Ship Stability

Ch. 6 Free Surface Effect

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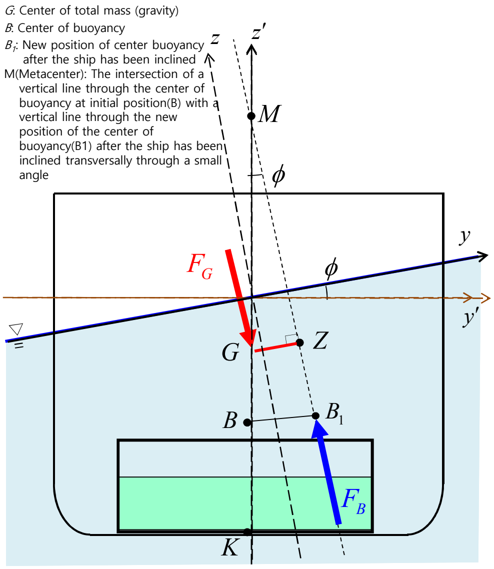
Free Surface Effect

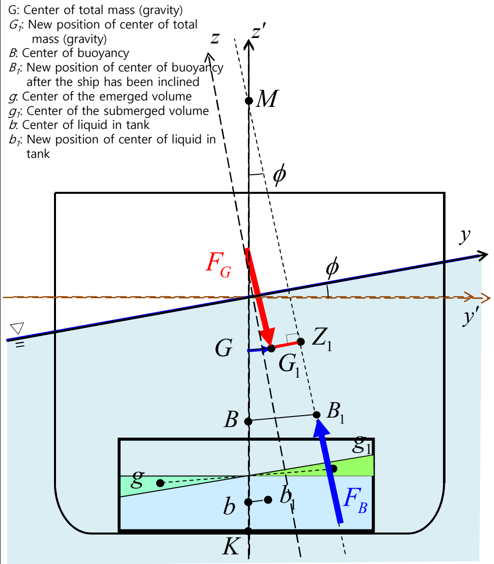


If the cargo in hold* is fixed, e.g. a solid cargo, this keeps its original position when a ship is inclined.

If there is a liquid cargo in hold, what will happen when the ship is inclined?

* Hold or Cargo Hold: Space for loading the cargo in the ship

Definition of Free Surface Effect

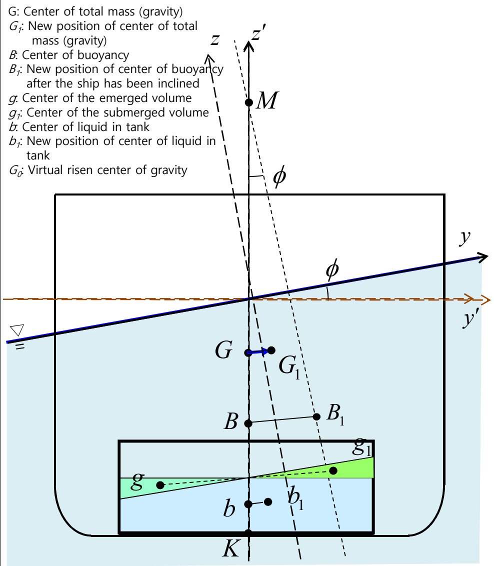


- When the ship is inclined, the liquid in the tank is also inclined. And the center of gravity of the liquid shifts toward the inclined side.
- This causes the ship's center of gravity to move toward the inclined side, **reducing the righting arm**.

Definition of Free Surface Effect

- The motion of the liquid in a tank that is partially full causes the ship's center of gravity to move.
- This reduces the righting arm and reduces the ship's stability.

Assumption to Evaluate the Effect of Free Surface



✓ The effects of free surface depend on the dimensions of the surface of the liquid.

