Lecture Note of Design Theories of Ship and Offshore Plant

Design Theories of Ship and Offshore Plant

Part I. Ship Design

Ch. 5 Naval Architectural Calculation

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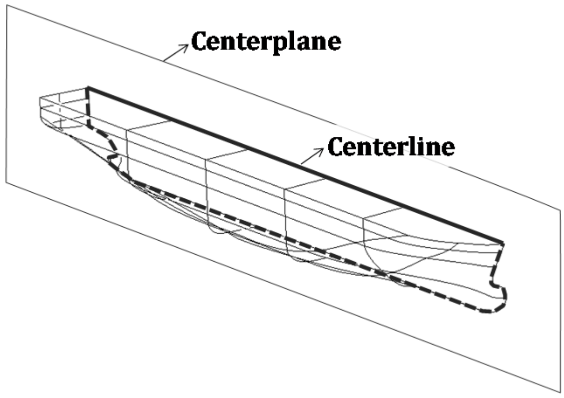
Contents

Ch. 5 Naval Architectural Calculation

5.1 Static Equilibrium

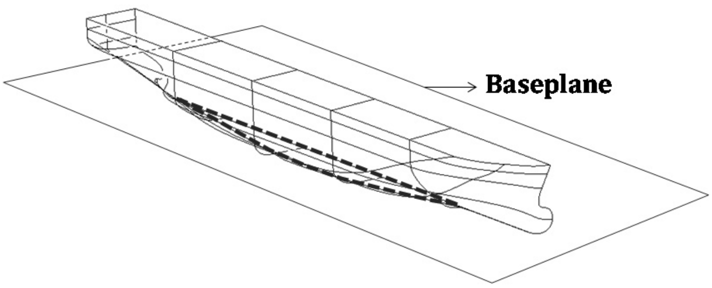
Center Plane

Before defining the coordinate system of a ship, we first introduce three planes, which are all standing perpendicular to each other.



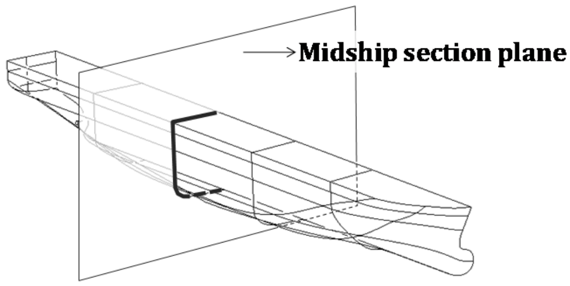
Generally, a ship is **symmetrical** about starboard and port.
The first plane is the vertical longitudinal plane of symmetry, or **center plane**.

Base Plane



The second plane is the horizontal plane, containing the bottom of the ship, which is called **base plane**.

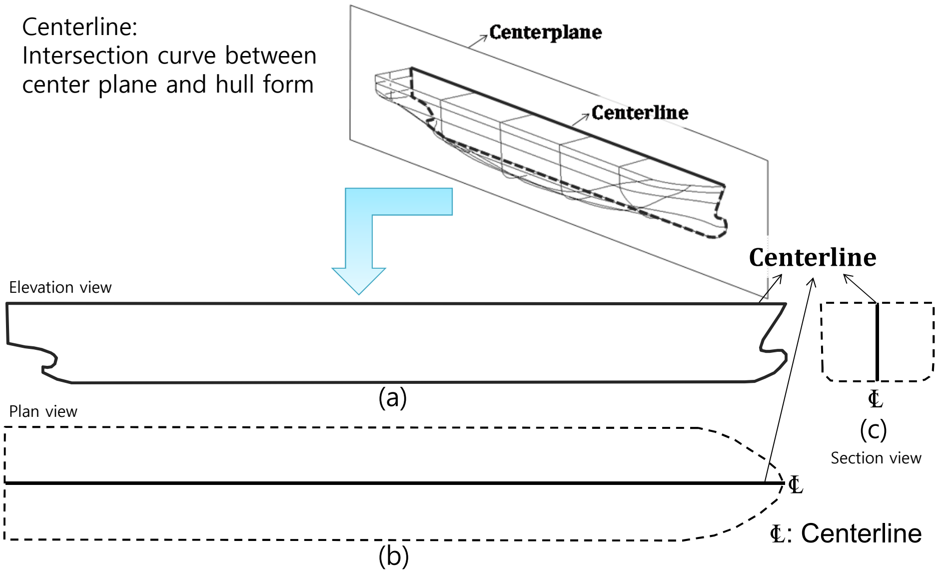
Midship Section Plane



The third plane is the vertical transverse plane through the midship, which is called **midship section plane.**

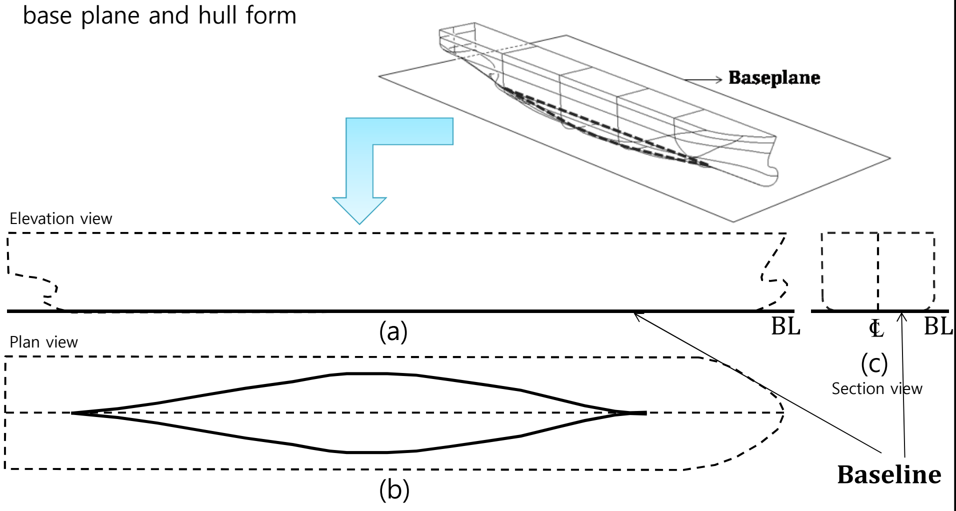
Centerline in (a) Elevation view, (b) Plan view, and (c) Section view

Centerline:
Intersection curve between center plane and hull form

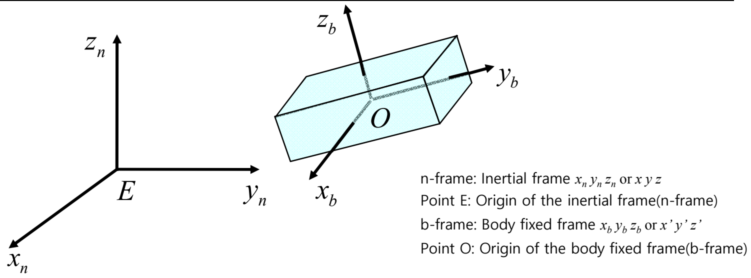


Baseline in (a) Elevation view, (b) Plan view, and (c) Section view

Baseline:
Intersection curve between base plane and hull form



System of Coordinates



1) ***Body fixed coordinate system***
The right handed coordinate system with the axis called x_b(or x'), y_b(or y'), and z_b(or z') is **fixed to the object**. This coordinate system is called ***body fixed coordinate system*** or ***body fixed reference frame (b-frame)***.

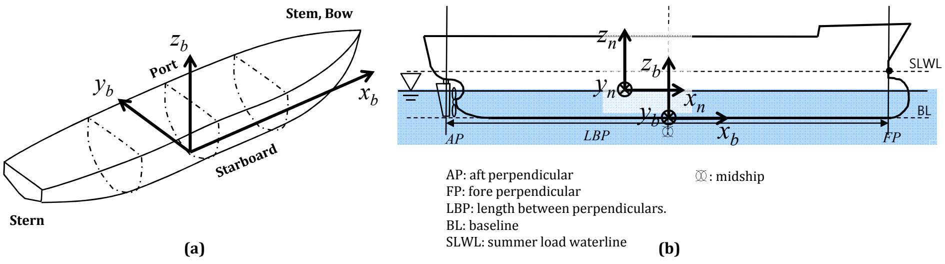
2) ***Space fixed coordinate system***
The right handed coordinate system with the axis called x_n(or x), y_n(or y) and z_n(or z) is **fixed to the space**. This coordinate system is called ***space fixed coordinate system*** or ***space fixed reference frame*** or ***inertial frame (n-frame)***.

In general, a change in the position and orientation of the object is described with respect to the inertial frame. Moreover Newton's 2nd law is only valid for the inertial frame.

System of Coordinates for a Ship

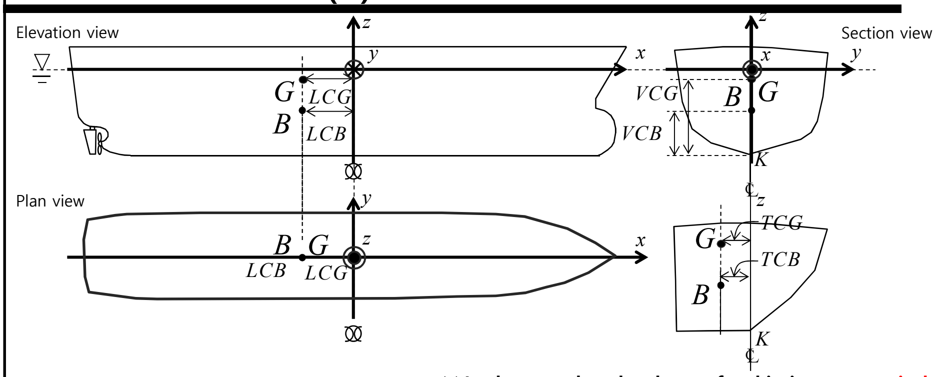
Body fixed coordinate system (b-frame): Body fixed frame $x_b\, y_b\, z_b$ or $x'\, y'\, z'$

Space fixed coordinate system (n-frame): Inertial frame $x_n\, y_n\, z_n$ or $x\, y\, z$



Center of Buoyancy (B) and Center of Mass (G)

K: keel
LCB: longitudinal center of buoyancy
VCB: vertical center of buoyancy
TCB: transverse center of buoyancy
LCG: longitudinal center of gravity
VCG: vertical center of gravity
TCG: transverse center of gravity



※ In the case that the shape of a ship is asymmetrical with respect to the centerline.

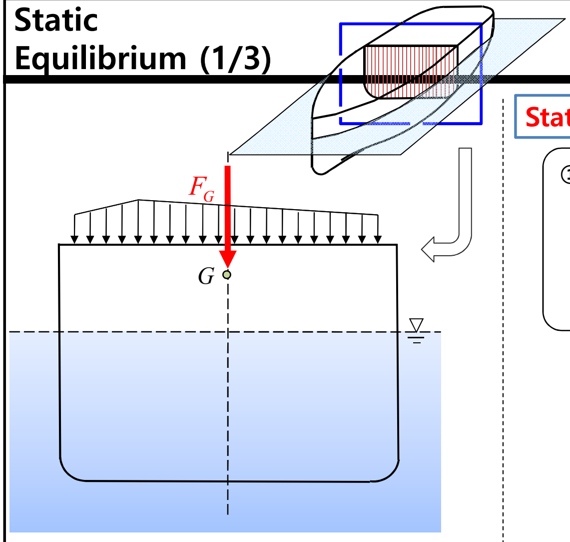
Center of buoyancy (B)

It is the point at which all the vertically upward forces of support (buoyant force) can be considered to act.
It is equal to the center of volume of the submerged volume of the ship. Also, It is equal to the first moment of the submerged volume of the ship about particular axis divided by the total buoyant force (displacement).

Center of mass or Center of gravity (G)

It is the point at which all the vertically downward forces of weight of the ship (gravitational force) can be considered to act.
It is equal to the first moment of the weight of the ship about particular axis divided by the total weight of the ship.

Static Equilibrium (1/3)



m: mass of ship
a: acceleration of ship

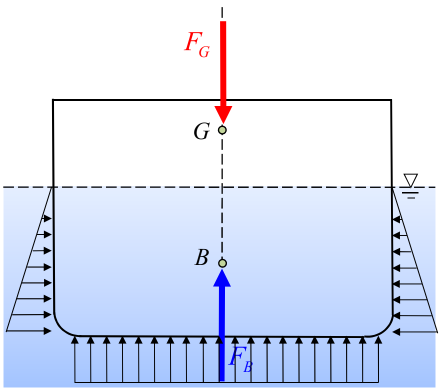
G: Center of mass
F_G: Gravitational force of ship

Static Equilibrium

① **Newton's 2nd law**

$$ma = \sum F$$
$$= -F_G$$

Static Equilibrium (2/3)



B: Center of buoyancy at upright position(center of volume of the submerged volume of the ship)
F_B: Buoyant force acting on ship

Static Equilibrium

① **Newton's 2nd law**

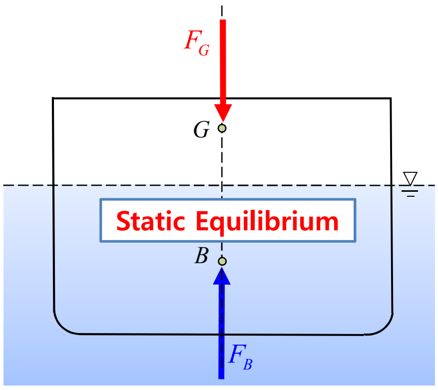
$$ma = \sum F$$
$$= -F_G + F_B$$

for the ship to be in static equilibrium

$$0 = \sum F \quad ,(\because a = 0)$$

$$\therefore F_G = F_B$$

Static Equilibrium (3/3)



τ: Moment
I: Mass moment of inertia
ω: Angular velocity

Static Equilibrium

① Newton's 2nd law

$$ma = \sum F$$
$$= -F_G + F_B$$

for the ship to be in static equilibrium

$$0 = \sum F \quad ,(\because a = 0)$$

$$\therefore F_G = F_B$$

② Euler equation

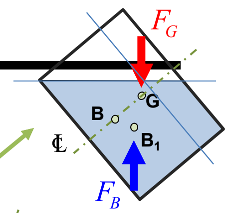
$$I\dot{\omega} = \sum \tau$$

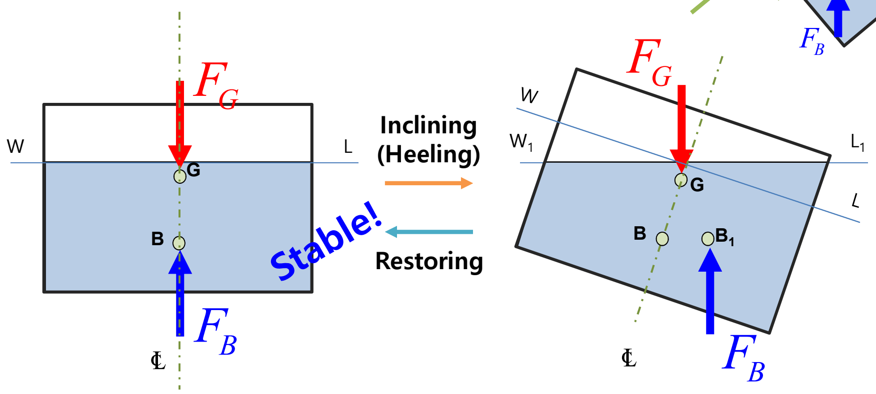
for the ship to be in static equilibrium

$$0 = \sum \tau \quad ,(\because \dot{\omega} = 0)$$

When the buoyant force (F_B) lies on the same line of action as the gravitational force (F_G), total summation of the moment becomes 0.

What is "Stability"?

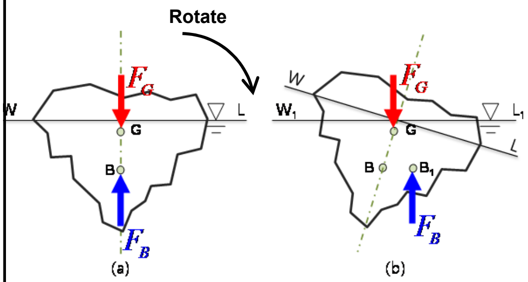




Stability = Stable + Ability

Stability of a Floating Object

- You have a torque on this object relative to any point that you choose. It does not matter where you pick a point.
- The torque will only be zero when the buoyant force and the gravitational force are on one line. Then the torque becomes zero.



Static Equilibrium

① Newton's 2nd law

$$ma = \sum F$$
$$= -F_G + F_B$$

for the ship to be in static equilibrium

$$0 = \sum F \quad ,(\because a = 0)$$

$$\therefore F_G = F_B$$

② Euler equation

$$I\dot{\omega} = \sum \tau$$

for the ship to be in static equilibrium

$$0 = \sum \tau \quad ,(\because \dot{\omega} = 0)$$

When the buoyant force (F_B) lies on the same line of action as the gravitational force (F_G), total summation of the moment becomes 0.

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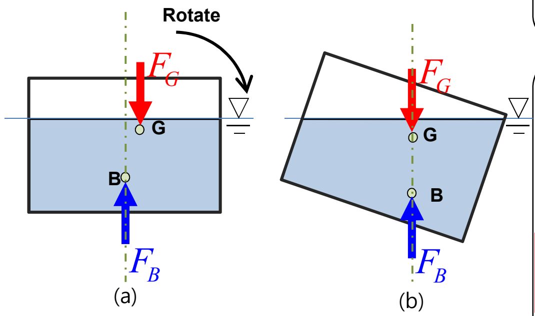
Stability of a Ship

- You have a torque on this object relative to any point that you choose. It does not matter where you pick a point.
- The torque will only be zero when the buoyant force and the gravitational force are on one line. Then the torque becomes zero.



Static Equilibrium

Static Equilibrium

① Newton's 2nd law

$$ma = \sum F$$
$$= -F_G + F_B$$

for the ship to be in static equilibrium

$$0 = \sum F \quad ,(\because a = 0)$$

$$\therefore F_G = F_B$$

② Euler equation

$$I\dot{\omega} = \sum \tau$$

for the ship to be in static equilibrium

$$0 = \sum \tau \quad ,(\because \dot{\omega} = 0)$$

When the buoyant force (F_B) lies on the same line of action as the gravitational force (F_G), total summation of the moment becomes 0.

