw (o)	Pitch (o)	Roll (o)
Fishing boats L_{OA} = 25-60 m	LO/LO Elevator crane Suction pump	0.75 0.08 1.5	1.5 0.15	0.3	3-5	4	3-5 1.5

Coasters LOA = 60-150m	Ship crane Berth crane	1.0 1.0	1.5 1.5	0.5 0.6	1-3 2-4	1-2 1-2	2-3 3-5
Container ships LOA = 100-200	90-100% efficiency 50 % efficiency	0.5 1.0	0.8 2.0	0.45 0.6	0.5 1.5	1.5 2.5	3 6
Ferries LOA = 100-150			0.8	0.5	1	1	2

5.5 Static Floating Stability

The operating criteria mentioned above are to be considered during examination of the Serviceability Limit State of the structure design. The static stability treated in this paragraph is in the mode of the Ultimate Limit State. As result of loads acting in a floating structure the, it will translate or/and rotate about its center of gravity. The static stability encompasses the up-righting properties of the structure by an acting force or moment on the floating structure.

Diagram below shows significant parameters while testing the static stability.

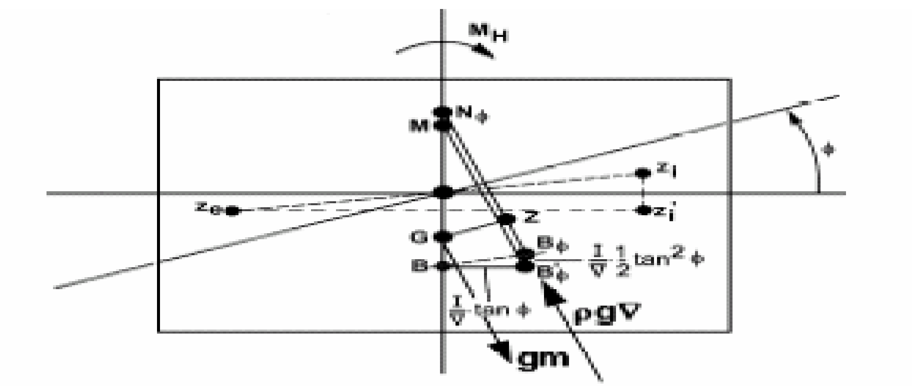


Figure: Static stability of a rectangular barge

Journée [5-9] For practical applications it is very convenient to present the stability in the form of *righting moments* or lever arms about the center of gravity G, while the floating structure is heeled at a certain displacement, ϕ. This is then expressed as a function of ϕ . Such a function will generally look something like and is known as the static stability curve or the GZ-curve.

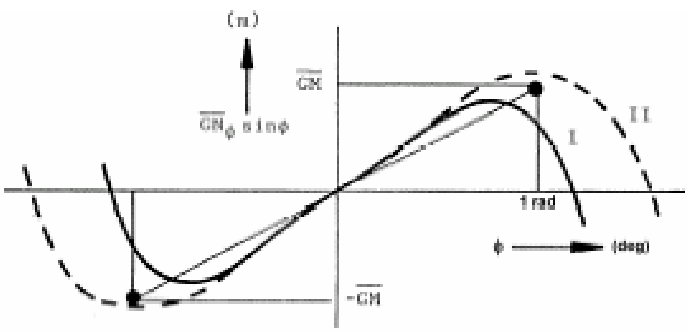


Figure: Static Stability Curve

1. Slope at the Origin
For small angles of heel, the righting lever arm is proportional to the curve slope and the metacenter is effectively a fixed point. It follows, that the tangent to the GZ curve at the origin represents the metacentric height GM.

2. Maximum GZ Value
The maximum GZ value is rules the largest steady heeling moment that the floating structure can resist without capsizing. Its value and the angle at which it occurs are both important. The shape of the above-water part of the floating structure is of great importance for the maximum attainable value of the stability lever arm.

3. Range of Stability
At some angle of heel (sometimes even greater than 90 degrees) the GZ value decreases
again to zero and even becomes negative for larger inclinations. This angle is known as the angle of vanishing stability. The range of angles for which GZ is positive is known as the range of stability. This range is of great importance for the maximum attainable area under the stability curve and thereby also on the maximum potential energy that the structure can absorb via a roll motion. The shape of the above-water part has a large influence on the angle of vanishing.

4. Angle of Deck Edge Immersion
For most floating structures, there is a point of inflection in the stability curve, corresponding roughly to the angle at which the deck edge becomes immersed. This point is not so much of interest in its own right as in the fact that it provides guidance to the designer upon the possible effect of certain design changes on stability. The shape of the above water part of the structure can have a large influence on its static stability. More or less the same statement can be made when the bilge or the bottom chine emerges, because of the decrease of the breadth of the water line. Keep in mind that for wall-sided structures, when the deck enters the water or the bottom chine comes above the water level, the immersed and emerged wedges are no longer nice triangles, calculations become much more cumbersome!

5. Area under the Static Stability Curve
An important parameter when judging the stability properties of a structure floating upright is the work that has to be done to reach a chosen heel angle. This means that the area under the static stability curve is an important quantity for the evaluation of the stability properties. It represents the ability of the floating structure to absorb roll energy imparted to it by winds, waves or any other external effect.

5.6 Simulation model SEAWAY

Computer models are usually used to simulate the response and the (potential) coefficients of floating structures on wave loads. A summary of the manual of the simulation model SEAWAY is given in this paragraph.

Journée [5-10] SEAWAY is a frequency-domain ship motions PC program, based on both the ordinary and the modified strip theory, to calculate the wave-induced loads and motions with six degrees of freedom of mono-hull ships and barges in seaway. When not accounting for interaction effects between the two

individual hulls, also these calculations can be carried out for twin hull ships, such as semi-submersibles or catamarans. The program is suitable for deep and shallow water. The underlying theory of the program has been given by [Journeé, 2001b]. This new User Manual of program SEAWAY replaces the previous old manuals.
SEAWAY requires two separate input data files:

- A hull form data file and
- A hydromechanical input data file.

The offsets of the cross-sections of the fully loaded ship have to be stored in a hull form data file, which can be obtained in different ways:

- The hull form data file can be made manually with any ASCII word processor, simply by following the descriptions given in this manual.
- Also, the hull form data file can be an output file of the PIAS program of SARC, and hydrostatic program which is frequently used in the Netherlands.
- For preliminary calculations, a set of hull form data files with 123 non-dimensional "parent hull forms" has been made available for the users. Selected hull forms from this set – with acceptable water plane area coefficients and block coefficients - can be scaled easily by the user to the principal dimensions of his actual ship.

