Lecture Note of Naval Architectural Calculation

Ship Stability

Ch. 13 Probabilistic Damage Stability

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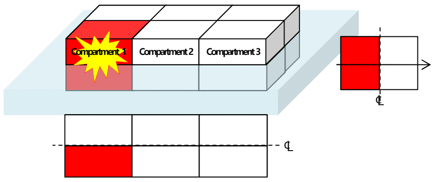
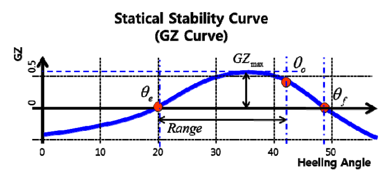
Ch. 13 Probabilistic Damage Stability (Subdivision and Damage Stability, SDS)

1. Introduction to Subdivision and Damage Stability

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

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.

$$A \geq R$$

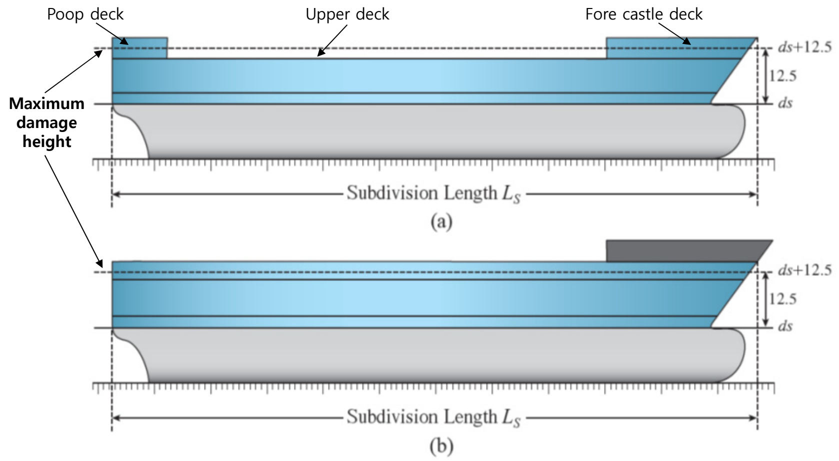
Ship Types for Subdivision & Damage Stability

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

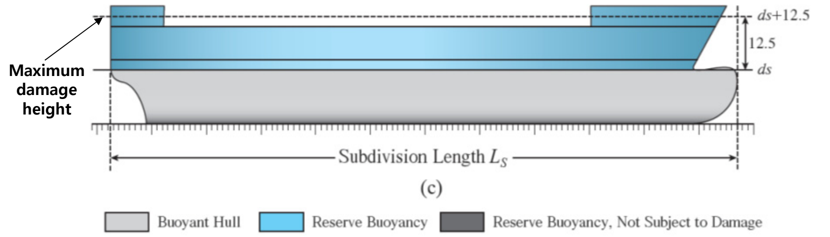
Ship Type	Freeboard Type	Deterministic Damage Stability				Probabilistic Damage Stability
		ICLL[1]	MARPOL[2]	IBC[3]	IGC[4]	SOLAS[5]
Oil Tankers	A[6]	O	O			
	B[7]		O			
Chemical Tankers	A	O		O		
Gas Carriers	B				O	
Bulk Carriers	B					O
	B-60	O				
	B-100	O				
Container Carriers Ro-Ro Ships Passenger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

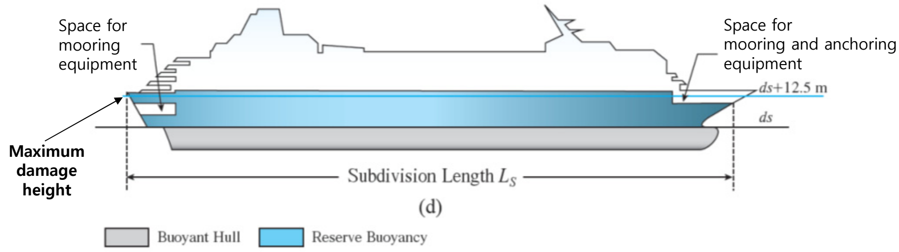
Definition of Subdivision Length (L_s) (1/2)

- ☑ 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.

$$A \geq R$$ 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.

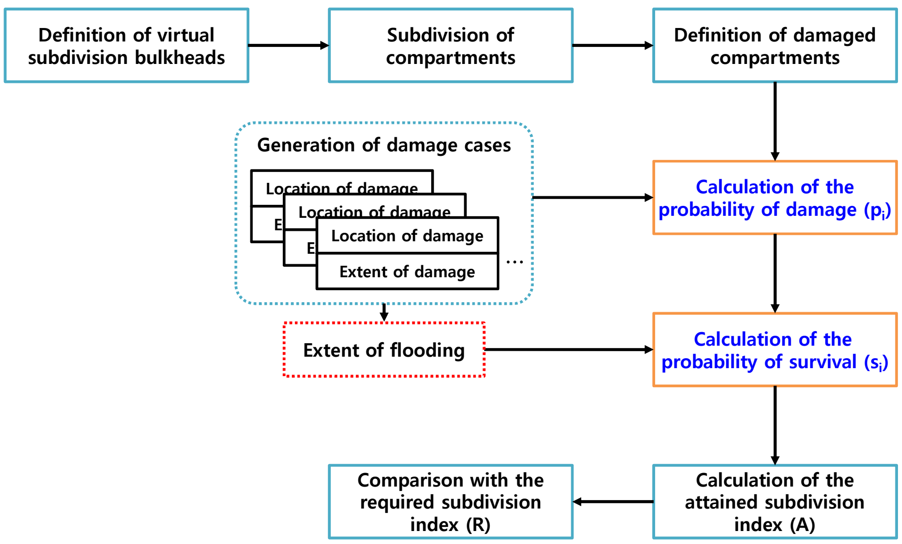
☑ The deepest subdivision draft (d_s): corresponding to summer draft (scantling draft)

☑ 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:

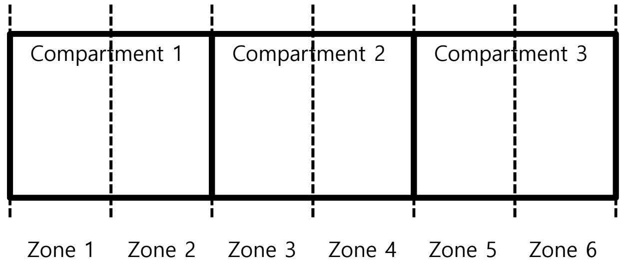
$$d_p = d_l + 0.6(d_s - d_l)$$

Overall Procedures to Evaluate the Probabilistic Damage Stability



2. Definition of Virtual Subdivision Bulkheads

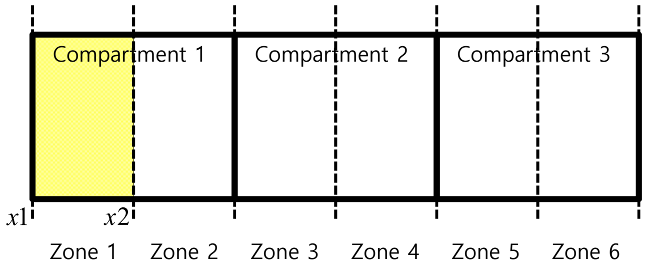
Definition of Virtual Subdivision Bulkheads - Compartment vs. Zone



Compartment – an onboard space within watertight boundaries.
➡ **Actual subdivision** of the ship.

Zone – a longitudinal interval of the ship within the subdivision length.
➡ **Conceptual subdivision** for calculation of the probability of damage "p_i".

Definition of Virtual Subdivision Bulkheads - One Zone Damage Case vs. Multi Zone Damage Case



Only one zone is damaged, this case is called "one zone damage case".
Two adjacent zones are damaged, this case is called "two zone damage case".

Example) One zone damage case: (Zone 1), (Zone 2), …
Two zone damage case: (Zone 1, Zone 2), (Zone 2, Zone 3), …

And, the length of damage in this case can be expressed by x1 and x2.

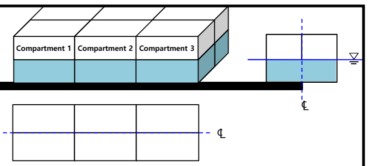
$x1$ = the distance from the aft terminal to the aft end of the zone in question.
$x2$ = the distance from the aft terminal to the forward end of the zone in question.

x_1 and x_2 represent the terminals of the compartment or group of compartments.

* Compartment: Onboard space within watertight boundaries.
* Zone: Longitudinal interval of the ship within the subdivision length.

3. Probability of Damage (p_i)

Probability of Damage



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

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

What is the factor "p_i"?

: **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

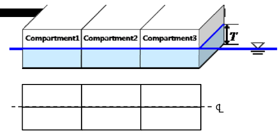
➡ Not dependent on the **draft**. Thus, we use the **deepest subdivision draft "ds"**.

Probability of Damage in Longitudinal Subdivision (p)

Consideration of the Probability Related to the Longitudinal Subdivision

$p_i = p \cdot r$

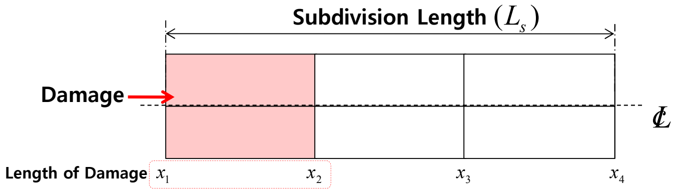
$p = p(x1, x2, L_s)$



What is the factor "p"?

: **Probability of damage in the longitudinal subdivision**

$$p = p(x1, x2, L_s)$$



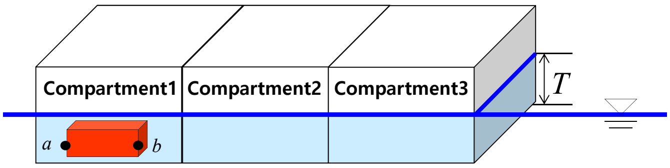
: The **factor** "p" is dependent on the **length of damage** ($x2 - x1$) and the **subdivision length** "L_s" of a ship.

[Example] Box-Shaped Ship - Damage Generator

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

How can we obtain the value of "p" for a box-shaped ship?