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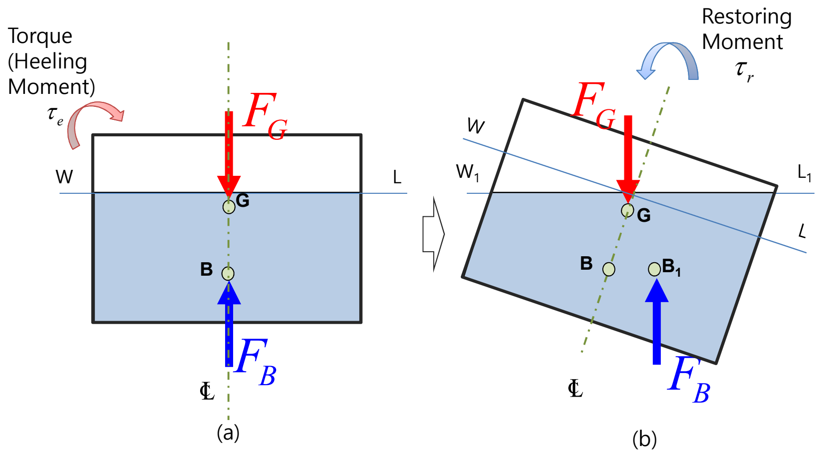
Interaction of Weight and Buoyancy of a Floating Body (1/2)

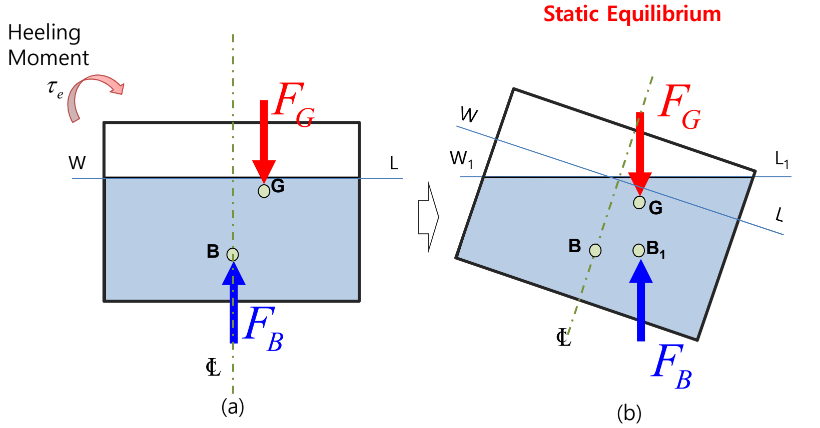


Euler equation: $I\dot{\omega} = \sum \tau$ ➡ $\dot{\omega} \neq 0$

Interaction of weight and buoyancy resulting in intermediate state

Interaction of Weight and Buoyancy of a Floating Body (2/2)

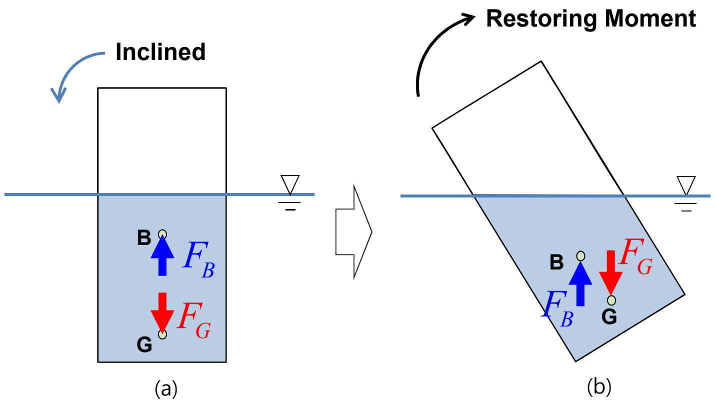
Static Equilibrium



Euler equation: $I\dot{\omega} = \sum \tau$ ➡ $\dot{\omega} = 0$

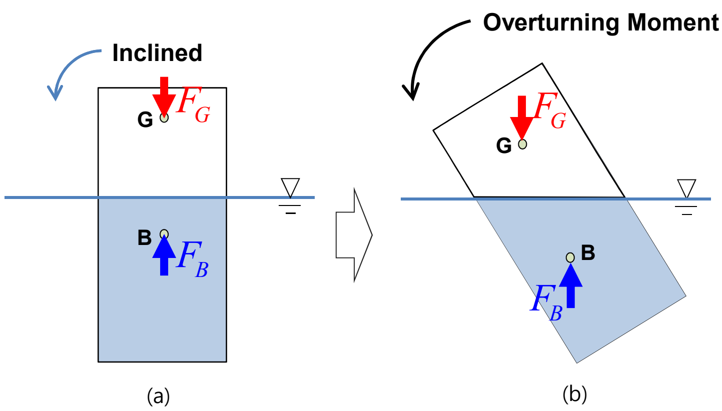
Interaction of weight and buoyancy resulting in static equilibrium state

Stability of a Floating Body (1/2)



Floating body in stable state

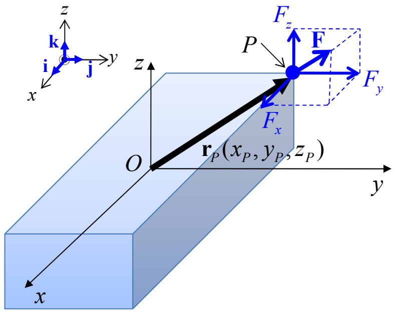
Stability of a Floating Body (2/2)



Floating body in unstable state

Transverse, Longitudinal, and Yaw Moment

Question) **If the force F is applied on the point of rectangle object, what is the moment?**



$$\mathbf{M} = \mathbf{r}_P \times \mathbf{F}$$

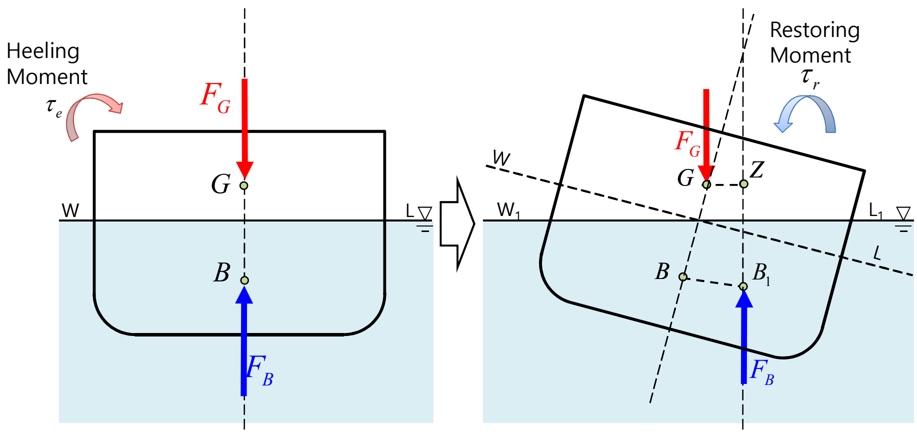
Transverse moment, Longitudinal moment, Yaw moment

$$= \begin{bmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ x_P & y_P & z_P \\ F_x & F_y & F_z \end{bmatrix} = \mathbf{i}\underbrace{(y_P \cdot F_z - z_P \cdot F_y)}_{M_x} + \mathbf{j}\underbrace{(-x_P \cdot F_z + z_P \cdot F_x)}_{M_y} + \mathbf{k}\underbrace{(x_P \cdot F_y - y_P \cdot F_x)}_{M_z}$$

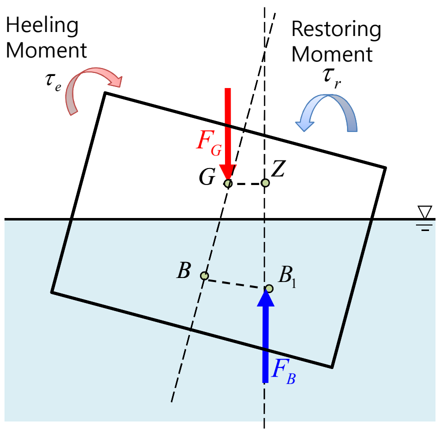
The x-component of the moment, i.e., the bracket term of unit vector **i,** indicates the **transverse moment,** which is the moment caused by the force F acting on the point P **about x axis**. Whereas the y-component, the term of unit vector **j,** indicates the **longitudinal moment about y axis**, and the z-component, the last term **k**, represents the **yaw moment about z axis**.

5.2 Restoring Moment and Restoring Arm

Restoring Moment Acting on an Inclined Ship



Restoring Arm (GZ, Righting Arm)



- The value of the restoring moment is found by multiplying the buoyant force of the ship (displacement), F_B, by the perpendicular distance from G to the line of action of F_B.
- It is customary to label as *Z* the point of intersection of the line of action of F_B and the parallel line to the waterline through *G* to it.
- This distance *GZ* is known as the '**restoring arm**' or '**righting arm**'.

- **Transverse Restoring Moment**

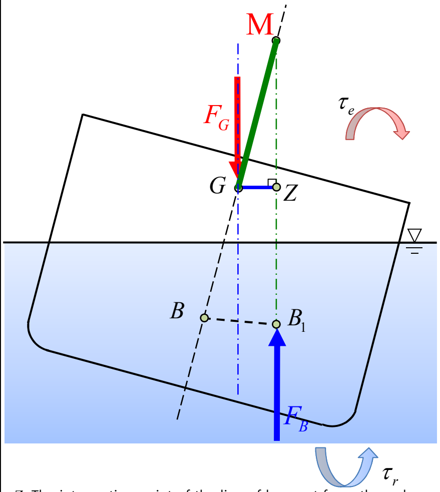
$$\tau_{restoring} = F_B \cdot GZ$$

G: Center of mass K: Keel
B: Center of buoyancy at upright position
B_1: Changed center of buoyancy
F_G: Weight of ship F_B: Buoyant force acting on ship

Metacenter (M)

• Restoring Moment

$\tau_{restoring} = F_B \cdot GZ$



Z: The intersection point of the line of buoyant force through B_1 with the transverse line through G

Definition of M (Metacenter)

• The intersection point of the vertical line through the center of buoyancy at **previous position (*B*)** with the vertical line through the center of buoyancy at **new position (*B₁*)** **after inclination**

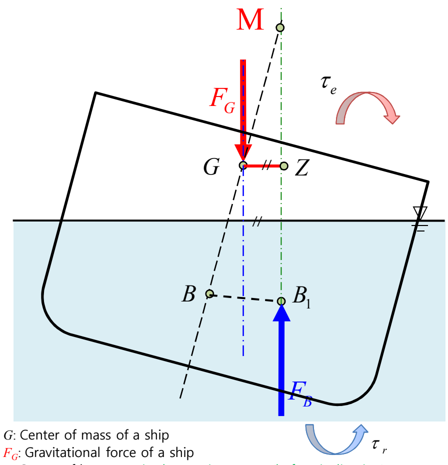
• The term **meta** was selected as a prefix for center because its Greek meaning implies **movement**. The **metacenter** therefore is a **moving center**.

• GM ➡ Metacentric height

• From the figure, GZ can be obtained with assumption that *M* does not change within a small angle of inclination (about 7° to 10°), as below.

$$GZ \approx GM \cdot \sin\phi$$

Restoring Moment at Large Angle of Inclination (1/3)



G: Center of mass of a ship
F_G: Gravitational force of a ship
B: Center of buoyancy in the previous state (before inclination)
F_B: Buoyant force acting on a ship
B_1: New position of center of buoyancy after the ship has been inclined
Z: The intersection point of a vertical line through the new position of the center of buoyancy(B_1) with the transversely parallel line to a waterline through the center of mass(G)

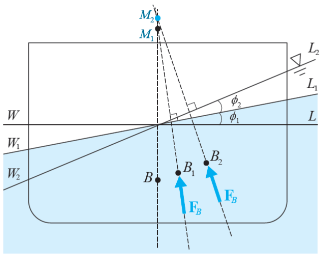
$$GZ \approx GM \cdot \sin\phi$$

For a small angle of inclination (about 7° to 10°)

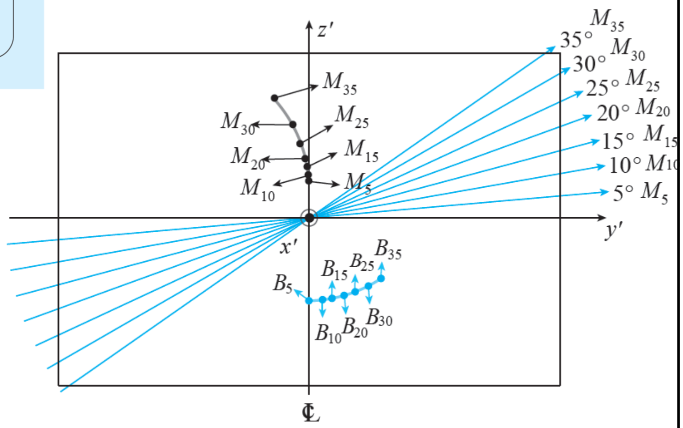
• The use of metacentric height (GM) as the restoring arm is not valid for a ship at a large angle of inclination.

To determine the restoring arm "GZ", it is necessary to know the positions of the center of mass (G) and the new position of the center of buoyancy (B_1).

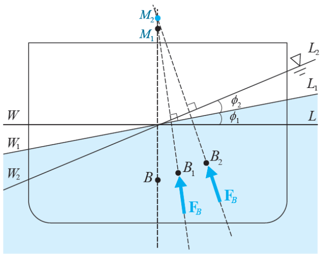
Restoring Moment at Large Angle of Inclination (2/3)



M: The intersection point of the vertical line through the center of buoyancy at **previous position** (B_{i-1}) with the vertical line through the center of buoyancy at **present position** (B_i) **after inclination**

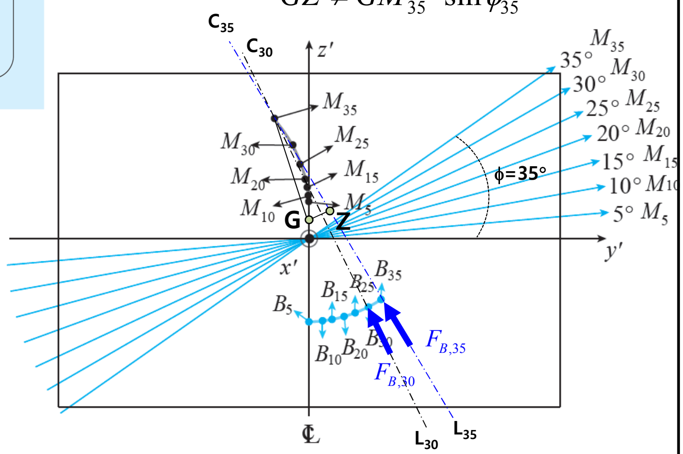


Restoring Moment at Large Angle of Inclination (3/3)



M: The intersection point of the vertical line through the center of buoyancy at **previous position** (B_{i-1}) with the vertical line through the center of buoyancy at **present position** (B_i) **after inclination**

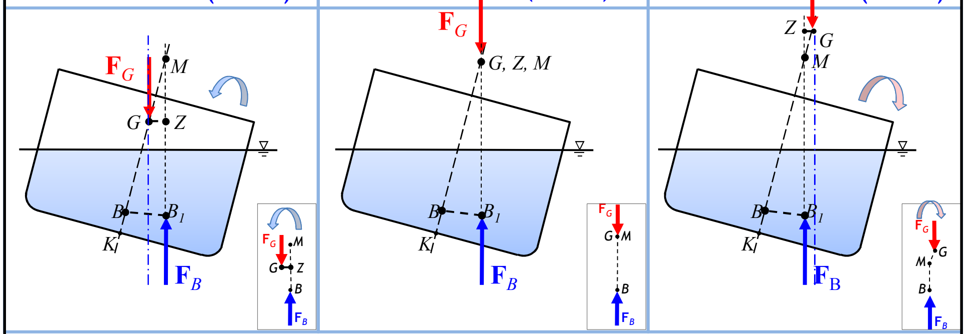
$$GZ \neq GM_{35} \cdot \sin\phi_{35}$$



Stability of a Ship According to Relative Position between "G", "B", and "M" at Small Angle of Inclination

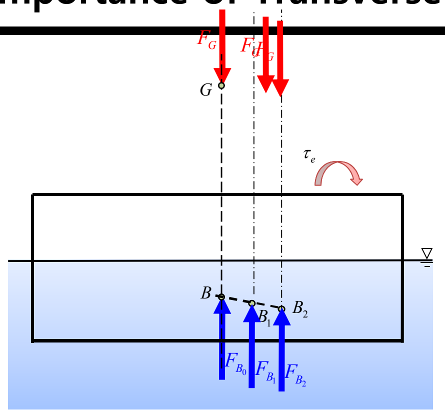
- **Righting (Restoring) Moment:** Moment to return the ship to the upright floating position
- **Stable / Neutral / Unstable Condition:** Relative height of G with respect to M is one measure of stability.

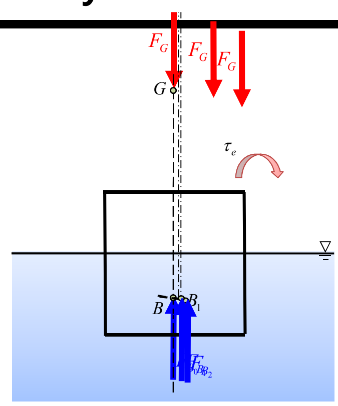
• Stable Condition **(G < M)** • Neutral Condition **(G = M)** • Unstable Condition **(G > M)**



G: Center of mass *K*: Keel
B: Center of buoyancy at upright position B_1: Changed center of buoyancy
F_G: Weight of ship F_B: Buoyant force acting on ship
Z: The intersection of the line of buoyant force through B_1 with the transverse line through G
M: The intersection of the line of buoyant force through B_1 with the centerline of the ship

Importance of Transverse Stability





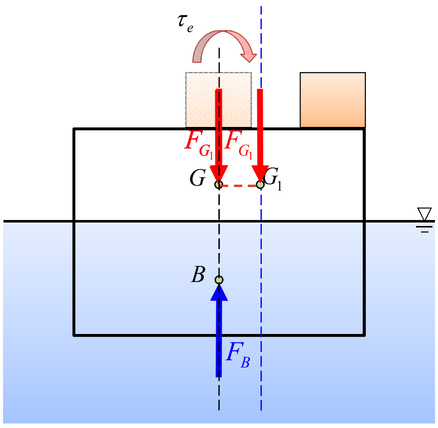
The ship is inclined further from it.
The ship is in static equilibrium state.

The ship is inclined further from it.
Because of the limit of the breadth, "B" can not move further. the ship will capsize.

As the ship is inclined, the position of the center of buoyancy "B" is changed.
Also the **position of the center of mass "G" relative to inertial frame is changed**.

One of the most important factors of stability is the breadth.
So, we usually consider that transverse stability is more important than longitudinal stability.