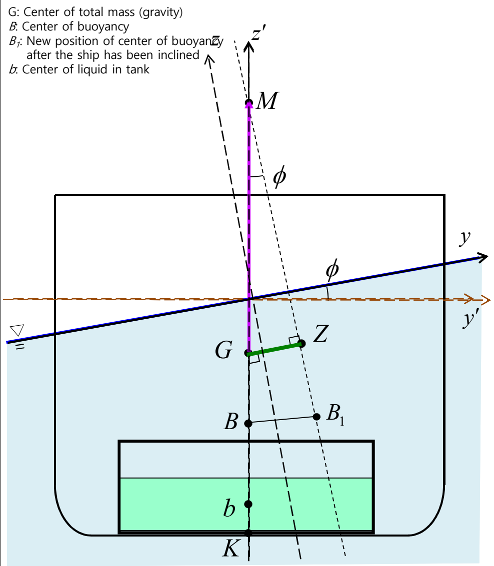
What assumption is appropriate to evaluate the effect of free surface in a ship's tank?

Assumption: Small inclination

The metacentric height (GM) provides a fairly accurate evaluation of the righting moment up to 7~10 degrees.

And, surface of the liquid does not reach the top or bottom of the tank during this inclination.

Transverse Righting Moment When there is no Effect of Free Surface



✓ **Transverse Righting Moment**

Righting arm: GZ

- **Transverse Righting Moment**

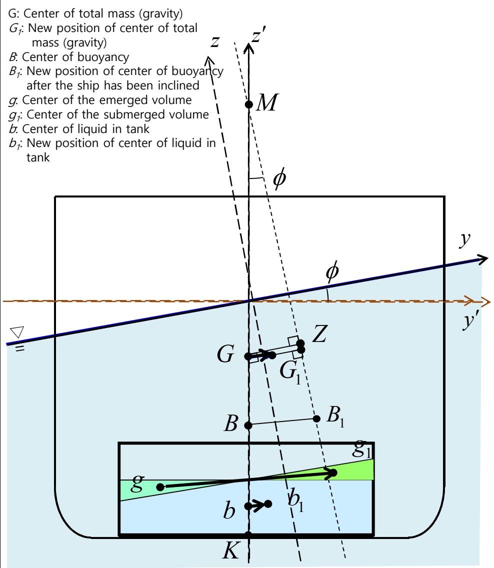
$$\tau_{righting} = F_B \cdot GZ$$

$$GZ = GM \sin\phi$$

$$GM = KB + BM - KG$$

The Influence of Free Surface on the Initial Stability at Small Angle (1/5)

$$\tau_{restoring} = GZ \cdot F_B$$
$$GZ = GM \cdot \sin\phi$$
$$GM = KB + BM - KG$$



✓ Evaluation of effect of free surface on metacentric height

If a ship is inclined, the plane of liquid in tank is changed to be parallel to water plane.

$$bb_1 // gg_1 // GG_1$$

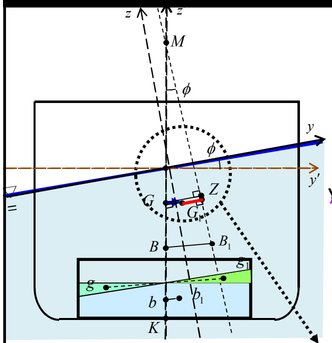
And the relation between change in total center of gravity and center of liquid in tank is

$$GG_1 = \frac{w}{F_G} bb_1$$

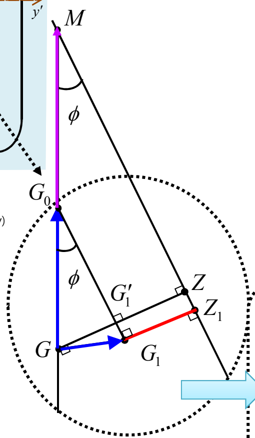
The Influence of Free Surface on the Initial Stability at Small Angle (2/5)