Wave loads can be calculated by either the classic relative motion approach or by a simplified diffraction method. Always, the wave potentials are defined for the actual water depth. The input data of the longitudinal mass distribution, required for calculating the vertical and horizontal shear forces and bending moments and the torsion moments, are independent of the hull form input.
Damping coefficients, as derived from model tests, can be input too. If required, the program will carry out the linearization. Free surface anti-rolling tanks – based on theory or on experimental data - are included. External roll moments, to be defined by the user, can be input. Linear springs (mooring) can be used too.
At choice, the unidirectional wave spectra can be defined by the ideal Neumann spectra, modified Pierson-Moskowitz, ITTC, ISSC or Bretschneider spectra or JONSWAP spectra and by an input of (measured) wave spectra. Either the spectral centre period or the zero-crossing period can define these wave spectra. The printed output data of the statistics of the responses will follow this definition.

6 Floating structures and applications

Various concepts for floating structures already exist especially in the offshore world. Literature about the applications and important design aspects of Pontoons, semi-submersibles and others is the theme of this chapter.

6.1 Mega Floats

Taguchi [6-1] Mega-Float is a Very Large Floating Structure (VLFS) with potential long-term durability for use in sea areas. Its several units, which are constructed from iron and steel products are welded together offshore. Through the construction of facilities on its artificial landbase, Mega-Float promotes the extensive use of our ocean spaces.
Mega-Float is characterized by features that include being unaffected by earthquake, having few environmental impacts on ocean currents and marine eco-systems, being able to be constructed at low cost and in a short period of time independent of ocean depth and ground condition, and also earmarking the possible use of its immense internal spaces.
Furthermore, Mega- Float is expected to supplement current construction technology on land filling and other construction as a new technology that can be applied to many fields.
Mega-Float was a focus of constant attention in regards to the feasibility of housing airport facilities on its foundations, particularly for metropolitan cities that typically require large airports, but only have limited construction space.

Figure: floating airport Japan

In 1997 the "Mega-Float Airport Investigation Committee" (Koichiro Yoshida, Professor of Tokai University as Chairman) was set up within the Ministry of Land, Infrastructure and Transport (at that time the former Ministry of Transport) to investigate the technical aspects of using Mega-Float as a floating airport.

A number of programs were developed to design a large scale Mega Float airport taking into account of hydro-elastic response. Using these programs, test designs of an approximately 5000m long floating airport containing a 4000m-class runway were drafted

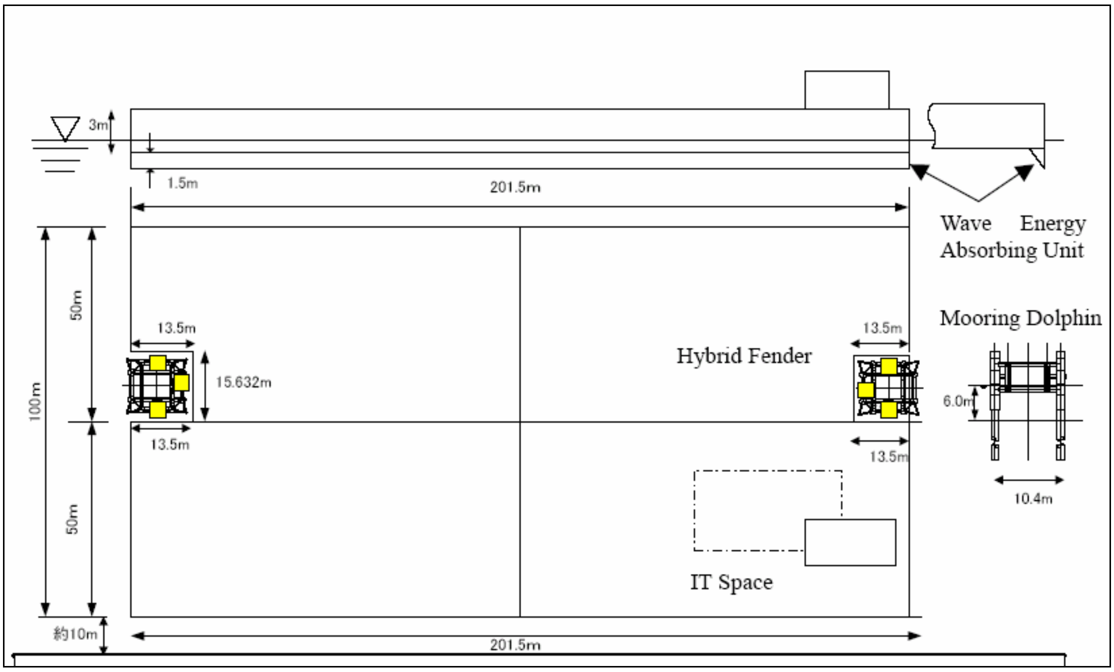


Figure: top and side views of a Mega Float unit

In March of 2001, the "Mega-float Airport Investigation Committee" put together a detailed evaluation of the verification tests on the 1000m Mega-Float airport and the 4000m-class test design, and announced in their final report that a Mega-Float airport with a scale of up to 4000m as being more than feasible.

Environmental and design conditions Haneda Airport:

Site	Off-Haneda Airport Tokyo Bay	
Dimensions	3120m x 535m(max)	
Water Depth		A.P.-20m to A.P.-10m
Tide	H.H.W.L	(A.P.+4.0 m)
Wave	(Storm condition: 100years R.P.)	
	H1/3	4.1m
	Hmax	7.4m
	T1/3	7.0s
Wind	(Storm condition: 100years R.P.)	
	10min.mean	36.0m/s

6.2 Pneumatic Stabilized Platform

Float [6-2] offshore airports, oil and gas production facilities, floating Islands, mobile offshore military bases, additional real estate for coastal cities, floating harbors, floating breakwaters, are just some of the possible uses of this new technology.

A pneumatic floating platform utilizes indirect displacement, in which the platform rests on trapped air that displaces the water. The primary buoyancy force is provided by air pressure acting on the underside of the deck.

The PSP is a distinct type of pneumatic platform, one in which the platform is composed of a number of cylindrical shaped components packed together in a rectangular pattern to form a module. Each cylinder is sealed at the top, open to the ocean at its base, and contains air at a pressure slightly above atmospheric pressure. Modules can be of a size that is relatively easy to manipulate, as shown in the simplified drawing below.