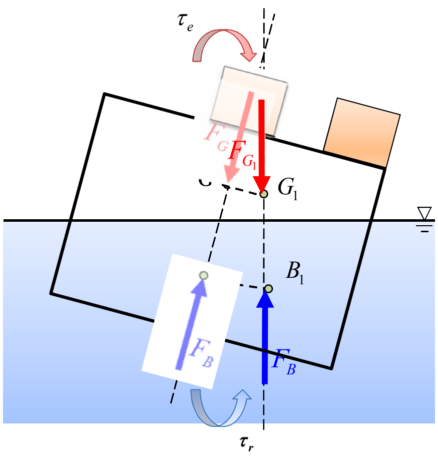
Summary of Static Stability of a Ship (1/3)



G: Center of mass of a ship
G_1: New position of center of mass after the object on the deck moves to the right side
F_G: Gravitational force of a ship
B: Center of buoyancy at initial position
F_B: Buoyant force acting on a ship
B_1: New position of center of buoyancy after the ship has been inclined
Z: The intersection of a line of buoyant force(F_B) through the new position of the center of buoyancy (B_1) with the transversely parallel line to the waterline through the center of mass of a ship(G)

- When an object on the deck moves to the right side of a ship, the total center of mass of the ship moves to the point G_1, off the centerline.
- Because the buoyant force and the gravitational force are not on one line, the forces induces a moment to incline the ship.
  - * We have a moment on this object relative to any point that we choose. It does not matter where we pick a point.

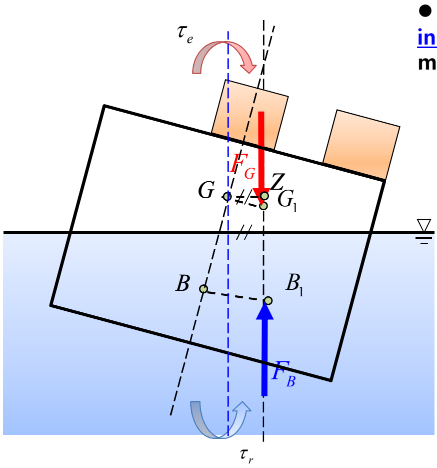
Summary of Static Stability of a Ship (2/3)



G: Center of mass of a ship
G_1: New position of center of mass after the object on the deck moves to the right side
F_G: Gravitational force of a ship
B: Center of buoyancy at initial position
F_B: Buoyant force acting on a ship
B_1: New position of center of buoyancy after the ship has been inclined
Z: The intersection of a line of buoyant force(F_B) through the new position of the center of buoyancy (B_1) with the transversely parallel line to the waterline through the center of mass of a ship(G)

- The total moment will only be zero when the buoyant force and the gravitational force are on one line. If the moment becomes zero, the ship is in static equilibrium state.

Summary of Static Stability of a Ship (3/3)



G: Center of mass of a ship
G_1: New position of center of mass after the object on the deck moves to the right side
F_G: Gravitational force of a ship
B: Center of buoyancy at initial position
F_B: Buoyant force acting on a ship
B_1: New position of center of buoyancy after the ship has been inclined
Z: The intersection of a line of buoyant force(F_B) through the new position of the center of buoyancy (B_1) with the transversely parallel line to the waterline through the center of mass of a ship(G)

- When the object on the deck returns to the initial position in the centerline, the center of mass of the ship returns to the initial point G.
  - Then, because the buoyant force and the gravitational force are not on one line, the forces induces a restoring moment to return the ship to the initial position.

  ※ Naval architects refer to the restoring moment as "righting moment".

  - The moment arm of the buoyant force and gravitational force about G is expressed by GZ, where Z is defined as the intersection point of the line of buoyant force(F_B) through the new position of the center of buoyancy(B_1) with the transversely parallel line to the waterline through the center of mass of the ship (G).

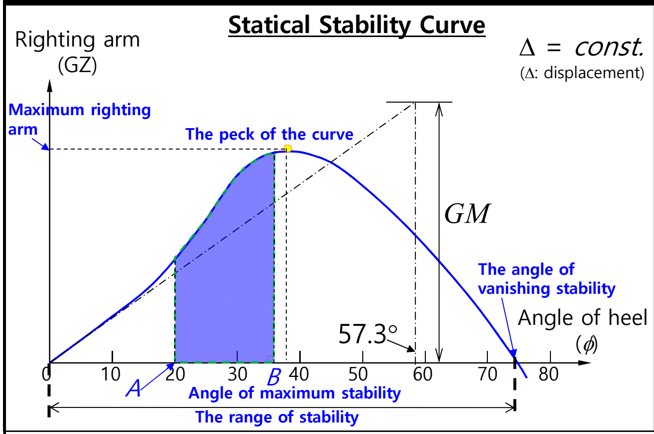
• Transverse Righting Moment

$$\tau_{righting} = F_B \cdot \underline{GZ}$$

  - By the restoring moment, the ship returns to the initial position.

5.3 Evaluation of Stability

[Review] Statical Stability Curve



✓Slope of the curve at zero degree: metacentric height (GM)

$$GZ \approx GM \sin|\phi|$$

✓The peak of a statical stability curve: maximum righting arm, angle of maximum stability

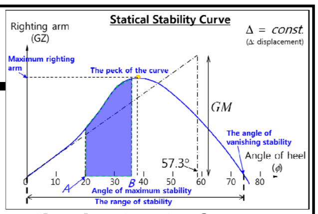
✓The product of the displacement and the maximum righting arm: the maximum heeling moment that the ship can experience without capsizing

✓The range of stability: the range over which the ship has positive righting arms

✓ The area under the curve, such as between angle A and angle B: the work required to heel the ship from angle A to angle B.

What criteria is considered to evaluate the ship's stability?
What is satisfactory stability? How much stable a ship must be?

Stability Criteria in General



☑ Various researchers and regulatory bodies prescribed criteria for deciding if the stability is satisfactory.
In this chapter, we present examples of such criteria based on consideration of actual shape and characteristics of the curves of righting and heeling moment (or arm) for an undamaged ship (intact ship) through large angles of heel.

☑ Features of the curves that warrant consideration from a purely static viewpoint are:

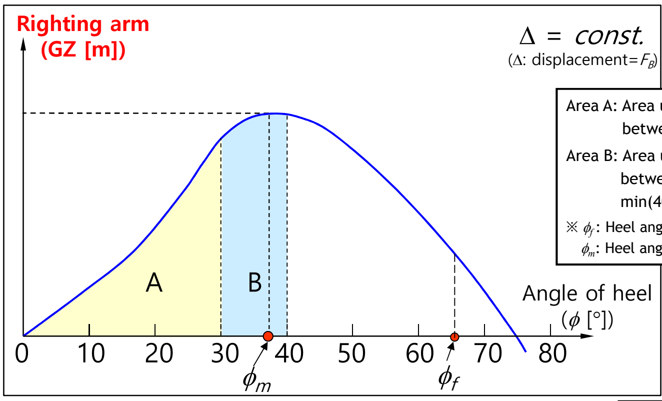
Static considerations
- The angle of steady heel
- The range of positive stability
- The relative magnitudes of the heeling arm and the maximum righting arm.

The work and energy considerations (dynamic stability)

Stability Criteria
- IMO Regulations for Intact Stability

(IMO Res.A-749(18) ch.3.1)

$\tau_r = GZ \cdot F_B$



Area A: Area under the righting arm curve between the heel angle of 0° and 30°

Area B: Area under the righting arm curve between the heel angle of 30° and min(40°, ϕ_f)

※ ϕ_f: Heel angle at which openings in the hull submerge
ϕ_m: Heel angle of maximum righting arm

IMO Regulations for Intact Stability

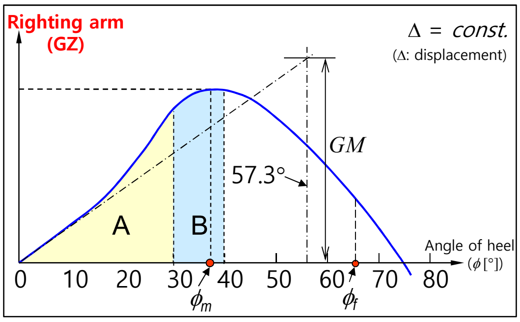
(a) Area A ≥ 0.055 (m·rad)
(b) Area A + B ≥ 0.09 (m·rad)
(c) Area B ≥ 0.030 (m·rad)
(d) GZ ≥ 0.20 (m) at an angle of heel equal to or greater than 30°.
(e) GZ_{max} should occur at an angle of heel equal to or greater than 25°.
(f) The initial metacentric height GM_o should not be less than 0.15 (m).

※ After receiving the approval for the intact and damage stability of IMO regulation from owner and classification society, ship construction can be proceed.

Merchant Ship Stability Criteria
- IMO Regulations for Intact Stability

(IMO Res.A-749(18) ch.3.1)

☑ **IMO recommendation on intact stability for passenger and cargo ships**



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※ ϕ_f: Heel angle at which openings in the hull
ϕ_m: Heel angle of maximum righting arm

※ After receiving approval of calculation of IMO regulation from Owner and Classification Society, ship construction can proceed.

IMO Regulations for Intact Stability

(a) Area A ≥ 0.055 (m·rad)
(b) Area A + B ≥ 0.09 (m·rad)
(c) Area B ≥ 0.030 (m·rad)

→ **The work and energy considerations (dynamic stability)**

(d) GZ ≥ 0.20 (m) at an angle of heel equal to or greater than 30°
(e) GZ_{max} should occur at an angle of heel preferably exceeding 30° but not less than 25°.
(f) The initial metacentric height GM_o should not be less than 0.15 (m).

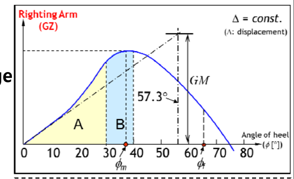
→ **Static considerations**

Merchant Ship Stability Criteria
- IMO Regulations for Intact Stability

(IMO Res.A-749(18) ch.4.9)

☑ Special Criteria for Certain Types of Ships
- Containerships greater than 100 m

These requirements apply to containerships greater than 100 m. They may also be applied to other cargo ships with considerable flare or large water plane areas. The administration may apply the following criteria instead of those in paragraphs of previous slide.



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IMO Regulations for containerships greater than 100 m

(a) Area A ≥ 0.009/C (m-rad)

(b) Area A + B ≥ 0.016/C (m-rad)

(c) Area B ≥ 0.006/C (m-rad)

(d) GZ ≥ 0.033/C (m) at an angle of heel equal to or greater than 30°

(e) GZ_{max} ≥ 0.042/C (m)

(f) The total area under the righting arm curve (GZ curve) up to the angle of flooding ϕ_f should not be less than 0.029/C (m-rad)

In the above criteria **the form factor C** should be calculated using the formula and figure on the right-hand side.

$$C = \frac{dD'}{B^2_m}\sqrt{\frac{d}{KG}\left(\frac{C_B}{C_W}\right)}\sqrt[2]{\frac{100}{L}}$$

where, d: Mean draught (m)

$D' = D + h\frac{2b - B_D}{B_D}\left(\frac{2\sum l_H}{L}\right)$ as defined in figure on the right-hand side.

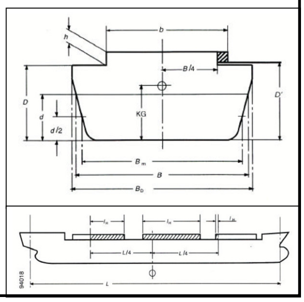
D: Moulded depth of the ship (m)

B: Moulded breadth of the ship (m)

KG: Height of the centre of gravity in (m) above the keel not to be taken as less than d

C_B: Block coefficient

C_W: Water plane coefficient

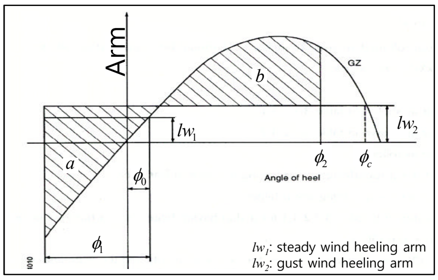


Design Criteria Applicable to All Ships
- IMO Regulations for Severe Wind and Rolling Criteria (Weather Criteria)

(IMO Res.A-749(18) ch.3.2)

☑ Scope

The weather criteria should govern the minimum requirements for passenger or cargo ships of 24 m in length and over.



ϕ_0: Angle of heel under action of steady wind

ϕ_1: Angle of roll to windward due to wave action

ϕ_2: Angle of down flooding (ϕ_f) or 50°, whichever is less

where,

ϕ_f: Angle of heel at which openings in the hull submerge

ϕ_c: Angle of the second intersection between wind heeling arm and GZ(righting arm) curves

Area a: The shaded area between angle ϕ_1 and the first intersection of righting arm curve with heeling arm curve

Area b: The shaded area between the first intersection of righting arm curve with heeling arm curve and angle ϕ_2

IMO Regulations for Severe Wind and Rolling Criteria (Weather Criteria)

(a) ϕ_0 should be limited to 16° or 80% of the angle of deck edge immersion (ϕ_f), whichever is less.

The ship is subjects to a steady wind pressure acting perpendicular to the ship's center line which results in a steady wind heeling arm (lw_1).

$$lw_1 = \frac{P \cdot A \cdot Z}{1000 \cdot g \cdot \nabla}\ (m) \qquad (P = 504\ N/m^2,\ g = 9.81\,m/s^2)$$

A : Lateral projected area above water line.
Z : Vertical distance from the center of wind pressure to the center of water pressure

(b) Under these circumstances, *area b* should be equal to or greater than *area a*. ⇨ **The work and energy considerations (dynamic stability)**

The ship is subjected to a gust wind pressure which results in a gust wind heeling arm (lw_2).

$$lw_2 = 1.5 \cdot lw_1\ (m)$$

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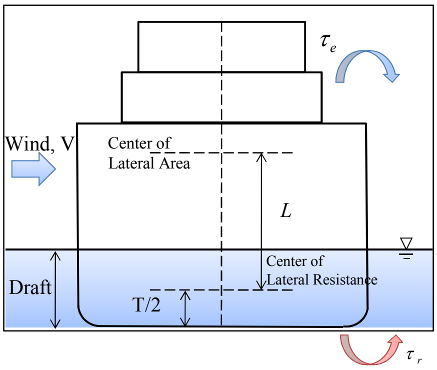
War Ship Stability Criteria
- U.S. Navy Criteria (1/2)

☑ **General U.S. Navy criteria are intended to ensure the adequacy of stability of all types and sizes of naval ships, as evidenced by sufficient righting energy to withstand various types of upsetting of heeling moments.**

(Example) Beam Winds Combined with Rolling



When winds of high velocity exist, beam winds and rolling are considered simultaneously.

If the water were still, the ship would require only sufficient righting moment to overcome the heeling moment produced by the action of the wind on the ship's "sail area".

However, when the probability of wave action is taken into account, an additional allowance of dynamic stability is required to absorb the energy imparted to the ship by the rolling motion.

L: Center height of projected sail area above 0.5T
A: Projected sail area (ft²), V: average wind speed (knots)
ϕ: Angle of heel (degree), Δ: Displacement (LT)
ϕ_m: Angle of maximum righting arm (degree)

* Brown, A.J., Deybach, F., "Towards A Rational Intact Stability Criteria For Naval Ships", Naval Engineers Journal, pp.65-77, 1998

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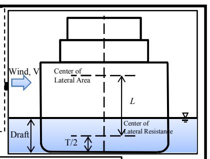
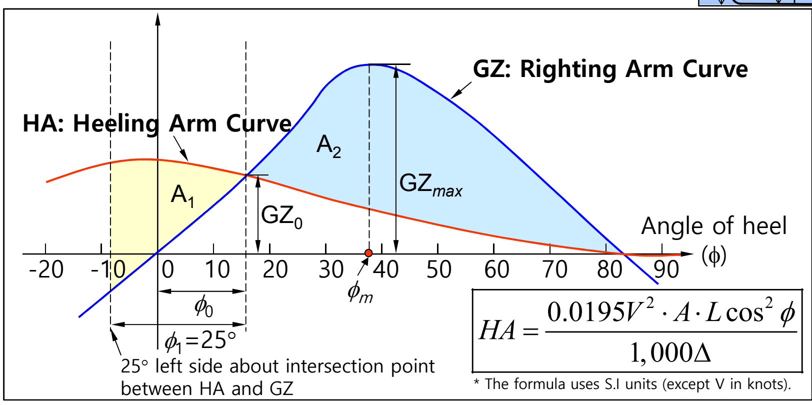
War Ship Stability Criteria
- U.S. Navy Criteria (2/2)

L: Center height of projected sail area above 0.5T
A: Projected sail area (ft²)
V: Average wind speed (knots)
ϕ: Angle of heel (degree)
Δ: Displacement (LT)
ϕ_m: Angle of maximum righting arm



☑ **Stability is considered satisfactory if:**



$$HA = \frac{0.0195V^2 \cdot A \cdot L\cos^2\phi}{1{,}000\Delta}$$

* The formula uses S.I units (except V in knots).

- **Regulation**

(a) $GZ_0 \le 0.6 \cdot GZ_{max}$: **Static considerations**

(b) $A_2 \ge 1.4 \cdot A_1$: **The work and energy considerations (dynamic stability)**

* Brown, A.J., Deybach, F., "Towards A Rational Intact Stability Criteria For Naval Ships", Naval Engineers Journal, pp.65-77, 1998

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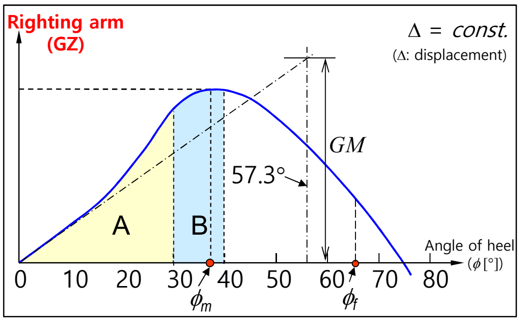
5.4 Example of Stability Evaluation for 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition (14mt)

Merchant Ship Stability Criteria - IMO Regulations for Intact Stability

(IMO Res.A-749(18) ch.3.1)

☑ **IMO recommendation on intact stability for passenger and cargo ships**



Area A: Area under the righting arm curve between the heel angle of 0° and 30°

Area B: Area under the righting arm curve between the heel angle of 30° and min(40°, ϕ_f)

※ ϕ_f : Heel angle at which openings in the hull

ϕ_m: Heel angle of maximum righting arm

※ After receiving approval of calculation of IMO regulation from owner and classification society, ship construction can proceed.

IMO Regulations for Intact Stability

(a) Area A ≥ 0.055 (m·rad)
(b) Area A + B ≥ 0.09 (m·rad)
(c) Area B ≥ 0.030 (m·rad)

→ **The work and energy considerations (dynamic stability)**

(d) GZ ≥ 0.20 (m) at an angle of heel equal to or greater than 30°
(e) GZ_{max} should occur at an angle of heel preferably exceeding 30° but not less than 25°.
(f) The initial metacentric height GM_o should not be less than 0.15 (m).

→ **Static considerations**

Effect of Free Surfaces of Liquids in Tanks

(IMO Res.A-749(18) ch.3.3)

For all conditions, the initial metacentric height (GM) and the stability curves should be corrected for the effect of free surfaces of liquids in tanks.