$\tau_{restoring} = GZ \cdot F_B$
$GZ = GM \cdot \sin\phi$
$GM = KB + BM - KG$

$bb_1 // gg_1 // GG_1$



G: Center of total mass (gravity)
G_0: Virtual risen center of gravity
G_1: New position of center of total mass (gravity)
G_1': The intersection of the line GZ with G_0G_1
B: Center of buoyancy
B_1: New position of center of buoyancy after the ship has been inclined
g: Center of the emerged volume
g_1: Center of the submerged volume
b: Center of liquid in tank
b_1: New position of center of liquid in tank
m: Metacenter of cargo hold



GG_0 : free surface correction

✓ Evaluation of effect of free surface on metacentric height

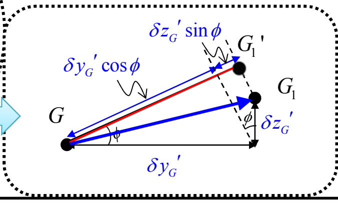
From the geometric shape, the righting arm G_1Z_1 is expressed as follows:

$$G_1Z_1 = GZ - GG_1'$$
$$= GZ - (\delta y_G' \cos\phi + \delta z_G' \sin\phi)$$

This term has negative effect to the restoring moment arm.

: It means that the shift of center of total gravity GG_1 causes reduction of righting arm. And it causes stability to be worse.

: **Free Surface Effect (FSE)**
➡ **Reduction of righting arm**
(It causes stability to be worse.)



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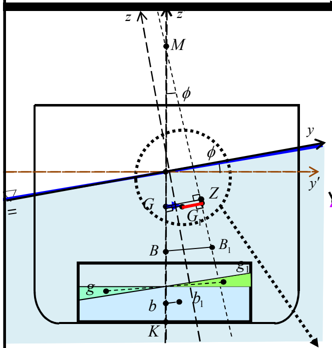
The Influence of Free Surface on the Initial Stability at Small Angle (3/5)

GG_0: free surface correction

$\tau_{restoring} = GZ \cdot F_B$
$GZ = GM \cdot \sin\phi$
$GM = KB + BM - KG$

$bb_1 // gg_1 // GG_1$



G: Center of total mass (gravity)
G_0: Virtual risen center of gravity
G_1: New position of center of total mass (gravity)
G_1': The intersection of the line GZ with G_0G_1
B: Center of buoyancy
B_1: New position of center of buoyancy after the ship has been inclined
g: Center of the emerged volume
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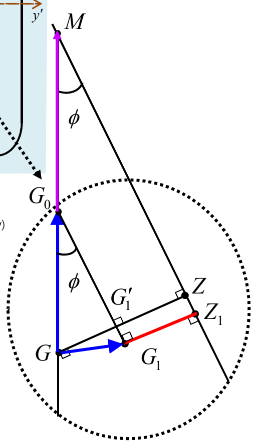
m: Metacenter of cargo hold



✓ Evaluation of effect of free surface on metacentric height

: **Free Surface Effect (FSE)**
➡ **Reduction of righting arm**
(It causes stability to be worse.)

Assume that $\phi << 1$, then from the geometric shape, the righting arm G_1Z_1 is expressed as follows:

$$G_1Z_1 = GZ - GG_1'$$
$$= GM\sin\phi - GG_0\sin\phi$$
$$= (GM - GG_0)\sin\phi$$
$$= G_0M\sin\phi$$

It means that the shift of center of total gravity GG_1 is considered as the elevation of center of total gravity from G to G_0.

GG_0: free surface correction

$GM = KB + BM - KG$

⇩

KG_0

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The Influence of Free Surface on the Initial Stability at Small Angle (4/5)