✓Assume that the dimensions of the compartments are same.

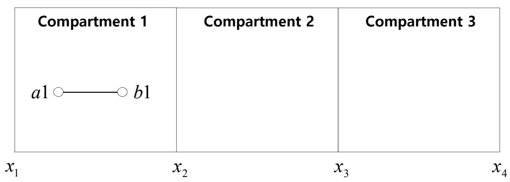
- ✓ The ship is damaged by the "**damage generator**" defined by the **extent of damage in horizontal, transverse, and vertical direction.**
- ✓ Define that the **each end point of the "damage generator"** is "a" and "b".

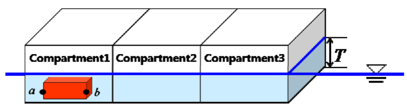
[Example] Box-Shaped Ship - Damage Length

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

What is the "damage length" (length of the damage)?





For example, when one compartment is damaged, the end points become "$a1$" and "$b1$".

- ✓ What we consider in this part is "**damage length**". **Each end of the damage length is "$x1$" (left) and "$x2$" (right)** and we can calculate the probability of damage by this **length** $(x2 - x1)$.

* The damage length is represented by the non-dimensional damage length in the SOLAS regulation:

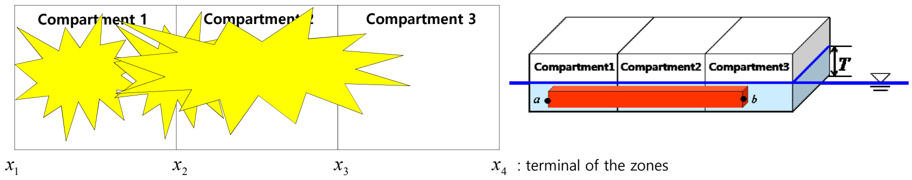
Non-dimensional damage length: "J" = $\frac{(x_2 - x_1)}{L_s}$

[Example] Box-Shaped Ship - Damage Zone

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

What is the "damage zone"?



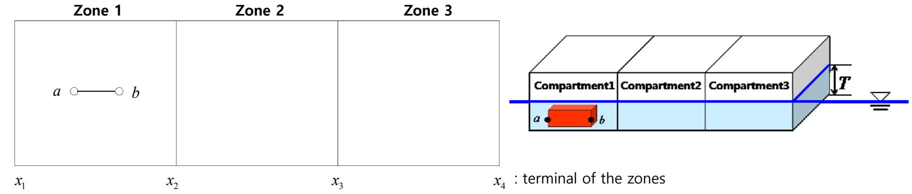
- ✓ **Damage zone** is a **longitudinal interval of the ship** within the subdivision length.
- ✓ In general, the zones are placed in accordance with the watertight arrangement. However, **the zones can be placed in accordance with the virtual subdivision**.
- ✓ For this example, we place the zones in accordance with the compartments (the watertight arrangement).

[Example] Box-Shaped Ship - One Zone Damage Case

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

How can we obtain the value of "p" when one zone is damaged?



Example) What is the probability that zone 1 is damaged?

Probability that "a" is located in zone 1 × **Probability that "b" is located in zone 1**

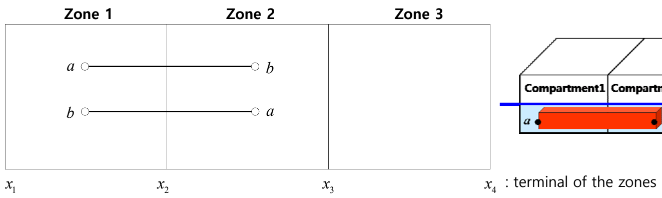
$$\frac{1}{3} \times \frac{1}{3} = \frac{1}{9}$$

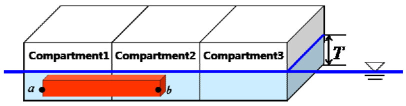
[Example] Box-Shaped Ship - Two Zones Damage Case (1/2)

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

How can we obtain the value of "p" when two adjacent zones are damaged?





Example) What is the probability that zone 1 and zone 2 are damaged simultaneously?

[Probability that "a" is located in zone 1] × [Probability that "b" is located in zone 2] + [Probability that "b" is located in zone 1] × [Probability that "a" is located in zone 2]

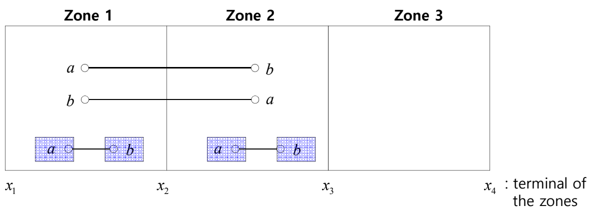
$$\frac{1}{3} \times \frac{1}{3} + \frac{1}{3} \times \frac{1}{3} = \frac{2}{9}$$

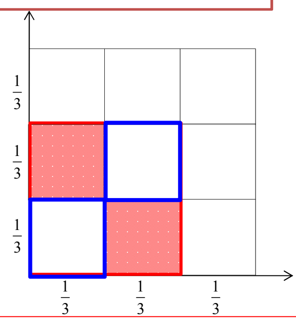
[Example] Box-Shaped Ship - Two Zones Damage Case (2/2)

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

How can we obtain the value of "p" that two adjacent zones are damaged by different representation method?





In the figure, the red area means the probability that zone 1 and zone 2 are damaged simultaneously.

Example) What is the probability that zone 1 and zone 2 are damaged simultaneously?

[Probability that "a" is located in zone 1 or zone 2] × [Probability that "b" is located in zone 1 or zone 2] − [Probability that "a" is located in zone 1] × [Probability that "b" is located in zone 1] − [Probability that "a" is located in zone 2] × [Probability that "b" is located in zone 2]

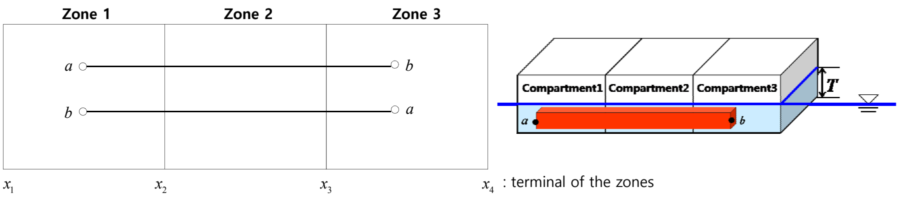
$$\frac{2}{3} \times \frac{2}{3} - \frac{1}{3} \times \frac{1}{3} - \frac{1}{3} \times \frac{1}{3} = \frac{2}{9}$$

[Example] Box-Shaped Ship - Three Zones Damage Case (1/3)

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

How can we obtain the value of "p" when three zones are damaged?



Example) What is the probability that zone 1, zone 2, and zone 3 are damaged simultaneously?

Probability that "a" is located in zone 1	×	Probability that "b" is located in zone 3	+	Probability that "b" is located in zone 1	×	Probability that "a" is located in zone 3	
$\frac{1}{3}$	×	$\frac{1}{3}$	+	$\frac{1}{3}$	×	$\frac{1}{3}$	$= \frac{2}{9}$

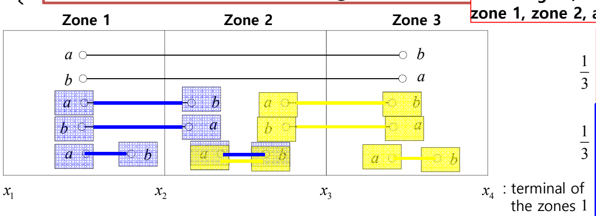
[Example] Box-Shaped Ship - Three Zones Damage Case (2/3)

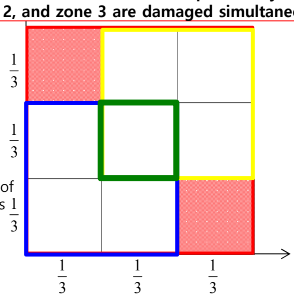
$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

How can we obtain the value of "p" by different representation method when three zones are damaged?

In the figure, the red area means the probability that zone 1, zone 2, and zone 3 are damaged simultaneously.





Example) What is the probability that zone 1, zone 2, and zone 3 are damaged simultaneously?

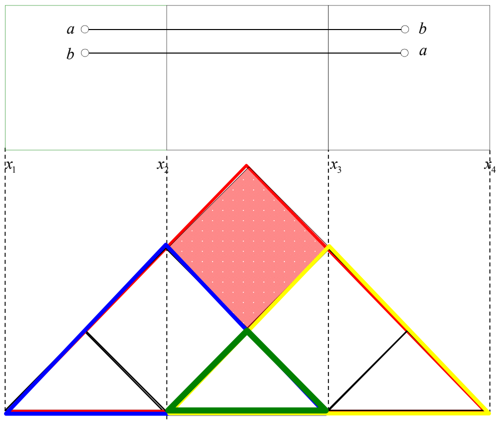
					Representation in terms of "p"
	Probability that "a" is located in zone 1 or zone 2 or zone 3	×	Probability that "b" is located in zone 1 or zone 2 or zone 3	$\frac{3}{3} \times \frac{3}{3}$	⇨ $p(x_1, x_4)$
−	Probability that "a" is located in zone 1 or zone 2	×	Probability that "b" is located in zone 1 or zone 2	$\frac{2}{3} \times \frac{2}{3}$	⇨ $p(x_1, x_3)$
−	Probability that "a" is located in zone 2 or zone 3	×	Probability that "b" is located in zone 2 or zone 3	$\frac{2}{3} \times \frac{2}{3}$	⇨ $p(x_2, x_4)$
+	Probability that "a" is located in zone 2	×	Probability that "b" is located in zone 2	$\frac{1}{3} \times \frac{1}{3}$	⇨ $p(x_2, x_3)$
				$= \frac{2}{9}$	

[Example] Box-Shaped Ship - Three Zones Damage Case (3/3)

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

How can we obtain the value of "p" by different representation method when three zones are damaged?



In the figure, the red area means the probability that zone 1, zone 2, and zone 3 are damaged simultaneously.

