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Cochin University of Science & Technology

07, 11, 12 Mar 2025

Stability of Ships

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Department of Ship Technology
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3 credits

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Stability of Ships. Course Content. Exam question paper will be based on this.

Course Content:

1. **Module I**
   Stability terms. Potential energy. Equilibrium. Weight displacement and Volume displacement; Change of density, FWA, DWA. Equi-volume inclinations, shift of CoB due to inclinations, CoB curve in lateral plane, (*initial*) metacentre, metacentric radius, metacentric height; metacentre at large angles of inclinations, pro-metacentre. CoG, righting moment and lever; Statical, metacentric, residuary, form and weight stabilities. Surface of flotation, curve of flotation. Derivation of BM = I / V.

2. **Module II**
   Initial (*transverse*) stability: GM_0, GZ at small angles of inclinations, Wall sided ships. Sinkage and stability due to addition, removal and shift (transverse and vertical) of weight, suspended weights and free surface of liquids; Inclining Experiment; stability while docking and grounding; Stiff/ Tender ship.

3. **Module III**
   Large angle (*transverse*) stability: Diagram of statical stability (GZ curve), characteristics of GZ curve, effect of form, shift of G and super structure on GZ curve, static equilibrium criteria, Methods of calculating GZ curve (Prohaska, Krylov and from ship form), Cross curves of stability.
   Dynamical stability, diagram of dynamical stability, dynamic stability criteria.
   Moments due to wind, shift of Cargo and passengers, turning and non-symmetric accumulation of ice.
   Intact stability rules, Heel/ Load test.
   Practical: Diagram of statical stability / Cross curves of stability (Krylov's method).

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4. **Module IV**
   Longitudinal Stability: Trim, longitudinal metacentre, longitudinal centre of flotation, moment to change trim, trimming moment, change of trim and drafts due to addition,

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removal and longitudinal shift of weight, trim and draft change due to change of density. Rules on draft and trim.

5. **Module V**
   Damage stability: Bilging, Surface and volume permeability; Sinkage, heel, change of trim and drafts due to bilging of midship, side and end compartments.

Practical: Floodable length calculation and subdivision of ship. Stability in waves,

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Course Content

Completed

- Module 1. Stability Terms. 06 Lectures.
- Module 2. Initial (Transverse) Stability. 07 lectures.
- Module 3. Large Angle Transverse Stability. 07 lectures.
- Module 4. Longitudinal Stability. 03 Lectures

Today

- 5. Damaged Stability

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Module 5

- 5.1 What is damaged stability?
- 5.2 Bilging
- 5.3 Surface and volume permeability
- 5.4 Two methods for assessing damaged stability
- 5.5 Bilging of a midship compartment
- 5.6 Flooding of a side compartment at midship
- 5.7 Exact analysis of a barge with an off-center full-length flooded compartment
- 5.8 Flooding of a side compartment forward of CoF. General case.
- 5.9 Floodable length curve

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Module 5

- Read Biran Chapter 11
- Read Tupper pp 118-127 Damaged Stability (uploaded in Classroom)

- There will be questions from all modules in the End-Semester Exam.

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5.1 What is damaged stability?

FLOODING AND DAMAGED STABILITY

So far only the stability of an intact ship has been considered. In the event of collision, grounding or just springing a leak, water can enter the ship. If unrestricted, this flooding would eventually cause the ship to founder, that is sink bodily, or capsize, that is turn over. To reduce the probability of this, the hull is divided into a series of watertight compartments by means of bulkheads. In action, warships are expected to take punishment from the enemy so damage stability is clearly an important consideration in their design. However, damage is a possibility for any ship.

Bulkheads cannot ensure complete safety in the event of damage. If the hull is opened up over a sufficient length several compartments can be flooded. This was the case in the tragedy of the *Titanic*. Any flooding can cause a reduction in stability and if this reduction becomes great enough the ship will capsize. Even if the reduction does not cause capsize it may lead to an angle of heel at which it is difficult, or impossible, to launch lifeboats. The losses of buoyancy and stability due to flooding are considered in the following sections.

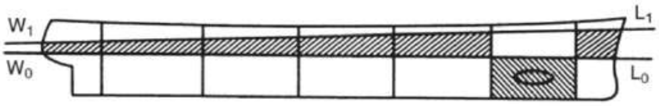

Figure 7.12 Compartment open to the sea

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- In Fig. 7.12, the bulkheads go above W_1L_1
- The thick vertical lines are bulkheads that go up to the bulkhead deck

Sinkage and trim when a compartment is open to the sea

Suppose a forward compartment is open to the sea, Figure 7.12. The buoyancy of the ship between the containing bulkheads is lost and the ship settles in the water until it picks up enough buoyancy from the rest

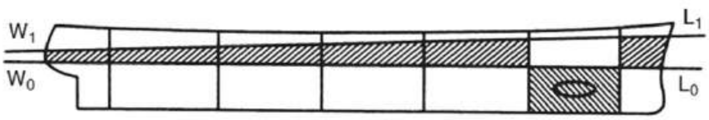

Figure 7.12 Compartment open to the sea

of the ship to restore equilibrium. At the same time the position of the LCB moves and the ship must trim until G and B are again in a vertical line. The ship which was originally floating at waterline W_0L_0 now floats at W_1L_1. Should W_1L_1 be higher at any point than the deck at which the bulkheads stop (the *bulkhead deck*) it is usually assumed that the ship would be lost as a result of the water pressure in the damaged compartment forcing off the hatches and leading to unrestricted flooding fore and aft. In practice the ship might still remain afloat for a considerable time.

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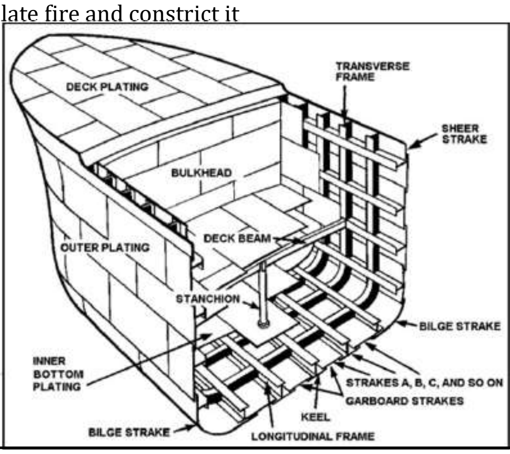
Bulkhead Deck

- Bulk head construction on board vessels serves many purposes as defined below:

1. Strengthening the vessel's structure
2. Creates separate areas that can be isolated
3. Create water tight locks on board vessel
4. Can be used to isolate fire and constrict it



Strake: a continuous line of planking or plates from the stem to the stern of a ship or boat.
Stanchion: an upright bar, post, or frame forming a support or barrier.