(Assumption) Small angle of inclination

Initial metacentric height(GM)

$$GM = KB + BM - KG$$

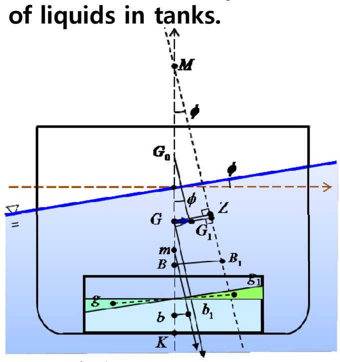
Correction for the effect of free surfaces of liquids in tanks

$$KG \rightarrow KG_0 = KG + GG_0$$

$$G_0M = KB + BM - (KG + GG_0)$$
$$= (KB + BM - KG) - GG_0$$
$$= GM - GG_0$$

$$GG_0 = \frac{\sum \rho_F \cdot i_T}{\rho_{SW} \nabla}$$

$\sum \rho_F \cdot i_T$: **Free surface moment**



G: Center of total mass (gravity)
G0: Virtual risen center of gravity
G1: New position of center of total mass (gravity)
G1': The intersection of the line GZ with G_0G_1
B: Center of buoyancy
B1: New position of center of buoyancy after the ship has been inclined
g: Center of the emerged volume
g1: Center of the submerged volume
b: Center of liquid in tank
b1: New position of center of liquid in tank
m: Metacenter of cargo hold

i_T: Moment of inertia of liquid plane area in tank about longitudinal axis
ρ_F: Density of liquid in tank
ρ_{SW}: Density of sea water
∇: Displacement volume of the ship

How can you get the value of free surface moment?

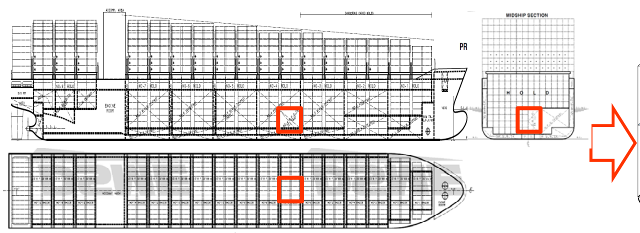
Effect of Free Surfaces of Liquids in Tanks

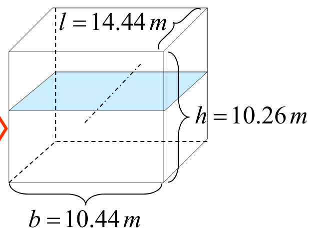
- 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition

$$GG_0 = \frac{\sum \rho_F \cdot i_T}{\rho_{SW} \nabla}$$

$\sum \rho_F \cdot i_T$: **Free surface moment**

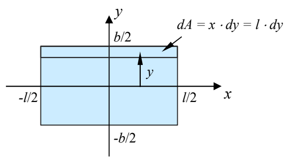
(Example) Free surface moment of No. 4 heavy fuel oil tank (center) in No. 4 hold





$$i_T = \frac{l \cdot b^3}{12} = \frac{(14.44) \cdot (10.44)^3}{12} = 1,369 (m^4)$$

$$\text{Free surface moment}_{NO.4HFOT(C)} = \rho_F \cdot i_T$$
$$= 0.98 \cdot 1,369$$
$$= 1,342 (m \cdot ton)$$



$$i_T = i_x = \int_{-b/2}^{b/2} y^2 dA = \int_{-b/2}^{b/2} y^2 (l \cdot dy)$$
$$= l \int_{-b/2}^{b/2} y^2 dy = \frac{l \cdot b^3}{12}$$

i_T: Moment of inertia of liquid plane area in tank about longitudinal axis
ρ_F: Density of liquid in tank (heavy fuel oil) = 0.98 (ton/m³)

Effect of Free Surfaces of Liquids in Tanks
- 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition

$GG_0 = \frac{\sum \rho_F \cdot i_T}{\rho_{SW} \nabla}$ ($\sum \rho_F \cdot i_T$: Free surface moment)

$\text{Free surface moment}_{NO.4\,HFOT(C)} = 1,342\,(m \cdot ton)$

Free surface moments of all heavy fuel oil tanks

WEIGHT ITEMS	FILL.	S.G	WEIGHT	L.C.G	V.C.G	F.S.M
NO4 HFOT(C)	0.00	0.9800	0.0	179.625	7.184	1341.8
NO4 HFOT(P)	0.00	0.9800	0.0	179.625	7.870	1822.2
NO4 HFOT(S)	0.00	0.9800	0.0	179.625	7.870	1822.2
NO5 DEEP HFOT(P)	0.00	0.9800	0.0	129.975	11.297	299.4
NO5 DEEP HFOT(S)	0.00	0.9800	0.0	129.975	11.297	299.4
NO6 DEEP HFOT(P)	0.00	0.9800	0.0	101.075	11.297	299.4
NO6 DEEP HFOT(S)	0.00	0.9800	0.0	101.075	11.297	299.4
NO7 DEEP HFOT(P)	54.06	0.9800	222.1	72.100	7.931	296.0
NO7 DEEP HFOT(S)	54.06	0.9800	222.1	72.100	7.931	296.0
NO1 HFO SETT.TK	98.00	0.9800	89.0	69.900	17.500	83.4
NO2 HFO SETT.TK	98.00	0.9800	89.0	69.900	17.500	83.4
NO1 HFO SERV.TK	98.00	0.9800	89.0	69.900	17.500	83.4
NO2 HFO SERV.TK	98.00	0.9800	89.0	69.900	17.500	83.4

$\text{Free surface moment}_{Total\ HFOT} = 7,109.2\,(m \cdot ton)$

Effect of Free Surfaces of Liquids in Tanks
- 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition

$GG_0 = \frac{\sum \rho_F \cdot i_T}{\rho_{SW} \nabla}$ ($\sum \rho_F \cdot i_T$: Free surface moment)

Calculating free surface moment of other tank at homo. scantling arrival condition(14mt)

WEIGHT ITEMS	FILL. (%)	S.G	WEIGHT (MT)	L.C.G (M)	V.C.G (M)	F.S.M (MT-M)
NO2 DB WBT(P)	100.00	1.0250	560.1	228.280	2.640	0.0
NO2 DB WBT(S)	100.00	1.0250	560.1	228.280	2.640	0.0
NO3 DB WBT(P)	100.00	1.0250	940.7	200.357	2.015	0.0
NO3 DB WBT(S)	100.00	1.0250	940.7	200.357	2.015	0.0
NO3 WWBT(P)	100.00	1.0250	1070.1	201.907	11.873	0.0
NO3 WWBT(S)	100.00	1.0250	1070.1	201.907	11.873	0.0
NO4 DB WBT(P)	100.00	1.0250	1266.8	173.078	1.923	0.0
NO4 DB WBT(S)	100.00	1.0250	1266.8	173.078	1.923	0.0
NO5 DB WBT(P)	100.00	1.0250	1145.4	143.534	1.690	0.0
NO5 DB WBT(S)	100.00	1.0250	1145.4	143.534	1.690	0.0
NO5 WWBT(P)	100.00	1.0250	977.8	143.500	12.369	24.3
NO5 WWBT(S)	100.00	1.0250	977.8	143.500	12.369	24.3
NO6 DB WBT(P)	100.00	1.0250	1143.6	114.585	1.690	0.0
NO6 DB WBT(S)	100.00	1.0250	1143.6	114.585	1.690	0.0
NO7 DB WBT(P)	100.00	1.0250	1031.2	85.978	1.778	0.0
NO7 DB WBT(S)	100.00	1.0250	1031.2	85.978	1.778	0.0
TOTAL WATER BALLAST			16271.3	156.848	4.463	48.7
FRESH WATER			41.6	45.600	12.757	20.7
HEAVY FUEL OIL			800.0	71.121	12.188	7109.2
DIESEL OIL			40.0	66.300	11.175	60.5
LUBRICATING OIL			47.4	66.318	7.861	14.1
DEADWEIGHT CONSTANT			900.0	73.100	24.200	0.0
TOTAL DEADWEIGHT			92328	143.449	18.408	7253.3
LIGHT SHIP			27710	122.656	16.000	
TOTAL DISPLACEMENT			120038	138.649	17.852	7253.3

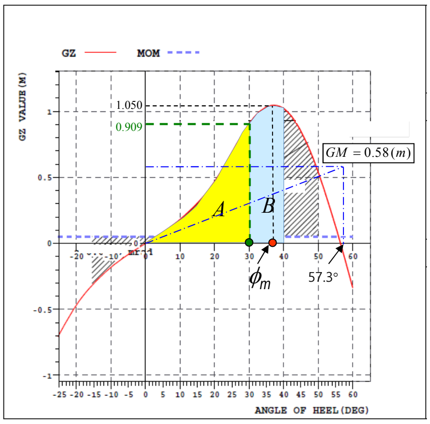
$$GG_0 = \frac{\sum \rho_F \cdot i_T}{\rho_{SW} \nabla} = \frac{7,253.3}{120,038} = 0.06(m)$$

Correction for effect of free surface of liquid in tanks is as follows:

$G_0M = GM - GG_0$ ← Initial metacentric height (GM) at this loading condition = 0.64(m)

$= 0.64 - 0.06 = 0.58\,(m)$

IMO Regulations for General Intact Stability Criteria
- 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition



Area A: Area under the righting arm curve between the heel angle of 0° and 30°

Area B: Area under the righting arm curve between the heel angle of 30° and min(40°, ϕ_f)

※ ϕ_f: Heel angle at which openings in the hull

ϕ_f = 50°

Area B: Area under the righting arm curve between the heel angle of 30° and 40°

※ ϕ_m: Heel angle of maximum righting arm = 36.8°

(a) Area A ≥ 0.055 (m·rad)

$$Area\ \ A = 0.148(m \cdot rad) \geq 0.055(m \cdot rad)$$

(b) Area A + B ≥ 0.09 (m·rad)

$$Area\ \ A + B = 0.301(m \cdot rad) \geq 0.090(m \cdot rad)$$

(c) Area B ≥ 0.030 (m·rad)

$$Area\ \ B = 0.153(m \cdot rad) \geq 0.030(m \cdot rad)$$

(d) GZ ≥ 0.20 (m) at an angle of heel equal to or greater than 30°

$$GZ_{at\,angle\ of\ heel=30°} = 0.909(m) \geq 0.20(m)$$

(e) GZ_{max} should occur at an angle of heel preferably exceeding 30° but not less than 25°.

$$\phi_m = 36.8° \geq 25°$$

(f) The initial metacentric height GM_0 should not be less than 0.15 (m).

$$GM = 0.58m \geq 0.15(m)$$

All regulations are satisfied.

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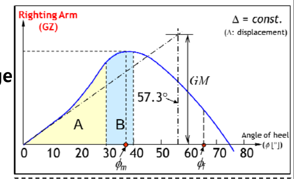
Merchant Ship Stability Criteria
- IMO Regulations for Intact Stability

☑ **Special Criteria for Certain Types of Ships**

(IMO Res.A-749(18) ch.4.9)

- **Containerships greater than 100 m**

These requirements apply to containerships greater than 100 m. They may also be applied to other cargo ships with considerable flare or large water plane areas. The administration may apply the following criteria instead of those in paragraphs of previous slide.



Area A: Area under the righting arm curve between the heel angle of 0° and 30°

Area B: Area under the righting arm curve between the heel angle of 30° and min(40°, ϕ_f)

※ ϕ_f: Heel angle at which openings in the hull submerge
ϕ_m: Heel angle of maximum righting arm

IMO Regulations for containerships greater than 100 m

(a) Area A ≥ 0.009/C (m-rad)

(b) Area A + B ≥ 0.016/C (m-rad)

(c) Area B ≥ 0.006/C (m-rad)

(d) GZ ≥ 0.033/C (m) at an angle of heel equal to or greater than 30°

(e) GZ_{max} ≥ 0.042/C (m)

(f) The total area under the righting lever curve (GZ curve) up to the angle of flooding ϕ_f should not be less than 0.029/C (m-rad)

In the above criteria **the form factor C** should be calculated using the formula and figure on the right-hand side.

$$C = \frac{dD'}{B_m^2}\sqrt{\frac{d}{KG}}\left(\frac{C_B}{C_W}\right)\sqrt[2]{\frac{100}{L}}$$

where, d: Mean draught (m)

$$D' = D + h\frac{2b - B_D}{B_D}\left(\frac{2\sum l_H}{L}\right)$$ as defined in figure on the right-hand side.

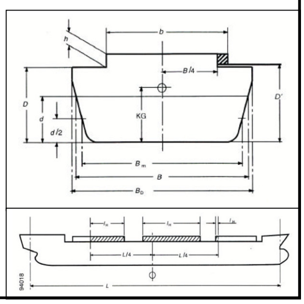
D: Moulded depth of the ship (m)

B: Moulded breadth of the ship (m)

KG: Height of the centre of gravity in (m) above the keel not to be taken as less than d

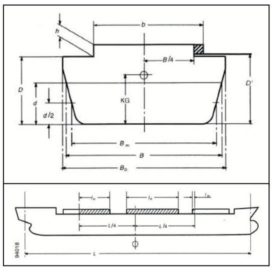
C_B: Block coefficient

C_W: Water plane coefficient



IMO Regulations for Intact Stability: Containerships greater than 100 m - 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition

In the above criteria **the form factor C** should be calculated using the formula and figure on the right-hand side.



$$C = \frac{dD'}{B_m^2}\sqrt{\frac{d}{KG}}\left(\frac{C_B}{C_W}\right)^2\sqrt{\frac{100}{L}}$$

where, d: Mean draft (m)

$$D' = D + h\frac{2b - B_D}{B_D}\left(\frac{2\sum l_H}{L}\right)$$

KG: Height of the centre of gravity in m above the keel (m) not to be taken as less than d

D: Moulded depth of the ship (m)

B: Moulded breadth of the ship (m)

C_B: Block coefficient

C_W: Water plane coefficient

d	D'	D	B	KG	CB	CW
14.15	25.452125	24.2	40	17.852	0.71693	0.89044
				KG0		
				17.913		
h	b	BD	lH	L		
1.8	35.9	40	126	288		
C				72		
0.07654965						

⇨ **All regulations are satisfied.**

IMO regulations for containerships greater than 100 m

(a) Area A ≥ 0.009/C = 0.117 (m·rad) $Area\ A = 0.148(m \cdot rad)$

(b) Area A + B ≥ 0.016/C = 0.209 (m·rad) $Area\ A + B = 0.301(m \cdot rad)$

(c) Area B ≥ 0.006/C = 0.078 (m·rad) $Area\ B = 0.153(m \cdot rad)$

(d) GZ ≥ 0.033/C = 0.431 (m) at an angle of heel equal to or greater than 30° $GZ_{at\ angle\ of\ heel=30°} = 0.909(m)$

(e) GZ_{max} ≥ 0.042/C = 0.549 (m) $GZ_{max} = 1.050(m)$

(f) The total area under the righting arm curve (GZ curve) up to the angle of flooding ϕ_f should not be less than 0.029/C = 0.379 (m·rad) $Area\ GZ\ Curve = 0.4644(m \cdot rad)$

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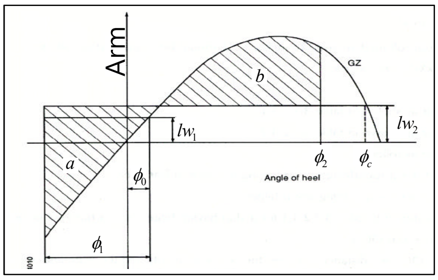
Design Criteria Applicable to All Ships - IMO Regulations for Severe Wind and Rolling Criteria (Weather Criteria)

☑ **Scope** **(IMO Res.A-749(18) ch.3.2)**

The weather criteria should govern the minimum requirements for passenger or cargo ships of 24 m in length and over.



ϕ_0: Angle of heel under action of steady wind

ϕ_1: Angle of roll to windward due to wave action

ϕ_2: Angle of down flooding (ϕ_f) or 50°, whichever is less

where,

ϕ_f: Angle of heel at which openings in the hull submerge

ϕ_c: Angle of the second intersection between wind heeling arm and GZ(righting arm) curves

Area a: The shaded area between angle ϕ_1 and the first intersection of righting arm curve with heeling arm curve

Area b: The shaded area between the first intersection of righting arm curve with heeling arm curve and angle ϕ_2

IMO Regulations for Severe Wind and Rolling Criteria (Weather Criteria)

(a) ϕ_0 should be limited to 16° or 80% of the angle of deck edge immersion (ϕ_f), whichever is less.

The ship is subjects to a steady wind pressure acting perpendicular to the ship's center line which results in a steady wind heeling arm (lw_1).

$$lw_1 = \frac{P \cdot A \cdot Z}{1000 \cdot g \cdot \nabla}\ (m) \qquad (P = 504\ N/m^2,\ g = 9.81 m/s^2)$$

A : Lateral projected area above water line.
Z : Vertical distance from the center of wind pressure to the center of water pressure

(b) Under these circumstances, *area b* should be equal to or greater than *area a*. ⇨ **The work and energy considerations (dynamic stability)**

The ship is subjected to a gust wind pressure which results in a gust wind heeling arm (lw_2).

$$lw_2 = 1.5 \cdot lw_1\ (m)$$

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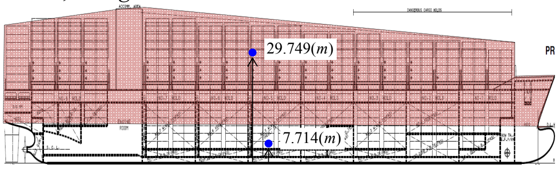
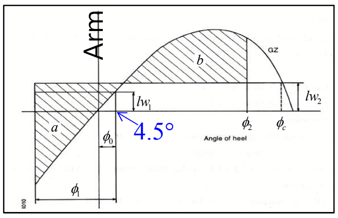
IMO Regulations for Severe Wind and Rolling Criteria (Weather Criteria) - 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition

(a) ϕ_0 is suggested to 16° or 80% of the angle of deck edge immersion (ϕ_f), whichever is less.

First, we have to know the value of a steady wind heeling arm (lw_1).

$$lw_1 = \frac{P \cdot A \cdot Z}{1{,}000 \cdot g \cdot \nabla} \ (m) \qquad P = 504(N/m^2),\ g = 9.81(m/s^2)$$





A : Lateral projected area above water line = 9,871(m[2])

Z : Vertical distance from center of wind pressure to center of water pressure

= (Vertical distance from base line to center of wind pressure) - (Vertical distance from base line to center of water pressure)

= 29.749 – 7.714 = 22.04(m)

$$lw_1 = \frac{P \cdot A \cdot Z}{1{,}000 \cdot g \cdot \nabla} = \frac{504 \cdot 9{,}871 \cdot 22.04}{1{,}000 \cdot 9.81 \cdot 117{,}110} = 0.1(m)$$

Second, the angle of heel under action of steady wind (ϕ_0) is angle of intersection between GZ curve and lw$_1$. The ϕ_0 is 4.5°.