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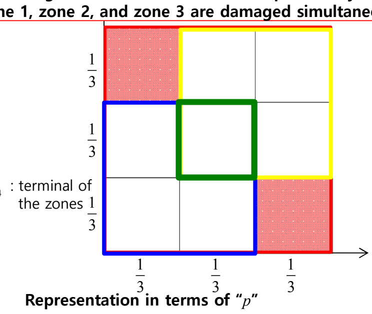


Representation in terms of "p"

$\frac{3}{3} \times \frac{3}{3} \Rightarrow p(x_1, x_4)$

$\frac{2}{3} \times \frac{2}{3} \Rightarrow p(x_1, x_3)$

$\frac{2}{3} \times \frac{2}{3} \Rightarrow p(x_2, x_4)$

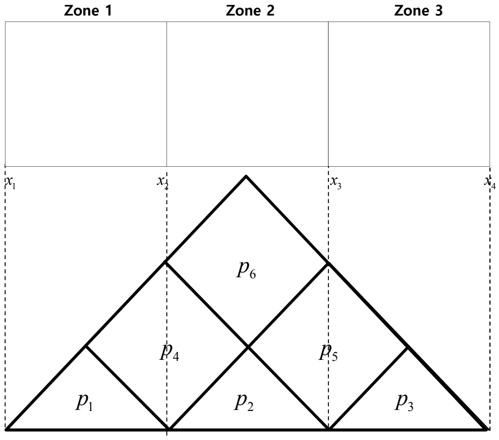
$\frac{1}{3} \times \frac{1}{3} \Rightarrow p(x_2, x_3)$

$= \frac{2}{9}$

[Example] Box-Shaped Ship - Total Damage Cases

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$



One zone damage case

$p_1 = p(x_1, x_2)$

$p_2 = p(x_2, x_3)$

$p_3 = p(x_3, x_4)$

Two zones damage case

$p_4 = p(x_1, x_3) - p(x_1, x_2) - p(x_2, x_3)$

$p_5 = p(x_2, x_4) - p(x_2, x_3) - p(x_3, x_4)$

Three zones damage case

$p_6 = p(x_1, x_4) - p(x_1, x_3) - p(x_2, x_4)$
$\quad + p(x_2, x_3)$

* Assume that the factor "r" is constant(r=1).

After the calculation of the factor "p_i" in each damage case, we can calculate "s_i" of "that damage case" in a given draft such as "dp", "ds", "dl".

$$A = \sum p_i \cdot s_i$$

$p(x_i, x_j)$: **This function gives the probability of all cases when the compartments between i^th subdivision line and j^th subdivision line can be damaged.**

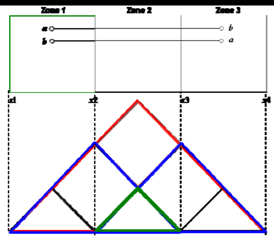
[Reference] Recurrence Formula for Three or More Adjacent Zones Damage Case

$p_i = p \cdot r$

$p = p(x1, x2, L_s)$

Three zones damage case:

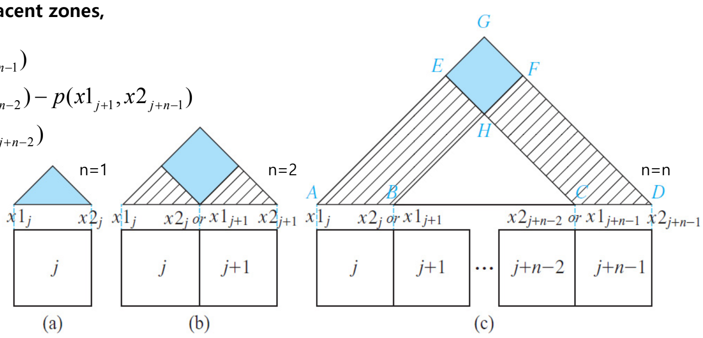
$$p_6 = p(x_1, x_4) - p(x_1, x_3) - p(x_2, x_4) + p(x_2, x_3)$$



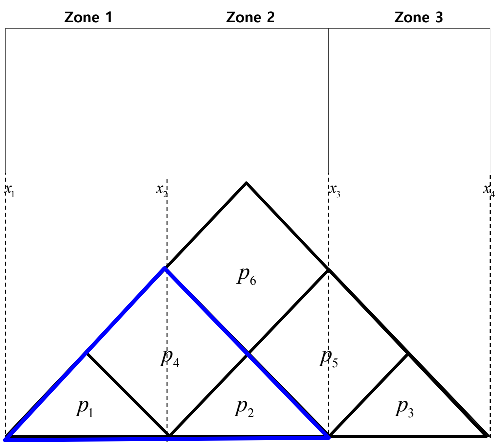
Three or more adjacent zones, pure subdivision:

$$p_{j,n} = p(x1_j, x2_{j+n-1}) - p(x1_j, x2_{j+n-2}) - p(x1_{j+1}, x2_{j+n-1}) + p(x1_{j+1}, x2_{j+n-2})$$

where, n: number of zones to be damaged



[Reference] Calculation of the Probability of Damage by Using the Area of Triangle



$p(x_i, x_j)$ means the probability that all compartments between x_i and x_j are damaged, and it can be calculated from the area of triangle which side length is the distance from x_i to x_j.

For example, $p(x_1, x_3)$ means the probability that includes a damage case of zone 1, a case of zone 2, and a case of zone 1 & 2, and it can be calculated from the area of blue triangle in the left figure.

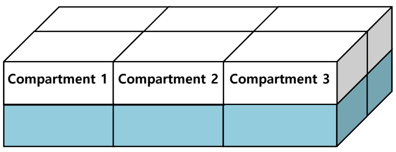
Probability of Damage in Transverse Subdivision (r)

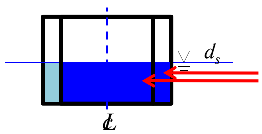
Consideration of the Probability Related to the Transverse Subdivision (1/2)

$p_i = p \cdot r$

Is there only longitudinal subdivision to consider "p_i"?

d_s: Deepest subdivision draft

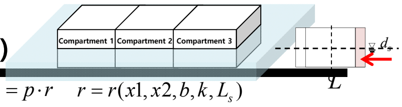




No!

- We have to consider the probability related to the **transverse subdivision and penetration**.
- The probability of damage in transverse subdivision and penetration is represented by the **factor "r"**.
- The factor "r" is determined **after deciding the longitudinal damage case**.

Consideration of the Probability Related to the Transverse Subdivision (2/2)



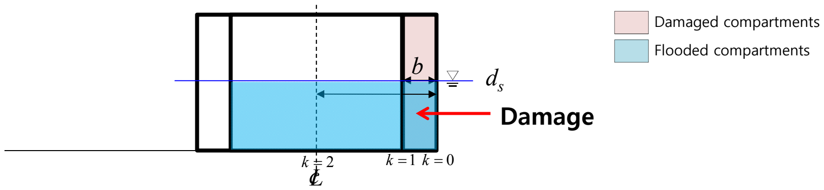
$p_i = p \cdot r$ $r = r(x1, x2, b, k, L_s)$

b: penetration depth
k: the number of a particular longitudinal bulkhead

What is the factor "*r*"?

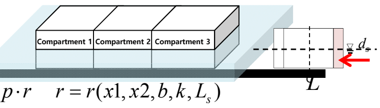
: Probability of damage in the transverse subdivision

$$r = r(x1, x2, b, k, L_s)$$



: The **factor "*r*"** is dependent on the **penetration depth "*b*"** and the **number of a particular longitudinal bulkhead "*k*".**
Where, **"*k*" is counted from shell towards the centerline**. And **"*b*" is measured at deepest subdivision draught "d_s".**

Range of the Factor "*b*" Towards the Centerline (1/4)



$p_i = p \cdot r$ $r = r(x1, x2, b, k, L_s)$

b: penetration depth
k: the number of a particular longitudinal bulkhead

What is the factor "*r*" when this factor "*b*" is zero?
And what is the factor "*r*" when this factor "*b*" is *B/2*?

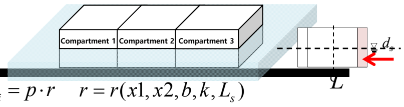
Where "*B*" is the maximum breadth of the ship at the deepest subdivision draught "d_s".

The value of "*r*" is equal to 0, if the penetration depth is *0*.

The value of "*r*" is equal to 1, if the penetration depth is *B/2*.

"*b*" is not being taken greater than *B/2*.
The transverse penetration is calculated **only considering one side of the ship**. (Assumption: The hull form of the ship is symmetric.)

Range of the Factor "b" Towards the Centerline (2/4)

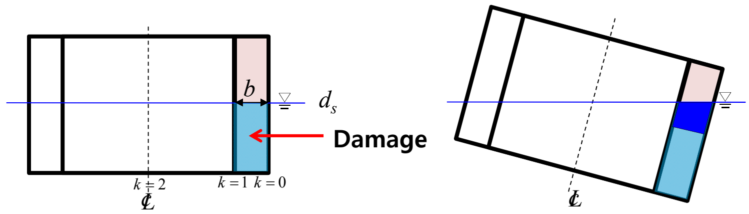


$p_i = p \cdot r \quad r = r(x1, x2, b, k, L_s)$

b: penetration depth
k: the number of a particular longitudinal bulkhead

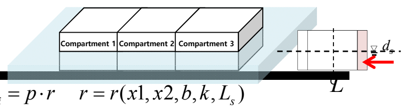
Why the factor "b" is only considered to extend to $B/2$?

When the first compartment is damaged,



Damaged compartments
Flooded compartments

Range of the Factor "b" Towards the Centerline (3/4)

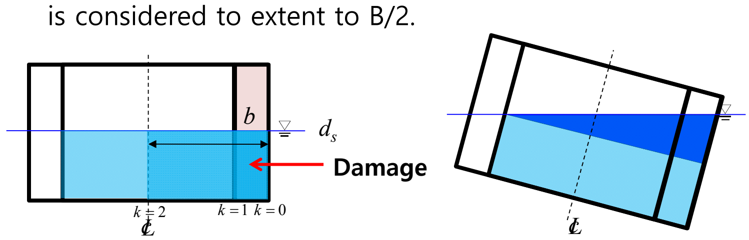


$p_i = p \cdot r \quad r = r(x1, x2, b, k, L_s)$

b: penetration depth
k: the number of a particular longitudinal bulkhead

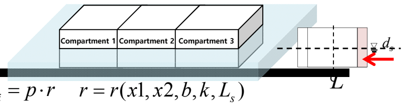
Why the factor "b" is only considered to extend to $B/2$?