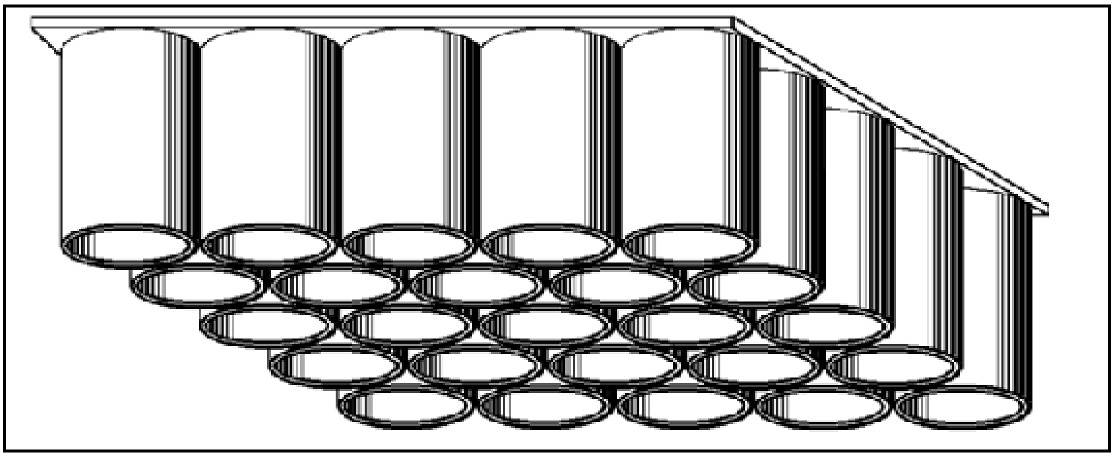


Figure: pneumatic stabilized platform

Another aspect of the PSP design is that, when needed, air is allowed to flow from a cylinder to its neighbors through manifold or connecting orifices. The airflow provides a mechanism to help reduce the peaks in the pressure distribution beneath the structure and provide platform stability as well as a mechanism for dissipating wave energy. Directing the moving air through turbo-generators to produce electrical energy is a capability that is now generating considerable interest.

An assembly of cylinders results in enclosed interstitial regions between cylinders, which may be filled with air, foam or other material. These regions are isolated from the air pockets within the cylinders to provide additional buoyancy and righting moment. In comparison to conventional floating platforms, the designers of a pneumatic platform can modify the distribution of the flotation force as needed to minimize the hogging moment or in response to large concentrated loads on the deck. Further, it is possible, for a particular sea state, to tune the oscillation of the water columns inside the cylinders to minimize the overall hydrodynamic loading to which the platform is subjected.

Extensive model tests were conducted at the Offshore Model Basin in Escondido, California during June and July of 1998. A scale of 1/48.73 was selected and models representing platforms of 600 x 400 and 200 x 1200 feet in prototype scale were constructed. Tests were conducted with the models constrained (fixed to a truss spanning the basin) and free floating. Several air exchange (manifold) configurations were studied. 30 wave sets, with periods from 6 to 20 seconds, wave lengths from 180 to 2050 feet and wave heights from 3.5 to 68 feet, all in prototype scale, were used. Installed sensors measured cylinder air pressure, water pressure at the base of the model, wave height within the cylinders, motion of the models in 6-degrees of freedom and the forces exerted by the model on the supporting truss.

Open ocean applications can also benefit from this development. Large platform configurations, with significant areas inside their perimeter, could incorporate simpler and less expensive cylinders in the central area. The PSP arrays, with full air exchange capabilities, would still comprise the platform's perimeter. One open ocean estimate is $7.5 million an acre. This is based on the design of 100x300 foot prototype platform, using cylinders 20 feet in diameter and 40 feet high, intended to be moored off the coast near San Diego. This was to be a small, one of a kind, demonstration platform. Larger platforms in a similar environment, having the benefit of an economy of scale, should cost less than $5 million acre. The reality remains that each platform will have to be designed for its proposed function and location. Therefore, it will probably never be possible to quote a fixed per acre cost that will apply everywhere.

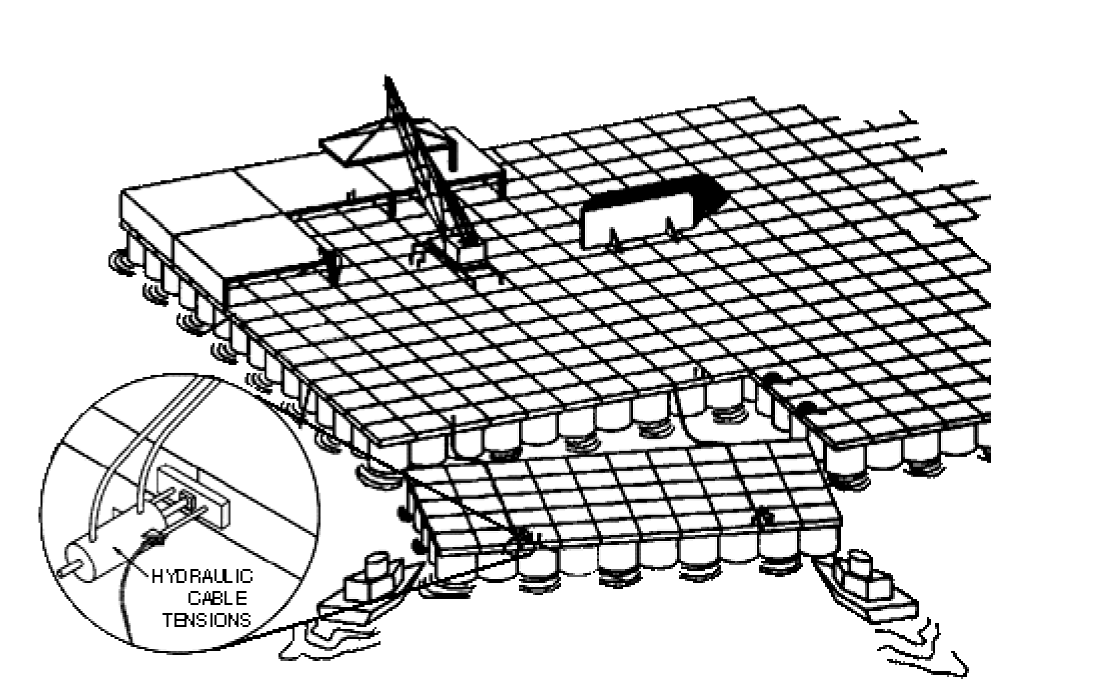


Figure: PSP On-site module assembly of

6.3 Semi-Submersibles

Journée [6-3] A Semi-Submersible Platform consists of a rectangular deck structure supported by 4 to 8 surface-piercing vertical columns standing on submerged horizontal floaters. These vessels have good motion characteristics and do not require the heading changed as the predominant direction of the weather changes. The vessels are moored by means of 8 to 12 catenary mooring lines consisting of chains or combinations of chain and wire. Parts of the pipe lines transporting the oil to the floater have to be flexible to allow for the wave induced motions of the floater. These flexible pipe lines have to be sufficiently strong and resilient to withstand high pressures and temperatures of the crude oil as well as the continual flexing due to the ‡oater motions

