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MASTER'S THESIS

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Preface

This Master Thesis is about static stability. It is written at the University of Stavanger in 2015 and represents a completion of a Masters degree in offshore engineering. The idea of writing the thesis came after reading the journal paper on "the historical roots of the theory of hydrostatic stability of ships". (Nowacki and Ferreiro, 2011). It left me wanting to know more about the fundamentals of vessel stability, how it is calculated and the parameters affecting it.

Working with this thesis has been both interesting and frustrating. I decide to write the thesis using Latex. It made the writing a bit more challenging but it was worth it in the end. I also had to learn the DNV software to perform the analysis. I have learned a lot about the topic and overall it has been a good experience to take with me into the next chapter of my life.

Stavanger, 2015-06-15

Sondre Vinje

Acknowledgment

I would like to thank John Austevik at Ugland Construction for giving me a field trip to their yard in Steinvik and providing me with detailed drawings of the UG-97 barge. I would like to thank me colleagues at IKM for giving me the time to finish this thesis. Gratitude should also be given to Ove Tobias Gudmestad for supervising me during the work with the thesis.

I would also like to thank my cohabitant Mona for all the support during these last months, it is highly appreciated. Finally yet importantly, I would like to thank my fellow students from "Datarommet" for all the good times we have had over the past years. It would not have been the same without all of you.

S.V.

Sondre Vinje

Abstract

Barges have long been the one of the preferred method of transportation of heavy objects at sea because of their large capacity and versatile design. This thesis addresses the main issues related to the the stability of barges. Having a good understanding of what increases and reduces the stability can give knowledge into how to improve the performance and find the limiting transport capacity.

The thesis reviews the central literature topics in relevant stability theory. This includes; Fundamental hydrostatics, initial and intact stability, relevant standards and heeling moments.

The analysis was performed by applying hydrostatic principles and computer simulation using the program HydroD, finding out how design and loading condition changed the stability characteristics of the barge. By analysing the changes in stability characteristics for different loading conditions the limiting criteria for compliance with regulations were found.

The results of this thesis can provide the reader with an insight into how the stability of a barge changes with dimensions, loading and damaged conditions.

Contents

Nomenclature

The thesis follows the sign convention used in "Ship Hydrostatics and Stability". (Biran and Pulido, 2013)

B Breadth, beam or Width [m]

g Gravity Constant [m/s^2]

D Depth [m]

T Draft [m]

L Length [m]

c Shape Coefficient

P Pressure [N/m^2]

F Force [N]

G Centre of Gravity

BM Metacentric Radius [m]

GZ Righting Arm [m]

di Angle of deck immersion [deg]

KG Distance from Keel to Centre of Gravity [m]

f freeboard [m]

r Radius [m]

M Moment [Nm]

l lever length [m]

Δ Displacement mass, [Tonnes]

∇ Displacement volume, [m^3]

C_B Block Coefficient

φ Heel Angle [Deg]

$\overline{GM}_0$ Initial Metacentric Height [m]

$\overline{GM}_\varphi$ Instantaneous Metacentric height

T_0 Natural period [s]

k_4 Radius of Gyration [m]

I_{xx} Second Moment of Area [m^4]

m_a Added mass [Tonnes]

ρ_{SW} Density of Seawater [kg/m^3]

h_h Height of Head log [m]

h_k Height of Keel [m]

L_k Length of Keel [m]

α Angle of stern/aft

p_w Pressure from wind

I_{comp} Second Moment of Area of Compartment

ρ_l density of compartment liquid

L_{Dl} Displaced load lever

l_{FS} Free surface lever

m_l Mass of Load

Chapter 1

Introduction

1.1 Background

The scope of this thesis is to investigate how the stability of a barge changes with alterations in design and loading conditions. This is done to gain a better understanding of static stability in general and how dimensions, loads and hull damage can affect the characteristics of a barge.

The concept of static stability is the foundation behind all of the other areas of marine transportation. Gaining knowledge on this subject can create awareness on important aspects to consider when planning marine operations. The barge studied is a standard North Sea barge commonly used in the North Sea. The stability analysis is done with the help of Hydro and GeniE simulation programs. The results are combined with calculations of heeling moments from wind, free surface effects and displacing loads.

The main objectives for this thesis are:

- Find the loading limits for initial and intact stability for a standard North Sea barge.
- Investigate how design changes and loading conditions change the stability characteristics of the barge.
- Compare operational loading conditions in normal and damage condition to see the effect of lost buoyancy.

Literature Survey

The most important literature studied in over the course of this thesis is presented here:

- In Principles of Naval Architecture, (Lewis, 1988) has published a three volume book covering the important concepts in marine architecture. The book contains a large amount of information on both basic and complex areas in marine engineering
- Ship hydrostatics and stability written by (Biran and Pulido, 2013) provides information about the most important theory and context about the stability of ships. It also contains information about computer modelling and computational techniques in hydrostatics.
- Ship stability for masters and mates (Barrass and Derrett, 2011) has a practical approach to many of the concepts that are discussed more theoretical in other sources of literature.
- (Nowacki and Ferreiro, 2011) gives a short introduction to the historical development of calculations on ship hydrostatics and stability in this journal paper covering the development in the topic from Archimedes to modern ages.

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1.2 Limitations

The main limitations of this thesis are:

- The stability concepts studied here are limited to generic the generic geometry of barges. The same concepts still apply for more complex shaped ships, but the results may be very different.
- This thesis only considers the transverse stability, as this is the most crucial point to visit.
- The thesis is limited to initial and intact stability. To apprehend understand the concept of stability fully ship motions should be investigated further.

1.3 Structure of the Report

The first chapter includes the background, objectives, literature review, limitations and structure of the report.

The second chapter consists of a short introduction to the historical development in ship stability and information about the construction and properties of North sea Barges.

The third chapter includes the relevant theories and background literature. In the first section a short introduction to the history of ship stability is given. Secondly the basic theory on vessel stability is reviewed. The next section covers the possible heeling moments present before closing with a introduction to the relevant standards.

The fourth chapter the modelling and analysis process is described. The developed models is explained together with the important equations used.

In the fifth chapter the results from the analysis and calculations are presented. The presentation is divided into four sections that addresses different aspects of vessel stability.

In the sixth chapter the results found in the analysis is interpreted more thoroughly. The data found in each section of the analysis is discussed in detail in the separate sections, with emphasis on linking the data to the theory subjects studied in the literature review.

In chapter seven the final conclusions from the analysis is presented

Chapter 2

State of Art

This chapter consists of a short introduction to the historical development in ship stability and information about the construction and properties of North Sea Barges.

2.1 Historical Overview

The oceans has been used for travel for millennia. Researchers have found evidence indicating that ancient humans conquered the Mediterranean sea some 130000 years ago (Pringle, 2010). This shows that an intuitive understanding of balancing a floating structure existed long before anyone described the mechanics behind it.

The first indications of someone trying to describe the theory relates back to the famous tale about Archimedes' bath that led to the discovery of one of the most fundamental principles of hydrostatics, described in his first book "on floating bodies”. (Nowacki and Ferreiro, 2011)

> *Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.* (Archimedes, 0 BC)

Prior to this discovery, he had written other important treatises. In his writings *“On the Equilibrium of Planes”* and *“The method Concerning Mechanical Theorems”* he writes about moments around a fulcrum in a lever system and centroids of mass and area, both very important to describe the mechanics of static stability.

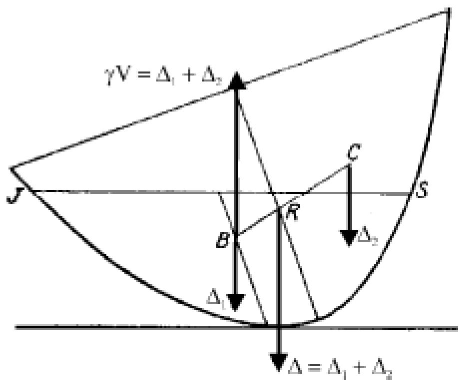

Figure 2.1: Restoring moments, righting arms for inclined homogeneous paraboloid, based on Archimedes' on floating bodies

The theories that were developed during his lifetime between Ca. 287-212 B.C. laid the foundation of future development of the theory behind static stability. Archimedes' work was only described for a simple parabola and could not be generalized to use with ship shaped vessels. Figure 2.1 shows the developed principle. It would take around 1800 years before we would see any development in the area.

During the start of the modern era contribution from different scientists touched into the subject. One of them was Simon Stevin (1548 – 1620). His work "De Beghinselen des Waterwichts" was published in 1586. Here he described hydrostatic pressure distributions on a submerged body equal to the weight of the above lying water column and in his note "Van de Vlietende Topswaerheyt" he confirms that for equilibrium buoyancy the weight and buoyancy force resultants must act in the same line through the centres of buoyancy and gravity.

In the 1500-1600 methods for calculating displacement of ships were developed with incentives from shipbuilders, port owners and the marine to accurately calculate tonnages and ballast. (Nowacki and Ferreiro, 2011)

These are all concepts that holds today. With the arrival of calculus and later computers the methods of describing the static stability has change to static determinations of pressures on submerged volumes.

2.2 Design/specifications of a barge

Barges is one of the preferred construction for moving cargo around the seas. These versatile vessels can be configured in many different ways, depending on the cargo. Barges can also be constructed with bunkers for liquid cargo, specially strengthened hulls for heavy objects, equipped with a crane to perform lifting operations or even floatation towers for submerging.

In the IMO Code a barge is defined as (Organization, 2008):

- Non self-propelled
- Unmanned
- Carrying only deck cargo
- Having a Block Coefficient of 0.9 or grater
- Having a breadth/depth ratio greater than 3
- Having no hatchways in the deck, except small manholes closed with gasket covers

Other main characteristics are:

- Flat top decks
- Flat bottom
- ballasting system
- Diesel-electric power system
- Ballast treatment system
- Towing arrangement

The shape of the barge is a box shaped mid-section with short radius rounded keels. The front and back part of the bottom plating is angled to make towing more efficient. In the stern it is common to fit skegs protruding from down to improve the directional stability of the barge.

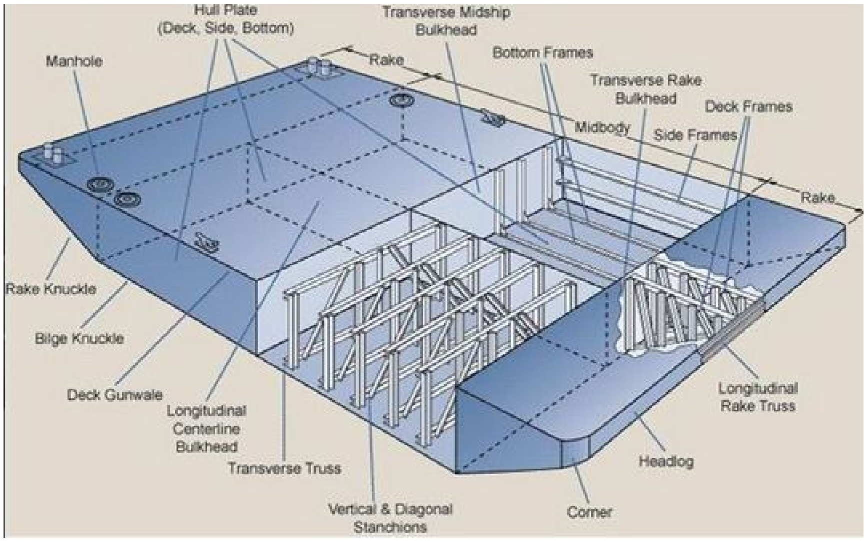

Figure 2.2: Schematics of a barge (Brighthubengineering, 2013)

Without these fins, the barge is prone to sway during tugging. Around the hull, it is common to fit fenders to allow for manoeuvring of the barge with tugboats without damaging the hull.

The normal construction of a barge can be seen in figure 2.2. It consist mainly of thick steel plate hull and deck, a truss structure for strengthening and horizontal and vertical bulkheads making up the ballast compartments in the barge. These bulkheads are equipped with pipes connected to ballast pumps to be able to make trim and heel changes to the vessel. Bulkheads also increases the structural integrity of the barge by dividing the hull into separate compartments. This ensures that the buoyancy can be maintained if damage is caused to parts of the hull. Structural loading capacities is in the range of 20-25 tonnes uniform deck load per m^2 and point loads of 200-1000 tonnes.

A very common type is the standard North Sea barge. Typical data can be found in table 2.1. Although not a standardized size, it has been the most used barge for marine operations in the North Sea. An example is illustrated in Figure 2.3.
Besides the pump room with surrounding tanks for hydraulics and cooling, the internal volume of the barge is made of compartments for ballasting. It is common to assign permeability ratios of around 98% for all of the compartments. This means that the tanks can be filled to 98% of the volume

Figure 2.3: Ugland Rederier, UG-97 Standard North Sea Barge (Ugland Rederier AS, 2013)

Table 2.1: Dimension of a standard North Sea Barge

Standard North Sea Barge UR-97	
Principal Dimensions	[m]
Loa	91.44
Lpp	91.44
Moulded Beam, B	27.43
Moulded Depth, D	6.1
Moulded Draft, T	4.84
Displacements [tonnes]	
Lightship	2334
Deadweight	9094

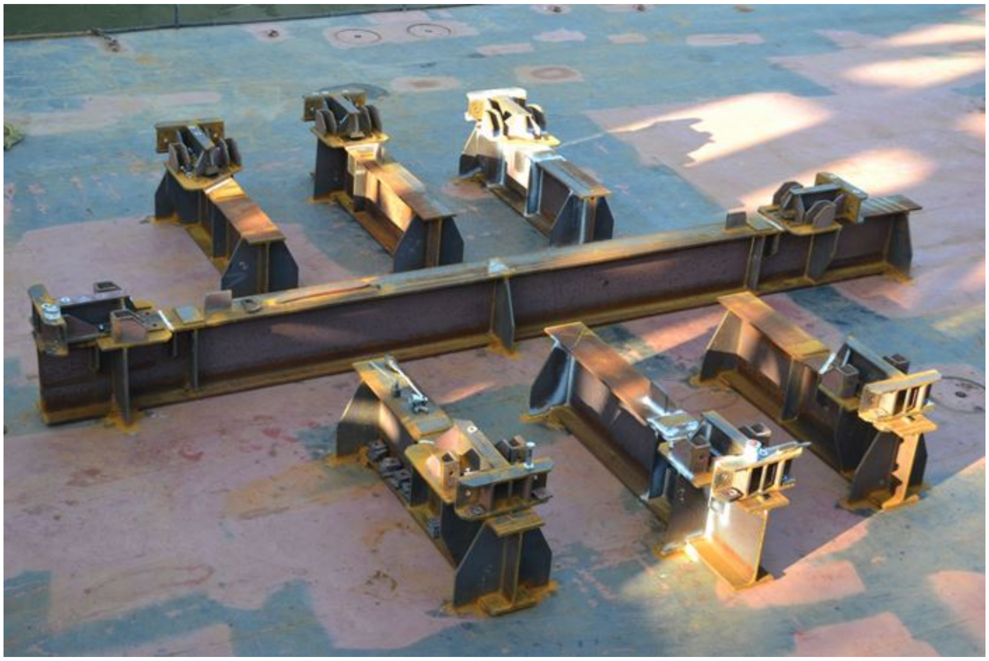

Figure 2.4: Grillage for load distribution

Sea fastening is done by temporary arrangements. This means that for each operation the sea fastening is fitted to the flat top of the deck by timer cribbing, welding and bolting to the superstructure of the barge. This depends on the load out method. For lift out or float-over cargo, it is common to use timber cribbing. Cargo that is skidded out is normally remain in the skids and roll out loading requires grillage that is higher than the minimum trailer height. An example of grillage can be seen in Figure 2.4. Seafastening of irregular shaped structures and objects that would produce higher point loads than allowable also to be fitted with grillage or cribbing to redistribute the loads into the structure. Other equipment with lower weight than 100 tonnes is often fastened with chain, wire or webbing lashings. (Denton, 2013)

2.3 Important weight and loading specifications

In Naval architecture a number of different weight acronyms are used to determine the specifications and capacities of a vessel. The main ones are described here:

Displacement tonnage

Displacement tonnage is the total weight of water it displaces when it is sitting in the water.

Standard displacement tonnage

Standard displacement tonnage is similar to displacement tonnage. The difference is that the weight of liquids placed on board the vessel is subtracted. This can be fuel, drinking water, cooling water etc.

Lightweight tonnage, LWT

Lightweight, or lightship, tonnage is best described as the weight of the ship as built. This include all of the framing, machinery, deck, and grillage. It does not include any fuel, water or other consumables or temporary equipment.

Deadweight tonnage, DWT

Deadweight tonnage is the weight of the cargo, supplies, crew, fuel etc. carried on board, also defined as the loading capability.

$$Deadweight = Displacement\ tonnage - Lightweight\ tonnage \tag{2.1}$$

Gross registered tonnage

Gross registered tonnage is the measurement of the total enclosed volume of the vessel

Net registered tonnage

Net registered tonnage is a measurement of the volume of the cargo storage.

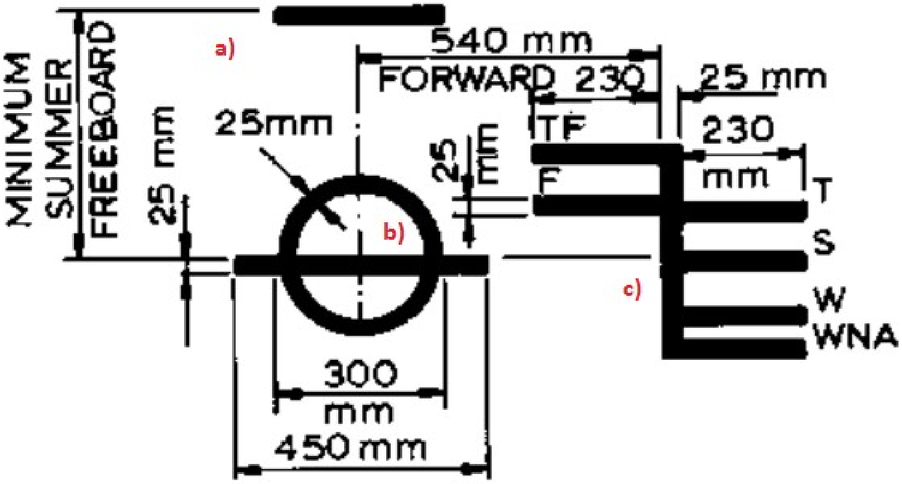

Figure 2.5: Load line marking for B-type vessels (DNV, 2001)

2.3.1 Load Line Markings

Regulations demands ship masters to perform physical inspections before any operation commences. (Organization, 2008) This is done by verifying that the vessel is according to the specifics of the loading manual. Since the vessels are used during different seasons and at different locations around the world, it is necessary to adjust the loading regulations accordingly. To make this easier all ships are equipped with load line markings which indicates the loading condition visually. Figure 2.5 shows a load line marking used for commercial vessels. The load line markings are made up of the following indications:

1. Deck line indicating the freeboard deck surface
2. Load line mark that is placed with the centre of the ring amidships at a distance below the deck line equal to the assigned summer freeboard.
3. Different loading lines indicating the water level at different conditions
    (a) WNA: The Winter North Atlantic Load Line
    (b) W: the Winter Load Line
    (c) S: Summer Load line at the same level as the load line mark
    (d) T: Tropical Load Line

(e) F: Fresh water Load Line

(f) TF: Tropical fresh water Load Line

2.3.2 Ballast systems

Ever since steel hull vessels were introduced, water has been used as ballast to stabilize vessels at sea. Before this, it was common to use solid ballast in the ships to correct lists or improve the vessel properties. The solid ballasting was in most cases high-density materials like steel or concrete. During a voyage, it may be necessary to re-ballast the vessel, this can be in situations where the vessel has to pass a shallow canal, weight shifts or cargo loading or unloading. As time passed and vessels kept increasing in size, solid ballasting became too complicated and time consuming.

Modern ballasting systems uses seawater as ballasting to ensure the correct trim, stability and structural integrity. The vessels have a multiple of sealed compartments that allows for ballasting. Between the compartments, a network of piping and pumps allows for ballasting, discharging and shifting of weights. This process is quick compared to solid ballasting, making it much more efficient.

There is much talk about slack tanks and free surface effects. This is one of the drawbacks of using liquid ballast compared to solids. If the water is free to move around inside the tanks it will create heeling moments that can reduce the stability and even permanent damage to the internal structure or hull of the vessel on impact.. The effect of the free liquid is reduced when splitting the ballast tanks into smaller sections and can be completely removed if the tanks are filled completely.

Another drawback is the material deterioration. The internal compartments and equipment of a vessel is less resistant to the corrosive effect of seawater, and if not adhered to it can reduce the structural strength of the vessel. If this is not controlled the damage could create pathways for free liquid to move. This can increase the effect of free liquid.

While ballasting is essential for improving the stability it may pose serious ecological problems and health damage to the marine environment if not managed properly. Our oceans are connected but it is composed of many separate ecosystems that can be threatened if alien lifeforms are introduced. The IMO standard clearly states that the stability should be ensured during all parts of a voyage. This means that it may be necessary to re-ballast the vessel when cargo is loaded or unloaded. If water is then added to tanks at one location and discharged at another transferring of marine species could occur. This has been recognized by marine agencies and requirements of ballast water management plans have been adopted in resolution A.868(20). All ballast tanks are fitted with treatment systems to inhibit transfer of lifeforms.

2.3.3 Vessel motions

Vessel motion is a six degree of freedom system, divided into translational and rotational motion, where:

- Heave, surge and sway are the translational motions measured in meters
- Roll, pitch and yaw are the rotational motions measured in degrees

A vessels response to the surrounding ocean is a complicated phenomenon, involving interaction between the vessels movement and hydrodynamic forces. By using linear theory, it is possible to predict the motions of a vessel under the influence of hydrodynamic forces. Although all vessel motions are to some extent non-linear, using linear theory makes it possible to describe these motions sufficiently.

When studying transverse stability roll periods are the most important motion to investigate.

Roll motions

Roll motions are the most difficult to predict. For vessels with values of $\overline{GM}_t$ near the width of the beam rolling motions are severe in beam seas. This can lead to severe rolling. The roll resonant period is according to (Lewis, 1988) given by equation 2.2

$$T_0 = 2\pi \frac{k_4}{\sqrt{g\,\overline{GM}}} \tag{2.2}$$

where k_4 is the radius of gyration. which is found from equation 2.3

$$k_4 = \sqrt{\frac{Ixx\, m_a}{\Delta}} \tag{2.3}$$

where:

m_a = Added mass
I_{xx} = Second moment of area

The exact value of the radius of gyration can be found by knowing the exact position of all the weights on the vessel, which can be difficult ff there is no knowledge of this. There is a strong relationship between a vessels beam and radius of gyration. From (Biran and Pulido, 2013) a simplification that replaces the radius of gyration k_4 by a shape coefficient c. The value depends on the shape of the vessel and for barges it is given as 0.79.

This thesis mostly covers transverse stability, and therefore only the roll motions are considered.

Chapter 3

Literature Review

In this chapter, the relevant theories and background literature will be described. In the first section a short introduction to the history of ship stability is given. Secondly, the basic theory on vessel stability is reviewed. The next section covers the possible heeling moments present before closing with an introduction to the relevant standards.

3.1 Basic Hydrostatics

Hydrostatics is the area of physics revolving around fluids at rest, and the pressure exerted on bodies submerged in it. (Calvert, 2007). When studying fluids in a permanent state it can be assumed no viscous losses, independence of time and equilibrium of forces. Hydrostatics makes it possible to describe the correlation between pressure in the fluid and depth, which is an essential part of marine architecture.

3.1.1 Pascals law

Blaise Pascal described a very important principle in fluid hydrostatics. An intuitive explanation behind this is the change of pressure between two elevations in a fluid, which is widely used.

> *A change of pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid*

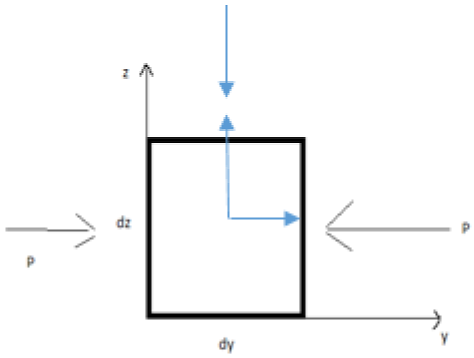

Figure 3.1: water volume element seen in z-y directin

For general purposes hydrostatics are independent of time, implying that to deduce the principles needed in this section the fluids is seen as having no viscosity. This means that the fluid being put into movement by an external force will not provide any resistance for the water in movement. In real applications, this is not true, which is seen from the added mass in a moving system in water.

Another point worth mentioning is that water is seen as an incompressible fluid. Although this is an idealised situation, it holds for studying stability where the water particles in question are very near the water surface where the pressure is almost equal to atmospheric pressure. This simplification allows us to solve the basic hydrostatic equations readily.

3.1.2 Basic Hydrostatic Equations

Consider the equilibrium of a water volume element.
Assuming static conditions and that Newton's laws of motion states that the sum of forces on a body at rest is zero, Pascal's law can be validated. The equations are derived in equations 3.1 through 3.8

The forces exerted on the element are in Y and X direction are:

$$P\,dz\,dx + f_y\,dy\,dz\,dx - (P + \frac{\delta P}{\delta y}dy)\,dz\,dx = 0 \tag{3.1}$$

$$f_y - \frac{\delta P}{\delta y} = 0 \tag{3.2}$$

And similarly for the x-direction:

$$P\,dz\,dy + f_x\,dx\,dz\,dy\ -(P + \frac{\delta P}{\delta x}dx)\,dz\,dy = 0 \tag{3.3}$$

$$f_x - \frac{\delta P}{\delta x} = 0 \tag{3.4}$$

This means that if the unit force f_y and f_x is zero the pressure differential over the element and the forces in the direction is zero. In the z-direction, there is a contribution from gravity, giving us:

$$P\,dx\,dy + f_z\,dz\,dx\,dy\ -(P + \frac{\delta P}{\delta z}dz)\,dy\,dx = 0 \tag{3.5}$$

$$f_z - \frac{\delta P}{\delta z} = 0 \tag{3.6}$$

Forces from gravity:

$$f_z = -\rho\,dV\,g \tag{3.7}$$

This leads to:

$$\frac{\delta P}{\delta z} = -\rho\,g \tag{3.8}$$

This equation is used to expresses the pressure in an incompressible fluid by integrating from the surface down to the object. In hydrostatic simulation, these are the underlying principles used, with the help of calculus.