When the second compartment is damaged,
It is the most severe damage case because the factor "b" is considered to extent to B/2.



Damaged compartments
Flooded compartments

Range of the Factor "b" Towards the Centerline (4/4)

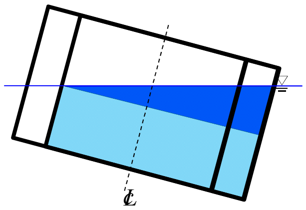


$p_i = p \cdot r \quad r = r(x1, x2, b, k, L_s)$

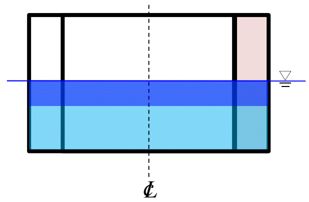
b: penetration depth
k: the number of a particular longitudinal bulkhead

Why the factor "b" is only considered to extend to $B/2$?

It is the most severe damage case because the factor "b" is considered to extent to B/2.

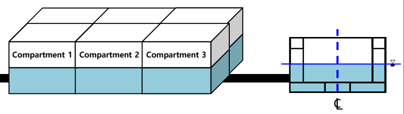


What if the factor "b" is considered to extent to B?



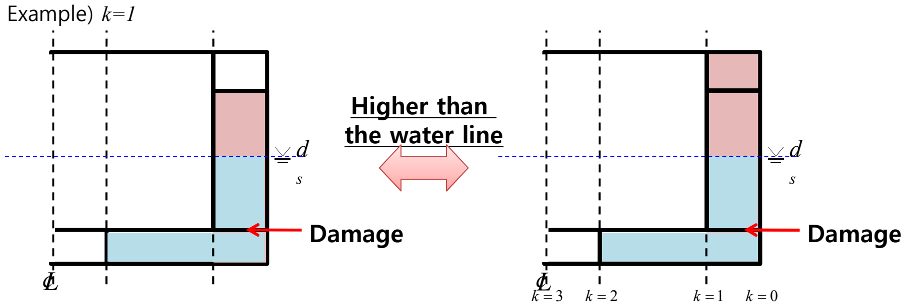
Because the result calculated for one side of the ship causes **more severe result** than for both side of the ship, the factor "b" is only considered to extend to B/2.

Vertical Extent - "Higher Extent"



The assumed vertical extent of damage is to extend from the baseline upwards to any watertight horizontal subdivision **above the water line** or **higher**. That is, higher horizontal subdivision is also to be assumed.

Example) $k=1$



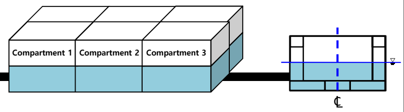
"Normal extent"

"Higher extent"

Damaged compartments

Flooded compartments

Vertical Extent - "Lesser Extent"

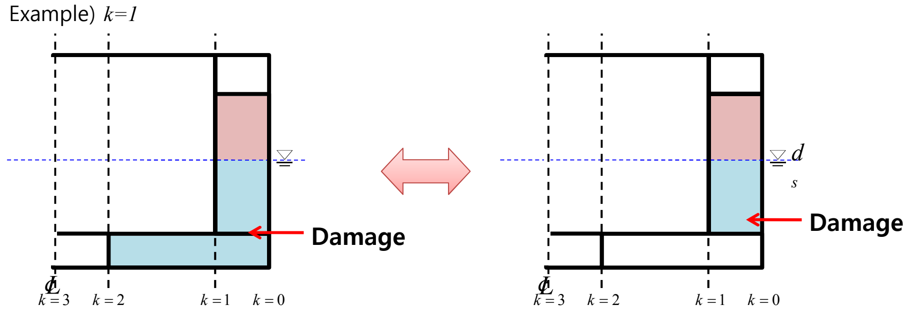


The flooding always extends to baseline?

⚠ No!

If **a lesser extent of damage will give a more severe result**, **such extent is to be assumed**.

Example) $k=1$



Damaged compartments

Flooded compartments

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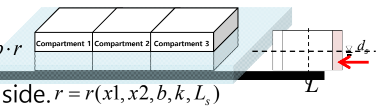
Case 1) Three Longitudinal Bulkheads (2 Wing Tanks+2 Cargo Holds)

$p_i = p \cdot r$

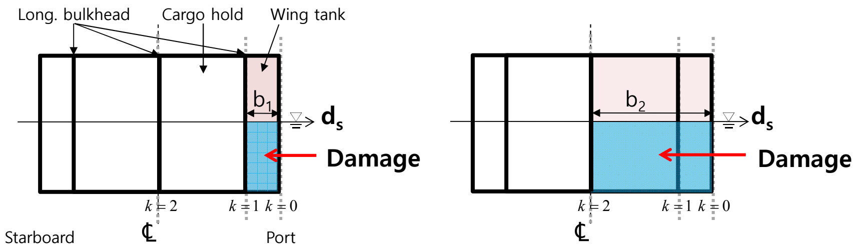


Assume that we calculate the value of r in the port side. $r = r(x1, x2, b, k, L_s)$

* b is measured at **deepest subdivision draft (d_s)**.

b: penetration depth
k: the number of a particular longitudinal bulkhead

How can we obtain the value of "r" for a box-shaped ship?



k=1: b=b_1
(wing tank(P))

k=2: b=b_2=B/2
(wing tank(P)+cargo hold(P))

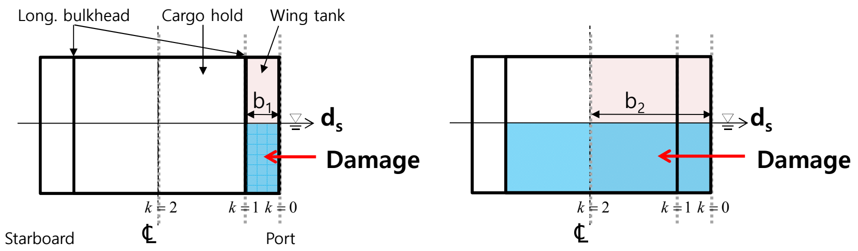
Damaged compartments

Flooded compartments

Case 2) Two Longitudinal Bulkheads (2 Wing Tanks+1 Cargo Hold)

Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

How can we obtain the value of "*r*" for a box-shaped ship?



k=1: $b=b_1$
(wing tank(P))

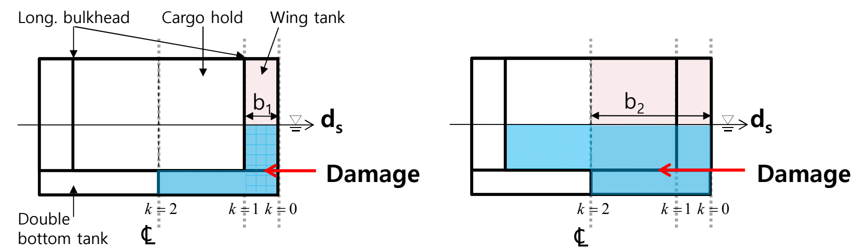
k=2: $b=b_2=B/2$
(wing tank(P)+cargo hold)

Damaged compartments
Flooded compartments

Case 3) Two Longitudinal Bulkheads (2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks)

Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

How can we obtain the value of "*r*" for a box-shaped ship?



k=1: $b=b_1$
(wing tank(P)+double bottom tank(P))

k=2: $b=b_2=B/2$
(wing tank(P)+double bottom tank(P)+cargo hold)

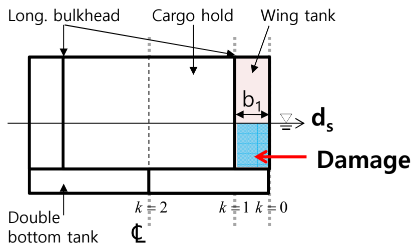
Damaged compartments
Flooded compartments

Case 3) Two Longitudinal Bulkheads (2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks)

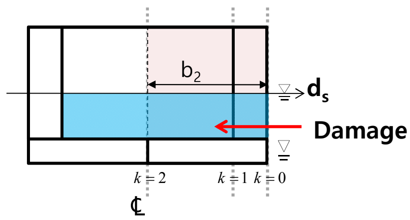
Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

How can we obtain the value of "r" for a box-shaped ship?

*** Lesser extent damage cases**



k=1: b=b_1
(wing tank(P))



k=2: b=b_2=B/2
(wing tank(P)+cargo hold)

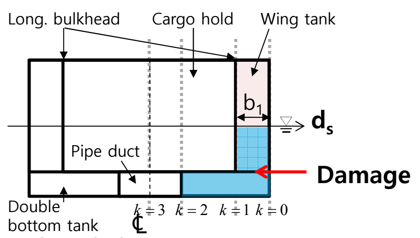
Damaged compartments
Flooded compartments

Case 4) Two Longitudinal Bulkheads (2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks+Pipe Duct)

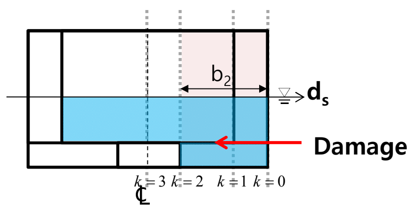
Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

Damaged compartments
Flooded compartments

How can we obtain the value of "r" for a box-shaped ship?

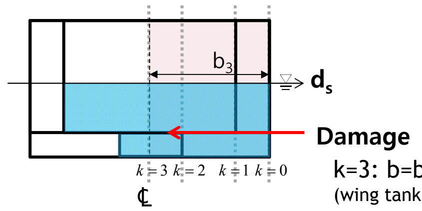


k=1: b=b_1
(wing tank(P)+double bottom tank(P))



k=2: b=b_2
(wing tank(P)+double bottom tank(P)+cargo hold)

If the upper part of a longitudinal bulkhead is below the deepest subdivision load line, the vertical plane used for determination of b is assumed to extend upwards to the deepest subdivision waterline.



k=3: b=b_3=B/2
(wing tank(P)+double bottom tank(P)+cargo hold+pipe duct)

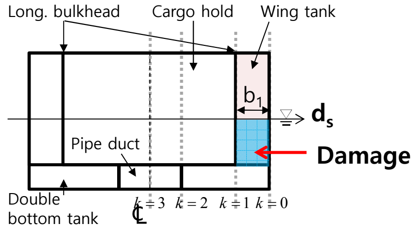
Case 4) Two Longitudinal Bulkheads
(2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks+Pipe Duct)

Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

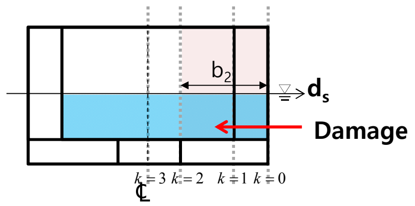
Damaged compartments
Flooded compartments

How can we obtain the value of "*r*" for a box-shaped ship?