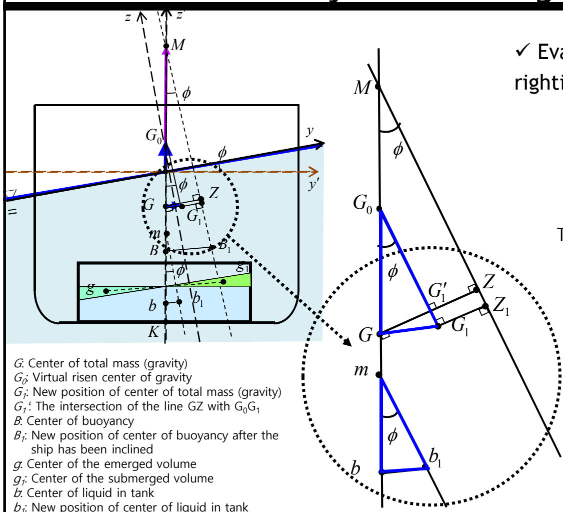
$\tau_{restoring} = GZ \cdot F_B$

$GZ = GM \cdot \sin\phi$

$GM = KB + BM - KG$

KG_0

$bb_1 // gg_1 // GG_1$



G: Center of total mass (gravity)
G₀: Virtual risen center of gravity
G₁: New position of center of total mass (gravity)
Z₁: 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
w: Weight of liquid in tank

✓ Evaluation of effect of free surface on righting arm

$$GG_1 // bb_1, \quad GG_0 // bm, \quad G_1G_0 // b_1m$$

Triangle GG_1G_0 is similar to triangle bb_1m.

$$\frac{GG_1}{bb_1} = \frac{w}{F_G} \Rightarrow GG_1 = \frac{w}{F_G} bb_1$$

The Influence of Free Surface on the Initial Stability at Small Angle (5/5)

$GG_1 = \frac{w}{F_G} bb_1$

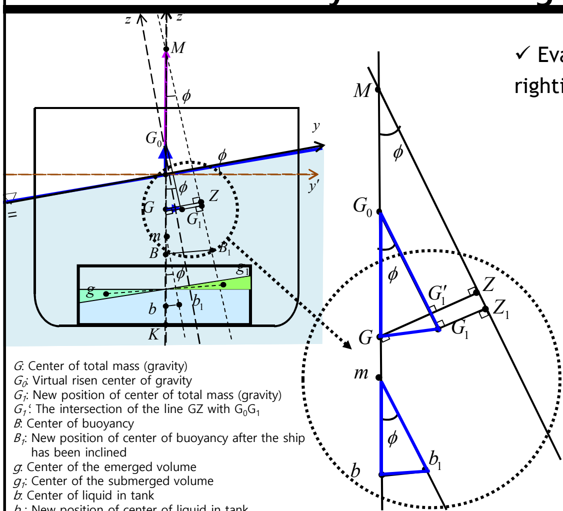
$\tau_{restoring} = GZ \cdot F_B$

$GZ = GM \cdot \sin\phi$

$GM = KB + BM - KG$

KG_0

$bb_1 // gg_1 // GG_1$



G: Center of total mass (gravity)
G₀: Virtual risen center of gravity
G₁: New position of center of total mass (gravity)
Z₁: The intersection of the line GZ with G_0G_1
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b: Center of liquid in tank
b₁: New position of center of liquid in tank
m: Metacenter of cargo hold
w: Weight of liquid in tank
i₁: Moment of inertia of liquid plane area in tank about x' axis
ρ_F: Density of liquid in tank, ρ_{SW}: Density of sea water
∇ : Displacement volume
v: Volume of liquid in tank

✓ Evaluation of effect of free surface on righting arm

Because ϕ is small, (small inclination)

$$GG_1 \approx GG_1', \quad GG_1' = GG_0 \sin\phi,$$

$$\rightarrow GG_1 = GG_0 \sin\phi,$$

In the same manner, $bb_1 \approx bm \sin\phi$

$$\Rightarrow GG_1 = GG_0 \sin\phi = \frac{w}{F_G} bb_1 = \frac{w}{F_G} bm \sin\phi$$

$$GG_0 = \frac{w}{F_G} bm$$

$$= \frac{w}{F_G}\frac{i_T}{v} = \frac{\rho_F g v}{\rho_{SW} g \nabla}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$$

$\rho_F i_T$: **Free Surface Moment**

The elevation of center of total gravity due to the shift of center of gravity of liquid in tank is related to **the density of liquid in tank** and **moment of inertia of liquid plane area in tank**.