3.1.3 Archimedes' principle

Archimedes is truly the father of hydrostatics. The famous tale about how he discovered the principle during a bath in his own home is probably fictional but it explains the background for the theory in a way that most people can relate to. More specifically, he was engaged to find the specific gravity of a crown of a very complex form and compared it to the weight of gold to determine if the blacksmith had used pure gold or a composite of other materials. This led him to compare the displaced volume of the crown in water to its weight, revealing that the specific gravity of the crown had decreased. This indicated that the crown was not made up of solid gold. This was possible to compare since the crown displaces the same amount of volume independent of what material it is but the weight of gold is almost twice the weight of silver that was used.

Archimedes' principle on displaced fluid was developed long before calculus. However, by studying the basic hydrostatic his axiom can be demonstrated.

3.2 Ship Stability

> *Stability is the ability of a body, in this setting a ship or floating vessel, to resist the overturning forces and return to its original position after the disturbing forces are removed.* (OveTobiasGudmestad, 2015)

A ship floating at rest is in static equilibrium. In this condition, the forces from buoyancy and gravity are equally in size and opposite in direction and working in line with each other. If the force from buoyancy is greater than from gravity, the ship rises in the water. If the forces from gravity is larger than those from buoyancy, the ship is sinking. If the forces from buoyancy is offset from gravity or vice versa, the ship will have an overturning or restoring moment working on the ship trying to reach equilibrium again.

All of these properties are dependent on the weight, size shape of the vessel. Depending on the application, the design will change. Choosing the wrong vessel type for your application can result in reduced stability, reduced seagoing capabilities, bad fuel economy or in the worst case capsizing. A wider ship will have a much higher cross-sectional stability but it will decrease fuel economy, longer ships will have better longitudinal stability but will be less manoeuvrable.

3.2.1 Important concepts and dimensions in ship design

To be able to understand the terms used when discussing stability there are certain important terms that has to be described. Figure 3.2 shows the general dimension and important properties in stability analysis.

Some of the terms used in figure 3.2 are self-explaining, while some needs a bit for revising to be clarified for the further discussion.

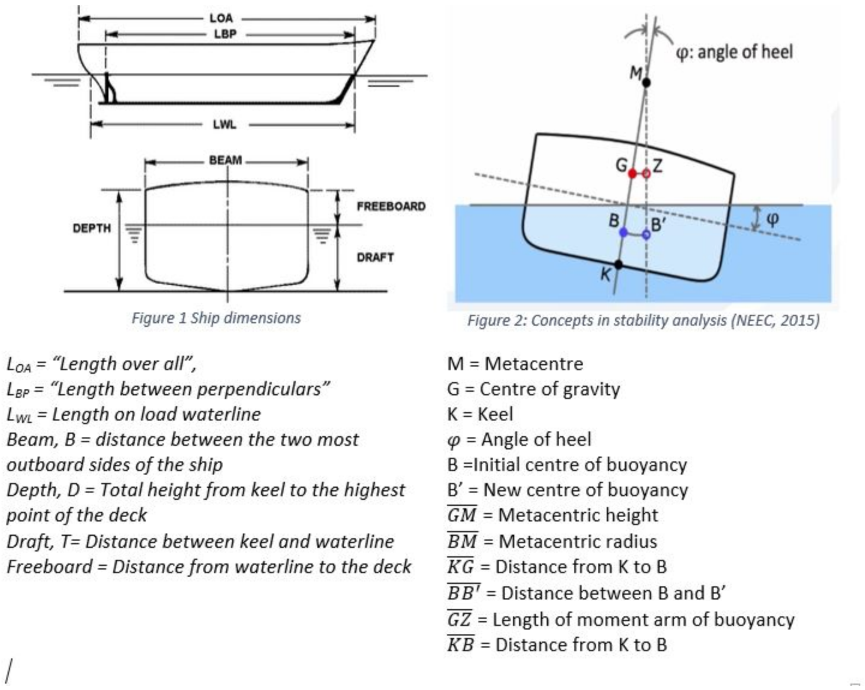

Figure 1 Ship dimensions

Figure 2: Concepts in stability analysis (NEEC, 2015)

L_{OA} = "Length over all",
L_{BP} = "Length between perpendiculars"
L_{WL} = Length on load waterline
Beam, B = distance between the two most outboard sides of the ship
Depth, D = Total height from keel to the highest point of the deck
Draft, T= Distance between keel and waterline
Freeboard = Distance from waterline to the deck

M = Metacentre
G = Centre of gravity
K = Keel
φ = Angle of heel
B =Initial centre of buoyancy
B' = New centre of buoyancy
$\overline{GM}$ = Metacentric height
$\overline{BM}$ = Metacentric radius
$\overline{KG}$ = Distance from K to B
$\overline{BB'}$ = Distance between B and B'
$\overline{GZ}$ = Length of moment arm of buoyancy
$\overline{KB}$ = Distance from K to B

Figure 3.2: General ship dimension (engineering education center)

Metacentre, M:

The metacentre is an imaginary point above the vessel. This point is used as a reference point for rotation. It is located at the intersection between the two lines $\overline{BM}$ and $\overline{GM}$ in Figure 3.2.

Metacentric height, $\overline{GM}_0$

The metacentric height is the distance between centre of gravity and metacentric height. This value is dependant of the relationship between weight, shape and buoyancy of the ship

Metacentric radius, $\overline{BM}$

The metacentric radius is the distance between the instantaneous centre of buoyancy and the metacentre.

The metacentric radius is defined as:

$$\overline{BM} = \frac{I}{\nabla} \tag{3.9}$$

I = Area moment of inertia of the waterline area

∇ = Volume of displaced water

In addition, some important definitions related to ship geometry:

Area of waterline, $A_W L$**:**

This is the area made up of the width of the ship, in the case of a barge the beam, and the Length of load waterline,L_{WL}

Block Coefficient, C_B

The block coefficient is the ratio between the immersed volume and the product of the length, beam and draft. It describes the shape of the hull of a vessel. A large block coefficient implies that the shape of the hull is rectangular like the one seen in figure 3.2. Block coefficients

$$C_B = \frac{\nabla}{Loa\, B_{WL} T} \tag{3.10}$$

Waterline Area Coefficient, C_W**:**

The waterline area coefficient, also defined as the slenderness of the ship is the relationship between the waterline area and the length of the ship:

$$C_W = \frac{L_{WL}}{A_{WL}} \tag{3.11}$$

3.2.2 Intact stability, in general

Stability is defined as an objects capability to return to its initial position when inclined to an angle. To quantify these values, and find the righting moment that resist the inclination and returns the object to equilibrium, it is necessary to find the righting arm and the force.

From the section on hydrostatics, the upward trust that an object receives is found to be equal to its buoyancy or displaced weight of water. Even though the waterline area of the vessel increases as the ship heels, the weight of the vessel does not change, so the buoyancy force is held constant according to Archimedes. This means that the buoyancy force, or weight of displaced water found initially is the force resisting the heeling, in all cases.

Further, it is stated that the centre of buoyancy is of a submerged object is always placed in the geometric centre of the displaced volume. When the ship heels the underwater volume of the hull moves in the direction of the heel. This causes the centre of buoyancy to shift in the same direction. The situation now is that the force vector pointing downwards from the centre of gravity of the object, which does not change with heel angle and the force vector from the centre of buoyancy, is no longer acting in line with each other. This creates a righting moment that tries to restore the vessel back to even keel, or to the position of rest.

Since the centre of gravity does not move it is natural to use it as a centre of rotation, and it is in most cases used to find the righting moment. Figure 3.2 illustrates a ship with a heel. The product of the force from buoyancy, located in point B and found from calculating the upward trust from the displaced water, and the distance from the that point to the centre of gravity of the object $\overline{GZ}$ gives us the righting moment of the vessel, shown in equation 3.12

$$Righting\ Moment = \overline{GZ}\,\nabla\, g\rho \tag{3.12}$$

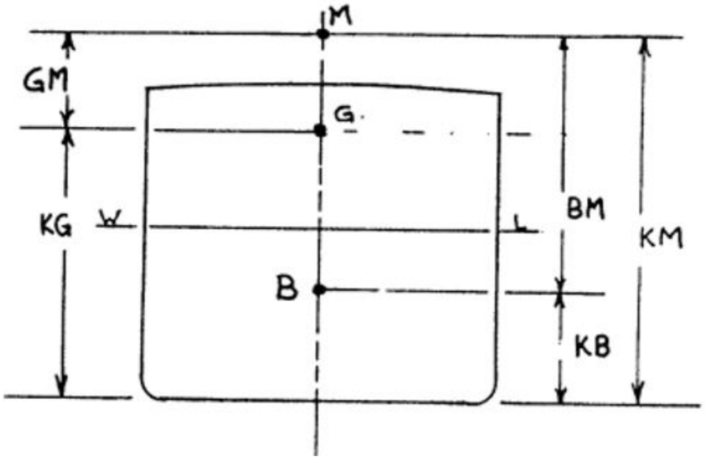

Figure 3.3: Initial stability calculation

3.2.3 Initial stability

Before any operation involving floating structures can commence the master has to establish that the vessel is seaworthy according to the stability manual. This involves confirming initial stability. With modern computer aided designs, it is common to make these calculations beforehand However in some cases this is still done by manual interpretation of stability data for smaller vessels and sporting boats. To have an initially stable vessel the following criteria has to be fulfilled:

1. The vessel must be floating

Maybe trivial, but all though the most fundamental criteria. From Archimedes principle, it is shown that the buoyancy force exerted on an object floating in water is equal to the displaced displacement. This can be used to find the loading capacity of the vessel. By finding the maximum theoretical displacement of the hull from geometry. Subtracting the weight of the vessel itself for cargo capability.

2. A positive metacentric height, $\overline{GM_0} > 0$

Confirming a positive $\overline{GM}$ is as fundamental as a having a floating vessel. The initial stability calculation is done with the relationship shown in equation 3.13. See Figure 3.3

$$\overline{GM_0} = \overline{KB} + \overline{BM} - \overline{KG} \tag{3.13}$$

There are three different states for the metacentric height:

- $\overline{GM} > 0$: This means that the metacentric height is positive. Introducing a small angle of heel, the ship will go back to its initial position
- $\overline{GM} = 0$: Here, the metacentre is placed in at the same height above the keel as the centre of gravity. If heeled the vessel would stay in that position when the force holding it there is gone. The stability is neutral.
- $\overline{GM} < 0$: In this case, the metacentre is placed below the centre of gravity. There is a negative metacentric radius and the vessel will capsize if disturbed from equilibrium.

As mentioned the metacentre is a virtual point of orbit placed at the intersection between the lines extending from the centre of gravity and centre of buoyancy. Meaning that it is not a physical value. A vessel in equilibrium will continue to float even though it has a negative $\overline{GM}$, but the instance it is disturbed from rest it will continue to move until it finds a new angle of rest, which for most vessels will be hull sided.

The best way of obtaining an intuitive understanding of $\overline{GM}$ is the rolling period of the vessel. A vessel having a very small $\overline{GM}$ will be prone to large rolling motions and for a large $\overline{GM}$ it will have very short roll periods.

3. If the vessel is floating on a list, it is the master's responsibility to either confirm that the vessel is capable. If not, rearranging of loads or ballasting is necessary.

A vessel can perform safely even though it is not on an even keel or trim. The issue is that if the vessel is loaded with an angle of heel or trim the reserve stability will be reduced in the direction of the heel. On the opposite side the stability will be increased against the heel.

3.2.4 Stability at small angles

For small angles of heel, the metacentric radius is assumed constant. This yields up to 5-25 ° of heel, depending on structure of the hull and loading condition. This means that for small angles it can be assume that the vessel orbits around a fixed metacentre M_0, found in the initial stability

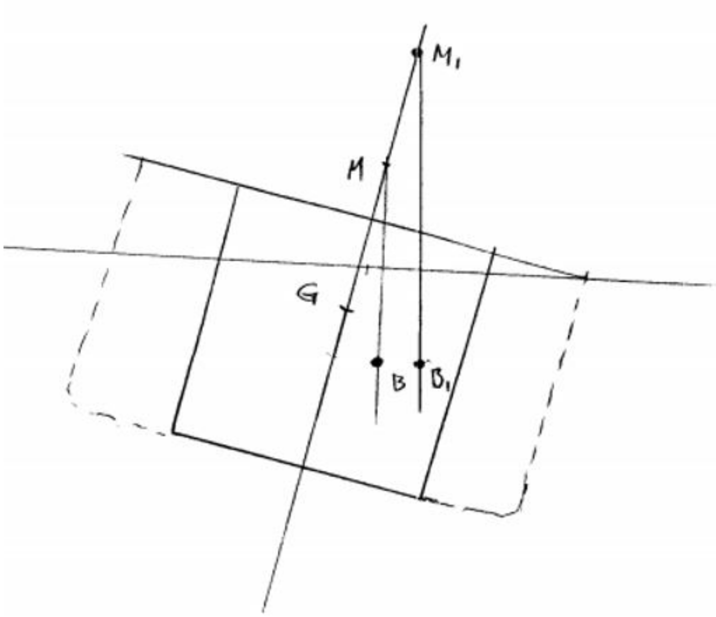

Figure 3.4: Instantaneous metacentre M_I

calculations. This way the righting moment found at small angles of heel can be calculated by the relation given in equation 3.14.

$$Righting\ moment_{smallangles} = \Delta\, \overline{GM_0} \sin(\varphi) \tag{3.14}$$

where:

$$0 < \varphi < 5 - 25°$$

For stability calculations for small angles of heel it is possible to continue to use the initial value for metacentric height $\overline{GM_0}$. The limit for where this relationship is valid depends on the shape of the hull.

3.2.5 Stability at larger angles of heel

The principles derived on initial metacentric height are only valid for small angles of heel. The explanation behind this lies in the displacement of the centre of buoyancy. For small angles of heel the centre of buoyancy and gravity will point to the virtual metacentre. This is not the case for larger angles of heel. See Figure 3.4. When the vessel is heeled by an external force, the centre of buoyancy shifts in the same direction as the heel and relocates in the geometric centre of the new underwater volume. On the other hand, if there is no movement of cargo or free surface effects present the centre of gravity will remain in the same position and the force vector will be pointing vertically downwards. The situation now is that the vessel is no longer in equilibrium, the force components from gravity and buoyancy is no longer placed on the same vertical line. The horizontal distance from the centre of gravity to the vertical line that runs through the centre of buoyancy is known as the righting lever arm $\overline{GZ}$. A vessels transverse stability is defined as its capability to restore itself to the initial equilibrium . The length of the righting lever is the measure of a ships resistance against capsizing for larger angles of heel.

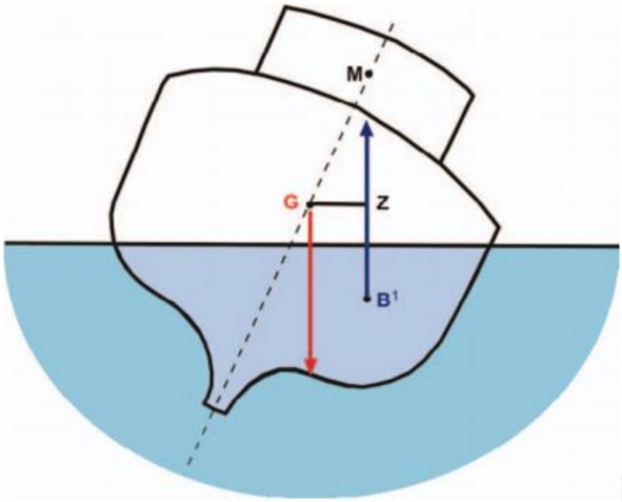

Figure 3.5: Lever arms

In figure 3.5 the righting arm is displayed together with the gravity and buoyancy force. These two vectors will always be equal in length and opposite in direction when the vessel is in equilibrium. When the vessel heels from an external force the geometry of the underwater volume will change. Since the centre of buoyancy is always placed in the geometric centre of the underwater volume, it will shift in the direction of the heel. This can be seen in figure 3.5

To find the righting moment working against an inclination the righting lever and the force has to be found.

In static stability conditions the buoyancy force is always equal to the upward trust generated from the displacement of fluids. In the section of hydrostatics it is shown, according to Pascal's law, that the pressure in a liquid is equal in all parts of the liquid. This can be utilized in stability calculations to find the buoyancy force, if the underwater volume geometry is know.. This is the mathematical explanation behind Archimedes' principle described earlier. This gives us two tools for finding the buoyancy, and hence the force resisting the inclination of a floating body.

In most static stability calculations it has to be assumed that there are no discharge or gain of mass. This means that it has to be assumed that the buoyancy force is constant for all angles of inclination. Shown in equation 3.15

$$\Delta_{Static} = \rho\, g\, \nabla = Const \tag{3.15}$$

As mentioned the moment arm is the righting lever GZ. The process of finding the length of the righting arm is rather complex. For all cases the B is always placed in the geometric centre of the underwater volume. As the vessel heels the underwater area can become rather cumbersome to compute manually. In modern technology computers are used to make thee calculations making it far easier to create good estimates of stability.

Equation 3.16 that for wall sided vessel, like a barge, the GZ up to when the water touches the deck line can be found from the wall sided equation. (Rawson, 2001)

$$GZ_{Wall\,sided} = (GM + \frac{1}{2}\, BM\, tan^2\varphi)\sin\varphi \tag{3.16}$$

This equation holds for vessels having vertical hull sides, meaning that the portions of the hull that is in contact with the water plane is vertical when the vessel is upright.

3.2.6 Longitudinal Stability

In general, longitudinal stability is less important to discuss in terms of the danger of capsizing and general safety of the vessel. The centre of gravity are so large that it would require very large forces to overturn the vessel. On the other hand, longitudinal stability plays a very big role in defining sea keeping properties, fuel economy and motions in waves.

3.2.7 Curve of Intact Stability, GZ curve

To illustrate the length of the righting arm as a function the angle of heel it is common to make a graphical plot, a GZ curve. The curve gives a good description of the stability characteristics of the vessel. GZ curves are made on the assumption that the heeling moment is applied in infinitely small steps to ensure that the equilibrium of forces always applies. This means that it does not take into account the dynamics of a vessel rolling, rotational momentum, added mass etc. It is therefore a strong idealization of a real system, but it makes it possible to make comparisons of loading conditions, different hulls and reductions to stability from free surface effects or wind heeling moments. Each of the intact stability curves are for a single loading condition. If the displacement or centre of gravity change the curve has to be corrected, or a new curve has to be made.

The key properties to note from the righting curve: (see Figure 3.6)

- A vessel is defined as stable as long as the metacentric height is positive. This implies that when the metacentric height is positive there is a positive GZ.
- The metacentric height is plotted on the curve and a line is drawn from that point to the origin. Initially it was stated that for small angles of heel the stability, and hence the righting moment, could be found directly from the metacentric height multiplied with the angle of heel. This is shown in figure 3.6. The curve coincides with the straight line drawn. The validity of the initial stability criteria holds until the GZ curve differs from the straight line.
- The point where the curve crosses the x-axis is called the point of vanishing stability. Here

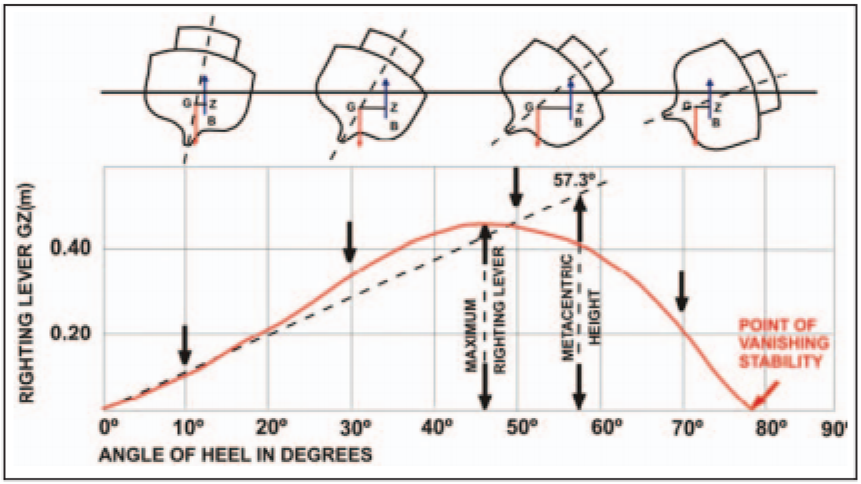

Figure 3.6: Important properties of the righting lever curve (engineering education center)

the righting lever is zero and if the vessel rotates beyond this point it will keep rotating until it reaches a new equilibrium in a state where the vessel is keeled over.

- The distance between the origin and the point of vanishing stability is the range of stability of the vessel.
- The highest point on the curve is where the righting lever is on its maximum. Beyond the maximum righting lever the stability decreases This means that if a vessel is inclined to an angle of heel equal to the maximum level and the moment that imposes the inclination does not reduce the vessel will keep heeling.

3.2.8 Dynamical Stability

General stability calculations are based on the assumption that the heeling moments are applied in infinitesimal small steps, this way the equilibrium is withheld. This idealized situation rarely apply. Gusts of wind appears suddenly, cargo shifts or dropping of loads gives instant impact loads and waves hit at random intervals. In these situations dynamical stability is a more suitable approach.

In static stability considerations heeling and righting arms are compared, while in dynamic stability the potential energy and work done by the righting and heeling moments are checked.

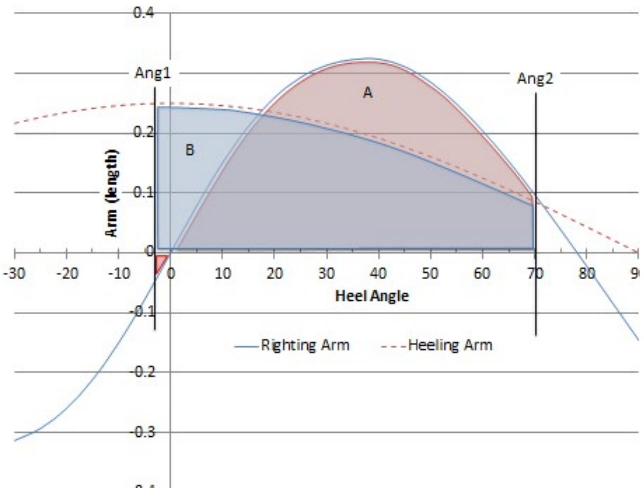

Figure 3.7: Area under the curve showing work done

From mechanics it is shown that the work done is equal to the force multiplied with the distance it is applied over. This implies that the work done by a heeling moment can be found in the same way, by finding the distance the force is applied. This is illustrated in figure 3.7. Equation 3.17 and 3.18 shows that the moment is equal to the force times the length of the heeling arm multiplied by the angle. (Biran and Pulido, 2013)

$$W = \int_{\varphi_1}^{\varphi_2} F\ r\, d\varphi = \int_{\varphi_1}^{\varphi_2} M\, d\varphi \tag{3.17}$$

or with the force from buoyancy and the righting arm:

$$W = \int_{\varphi_1}^{\varphi_2} M_h\, d\varphi = \int_{\varphi_1}^{\varphi_2} \Delta\, \overline{GZ}\, d\varphi \tag{3.18}$$

Here it is possible to make use of the GZ curve found in static stability calculations to find the new angle of equilibrium. From these relationships it is also possible to see that the work done is also equal to the area under the righting curve, the energy obtained by the heeling curve. When the work done by the heeling moment equals the energy of righting moment the vessel will stop moving, or if the moment seizes it will go back to a new angle of equilibrium. Further, this means that it is possible to find the potential work from the righting curve and subtract the heeling moment work to find “reserve stability”. Equation 3.19 gives us the maximum dynamic angle:

$$\int_{\varphi_1}^{\varphi_2} \overline{GZ}\, d\varphi - = \int_{\varphi_1}^{\varphi_2} l_I d\varphi \tag{3.19}$$

3.3 Means of improving/ensuring Stability

Most of the work to ensure that a vessel can be kept stable has to be done during the design stage. The naval architect has to consider the type of cargo it will be carrying, working environment and so fourth.

During the design phase the form factors affecting the stability are the beam(width), freeboard(height) and COG of the vessel. Working within the limitations of the vessels functional design the naval architect can benefit from increasing these parameters. This will of course have an effect on the total weight, running economy and building cost.

If for some reason the stability is not satisfactory there are some ways if increasing the stability of the vessel. The most known method of increasing stability is by ballasting, which has been discussed earlier. The process of ballasting will shift the COG for the vessel towards the location of the ballast. This is a very efficient way of bringing the vessel back to even keel if the loading from cargo is unsymmetrical. However, another effect of ballasting is that in most cases that the vertical centre of gravity will be lower(where the ballast tanks are placed in the bottom of the vessel). This will as pointed out earlier increase the metacentric height.

Another way is to reduce the topside weight. This is the most efficient way of improving stability. Removal of topside weights has an effect on two factors; Reducing VCOG and increasing the righting arm by increasing the distance out to the centroid of the submerged volume.

In modern vessels there are active stabilization systems that can improve stability even further. In lifting vessels there may be installed compressors that can shift water around the sealed compartments quickly, making it possible to increase lifting capacity.

3.4 Heeling Arms and Moments

A vessel at rest may be disturbed of various reasons. In most cases, the focus is on forces from wind pushing against the side of the ship or waves. Also important to remember is that the vessel may be heeling as a result of the centrifugal force while turning, shifting of weights, towing gear, free surface effects, water on deck, added weight from ice accumulation, cargo water absorption or damaged stability conditions. The most predominant is wind forces, free surface liquids and transverse displaced loads. These will be discussed further.

As for the righting arms discussed earlier it is assumed that the forces that develops are applied in small steps to maintain the equilibrium, to which static calculations apply. If this is not the case it is a dynamical system, and the principles of work done, which is discussed in the section on dynamical stability has to be used.

The stability is expressed with the use of GZ curves. These righting arms is coupled with the displacement that creates righting moments. To be able to compare the forces, and hence moments, that can sacrifice the stability the same analogy is used. The created heeling arms are superimposed into the righting arm curve. This way the resulting angle of heel is found.