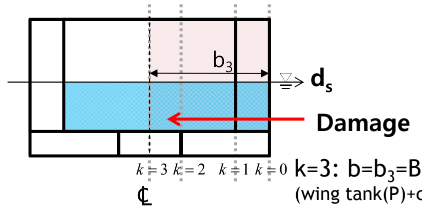
*** Lesser extent damage cases**



k=1: $b=b_1$
(wing tank(P))



k=2: $b=b_2$
(wing tank(P)+cargo hold)



k=3: $b=b_3=B/2$
(wing tank(P)+cargo hold)

In the flooding calculations carried out according to the regulations, only one breach of the hull and only one free surface need to be assumed. The assumed vertical extent of damage is to extend from the baseline upwards to any watertight horizontal subdivision above the waterline or higher. However, if a lesser extent of damage will give a more severe result, such extent is to be assumed.

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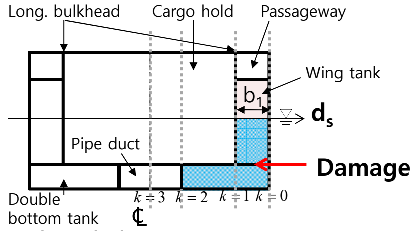
Case 4) Two Longitudinal Bulkheads
(2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks+Pipe Duct+Passageway)

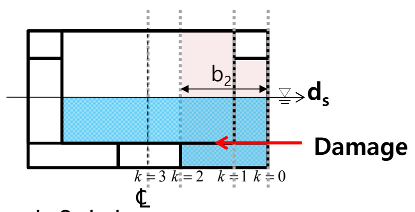
Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

Damaged compartments
Flooded compartments

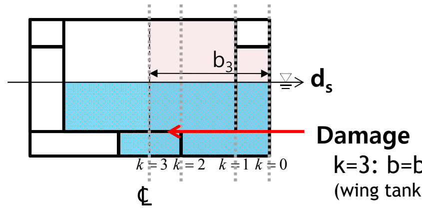
How can we obtain the value of "*r*" for a box-shaped ship?



k=1: $b=b_1$
(wing tank(P)+double bottom tank(P))



k=2: $b=b_2$
(wing tank(P)+double bottom tank(P)+cargo hold)



k=3: $b=b_3=B/2$
(wing tank(P)+double bottom tank(P)+cargo hold+pipe duct)

48

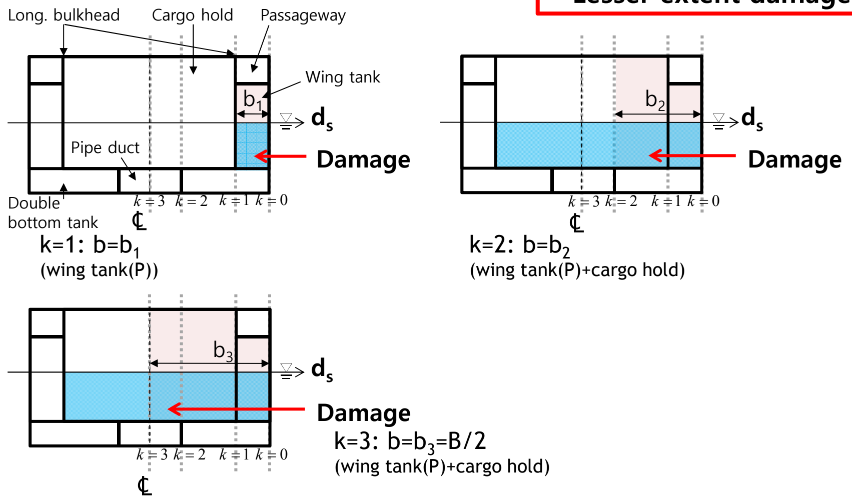
Case 4) Two Longitudinal Bulkheads
(2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks+Pipe Duct+Passageway)

Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

Damaged compartments
Flooded compartments

How can we obtain the value of "*r*" for a box-shaped ship?

*** Lesser extent damage cases**



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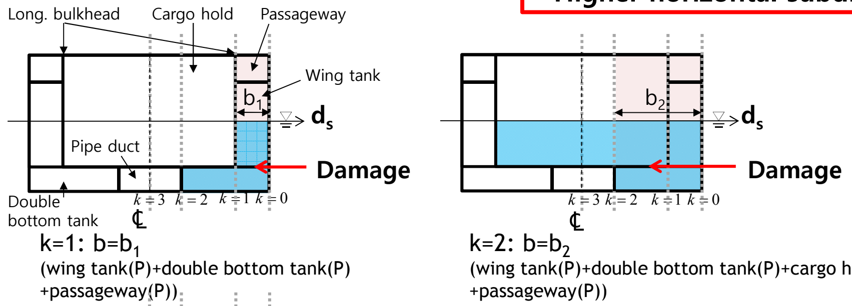
Case 4) Two Longitudinal Bulkheads
(2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks+Pipe Duct+Passageway)

Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

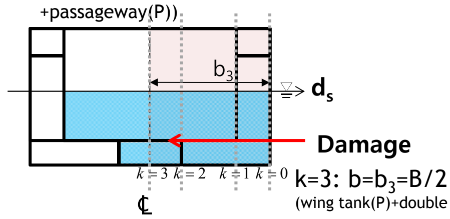
Damaged compartments
Flooded compartments

How can we obtain the value of "*r*" for a box-shaped ship?

*** Higher horizontal subdivision**



In the flooding calculations carried out according to the regulations, only one breach of the hull and only one free surface need to be assumed. The assumed vertical extent of damage is to extend from the baseline upwards to any watertight horizontal subdivision above the waterline or higher. However, if a lesser extent of damage will give a more severe result, such extent is to be assumed.



k=3: $b=b_3=B/2$
(wing tank(P)+double bottom tank(P)+cargo hold+pipe duct+passageway(P))

50

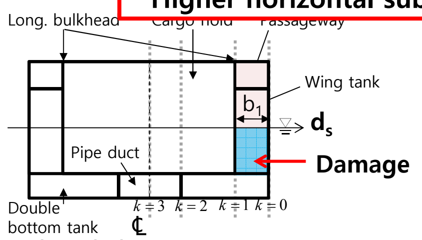
Case 4) Two Longitudinal Bulkheads
(2 Wing Tanks+1 Cargo Hold+2 Double Bottom Tanks+Pipe Duct+Passageway)

Assume that we calculate the value of *r* in the port side.
* *b* is measured at **deepest subdivision draft (d_s)**.

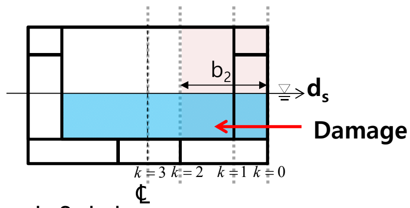
Damaged compartments
Flooded compartments

How can we obtain the value of "*r*" for a box-shaped ship?

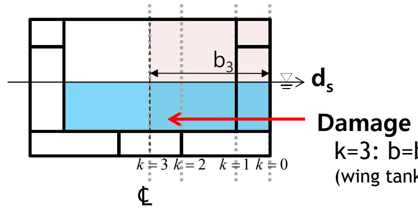
*** Higher horizontal subdivision** | *** Lesser extent damage cases**



k=1: $b=b_1$
(wing tank(P)+passageway(P))



k=2: $b=b_2$
(wing tank(P)+cargo hold+passageway(P))



k=3: $b=b_3=B/2$
(wing tank(P)+cargo hold+passageway(P))

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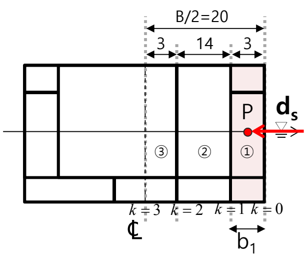
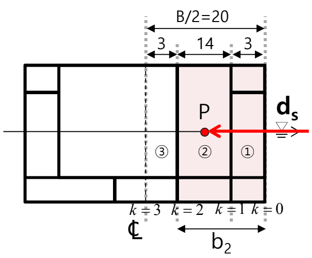
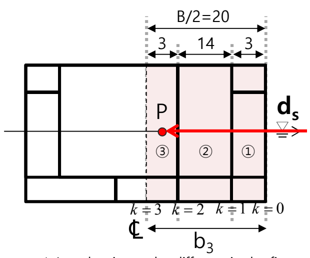
Calculation of the value of "*r*"

P: Damage generator (e.g., Awl)
Damaged compartments







* Actual ratio can be different in the figures.