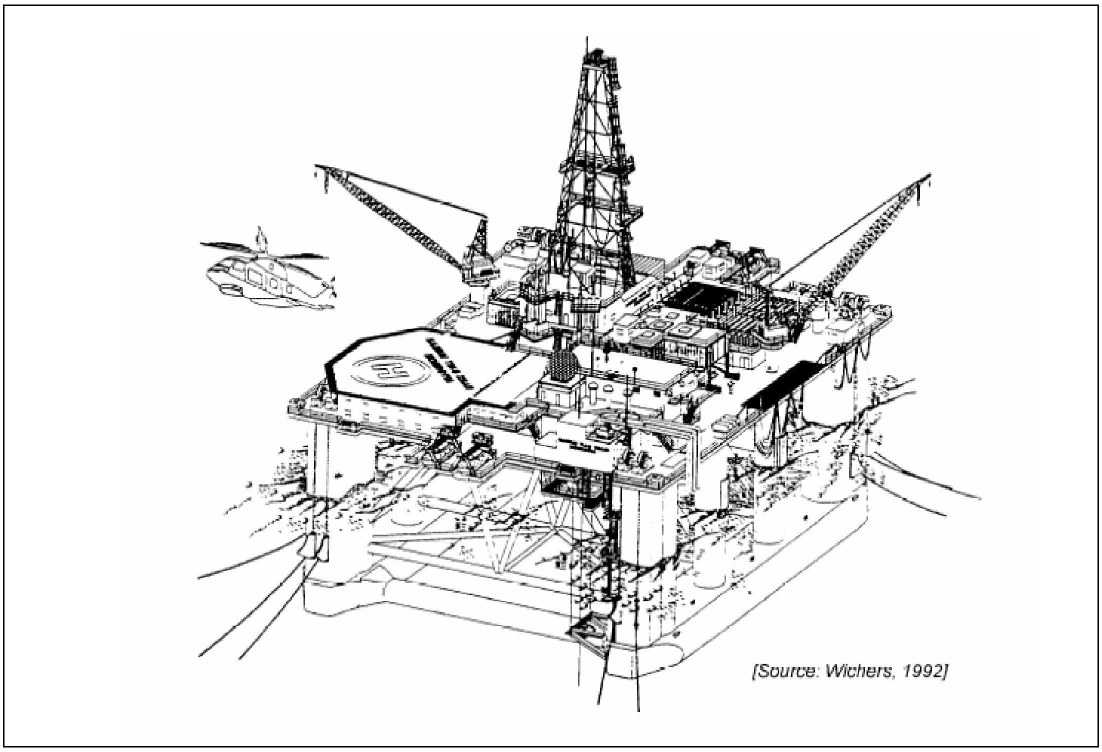


Figure: Semi-submersible Production Platform

Faltinsen [6-4] the natural periods of heave for a semi-submersible or a ship, or any other type of freely floating body can be written as:

$$T_{n3} = 2\pi(\frac{M + A_{33}}{\rho g A_w})^{\frac{1}{2}}$$

$$A_{33} = \frac{\rho}{2}\pi R^2$$

Where Aw is the waterplane area. It is common design procedure for semi-submersibles to require that the natural =periods in heave, pitch and roll are larger than T = 20s, this is possible to achieve by the low water-plane area of semi-submersibles.

6.4 Tension Leg Platform (TLP)

Journée [6-5] A Tension Leg Platform (TLP) consists of a semi-submersible type hull with for instance four vertical surface-piercing columns standing on underwater floaters and supporting a large rectangular deck; see figure. At each of the four corners of the floater, pre-tensioned tethers extend vertically downwards to foundation templates which are piled into the sea bed. *Due to the vertical tendons, which are pre-tensioned to such a degree that they never become slack, any vertical motion of the TLP will be eliminated.* This allows for steel pipe line connections between the wells and the floater, without the need for flexible sections of pipe lines. As a result, it is possible to install the well head control valves on the deck of the floater instead of on the sea bed. This represents a considerable advantage from the point of view of ease of maintenance and investment.

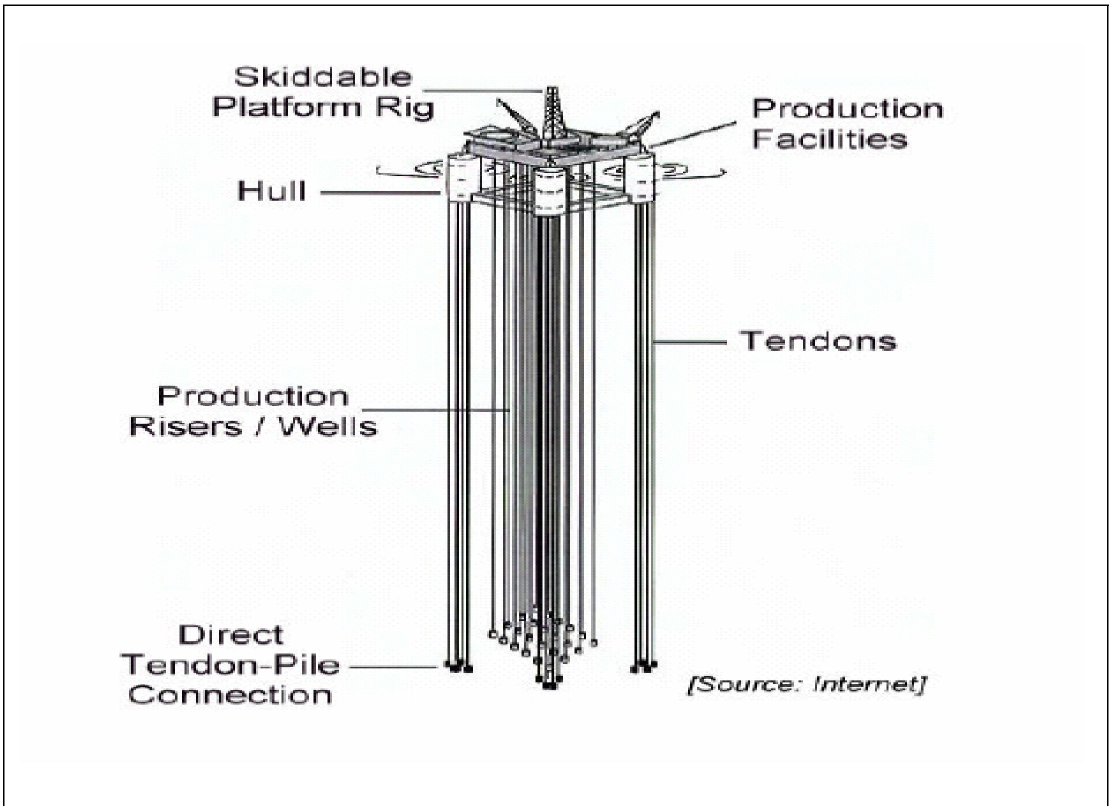


Figure: Tension Leg Platform

6.5 Station keeping of floating structures

Faltinsen [6-6] thrusters and mooring systems are important means of holding structures against wind, wave and currents. *A Mooring systems* is a number of cables which are attached to the floating structure at different points with the lower ends of the cables anchored at the sea bed.