(It's not related to weight of liquid in tank.)

The Effects of Free Surface

G: Center of total mass (gravity)
G_1: New position of center of total mass (gravity)
w: Weight of liquid in tank
i_T: Moment of inertia of liquid plane area in tank about x' axis

ρ_F: Density of liquid in tank
ρ_{SW}: Density of sea water
∇: Displacement volume
v: Volume of liquid in tank

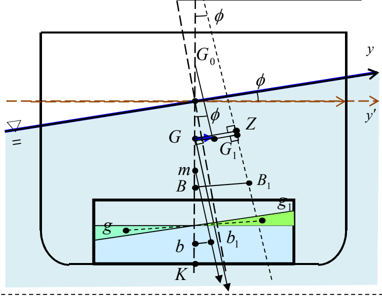
- **Free Surface Effect**

$$GM = KB + BM - KG_0,\ KG_0 = KG + GG_0$$

$$GG_0 = \frac{w}{W}\frac{i_T}{v} = \frac{\rho_F g v}{\rho_{SW} g \nabla}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$$

: free surface correction

$\rho_F i_T$: free Surface Moment



- The effects of free surface do not depend on the amount of liquid in the tanks.
- The weight and vertical position of the liquid which have an effect on transverse stability is not associated with free surface effects.
- The effects of free surface depend on the ratio of density of the liquid in the tank to the density of the liquid in which the ship is floating.
- The breadth of liquid, which almost wholly accounts for free surface effects, changes when inclined, depending on the height of the liquid in the tank, the degree of inclination, and the breadth depth ratio of the tank.

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Question) Effect of Tank Size on Free Surface

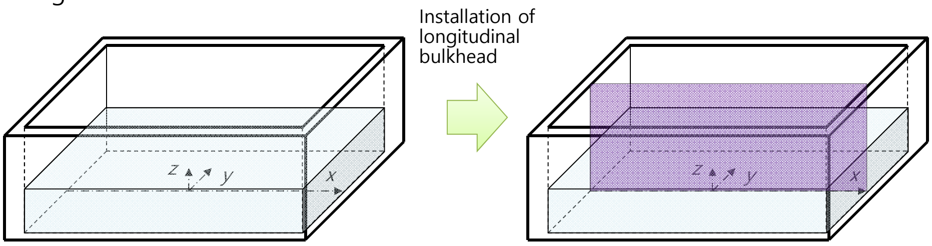
$$GG_0 = \frac{w}{W}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$$

: free surface correction

- Effect of the breadth of liquid in a tank which almost wholly accounts for free surface effects.

Question)

Sea water is filled partially in tank with water plane of rectangular shape.
If a longitudinal bulkhead is installed in center of tank, how much GM will be changed?



Hint)

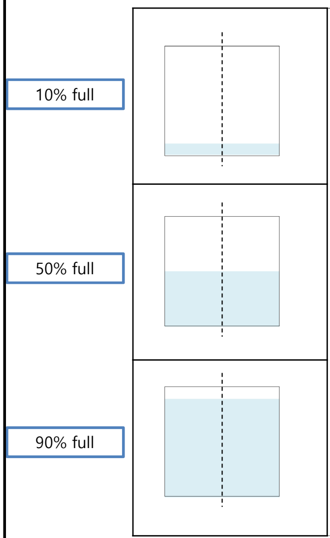
$$i_T = \int y^2 dA = \frac{l \cdot b^3}{12}$$

Answer)

$$i_{T1} = \frac{l \cdot b^3}{12},\quad i_{T2} = 2 \cdot \frac{l \cdot (b/2)^3}{12} = \frac{l \cdot b^3}{48} = \frac{1}{4} i_{T1}$$

The Influence of Free Surface at Large Angles of Heel (1/5)

$GG_0 = \frac{w}{W}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$: free surface correction