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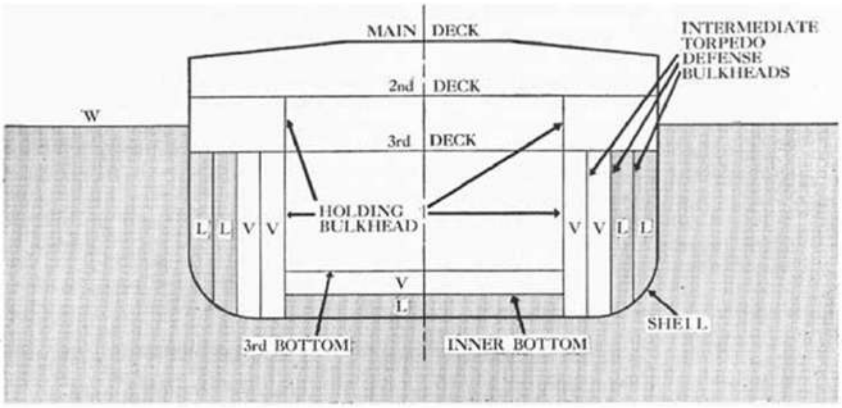
maritime.org
San Francisco Maritime

- Figure 15-1. Diagram to illustrate a modern torpedo-protection system. This book was written in 1945.
- **15-11. Classes of ships designed with torpedo-protection systems.** All battleships following BB-42 and all large aircraft carriers (CV-2 and 3, CV-5, 6, and 8, and subsequent CV's) were designed with torpedo-protection bulkhead systems. Certain ships originally designed with torpedo-protection systems have had blisters added to improve torpedo protection, buoyancy, and stability."



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Anti-Torpedo Blisters

Left: HMS Glatton in drydock, circa 1914–1918, showing her anti-torpedo bulge

Below: USS Texas (BB-35) in floating dry dock at Galveston, Texas. It has anti-torpedo blisters.

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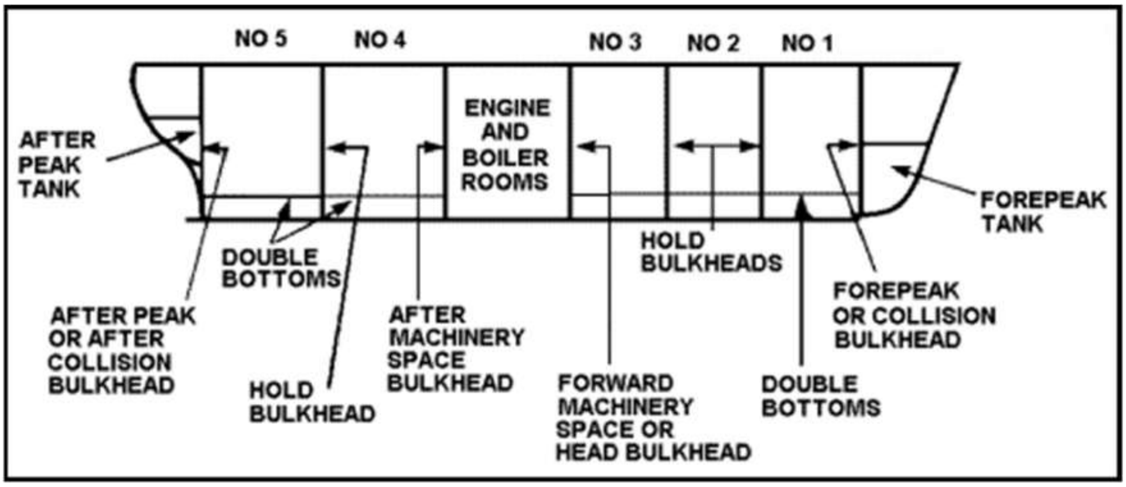
5.1 What is damaged stability?



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5.2 Bilging

- Bilge Tank vs Bilged

The primary bilge tank helps in separation of the oil from the water and the oil can be visually seen and put in dirty oil tank and the cleaner bilge water can be put to the bilge tank. Steam coils are provided in the primary bilge tank and they can be used for effective separation.

Bilging amidships compartments

When a vessel floats in still water it displaces its own weight of water. Figure 22.1(a) shows a box-shaped vessel floating at the waterline, WL. The weight of the vessel (W) is considered to act downwards through G, the centre of gravity. The force of buoyancy is also equal to W and acts upwards through B, the centre of buoyancy; b = W.

Now let an empty compartment amidships be holed below the waterline to such an extent that the water may flow freely into and out of the compartment. A vessel holed in this way is said to be 'bilged'.

Figure 22.1(b) shows the vessel in the bilged condition. The buoyancy provided by the bilged compartment is lost. The draft has increased and the vessel now floats at the waterline W_1L_1, where it is again displacing its own

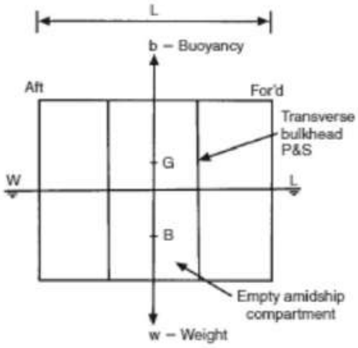

Fig. 22.1(a)

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5.2 Bilging

- Barrass
- Midship compartment is flooded
- v = volume of lost buoyancy ≠ volume of water in the compartment after flooding
- A = WPA before bilging
- a = WPA of bilged compartment
- Volume $y + z$ = Unbilged area * Change in draft = (A-a)x
- The bulkhead deck is above W1L1. After flooding, water will rise to W1L1. That is why the unflooded area is A-a.