In a *spread mooring system*, several pre-tensioned anchor lines are arrayed around the structure to it desired location. The normal case is that the anchors can be easily moved. This implies that the anchor in operation cannot be loaded by too large vertical forces and to insure that the anchors are kept in position, it is necessary that a significant part of the anchor lines lie on the seabed. The initial tension, or pre-tension in a cable is often established by the use of winches on the platform. The winches pull the cables to establish the desired cable configuration. As the unit moves in response to unsteady environmental loads the tension in the cables varying cable geometry.

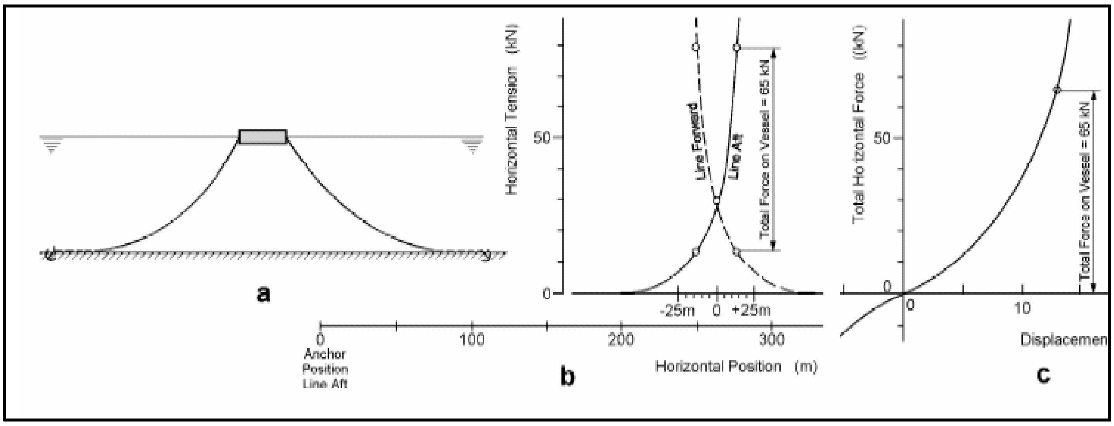


Figure: Horizontal Forces on a Platform as Function of its Horizontal Displacement

Thrusters may be used in combination with a mooring system or alone to keep a vessel in motion. Thrusters may lose efficiency due to interaction with other thrusters, the hull, current and waves.

If thrusters are a part of dynamic positioning (DP) system, an idealized simplification of the total thruster forces on structure can be written as:

$$F_k = F'_k - \sum_{j=1}^{6} (B_{kj}^{DP} \dot{\eta}_j + C_{kj}^{DP} \eta_j)$$

$$k = 1, ..., 6$$

Here k=1 means surge force, k=2 sway force, k=3 heave force, k=4 roll moment, k=5 pitch moment and k= 6 yaw moment. For a dynamically positioned ship it is only k=1,2 and 6 that are of interest. F'_k means mean forces. They have to balance the mean wave, current and wind loads. Further, nj are the slowly varying motions of the structure, obtained through proper filtering of the motion reference measurements. It is the high-frequency motion due to waves that are filtered put. It is generally impossible to have a system that can react to high frequency wave forces

In the design of mooring systems for offshore structures loads due to current, wind, wave-drift forces and wind- and wave-induced motion are generally of equal importance. There are two important design parameters. One is the breaking strength of the mooring lines. The other is the flexibility of the riser system which

means, in practice, for a rigid riser system that the extreme horizontal offsets of the platform relative to the connection point of the riser to the sea floor should be less than say 10%.
Wind, current, mean wave drift forces and slowly varying wave drift forces are also important in the design of thrusters and in station keeping of crane vessels, diving vessels, supply ships, offshore loading tankers and pipe laying vessels.

References

[2-1] *LNG floating terminal*, American Bureau of Shipping (ABS), 2003
http://www.eagle.org/news/pubs/bulletins/Lng.pdf

[2-2] *ARCO Floating LPG Terminal*, BERGER/ABAM Engineers Inc,
http://www.abam.com/capabilities/offshoreframe.htm

[2-3] Safety and Security Zones, Department of Transportation, USA, 2001.
http://www.uscg.mil/d1/units/msobos/Harborguardian/lngseczone.pdf

[2-4] Journée, J.M.J and Massie, W.W., Delft University of Technology, The Netherlands: Offshore Hydrodynamics, First edition, January 2001.

[2-5] BUISNESS TIMES, August 20, 2003

[2-6] Terenzi, M., '*Floating terminals: advantages and application'*, Port Technology International, 2003
http://www.coeclerici.com/05/pdf/Port_Technology_Summer_2003.pdf

[2-7] *A semi-floating breakwater with built-in-facilities*, Principality of Monaco,
http://www.monte- carlo.mc/principalitymonaco/globalinformations/fontvielle

---

[3-1] Demas, P. 'hub-and-spoke systems'. American shipper, 2003

[3-2] Dongwoo, H., *Asian Container Shipping and Port Network Development: Towards Integrated Transport.*
http://www.koti.re.kr/icons/publication/others-4.pdf

[3-3] Kleywegt, A. '*Competition between the Ports of Singapore and Malaysia*'. The Logistics Institute, Georgia Tech, 2002.
http://www.isye.gatech.edu/research/files/kley-2002-02.pdf

[3-4] Ligteringen, H., Delft University of Technology, the Netherlands: Ports and Terminals, September 2000.0

[3-5] Baird, A., TRI Maritime Research Group, Scotland: Establishment of a container transshipment container terminal in Scapa Flow, Orkney.
http://www.hie.co.uk/orkney/HIE-TRANSHIPDOC.pdf

[4-1] Journée, J.M.J and Massie, W.W., Delft University of Technology, The Netherlands: Offshore Hydrodynamics, First edition, January 2001.

[4-2] Ligteringen, H., Delft University of Technology, the Netherlands: Ports and Terminals, September 2000.

[4-3] Ligteringen, H., Delft University of Technology, the Netherlands: Ports and Terminals, September 2000.

[4-4] Ligteringen, H., Delft University of Technology, the Netherlands: Ports and Terminals, September 2000.

[5-1] Journée, J.M.J and Massie, W.W., Delft University of Technology, The Netherlands: Offshore Hydrodynamics, First edition, January 2001.

[5-2] Pianc: Criteria for movements of moored ships, a practical guide, Report of working group no. 24, 1995.