3.4.1 Wind heeling moment

During an offshore operation there is always the probability of hitting bad weather, especially in exposed waters like the North Sea. In the situation where there is beam wind forces that develop from the wind pressures against the side of the hull and cargo can become very large and thus creating large heeling moments. The forces from wind can be found from the developed pressure over the area as shown in equation 3.20 through 3.22: (Biran and Pulido, 2013)

$$F_V = C_S C_H p_V A_V \tag{3.20}$$

Where:

$$p_V = \frac{1}{2}\rho V_w^2 \tag{3.21}$$

- $C_S = Shape\,Coefficient$

- $C_H = Height\, Coefficient$
- $V_w = Vind\, speed$
- $h_V = Centre\, height\, of\, projected\, area$

The shape factor depends on the shape of the cargo and the height factor takes into account the change in wind speed with height. These are calculated by inspecting the shape and solidness of the cargo and relevant wind profiles for the area and storm conditions.
Tabular values can be found in relevant standards. (Organization, 2008)

This force will be opposed by the reaction force from the water. Assuming that the reaction force acts at half draught, T/2, and is equal in size, these two forces will incline the vessel until the righting moment is in equilibrium with the heeling moment.

The righting arm ℓ_V will then be:

$$\ell_V(\varphi) = \frac{p_V A_v (h_V + T/2)}{g\Delta} \cos^2(\varphi) \tag{3.22}$$

According to IMO a minimum wind speed used in the calculations should be 36 m/s for normal operation conditions and 51.5 m/s in storm conditions. In general, the winds speed has to be estimated based on wind speed data available for the area of operation. The wind heeling moment should be prepared for the whole range of loading conditions applicable for the operation in mind.

3.4.2 Free surface effect

The free surface effect is an important concept in marine engineering. It is caused by liquids that are free to move inside enclosures. These tanks are known as slack tanks. All vessels are equipped with tanks containing liquid of some kind. Liquid carriers, ballast tanks, fuel tank, cooling water and so on. Depending on the type of liquid contained in the tanks the filling fraction of the tanks can vary, ballasting control can result in slack tanks and some of the fluids are used up during the operation. How these tanks are managed plays an important role for the stability of the vessel.

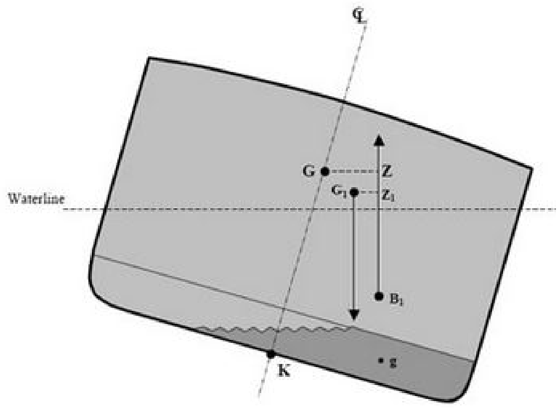

Figure 3.8: the effect of free surface liquid on GZ

A full compartment can be considered as a static weight having its centre of gravity at the centre of the liquid while tanks having filling fractions below 98% has to be considered during stability calculations.(Biran and Pulido, 2013)

If an angle of heel is present, the free surface of the liquid in the slack tank will cause it to move in the same direction as the inclination as seen in figure 3.8. This results in a shift of the centre of gravity of the liquid, consequently moving the centre of gravity of the vessel in the same direction. The heeling moment from free surface effects can then be calculated as seen if equation 3.23:

$$M_l = \rho_l I_l \tan(\varphi) \tag{3.23}$$

There are different ways of approaching the influence of surface effects on the stability of a vessel, but the most common way is to reduce the metacentric height by finding the shift of the centre of gravity according to equation 3.24.

$$GG_I = (\frac{\rho_l}{\rho_{sw}})\frac{I_l}{\Delta_{sw}} \tag{3.24}$$

- $\rho_l = Density\ of\ liquid$
- $\rho_{sw} = Density\ of\ seawater$
- $I_l = Second\ Moment\ of\ Area\ for\ the\ surface\ of\ the\ tank$
- $\Delta_s = Displaced\ water\ weight$

In figure 3.8 the effect is illustrated by reducing the righting arm GZ by an amount equal to the horizontal component of GG_{II}. This means that the heeling arm from free surface effects can be expressed as seen in equation 3.25 and 3.26

$$GZ_{Freesurface} = \frac{\rho_l I_l}{\Delta} \sin(\varphi) \tag{3.25}$$

And if there are multiple tanks:

$$GZ_{Freesurface} = \sum \frac{\rho_i I_i}{\Delta} \sin(\varphi) \tag{3.26}$$

Equation 3.24 is made up of four components, where the specific density and the displacement is constant while the second moment of area changes as the vessel is inclined. In most cases the free surface in tanks are rectangular. The second moment of area for a rectangle is $\frac{LB^3}{12}$. This implies that the breadth of the tank plays a huge role on the amount of free surface effects that has to be accounted for. This is possible to comprehend as the possible amount of liquid that can relocate its centre of gravity is dependent of the available area. By halving the breadth of the tank the free surface can be reduced by a factor of 4. This shows why important it is to fit longitudinal bulkheads in the vessel.

Worth noticing is that the reduction of stability from free surface effects is independent of location of the tank in the vessel (Barrass and Derrett, 2011). Also the height of the tank has no influence on the free surface effects. For this reason it is preferable to have tanks with small surface areas that extends the whole draught of the vessel. This expression takes an conservative approach. Since the area will be reduced when the water level in the tanks make them touch the top and bottom of the tanks the effect is less.

3.4.3 Transverse and Vertically Displaced Loads

Loads displaced transversely and vertically will affect the stability of the vessel by a great amount. Many of the objects transported by ships and barges are so large that they have to be placed off the centreline of the vessel. This means that to get the vessel to even keel it has to be ballasted on the other side of the vessel. The off-centre weight will cause a moment around the centre line

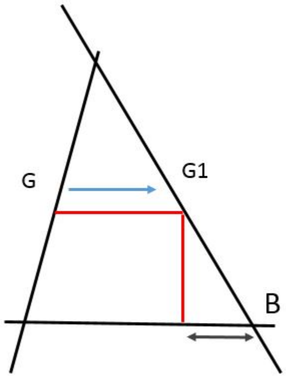

Figure 3.9: transversely moved load impact on GZ curve

that has to be accounted for on the other side. This means that for a single item transportation where the centre of gravity is offset from the centreline the capacity of the vessel is reduced by a factor of two times the original weight. This emphasizes the importance of proper deck layout planning.

In the section on adding, jettison and displacing of weights the equations for calculating changes in COG is presented. These equations can be used further to check the impact on the stability curve.

The heeling arm for a transversely moved load can be expressed from equation 3.27

$$GZ_Y = GG_1`; cos\,\varphi \tag{3.27}$$

and the righting arm for the vertically moved load can be expressed by equation 3.28:

$$GZ_Z = GG_2\, sin\,\varphi \tag{3.28}$$

These equations are known as the cosine and sine correction curves, respectively.

Cosine Correction

The cosine correction gives is the reduction of the stability curve from transversely moved loads. The reasoning behind the reduction can be found from figure 3.9.

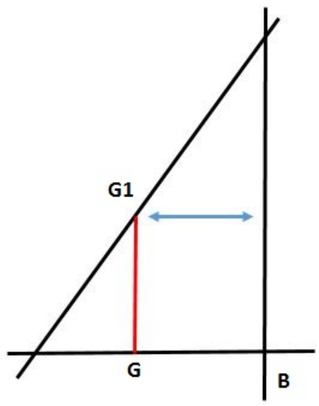

Figure 3.10: transversely moved load impact on GZ curve

When the vessel heels the newly located centre of gravity does not move but the centre of buoyancy does. Since the length of the heeling arms varies with the angle of heel, the functions are plotted for the instantaneous length according to the angle. This plot is super positioned over the righting curve for the vessel.
A few comments to the righting curves:

1. Since Cos(0) = 1 the loss of righting arm at zero degrees of heel is equal to the correction in centre of gravity GG_1
2. At 60° of heel the cosine correction equals to half the initial correction.
3. Cos(90)= 0, this means that at 90 degrees of heel the righting moment for transversely moved loads is zero.

Sine Correction

The same process can be done for the sine correction curve:

1. sin(0)= 0. This means that the correction in vertical position is zero.
2. sin(30) = 0.5 meaning that the heeling arm is half the length of the relocation of COG.

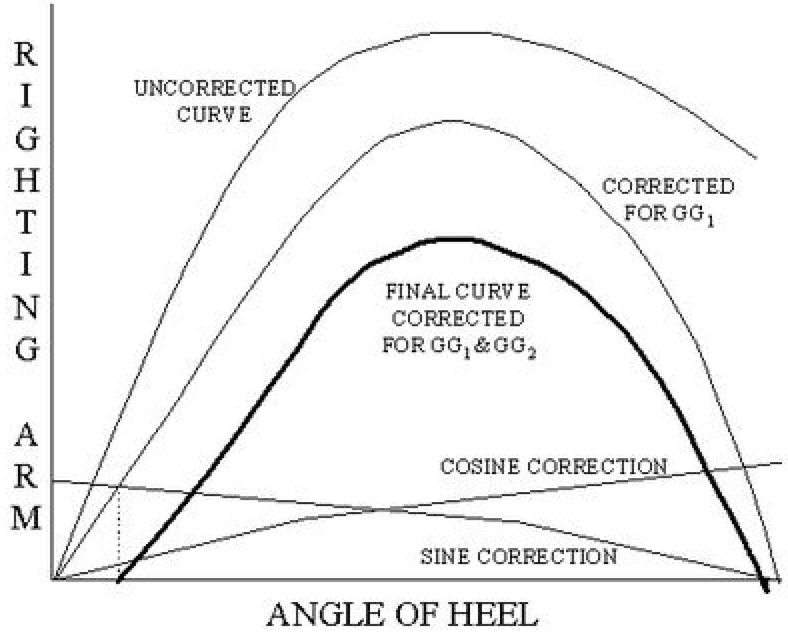

Figure 3.11: Sine and Cosine reduction impact on stability

3. Sin(90)= 1 leading to a maximum reduction at 90 degrees of heel.

A point to take from the preceding points is that transversely movement of the centre of gravity of the vessel will have much more impact on stability at small angles of heel while vertical displacement will have a higher impact as the heel increases.

Applying sine and cosine corrections to the righting stability curve

Since the stability curve is the preferred method of presenting the overall condition of the vessel it is important to include the reduction from relocation of COG in to the same curve. In most cases the adding, removing or relocation of weight in a vessel will have a vertical and horizontal impact on G, both need to be plotted into the curve.

The sine and cosine reductions are independent of each other and can be added to the same graph. When both components are calculated they are plotted into the stability curve together with the original stability curve. These are then subtracted from the uncorrected curve and the result will be as seen in figure 3.11.

3.5 Damage stability

Damage stability calculations are done to ensure that the vessel can meet stability regulations during an operation, in situations where the structural integrity of vessel is reduced from damage. Damages to the vessel can come from a numerous reasons. This can be damage resulting in a hull breach from grounding, ship collision, iceberg collision and slamming from waves, but also lost integrity from water entering compartment openings that are not closed or with faulty gaskets. A damage condition can change the trim, draught and heel of the vessel, consequently reducing the stability to of the vessel that in worst case could lead to losing the vessel and cargo. To be able to withstand a reasonable amount of damage the vessel has to be able to stay floating with reduced stability because of flooded compartments.

3.5.1 Different approaches to damage stability calculations

The are two methods for calculation the effect of flooding (Tupper, 2013)

1. **Method of lost buoyancy**
   This method assume that the flooded compartment does not add buoyancy, which is the real effect of compartment flooding. From Archimedes' principle it is shown that the vessels buoyancy is equal to the volume of the displaced fluid. Since water is allowed to enter the volume the compartment comprises it will no longer contribute to the vessels buoyancy.

2. **Method of added weight**
   In the method of added weight the water entering a compartment is considered as belonging to the ship. This means that its mass must be added to the weight of the ship during stability calculations

The two different approaches gives the same value to the measurement of the stability of the vessels righting moment, but not to the initial stability calculations. The added weight method increases the weight of the vessel leading to an increase in displacement but decrease in KG and takes into account free surface effects, while the lost buoyancy method will have only have reduced buoyancy. The reason for this is that the increase in displacement from added weight

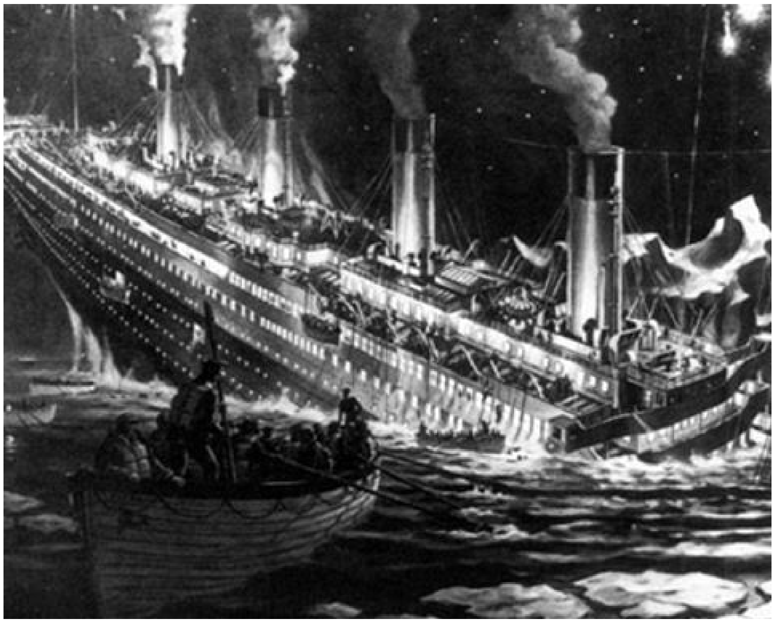

Figure 3.12: Titanic sinking in April 2012 off Newfoundland.

gives a larger force but a shorter righting arm but on the other hand the reduced buoyancy gives less force but a longer righting arm. Computer analysis tools use the lost buoyancy method for final stage design for damage stability analysis. The reason for this is that it is often most interesting to investigate the most severe condition where the whole volume of displacement is lost. In reality the flooding of a tank with a fairly small opening will be time dependant as the filling of the tank will not be instant. As a guiding rule the most conservative approach should be chosen which make lost buoyancy calculations more reasonable.

3.5.2 Damage stability requirements

A good example of faulty design leading to sinking was the famous Titanic disaster in April 1912 illustrated in Figure 3.12. The ship sunk in 3 hours after hitting an iceberg off the coast of Newfoundland. The ship engineers claimed that the ship was "unsinkable" as they had fitted it with both transverse and longitudinal bulkheads separating the hull into 16 compartments. The iceberg collision resulted in a rupture of the hull over six compartments. The problem was only that the compartments were only separated to about four feet above the waterline. When the draft increased the water entered the compartments and the water was allowed to spill into adjacent compartments leading to liquid flowing to one side of the hull causing the rapid sinking.

This led to the adoption of a regulation concerning subdivision of the hull by watertight compartments in a convention led by the International Convention of the Safety of life at Sea(SOLAS) in 1914. Since then changes to the regulations has been in correlation of the technological developments in ship design, and it covers: sizes of hatches, man-holes, allowance for cross flooding, pipe sizing's etc. For the sake of this thesis the focus will be on regulations concerning single and adjacent compartments.
According to DNV the following stability requirements: (DNV, 2011)

1. **B301**: The barge should have an acceptable stability and reserve buoyancy, and remain floating in an acceptable manner with any one submerged or partly submerged compartment flooded.
2. **B302**: An acceptable floating condition is defined as:
    (a) The design resistance of any part of the barge, cargo seafastening or grillage should not be exceeded.
    (b) The barge should have sufficient freeboard considering environmental effects to any open compartment, where flooding may occur.
    (c) The area under the righting moment curve should be greater than the minimum area under the wind heeling moment curve (illustrated in Figure 3.13) up to:
        i. The second intercept, or
        ii. The down flooding angle, whichever is less.
3. **B303**: The consequence of a damage stability situation should be thoroughly evaluated, in particular with respect to:
    (a) Progressive flooding
    (b) Local strength of watertight boundaries
    (c) Loads on seafastening
4. Calculations of damage stability should be done assuming a wind velocity of 26 m/s in the most critical direction.

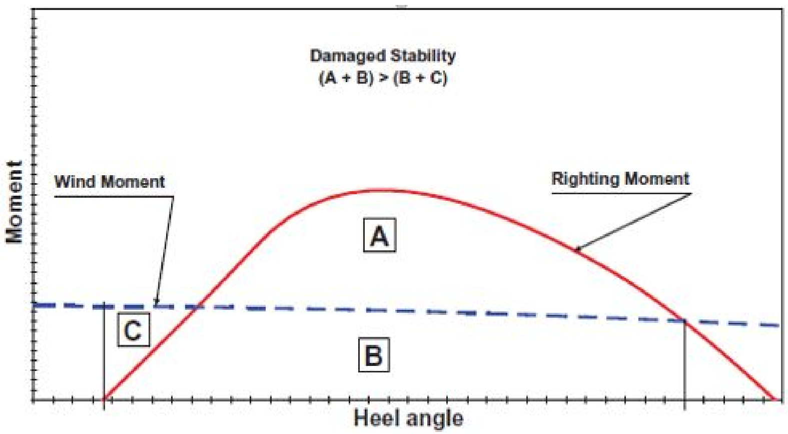

Figure 3.13: Wind heeling moment criteria

3.5.3 Flooded Compartments Impact on Stability

The result of a damaged hull and flooding of compartments can cause the vessel to sink. There are three possible scenarios:

1. Loss of buoyancy, causing the vessel to founder, T>d

If the loss of buoyancy is of an extent large enough to increase the displacement needed beyond the theoretical maximum limit of the vessel will sink.

2. Negative metacentric height GM_0, causing the vessel to capsize

A study of the initial stability calculation can reveal the effect of flooding of compartments using the method of lost buoyancy and assuming negligible angle of heel, equation 3.29 applies:

$$\overline{GM_0} = \overline{KB} + \overline{BM} - \overline{KG} \tag{3.29}$$

Flooding of a compartment would cause the metacentric height to decrease since:

- The vessel would have the same displacement as before the damage, meaning that the draft has to increase as a result of the lost surface area. This leads to an increase in KB
- The metacentric radius will be reduced from both the increase in displacement and the reduction on the moment of inertia, which is dependent on waterline surface area.

3.5.4 Flooded compartments impact on stability

If the flooded compartments is placed on starboard/port or aft/bow part of the vessel, it could heel beyond the limit of initial stability range. In this situation the vessel would have a list and it would have reduced freeboard and consequently reduced reserve stability. In this case the vessel would have a reduced heeling angle towards the same side as the list but on the other hand the angle of stability for heeling towards the opposite side as the list.

This is utilized in lifting operations. The crane vessel can fill the compartments on the opposite side as the operation to increase the directional stability.

To reduce the change of obtaining a list during an operation it is common to fill the crucial tanks with ballast water. This way there is no loss of buoyancy if the compartment is breached.

3.6 Minimum Freeboard Calculation

During classification of vessels the calculations for minimum freeboard has to be stated in the stability booklet. Depending on the dimensions of the vessel the freeboard will be corrected differently. DNVs Rules for ships provides the instructions for how the classification of a vessels minimum freeboard should be conducted. The process involves establishing a Tabular freeboard according to tables and then making corrections to the tabular freeboard by calculating adjustment parameters. The final value is found by adding the values together.

$$F_{min} = (f_0 + f_1 + f_2 + f_3 + f_4 + ...f_n)\ (0.75) \tag{3.30}$$

The following parameters are used in the establishment of minimum freeboard for a standard North Sea barge according to DNV rules for ships pt.3 Ch.5 Sec 3 part C:

- f_0 = Tabular Freeboard
- f_1 = Regulation 29, Correction to the freeboard for ships under 100m length
- f_2 = Regulation 30, Correction for block coefficient

- f_3 = Regulation 31, Correction for depth
- f_4 = Regulation 34, Correction for superstructure
- f_5 = Regulation 38, Sheer correction

DNV classification of ships gives the following guidelines for calculating the coefficients used in the calculation:

- The tabular length is found from the tables in the classification note from effective length calculated
- The length shall be taken as 96% of the length on a waterline at 85% of the least moulded draught
- Correction of freeboard for ships under 100m of length: E = Effective length of Superstructure

$$F_{lc} = 7.6(100 - L_f)(0.35 - \frac{E}{L_f} \tag{3.31}$$

- Block Coefficient:

$$C_B = \frac{\Delta}{L_f B d_1} \tag{3.32}$$

- Depth for freeboard D is the moulded depth amidships plus the thickness of the freeboard stringer plate if fitted
- Superstructures placed on deck can be included in stability calculations if they extend across the whole width of the vessel. On a barge where there is a small forecastle, which do not extend over the whole ship breadth.
- Sheer correction takes into account the superstructure protruding up from the deck adding to the buoyancy.

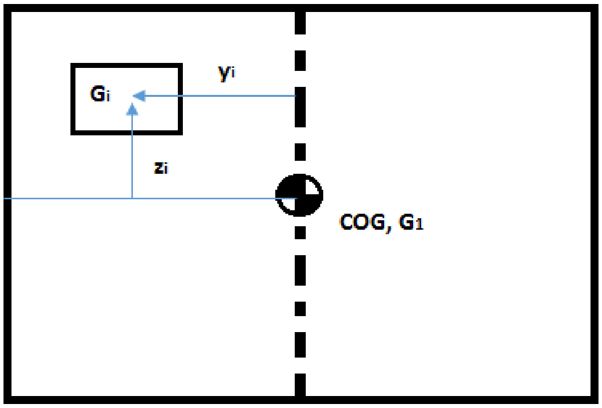

Figure 3.14: COG calculations

3.7 Centre of gravity calculations

When trying to determine the stability of a vessel and its cargo, a central part of it revolves around getting the centre of gravity correct. The effect of faulty established COG for a loading condition could result in reduced stability and miscalculation of the seakeeping capabilities of the vessel.

A vessel has its own centre of gravity in lightship condition, G_0 During loading and unloading of cargo, fuel, ballast, crew etc. the centre of gravity for the vessel in displaced condition has changed. Each mass has a centre of gravity G_i, and is placed at a distance d_i from the ships centre of gravity. The summation is done by adding the weight and its corresponding distance from G_0 and a new centre of gravity is found. See figure 3.14
The height of the COG is found from equation 3.33:

$$KG' = \frac{\sum z_i G_i}{G} \tag{3.33}$$

Distance from centerline is found from equation 3.34:

$$CG' = \frac{\sum y_i G_i}{G} \tag{3.34}$$

This change of COG has to be known to be able to ensure that the stability requirements are met. This process is done by lever arm principle, and equation 3.35 apply: (Barrass and Derrett, 2011)

$$G_1G' = \frac{G_i\, d_i}{Final\, displacement} \tag{3.35}$$

1. Adding a mass with centre of gravity Gi to a vessel at a distance d_i from the centre of gravity G will cause the centre of gravity to move directly towards the added weight.

2. Removing a mass G_i from the vessel that is placed at a distance d_i from the centre of gravity will cause the centre of gravity to move directly away from the initial centre of gravity G_1, towards the position of the removed weight.

Since the weight is already accounted for in the displacement the change is dependent on the relationship between the weight of the cargo moved and the total weight of the vessel. For removal and adding of mass the direction of G_1G' was directly away from the added/removed weight. For the situation of shifting weights the direction will be parallel to the vector for the moved mass.

Suspended weights are also common in naval transportation. The lifting capacity of a crane vessel is strongly related to the vessels stability. The process of including the effect of hanging loads on a vessels initial stability is analogous with weight calculation. The only difference being the attack point of the gravity force. For a hanging load the attack point would be the point of suspension. This means that the suspension length will have no influence on the resulting moment arm.

$$G_1G' = \frac{G_i\, d_i}{G_i} \tag{3.36}$$

3.8 Stability Standards and Recommendations

The International maritime organization (IMO) is the United Nations specialized agency with responsibility for the safety of shipping and the prevention of marine pollution by ships. Its role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and implemented(Organization, 2008)

By setting a common standard for the complete shipping industry, implementing safe and effective regulations common to all participating countries, the ship owners has to comply to the same set of rules and competing on equal terms.

IMO has been developing intact stability criteria for various types of ships for a few centuries. The first complete code for all types of ships covered by the IMO instruments was compiled in 1993 and included fundamental principles and precautions against capsizing. This involved; weather criteria, metacentric height and lever arm criteria as well as weather criteria and the effect of free surface and icing. It also addresses related operational aspects like information for the master including; stability and operation manuals, stability curves and procedures in heavy weather.

To keep up with the technological development in the industry the revised IMO 2008 Intact Stability Code was released in 2008. This document includes both mandatory requirements and recommended provisions on stability that will function as a standard for the underlying participants for the future.

3.8.1 IMO 2008 Intact Stability Code

The IMO code on stability is intended to provide stability requirements for all types of ships used for commercial purposes above 24 m of length. This includes; Cargo ships, passenger ships, Fishing vessels, offshore supply vessels, MODUs, Barges and Container ships.

Providing general requirements for all of the types of vessels listed above is difficult. To cope with this the code provides a set of general requirements for all and specifying special requirements for the different classes. A general code for all types of ship would mean that the same criteria were set for all the different types of cargo and shape of vessels. If this was the case the ship owners would have a mere impossible task on hand as some of the requirements are much harder to comply to.

The first part of the IMO code describes the general regards that has to be taken to make sure that the vessel complies with the regulations. This includes a set of general safety precautions, righting lever curve properties and severe wind and rolling criteria.

As a general precaution all vessels sand ship owners should:

- Account for free surface effects in all conditions of loading
- If anti rolling devices is installed the intact stability requirement should be met even if the device fails
- Water on deck, icing etc. influencing the stability should be accounted for as far as possible
- The stability requirements should be met for all stages of the voyage, taking into account addition and loss of weights
- Stability booklets or stability instruments should be provided to the master of the ship
- If curves or tables of minimum operational $\overline{GM}$ or VCOG are used to ensure compliance with the code the curves/tables should extend over the full range of operational trims.

Criteria regarding righting lever curve properties

To make sure that the vessel is stable the IMO code supplies general requirement for the properties of the vessels GZ curves.