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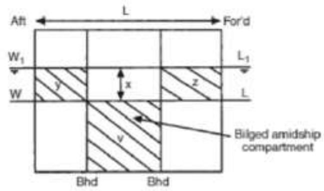

Fig. 22.1(b)

weight of water. 'X' represents the increase in draft due to bilging. The volume of lost buoyancy (v) is made good by the volumes 'y' and 'z'.

$$\therefore \; v = y + z$$

Let 'A' be the area of the water-plane before bilging, and let 'a' be the area of the bilged compartment. Then:

$$y + z = Ax - ax$$

or

$$v = x(A - a)$$

$$\text{Increase in draft} = x = \frac{v}{A - a}$$

i.e.

$$\text{Increase in draft} = \frac{\text{Volume of lost buoyancy}}{\text{Area of intact waterplane}}$$

Note. Since the distribution of weight within the vessel has not been altered the KG after bilging will be the same as the KG before bilging.

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Permeability, μ

Permeability is the amount of water that can enter a compartment or tank after it has been bilged. When an empty compartment is bilged, the whole of the buoyancy provided by that compartment is lost. Typical values for permeability, μ, are as follows:

Empty compartment	μ = 100%
Engine room	μ = 80% to 85%
Grain-filled cargo hold	μ = 60% to 65%
Coal-filled compartment	μ = 36% approximately
Filled water ballast tank (when ship is in salt water)	μ = 0%

Consequently, the higher the value of the permeability for a bilged compartment, the greater will be a ship's loss of buoyancy when the ship is bilged.

The permeability of a compartment can be found from the formula:

$$\mu = \text{Permeability} = \frac{\text{Broken stowage}}{\text{Stowage factor}} \times 100 \text{ per cent}$$

The broken stowage to be used in this formula is the broken stowage per tonne of stow.

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Most compartments in a ship contain items which will reduce the volume of water that can enter. Even 'empty' spaces usually have frames or beams in them. At the other extreme some spaces may already be full of ballast water or fuel. The ratio of the volume that is floodable to the total volume is called the *permeability* of the space. Formulae for calculating permeabilities for merchant ships are laid down in the Merchant Ship (Construction) Rules. Typical values are presented in Table 7.3. Although not strictly accurate, the same values of permeability are usually applied as factors when assessing the area and inertias of the waterplane in way of damage.

Table 7.3

Space	*Permeability* (%)
Watertight compartment	97 (warship) 95 (merchant ship)
Accommodation spaces	95 (passengers or crew)
Machinery compartments	85
Cargo holds	60
Stores	60

To calculate the damaged waterline successive approximation is needed. The assumptions of small changes do not apply. There are two

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Biran. Volume and Surface Permeability.

Let us suppose that calculating the volume of a compartment starting from its dimensions we obtain the value v. There is almost no case in which this volume can be fully flooded because almost always there are some objects in the compartment. Even in an empty tank there are usually structural members – such as frames, floors, and deck beams – sounding instruments and stairs for entering the tank and inspecting it. If we deduct the volumes of such objects from the volume v we obtain the volume of the water that can flood the compartment; let it be v_F. The ratio

$$\mu = \frac{v_F}{v} \tag{11.1}$$

is called **permeability**; it is often noted by μ. More correctly, we should talk about **volume permeability**, to distinguish it from a related notion that is the **surface permeability**. Indeed, because of the objects stored or located in a compartment, the free-surface area is smaller than that calculated from the dimensions of the compartment. Also the moment of inertia of the free-surface area is calculated on the basis of the dimensions of the compartment. For example, if the calculations are carried on by a computer programme, they are based on an input that describes only the geometry of the tank and not its contents. The moment of inertia of the surface free to heel is smaller than the value found as above because the area considered is partially occupied by fixed objects that do not contribute to the free-surface effect. Then, it is necessary to multiply the calculated value by the surface permeability.

5.3 Surface and volume permeability

Typical values of volume permeability can be found in textbooks and in various regulations. Examples of the latter are given in this chapter. When the recommended values do not seem plausible, it is necessary to calculate in detail the volume of the objects found in the compartment. When there are no better data, the surface permeability can be assumed equal to the volume permeability of the same compartment.

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5.4 Two methods for assessing damaged stability

Fig. 2.4 is on the next slide

- Biran

11.3 Two Methods for Finding the Ship Condition After Flooding

There are two ways of calculating the effect of flooding. One way is known as the **method of lost buoyancy**, the other as the **method of added weight**.

The method of lost buoyancy assumes that a flooded compartment does not supply buoyancy. This is what happens in reality. If we refer to Figures 2.4 and 2.5, we can imagine that if there is open communication between a compartment and the surrounding water, the water inside the compartment exercises pressures equal to and opposed to those of the external water. Then, the buoyancy force predicted by the Archimedes' principle is cancelled by the pressure of the flooding water.

Pressures on the inner and outer surfaces of the flooded compartment cancel each other and so there is no buoyancy

In the method of lost buoyancy the volume of the flooded compartment does not belong anymore to the vessel, while the weight of its structures is still part of the displacement. The 'remaining' vessel must change position until force and moment equilibria are reestablished. During the process not only the displacement, but also the position of the centre of gravity remains constant. The method is also known as **method of constant displacement**. As the flooding water does not belong to the ship, it causes no free-surface effect.

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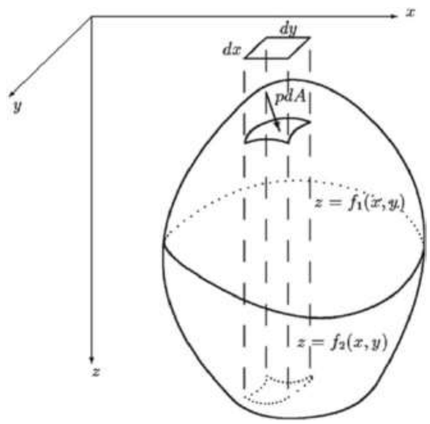
- Fig. 2.4 in Biran.
- The pressure at the top (of the compartment) is less than the pressure at the bottom. Therefore, there is a net buoyancy force.
- If a compartment is flooded, the pressure on the inner and outer surfaces of the hull are the same and there is no net force on the hull.