[5-3] Faltinsen, O.M., Norwegian Institute of Technology, Norway: Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1990.

[5-4] Journée, J.M.J and Massie, W.W., Delft University of Technology, The Netherlands: Offshore Hydrodynamics, First edition, January 2001.

[5-5] Faltinsen, O.M., Norwegian Institute of Technology, Norway: Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1990.

[5-6] Ligteringen, H., Delft University of Technology, the Netherlands: Ports and Terminals, September 2000.

[5-7] Pianc: Criteria for movements of moored ships, a practical guide, Report of working group no. 24, 1995.

[5-8] Faltinsen, O.M., Norwegian Institute of Technology, Norway: Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1990.

[5-9] Journée, J.M.J and Massie, W.W., Delft University of Technology, The Netherlands: Offshore Hydrodynamics, First edition, January 2001.

[5-10] Journée, J.M.J, Delft University of Technology, the Netherlands: User Manual of SEAWAY, February 2001

[6-1] Taguchi, A., Ministry of Land, Infrastructure and Transport of Japan: A Stamp of Approval to Mega-Float Airport Feasibility, 2001.

[6-2] Float Incorporated, California, USA: Pneumatic stabilized Platform, 1997

[6-3] Journée, J.M.J and Massie, W.W., Delft University of Technology, The Netherlands: Offshore Hydrodynamics, First edition, January 2001.

[6-4] Faltinsen, O.M., Norwegian Institute of Technology, Norway: Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1990.

[6-5] Journée, J.M.J and Massie, W.W., Delft University of Technology, The Netherlands: Offshore Hydrodynamics, First edition, January 2001.

[6-6] Faltinsen, O.M., Norwegian Institute of Technology, Norway: Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1990.

List of Contents

1 Introduction

The concept of a floating port is broad, and examining its feasibility requires refinement of the problem in a preliminary stage. The preliminary study carried out in this report is intended to mark out the borders of the problem and lead to the formulation of a less general objective. This is done by finding answers to a number of basic questions

1. Is there a need or demand for floating ports, and what are the advantages of a floating port compared to a traditional port?
2. There are different types of ports or terminals, each with its own characteristics and functions. Which type would be the most suitable for a floating terminal?
3. What are the potential locations for the floating port?
4. The maximum production or throughput of a terminal is proportional to surface area. In which size scale should this terminal be, keeping in mind that it is a floating structure?

2 Applications & advantages

In order to choose for a floating port instead of a traditional port, there have to be enough convincing reasons. In this section, there will be an inventory of possible advantages of a floating port with respect to fast land ports. These arguments should give answer to the question 'why a floating port?'

- Land reclamation (fill): the cut-and- fill method is recommended when creating space for a new port or expanding an existing one. The problem emerges when the soil to be used for land fill is unsuitable or contaminated. Recovering the contaminated material could be very expensive. In this case, a floating terminal may offer a good solution.

- Environmental issues: preserving the sea life and keeping the balance of the ecological system along the coastal areas, became an important issue the last decennia. Shipping and habitats seem to have contradictory interests which have often resulted in the freezing of many projects. In order to compensate for the reclaimed land of The 2^{nd} Maasvlakte in the Netherlands with a total area of 1000 ha, an area of more than 3000 ha had to be declared as sea reserve.

- Mobility: A terminal built up of a number of floating elements connected to each other could give the way for a mobile terminal. Whenever there is the need to relocate the terminal- where it could be more efficient- this could be achieved by disconnecting these elements and tugging them to the other location.

- Sustainability: the idea of using empty containers in order to create extra storage areas by stacking them up in shallow water may be economically attractive solution, but certainly not sustainable. A Floating terminal with a life span of tens of years will offer the same mobility, rather in a sustainable way.

- Flexibility & Expansion: the steadily changing demands, with regard to the layout of the terminal could affect its efficiency. The possibility of configuration changes or expansions would be much easier in the case of a floating terminal made up of a number of connected elements.

- Shipping traffic: In many busy ports of the world the intensity of the vessel traffic on the wet infrastructure is too high. This leads capacity problems and longer turnaroundtime of the vessels. An offshore floating terminal could help reducing the pressure on these ports and at the same time improving the level of serviceability.

- Maintenance: dredging makes a considerable contribution to the running costs of ports. Maintenance and deepening of the approach channel and the port basins are costly activities, especially when the problem of the contaminated dredged spill rises. The rapid increase in the vessels size demands also large waterdepths. These problems will be certainly be avoided in the case of offshore floating terminal.

The above mentioned, are common advantages and apply for all types of terminals (ports). Additional specific advantages per terminal type will be treated in the next chapter.

3 Determining terminal type

Each type of terminal has its own characteristics and design requirements. The berthing facilities, the load/unload process, the storage and intern transport could vary from one to another. In this section a number of alternatives will be proposed, from which finally one will be selected as the model for the 'floating port'.
In addition to the common advantages mentioned above, some other specific advantages per type of terminal will be discussed.

3.1 Liquid bulk terminals

Safety is a significant aspect during the design and operation of Oil, LNG or LPG terminals. The nature of the products demands special safety requirements. The scale of the environmental damage caused by the sinking of Large Crude Carriers is often classified as 'ramp'. The damage to the ecosystem caused by the spilled material in shallow water and the breaker zone -which is often rich with sea life- is severe and long lasting. A recent example is the sinking and collapse of the oil tanker before the Spanish coast in the year 2003.
Not only accidents resulting from human errors, but also intended destructive deeds have to be put in consideration. In some parts of the world Liquefied Gas Carriers vessels make use of the inland waterways to reach inland ports. The safety measurements taken to prevent such accidents in Boston (USA) have affected the whole net of navigation waterways in that region. [See DOT 2-3].
Other factors, such as the large dimensions of the crude carriers made it necessary to use offshore handling methods to avoid dredging. That's why the idea of using offshore terminals in the industry is not recent FPSO [see Journeé 2-3] and the SBM are applications of floating offshore terminals that already exist.

Establishing offshore floating liquid bulk terminals in large size-scales could be appealing for the following reasons:

1. There is an increasing demand for oil and liquefied gas products, especially LNG.
2. Loading/unloading is only possible within certain range of sea conditions. A large floating terminal could function as a floating breakwater and offer some protection against open sea loads for the vessels berthed at the lee side of the terminal.
3. The possibility of establishing a refinery on the terminal could also be examined. Achieving this, means that the most activities are to be done offshore. Pipelines could be used for transporting the products to the fast land where it will be pumped directly inside distribution tanker trucks.