- **Effect of filling ratio** of a ship and on free surface effects

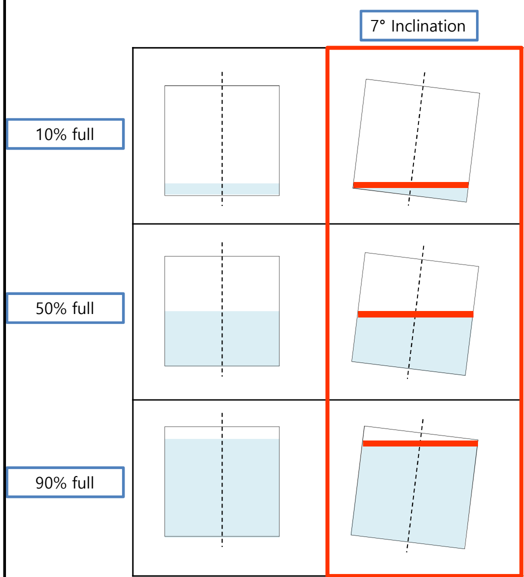
  ✓ In making the loading calculations, free surface corrections to GM must be made on the basis of reasonable assumptions **regarding the condition of all tanks**.

  Example)
  Departure condition & Arrival condition
  - Fuel oil system:
    Settling tank: assumed to be half full.
    Fuel oil tank: assumed to be 98% full or empty in merchant ship
  - Water ballast tank:
    Empty or nominally completely full (to have no effect)

* Settling tank: Tank for settling impurities in fuel oil before using it.

The Influence of Free Surface at Large Angles of Heel (2/5)

$GG_0 = \frac{w}{W}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$: free surface correction



- **Small angle of inclination**

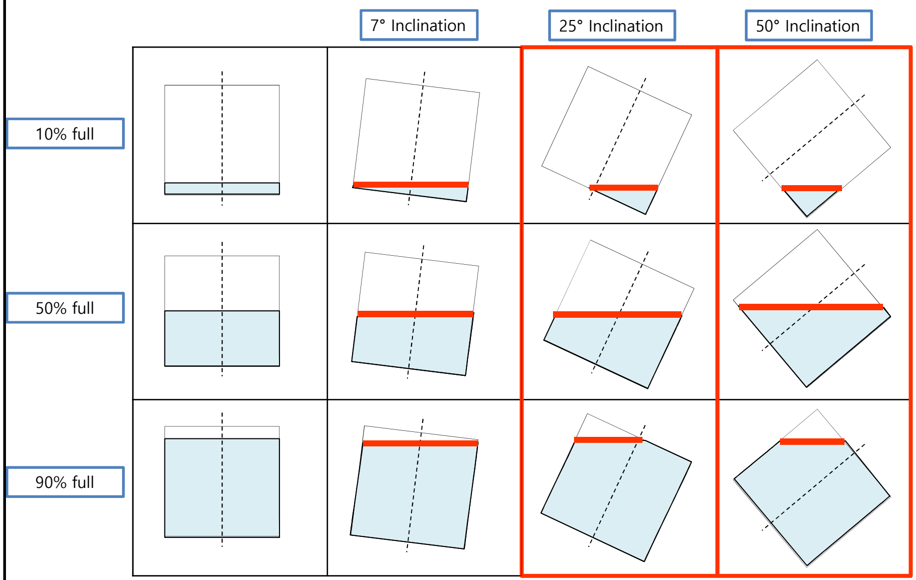
  ✓ It has been pointed out previously that the metacentric height (GM) provides a fairly accurate evaluation of the righting moment **up to 7~10 degrees**.

  ✓ In the same manner, when the metacentric height is reduced by the effect of free liquid, this assumption of **small angle** provides that the surface of the liquid does not reach the top or bottom of the tank during this inclination.