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In the method of added weight the water entering a damaged compartment is considered as belonging to the ship; its mass must be added to the ship displacement. Hence the term 'added weight.' Following modern practice we actually work with masses; however, we keep the traditional name of the method, that is we use the word 'weight.' Another reason may be the need to avoid confusion with the term **added mass** mentioned in Section 6.13 and detailed in Chapter 12. The latter term does not belong to the theory of flooding and damage stability.

In the method of added weight the displacement of the flooded vessel is calculated as the sum of the intact displacement and the mass of the flooding water. The position of the centre of gravity of the damaged vessel is obtained from the sums of the moments of the intact vessel and of the flooding water. Becoming part of the vessel, the flooding water produces a free-surface effect that must be calculated and considered in all equations.

For very small trim and negligible heel changes we can write

1. **Flooded Displacement** $\Delta_F = \Delta_I + \rho v$ **Biran. Δ = displacement = delta**
2. **Flooded LCG** $LCG_F \cdot \Delta_F = LCG_I \cdot \Delta_I + lcg \cdot \rho \cdot v$
3. **Flooded TCG** $TCG_F \cdot \Delta_F = tcg \cdot \rho \cdot v$ (11.2)

where the subscript F distinguishes the properties of the flooded vessel, and the subscript I those of the intact ship. By lcg we mean the longitudinal centre of gravity of the flooding water volume, v, and by tcg its transverse centre of gravity. We assume $TCG_I = 0$. The vertical centre of gravity, $\overline{KG}$, must be recalculated. When the trim and the heel are not negligible, we must consider the vertical coordinates of the centres of gravity of the intact ship and of the flooding water volume. Example 11.1 shows how to do this for non-zero trim and zero heel.

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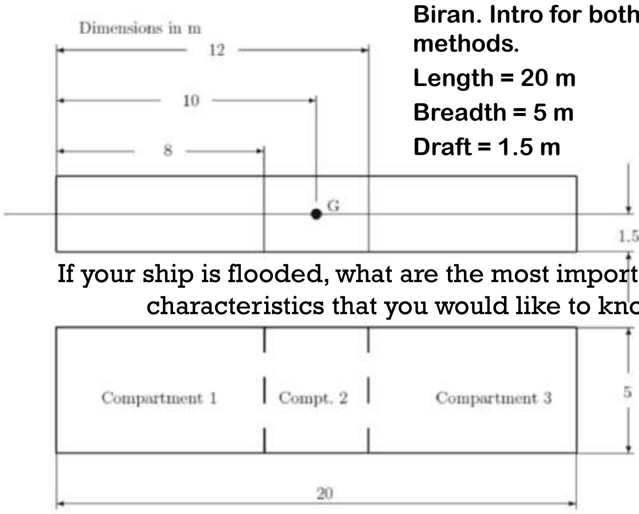
5.5 Bilging of a midship compartment

- After flooding, buoyancy and stability are important.
- Buoyancy: After flooding, find the new waterline. Is there enough buoyancy force to balance the gravitational force? Will the ship float?
- Stability: It is not enough if the ship floats. Will it be stable? What is the righting moment for small angles of heel?
- Find the new waterline and the righting moment for small angles of heel.

To exemplify the above principles we follow an idea presented in *Handbuch der Werften* and later used by Watson (1998). While the latter solves algebraically the general problem, we prefer to solve it numerically and allow thus the reader to visualize the differences between methods and those between the intact and the damaged vessel. We choose the very simple example of the pontoon shown in Figure 11.2. Two transverse bulkheads subdivide the hull into three watertight compartments. In the following two subsections we assume that

Biran. Intro for both methods.
Length = 20 m
Breadth = 5 m
Draft = 1.5 m



If your ship is flooded, what are the most important characteristics that you would like to know?

Figure 11.2 A simple pontoon—intact condition

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Lost Buoyancy and Added Mass (Weight)

- The buoyancy force $= \rho V g$ where V is the underwater volume. The underwater volume of the compartment is lBT. Therefore, the lost buoyancy force is $\rho lBTg$.
- After flooding, the new draft of the barge is $T + \delta T$. As the bulkhead deck is above the waterline, the water inside the flooded compartment will rise to the new waterline. The volume of water that has entered the barge is $lB(T + \delta T)$. Therefore, the added mass is $\rho lB(T + \delta T)$.

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Find the increase in the draft using two methods

❖Lost Buoyancy method

- Lost buoyancy volume $= lBT = 4$ *5*1.5 = 30 m^3 = additional buoyancy = $(L - l)B\delta T =$ (20-4)*5*δT. $\delta T =$ 30/(16*5) = 0.375 m.

❖Added weight method

- The original displacement of the barge is ρLBT.
- When the barge settles in the water, the draft increases by δT. The total added mass of water in the bilged compartment is $\rho lB(T + \delta T)$. Consider the barge to be intact. The additional buoyancy force is $\rho LB(\delta T)g$. So, $\rho lB(T + \delta T) = \rho LB(\delta T)$; $4(T + \delta T) = 20\delta T$; $4(1.5 + \delta T) = 20\delta T$; $6 = 16\,\delta T$; δT=3/8 = 0.375 m.

❖ Both methods yield an increase in the draft of 0.375 m.

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5.5 Bilging of a midship compartment

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Compartment 2 is damaged and calculate the consequences of its flooding. We choose deliberately a compartment symmetric about the midship transverse plane of symmetry of the pontoon. Thus, the flooding of Compartment 2 produces no trim. Also, the compartment extends for the full ship breadth and its flooding produces no heel. The only change of position is **parallel sinking**. Thus, the complex calculations necessary for conventional ship forms, for large trim, or for unsymmetrical flooding, do not obscure the principles and it is possible to obtain immediately a good insight of the processes involved. For the same reasons we assume that the volume and surface permeabilities are equal to 1. We leave to an exercise the informal proof that taking permeability into account does not change the qualitative results. Although based on different physical models, calculations by the two methods yield the same final draught, as it should be expected. Moreover, the stability properties calculated by the two methods are identical, if we compare the initial righting moments. Here, the term "initial" has the meaning defined in Chapter 2 where we consider 'initial stability' as a property governing the behaviour of the floating body in a small heel range around the upright position. In that range the righting moment equals

$$M_R = \Delta \overline{GM} \sin \phi$$

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As we are going to see, we obtain by the two methods the same M_R value. In the method of lost buoyancy the displacement remains equal to that of the intact vessel. In the method of added weight the displacement increases by the mass of the flooding water. To keep the product M_R constant, the other factor, $\overline{GM}$, must be smaller. At a first glance it may be surprising that the two methods yield different metacentric heights. The explanation given above shows that it should be so because the considered displacements are different. What should be kept in mind, after reading the examples, is that displacement and metacentric height have different significances in the two methods. Therefore, damage stability data should include the mention of the method by which they were obtained. Computer programmes use the method of lost buoyancy for final-stage calculations.