The regulation (a) is satisfied.

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IMO Regulations for Severe Wind and Rolling Criteria (Weather Criteria) - 7,000 TEU Container Carrier at Homo. Scantling Arrival Condition

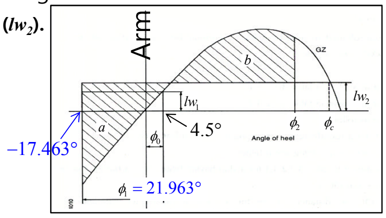
(b) Under these circumstances, *area b* should be equal to or greater than *area a*.

First, we have to know the value of a gust wind heeling arm (lw_2).

$$lw_2 = 1.5 \cdot lw_1 = 1.5 \cdot 0.1 = 0.15(m)$$

Second, we have to know the angle of roll (ϕ_1).

$$\phi_1 = 109 \cdot k \cdot x_1 \cdot x_2 \cdot \sqrt{r \cdot s} = 109 \cdot 0.99 \cdot 0.93 \cdot 1 \cdot \sqrt{0.887 \cdot 0.054} = 21.963°$$



Area a: The shaded area between angle ϕ_1 and the first intersection of righting arm curve with heeling arm curve

Area b: The shaded area between the first intersection of righting arm curve with heeling arm curve and angle ϕ_2

Third, ϕ_2 is angle of down flooding (ϕ_f) or 50°, whichever is less. We assume that ϕ_2 for this container carrier is 50°.

Forth, the area a is 0.0384 (m·rad) and the area b is 0.3661 (m·rad).

The regulation (b) is satisfied.

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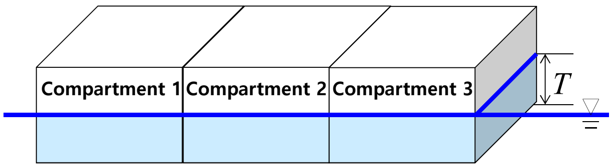
5.5 Damage Stability

Damage of a Box-Shaped Ship

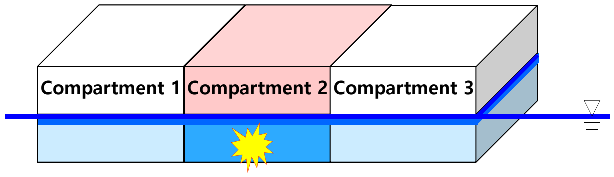
✓ A ship is composed of three compartments.



When a compartment of the ship is damaged, what is the new position of this ship?

Damage of a Box-Shaped Ship (Immersion)

When the compartment in the midship part is damaged, what is the new position of this ship?



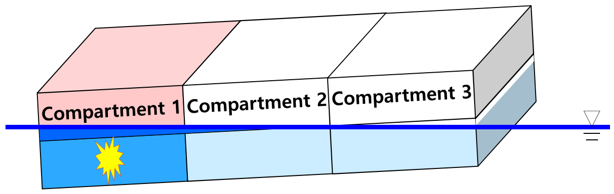
The position of the ship will be changed.

Immersion

* The new position of the ship can be calculated by **the lost buoyancy and added weight methods**.

Damage of a Box-Shaped Ship (Immersion, Trim)

When the compartment at the after part of the ship is damaged, what is the new position of this ship?



"Trim by stern"(draft at AP > draft at FP)

The position of the ship will be changed.

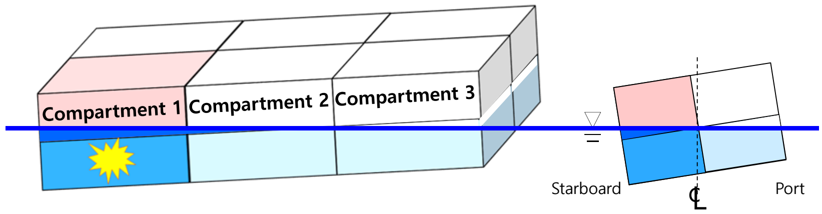
Immersion + **Trim**

* The new position of the ship can be calculated by **the lost buoyancy and added weight methods**.

Damage of a Box-Shaped Ship (Immersion, Trim, Heel)

✓ When the ship is composed of **"six" compartments**.

When the compartment at the **after and right** part of the ship is damaged, what is the new position of the ship?

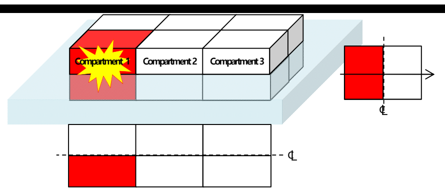


The position of the ship will be changed.

Immersion + **Trim** + **Heel**

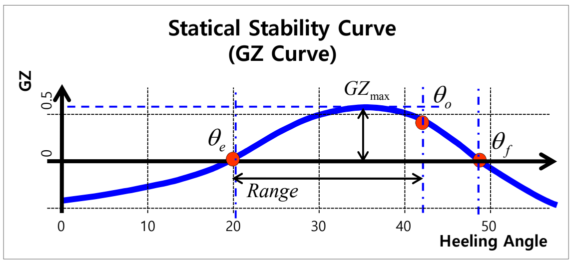
* The new position of the ship can be calculated by **the lost buoyancy and added weight methods**.

Damage of a Box-Shaped Ship (GZ Curve)



Immersion + **Trim** + **Heel**

✓ To measure the damage stability, we should find the a statical stability curve (GZ curve) of this damage case by finding the new center of buoyancy (B) and center of mass (G).



θ_e: Equilibrium heel angle

θ_v: minimum(θ_f, θ_o)

(in this case, θ_v equals to θ_o)

GZ_{max}: Maximum value of GZ

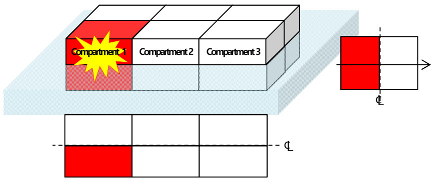
Range: Range of positive righting arm

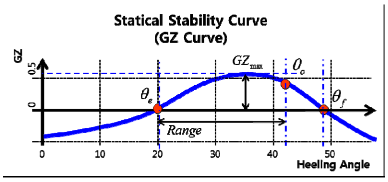
Flooding stage: Discrete step during the flooding process

θ_f: Angle of flooding (righting arm becomes negative)

θ_o: Angle at which an **"opening"** incapable of being closed weathertight becomes submerged

Two Methods to Measure the Ship's Damage Stability





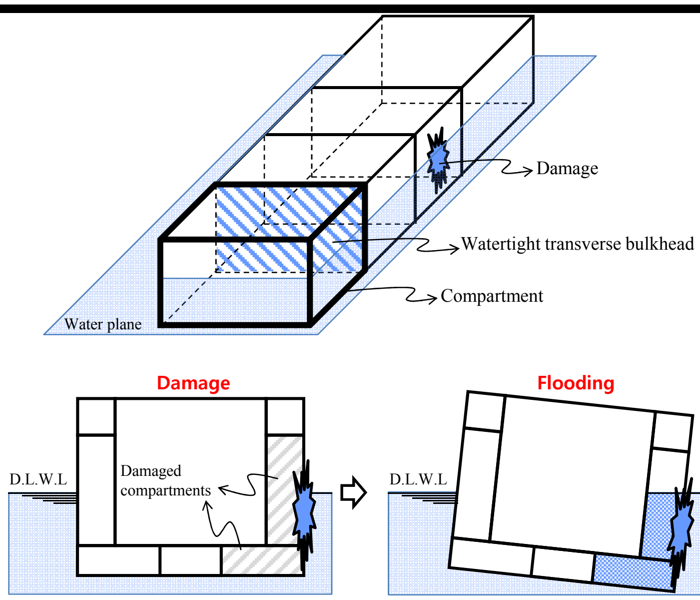
How to measure the ship's stability in a damaged condition?

Deterministic Method : Calculation of survivability of a ship based on the position, stability, and inclination in damaged conditions

Probabilistic Method : Calculation of survivability of a ship based on the probability of damage

Deterministic Damage Stability

Definition of Damage and Flooding



* D.L.W.L: Design Load Water Line

Procedures of Calculation of Deterministic Damage Stability

- ☑ **Step 1: Determination of international regulations to be applied according to ship type**
- ☑ **Step 2: Assumption of the location of damage according to ship length**
- ☑ **Step 3: Assumption of the extent of damage**
- ☑ **Step 4: Assumption of the permeability for each compartment**
- ☑ **Step 5: Evaluation of the required damage stability of international regulations**

Step 1: International Regulations for Damage Stability According to Ship Type

Ship Type	Freeboard Type	Deterministic Damage Stability				Probabilistic Damage Stability
		ICLL[1]	MARPOL[2]	IBC[3]	IGC[4]	SOLAS[5]
Oil Tankers	**A[6]**	**O**	**O**			
	B[7]		**O**			
Chemical Tankers	**A**	**O**		**O**		
Gas Carriers	**B**				**O**	
Bulk Carriers	**B**					**O**
	B-60	**O**				
	B-100	**O**				
Container Carriers Ro-Ro Ships Passenger Ships	**B**					**O**

1: International Convention on Load Lines
2: International Convention for the Prevention of Marine Pollution from Ships
3: International Bulk Chemical Code
4: International Gas Carrier Code
5: Safety Of Life At Sea
6: Freeboard type for a ship which carries liquid cargo (e.g., Tanker). Its freeboard is smaller than that of Type B.
7: Freeboard type for a ship which carries dry cargo (e.g., Container ship, passenger ship).

Step 2 & 3: Location and Extent of Damage in International Regulations - MARPOL, IBC, IGC

Location of damage

Regulation		MARPOL	IBC	IGC
Draft		For any operating draft reflecting loading conditions		
Location of Damage in Lengthwise	Anywhere	L_f>225m	Type 1[1)] Any L_f Type 2[1)] L_f>150m Type 3[1)] L_f>225m	Type 1G[2)], Type 2PG[2)] Any L_f Type 2G[2)] L_f>150m Type 3G[2)] L_f≥125m
	Anywhere (Engine room: 1 compartment)	150m<L_f<225m	Type 2 ≤150m Type 3 125m<L_f<225m	Type 2G L_f≤150m
	Anywhere (Engine room: exception)	L_f≤150m	Type 3 L_f<125m	L_f<125m Type 3G

Extent of damage

Regulation				MARPOL	IBC	IGC
Extent of Damage	Side Damage	Longitudinal Extent		$L_f^{2/3}$/3 or 14.5m, whichever is the lesser		
		Transverse Extent		B/5 or 11.5m, whichever is the lesser		
		Vertical Extent		No limit		
	Bottom Damage	Longitudinal Extent	FP'~0.3L_f	$L_f^{2/3}$/3 or 14.5m, whichever is the lesser		
			0.3L_f~Aft	$L_f^{2/3}$/3 or 5.0m, whichever is the lesser		L_f/10 or 5.0m, whichever is the lesser
		Transverse Extent	FP'~0.3L_f	B/6 or 10.0m, whichever is the lesser		
			0.3L_f~Aft	B/6 or 5.0m, whichever is the lesser		
		Vertical Extent		B/15 or 6.0m, whichever is the lesser		B/15 or 2m, whichever is the lesser

➡ bottom raking damage[3)], Reg. 28 of MARPOL 73/78
- Longitudinal Extent: 20,000ton ≤ DWT ≤ 75,000ton : 0.4L_f from FP'
  75,000ton ≤ DWT : 0.6L_f from FP'
- Transverse Extent: 20,000ton ≤ DWT : B/3 anywhere
- Vertical Extent: 20,000ton ≤ DWT : breach of outer hull[4)]

1) Type 1, Type 2, Type 3: Classification of chemical tanker according to the danger of the loaded cargo. The ship which carries most dangerous cargo is classified into Type 1.
2) Type 1G, Type 2G, Type 2PG, Type 3G: Classification of gas carrier according to the danger of the loaded cargo. The ship which carries most dangerous cargo is classified into Type 1G.
3) The bottom raking damage is only considered in MARPOL
4) The outer shell is only damaged in the vertical direction.

Step 2 & 3: Location and Extent of Damage in International Regulations - ICLL

Location of damage

Regulation		ICLL
Draft		Summer load line
Location of damage in lengthwise	Anywhere (Engine room: 1 compartment)	$L_f > 150m$ Ship type A: 1 compartment / B-60: 1 compartment / B-100: 2 compartments
	Anywhere (Engine room: exception)	$100m < L_f \leq 150m$ Ship type B-60: 1 compartment / B-100: 2 compartments

Extent of damage

Regulation			ICLL
Extent of Damage	Side Damage	Longitudinal Extent	Type A: 1 compartment Type B-60: 1 compartment Type B-100: 2 compartments
		Transverse Extent	1/5 or 11.5m, whichever is the lesser
		Vertical Extent	No limit

Damage assumptions

(a) The vertical extent of damage in all cases is assumed to be from the base line upwards without limit.
(b) The transverse extent of damage is equal to one-fifth (1/5) or 11.5 m, whichever is the lesser of breadth inboard from the side of the ship perpendicularly to the center line at the level of the summer load water line.
(c) No main transverse bulkhead is damaged.

Step 4: Permeability of Compartment (1/2)

When the ship is flooding, how to calculate the actual amount of flooding water?

The compartment of the ship already contains cargo, machinery, liquids, accommodations, or any other equipment or material. To consider this characteristics, the concept of permeability is introduced.

The permeability (μ) of a space is **the proportion of the immersed volume of that space which can be occupied by water**.

Permeability of each general compartment

Spaces	MARPOL	IBC	IGC	ICLL
Appropriated to stores		**0.60**		**0.95**
Occupied by accommodation		**0.95**		**0.95**
Occupied by machinery		**0.85**		**0.95**
Void spaces		**0.95**		**0.95**
Intended for liquids		**0 to 0.95***		**0.95**

* The permeability of partially filled compartments should be consistent with the amount of liquid carried in the compartment.

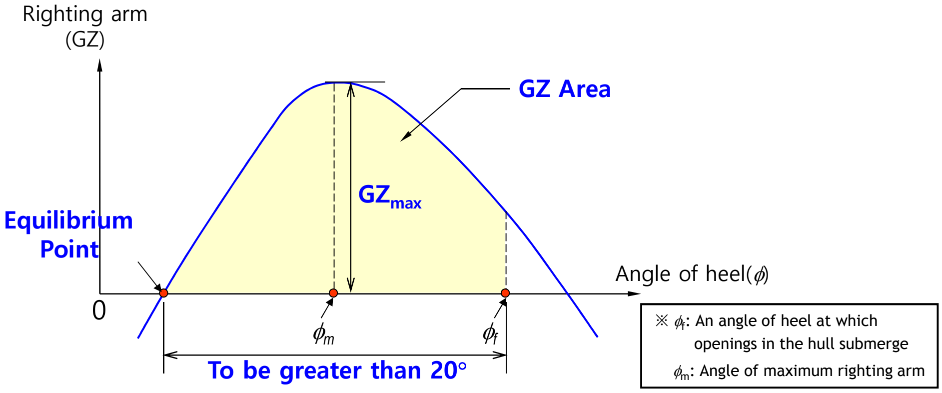
Step 4: Permeability of Compartment (2/2)

Permeability of each cargo compartment

Spaces	Permeability at draft d_s	Permeability at draft d_p	Permeability at draft d_l
Dry cargo spaces	**0.70**	**0.80**	**0.95**
Container cargo spaces	**0.70**	**0.80**	**0.95**
Ro-Ro spaces	**0.90**	**0.90**	**0.95**
Cargo liquids	**0.70**	**0.80**	**0.95**
Timber cargo in holds	**0.35**	**0.70**	**0.95**

Definitions of three draft
Light service draft (d_l): the service draft corresponding to the lightest anticipated loading and associated tankage, including, however, such ballast as may be necessary for stability and/or immersion. Passenger ships should include the full complement of passengers and crew on board.
Partial subdivision draft (d_p): the light service draft plus **60% of the difference between the light service draft and the deepest subdivision draft**.
Deepest subdivision draft (d_s): the waterline which corresponds to the **summer load line draft** of the ship

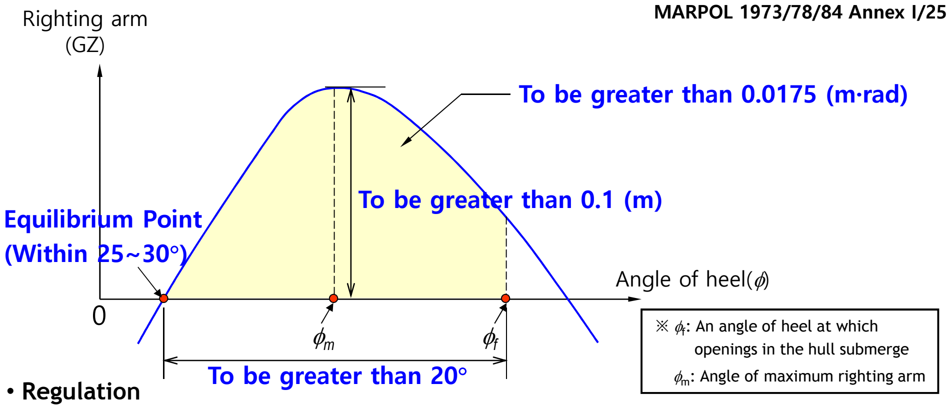
Step 5: Evaluation of the Required Damage Stability



Regulations	MARPOL	IBC	IGC	ICLL
Equilibrium point (angle of heel)	**Below 25° or 30°**		**Below 30°**	**Below 15° or 17°**
Maximum righting arm (GZ_{max})	**Over 0.1 m within the 20° range**			
Flooding angle (ϕ_f)	**Over 20° from the equilibrium point**			
Area under the curve within this range	**Over 0.0175 m·rad**			

Step 5: Evaluation of the Required Damage Stability
- MARPOL Regulation for Damage Stability

MARPOL 1973/78/84 Annex I/25



- **Regulation**

(a) The final waterline shall be below the lower edge of any opening through which progressive flooding may take place.

(b) The angle of heel due to unsymmetrical flooding shall not exceed 25 degrees, provided that this angle may be increased up to 30 degrees if no deck edge immersion occurs.