The general requirements for all types of vessels are:

- The area under the GZ curve should not be less than 0.055 m radians up to a heel angle of 30° and not less than 0.09 m radians up to 40° angle of heel or up to the angle of down flooding
- The area under the GZ curve between 30° to 40° of heel, or to the angle of down flooding, should not be less than 0.03 m radians.
- The righting lever GZ should be at least 0.2m an angle of heel equal to or greater than 30°
- The righting lever GZ shall occur at an angle of heel not less than 25° if applicable. If necessary adjustments may be done to this criteria under approval from administration.

These requirements are not intended for use with special types of vessels like barges, jack-ups, and MODUs to name a few. Here IMO has supplied separate requirements. They are included to show the difference.

Barge stability requirements:

- The area under the righting lever curve up the angle of maximum righting lever should not be less than 0.08 mrad
- The static angle of heel due to uniformly distributed wind load of 540Pa should not give an angle of heel corresponding to half the freeboard height. The wind lever arm is measured from half the draught to the centroid of the cargo area.
- The minimum range of stability should be:
    - $L \geq 100m$ 20°
    - $L \geq 150m$ 15°
    - For intermediate lengths by interpolation

These calculations should be performed on the following basis:

- Buoyancy of cargo should not be accounted for in the stability calculations
- Water absorption in cargo items should be give consideration together with ice accretion and water trapped in the cargo
- Wind pressure should be calculated by assuming a constant value over the whole stability range.
- centre of gravity calculations should be performed by assuming that the centre of gravity of the cargo lies in the centre
- Watertight manholes should not be considered as openings in which flooding can occur.

3.8.2 GL Noble Denton Stability Recommendations for barges

DNV GL Noble Denton is one of the underlying departments of DNV GL, which is one of the worlds leading advisory company within the Oil and Gas industry. Their publications are general recommendations besides the regulatory framework provided by the government and standardization like NORSOK and ISO. They provide classification and certification for many areas of the Oil and Gas industry.

For marine operations they provide sets of guidance covering the main related aspects. In their publication "Guideline for marine transportations" there is stated additional recommendations for the stability of vessels, giving further advice outside the standard provided by IMO. As a general requirements the standards should be addressed first, before the recommendations from GL are taken into account.
(Only the relevant points are included, for the full range of recommendations visit DNV GL)

Relevant Intact Stability recommendations outside those given by IMO2008IS

- Stability Range for Vessels or Towed objects with $LOA \geq 76m\ B \geq 23m$ should be minimum of 36°
- The initial metacentric height $\overline{GM}_0$ should include an adequate margin for computational errors. The minimum value of $\overline{GM}_0$ should not be less than 0.15 m under any circumstances but a value of 1 m is recommended.
- For intact conditions the area under the righting moment curve should not be less than 40% in excess of the area under the heeling arm curve, bound by 0 degrees and the angle of which this condition is met.
- Wind speed used in the calculations should be taken as the 1-minute design wind speed. In absence of other data 52 m/s should be used
- Under the damage stability condition the winds speed should be 26 m/s or 1-minute average speed. The wind should be applied in the most critical direction
- Positive stability about any horizontal axis with damage caused by penetration of 1.5m from external plating is required.
- The draught should be small enough to give adequate freeboard and stability and large enough to reduce motions and slamming. Normally between 35-60% is recommended. For vessels of 90 m the minimum draught should be 2.4 m

Chapter 4

Model and Method

In this chapter the modelling and analysis process is described. The developed models is explained together with the important equations used.

4.1 Method of analysis

The analysis is done with the help of software included in DNV's marine operation analysis package Sesam Marine. The first step in the process is to model the barges with the aid of the structural analysis and modelling tool GeniE, using parametric modelling. Then the models created are transferred into the hydrostatic and dynamic analysis environment HydroD. The data created in the simulation is exported to Microsoft Excel for further processing, comparison and visualization. The exported stability data is combined with the equations developed in the theoretical review into spreadsheets to establish stability profiles for the different setups. The equations used for the calculations of the force and effects developed are all provided in short in this section. For a more thorough explanation and derivation reader is advised to visit the respective chapters, references or bibliography. A description the analysis process is found in figure 4.1

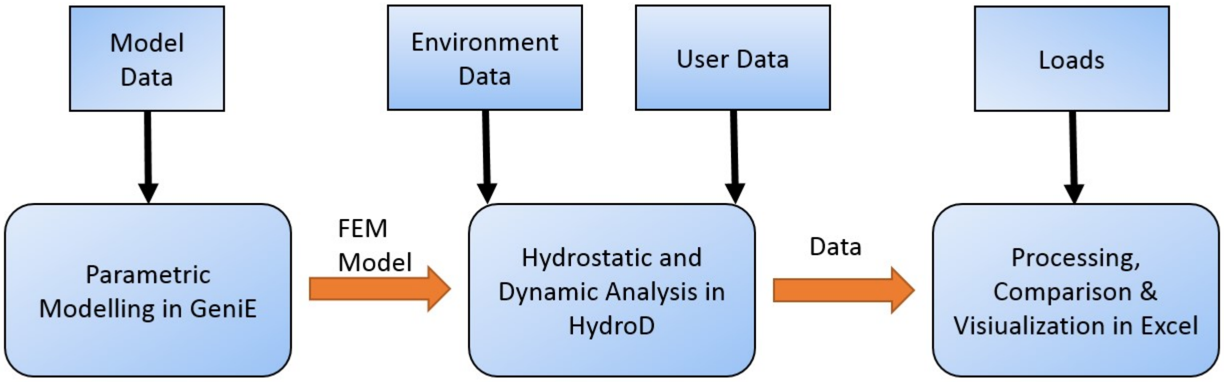

Figure 4.1: Description of steps in the analysis

4.2 Modelling in GeniE

The modelling is done in DNV GeniE. The process involves defining guide planes with model data and extruding the panels representing the outer shell and compartments of the barge. The model data for the parametric study is generic data, while for the rest of the study the data is found from the structural drawings provided by Ugland Construction AS. To have realistic dimensions and weights the model is as far as possible a replica of the standard North Sea Barge UG-97 (dimension in Table 4.1 but some differences may occur. The three mains steps in the modelling are:

1. Parametric modelling of the panel model and compartments according to dimensions and exporting a Panel model that contains a mesh which is used to transfer the hydrostatic and dynamic forces to the model from the analysis.
2. Creating Structural model to represent the loads from compartment contents.
3. Creating Mass models to simulate the equipment and masses that represents the cargo.

Table 4.1: Principal dimensions of UG-97

Length [m]	91.44	Lightship Displacement [Tonnes]	2400
Breadth [m]	27.432	Lightship mean draft [m]	1.1
Depth [m]	6.096	VCOG from bottom line [m]	3.452
Deck Area[m^2]	2500	LCOG from amidships [m]	2.730
# of compartments	20	Deadweight[Tonnes]	9000

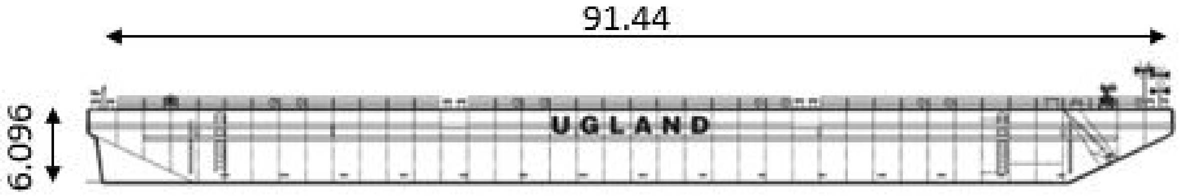

Figure 4.2: Side view of model barge

4.2.1 FEM Model

The analysis requires the user to produce 3 models to use in the hydrostatic and dynamic analysis. These models contain the entire model data needed.

1. **Panel model**

   The panel model contains the mesh used to transfer the hydrostatic and dynamic forces developed. Meshing is one of the most important part of FEM analysis as it provides the nodes and lines that the software uses to produce the results, transferring the forces from the surroundings to the model and the other way around. The accuracy of the mesh is what decides how well you are able to reflect the actual forces present. The mesh created for the models used would not include the rounded keel that was specified in the modelling, this might have affected the results created in the analysis as they change the static and motion characteristics of the vessel. The model is illustrated in Figure 4.3

2. **Structural model**

   The structural model provides the possibility to transfer loads internally in the model. In more a detailed analysis the structural model would contain all of the structural elements that the barge consists of, making it possible to study the forces developed in single members, pins and other elements. For the purpose of this analysis the structural model provides the possibility to transfer the forces from compartment liquids into the stability analysis. See Figure 4.4

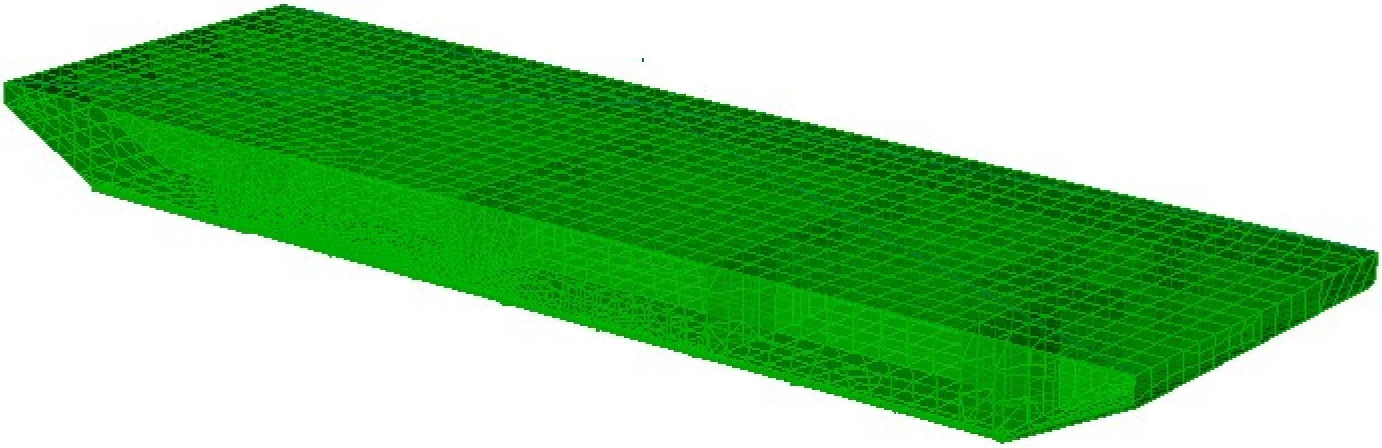

Figure 4.3: Panel model with mesh

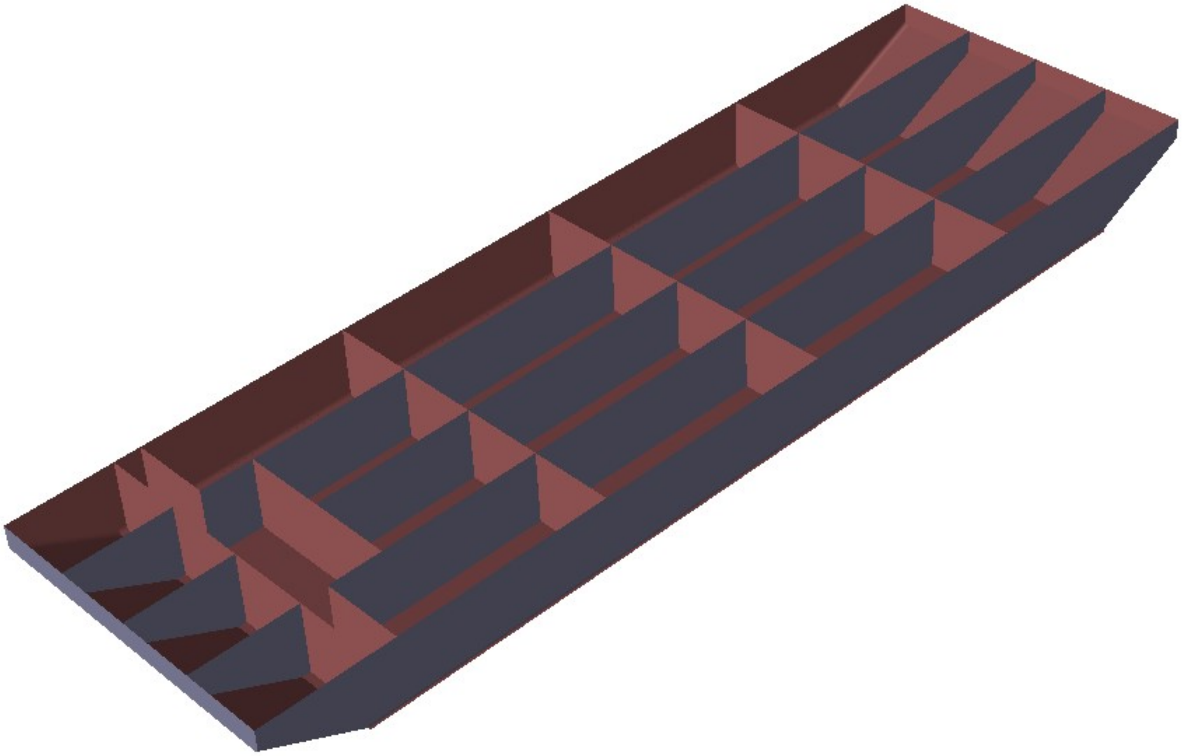

Figure 4.4: Structural model

3. **Mass model**

   The last model is the mass model. It represents the masses and loads that may be present from a structural point of view. This can be pressure on structure elements, point or distributed masses etc. The mass models gives the possibility to develop multiple loading conditions for the analysis without changing the panel and structure model, making it possible to include, remove and move masses and loads around in the model, which will be done in an operation. The mass models used in the analysis are mainly as point masses that are connected to the structure with beams that does not hold any properties other than transferring the masses to the model. See Figure 4.5

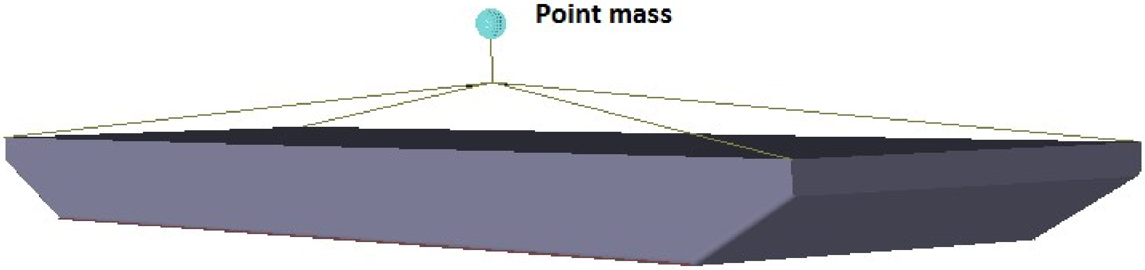

Figure 4.5: Mass model

Simplifications

The model used in the analysis is simplified to reduce the time consumption on the modelling. All of the structural aspects of the barge has been neglected; Plate thickness, girders, bulkheads, trusses, piping and so on are not included in the model. The reasoning behind this is that they do not have a large impact on the stability computations since the total COG of the vessel is known. The most important aspect that is overlooked by making this simplification is the Moment of Inertia of the vessel.

4.3 Hydrostatic and Hydrodynamic Analysis in HydroD

The analysis done in HydroD is split into separate sections called Stability, Wasim and Wadam, covering the different aspects of hydro analysis. Wasim calculates the hydrostatic forces developed in both dynamic and static conditions from waves and water streams on local and global points. Wadam is used to calculate hydrodynamic interactions between waves and the structure, while the stability section computes the stability properties from structure data and environmental loads.

4.3.1 Stability analysis

The stability analysis consists of creating loading conditions to be used in the analysis. This involves specifying the contents, filling fractions and permeability of compartments that are imported from the panel, structure and mass models. It also includes defining heeling moments from environmental loads and internal liquids. HydroD stability analysis also provides the possibility of doing Code checking to study the compliance with relevant standards for the structure. The data extracted from the stability analysis consists of GZ curves, heeling and righting moments, metacentric heights and other stability data like centre of buoyancy, radius of gyration and masses.

4.3.2 Wadam Analysis

To investigate how the response of the barge changes in different loading conditions a Wadam analysis has to be performed. Wadam runs a series of user defined waves and extracts the response of the barge. By doing this it is possible to find the natural periods of the barge by finding the resonance frequencies where the motions are large. The process is divided into four main steps:

1. Define the analysis environemnt
2. Defining Wave periods/frequencies
3. Import panel and mass model from GeniE

4. Specify wave directions

From the analysis it is possible to read a range of different data. The data extracted here were natural periods in Heave, Pitch and Roll.

4.4 Post Processing, Comparison and Visualization in MS Excel

The last part of the analysis was to extract the relevant data into spreadsheets to create visualizations and study the results. The equations derived in the literature review and background reading were used to make calculations on how the internal and external forces from wind, waves, liquids and cargo affected the stability. The data was then used to make alterations to the mass and panel models to further study the effect of changing loading conditions and dimensions of the structure.

4.5 Analysis Approach

The approach of the analysis is to develop stability data for a standard North Sea barge by visiting the most important concept in vessel stability. This is done by studying the effect of changes in parameters, develop extremes in the loading conditions according to relevant standards, and study the effect of external and internal loads. The results are combined to compare operational loading conditions to find what the most favourable loading condition is. Numerous models were created to develop an understanding on how changes in parameters affect the stability characteristics of the structure and find the extremes of the barge. The analysis is split into four parts:

1. Initial stability characteristics
2. Parametric study
3. Comparison of loading conditions
4. Operational condition comparison

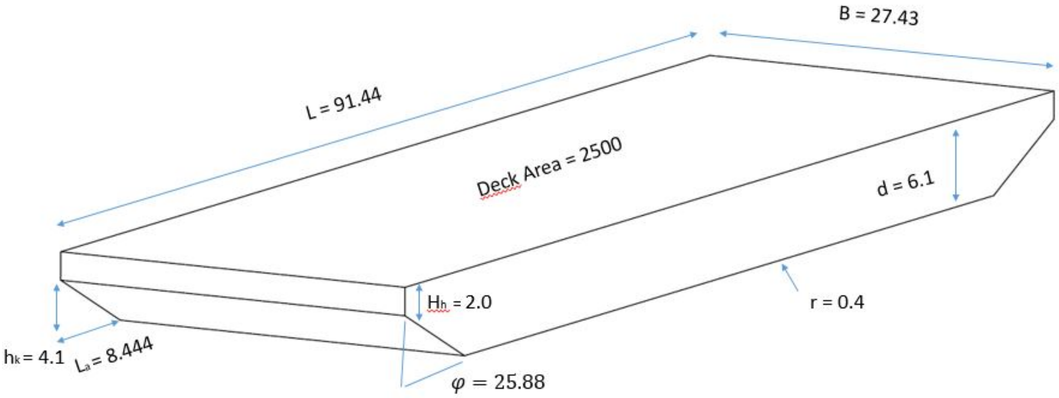

Figure 4.6: Principal dimensions of the barge

4.5.1 Initial Stability Characteristics

The first step of the analysis is to find the minimum freeboard according to the rules of classification (DNV, 2001) . This is done to determine the maximum allowable displacement. Next, the initial stability specifications of UG97 is found. This is done by calculating the initial metacentre GM_0 for a range of drafts. The calculated values is used to determine the allowable VCOG for different drafts and loading conditions in the intact stability analysis.

Table 4.2: Important parameters

Length ,L [m]	91.44	Length of fore keel, L_K [m]	8.44
Breadth ,B [m]	27.43	Length of aft keel, L_K [m]	8.44
Depth ,d [m]	6.1	Height of keels, h_k [m]	4.1
Height of headlog, h_h [m]	2.00	Angle of keels, α [Deg]	25.88
Radius of bilge ,r [m]	0,40		
Deck Area[m^2]	2500	Moulded Draught, T_{MLD} [m]	4.84
VCOG from bottom line [m]	3.45	Lightship Displacement [Tonnes]	2400
LCOG from amidships [m]	2.73	Lightship mean draught [m]	1.10

The data used is found in table 4.2 and illustrated in figure 4.6

Relevant Equations: Initial Stability

The equations used in the calculations of the initial stability parameters are shown here. The equations are based on geometrical aspects and principles found in relevant literature.

Draught:

$$T(\Delta) = \frac{\Delta}{\rho_{SW}(L-L_k)B - 2L\left(r^2 - \frac{\pi r^2}{4}\right) - \left(\frac{h_k}{\sin\alpha}\right)}\ , for \quad 0 \le T \le 4.1 \tag{4.1}$$

and:

$$T(\Delta) = (d - h_h) + \left(r^2 - \frac{\pi r^2}{4}\right),\ for \quad 4.10 < T \le 6.1 \tag{4.2}$$

Freeboard

$$f = d - T \tag{4.3}$$

Length of waterline:

$$L_{WL} = L - 2L_k + 2\left(\frac{L_k * T}{d-2}\right),\ for \quad 0 \le T \le 4.1 \tag{4.4}$$

and

$$L_{WL} = L,\ for \quad 4.10 < T \le d \tag{4.5}$$

Centre of Buoyancy:

$$COB = T - \frac{1}{3}\left(\frac{T}{2} + \frac{\Delta}{L_{WL}B\rho_{SW}}\right) \tag{4.6}$$

Metacentric Radius:

$$BM_t = \frac{L_{WL}B^3\rho_{SW}}{12\nabla} \tag{4.7}$$

Deck Immersion Angle:

$$\varphi_{Di} = \arctan\left(\frac{d-T}{B/2}\right) \tag{4.8}$$

Metacentric height:

$$GM_{0_t} = KG - BM_t \tag{4.9}$$

Relevant Equations: Minimum Freeboard

85% Draught, $T_{0.85d}$**:**

$$T_{0.85d} = 0.85d \tag{4.10}$$

Effective length:

$$L_{0.96} = L(0.85D)\,0.96 \tag{4.11}$$

Depth Correction:

$$f_D = \left(\frac{L}{0.48}\right)\left(\frac{D-L}{15}\right) \tag{4.12}$$

Block Coefficient Correction:

$$C_B = T_{0.85}LB - \left(\frac{L_k B T_{MLD}}{L_{0.96} B T_{0.85}}\right) \tag{4.13}$$

Tabular Freeboard

For B type ships:

$$\begin{bmatrix} L1 = 87.00\ m & f0_1 = 1.015\ m \\ L2 = 88.00\ m & f0_2 = 1.034\ m \end{bmatrix}$$

$$\Rightarrow \qquad f_{tab} = f0_1 + (f0_2 - f0_1)\frac{(L_{0.96} - L1)}{L2 - L1} \tag{4.14}$$

Lenght correction L<100 m

$$f_L = 7.5(100 - L_{0.96}) \tag{4.15}$$

Block Coefficient Correction

$$f_{C_B} = \left(f_L + f_{tab}\right)\left(\frac{C_B + 0.68}{1.36 - 1}\right) \tag{4.16}$$

Sheer Correction

$$S_A = \frac{\left(\frac{L_{0.96}}{3} + 10\right)(25 + (3 * 11.1) + (2.8 * 3))}{8} \tag{4.17}$$

$$S_S = \frac{\left(\frac{L_{0.96}}{3} + 10\right)(0 + (3 * 5.6) + (22.2 * 3) + 50)}{8} \tag{4.18}$$

$$S = \frac{S_F + S_A}{2} \tag{4.19}$$

$$\Rightarrow f_S = S\left(0.75 - \frac{s}{2L}\right) \tag{4.20}$$

Minimum freeboard

$$f_{min} = 0.75\left(f_D + f_{tab} + f_L + f_{C_B} + f_S\right) \tag{4.21}$$

4.5.2 2. Parameter Study

The second part of the analysis is done by comparing the stability of a generic barge with different dimensions to study the effect of increasing or decreasing the freeboard, VCOG and breadth. The analysis is done with equal displacement for all of the three cases and the parameters are changed in 20% increments making it possible to compare the different situations. This will give a good understanding on how the stability characteristics will change for different size vessels and loading conditions. The dimensions of the generic barge is shown in table 4.3.

The analysis is performed in the stability analysis section in HydroD by using different panel models for freeboard and breadth alterations to calculate the correct hydrostatic values. The panel model created for the regular vessel is used for the increased VCOG case, but the mass model is changed to include the the new COG.

Relevant Equations

Initial Metacentric Height

$$GM_0 = KB + BM - KG \tag{4.22}$$

Righting arm length

$$\overline{GZ} = \overline{GM}_{\varphi}\ \sin(\varphi) \tag{4.23}$$

Area under Righting Curve

$$Area = \sum_{0}^{\varphi_i} \frac{\pi}{180^\circ} GZ_i \tag{4.24}$$

4.5.3 Comparison of Loading Conditions

The third part of the analysis involves code checking and the establishment of allowable loading conditions for the barge according to standards. To be able to compare the stability in different

Table 4.3: Principal dimensions of model barges

	Length[m]	Width[m]	Height[m]	KG[m]
Regular vessel	91.44	27.34	6.10	5
Increased COG	91.44	27.34	6.10	5
Increased freeboard	91.44	27.34	7.32	5
Increased breadth	91.44	32.808	6.10	6
Displacement mass	Δ		5000 Tonnes	

loading conditions the barge is loaded to three various d rafts that represents the minimum, intermediate and maximum loading condition. The conditions are defined within the limits of the stability criteria as defined in IMO2008 and GL Noble Denton. The requirements defined in IMO2008 are combined with those found in GL Noble Denton, as a more conservative approach.

The limiting criteria was found to be the stability range in all the stability conditions stated in the comparison. All of the other conditions were met under more severe conditions than those described. The underlying reason for this is traced back to the comparatively large beam in relationship to the draft. This creates large righting arms very fast giving them a large GZ_{max} and area under the righting curve, which implies that the energy it can absorb is large over a large range of loading conditions.