The length of the assumed pontoon is $L = 20$ m, the beam, $B = 5$ m, and the draught in intact condition, $T_I = 1.5$ m. Let the vertical centre of gravity be $\overline{KG}_I = 1.5$ m. The following calculations were carried on in MATLAB, using the full precision of the software. The results are rounded off to a reasonable number of decimal digits. We first find the data of the intact pontoon. The displacement volume is Biran. Intro for both methods.

First, consider intact stability.

$$\nabla_I = LBT_I = 20 \times 5 \times 1.5 = 150 \text{ m}^3$$

Subscript I is for initial

The mass displacement equals

$$\Delta_I = \rho \nabla_I = 1.025 \times 150 = 153.75 \text{ t}$$

The moment of inertia of the waterplane area about the centreline equals

$$I_I = \frac{B^3 L}{12} = \frac{5^3 \times 20}{12} = 208.3333 \text{ m}^4$$

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5.5 Bilging of a midship compartment. Intact condition.

and the resulting metacentric radius is

First, consider intact stability.

$$\overline{BM}_I = \frac{I_I}{\nabla_I} = \frac{208.3333}{150} = 1.389 \text{ m}$$

For such a simple form we could have found directly the metacentric radius as

$$\overline{BM}_I = \frac{B^3L/12}{LBT_I} = \frac{B^2}{12T_I} = \frac{5^2}{12 \times 1.5} = 1.389 \text{ m}$$

The height of the centre of buoyancy is

$$\overline{KB}_I = \frac{T_I}{2} = 0.75 \text{ m}$$

Biran. Intro for both methods.

and the metacentric height

$$\overline{GM}_I = \overline{KB}_I + \overline{BM}_I - \overline{KG}_I = 0.75 + 1.389 - 1.50 = 0.639 \text{ m}$$

For small heel angles the righting moment in intact condition is calculated as

$$M_{RI} = \Delta_I \overline{GM}_I \sin\phi = 153.75 \times 0.639 \times \sin\phi = \boxed{98.229 \sin\phi \text{ t m}}$$

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5.5 Bilging of a midship compartment. Lost buoyancy method.

11.3.1 Lost Buoyancy

Four translations of the term 'method of lost buoyancy' are

Fr	La méthode des carènes perdues
G	Methode des wegfallender Verdrängung
I	Il metodo per perdita di galleggiabilità
S	Método de la pérdida de empuje

In the method of lost buoyancy the flooded compartment does not supply buoyancy. As shown in Figure 11.3, the buoyant hull is composed only of Compartments 1 and 3. After lo~~o~~sing the central compartment, the waterplane area is equal to

Subscript L is for Lost Buoyancy

$$A_L = (L - l)B = (20 - 4) \times 5 = 80 \text{ m}^2$$

To compensate for the loss of buoyancy of the central compartment the draught increases to

$$T_L = \frac{\nabla_I}{A_L} = \frac{150}{80} = 1.875 \text{ m}$$

The height of the centre of buoyancy increases to

$$\overline{KB}_L = \frac{T_L}{2} = \frac{1.875}{2} = 0.938 \text{ m}$$

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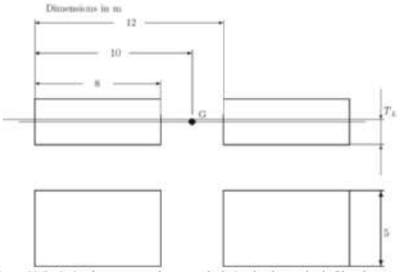

Figure 11.3 A simple pontoon—damage calculation by the method of lost buoyancy

5.5 Bilging of a midship compartment.
Lost buoyancy method

- Bad notation. The subscript L is for Lost Buoyancy and not Longitudinal. $\boldsymbol{I_L}$ is the <u>transverse</u> moment of inertia after buoyancy is lost.

We calculate the moment of inertia of the waterplane as

$$\boxed{I_L = \frac{B^3(L-l)}{12}} = \frac{5^3(20-4)}{12} = 166.6667 \text{ m}^4$$

and the metacentric radius as

$$\overline{BM}_L = \frac{I_L}{\nabla_I} = \frac{166.6667}{150} = 1.111 \text{ m}$$

Finally, the metacentric height is

Recall: $GM_I = 0.639$ m

$$\overline{GM}_L = \overline{KB}_L + \overline{BM}_L - \overline{KG}_I = 0.938 + 1.111 - 1.5 = 0.549 \text{ m}$$

and the righting moment for small heel angles, in the lost-buoyancy method

$$M_{RL} = \Delta_I \overline{GM}_L \sin\phi = 153.75 \times 0.549 \sin\phi = \boxed{84.349 \sin\phi \text{ t m}}$$

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5.5 Bilging of a midship compartment. Added weight method.