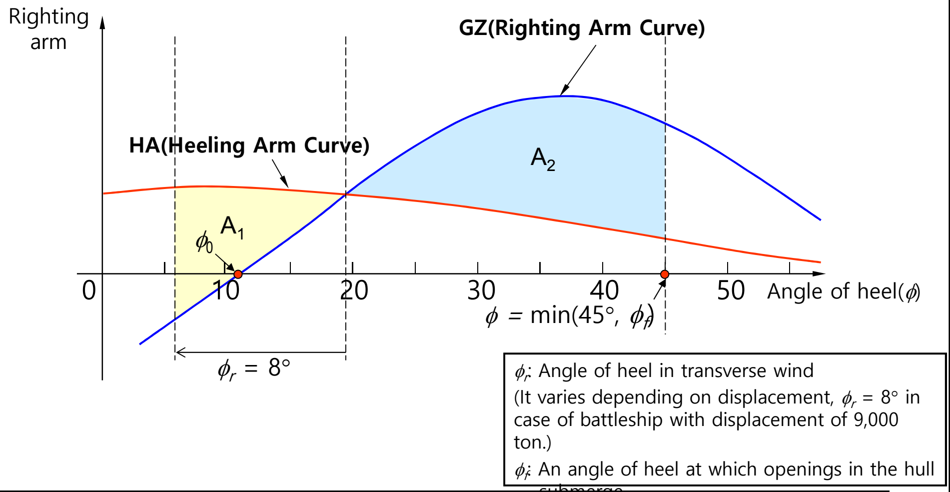
(c) The statical stability curve has at least a range of 20 degrees beyond the position of equilibrium in association with a maximum residual righting arm of at least 0.1 meter within the 20 degrees range

(d) The area under the curve within this range shall not be less than 0.0175 meter-radians.

Step 5: Evaluation of the Required Damage Stability
- Damage Stability Criteria in Battleship*

- **Regulation**

ϕ_0(Initial Angle of Heel) $\leq$ 15°, $A_2 \geq 1.4 \cdot A_1$



* Surko, S.W., "An Assessment of Current Warship Damaged Stability Criteria", Naval Engineers Journal, 1994

Probabilistic Damage Stability (Subdivision and Damage Stability, SDS)

Overview of Probabilistic Method - Subdivision & Damage Stability (SDS)

Probabilistic Method

The probability of damage "p_i" that a compartment or group of compartments may be flooded at the level of the deepest subdivision draft (scantling draft)

The probability of survival "s_i" after flooding in a given damage condition.

The attained subdivision index "A" is the summation of the probability of all damage cases.

$$A = p_1 \times s_1 + p_2 \times s_2 + p_3 \times s_3 + \cdots p_i \times s_i$$
$$= \sum p_i \times s_i$$

The required subdivision index "R" is the requirement of a minimum value of index "A" for a particular ship.

$$R = 1 - \frac{128}{L_s + 152}$$

where, "L_S" is called subdivision length and related with the ship's length.

$$A \geq R$$

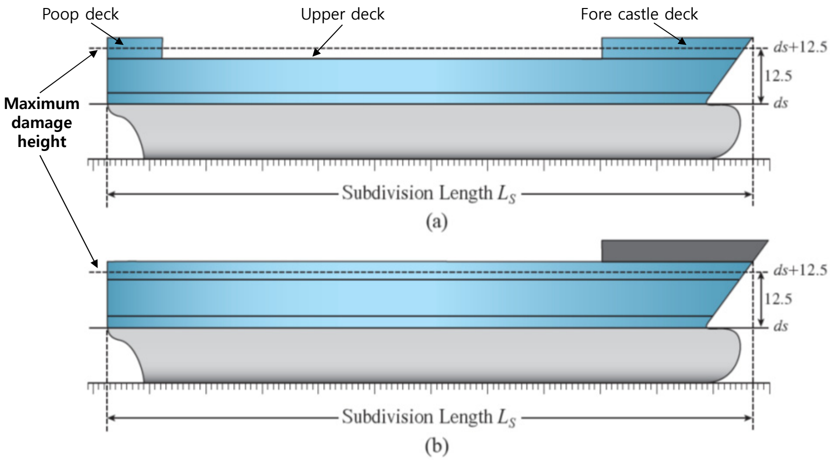
Ship Types for Subdivision & Damage Stability

- ☑ Bulk carriers, Container carriers, Ro-Ro ships having over 80m in length
- ☑ Passenger ships of any length

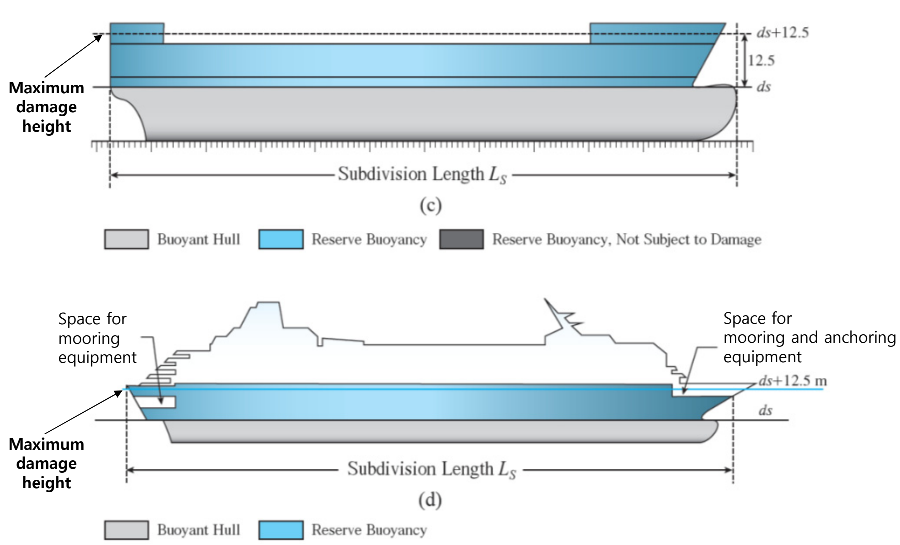
Ship Type	Freeboard Type	Deterministic Damage Stability				Probabilistic Damage Stability
		ICLL[1]	MARPOL[2]	IBC[3]	IGC[4]	SOLAS[5]
Oil Tankers	A[6]	O	O			
	B[7]		O			
Chemical Tankers	A	O		O		
Gas Carriers	B				O	
Bulk Carriers	B					O
	B-60	O				
	B-100	O				
Container Carriers Ro-Ro Ships Passenger Ships	B					O

Definition of Subdivision Length (L_s) (1/2)

- ☑ The greatest projected molded length of that part of the ship at or below deck or decks limiting the vertical extent of flooding with the ship (12.5m) at the deepest subdivision load line



Definition of Subdivision Length (L_s) (2/2)



Required Subdivision Index (R)

- ☑ **The regulation for subdivision & damage stability are intended to provide ships with a minimum standard of subdivision.**
- ☑ **The degree of subdivision to be provided is to be determined by the required subdivision index R.**
- ☑ **The index, a function of the subdivision length (L_s), is defined as follows.**
  - **for cargo ships over 100m in L_S:**

$$R = 1 - \frac{128}{L_s + 152}$$

  - **for cargo ships of 80m in L_S and upwards, but not exceeding 100m in length L_S:**

$$R = 1 - \frac{1}{1 + \frac{L_S}{100} \times \frac{R_0}{1 - R_0}}$$

  where R_0 is the value R as calculated in accordance with the formula relevant to ships over 100 m in L_S.

  - **for passenger ships**

$$R = 1 - \frac{5000}{1 + L_S + 2.5N + 15225}$$

  where, $N=N_1+2N_2$, N_1: number of persons for whom lifeboats are provided, N_2: number of persons (including officers and crew) the ship is permitted to carry in excess of N_1

Attained Subdivision Index (A)

☑ The attained subdivision index A, calculated in accordance with this regulation, is to be not less than the required subdivision index R.

$$A \geq R \qquad \text{Where } A = 0.4A_s + 0.4A_p + 0.2A_l$$

☑ The attained subdivision index A is to be calculated for the ship by the following formula.

$$A_s, A_p, A_l = \sum_i (p_i \times s_i)$$

Where,
i: Represents each compartment or group of compartments under consideration.
p_i: Accounts for the probability that only the compartment or group of compartments under consideration may be flooded, disregarding any horizontal subdivision, p_i is independent of the draft but includes the factor r.
s_i: Accounts for the probability of survival after flooding the compartment or group of compartments under consideration, including the effects of any horizontal subdivision, s_i is dependent on the draft and includes the factor v.

Considerations for Loading Conditions and Drafts

☑ The SDS calculation is carried out on the basis of three standard loading conditions relevant to the following drafts.

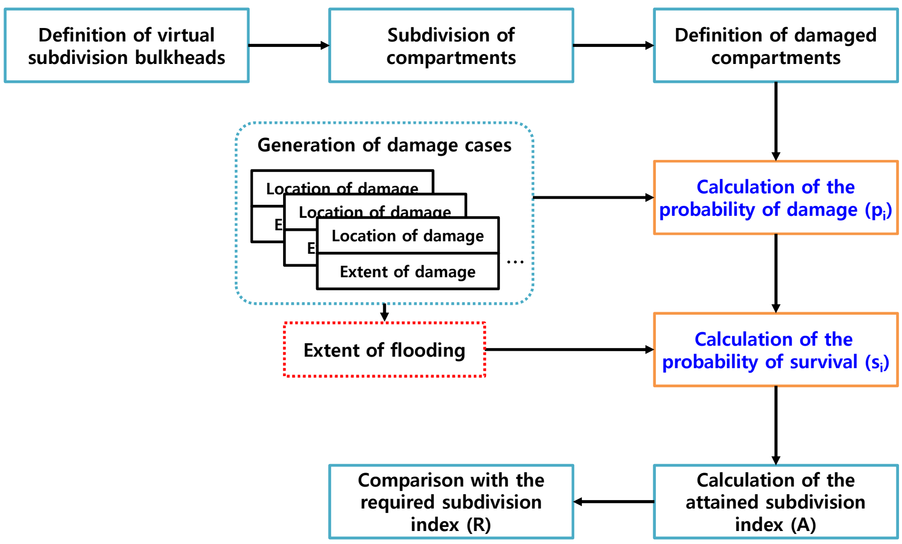
☑ The deepest subdivision draft (d_s): corresponding to summer draft (scantling draft)

☑ The light service draft (d_l): corresponding to the lightest loading condition ("ballast arrival condition") included in the ship's stability manual

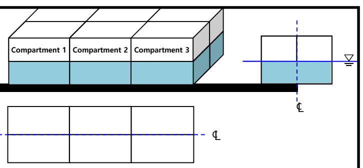
☑ The partial subdivision draft (d_p): corresponding to the light service draft (d_l) plus 60% of the difference between the deepest subdivision draft (d_s) and the light service draft:

$$d_p = d_l + 0.6(d_s - d_l)$$

Overall Procedures to Evaluate the Probabilistic Damage Stability



Probability of Damage



$$A = \sum p_i \times s_i$$

What is the factor "p_i"?

A: Subdivision index
p_i: Probability of damage
s_i: Probability of survival

: Probability of damage that a compartment or group of compartments may be flooded at the level of the deepest subdivision draft "ds", that is, scantling draft.

: Related to the generation of "Damage Case"

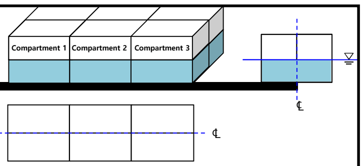
➡ Dependent on the **geometry of the ship**
(Watertight arrangement and main dimensions of the ship)

$$p_i = p \cdot r$$

p : The probability of damage in the longitudinal subdivision
r : The probability of damage in the transverse subdivision

➡ Not dependent on the **draft**. Thus, we use the deepest subdivision draft "ds".

Probability of Survival (1/2)



$$A = \sum p_i \times s_i$$

A: Subdivision index
p_i: Probability of damage
s_i: Probability of survival

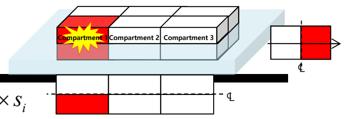
What is the factor "s_i"?

: The factor "s_i" is the probability of survival after flooding in a given damage condition.

: Calculation the probability of survival in a given "Damage Case"

➡ Dependent on the **"initial draft (d_s, d_p, d_l)"**

Probability of Survival (2/2)

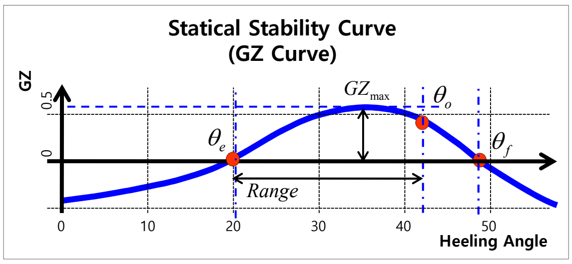


$A = \sum p_i \times s_i$

What is related to the factor "s_i"?

$$s_i = s_i(\theta_e, \theta_v, GZ_{\max}, Range, Flooding\ stage)$$ **(For cargo ships)**

: The **factor "*s*"** is to be calculated according to the range of *GZ* curve and $GZ_{\max}$.



θ_e: Equilibrium point(angle of heel)
θ_v: minimum(θ_f, θ_o)
(in this case, θ_v equals to θ_o)
GZ_{max}: Maximum value of *GZ*
Range: Range of positive righting arm
Flooding stage: Discrete step during the flooding process

θ_f: Angle of flooding (righting arm becomes negative)
θ_o: Angle at which an "opening" incapable of being closed weathertight becomes submerged

Comparison Between the Deterministic and Probabilistic Damage Stability

Items	Deterministic Damage Stability		Probabilistic Damage Stability
	ICLL[1]	MARPOL[2]	SOLAS
Ships	Oil tankers, Chemical tankers		**Bulk carriers, Container carriers, Ro-Ro ships, Passenger ships**
Definition of damaged compartments	Define the compartments as same with actual compartments		**Define virtual damage compartments after subdividing the compartments by using virtual subdivision bulkheads**
Assumption of extent of damage	Assume the extent of damage with actual compartments as a basis		**Assume the extent of damage with the virtual damage compartments as a basis**
Generation of damage cases	Generate a damage case per two compartments	Generate a damage case per one or two compartments	**Generate a damage case for each extent of damage**
Draft under consideration	The deepest subdivision draft (d_s)	All drafts to be applied in the intact stability calculation	**The deepest subdivision draft (d_s), the partial subdivision draft (d_p), the light service draft (d_l)**
Evaluation of damage stability	All damage cases should satisfy each criterion for the regulation of damage stability.		**The attained subdivision index should satisfy the regulation of damage stability (A≥R).**

1: International Convention on Load Lines
2: International Convention for the Prevention of Marine Pollution from Ships

5.6 Hydrostatic Values

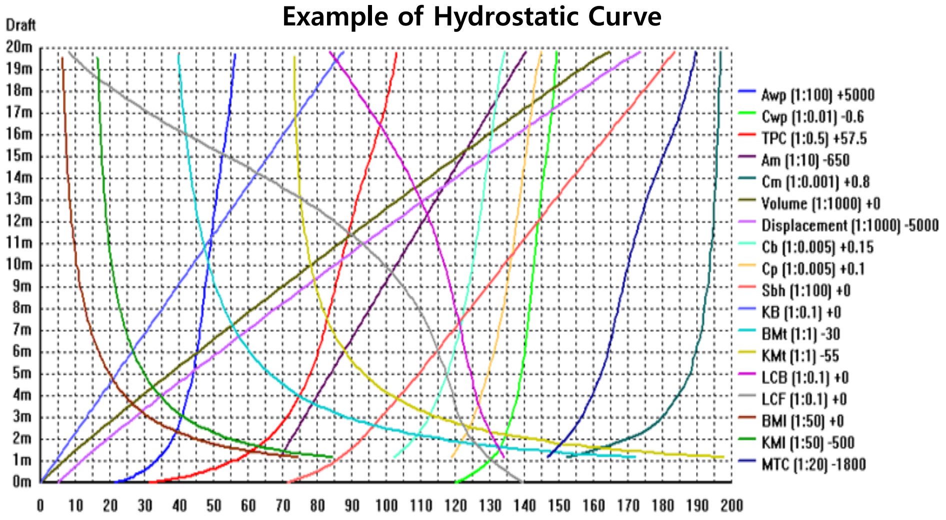
Hydrostatic Values

- ☑ $Draft_{Mld}$, $Draft_{Scant}$: Draft from base line, moulded / scantling (m)
- ☑ $Volume_{Mld}(\nabla)$, $Volume_{Ext}$: Displacement volume, moulded / extreme (m^3)
- ☑ $Displacement_{Mld}(\Delta)$, $Displacement_{Ext}$: Displacement, moulded / extreme (ton)
- ☑ LCB: Longitudinal center of buoyancy from midship (Sign: - Aft / + Forward)
- ☑ LCF: Longitudinal center of floatation from midship (Sign: - Aft / + Forward)
- ☑ VCB: Vertical center of buoyancy above base line (m)
- ☑ TCB: Transverse center of buoyancy from center line (m)
- ☑ KM_T: Transverse metacenter height above base line (m)
- ☑ KM_L: Longitudinal metacenter height above base line (m)
- ☑ MTC: Moment to change trim one centimeter (ton-m)
- ☑ TPC: Increase in $Displacement_{Mld}$ (ton) per one centimeter immersion
- ☑ WSA: Wetted surface area (m^2)
- ☑ C_B: Block coefficient
- ☑ C_{WP}: Water plane area coefficient
- ☑ C_M: Midship section area coefficient
- ☑ C_P: Prismatic coefficient
- ☑ Trim: Trim(= after draft – forward draft) (m)

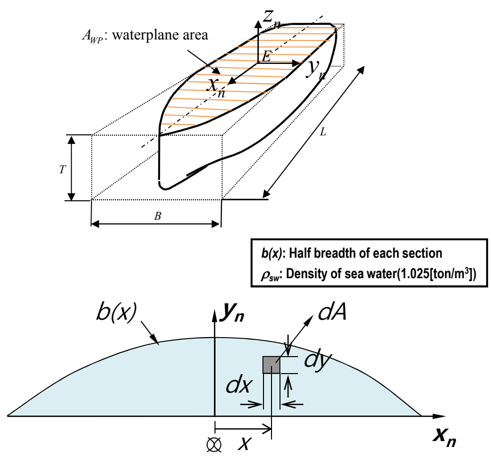
Hydrostatic Curve

- ☑ Hydrostatic curve: Curve for representing hydrostatic values

Example of Hydrostatic Curve



Water Plane Area (A_{WP}), Tones Per 1cm Immersion (TPC), Longitudinal Moment of Area (L_{WP}), Longitudinal Center of Floatation (LCF)



$Ex_ny_nz_n$: Water plane fixed frame

✓ **Water plane area**

$$A_{WP} = \int dA = 2 \cdot \int_0^L b(x)\,dx$$

✓ **Tones Per 1 Cm immersion (TPC)**

$$TPC = \rho_{sw} \cdot A_{WP} \cdot \frac{1}{100}$$

ρ_{sw} : density of sea water

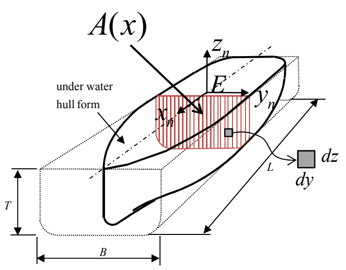
✓ **1st moment of water plane area about y axis**

$$M_{WP} = M_y = \int x\,dA = \iint x\,dx\,dy$$

✓ **Longitudinal Center of Floatation**

$$LCF = \frac{M_{WP}}{A_{WP}}$$

Sectional Area (A), Displacement Volume (∇)



$Ex_ny_nz_n$: Water plane fixed frame

✓ **Sectional area**

$$A(x) = \int dA = \iint dy\,dz$$

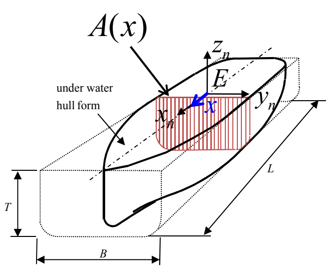
✓ **Displacement volume**

$$\nabla = \int dV = \iiint dx\,dy\,dz$$
$$= \int \left(\iint dy\,dz \right) dx$$
$$\Rightarrow A(x)$$

$$\therefore \nabla = \int A(x)dx$$

After calculating each sectional area, displacement volume can be calculated by integration of section area over the length of a ship.