The approach for the analysis was to find the maximum VCOG for a given draft, which corresponded to minimum, intermediate and maximum displacement, but with remaining compliance to the requirements of IMO2008 and GL NobleDenton. The relevant points are summarized in Table 4.4 They have equal point of vanishing stability, meaning that they can be inclined to the same angle, but the stability characteristics are very different. This will describe how the barge will perform when loaded to different configurations when exposed to environmental forces under operational condition:

Minimum Loading The GZ curve can be seen in figure B.3 and the stability data is listed in Table B.1 in the appendix

Intermediate Loading The barge is displaced to the intermediate draft. The GZ curve can be seen in Figure B.5 and the stability data is listed in Table B.2 in the appendix

Maximum Loading The barge is displaced to the maximum allowed draft and range of stability. The GZ curve can be seen in figure B.7 and the stability data is listed in Table B.7 in the appendix

Table 4.4: Stability requirements for the barge according to IMO2008 and the recommendations from GL Noble Denton that are used as limiting criteria for the comparison and their origin

Stability Criteria	**GL Noble Denton**	**IMO 2008 IS**
Stability Range[Deg]	36	-
GM_0 [m]	0.15 (1)	-
Area, 0° → $\varphi_{GZ_{Max}}$ [m Rad]	-	0.08
Minimum Draft	2.4m	-
Static Wind angle of heel	-	Equal to half the freeboard
Wind Overturning	Righting moment in 40% excess of heeling moment	-
Damage Stability	Positive Stability under damage condition	-
Angle of list	< 1.0°	Even keel as far as possible

4.5.4 Operational Condition Comparison

The operational condition comparison combines changes in displacement with loads from the environmental loads. This is done to investigate which is the most favourable loading state. This is done to find out when the barge is most stable. The heeling moments defined in the standards are included to find out if the loading conditions could create dangerous conditions. Common to both of these loading conditions is the same panel and structural model created are used but the changing the mass model to simulate the different cases.

To study the effect of the heeling moments the barge is loaded to two different operational conditions; light and heavy load. This way the operational conditions can be compared and it will be possible to obtain an understanding of the stability in the separate cases, providing insight into which is the preferred loading condition. Should the prime concern for marine operations

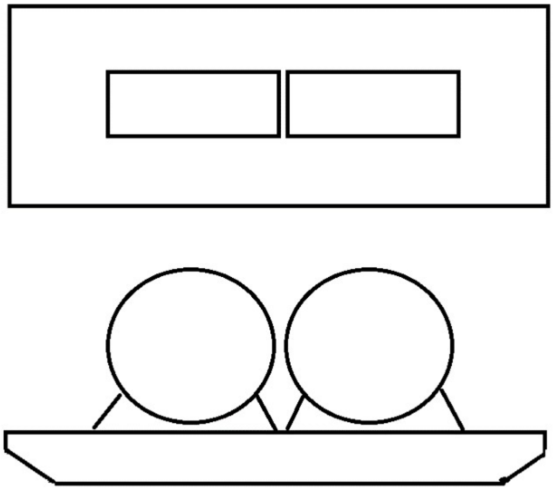

Figure 4.7: Deck Layout

with barges be to preserve buoyancy to obtain a light vessel, or should the displacement be increased by ballasting down the vessel to design draft? Applying the heeling moments developed will visualize how the barges will perform under the effect of environmental loads from wind waves, free liquids and displaced cargo.
The barge is loading with two pipeline reels with piping reeled on them, having a flange diameter of 22 m and a weight of 1600 metric tonnes. The reels are placed in cribbing with a height of 1.0 m. See Figure 4.7

The deck layout is done to minimize the risk of capsizing in the event of a damage condition where buoyancy is lost in either the port or stern compartments. By placing the cargo on the centreline the developed righting moment is less than if the cargo were placed off the centreline. The placement of the reels can be seen in figure The two reels are placed on the centreline and in-line in the longitudinal direction. The clearance between them is 5 meters, 2.5 meters in each direction from amidships

To take into account the possibility that loads may displace in the event of large motions this is taken into consideration during the analysis. The analysed condition is that one of the reels moves 0.5 m creating a heeling moment around the centreline

Light Displacement

The light displacement correspond to a light vessel with cargo placed on top of it. The loading within the regulations. This gives the following loading data:

Table 4.5: Loading Data for Light Displacement

Displacement, Δ	[Tonnes]	5600
Draft, T [m]	[m]	2.50
VCOG, [m]	[m]	11.82
COB, [m]	[m]	1.28

The wind data is summarized in table 4.9

Table 4.6: Wind area for light displacement

Barge	
Wind sail area Barge [m^2]	328
Height of centroid [m]	4.84
Cargo	
Wind sail area Cargo [m^2]	760
Height of centroid [m]	16.84
Resulting values	
Height of centroid [m]	13.22
Wind Sail area [m^2	1088

The righting lever from free surface effect is shown in table 4.7

Table 4.7: Free surface effect light displacement

Displacement	11261.5
# of compartments	Heeling Leever[m]
1	0.1
2	0.2

Heavy Displacement

Heavy displacement corresponds to the barge fitted with cargo but with ballast in the tanks to increase the draft down to maximum allowable draft. This is a common approach taken to change the natural periods of the barge to improve the sea keeping properties.

The loading data is found in table 4.8

Table 4.8: Loading data for Heavy displacement

Displacement, Δ	Tonnes	11252
Draft, T	[m]	4.76
VCOG	[m]	7.41
COB	[m]	2.47

The wind data is summarized in table 4.9

Table 4.9: Wind area for heavy displacement

Barge	
Wind sail area Barge [m^2]	328
Height of centroid [m]	0.666
Cargo	
Height of centroid [m]	15.71
Wind sail area Cargo [m^2]	760
Resulting values	
Height of centroid [m]	13.63
Wind Sail area [m^2]	882

The righting lever from free surface effect is shown in table 4.10

Table 4.10: Free surface effect heavy displacement

Displacement	11261.5
# of compartments flooded	Heeling Leever[m]
1	0.05
2	0.1

Relevant Equations

Wind Heeling Arm

$$l_w = \frac{P_w A}{\Delta g} \tag{4.25}$$

Free surface heeling lever

$$l_{FS} = \frac{\rho_l I_{comp}}{\Delta} \tag{4.26}$$

Displaced Load lever

$$l_{Dl} = \frac{m_l}{\Delta} \tag{4.27}$$

Chapter 5

Presentation of Results

In this chapter the results from the analysis and calculations are presented. The presentation is divided into four sections that addresses different aspects of vessel stability. In the first section the initial stability characteristics are developed with the help of manual calculations. The second and third section focus on how changes in vessel dimensions and loading conditions affects the stability of the barge. In the fourth and last section the barge is subjected to heeling moments according to those defined in the relevant standards. This is done to investigate how the stability characteristics of the barge change under different operational conditions.

In each of the sections the results are presented with a graph for visualization and a table showing the important parameters. The viewer is advised to look in the corresponding appendixes for more information on each of the plots as only the main results are presented.

5.1 Initial Stability Characteristics

The initial stability calculations focuses on defining the limits for draft, displacement and vertical centre of gravity for the barge used in the analysis. These values are limiting boundaries both from hydrostatic principles and the three fundamental stability requirements defined in section 3.2

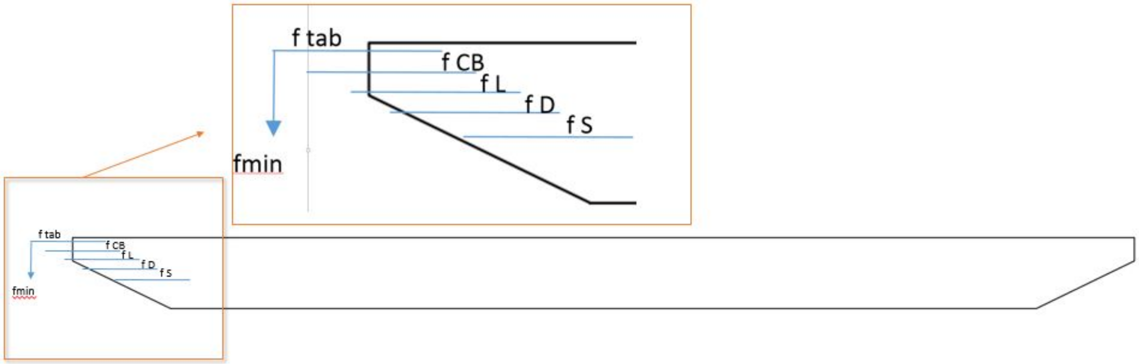

Figure 5.1: Freeboard Corrections

5.1.1 Minimum Freeboard calculations

Table 5.1 shows the calculated minimum freeboard according to the rules of classification. (DNV, 2001) An illustration is given in Figure 5.1 showing the resulting freeboard from the correction parameters. The relevant equations can be found in chapter 4.5.

Table 5.1: Minimum freeboard calculations according to DNV Rules for classification of ships

Correction #	Parameter	Value[mm]
f_{tab}	Tabular freeboard	1030
f_D	Correction for Loa < 100	32
f_L	corection for block coeff CB	222.5
f_{C_B}	correction for Depth, D	48.5
f_S	Correction for sheer	368.5
$f_{min} = 0.75(f_{tab} + f_D + f_L + f_{C_B} + f_S)$		1276.1

The limiting freeboard of f_{min}=1.2761 m the smallest allowable freeboard for any loading condition. This limiting freeboard is used in the calculations of maximum displacement, and hence the cargo holding capacity.

The reserve buoyancy is found from equation 5.1:

$$Reserve\ buoyancy = 27.342 * 91.44 * 1.2761 = 3200\ Tonnes \tag{5.1}$$

5.1.2 Maximum KG

Figure 5.2 shows the maximum vertical centre of gravity for the barge and cargo combined, for the whole range of displacements with a positive metacentric height as specified in the guidelines (Organization, 2008).

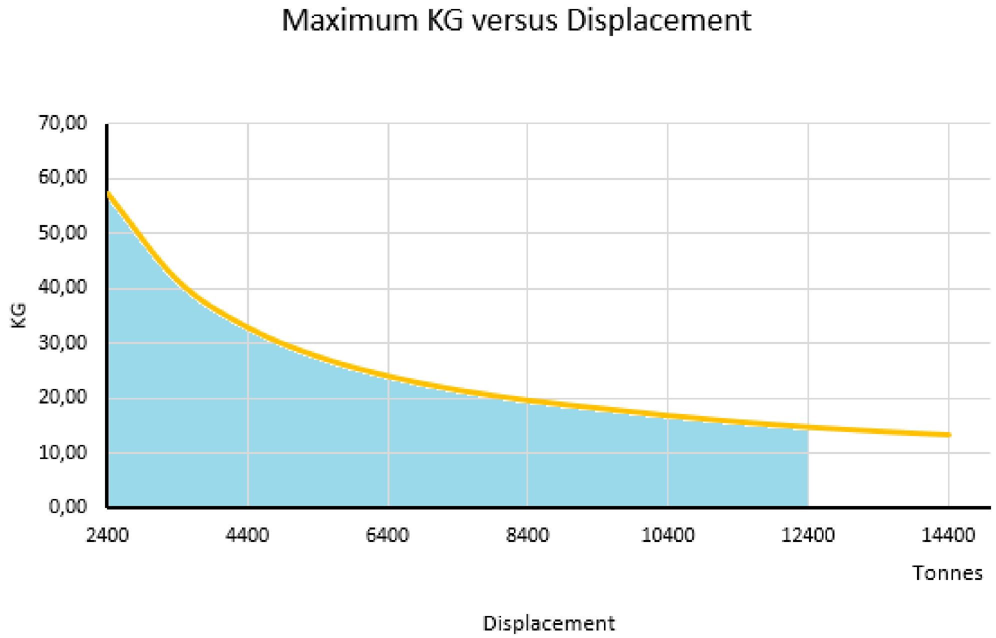

Figure 5.2: KG max versus displacement for UG97

Figure 5.2 shows that according to initial stability calculations the maximum obtainable VCOG under light displacement is much larger than at maximum displacement. The graph also shows that the reduction of metacentric height with increase in displacement, , $\frac{dKG}{d\Delta}$, reduces as the draft increases. The data is presented in table 5.2.

Table 5.2: Range of vertical centre of gravity for different drafts

	Displacment[Δ]	KG_{Max}[m]
Light	2400	58.4
	3400	42.5
	4400	33.9
	5400	28.6
	6400	25.1
	7400	22.5
	8400	20.7
	9400	19.2
	10400	17.9
Max	11262	16.9

5.1.3 Initial Stability Chart

In Figure 5.3 the metacentric height for a range of different VCOG are plotted against the displacement. The red line show how the draft increases with the displacement and crosses the dotted black line at the point of maximum displacement as specified in subsection 5.1.1.

Table 5.3: Range of metacentric height for different displacements and KG

		GM values		
Displacement	draft	KG = 3.45	KG = 17	KG = 53
2400	1.03	54.93	41.38	5.38
3400	1.46	39.04	25.49	-10.51
4400	1.89	30.48	16.93	-19.07
5400	2.31	25.17	11.63	-24.37
6400	2.74	21.60	8.06	-27.94
7400	3.17	19.07	5.52	-30.48
8400	3.60	17.20	3.65	-32.35
9400	4.03	15.78	2.23	-33.77
10400	4.48	14.44	0.89	-35.11
11400	4.87	13.27	-0.27	-36.27
12400	5.26	12.33	-1.22	-37.22
13400	5.65	11.55	-2.00	-38.00
14400	6.04	10.91	-2.64	-38.64

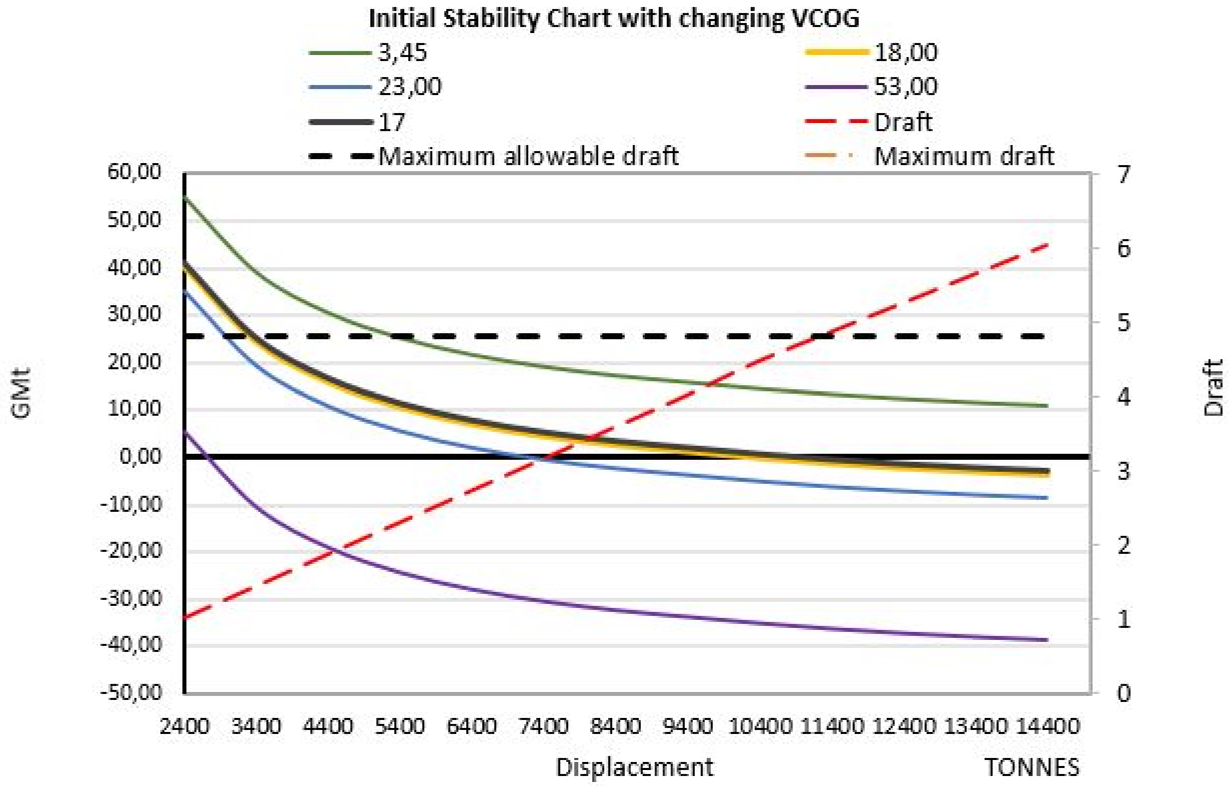

Figure 5.3: GM values for different metacentric heights and displacements

5.2 Parameter Study

The parametric study is done by changing the principal dimensions affecting stability. The characteristics are compared with changes in width, VCOG and freeboard while keeping the displacement equal for all three cases.

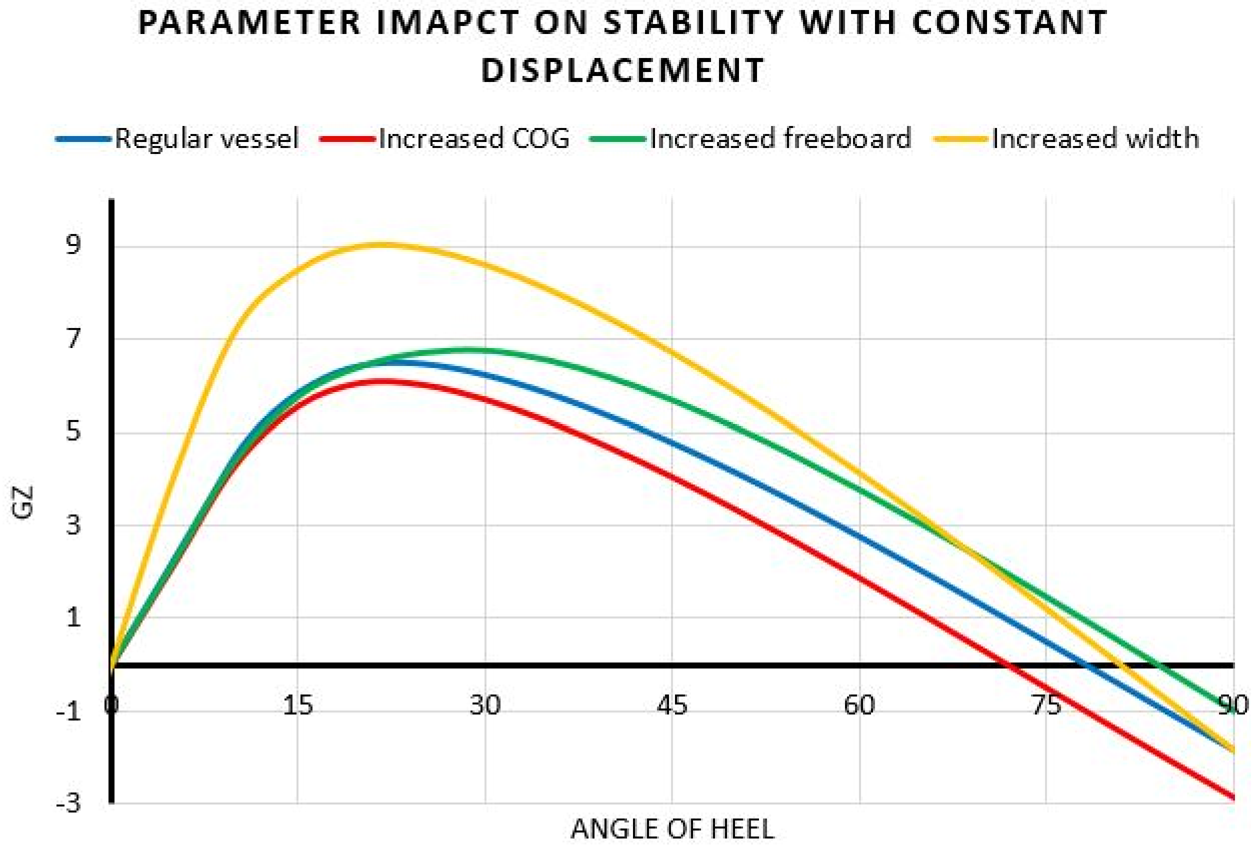

Figure 5.4: Parameter impact on stability with constant displacement

Figure 5.4 shows the righting curves for the three conditions. Changes in width has the highest impact on the height of the curve while increasing the freeboard gives the highest increase in range. Increasing the VCOG gives an small reduction in both height and range. The stability data can be found in table 5.4

Table 5.4: Stability Characteristics with changing parameters

	GZ_{max}[m] (angle)	Range Of Stability[°]	GM_0[m]
Regular	6.5 (23°)	78.1	25.7
Higher COG	6.1 (20°)	71.9	24.7
Increased Freeboard	6.8 (30°)	83.9	25.2
Increased Width	9.0 (20°)	80.9	46,1

5.3 Comparison of Loading Conditions

The comparison is done by defining three different loading conditions; Minimum, intermediate and maximum loading. The loading is done in compliance with the stability conditions found in (Denton, 2013) and (Organization, 2008) which is summarized in section 4.5.3. In each of the states the VCOG represents the maximum allowable value.

Table 5.5: Stability data for minimum, intermediate and maximum loading

Minimum		**Intermediate**		**Maximum**	
Displacement [$Tonnes$]	5500	Displacement [$Tonnes$]	7500	Displacement [$Tonnes$]	11262
Draft[T]	2.46	Draft[T]	3.29	Draft[T]	4.76
Angle [Deg]	Gzmax	Angle [Deg]	Gzmax	Angle [Deg]	Gzmax
16	3.24	16.5	2.585	11.5	1.304
KG [m]	16.4	KG [m]	11.8	KG [m]	7.01
GM [m]	14.39	GM [m]	10.6	GM [m]	6.69
Area GZ_{max} [m RAD]	0.564	Area GZ_{max} [m RAD]	0.429	Area GZ_{max} [m RAD]	0.180
Range [Deg]	36.5	Range [Deg]	36.1	Range [Deg]	36.5
Angle of deck immersion [Deg]	25.8	Angle of deck immersion [Deg]	11.8	Angle of deck immersion [Deg]	5.55
Radius of Gyration	14.8	Radius of Gyration	8.51	Radius of Gyration	2.34

In Table 5.5 the loading and stability data is shown for the three conditions. The range of stability is almost equal for the tree cases.

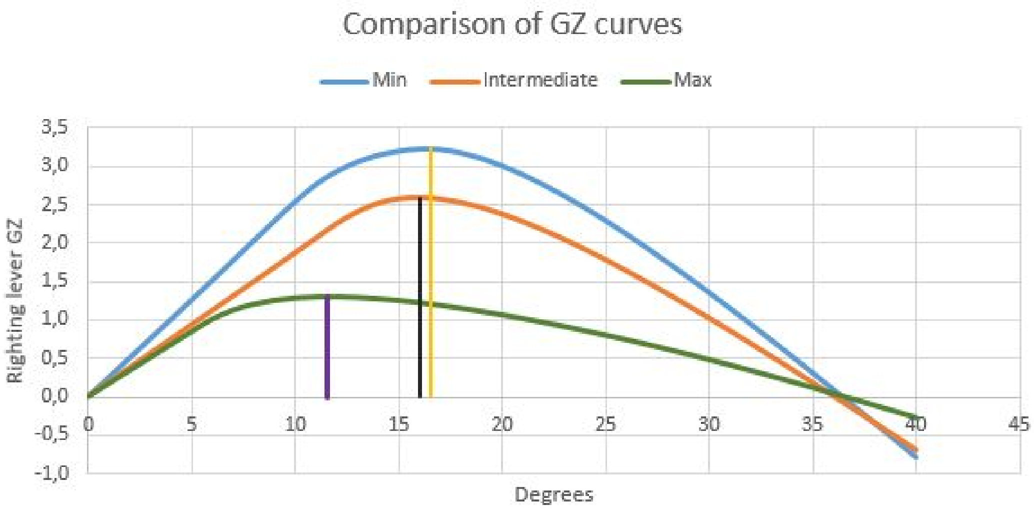

Figure 5.5: Comparison of GZ curves for minimum, intermediate and maximum loading condition

Figure 5.5 presents the stability and loading data for the three conditions. The range of stability is the same for all three cases. It shows that the height of the righting curve reduces and that the angle of GZ_{Max} shifts towards smaller angles of heel with increasing displacement.

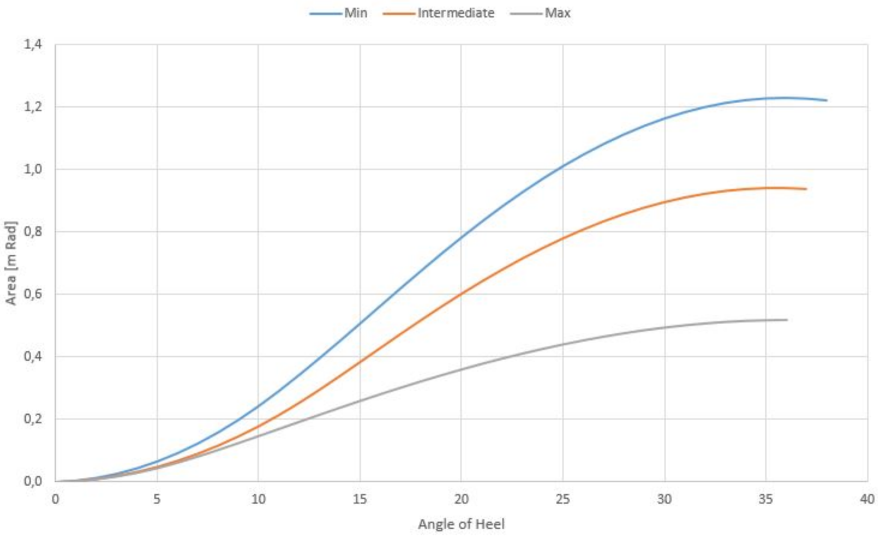

Figure 5.6: Changes in GZ area

In Figure 5.6 the areas for the tree situations are plotted from 0 degrees to the angle of vanishing stability. Showing how the area, and hence the dynamical stability, reduces with increasing displacement.