Definition of $r(b_k)$ in SOLAS

$r(b_k)$: **Probability that "P" is located between the bulkheads of 0 and k**
: Probability that "P" is located in the position ① = **Area of ① / total area**

$r(b_0)$: Probability that "P" is located between the bulkheads of 0 and 0 ➡ 0
$r(b_1)$: Probability that "P" is located between the bulkheads of 0 and 1 ➡ 3/20
$r(b_2)$: Probability that "P" is located between the bulkheads of 0 and 2 ➡ 17/20
$r(b_3)$: Probability that "P" is located between the bulkheads of 0 and 3 ➡ 20/20

$r_k(b_k, b_{k-1}) = r_k$: **Probability that compartments are damaged up to "P"**

$r_1 = r(b_1) - r(b_0) = 3/20 - 0 = 3/20$

$r_2 = r(b_2) - r(b_1) = 17/20 - 3/20 = 14/20$

$r_3 = r(b_3) - r(b_2) = 20/20 - 17/20 = 3/20$

$r_k(x1, x2, b_k, b_{k-1}) = r(x1, x2, b_k) - r(x1, x2, b_{k-1})$

$Simply,\ r_k = r(b_k) - r(b_{k-1})$

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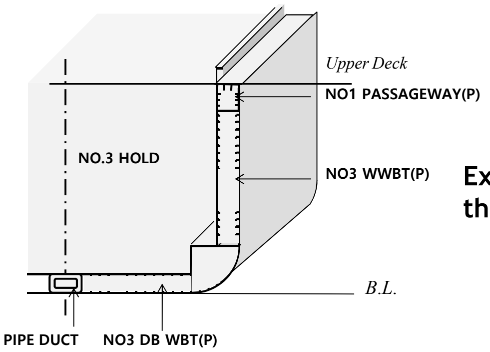
[Example] 7,000 TEU Container Carrier - One Zone Damage: Z8

$r = r(x1, x2, b, k, L_s)$

b: penetration depth
k: the number of a particular longitudinal bulkhead

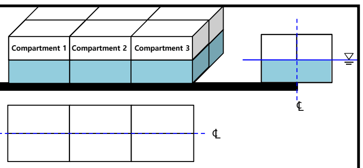
How can we obtain the values of "r"?



Extend the concept learned from the examples of a box-shaped ship.

4. Probability of Survival (s_i)

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

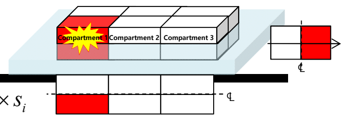
What is the factor "s_i"?

: 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)

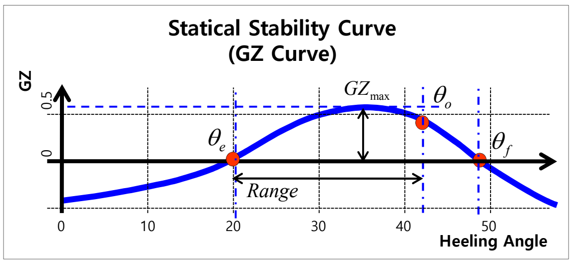


$A = \sum p_i \times s_i$

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

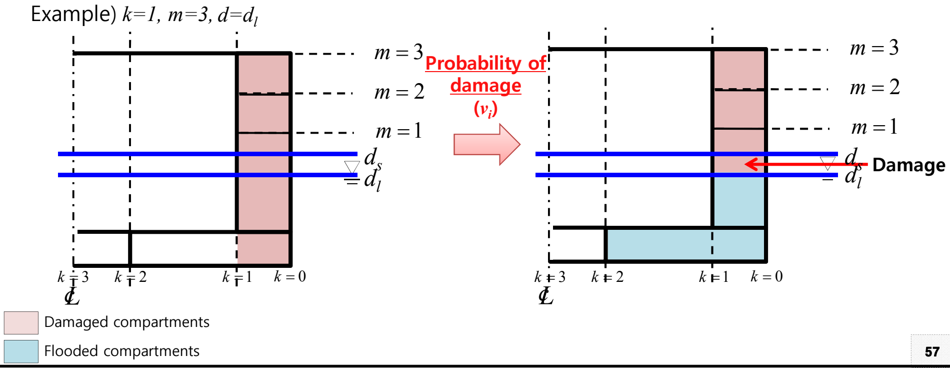
Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m"

When the horizontal watertight boundaries above the waterline are considered, the "s_i" value is obtained **by multiplying the reduction factor "v_m"**.

"v_m" represents **the probability that the spaces above the horizontal subdivision line will be flooded or compartments will be damaged**.

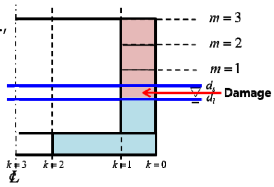
Where "m" represents each **horizontal boundary** counted upwards from the waterline **under consideration**.

Example) $k=1,\ m=3,\ d=d_l$

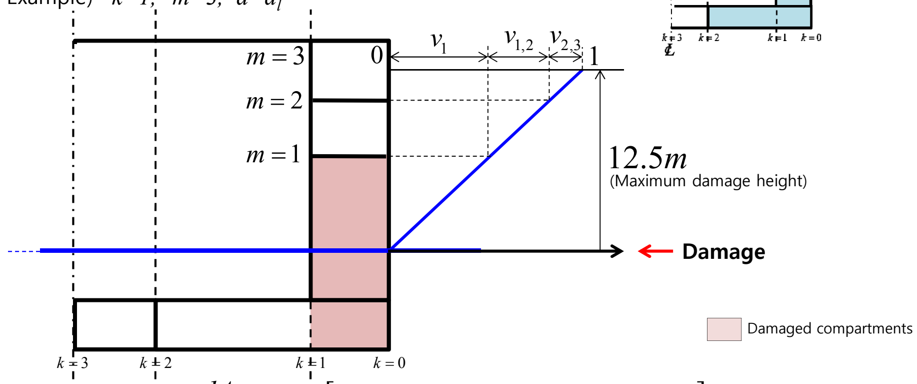


Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m": Stage 1) Damage (Initial Condition) (1/4)

After determining the longitudinal and transverse damage cases, i.e., **p and r are determined**, $v_{m-1,m}$ and $s_{min,m}$ are calculated. $s_{min,m}$ is the probability of survival when the compartment is flooded up to deck number m.



Example) $k=1,\ m=3,\ d=d_l$



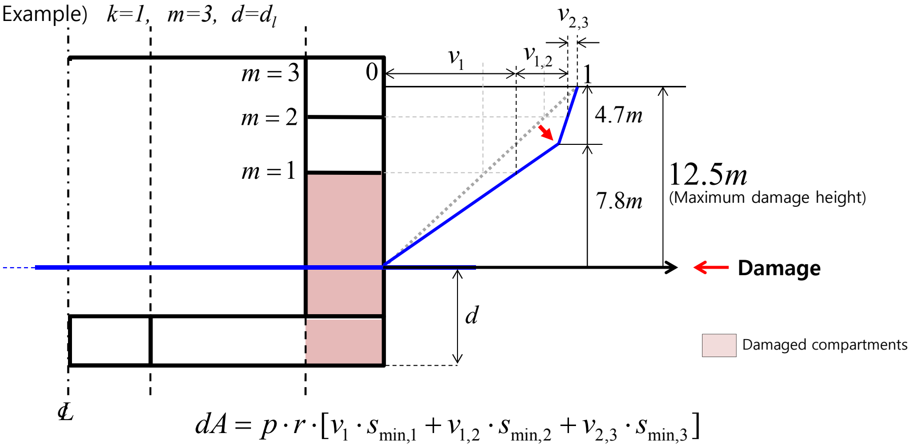
$$dA = p \cdot r \cdot [v_1 \cdot s_{min,1} + v_{1,2} \cdot s_{min,2} + v_{2,3} \cdot s_{min,3}]$$

v_1: Probability of damage to m=1, $v_{1,2}$: Probability of damage to m=1~2, $v_{2,3}$: Probability of damage to m=2~3
Each probability is determined: (1) after normalizing the distance from the damaged part to 12.5m into the length of 1, (2) with the ratio of height from the previous line to the corresponding horizontal subdivision line.
It is noted that this calculation should be performed after determining the longitudinal and transverse damage case.

Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m": Stage 1) Damage (Initial Condition) (2/4)

However, **the horizontal subdivision line located lower can be flooded easier than that located higher**. Therefore, the interpolation line between zero and one is modified as shown in following figure.

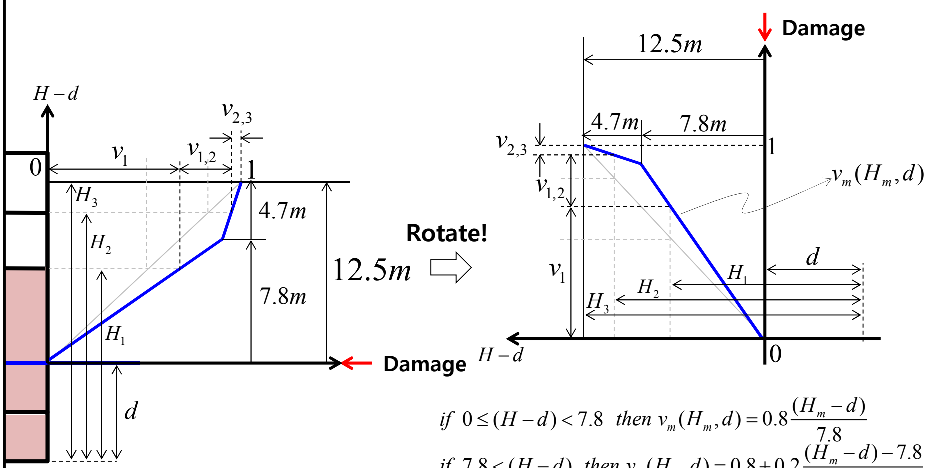
Example) $k=1$, $m=3$, $d=d_l$



$$dA = p \cdot r \cdot [v_1 \cdot s_{\min,1} + v_{1,2} \cdot s_{\min,2} + v_{2,3} \cdot s_{\min,3}]$$

where, $\sum v_i = 1$

Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m": Stage 1) Damage (Initial Condition) (3/4)



$$if\ 0 \le (H-d) < 7.8\ \ then\ v_m(H_m,d) = 0.8\frac{(H_m-d)}{7.8}$$

$$if\ 7.8 < (H-d)\ \ then\ v_m(H_m,d) = 0.8 + 0.2\frac{(H_m-d)-7.8}{4.7}$$

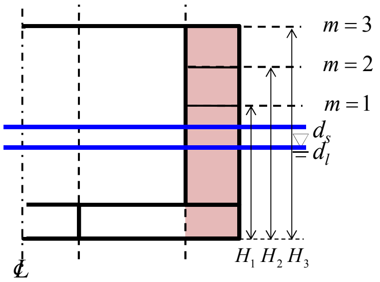
Therefore

$$v_1 = v_1(H_1,d), \quad v_{1,2} = v_2(H_2,d) - v_1(H_1,d)$$

$$v_{2,3} = v_3(H_3,d) - v_2(H_2,d)$$

Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m": Stage 1) Damage (Initial Condition) (4/4)