11.3.2 Added Weight

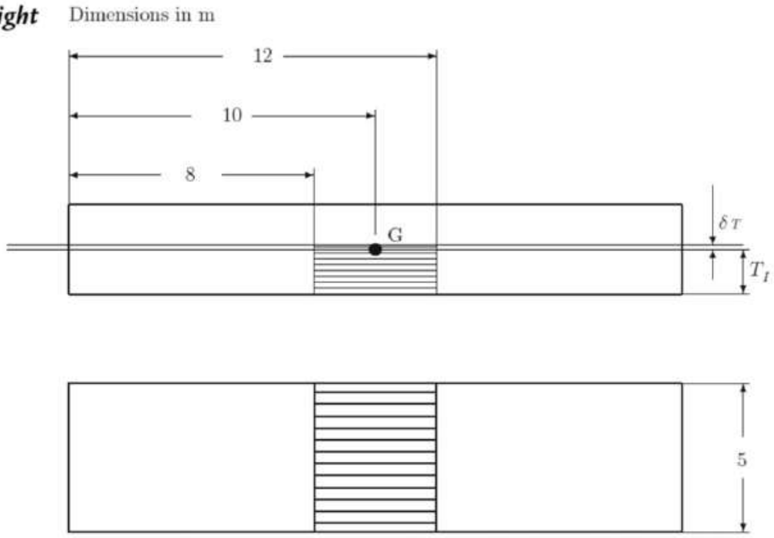

Figure 11.4 A simple pontoon—damage calculation by the method of added weight

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For this subsection see Figure 11.4. Because of the added weight of the flooding water the draught of the pontoon must increase by a quantity δT. The volume of flooding water equals

Where is the bulkhead deck? Above W1L1.

$$v = lB(T_I + \delta T) \qquad \boxed{v = \delta\nabla.} \qquad (11.$$

The additional buoyant volume of the vessel, due to parallel sinking, is

$$\delta\nabla = LB\delta T \qquad (11.$$

To obtain the draught increment, δT, we equate the two volumes, that is we write $v = \delta\nabla$. Algebraic manipulation and numerical calculation yield

$$\delta T = \frac{lT_I}{L - l} = \frac{4 \times 1.5}{20 - 4} = 0.375 \text{ m}$$

The draught after flooding is

$$T_A = T_I + \delta T = 1.500 + 0.375 = 1.875 \text{ m}$$

The volume of flooding water is calculated as

$$v = lBT_A = 4 \times 5 \times 1.875 = 37.5 \text{ m}^3$$

and the height of its centre of gravity

$$\overline{kb} = \frac{T_A}{2} = \frac{1.875}{2} = 0.938 \text{ m}$$

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5.5 Bilging of a midship compartment. Added weight method.

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Table 11.1 $\overline{KG}$ by the method of added weight

	~~Volume~~ Mass	Centre of Gravity	Moment
Initial	150.0 ρ	1.5	225.000 ρ
Added	37.5 ρ	0.938	35.156 ρ
Total	187.5 ρ	$\boxed{1.388}$	260.156 ρ

$\frac{260.156}{187.5} = 1.388.$

The displacement volume of the flooded pontoon is

$$\nabla_A = LBT_A = 20 \times 5 \times 1.875 = 187.5 \text{ m}^3$$

We consider the flooding water as an added weight; therefore, we must calculate a new centre of gravity. The calculations are shown in Table 11.1.

The moment of inertia of the damage waterplane is the same as in the initial condition, that is $I_A = 208.333 \text{ m}^4$. Then, the metacentric radius equals

$$\overline{BM}_A = \frac{I_A}{\nabla_A} = \frac{208.333}{187.5} = 1.111 \text{ m}$$

I does not change.
$\overline{BM}$ decreases.

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Recall. Free-Surface Effect.

$$y = \frac{1}{12} \cdot \frac{B^2}{T} \tan\phi$$
$$z = \frac{1}{24} \cdot \frac{B^2}{T} \tan^2\phi$$

- This effect has to be considered in the added weight method.
- Recall that for a wall-sided barge the coords of the CoB are $y = \overline{BM}\ \tan(\phi)$ and $z = \overline{BM}\ \tan^2(\phi)/2$. [Biran, 2nd Ed. P 60. Eq. (2.65)]

Figure 6.12a shows a tank containing a liquid whose surface is free to move within a large range of heeling angles without touching the tank top or bottom. Let us consider that the liquid volume behaves like a ship hull and consider the free surface a waterplane. Then, the centre of gravity of the liquid is the buoyancy centre of the liquid hull. Therefore, we use for it the notation b_0. While the ship heels, the centre of gravity of the liquid moves along the curve of the centre of the buoyancy, "around" the metacentre, m. The horizontal distance between the initial position, b_0, and the inclined position, b_ϕ, is

The CoB moves on the arc of a circle with center as M and radius $\overline{BM} = \overline{b_0 m}$. So, the horizontal distance by which it moves is $\overline{b_0 m}\ \tan\phi$ $\quad \overline{b_0 m}\tan\phi$

If v is the volume occupied by the liquid, i_B the moment of inertia of the liquid surface with respect to the barycentric axis (of the free surface) parallel to the axis of heeling, and ρ the

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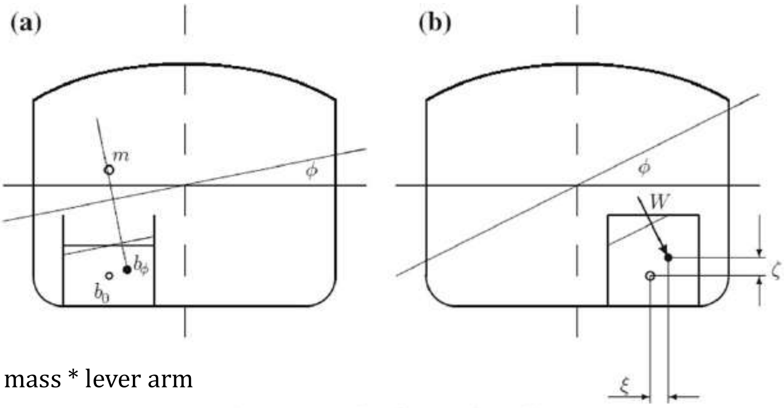
Recall. Free-Surface Effect.



Moment = mass * lever arm

Figure 6.12 The free-surface effect

liquid density, the heeling moment produced by the inclination of the liquid surface is

$$M_l = \rho v \frac{i_B}{v} \tan\phi = \rho i_B \tan\phi$$

where M_l has the dimensions of mass times length

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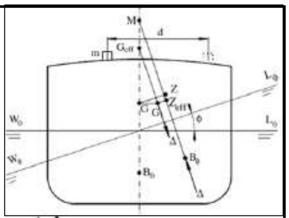
Recall. Free-Surface Effect.