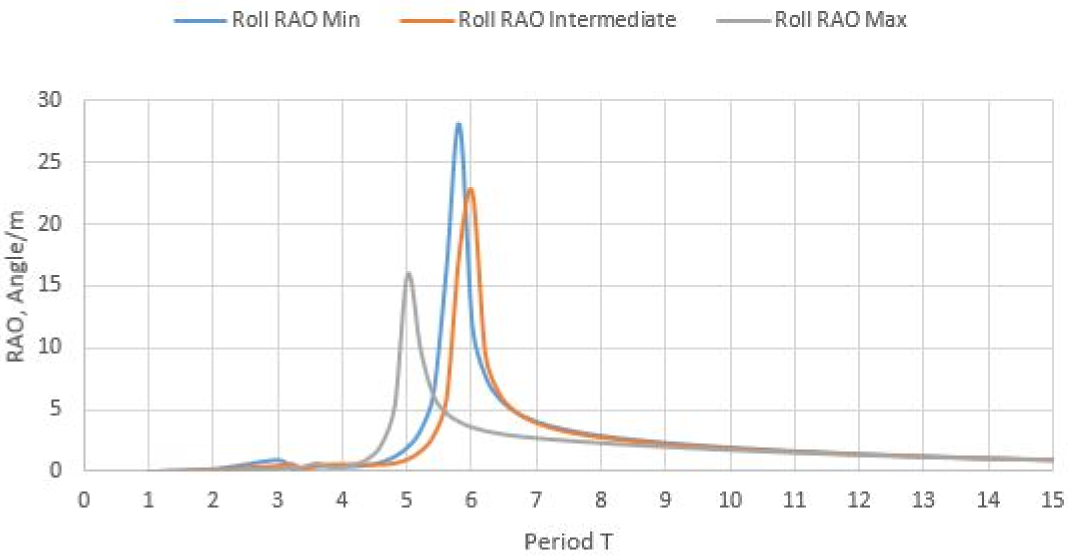

Figure 5.7: Change in Roll RAO

In Figure 5.7 the response parameter for roll motion is shown for the three conditions. From table 5.7 it can be seen that the lighter vessel has the highest RAO and that it decreases with the increasing displacement. The intermediate condition, having a more balanced load, has a lower amplitude but is moved to higher periods than the other conditions.

Table 5.6: Natural Period data

Property	Min	intermediate	max
ROG[m]	11.54	8.51	2.34
GM[m]	14.39	10.59	9.69
RAO[deg/m]	28.09	22.58	15.85
Period[s]	5.8	6	5

5.4 Operational Condition Comparison

The analysis compares the performance of the barge under light and heavy displacement for normal and damaged condition, with the same cargo in all of the cases. This analysis also includes heeling moments from wind, free surface effects and displacing loads.

5.4.1 Normal Operational Condition

In Figure 5.8 the righting curve for normal operational condition is shown with the resulting heeling lever from wind, liquids and displacing loads. The loading and stability data is presented in table 5.7.

Table 5.7: Loading and stability data normal operating condition

Property	Light	Heavy
Loading Data		
Displacement[Tonnes]	5600	11262
Draft[m]	2.50	4.76
VCOG [m]	11.82	7.41
Stability data		
GM [m]	16.165	9.38
Gz max [m]	3.81	1.24
Range[deg]	42	36
Area [m^2]	1.68	0.46
Heeling levers		
Wind [m]	0.131	0.059
Free surface [m]	0.202	0.100
Loads [m]	0.143	0.071

Figure 5.8 shows that by ballasting the barge down to maximum draft the righting curve reduces in range, height ,angle of GZ_{max} and area. The barge complies with the requirements given in table 4.4 for both of the cases.

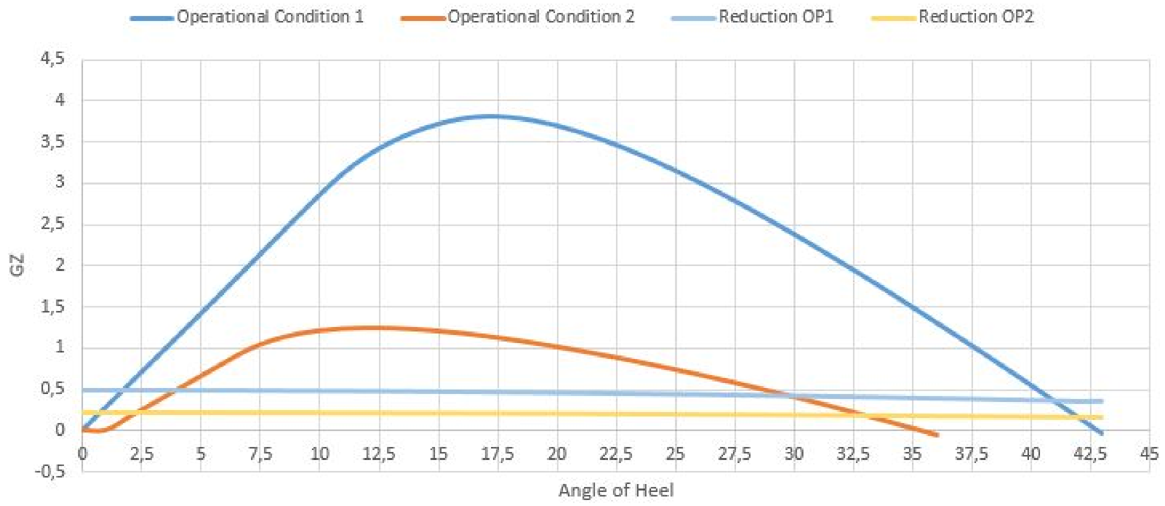

Figure 5.8: GZ curves and reductions from heeling moments

The resulting heeling levers are also shown in Figure 5.8. The lever is smaller in the cases of heavy displacement in magnitude but in comparison to the respective righting curve it is larger.

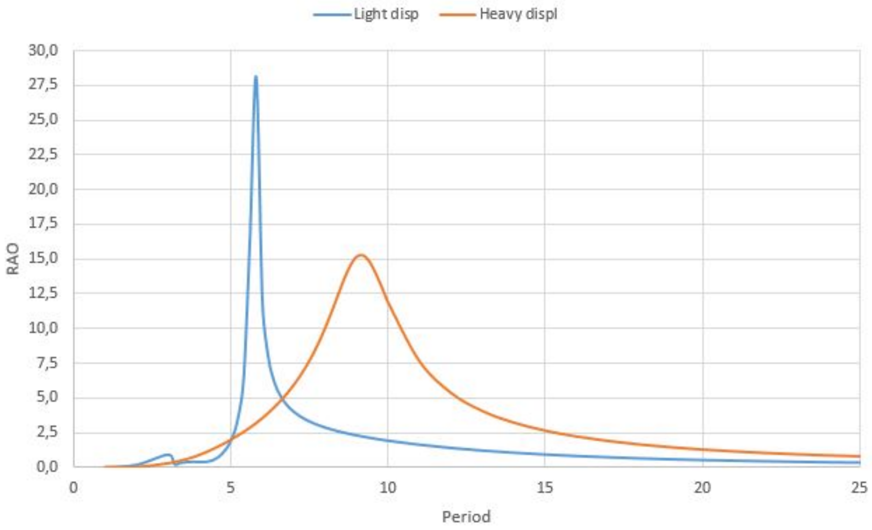

Figure 5.9: Response spectrum for light and heavy displacement

In Figure 5.9 the response spectrum for roll motion of the barge is shown for both loading conditions. The resonance period for the light displacement is narrow and placed at a short period while the heavy displaced barge has a lower and wider response spectrum with a higher peak period.

5.4.2 Damaged Condition

The damaged condition righting curve for light and heavy displacement are shown in 5.10 and 5.11 respectively. The figure include a graph of both the combined righting lever together with the single contributions.

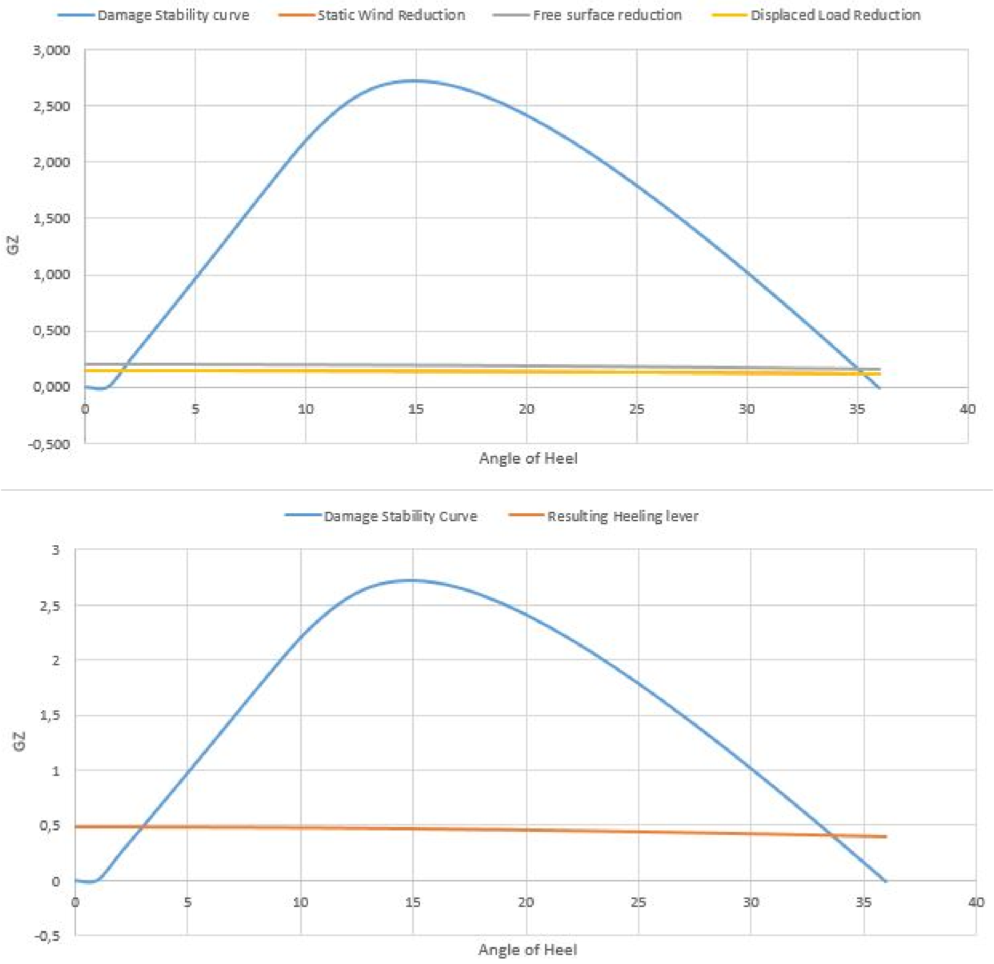

Figure 5.10: Damage Stability condition for OP1

For the light displacement seen in Figure 5.10 the righting curve reduces in length, height and area. The heeling lever curve crosses the righting curve at approximately 2.5 degrees. The stability is still in the required range, even with damage to a critical compartment.

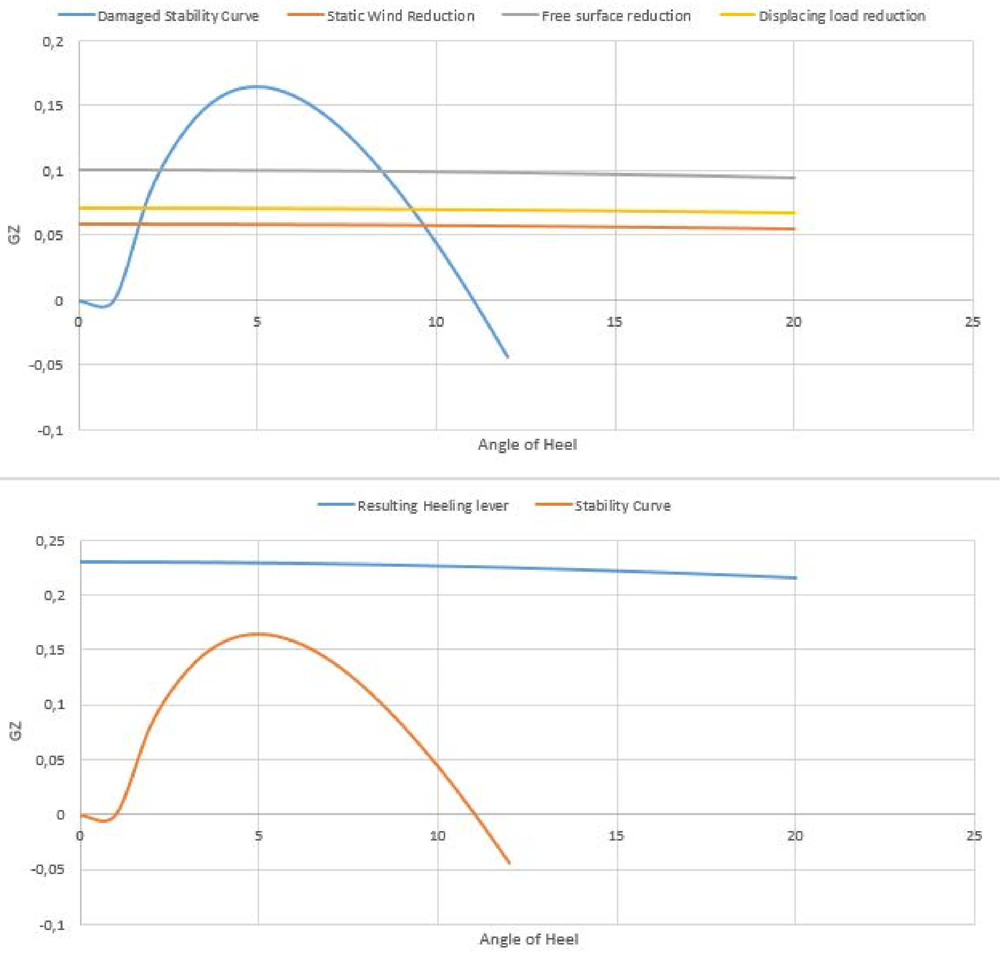

Figure 5.11: Damage Stability condition for OP2

In Figure 5.11 the righting curve for the heavy displacement in damage condition is shown with the heeling levers from wind, liquid and displaced load. In the situation where no loads displace the barge is still positively stable, but adding the heeling from the load creates a heeling arm larger than the righting arm, for all angles of heel.

The damage condition curves are combined in Figure 5.12 for comparison. The curves are plotted without any interaction of heeling arms. The graphs shows the large difference in stability for the two cases.

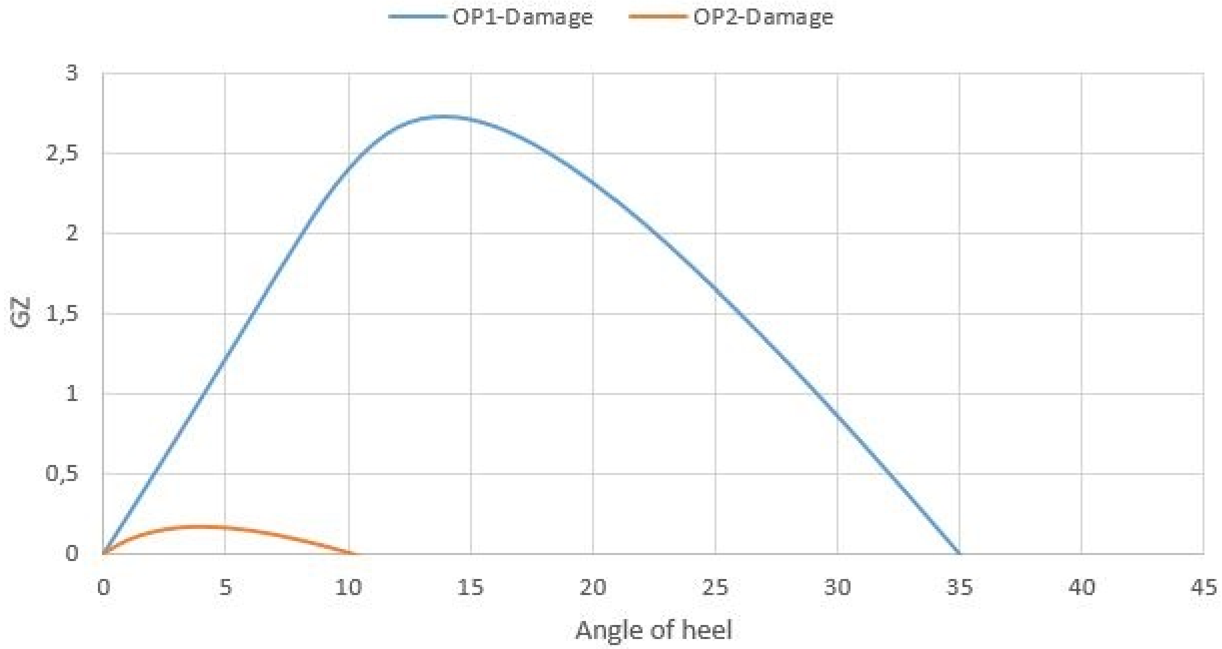

Figure 5.12: Comparison of damage condition

The stability data is summarized in table 5.8

Table 5.8: Stability data for damaged condition

Property	Light Displacement	Heavy Displacement
KG	11.04	7.1
GZmax angle	14	4
Stability Range	34	10
Area to gzmax	0.42	0.009
Total Area	0.987	0.019

Chapter 6

Discussion

In this chapter the results found in the analysis is interpreted more thoroughly. The data found in each section of the analysis is discussed in detail in the separate sections, with emphasis on linking the data to the theory subjects studied in the literature review.

6.1 Initial Stability Characteristics

Ensuring initial stability is the first step in any operation involving floating structures. Having a vessel that does not comply with the fundamental criteria described in section 3.2 will not be able to perform safely. In this section the results found on initial stability characteristics are discussed.

6.1.1 Minimum Freeboard calculations

The first criteria of positive buoyancy is fulfilled by assuring that the draft is less than the depth of the hull. For safety reasons the draft cannot reach the maximum level and a minimum freeboard has to be defined. This is done to give allowance for water absorption from sea spray and rain, icing or changes in water density.

The calculation performed specifies a minimum freeboard of 1.2761 m. This is an increase of 0.246 m from the tabular freeboard found in table B in the classification rules (DNV, 2001). The highest contributors to the limiting freeboard is the high block coefficient and reduced buoyancy from missing sheer in barges. The limiting freeboard means that the reserve displacement of the barge is around 3200 tonnes. This increases the survivability of the vessel in emergency situations if unpredicted events should occur.

6.1.2 Maximum KG

The next step in the process of ensuring seaworthiness is to determine the maximum size of the cargo, to make sure that the vessel is floating safely. From the calculations described in section 4.5.1 the maximum VCOG to fulfil the criteria of positive metacentric height was found and illustrated in figure 5.2. The values that fall underneath the curve are all possible loading conditions according to the condition of positive metacentric height. The values outside the shaded area will cause the barge to have negative initial metacentric height, which results in one of two things; the vessel will be floating on a list or tumble over.

Figure 5.2 shows that the allowable VCOG decreases rapidly for light displacements while evening out as the displacement increase. This shows that the barge is very sensitive with light displacements, and relatively small increases in weight causes large alterations in the stability. This proves that caution has to be taken when loading vessels with shallow drafts and high KG.

6.1.3 Initial Stability

In the initial stability chart illustrated in figure 5.3 the obtainable metacentric height is displayed for different vaules of KG. The possible combinations are limited by the criteria of positive metacentric height and maximum displacement. This area is enclosed by the positive horizontal and vertical axis and point where the draft intersects the black dotted line. From the figure it can be shown that for KG values below 17.0 m the draft is the limiting criteria. Values of KG above this value will not be able to displace down to minimum freeboard, while the lower values can. This illustrates the large effect that a high metacentric height has on the stability.

The initial stability equation presented in section 3.2 states the relation of initial metacentric height. BM and KB are dependent on ship form while KG is dependent on loading. This implies that the only parameter possible to affect for a already existing vessel is how it is loaded. The other factors can only be affected by choosing different vessel shapes.

6.2 Parameter study

Having established an understanding of the initial stability the next step is to determine the intact stability, in situations where the initial stability relation does not hold. To determine how changes in the dimensions affects the stability characteristics of a barge a parameter study was performed. Figure 5.4 illustrates the effect of changing freeboard, beam and VCOG. Since the analysis is performed with constant displacement the performance can be compared without considering the weight of the cargo.

The increased COG gives a decrease in both range and righting lever, as expected. A 20% increase in beam gives a increase in maximum righting lever of 38.5%. A increase in freeboard of 20% gives a increase in range of 7.4%.

The figure shows that a increase in beam gives the highest increase in righting arm, implying that a barge with a wider beam provides a higher resistance against heeling and can withstand larger overturning moments. The downside of the wider barge is the increased stiffness caused by the larger relocation of the centre of buoyancy in the transverse direction. This results in larger accelerations which again puts more stress on the structure and seafastening that could lead to displacement of loads.(Fjelde, 2008)

Increasing freeboard gives the largest increase in range of stability. From the figure it can be seen that the righting curve for the increased freeboard coincides with the curve for the regular vessel. Since there is no change in the dimensions before the waterline reaches the deck immersion angle for the regular shaped vessel this is expected. When the heeling continues beyond this point the righting arm continues to increase until the deck immersion angle for the increased freeboard reaches the waterline. Relating this to the stability calculations the increased stability is caused by the increase in waterline area (and hence BM). This is in line with the theory presented in (Barrass and Derrett, 2011).

Although there is no downside of increasing the freeboard with respect to the stability it will cause larger wind sail areas that will lead to higher wind overturning moments.

6.3 Comparison of Loading Conditions

In the comparison of the different loading conditions the barge was loaded to three different states with very different characteristics. The loading was done in compliance with the regulations found in IMO2008IS (Organization, 2008) together with the recommendations from GL Noble Denton (Denton, 2013). The table summarizing the requirements is found in section 4.5. The minimum loading condition provides insight into the stability of a barge with shallow draft and high metacentre while the maximum loading addresses the situation of having a deep draft with a smaller VCOG. The third condition was more balanced with an intermediate draft and VCOG.

The process of finding the limiting loading conditions involved running numerous drafts with different VCOG. The studies showed that the limiting criteria for barges for complying to the standards will be the range of stability. Because of the large $\frac{B}{D}$ relation the developed righting arms will be much larger than the recommended values. This will also provide large areas under the righting curve providing very good capacities in dynamic stability.

The loading at minimum draft gave the highest GZ_{Max} at the highest angle, as expected. The areas under the righting curve up to maximum lever and the total area were in far excess of the required values, giving further proof to the fact that the area under the righting curve will not be a limiting factor for compliance to regulations. From section 6.1 the value of KG providing positive metacentric height of 1.0 m which is recommended by GL Noble Denton at a displacement of 5500 Tonnes was found to be 27.6 m, while the value found in the analysis(with compliance to standards) was 16.4 m. This shows how the standards effectively limits the possible loading conditions

The maximum displacement conditions has a much lower area up to GZ_{max} of 0.18 m Rad. At its maximum condition the barge is not in any danger of reaching the minimum requirement of 0.08 m Rad found in IMO2008IS, adding to the statement that the area will not be a limiting criteria.

The data suggests that increasing KG will lead to a shift in towards higher angles of heel while increasing the draft leads to a decrease in GZ max.

The roll periods for the three loading conditions are shown in figure 5.7. In subsection 2.3.3 it was stated that there is a strong relation between Eigen periods and metacentric height. The same can be seen here for the minimum and maximum condition, while the intermediate condition has a higher natural period. In Table 5.6 it can be shown that the metacentric height for intermediate and maximum loading does not differ to much, but the resulting roll motion characteristics shows that a heavily loaded vessel does not always give higher natural periods.

6.4 Operational Condition

In the operational condition study the barge was loaded with two pipeline reels and subjected to heeling moments from wind, waves, free surface effects and displacing loads. This was done to investigate the stability properties during operational conditions. The damage condition was also investigated.

6.4.1 Normal Condition

Righting Curve

The comparison of the two loading conditions in Figure 5.8 shows that the righting curve reduces for the heavily displaced barge. The maximum righting arm decreases and the angle at which it is found is reduced. There is also a reduction in the range of stability. The heeling levers presented in the same figure shows that the heavily displaced barge has a smaller combined lever than the light displaced barge.

Table 6.1: Heeling moments for operational comparison

	Moment Light Displacement [MNm]	Moment heavy Displacement [MNm]
Wind	7.77	6.50
Liquid	1.12	0.56
Load	0.143	0.071
Sum	9.035	7.126

Table 6.1 shows the resulting heeling moment for the two barges. This shows that heeling lever is larger in absolute size for light displacement, and the increased draft creates more resistance against the heeling, reducing the heeling arm. The heeling arms are compared with the maximum righting arm in Table 6.2 for the respective curves.

Table 6.2: Comparison of righting and heeling levers

	GZ_{Max} Heavy Displacement	GZ_{Max} Light Displacement
Righting	3.81	0.48
Heeling	1.25	0.196
Ratio	0.328	0.408

The results show that the reserve stability (reserve resistance against heeling) is reduced more for the heavily displaced barge. The analysis indicates that the displacing the barge has a negative effect on stability when all the changes are accounted for.

Motion Characteristics

In Figure 5.9 the response spectrum for the two loading conditions are shown. The analysis shows the light displaced barge has a narrow and peaked spectrum centred around 6 seconds. The response is in the range of 28.2 deg/m . This indicates that the barge will experience severe rolling if the interaction between vessel and environment meets the resonance period. Figure 5.8 shows that the barge has a range of stability of around 41 degrees when subtracting the heeling levers. The combined effect of the interaction with waves and heeling combined would lead most certainly lead to capsizing.

The heavily displaced barge has a wide spectrum with a peak around 8.5 seconds. The response at peak period is around 15.1 deg/meters. This means that the barge would perform better in the critical region of 4-6 seconds with the lower amplitude. The stability in the most common wave periods would be very much improved.

The case study indicates that the result of displacing the barge is a much more stable vessel. The response period is moved out of the critical zone and reduced in amplitude. Although this is on the cost of dynamic area, maximum righting lever and resistance against rolling.

6.4.2 Damaged Condition

The stability curves for damage condition for the two loading conditions show the difference in performance when it has lost buoyancy from the most critical compartment. In figure 5.10 and 5.11 the stability curves for damaged condition shows how the barge will perform.

With light displacement the barge is able to maintain a fairly even keel, even though buoyancy is lost. The effect of the heeling arms from both wind and free surface liquid does not reduce the stability into critical regions. The barge is able to obtain a stability range of around 33 degrees when the levers are subtracted. The list from the heeling is around 2.5 degrees. This is below the recommended value but not in range of crucial values.

For heavy displacement the reduced stability curve for damaged condition proves much more crucial. The range is reduced to a very low value of 12 degrees and the maximum lever is below the recommended value 1.0 m. In the case of heeling from wind and free liquid the barge is barely able to obtain positive stability. If the event of moving loads occurs the barge would not be able to stay upright and would tumble over. The resulting heeling lever is larger than the maximum obtainable righting lever for all angles of heel.