Longitudinal Moment of Displacement Volume ($M_{\nabla,L}$) and Longitudinal Center of Buoyancy (LCB)



✓ **Longitudinal moment of displacement volume**

$$M_{\nabla,L} = M_{yz} = \int x\,dV$$
$$= \iiint x\,dx\,dy\,dz$$
$$= \int \left(\iint x\,dy\,dz \right) dx$$
$$\Rightarrow M_{A,L}$$

$M_{A,L}$: Longitudinal moment of area about y axis

$$\therefore M_{\nabla,L} = \int M_{A,L}\,dx$$

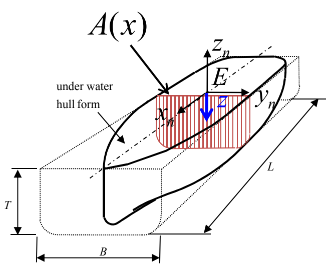
After calculating each longitudinal moment of sectional area about the y axis ($M_{A,L}$), longitudinal moment of displacement volume can be calculated by integration of longitudinal moment of section area over the length of ship.

✓ **Longitudinal Center of Buoyancy**

$$LCB = \frac{M_{\nabla,L}}{\nabla}$$

$Ex_ny_nz_n$: Water plane fixed frame

Vertical Moment of Displacement Volume ($M_{\nabla,V}$) and Vertical Center of Buoyancy (VCB or KB)



✓ **Vertical moment of displacement volume**

$$M_{\nabla,V} = M_{xy} = \int z\,dV$$
$$= \iiint z\,dx\,dy\,dz$$
$$= \int \left(\iint z\,dy\,dz \right) dx$$
$$\Rightarrow M_{A,V}$$

$M_{A,V}$: Vertical moment of area about y axis

$$\therefore M_{\nabla,V} = \int M_{A,V}\,dx$$

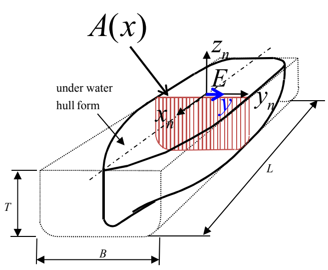
After calculating each vertical moment of sectional area about the y axis ($M_{A,V}$), vertical moment of displacement volume can be calculated by integration of vertical moment of section area over the length of ship.

✓ **Vertical Center of Buoyancy**

$$VCB = KB = \frac{M_{\nabla,V}}{\nabla}$$

$Ex_ny_nz_n$: Water plane fixed frame

Transverse Moment of Displacement Volume ($M_{\nabla,T}$) and Transverse Center of Buoyancy (TCB)



✓ **Transverse moment of displacement volume**

$$M_{\nabla,T} = M_{xz} = \int y\, dV$$
$$= \iiint y\, dx\, dy\, dz$$
$$= \int \left(\iint y\, dy\, dz \right) dx$$
$$\Rightarrow M_{A,T}$$

$M_{A,T}$: Vertical moment of area about z axis

$$\therefore M_{\nabla,T} = \int M_{A,T}\, dx$$

After calculating each transverse moment of sectional area about the z axis ($M_{A,T}$), transverse moment of displacement volume can be calculated by integration of transverse moment of section area over the length of a ship.

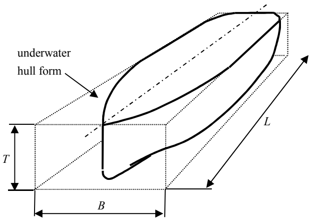
✓ **Transverse Center of Buoyancy**

$$TCB = \frac{M_{\nabla,T}}{\nabla}$$

$Ex_n y_n z_n$: Water plane fixed frame

Block Coefficient (C_B) and Water Plane Area Coefficient (C_{WP})

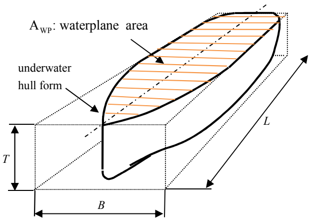
C_B (Block coefficient)



$$C_B = \frac{\nabla}{L \cdot B_{mld} \cdot T}$$

∇: Moulded volume of displacement
L: Length (L_{WL} or L_{BP})
B_{mld}: Moulded breadth
T_{mld}: Moulded draft

C_{WP} (Water Plane Area Coefficient)

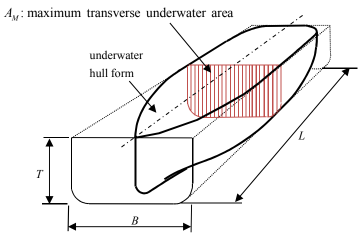


$$C_{WP} = \frac{A_{WP}}{L \cdot B_{mld}}$$

A_{WP}: Water plane area
L: Length (L_{WL} or L_{BP})
B_{mld}: Moulded breadth

Midship Section Coefficient (C_M) and Prismatic Coefficient (C_P)

C_M (Midship Section Coefficient)



$$C_M = \frac{A_M}{B_{mld} \times T}$$

B_{mld}: Moulded breadth
T_{mld}: Moulded draft
A_M: Sectional area at midship

C_P (Prismatic Coefficient)

$$C_P = \frac{\nabla}{L_{BP} \cdot A_M} = \frac{\nabla}{L_{BP} \cdot B_{mld} \cdot T \cdot C_M} = \frac{C_B}{C_M}$$

∇: Moulded volume of displacement
L: Length (L_{WL} or L_{BP})
B_{mld}: Moulded breadth
T_{mld}: Moulded draft
C_M: Midship section coefficient
C_B: Block coefficient

Transverse Metacentric Radius (BM), Longitudinal Metacentric Radius (BM_L), Moment to change Trim 1 Cm (MTC), and Trim

BM

Transverse righting moment = $\Delta \cdot GZ \approx \Delta \cdot GM \cdot \sin\phi$

$$GM = KB + BM - KG$$

$$BM_0 = \frac{I_T}{\nabla}\left(1 + \tan^2\phi\right)$$

(ϕ: Angle of heel)
: Considering the change of the center of buoyancy in vertical direction

$$BM = \frac{I_T}{\nabla}$$

: Without considering the change of the center of buoyancy in vertical direction

GM: Transverse metacentric height
KB : Vertical center of displaced volume
BM: Transverse metacentric Radius
KG: Vertical center of gravity

BM_L

Longitudinal righting moment = $\Delta \cdot GZ_L = \Delta \cdot GM_L \cdot \sin\theta$

$$GM_L = KB + BM_L - KG$$

$$BM_{L0} = \frac{I_L}{\nabla}\left(1 + \tan^2\theta\right)$$

(θ: Angle of trim)
: Considering the change of the center of buoyancy in vertical direction

$$BM_L = \frac{I_L}{\nabla}$$

: Without considering the change of the center of buoyancy in vertical direction

GM_L: Longitudinal metacentric height
KB : Vertical center of displaced volume
BM_L: Longitudinal metacentric Radius
KG: Vertical center of gravity

MTC

Moment to change Trim 1 Cm

$$MTC = \Delta \cdot GM_L \cdot \frac{1}{L_{BP} \cdot 100}$$

(Unit conversion for centimeter)

$$GM_L = KB + BM_L - KG$$

If we assume that KB, KG are small than BM_L

$$GM_L \approx BM_L$$

$$\therefore MTC = \Delta \cdot BM_L \cdot \frac{1}{L_{BP} \cdot 100} = \frac{\rho \cdot I_L}{L_{BP} \cdot 100}$$

Trim

$$\text{Transverse Moment Arm} = LCB - LCG$$

$$Trim[m] = \frac{\Delta \cdot Trim\,Lever}{MTC \cdot 100}$$

$$MTC = \frac{\rho \cdot I_L}{L_{BP} \cdot 100}$$

Generation of Hydrostatic Tables and Hydrostatic Curves

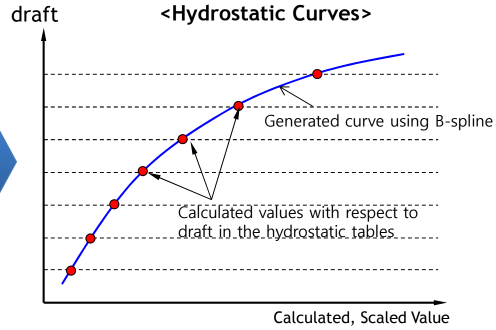
Given: Offsets table, Formulas for calculating hydrostatic values
Find: Hydrostatic tables as function of draft, Hydrostatic curves

✓ **Calculation of hydrostatic values as function of draft**

<Hydrostatic Tables>

Draft [m]

	Δ	LCB	TCB	KB	KM_T	…
0	…	…	…	…	…	…
1	…	…	…	…	…	…
2	…	…	…	…	…	…
3	…	…	…	…	…	…
4	…	…	…	…	…	…
5	…	…	…	…	…	…
…	…	…	…	…	…	…



Example of Offsets Table of a 6,300TEU Container Ship

→ Waterline

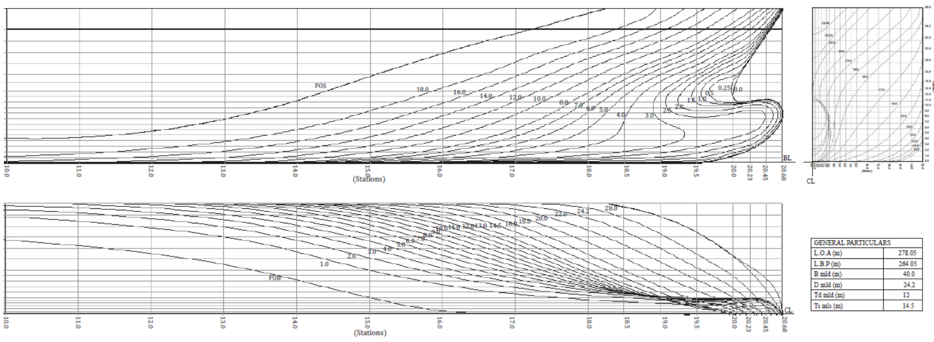
↓ Stations

* Unit: mm

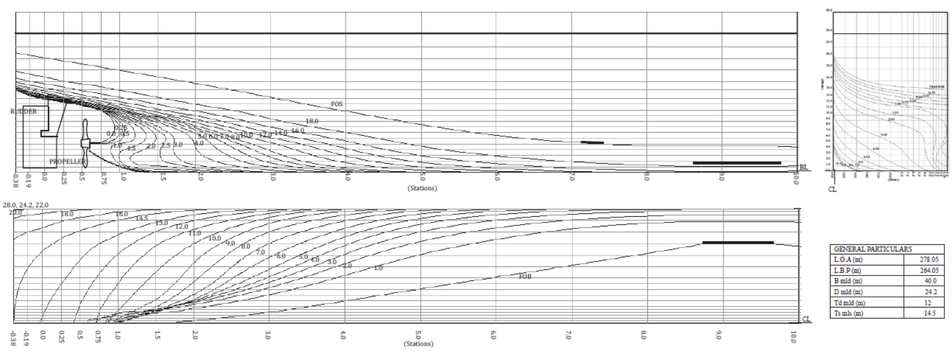
Half-Breadth

Station NO.	HALF BREADTH FROM CENTER LINE																				Station NO.
	BOTTOM LINE	1 W.L	2 W.L	3 W.L	4 W.L	5 W.L	6 W.L	7 W.L	8 W.L	9 W.L	10 W.L	11 W.L	12 W.L	13 W.L	14.5 W.L	16 W.L	18 W.L	20 W.L	22 W.L	24.2 W.L	
Trans. (-0.38)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14450	18262	19780	20000	20000	Trans. (-0.38)
-0.19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10525	15955	18890	19944	20000	*	-0.19
AP	-	-	-	-	-	-	-	-	-	-	-	-	-	2627	12572	16765	19204	19994	20000	*	AP
0.25	-	-	-	-	-	-	-	-	-	-	-	-	-	8474	14763	17871	19596	20000	*	*	0.25
0.5	-	-	-	-	-	-	-	-	-	-	-	-	3283	11746	16178	18456	19824	20000	*	*	0.5
0.75	-	-	-	487	933	530	-	-	-	-	0	1846	8680	13817	17230	18948	19956	20000	*	*	0.75
1	-	93	1802	1870	1462	863	397	183	280	895	2275	5061	12168	15561	18071	19440	20000	*	*	*	1
1.5	49	1879	2372	2520	2446	2215	2059	2283	2919	4288	9026	13623	16033	17687	19196	19906	20000	*	*	*	1.5
2	534	2677	3363	3734	3932	4029	4250	5085	7289	10680	13943	16341	17896	18937	19811	20000	*	*	*	*	2
3	2025	5058	6294	7228	8182	9483	11583	14000	16000	17469	18517	19244	19735	19990	20000	*	*	*	*	*	3
4	3974	8451	10473	12071	13627	15218	16635	17938	18937	19594	19941	20000	20000	20000	*	*	*	*	*	*	4
5	6091	12054	14349	16032	17344	18359	19152	19729	19996	20000	20000	*	*	*	*	*	*	*	*	*	5
6	8152	14697	16708	18069	19011	19627	19952	20000	20000	*	*	*	*	*	*	*	*	*	*	*	6
7	10187	16515	18101	19113	19728	19985	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	7
8	12286	17500	18738	19502	19915	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	8
9	13900	17562	18720	19408	19815	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	9
10	13517	17469	18718	19466	19926	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	10
11	12406	16799	18306	19265	19873	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	11
12	11001	15632	17338	18464	19316	19887	20000	20000	*	*	*	*	*	*	*	*	*	*	*	*	12
13	9018	14029	15875	17152	18138	18941	19528	19922	20000	20000	20000	20000	*	*	*	*	*	*	*	*	13
14	6196	11304	13404	14934	16146	17141	17974	18650	19199	19622	19886	19994	20000	20000	20000	*	*	*	*	*	14
15	2993	7980	10216	11870	13217	14356	15353	16246	17038	17740	18354	18882	19312	19633	19929	20000	20000	*	*	*	15
16	583	5356	7103	8420	9598	10677	11684	12651	13581	14471	15328	16159	16935	17624	18572	19322	19877	20000	20000	*	16
17	124	3602	4805	5656	6434	7181	7919	8674	9438	10248	11052	11859	12734	13663	15032	16321	17837	19014	19797	20000	17
18	100	2577	3442	3967	4341	4643	4932	5224	5554	5931	6346	6845	7479	8235	9516	10921	13033	15277	17449	19250	18
18.5	110	2286	2979	3414	3673	3815	3893	3951	4012	4115	4320	4603	4959	5458	6511	7872	10049	12543	15057	17488	18.5
19	112	1982	2596	2988	3195	3258	3215	3104	2954	2804	2723	2710	2780	3087	3833	4987	7036	9433	11867	14527	19
19.5	-	1538	2160	2550	2778	2891	2894	2784	2569	2231	1760	1385	1247	1279	1685	2532	4262	6237	8428	10884	19.5
FP	-	-	1195	1825	2310	2652	2859	2901	2768	2497	2060	1301	-	29	148	603	1551	2981	4700	6815	FP
20.23	-	-	-	1353	2045	2481	2753	2893	2890	2686	2125	697	-	-	-	-	-	1590	3135	5042	20.23
20.45	-	-	-	-	-	1300	1910	2258	2420	2400	2110	1320	-	-	-	-	-	-	-	2343	20.45
20.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20.68

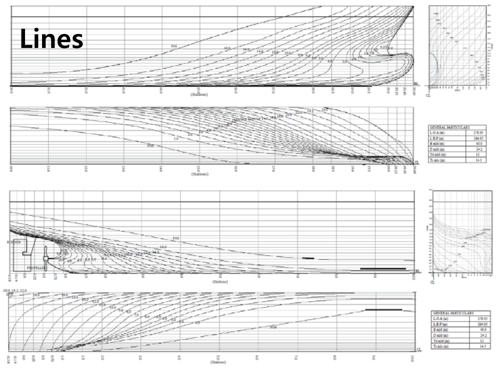
Example of Lines of a 6,300TEU Container Ship - Fore Body



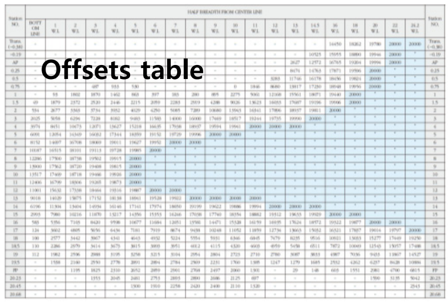
Example of Lines of a 6,300TEU Container Ship - After Body



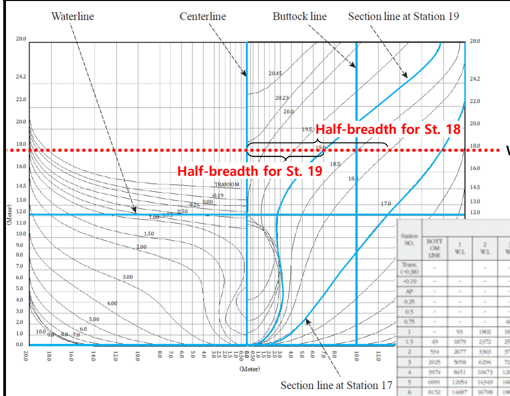
Relationship Between Lines and Offsets Table (1/2)

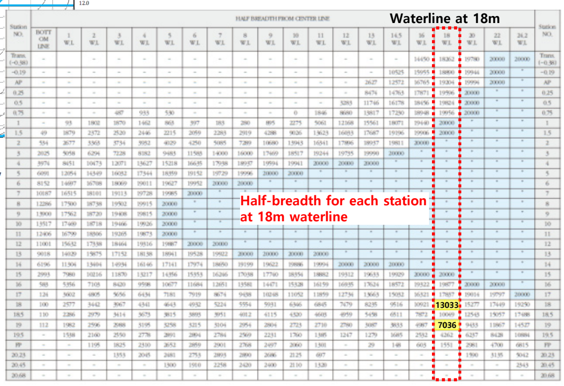


Generation of offsets table from the lines



Relationship Between Lines and Offsets Table (2/2)