Figure1: artistic impression of a floating terminal with refining facility onboard (internet)

3.2 Container terminals and shipping

The advantages of handling commodities in containers made the industry expand explosively. The predicted average container growth rates are 5-10% per annum [see Ligteringen 3-4]. World container traffic is expected to reach 391 million TEU in the year 2010 [see TRI 3-5]. To accommodate the increase in container traffic new terminals has to be built. That means that there will be worldwide a great demand for container terminals in the coming years.
Increase in container traffic, *Concentrations* (merges of shipping companies) and *rationalization* (maximizing slot usage) have lead to a remarkable increase in the size of the container vessels. Vessels with drafts up to 14.5m and capacity of 6600 TEU are already in use (Maersk Sealand). Predictions of many scenarios are expecting an increase of the maximum ship size up to 15000-18000 TEU.

These developments resembled a lot of difficulties for many ports around the world because:

1. The waterdepths inside these ports do not allow accommodating such large vessels.
2. The shipping lines demand short service time of their vessels.
3. Drastic configuration changes of the port are sometimes needed.

The need to minimize the turn-around-time and maximize the utilization of these vessels required in turn a radical reduction in the number of port calls on major routes. The so called hub-and-spoke transport (logistical) system has developed in the shipping industry. Very Large vessels call to a few ports; the so called ‘hub’ ports. From there, feeder ships distribute the containers to other regional ports.

Floating Transshipment container terminal:
As Shipping lines are expanding their use of transshipment for containerized freight, an offshore floating transshipment container terminal could have a great potential. It is

proposed as a terminal with no hinterland connection. All the containers are sea-sea containers and have to be transshipped.
From a financial point of view, a terminal with no hinterland connection could mean 3 things:

i) Considerable reduction of the construction costs. The contribution of the hinterland connection to the total costs are large, especially in the case of an offshore terminal. The figure next door shows a 33 kilometer bridge connecting the offshore terminal of Yangshan, in China

ii) Reduction in the average transportation cost /TEU/km as result of the shorter turn-around-time (depreciation of vessel) and the reduced number of port calls of the large vessel.

iii) An increase in the handling cost/TEU for that percentage of the containers with destination the hinterland. These containers will be handled twice.
However, as long as the percentage of these containers is small compared to the total number of containers, and the transshipment costs are not too high, the average total cost/TEU per container will be reduced. [see TRI 3-5]

Others:
i) Absence of the hinterland connection means more freedom to go as far as possible offshore and thus deeper water.
ii) Connecting the terminal to fast land with a non floating structure (e.g. bridge) constrains the *mobility* of the terminal, one of the advantages of the floating terminal mentioned in chapter 1.

The choice for a floating terminal with or without a hinterland connection is an economic optimization sum. For the arguments mentioned above-specially the first two- it is chosen for a floating transshipment container terminal, with **no** hinterland connection as an alternative for the floating port. It is also expected that the total average shipping cost/TEU would be reduced [See TRI 3-5]. Further explanation over the potential of such a terminal is given in chapter 4. This terminal will be further appointed with the term **FTCT** in this report.

3.3 Dry bulk terminal

Besides the common advantages illustrated in chapter 2, there are other reasons that could make the floating variant of a Dry bulk terminal more appealing.

1. The terminal could be located as close as possible to the production area. This could have positive effects on the problems of road traffic and reduces the transportation costs to and/or from the port.
2. Because of the nature of the products, a hinterland connection will be less complicated compared to for example to containerized freight. Fixed or floating

structure with conveyer belts (for up to a few kilometers) is a possible transport system to and from the fast land.
3. Dry bulk vessels are often equipped with self-unloading facilities onboard.

3.4 Marinas

Floating berth and breakwaters are common in the marina world. However, they are usually situated in protected waters such as lakes and bays.
An offshore floating marina could:
1. Provide berthing, and possibly shelter for yachts and boats during high sea conditions.
2. Beside the function of a 'refuge port' a recreational function for the marina could make it more attractive. Theaters, restaurants, hotel, swimming pool, and shops could be built onboard the floating marina.

3.5 Selection of terminal type

A *multi-criteria-analyses (MCA)* is used as an evaluation method to determine the type of terminal that will be adopted as a model for the 'floating port'. The alternatives that will be considered are listed below:
- Dry-bulk terminal.
- Oil- terminal
- Liquefied Gas (LPG/LNG) terminal.
- Transshipment container terminal.
- Marina.

To separate different functions, the possibility of a floating port consisting of two or more different types of terminals will be excluded. Furthermore, it will be always possible to build other terminals besides the existing terminal once its feasibility is determined.

An explanation of the criteria considered in the MCA- method is given below:
A) Demand: the demand for new terminals to be built of a certain type from the statistics or forecasting.
B) The economic aspect: the expected radical (positive) changes in the costs/revenues ratio when choosing for an offshore floating terminal instead of a traditional terminal.
C) Operational demands: The operational criteria with regard to the allowable vessels motions.
D) Environmental impact and safety: reduction of the environmental impact and risks as result of choosing for an offshore floating terminal. This will mainly depend on the nature of the product handled.
E) Spatial planning: the intensity of activities displaced to the sea and the area spared when choosing for the offshore variant.

	Scores
Criterion A	- High rates of growth in the containerized cargo in the last and coming years. An annual growth of 5% is predicted [see Ligteringen 3-4]. - Existing LPG/LNG terminals do not meet the growing demand in many parts of the world [see ABS 2-1]. - The nature of the dry bulk products and the handling methods make large vessels after some small adjustment eligible to function as offshore storage and handling facilities when needed, that why this alternative has the lowest score
Criterion B	Drastic cost cuts are expected when the costs for dredging and a hinterland connection are spared in the case of an FTCT. The oil industry has already developed solutions for the storage and handling of the oil in deep water. Examples are the SPM and the FPSO, see Journee 2-4]. An offshore floating oil terminal would have the least impact in the industry compared to other alternatives from an economic point of view. This the reason that this alternative is given the lowest score
Criterion C	The scores are ordered according to the criteria for ship motions for safe working conditions. Products which require the smallest motions are given the lowest score and vice verse.[see PIANC 2-10]
Criterion D	The nature of the gas products makes the chance of casualties by explosions very high, that's why the alternative is given the highest score. As earlier mentioned the environmental damage caused by the collapse of crude carrier onshore is severe. Keeping these vessels offshore (deepwater) will certainly lower the risks.
Criterion E	Container terminals require the largest surface areas. The positive impacts of displacing the facilities offshore are therefore the largest with regard to spatial planning. In the contrary, the storage and handling of oil products demands small surface area compared to other terminals.

The alternatives are *qualitatively* compared to each other. The alternative with the more plus's (+) weighs better than that with lesser plus's.