The comparison in figure 5.12 shows the righting curve without heeling moments and corresponding Table 5.8 shows the dynamical areas for the damage situation. The comparison clearly shows the large difference in stability in damage conditions. The area for heavy displacement and range of stability shows that even though not under the effect of heeling moments the barge would barely be able to stay upright, and a small disturbance could heel it over.

Chapter 7

Conclusions

The objective of this thesis is to provide insight into the static stability of the Standard North Sea barge, a widely used design for marine transportation in the North Sea. The study areas include; Parameter sensitivity, loading conditions and damaged stability. The analysis has been performed using the computer modelling tools GeniE and HydroD together with basic hydrostatic- and stability equations.

The maximum draft of the barge was found to be 4.76 m. To be able to reach the maximum draft calculations indicated that maximum allowable vertical centre of gravity was 17.0 m to have a positive metacentric height. This value reduces to 7.4 m to obtain compliance to intact stability recommendation of 36° range from GL Noble Denton.

The analysis indicated that the limiting criteria of compliance with the standards for the barge is the range of stability of 36°, in all loading conditions. The metacentric height at maximum allowable loading condition with required range is found to be 9.7 m, which is well above the required values.

The operational condition analysis shows that displacing the barge with ballast water will soften the vessel motions, reduce roll and increase the natural period, at the cost of statical and dynamical stability.

In the maximum loading condition of 11262 Tonnes, T=4.76 m, KG=7.4 m and GM=9.7 m the barge was stable with damage to the most critical compartment, under the effect beam wind pressure of 540 Pa and free surface effect. In the event of a displaced load the barge did not prove stable.

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Ugland Construction AS

Appendix A

Acronyms

VCOG Vertical Centre of Gracity

COB Centre of Buoyancy

IMO International Maritime Organization

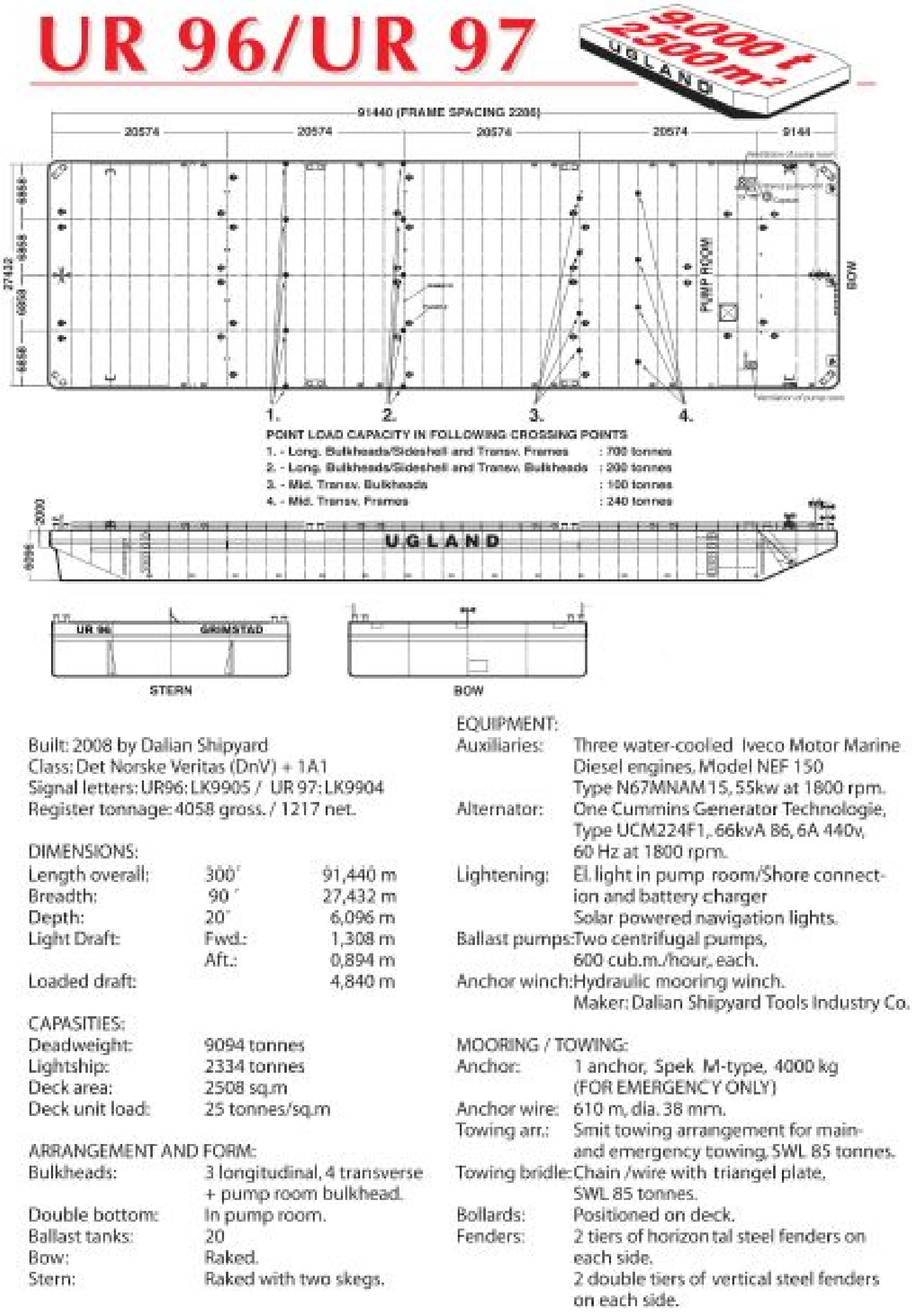
Loa Length Over All

Lpp Lenght Between Perpendiculars

Appendix B

Additional Information

This is an example of an Appendix. You can write an Appendix in the same way as a chapter, with sections, subsections, and so on.



UR 96/UR 97

POINT LOAD CAPACITY IN FOLLOWING CROSSING POINTS

1. - Long. Bulkheads/Sideshell and Transv. Frames : 700 tonnes
2. - Long. Bulkheads/Sideshell and Transv. Bulkheads : 200 tonnes
3. - Mid. Transv. Bulkheads : 100 tonnes
4. - Mid. Transv. Frames : 240 tonnes

Built: 2008 by Dalian Shipyard
Class: Det Norske Veritas (DnV) + 1A1
Signal letters: UR96: LK9905 / UR 97: LK9904
Register tonnage: 4058 gross. / 1217 net.

DIMENSIONS:

Length overall:	300´	91,440 m
Breadth:	90´	27,432 m
Depth:	20´	6,096 m
Light Draft:	Fwd.:	1,308 m
	Aft.:	0,894 m
Loaded draft:		4,840 m

CAPASITIES:

Deadweight:	9094 tonnes
Lightship:	2334 tonnes
Deck area:	2508 sq.m
Deck unit load:	25 tonnes/sq.m

ARRANGEMENT AND FORM:

Bulkheads:	3 longitudinal, 4 transverse + pump room bulkhead.
Double bottom:	In pump room.
Ballast tanks:	20
Bow:	Raked.
Stern:	Raked with two skegs.

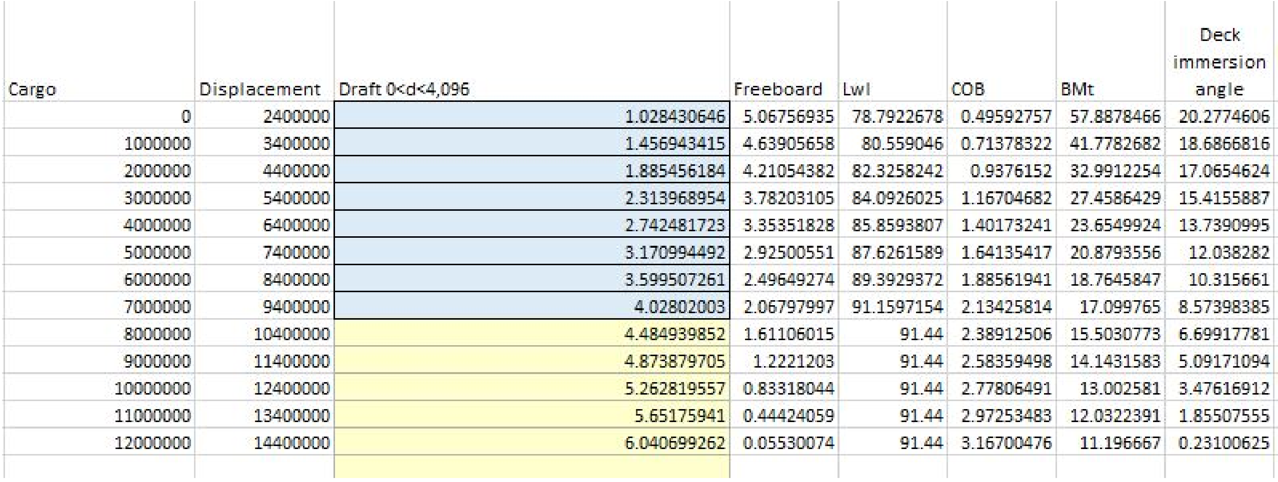
EQUIPMENT:

Auxiliaries:	Three water-cooled Iveco Motor Marine Diesel engines, Model NEF 150 Type N67MNAM 15, 55kw at 1800 rpm.
Alternator:	One Cummins Generator Technologie, Type UCM224F1, 66kvA 86, 6A 440v, 60 Hz at 1800 rpm.
Lightening:	El. light in pump room/Shore connection and battery charger Solar powered navigation lights.
Ballast pumps:	Two centrifugal pumps, 600 cub.m./hour, each.
Anchor winch:	Hydraulic mooring winch. Maker: Dalian Shipyard Tools Industry Co.

MOORING / TOWING:

Anchor:	1 anchor, Spek M-type, 4000 kg (FOR EMERGENCY ONLY)
Anchor wire:	610 m, dia. 38 mm.
Towing arr.:	Smit towing arrangement for main- and emergency towing, SWL 85 tonnes.
Towing bridle:	Chain /wire with triangel plate, SWL 85 tonnes.
Bollards:	Positioned on deck.
Fenders:	2 tiers of horizon tal steel fenders on each side. 2 double tiers of vertical steel fenders on each side.

Figure B.1: Ugland 97 North Sea Barge



Cargo	Displacement	Draft 0<d<4,096	Freeboard	Lwl	COB	BMt	Deck immersion angle
0	2400000	1.028430646	5.06756935	78.7922678	0.49592757	57.8878466	20.2774606
1000000	3400000	1.456943415	4.63905658	80.559046	0.71378322	41.7782682	18.6866816
2000000	4400000	1.885456184	4.21054382	82.3258242	0.9376152	32.9912254	17.0654624
3000000	5400000	2.313968954	3.78203105	84.0926025	1.16704682	27.4586429	15.4155887
4000000	6400000	2.742481723	3.35351828	85.8593807	1.40173241	23.6549924	13.7390995
5000000	7400000	3.170994492	2.92500551	87.6261589	1.64135417	20.8793556	12.038282
6000000	8400000	3.599507261	2.49649274	89.3929372	1.88561941	18.7645847	10.315661
7000000	9400000	4.02802003	2.06797997	91.1597154	2.13425814	17.099765	8.57398385
8000000	10400000	4.484939852	1.61106015	91.44	2.38912506	15.5030773	6.69917781
9000000	11400000	4.873879705	1.2221203	91.44	2.58359498	14.1431583	5.09171094
10000000	12400000	5.262819557	0.83318044	91.44	2.77806491	13.002581	3.47616912
11000000	13400000	5.65175941	0.44424059	91.44	2.97253483	12.0322391	1.85507555
12000000	14400000	6.040699262	0.05530074	91.44	3.16700476	11.196667	0.23100625

Figure B.2: Hydrostatic Calculations

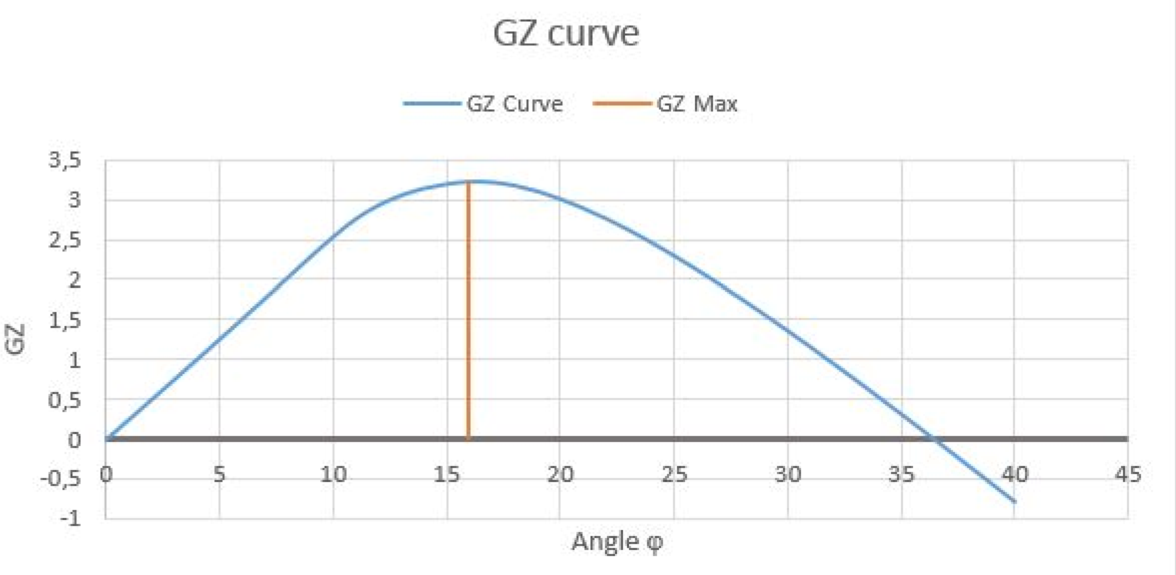


Figure B.3: Righting curve for minimum load

Table B.1: Stability data for minimum loading condition

KG	14	Range	36,5
Disp	5500 tonnes	Gzmax	3,24
Deck immersion angle	15,95 deg	Rao	28,09
GM	14,4 m	Area	1,23 mrad
Draft	2,46 m	Radius of G	11,54 m
Natural period	5,8 s	Gz max deg	16

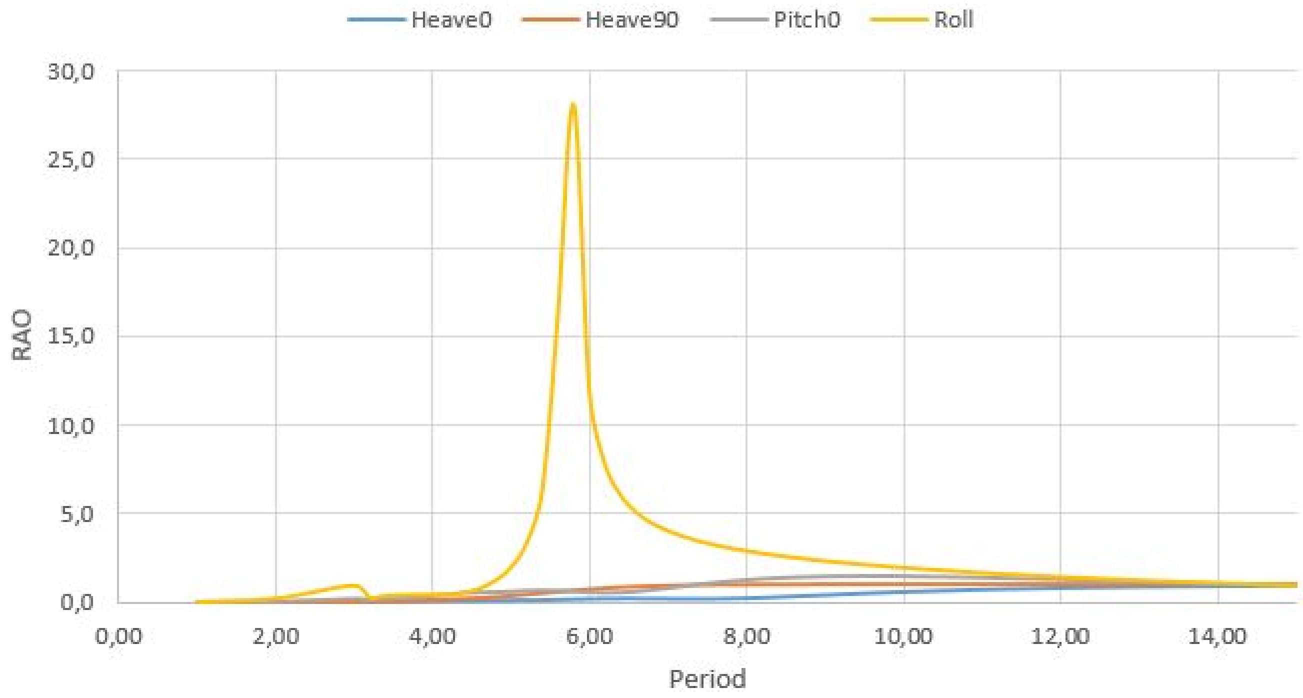


Figure B.4: Response spectrum minimum loading

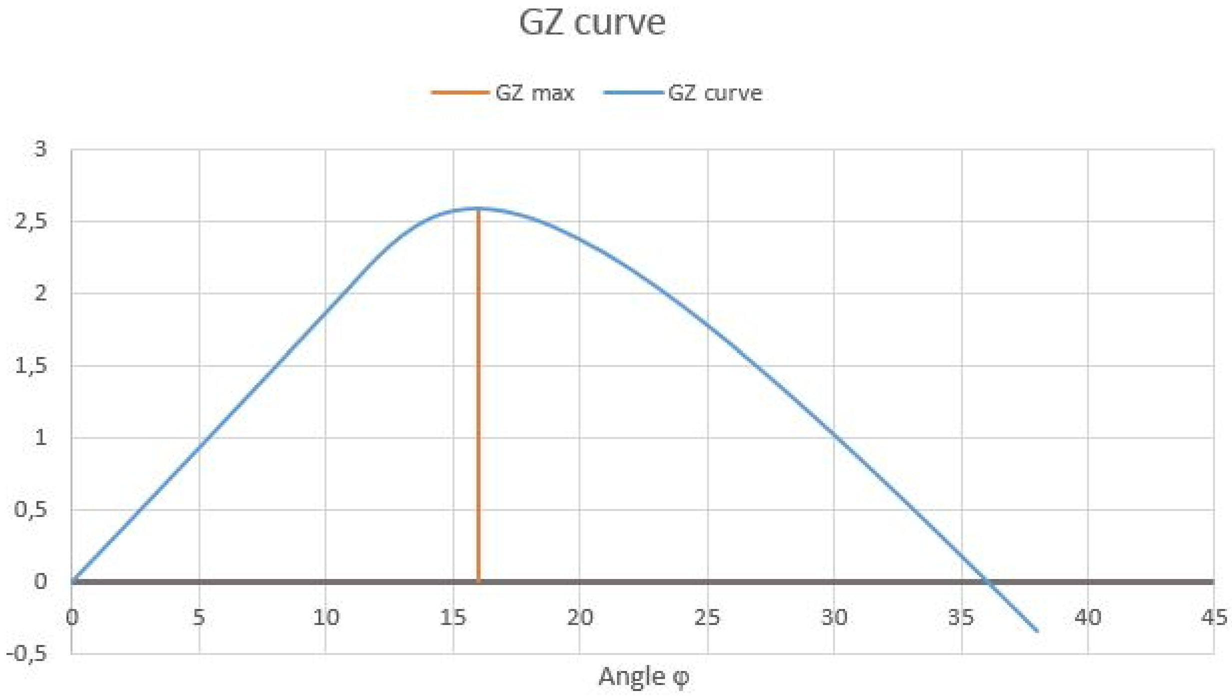


Figure B.5: Righting curve for intermediate load

Table B.2: Righting curve intermediate loading

KG	11,8	Range	36,1	Gz max angle	16 deg
Disp	7500	Gzmax	2,59		
Deck immersion angle	11,79	Rao roll resonance	22,6 deg/m		
GM	10,6	Area			
Draft	3,29	Radius of G	8,51		
Natural period	5,7s	Deck immersion	11,8		

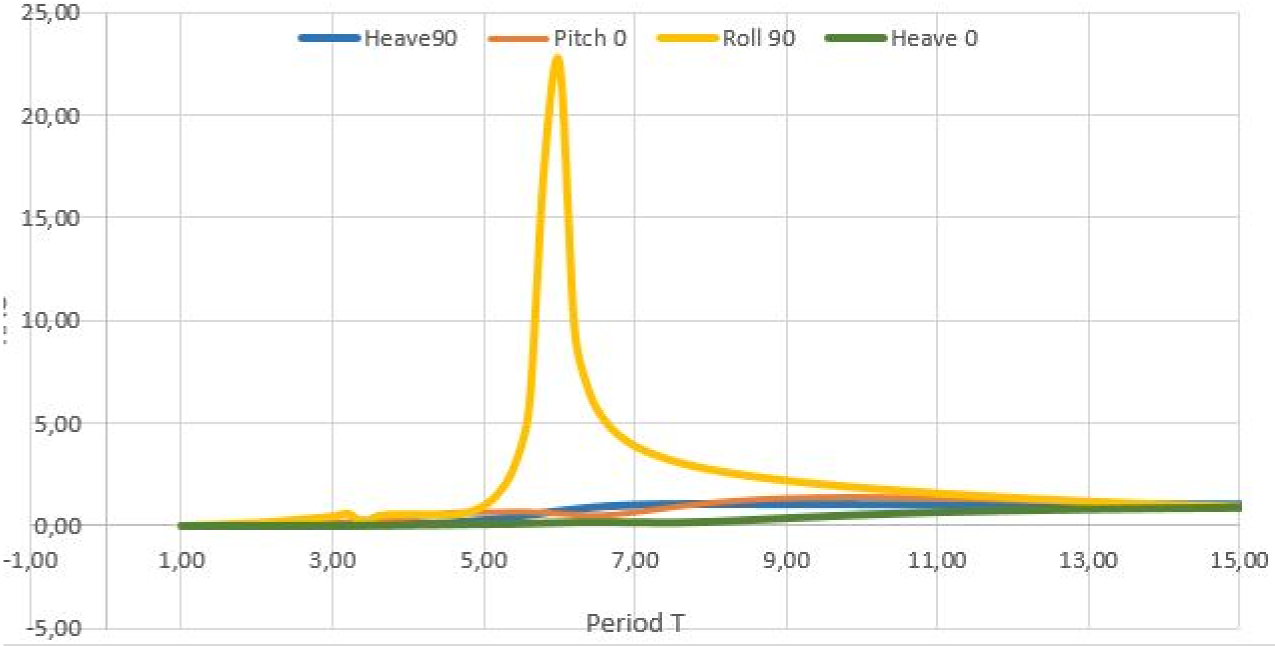


Figure B.6: Response spectrum intermediate loading

Table B.3: Stability data for maximum loading

Maximum Loading condition	Analysis 44		
KG	7,01	Gzmax	1,3
GM	6,69	Area	8,359674323 mrad
Displacement	11261500	Zero crossing	36,5 Deg
Radius of G	2,34	Natural Roll period	4,95 s
Roll RAO @ resonance	15,95 deg/m	Gz max deg	11,5