The Influence of Free Surface at Large Angles of Heel (3/5)

$$GG_0 = \frac{w}{W}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$$

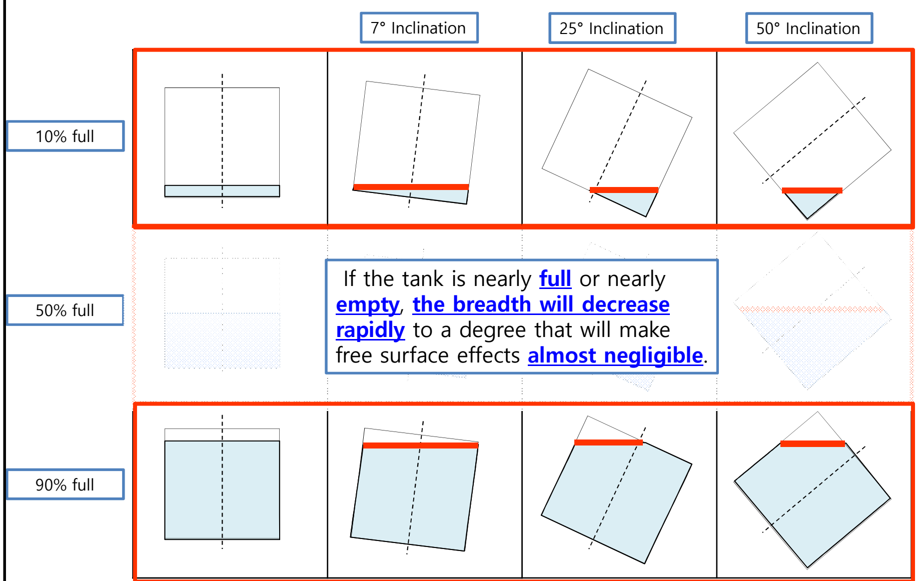
: free surface correction



The Influence of Free Surface at Large Angles of Heel (4/5)

$$GG_0 = \frac{w}{W}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$$

: free surface correction

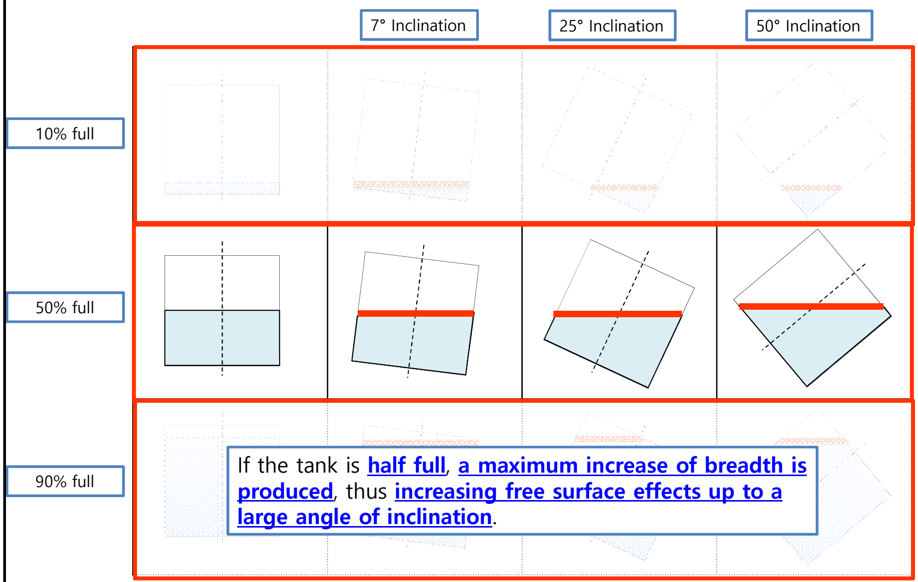


If the tank is nearly **full** or nearly **empty**, **the breadth will decrease rapidly** to a degree that will make free surface effects **almost negligible**.

The Influence of Free Surface at Large Angles of Heel (5/5)

$$GG_0 = \frac{w}{W}\frac{i_T}{v} = \frac{\rho_F}{\rho_{SW}}\frac{i_T}{\nabla}$$

: free surface correction



If the tank is **half full**, **a maximum increase of breadth is produced**, thus **increasing free surface effects up to a large angle of inclination**.