As a result, the ship centre of gravity moves transversely a distance equal to

$$\overline{GG_1} = \frac{\rho \cdot i_B}{\Delta} \tan \phi$$

By comparison with the preceding subsection we conclude that the **effective metacentric height** is

$$\overline{GM_{eff}} = \overline{GM} - \frac{\rho \cdot i_B}{\Delta}$$

$$\overline{GG_1} = \frac{dm}{\Delta}$$

an **effective** value

$$\overline{GZ_{eff}} = \overline{GZ} - \frac{dm}{\Delta} \cos \phi$$

and the **effective righting arm**,

$$\overline{GZ_{eff}} = \overline{GZ} - \frac{\rho \cdot i_B}{\Delta} \sin \phi$$

Instead of considering the free-surface effect as a virtual reduction of the metacentric height and of the righting lever, we can take it into account as the heeling lever of free movable liquids. Its value is

$$\ell_F = \frac{\rho \cdot i_B}{\Delta} \quad = \text{Decrease in GM} \qquad (6.38)$$

and the respective curve is proportional to $\sin \phi$. The latter approach is that adopted in the stability regulations of the German Navy.

The reduction of stability caused by the liquids in slack tanks is known as **free-surface effect**.

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5.5 Bilging of a midship compartment. Added weight method.

In this method the flooding water is considered as belonging to the displacement. Therefore, if there is a free surface its effect must be calculated. The moment of inertia of the free surface in the flooded compartment equals

i_B on the previous slide is i here

$$i = \frac{B^3 l}{12} = \frac{5^3 \times 4}{12} = 41.667 \text{ m}^4$$

and the lever arm of the free surface effect is

l_F = decrease in $\overline{GM}$ because of the free surface effect

$$\ell_F = \frac{\rho i}{\rho \nabla_A} = \frac{41.667}{187.5} = 0.222 \text{ m}$$

The height of the centre of buoyancy is yielded by

$$\overline{KB}_A = \frac{T_A}{2} = \frac{1.875}{2} = 0.938 \text{ m}$$

$\boldsymbol{\overline{KB}_A}$ is equal to $\boldsymbol{\overline{KB}_L}$

The corresponding metacentric height is calculated as

$$\overline{GM_A} = \overline{KB}_A + \overline{BM}_A - \overline{KG}_A - \ell_F = \underbrace{0.938}_{\overline{KB}_A} + \underbrace{1.111}_{\overline{BM}_A} - \underbrace{1.388}_{\overline{KG}_A} - \underbrace{0.222}_{\ell_F} = 0.439 \text{ m}$$

With the mass displacement

$$\Delta_A = \rho \nabla_A = 1.025 \times 187.5 = 192.188 \text{ t}$$

we obtain the righting moment for small angles of heel, in the added-weight method

M_{RA} is equal to M_{RL}

$$M_{RA} = \Delta_A \overline{GM}_A \sin \phi = 192.188 \times 0.439 \sin \phi = \boxed{84.349 \sin \phi \text{ t m}}$$

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5.5 Bilging of a midship compartment. Comparison of results obtained using 2 methods

Table 11.2 Flooding calculations—a comparison of methods

	Intact Condition	Damaged, Lost Buoyancy	Damaged, by Added Weight
Draught, m	1.500	1.875	1.875
∇, m^3	150.000	150.000	187.500
Δ, t	153.750	153.750	192.188
$\overline{KB}$, m	0.750	0.938	0.938
$\overline{BM}$, m	1.389	1.111	1.111
$\overline{KG}$, m	1.500	1.500	1.388
$\overline{GM}$, m	0.639	0.549	0.439
$\Delta\overline{GM}$, t m	98.229	84.349	84.349

11.3.3 The Comparison

Table 11.2 summarizes the results of the preceding two subsections. As expected, both the method of lost buoyancy and that of added weight yield the same draught 1.875 m, and the same initial righting moment, 84.349 sin ϕ t m. The displacements and the metacentric heights are different, but their products, $\Delta\overline{GM}$, are the same. As happens in most cases, the righting moment in damage condition is less than in intact condition.

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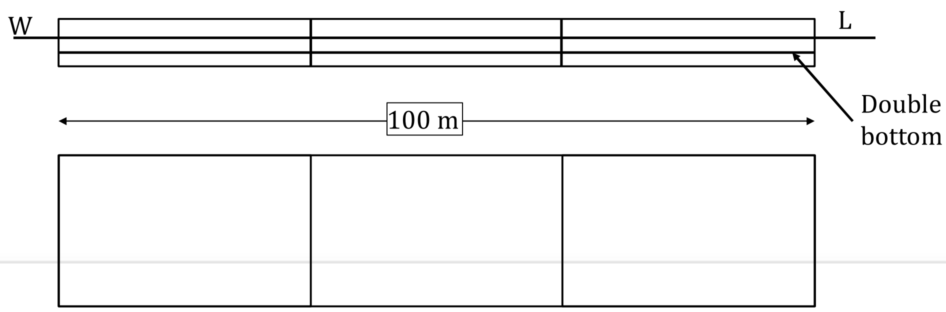
What if there is another watertight deck?

- A cuboidal barge has L=100 m, B = 20 m, T = 4 m, D = 6 m. It is sub-divided longitudinally by 3 transverse bulkheads that run from the keel to the main deck and from port to starboard. It has a double bottom that is 1 m deep. The central double-bottom tank is bilged. Find the new draft.



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Change in the CoG. General Case.

- A system has mass M. Its CoG is at G. A mass m is added at g. The new CoG is at G_1. The change in the CoG is $\overline{GG_1}$ and is parallel to the line joining G with g. $\overline{GG_1} = \frac{mg}{M+m}$. The new CoG lies between the original CoG and g.
- A system has mass M. Its CoG is at G. If the mass m is removed from g, $\overline{GG_1} = \frac{-mg}{M-m}$. The original CoG lies between the new CoG and g. This is used to find the change in the CoB in Flooding of a Side Compartment by B&D. L24&25&26S39. This expression is derived for the case of 2 masses on the next slide.
- The above expressions are derived by taking moments about the original CoG.

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Change in the CoG. Two masses.