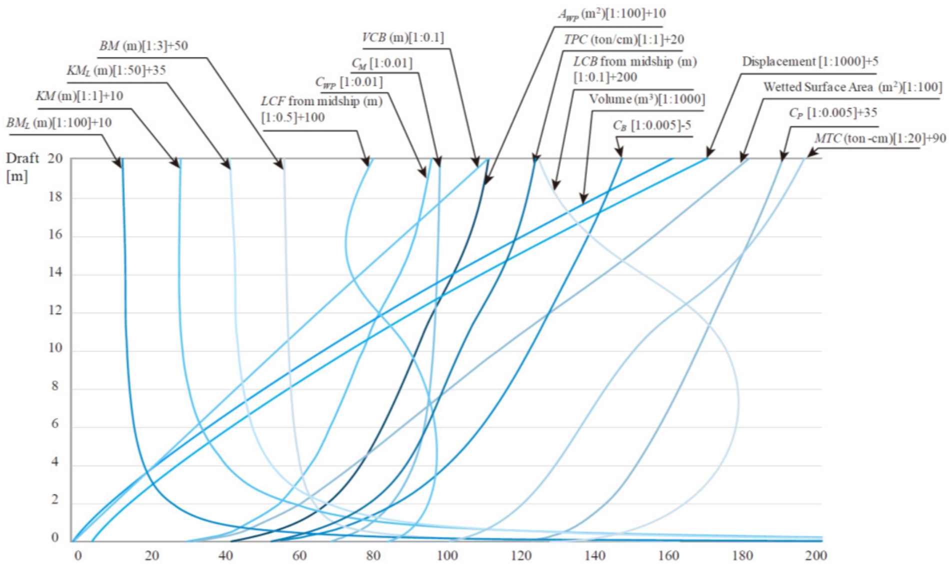
Example of Hydrostatic Tables of a 6,300TEU Container Ship (1/2)

DRAFT (M)	DISP MLD(M^3)	DISP EXT(Ton)	VCB (M)	LCB (M)	LCF (M)	KM (M)	KM_L (M)	MTC (T-M)	TPC (Ton)	WSA (M^2)	C_B	C_W	C_P	C_M
4.000	22054.0	22720.3	2.171	-2.732	-1.546	31.537	926.651	795.5	68.5	7474.0	0.5248	0.6332	0.5769	0.9097
4.050	22389.1	23064.3	2.199	-2.714	-1.535	31.314	916.847	798.9	68.7	7507.8	0.5261	0.6349	0.5777	0.9107
4.100	22726.2	23410.3	2.226	-2.697	-1.523	31.098	907.266	802.4	68.9	7541.5	0.5275	0.6367	0.5786	0.9118
4.150	23053.3	23756.4	2.253	-2.680	-1.511	30.889	897.964	805.9	69.1	7575.3	0.5288	0.6384	0.5794	0.9128
4.200	23400.4	24102.4	2.281	-2.663	-1.500	30.686	888.93	809.3	69.3	7609.1	0.5302	0.6402	0.5802	0.9138
4.250	23737.5	24448.5	2.308	-2.646	-1.488	30.490	880.152	812.8	69.5	7642.9	0.5314	0.6420	0.5810	0.9147
4.300	24077.3	24797.2	2.336	-2.630	-1.476	30.300	871.537	816.3	69.7	7676.7	0.5327	0.6437	0.5818	0.9157
4.350	24419.0	25148.0	2.363	-2.614	-1.465	30.115	863.102	819.8	69.9	7710.5	0.5341	0.6454	0.5826	0.9166
4.400	24760.7	25498.8	2.391	-2.598	-1.453	29.936	854.9	823.3	70.1	7744.3	0.5354	0.6472	0.5835	0.9176
4.450	25102.4	25849.6	2.418	-2.582	-1.441	29.762	846.921	826.7	70.3	7778.1	0.5366	0.6489	0.5843	0.9185
...														
7.500	47233.9	48564.4	4.087	-2.084	-2.217	21.918	560.803	1023.9	78.2	9736.7	0.5979	0.7224	0.6283	0.9517
7.550	47615.8	48956.4	4.115	-2.086	-2.257	21.852	558.143	1027.2	78.3	9768.7	0.5988	0.7235	0.6290	0.9520
7.600	47999.0	49349.6	4.142	-2.088	-2.302	21.785	555.428	1030.3	78.4	9800.7	0.5996	0.7246	0.6296	0.9523
7.650	48382.1	49742.8	4.170	-2.090	-2.348	21.722	552.756	1033.4	78.6	9832.7	0.6004	0.7256	0.6303	0.9527
7.700	48765.2	50136.0	4.197	-2.092	-2.393	21.659	550.126	1036.6	78.7	9864.6	0.6013	0.7267	0.6309	0.9530
7.750	49148.4	50529.3	4.224	-2.094	-2.438	21.598	547.537	1039.7	78.8	9896.6	0.6021	0.7277	0.6316	0.9533
7.800	49533.1	50924.1	4.252	-2.097	-2.483	21.538	544.992	1042.9	78.9	9928.6	0.6029	0.7288	0.6322	0.9536
7.850	49919.1	51320.2	4.279	-2.100	-2.527	21.481	542.488	1046.1	79.0	9960.7	0.6037	0.7298	0.6329	0.9539
7.900	50305.0	51716.3	4.307	-2.104	-2.571	21.424	540.023	1049.2	79.1	9992.8	0.6045	0.7309	0.6335	0.9542
7.950	50690.9	52112.3	4.334	-2.107	-2.615	21.369	537.595	1052.4	79.2	10024.8	0.6053	0.7319	0.6342	0.9544
...														

Example of Hydrostatic Tables of a 6,300TEU Container Ship (2/2)

DRAFT (M)	DISP MLD(M^3)	DISP EXT(Ton)	VCB (M)	LCB (M)	LCF (M)	KM (M)	KM_L (M)	MTC (T-M)	TPC (Ton)	WSA (M^2)	C_B	C_W	C_P	C_M
11.750	81677.2	83912.8	6.431	-3.298	-8.607	18.919	430.346	1347.2	88.1	12595.4	0.6593	0.8134	0.6803	0.9692
11.800	82107.4	84354.3	6.459	-3.326	-8.710	18.912	430.028	1353.1	88.2	12631.3	0.6600	0.8148	0.6809	0.9693
11.850	82539.1	84797.3	6.487	-3.355	-8.816	18.905	429.787	1359.4	88.4	12667.6	0.6606	0.8162	0.6815	0.9695
11.900	82970.8	85240.4	6.515	-3.384	-8.923	18.900	429.549	1365.5	88.5	12703.9	0.6613	0.8176	0.6820	0.9696
11.950	83402.4	85683.4	6.543	-3.413	-9.030	18.894	429.313	1371.9	88.7	12740.2	0.6620	0.8190	0.6826	0.9697
12.000	83634.1	86126.4	6.571	-3.442	-9.136	18.889	429.081	1378.1	88.8	12776.5	0.6626	0.8204	0.6832	0.9698
12.050	84267.9	86571.6	6.599	-3.471	-9.233	18.879	428.885	1384.5	89.0	12812.5	0.6633	0.8218	0.6838	0.9700
12.100	84703.3	87018.4	6.627	-3.501	-9.323	18.866	428.717	1391.0	89.1	12848.3	0.6639	0.8231	0.6844	0.9701
12.150	85138.6	87465.1	6.655	-3.531	-9.413	18.853	428.551	1397.5	89.3	12884.0	0.6646	0.8245	0.6850	0.9702
12.200	85573.9	87911.9	6.683	-3.561	-9.503	18.840	428.387	1404.0	89.4	12919.8	0.6652	0.8258	0.6856	0.9703
12.250	86009.2	88358.7	6.711	-3.591	-9.593	18.826	428.224	1410.5	89.5	12955.6	0.6659	0.8271	0.6862	0.9705
...														
14.250	104062.4	106885.2	7.843	-4.937	-12.788	18.585	423.63	1683.1	95.4	14391.6	0.6924	0.8808	0.7105	0.9746
14.300	104528.0	107363.1	7.872	-4.973	-12.837	18.604	423.328	1689.2	95.5	14426.2	0.6931	0.8819	0.7111	0.9747
14.350	104995.0	107842.2	7.901	-5.008	-12.880	18.683	423.056	1695.6	95.6	14461.0	0.6938	0.8831	0.7117	0.9748
14.400	105451.9	108321.3	7.929	-5.042	-12.940	18.683	422.786	1701.9	95.7	14495.8	0.6944	0.8843	0.7123	0.9749
14.450	105928.8	108800.4	7.958	-5.077	-12.992	18.682	422.519	1708.2	95.9	14530.6	0.6951	0.8854	0.7129	0.9750
14.500	106395.7	109279.6	7.986	-5.112	-13.043	18.682	422.255	1714.5	96.0	14565.4	0.6957	0.8866	0.7135	0.9751
14.550	106864.4	109760.5	8.015	-5.147	-13.090	18.682	422.01	1720.9	96.1	14600.3	0.6964	0.8878	0.7141	0.9751
14.600	107334.5	110242.8	8.043	-5.182	-13.133	18.681	421.779	1727.4	96.2	14635.1	0.6971	0.8889	0.7148	0.9752
14.650	107804.5	110725.1	8.072	-5.217	-13.176	18.681	421.55	1733.9	96.4	14970.0	0.6977	0.8901	0.7154	0.9753
14.700	108274.5	111207.4	8.101	-5.251	-13.219	18.681	421.323	1740.3	96.5	14704.9	0.6984	0.8912	0.7160	0.9754

Example of Hydrostatic Curves of a 6,300TEU Container Ship



Example of Programming for Calculation of the Hydrostatics - Example of Hydrostatic Tables of a 320K VLCC (1/2)

Hydrostatics Table

Draft	Awp	Cwp	TPC	Am	Cm	Disp. Vol.	Dispacement	Cb	Cp	
1	13969.707634	0.727589	143.189503	57.595373	0.959923	13274.704872	13606.572494	0.691391	0.720257	0
2	14665.449669	0.763826	150.320859	117.023844	0.975199	27625.670041	28316.311792	0.719418	0.737715	1
3	15077.051700	0.785263	154.539780	176.973600	0.983187	42515.292743	43578.175062	0.738113	0.750735	1
4	15357.591332	0.799875	157.415311	236.973600	0.987390	57741.104204	59184.631810	0.751837	0.761439	2
5	15581.372337	0.811530	159.709066	296.973600	0.989912	73212.579375	75042.893859	0.762631	0.770403	2
6	15749.689195	0.820296	161.434314	356.973600	0.991593	88884.693834	91106.811180	0.771569	0.778110	3
7	15875.551257	0.826852	162.724400	416.973600	0.992794	104697.883311	107315.330393	0.779002	0.784656	3
8	15995.591849	0.833104	163.954816	476.973600	0.993695	120634.354919	123650.213792	0.785380	0.790363	4
9	16108.202427	0.838969	165.109075	536.973600	0.994396	136685.843246	140102.989327	0.791006	0.795464	4
10	16220.139230	0.844799	166.256427	596.973600	0.994956	152848.654175	156669.870529	0.796087	0.800123	5
11	16334.646305	0.850763	167.430125	656.973600	0.995415	169122.501317	173350.563850	0.800769	0.804458	5
12	16456.300612	0.857099	168.677081	716.973600	0.995797	185509.431357	190147.167141	0.805162	0.808561	6
13	16586.144990	0.863862	170.007986	776.973600	0.996120	202010.815322	207061.085705	0.809338	0.812491	6
14	16733.101975	0.871516	171.514295	836.973600	0.996397	218662.950551	224129.524315	0.813478	0.816420	7
15	16880.258424	0.879180	173.022649	896.973600	0.996637	235526.994120	241415.168973	0.817802	0.820561	7
16	17033.256489	0.887149	174.590879	956.973600	0.996848	252548.055106	258861.756483	0.822097	0.824696	8
17	17190.202935	0.895323	176.199580	1016.973600	0.997033	269669.514686	276411.252553	0.826193	0.828652	8
18	17330.470220	0.902629	177.637320	1076.973600	0.997198	286937.720924	294111.163948	0.830260	0.832593	9
19	17450.827341	0.908897	178.870980	1136.973600	0.997345	304340.487982	311949.000181	0.834267	0.836487	9
20	17554.763112	0.914311	179.936322	1196.973600	0.997478	321853.728657	329900.071874	0.838161	0.840280	10
21	17654.425395	0.919501	180.957860	1256.973600	0.997598	339467.205809	347953.885955	0.841933	0.843960	10
22	17745.043330	0.924221	181.886694	1316.973600	0.997707	357175.445606	366104.831746	0.845586	0.847529	11
23	17829.121813	0.928600	182.748499	1376.973600	0.997807	374971.328289	384345.611496	0.849120	0.850986	11
24	17906.567070	0.932634	183.542312	1436.973600	0.997898	392848.739497	402669.957984	0.852536	0.854332	12
25	17977.456424	0.936326	184.268928	1496.973600	0.997982	410799.466249	421069.452905	0.855832	0.857562	12
26	18042.453063	0.939711	184.935144	1556.973600	0.998060	428815.884445	439536.281557	0.859006	0.860676	13
27	18109.462826	0.943201	185.621994	1616.973600	0.998132	446896.925743	458069.348887	0.862070	0.863683	14
28	18169.982624	0.946353	186.242322	1676.973600	0.998199	465040.875432	476666.897318	0.865031	0.866592	14
29	18227.152414	0.949331	186.828312	1736.973600	0.998261	483242.386920	495323.446593	0.867892	0.869404	15
30	18281.613265	0.952167	187.386536	1796.973600	0.998319	501498.412094	514035.872397	0.870657	0.872123	15

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Example of Programming for Calculation of the Hydrostatics - Example of Hydrostatic Tables of a 320K VLCC (2/2)

Hydrostatics Table

KB	BMt	KMt	LCB	LCF	BMl	KMl	MTC	Wetted Surface Area
0.509932	249.279769	249.789701	17.634696	16.988722	5579.686819	5580.196750	2314.646744	14102.067144
1.025653	131.559866	132.585519	17.124977	16.375976	2962.881019	2963.906672	2557.861669	15079.444762
1.543595	89.894069	91.437664	16.785825	15.944990	2045.756860	2047.300456	2717.998493	15882.807875
2.060474	68.385545	70.446019	16.518405	15.612685	1570.949684	1573.010157	2834.636543	16618.776733
2.576277	55.320467	57.896744	16.287570	15.207640	1281.933552	1284.509829	2932.926936	17331.697356
3.092244	46.498881	49.591125	16.069941	14.941734	1081.449552	1084.541796	3003.884761	18026.084613
3.607174	40.131690	43.738864	15.890147	14.769625	932.964856	936.572030	3052.482676	18706.387874
4.121509	35.310328	39.431836	15.716638	14.383665	824.011114	828.132622	3106.376536	19367.844148
4.635703	31.535720	36.171423	15.530695	13.873811	739.817809	744.453512	3160.081909	20026.661200
5.150036	28.499889	33.649925	15.320611	13.206166	673.530311	678.680346	3217.131299	20688.395322
5.664717	26.007295	31.672012	15.078149	12.389904	620.434826	626.099544	3279.046555	21355.594668
6.179868	23.940218	30.120085	14.798156	11.426314	577.378964	583.558831	3347.163851	22031.346533
6.695516	22.197901	28.893417	14.478059	10.313393	542.171603	548.867119	3422.641486	22719.069067
7.213571	20.701056	27.914627	14.108800	8.961314	514.225484	521.439055	3513.814422	23436.142778
7.736683	19.395506	27.132189	13.686550	7.550015	490.042460	497.779143	3606.819609	24153.666246
8.261164	18.253453	26.514617	13.221739	6.036404	469.665833	477.926997	3706.662270	24885.589906
8.784388	17.250265	26.034653	12.711991	4.427362	452.305205	461.089592	3811.653906	25648.473411
9.309007	16.358312	25.667320	12.168722	3.027873	435.400427	444.709435	3904.150199	26390.817987
9.834664	15.558514	25.393178	11.610030	1.874104	418.610230	428.444894	3981.251301	27121.767720
10.360640	14.833239	25.193879	11.052104	0.949584	402.322606	412.683246	4046.532211	27828.171680
10.886729	14.168543	25.055272	10.508656	0.314228	387.475682	398.362411	4110.477717	28519.892075
11.412880	13.555606	24.968487	9.990360	-0.119337	373.550750	384.963631	4169.473618	29205.249360
11.939003	12.987957	24.926960	9.503047	-0.379617	360.593551	372.532554	4225.382593	29882.641610
12.465035	12.463030	24.928065	9.049601	-0.523423	348.430560	360.895595	4277.515818	30554.971648
12.990852	11.977942	24.968794	8.629644	-0.588068	336.938839	349.929691	4325.446727	31223.264679
13.516351	11.528007	25.044358	8.242049	-0.578749	326.080741	339.597092	4369.643798	31887.840180
14.041601	11.109971	25.151572	7.887679	-0.442092	316.247188	330.288788	4416.559250	32557.540530
14.566638	10.721379	25.288016	7.565974	-0.286588	306.814475	321.381113	4458.789754	33226.725389
15.091404	10.360160	25.451564	7.274229	-0.103187	297.903898	312.995302	4498.743464	33896.183818
15.615903	10.023641	25.639544	7.010481	0.115336	289.495842	305.111745	4536.928276	52901.394845

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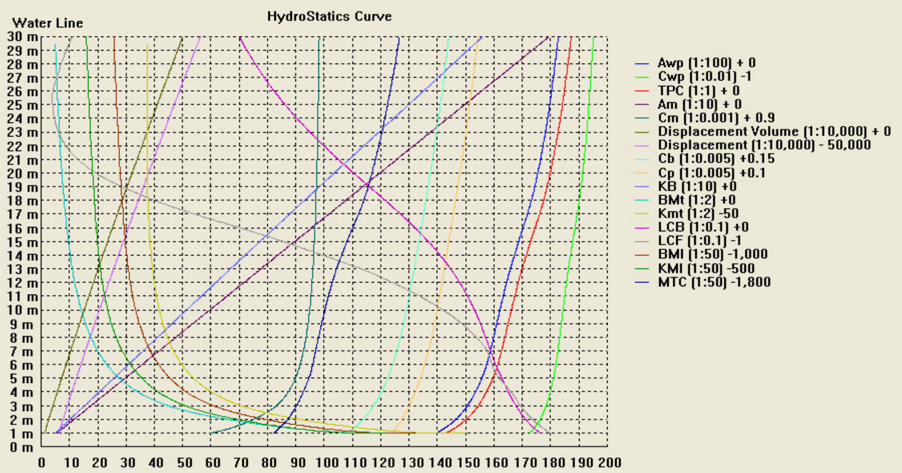
Example of Programming for Calculation of the Hydrostatics - Example of Hydrostatic Curves of a 320K VLCC

Hydrostatics



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