	Dry-bulk terminal	**Oil terminal**	**LNG/LPG terminal**	**FTCT**	**Marina**
Criterion A	+	+ + +	+ + + +	+ + + + +	+ +
Criterion B	+ + +	+	+ + + +	+ + + + +	+ +
Criterion C	+ + +	+ + + + +	+ + + +	+ +	+
Criterion D	+	+ + + +	+ + + + +	+ + +	++
Criterion E	+ + + +	+ +	+	+ + + + +	+ + +
	11+	15+	18+	20+	10+

The MCA final results show that a floating transshipment container terminal (**FTCT**) has the highest score.

4 Location

The potential for establishing an FTCT will be affected by a number of factors. Factors with relation to the site location for both economical and technical aspects are mentioned below:

1. Economic-strategic aspects

- Transshipment industry in the region: many ports worldwide experience high percentages of sea-sea container like Japan and Singapore. In the port of Singapore 80% of the containers are transshipment [See Kleywegt 3-3], while only 20% is designated to the hinterland. The potential for an FTCT will be higher is such ports or regions. For places like the port of Rotterdam where only 15% of the containers are transshipment, a hinterland connection it will be necessary.
- Regional demand for deep water terminals.
- Proximity to trunk routes; close proximity allows a short trunk-haul transit time.

Suggested locations with economic potential:

North-West Europe:	Orkney Islands, Scotland [see litertaure study TRI 3-5]
North America (East coast):	New York (USA), Halifax (Canada).
South- East Asia:	Singapore, Japan, the Maldives.

2. Technical aspects

The behavior of the structure depends mainly on the wave, wind and current conditions in the site location. Demands with respect to the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) have to be met.

SLS: The (un)load process should only continues if the ship motions (translations and rotations) are within the operating limits. In the case of an FTCT, both the vessel and the terminal are in motion. Therefore, the relative motions are relevant.
Also the mooring lines forces should also be within certain limits. The vessel should leave the terminal when these limits are exceeded as result of large motions of the vessel.
Furthermore, the amplitudes of the accelerations (of the FTCT) determine for the level of workability on the deck of the terminal and the seasickness of the personnel.

ULS: waves, wind, currents and activities on deck, determine the stability (static and dynamic), internal loads and the station keeping system of the floating body.

Bathymetry: the waterdepth in the location makes it possible to accommodate Mega-ships and of course the FTCT.

Determining site location

For the choice of site location, two approach methods are proposed:

1. Designating a specific location for the terminal and collecting the site data at that particular location. Thereafter, the feasibility of the designed terminal must be examined in that particular location.
2. Another approach is to design a floating structure in a way that the dynamic behavior is optimal. Using the given operating criteria for the maximum motion amplitudes, the ultimate sea state for the design could be determined. Locations with economic potential listed above, will be tested upon this ultimate sea conditions and controlled for eligibility.

It is chosen for the second approach. Conclusions drawn when choosing for the first approach will apply only for the chosen location. Therefore, it will not be possible to generalize the conclusion about the feasibility of the floating port for other locations.

5 Design Throughput & shipping traffic

Large throughputs of the terminal could ensure high revenues. On the other hand large surface area will be needed and thus higher costs. Container terminals require substantial surface area for the storage of containers. Two dominant parameters for determining of the required area are the containers mean dwell time and the stacking height.

The throughput-area (total gross surface area) for major container terminals in Asia is shown below: [see Ligteringen 3-5]

Terminal	TEU/ha
Kaohsiung	15,400
Singapore	22,000
Hong Kong	40,000 – 50,000

These are high ratios compared to the Port of Rotterdam, due to the low maximum container stacking height allowed in the later. Stacking many containers high could result in soil settlements under the floor of the storage yard. Moreover, stacking more than 5 containers high could affect the operation of the terminal and service time of the vessels.

Considering a floating terminal, it is expected that the container loads restriction will create no (draft) problems. The average stacking height of the container vessels is 9 containers. The only restriction is the required supple operations in the storage yards of the terminal which demands a maximum stacking height of 5 containers.

In this phase, the throughput-area ratio of a number of ports in Asia [see Ligteringen 3-5] will be used to determine the annual throughput starting from a certain surface area of the terminal. The following assumption is made:

The throughput-area ratio of the terminal is 20,000 TEU/ha. This is relatively low ratio compared to the most terminals in the Far-East.
A number of options are shown in the table below:

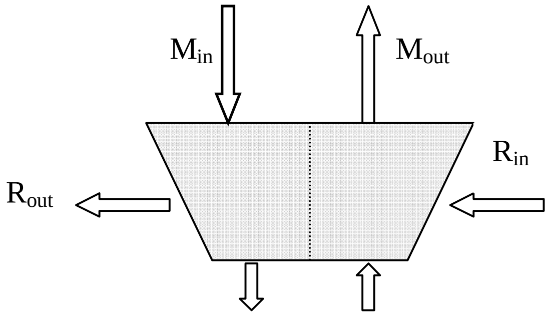
ha	TEU/year
25	500,000
50	1,000,000
100	2,000,000

A floating terminal with a gross area of 50ha (50,000 m^2 is less than half the area of the floating airport in Japan) and a throughput-area ratio of 20,000TEU/ha has an annual throughput of 1m TEU. This throughput is an average for the most moderate traditional container terminals and will therefore be initially adopted for the design of the FTCT. As mentioned before, the possibility of future expansions will always be there.

The modal split

M: annual main line cont. traffic
R: annual regional ports cont. traffic
H: hinter port cont. traffic
T: annual total throughput.

$T = M_{in} + M_{out} + R_{in} + R_{out} + H_{in} + H_{our}$
$= 2(M_{in} + M_{out})$



It is further assumed that the regions served by the floating terminal, have more or less the same economic growth. This will imply that the import/export ratio of the containers is equal to 1.
Now it follows that,

$M_{in} = M_{out}$
$T = 4M_{in} = 4M_{out} = 1m$ TEU
$M_{in} = M_{out} = 250{,}000$ TEU
$R_{out} + H_{out} = R_{in} + R_{out} = 250{,}000$ TEU

Based on the above, starting points are made with regard to average ship throughput per call (loaded + unloaded) and the shipping traffic flow (see table below). These starting points are of significance to the calculations of the required number of berths and the quay length of the terminal.

	Aver. Throughput per call (loaded + unloaded)	Vessel classification	No. calls per annum
Main line vessels	5000 TEU	4th generation – 15000 TEU vessels	100
Feeder vessels	1000 TEU	2nd – 3rd generation	500

Accordingl to the anticipated traffic flow, main line vessels will call twice per week. It is also assumed that there are two major traffic routes. One vessel per week per route means a maximum container dwell time of 7 days and an ***average dwell time* of 3 days**, for the mail line containers.

Average dwell time = (max dwell time + 2)/3

Assuming that there are five ports in the region to be served by feeder ships, this means that **from** each port (R_{in}) 50 vessels are expected per year (once per week). Therefore, the maximum dwell of the feeder containers is also 1 week and the ***average dwell time is equal to 3 days.***