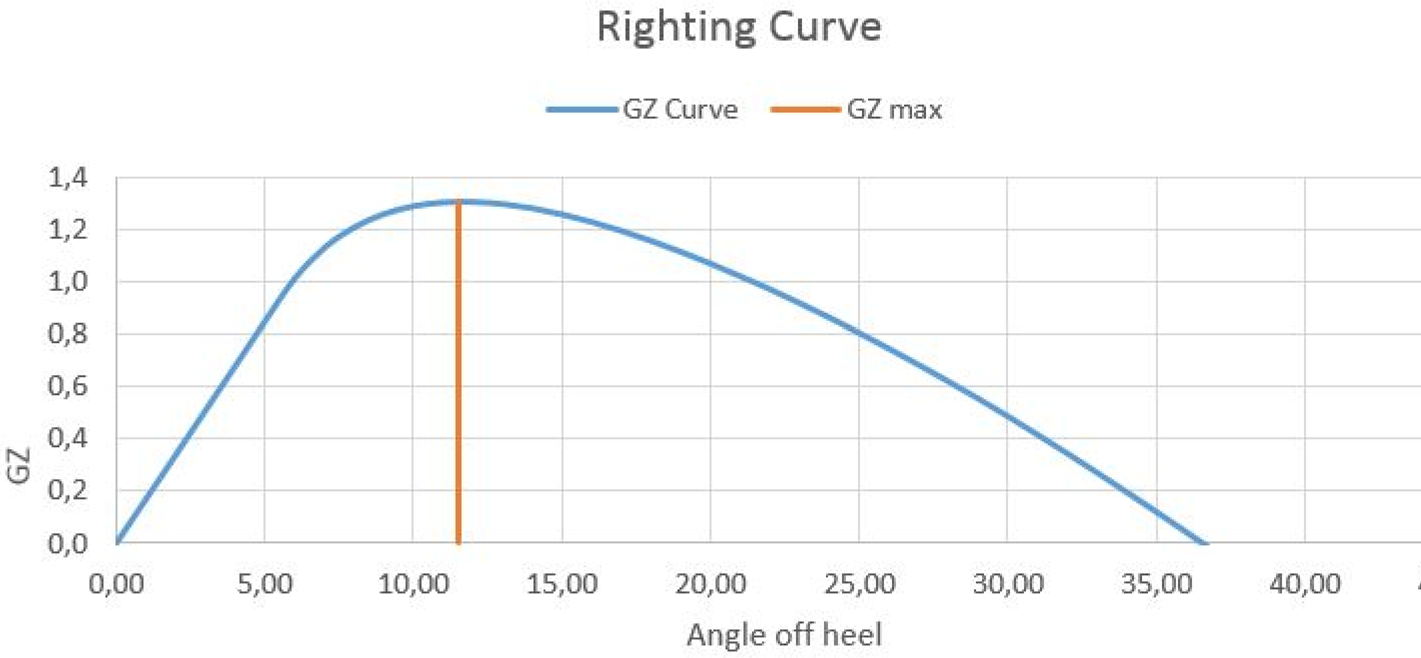


Figure B.7: Response spectrum intermediate loading

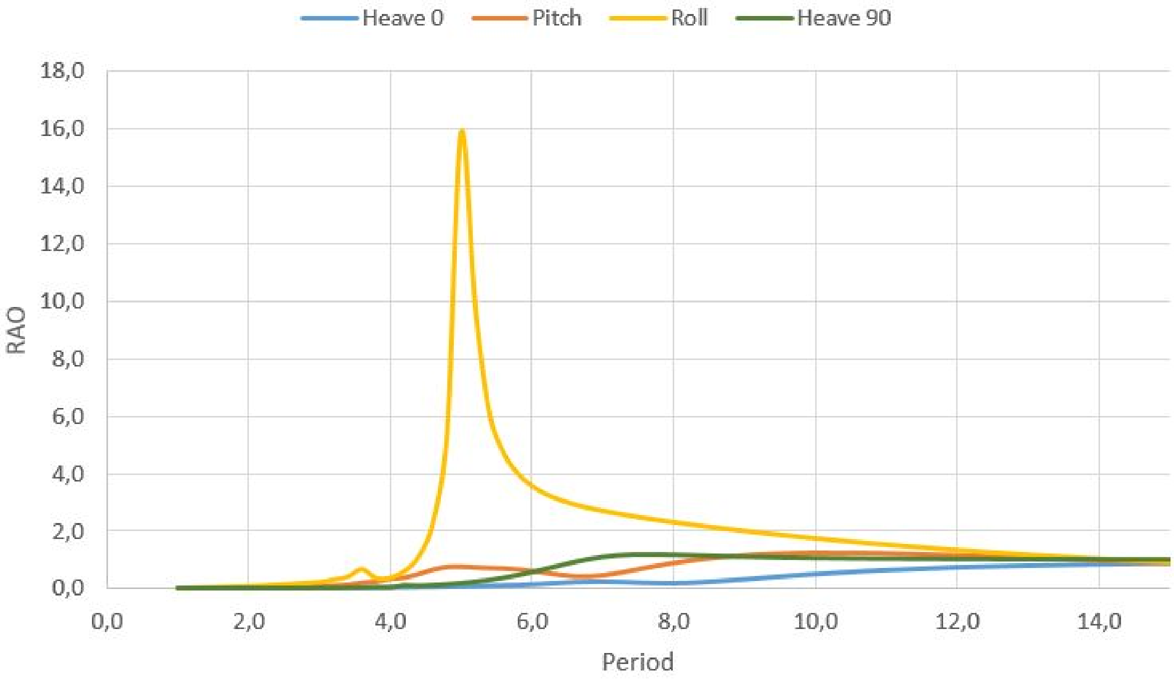


Figure B.8: Respons Spectrum for maximum condition

B.1 Introduction

B.2 State of Art

B.3 Literature Study and Background Reading

B.4 Model and Method

B.5 Results

B.5.1 Initial Stability Calculations

B.5.2 Comparison of loading conditions

B.5.3 Parameter Study

B.5.4 Operational Condition Comparison

OP1-Lightship Displacement

Table B.4: OP1-Lightship Stability Data

GMt	16,17 m
KG	11,82 m
GZ max	3,81 m
Angle at GZmax	17 deg
Stability Range	42 deg
Area to GZmax	0,707 m$\hat{2}$
Total Area	1,69 m$\hat{2}$

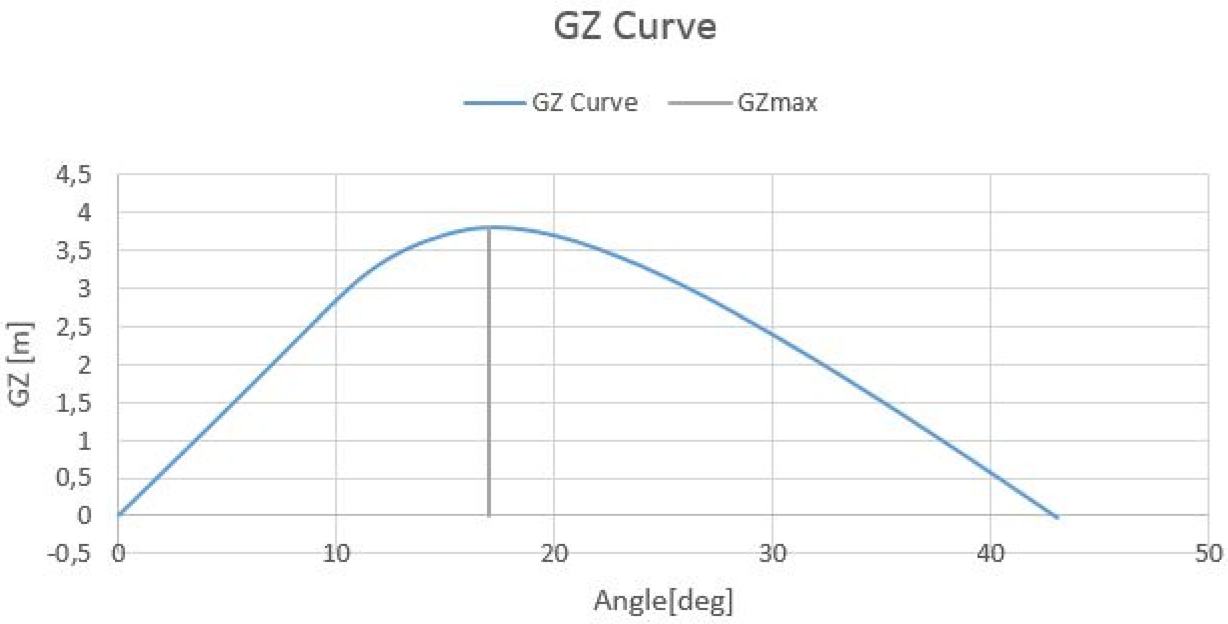


Figure B.9: GZ curve for OP1

Table B.5: OP1-Wind Sail Properties

	Barge
Wind sail area Barge	328 m2̂
Height of centroid	4,84 m
	Cargo
Wind sail area Cargo	760 m2̂
Height of centroid	16,84 m
Critical Angle	7,34 deg

Table B.6: Wind forces

Item	Moment	Lever
Cargo	8296998,55	0,1259
Barge	857514,14	0,0156
Total	**9154512,69**	**0,141**
Angle of heel from wind		Approx 0,5 deg
Freeboard reduction		0,12 m

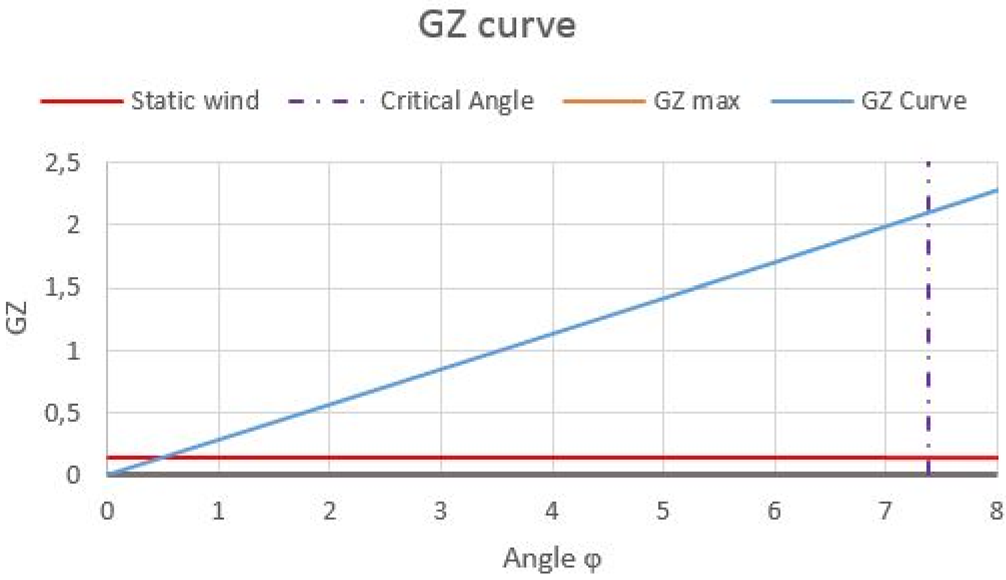


Figure B.10: OP1-Static wind heel angle

Table B.7: Free surface effect on light displacement

Displacement	5600
# of compartments	Heeling Lever
1	0,101
2	0,202

Table B.8: Dynamical stability data

Area GZ curve at second intercept	1,686 m Rad
Area Wind second intercept	0,093 m Rad
Requirement NobleDenton	40 %
Actual excess	1812 %

Table B.9: OP-1 Reduced GZ curve data

Gz Max reduced	3,48
Reduction	8,65 %
Ange of list	1 deg
Reduced range	1 degree

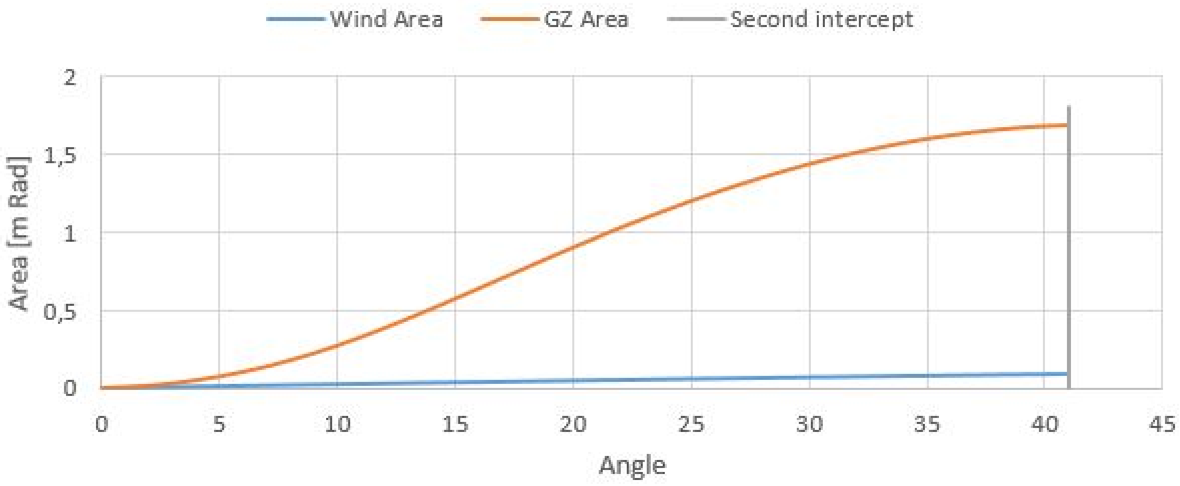


Figure B.11: Dynamic Wind Area

OP2-Heavy Displacement

Table B.10: OP-2 Reduced GZ curve data

Gz Max reduced	1,087
Reduction	12,60 %
Ange of list	1 deg
Reduced range	2 degrees

Table B.11: OP2-Loading data

Displacement	11252
Draft	4,76 m
VCOG	7,41 m
COB	2,47 m

Table B.12: GZ curve for heavy displacement

Property	IMO2008IS	GL Noble Denton	Actual	Status
Stability range	20	36	34	OK
GM0	Positive	0,15(1)	9,38	OK
Area to GZ max	0,08	-	0,164	OK
Minimum draught	-	2,4	2,5	OK
Maximum draught	-	4,8	4,76	OK

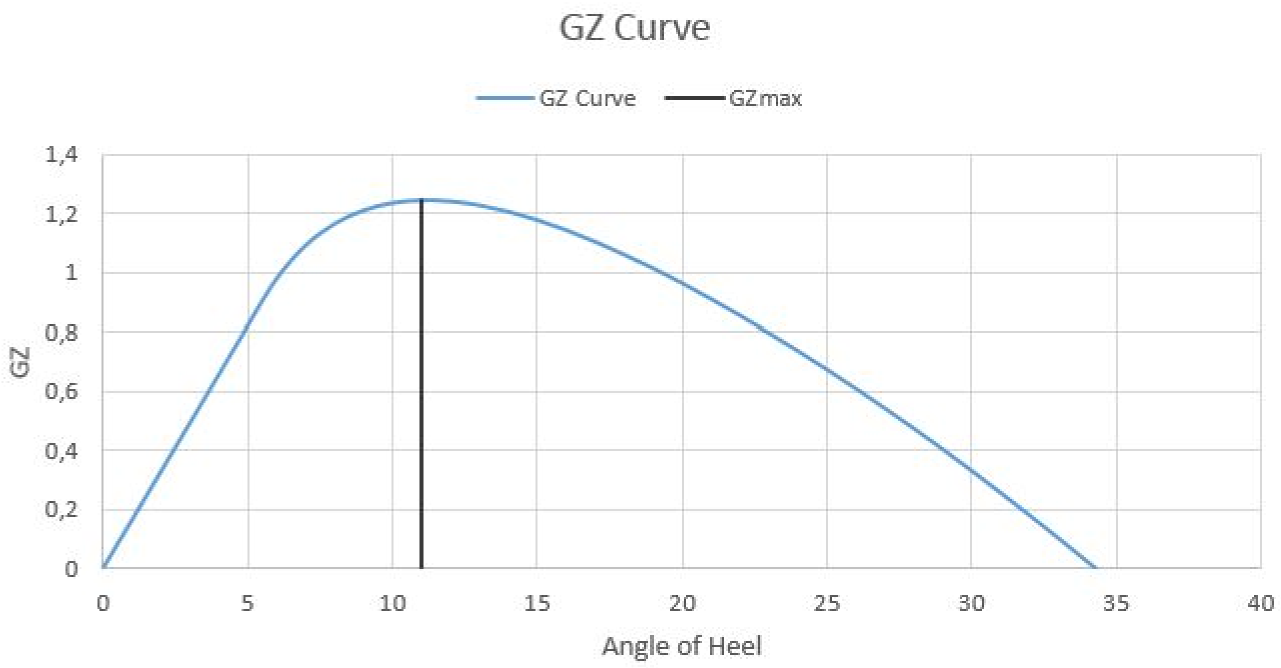


Figure B.12: OP2 righting curve

Table B.13: OP2 - Wind Sail Data

	Barge
Wind sail area Barge	121,8 m2̂
- Height of centroid	0,666 m
	Cargo
Wind sail area Cargo	760 m2̂
- Height of centroid	16,84 m
Critical Angle	2,705 deg

Table B.14: OP2 - Wind force

Item	Moment	Lever
Cargo	8296998,55	0,0,05844
Barge	857514,14	0,0004
Total	**9154512,69**	**0,0588**
Angle of heel from wind	Approx 0,2 deg	
Freeboard reduction	0,05 m	

Figure B.13: Static angle of heel

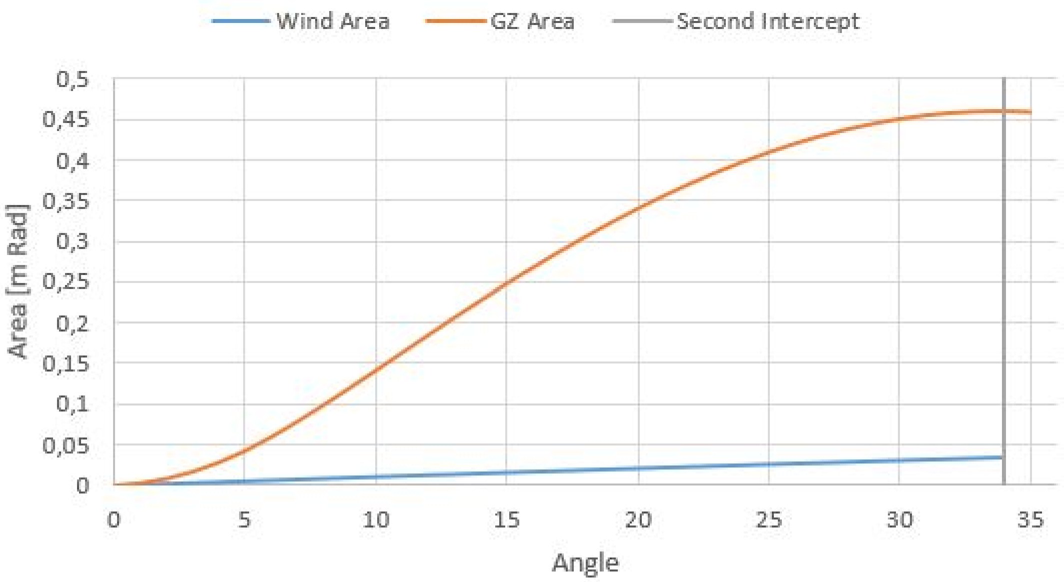


Figure B.14: OP2-Dynamic wind area

Table B.15: OP2-Dynamic Stability Data

Area GZ curve at second intercept	0,455 m Rad
Area Wind second intercept	0,031 m Rad
Requirement NobleDenton	40 %
Actual excess	1467 %

Table B.16: Reduced data for OP2

Gz Max reduced	1,087
Reduction	12,60 %
Ange of list	1 deg
Reduced range	2 degrees

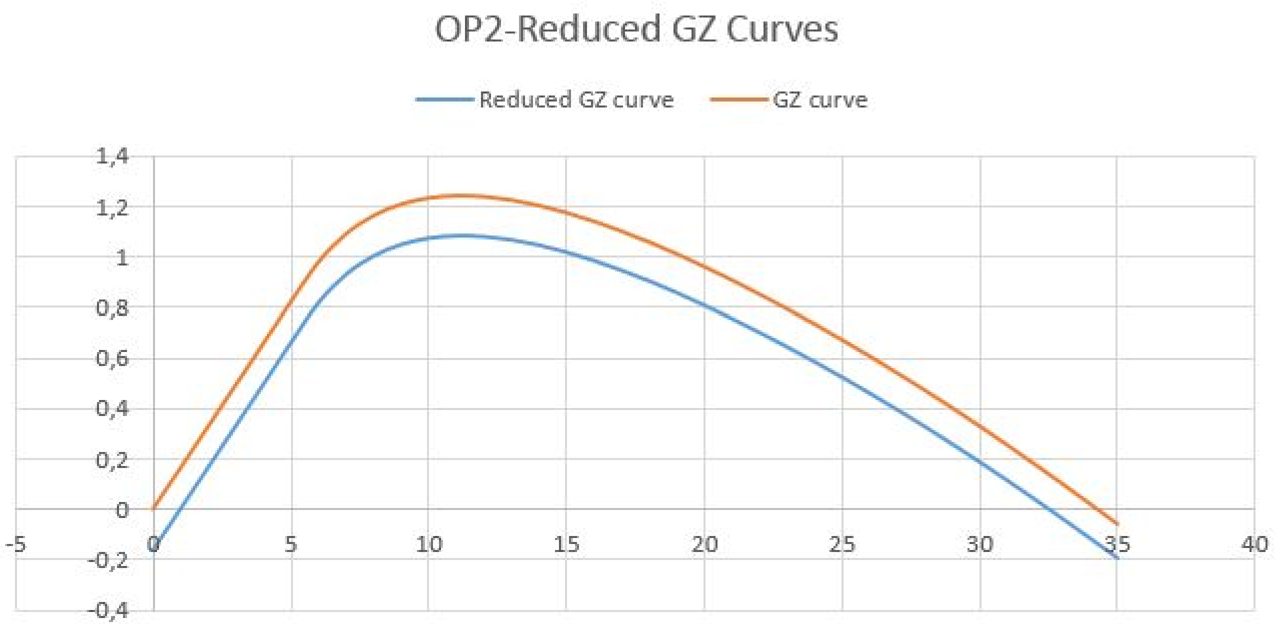


Figure B.15: Reduced Gz curve for OP2

OP3 - Damage Condition

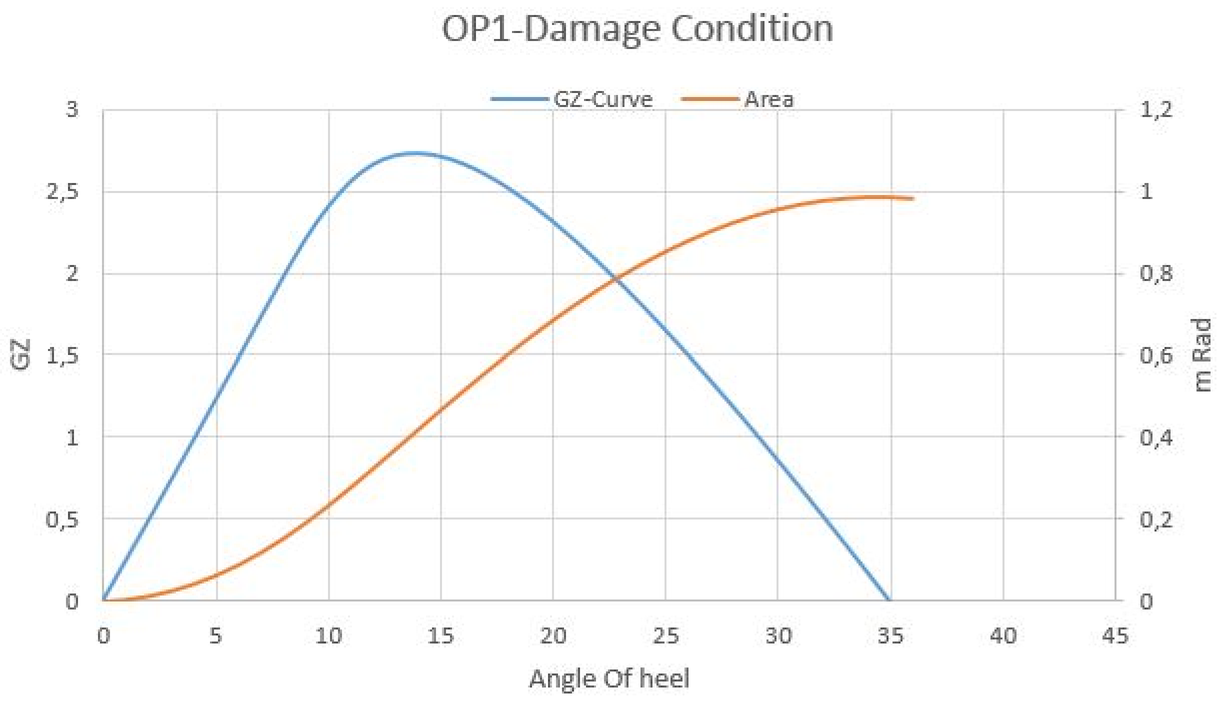


Figure B.16: Damage Stability for OP1

Table B.17: OP3-Lightship damage loading data

Dry displacement	5600 Tonnes
Total displacement(included water)	6061 Tonnes
Draft	2,7 m
VCOG	11,04m
COB	1,41 m

Table B.18: OP3-Lightship damange stability data

GMt	13,584 m
KG	11,04 m
GZ max	2,73 m
Angle at GZmax	14 deg
Stability Range	34 deg
Area to GZmax	0,420 m Rad
Total Area	0,987 m Rad

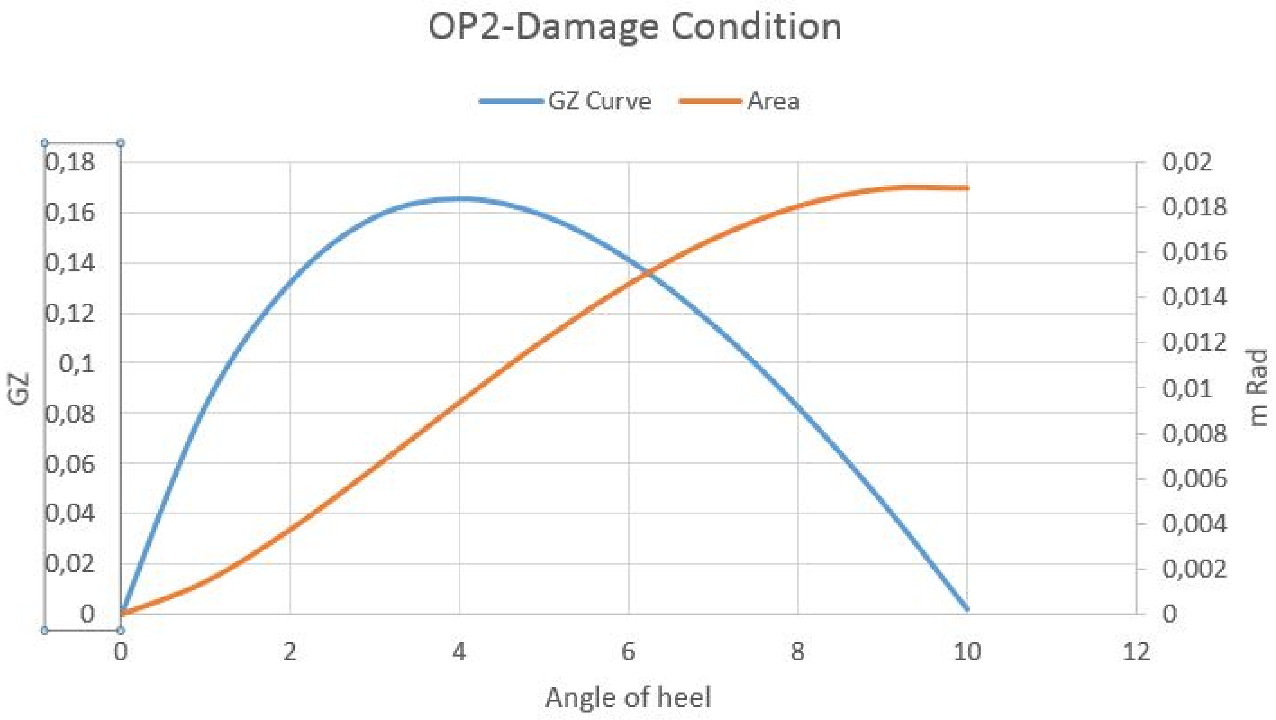


Figure B.17: Damage Stability for heavy displacement

Table B.19: OP3 - Heavy loading data

Dry displacement	11260 Tonnes
Total displacement(included water)	11260+852= 12112 Tonnes
Draft	5,03 m
VCOG	7,1 m
COB	2,71

Table B.20: OP3 - Heavy Damage stability data

GMt	13,584 m
KG	7,1
GZ max	0,165 m
Angle at GZmax	4 deg
Stability Range	10 deg
Area to GZmax	0,009 m Rad
Total Area	0,019 m Rad