Example) $k=1,\ m=3,\ d=d_l$



$$dA = p \cdot r \cdot [v_1 \cdot s_{\min,1} + v_{1,2} \cdot s_{\min,2} + v_{2,3} \cdot s_{\min,3}]$$

where,

$$v_1 = v_1(H_1, d), \quad v_{1,2} = v_2(H_2, d) - v_1(H_1, d)$$
$$v_{2,3} = v_3(H_3, d) - v_2(H_2, d)$$

$$if\ 0 \le (H-d) < 7.8\ \ then\ v_m(H_m, d) = 0.8\frac{(H_m - d)}{7.8}$$
$$if\ 7.8 < (H-d)\ \ then\ v_m(H_m, d) = 0.8 + 0.2\frac{(H_m - d) - 7.8}{4.7}$$

The factor "v_m" is dependent on the **geometry of the watertight arrangement (decks) "H_m"** of the ship and **the draft of the initial loading condition** (d: d_s, d_p, d_l).

$$v_m = v(H_m, d) - v(H_{m-1}, d)$$

- v_m: **Probability of damage of the compartment below m**
- $v(H_m, d)$: **Probability of damage of all compartments below m**
- $v(H_{m-1}, d)$: **Probability of damage of all compartments below m-1**

$$dA = p_i \cdot [v_1 \cdot s_{\min 1} + (v_2 - v_1) \cdot s_{\min 2} + \cdots + (1 - v_{m-1}) \cdot s_{\min m}]$$

Where $A = \sum dA$, $\sum v_i = 1$

The maximum possible vertical extent of damage is $d+12.5m$. Then, the factor "H_m" is equal to 1.

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Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m": Stage 2) Flooding up to $m=1$

The factor "v_m" is dependent on the **geometry of the watertight arrangement (decks) "H_m"** of the ship and **the draft of the initial loading condition** (d: d_s, d_p, d_l).

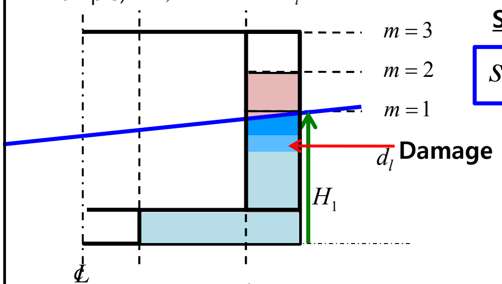
$$v_m = v(H_m, d) - v(H_{m-1}, d)$$

$$dA = p_i \cdot [v_1 \cdot s_{\min 1} + (v_2 - v_1) \cdot s_{\min 2} + \cdots + (1 - v_{m-1}) \cdot s_{\min m}]$$

Where $A = \sum dA$, $\sum v_i = 1$

The maximum possible vertical extent of damage is $d+12.5m$. Then, the factor "H_m" equals 1.

Example) $k=1,\ \ m=1\ \ \ d=d_l$



Stage 2) Flooding up to $m=1$

$$s_i = v_1 \cdot s_{\min 1}$$

where,

Damaged compartments

Flooded compartments

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Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m": Stage 3) Flooding up to m=2

The factor "v_m" is dependent on the **geometry of the watertight arrangement (decks) "H_m"** of the ship and **the draft of the initial loading condition** (d: d_s, d_p, d_l).

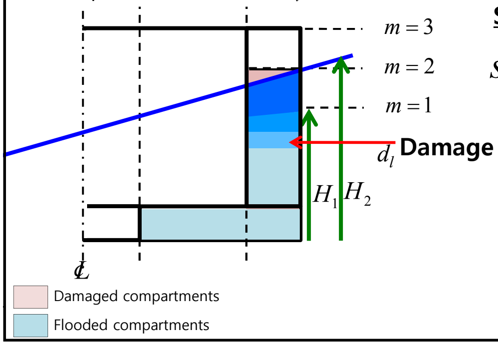
$$v_m = v(H_m, d) - v(H_{m-1}, d)$$

$$dA = p_i \cdot [v_1 \cdot s_{\min 1} + (v_2 - v_1) \cdot s_{\min 2} + \cdots + (1 - v_{m-1}) \cdot s_{\min m}]$$

Where $A = \sum dA$, $\sum v_i = 1$

The maximum possible vertical extent of damage is $d+12.5m$. Then, the factor "H_m" equals 1.

Example) $k=1$, $m=2$ $d=d_l$



Stage 3) Flooding up to m=2

$$s_i = v_1 \cdot s_{\min 1} + (v_2 - v_1) \cdot s_{\min 2}$$

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Consideration of Horizontal Subdivision in Flooding Stage - Factor "v_m": Stage 4) Flooding up to m=3

The factor "v_m" is dependent on the **geometry of the watertight arrangement (decks) "H_m"** of the ship and **the draft of the initial loading condition** (d: d_s, d_p, d_l).

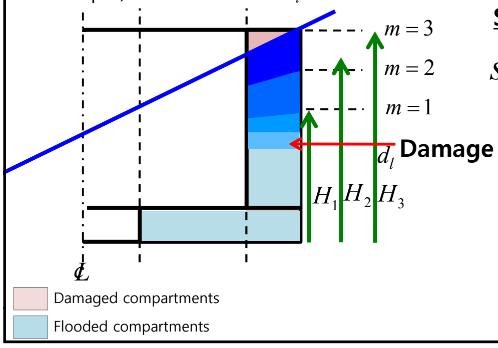
$$v_m = v(H_m, d) - v(H_{m-1}, d)$$

$$dA = p_i \cdot [v_1 \cdot s_{\min 1} + (v_2 - v_1) \cdot s_{\min 2} + \cdots + (1 - v_{m-1}) \cdot s_{\min m}]$$

Where $A = \sum dA$, $\sum v_i = 1$

The maximum possible vertical extent of damage is $d+12.5m$. Then, the factor "H_m" equals 1.

Example) $k=1$, $m=3$ $d=d_l$



Stage 4) Flooding up to m=3

$$s_i = v_1 \cdot s_{\min 1} + (v_2 - v_1) \cdot s_{\min 2} + (1 - v_2) \cdot s_{\min 3}$$

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Attained Subdivision Index "A"
- Check of the Attained Index "A"

Three loading conditions are to be considered and the result weighted as follows:

$$A_s, A_p, A_l \geq 0.5R \quad \text{: for cargo ships}$$
$$\geq 0.9R \quad \text{: for passenger ships}$$
$$A \geq R \qquad \text{Where } A = 0.4A_s + 0.4A_p + 0.2A_l$$

Where, the indices "*s*", "*p*", and "*l*" represent three loading conditions and the factor to be multiplied to the index indicates **how the index "*A*" from each loading condition is weighted**.

Attained Subdivision Index "A"
- Check of the Attained Index "A"

Producing an index A requires the calculation of various damage scenarios defined by the extent of damage and the initial loading conditions of the ship before damage.

Three loading conditions are to be considered and the result weighted as follows:

$$A_s, A_p, A_l \geq 0.5R \quad \text{: for cargo ships}$$
$$\geq 0.9R \quad \text{: for passenger ships}$$
$$A \geq R \qquad \text{Where } A = 0.4A_s + 0.4A_p + 0.2A_l$$

Where the indices "*s*", "*p*", and "*l*" represent the three loading conditions and the factor to be multiplied to the index indicates **how the index A from each loading condition is weighted**.

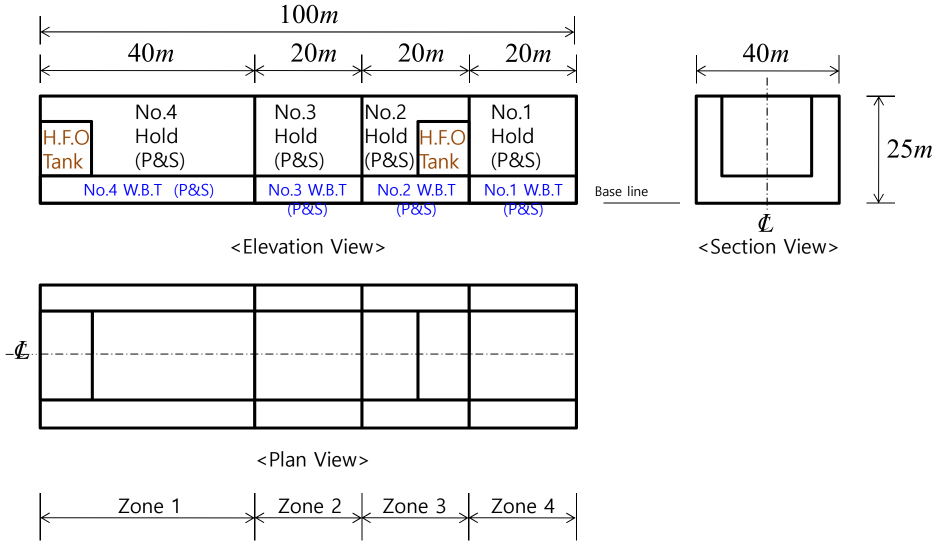
We can assume that the meaning of the weight factors 0.4, 0.4, and 0.2. In the ship's lifecycle, the lightship condition is rarely exist.

Normally, the loading condition is performed between the scantling draft and design draft. Thus, the weight factor considers this cruising condition.

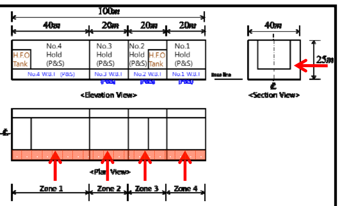
Definitions of three draft
Light service draft(dl): the service draft corresponding to the lightest anticipated loading and associated tankage, including, however, such ballast as may be necessary for stability and/or immersion. Passenger ships should include the full complement of passengers and crew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

5. Example of the Calculation of Attained Index A for Box-Shaped Ship

Assumption of Subdivision Zone



[Case 1] Calculation of Probability of Damage (p_i)



$$p_i = p(x1, x2, L_s) \times r(x1, x2, b, k, L_s)$$

Calculation Condition
: Scantling Draft (18.0m), b=4.0

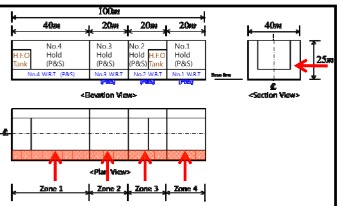
DAMAGES	x1	x2	Damage Length	J	p	r	p_i
<1 zone damage>				Cause	Effect		Effect
1.1.1	0	40	40	0.4	[illegible]	0.42119	[illegible]
2.1.1	40	60	20	0.2	[illegible]	0.36117	[illegible]
3.1.1	60	80	20	0.2	[illegible]	0.36117	[illegible]
4.1.1	80	100	20	0.2	[illegible]	0.58293	[illegible]
				Bigger	Bigger		Bigger
<2 zone damage>							
1-2.1.1	0	60	60	0.6	[illegible]	0.37975	[illegible]
2-3.1.1	40	80	40	0.4	[illegible]	0.34515	[illegible]
3-4.1.1	60	100	40	0.4	[illegible]	0.42119	[illegible]
				Bigger	Bigger		Bigger
<3 zone damage>							
1-3.1.1	0	80	80	0.8	[illegible]	0.35892	[illegible]
2-4.1.1	40	100	60	0.6	[illegible]	0.34563	[illegible]
				Bigger	Bigger		Bigger

J: Non-dimensional damage length $J = \frac{|x_2 - x_1|}{Ls}$

b: Mean transverse distance

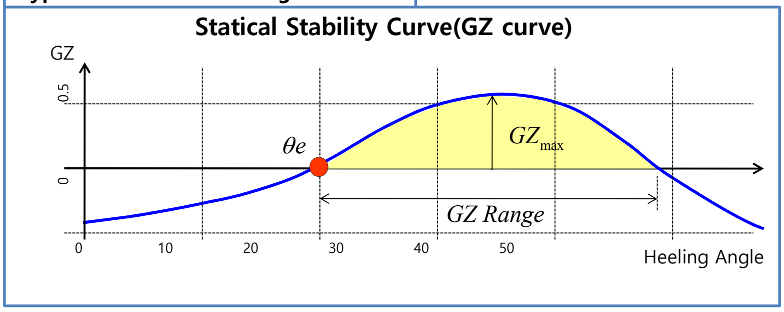
※ All results can be obtained using manual calculation.

[Case 1] Calculation of Probability of Survival (s_i)



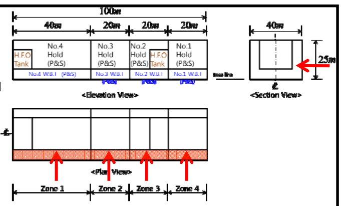
$$s_i = s_i(\theta_e, \theta_v, GZ_{max}, Range)$$

Typical GZ curve in damage condition



θ_e: The equilibrium angle of heel in any stage of flooding, in degrees
GZ_{max}: The maximum positive righting lever, in meters
Range: The range of positive righting arms, in degrees, measured from the angle θ_e

[Case 1] Calculation of Probability of Survival (s_i)



$$s_i = s_i(\theta_e, \theta_v, GZ_{\max}, Range)$$

Calculation Condition
: Scantling Draft (18.0m), b=4.0

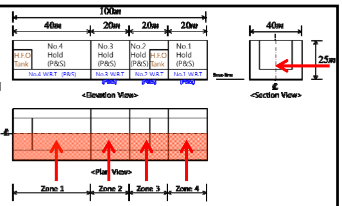
※ θ_e, GZ, GZ range were obtained using computational ship calculation software, "EzCOMPART".

DAMAGES	x1	x2	J	θ_e	GZ_{max}	GZ Range	s_i	p_i	A
<1 zone damage>			Cause	Effect	Effect	Effect	Effect		
1.1.1	0	40	0.4	[illegible]	[illegible]	[illegible]	[illegible]	0.17025	0.02666
2.1.1	40	60	0.2	[illegible]	[illegible]	[illegible]	[illegible]	0.05516	0.00864
3.1.1	60	80	0.2	[illegible]	[illegible]	[illegible]	[illegible]	0.05516	0.00864
4.1.1	80	100	0.2	[illegible]	[illegible]	[illegible]	[illegible]	0.10281	0.01610
			Bigger	Bigger	Smaller	Smaller	Smaller		
<2 zone damage>									
1-2.1.1	0	60	0.6	[illegible]	[illegible]	[illegible]	[illegible]	0.22945	0.03195
2-3.1.1	40	80	0.4	[illegible]	[illegible]	[illegible]	[illegible]	0.14097	0.02207
3-4.1.1	60	100	0.4	[illegible]	[illegible]	[illegible]	[illegible]	0.17025	0.02666
			Bigger	Bigger	Smaller	Smaller	Smaller		
<3 zone damage>									
1-3.1.1	0	80	0.8	[illegible]	[illegible]	[illegible]	[illegible]	0.28865	0.00000
2-4.1.1	40	100	0.6	[illegible]	[illegible]	[illegible]	[illegible]	0.21029	0.02928
			Bigger	Bigger	Smaller	Smaller	Smaller		

θ_e: Non-dimensional damage length

※ θ_e, GZ, GZ range are obtained using computer ship calculation software, "Ez-compart".

[Case 2] Calculation of Probability of Damage (p_i)



$$p_i = p(x1, x2, Ls) \times r(x1, x2, b, k, L_s)$$

Calculation Condition
: Scantling Draft (18.0m), b=20.0 Cause
Bigger

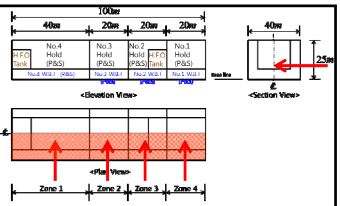
DAMAGES	x_1	x_2	Damage Length	J	p	r	p_i
<1 zone damage>					Effect	Effect	Effect
1.2.1	0	40	40	0.4000	[illegible]	[illegible]	[illegible]
2.2.1	40	60	20	0.2000	[illegible]	[illegible]	[illegible]
3.2.1	60	80	20	0.2000	[illegible]	[illegible]	[illegible]
4.2.1	80	100	20	0.2000	[illegible]	[illegible]	[illegible]
<2 zone damage>					Bigger	Bigger	Bigger
1-2.2.1	0	60	60	0.6000	[illegible]	[illegible]	[illegible]
2-3.2.1	40	80	40	0.4000	[illegible]	[illegible]	[illegible]
3-4.2.1	60	100	40	0.4000	[illegible]	[illegible]	[illegible]
<3 zone damage>							
1-3.2.1	0	80	80	0.8000	[illegible]	[illegible]	[illegible]
2-4.2.1	40	100	60	0.6000	[illegible]	[illegible]	[illegible]

J: Non-dimensional damage length $J = \frac{|x_2 - x_1|}{Ls}$

b: Mean transverse distance

※ Each results are obtained using manual calculation.

[Case 2] Calculation of Probability of Survival (s_i)



$$s_i = s_i(\theta_e, \theta_v, GZ_{\max}, Range)$$

Calculation Condition
: Scantling Draft (18.0m), b=20.0 Cause Bigger

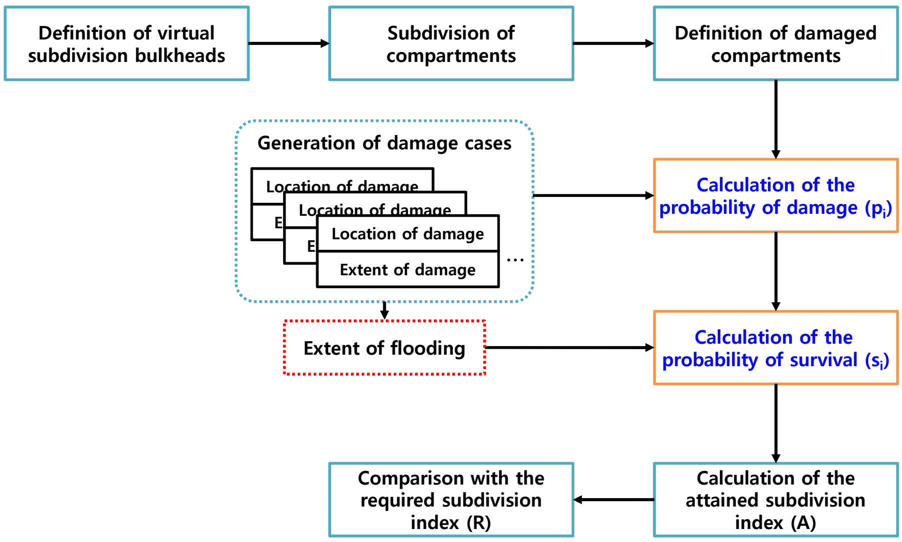
※ θ_e, GZ, and GZ range were obtained using computational ship calculation software, "EzCOMPART".

DAMAGES	x_1	x_2	J	θe	Max_GZ	Range	s_i	p_i	A
< 1 zone damage >				Effect	Effect	Effect	Effect		
1.2.1	0	40	0.4000	[illegible]	[illegible]	[illegible]	[illegible]	0.40421	0.00000
2.2.1	40	60	0.2000	[illegible]	[illegible]	[illegible]	[illegible]	0.15273	0.02392
3.2.1	60	80	0.2000	[illegible]	[illegible]	[illegible]	[illegible]	0.15273	0.02392
4.2.1	80	100	0.2000	[illegible]	[illegible]	[illegible]	[illegible]	0.17637	0.02099
< 2 zone damage >				Smaller	Smaller	Smaller	Smaller		
1-2.2.1	0	60	0.6000	[illegible]	[illegible]	[illegible]	[illegible]	0.60421	0.00000
2-3.2.1	40	80	0.4000	[illegible]	[illegible]	[illegible]	[illegible]	0.40842	0.00000
3-4.2.1	60	100	0.4000	[illegible]	[illegible]	[illegible]	[illegible]	0.40421	0.00000
< 3 zone damage >									
1-3.2.1	0	80	0.8000	[illegible]	[illegible]	[illegible]	[illegible]	0.80421	0.00000
2-4.2.1	40	100	0.6000	[illegible]	[illegible]	[illegible]	[illegible]	0.60842	0.00000

Attained index (A) is zero in most case, because too large areas are damaged.
We can expect that calculating '4 zone damage' cases are meaningless.

6. Summary

Overall Procedures to Evaluate the Probabilistic Damage Stability



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