- Masses m_1 and m_2 are at x_1 and x_2. Find the CoG. Mass m_2 is removed. Find the change in the CoG. Let $M = m_1+m_2$.
- $G = \text{CoG}_1 = (m_1x_1+m_2x_2)/(m_1+m_2)$. After m_2 is removed, $G_1 = \text{CoG2} = (m_1x_1)/(m_1) = x_1$. With respect to the COG_1, m_2 was at $g = x_2 - (m_1x_1+m_2x_2)/(m_1+m_2) = m_1(x_2-x_1)/(m_1+m_2)$. Therefore, wrt CoG_1, the final CoG is at $x_1 - (m_1x_1+m_2x_2)/(m_1+m_2) = m_2(x_1 - x_2)/(m_1+m_2) = - m_2g/ m_1 = - m_2g/(M-m_1) = \overline{GG_1}$

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5.6 Flooding of a side compartment at midship.
Barrass and Darrett. 7th Ed. p 140.

Example 1

A box-shaped vessel, of length 100 m and breadth 18 m, floats in salt water on an even keel at 7.5 m draft. KG = 4 m. The ship has a continuous centerline bulkhead that is watertight (see **Figure 14.2**). Find the list if a compartment amidships, which is 15 m long and is empty, is bilged on one side.

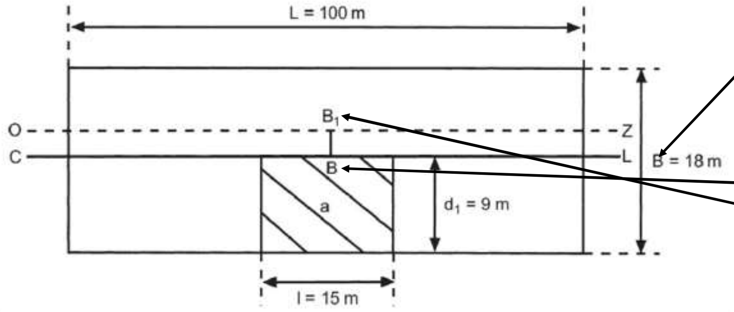

Figure 14.2

Waterplane area.
B = Breadth of vessel
l = length of flooded comp.
a = WPA of flooded comp.

B = CoB before flooding.
B_1 = CoB after flooding before the vessel heels.

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CHAPTER 14

Angle of List Due to Bilging of Side Compartments

When a compartment in a ship is bilged the buoyancy provided by that compartment is lost. This causes the center of buoyancy of the ship to move directly away from the center of the lost buoyancy and, unless the center of gravity of the compartment is on the ship's centerline, a listing moment will be created, b = w.

Let the ship in Figure 14.1 float upright at the waterline, WL. G represents the position of the ship's center of gravity and B the center of buoyancy.

Now let a compartment that is divided at the centerline be bilged on the starboard side, as shown in the figure. To make good the lost buoyancy the ship will sink to the waterline W_1L_1. That is, the lost buoyancy is made good by the layer between WL and W_1L_1.

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Approximate Analysis

The center of buoyancy will move from B to B_1, directly away from the center of gravity of the lost buoyancy, and the distance BB_1 is equal to $(w \times d)/W$, where w represents the lost buoyancy and d represents the distance between the ship's center of buoyancy and the center of the lost buoyancy.

The shift in the center of buoyancy produces a listing moment.

Let θ be the resultant list. Then: $\boxed{\tan\theta = \frac{GX}{XM} = \frac{BB_1}{XM}}$ XM = difference between z coords of G and M

where XM represents the initial metacentric height for the bilged condition.

B_1 is above B.
Show y$\overline{BB_1} = \frac{wd}{W}$.
w = lost volume.
d=yCoB of lost vol. W = uw vol. after bilging. See S39.

To find W_1L_1 consider equivolume sinkage. Original ∇=100*18*7.5 =13,500 m^3. WPA after flooding = WPA$_1$=100*18-15*9 = 1665 m^2. New draft = ∇/WPA$_1$ = 8.108 m

To find the new equivolume waterline, assume parallel sinkage followed by a list. For parallel sinkage, the CoB is B_1. After listing, the CoB is B_2.

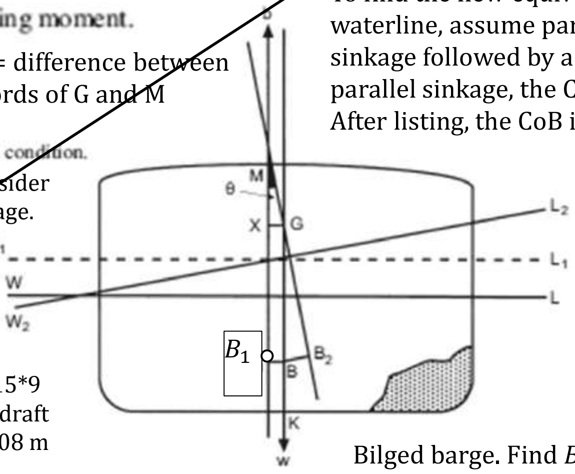

Figure 14.1

Bilged barge. Find B_1. See the next slide.

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Bilged Barge. CoB.

- Step 1. Equivolume parallel sinkage. Find the CoB B_1 after parallel sinkage. The centroid of the intact WPA is on the centerline. The CoB of the bilged barge is the centroid of the damaged WPA. To find the new yCoB, take moments about the centerline. The centroid of the lost WPA is d = centroid of lost volume.
- $[WPA_{intact} - WPA_{lost}]\, yCoB_{parallel} = [WPA_{intact}0 - WPA_{lost}d]$
- $yCoB_{parallel} = -\frac{WPA_{lost}d}{[WPA_{intact} - WPA_{lost}]}$ for a cuboidal barge. See S39.
- For the general case $yCoB_{parallel} = -\frac{UWV_{lost}d}{[UWV_{intact} - UWV_{lost}]}$. See $\overline{GG_1} = \frac{-mg}{M-m}$ on S39
- What is B_1 for a ship? Find the lost volume. A layer of water is added above the original waterline. Find its thickness by using the hydrostatic curve for WPA. $\int_{T_1}^{T_2}[WPA - a(T)]\,\mathrm{d}T$ = lost volume
- Step 2. Equivolume inclination.
- See S43 and S46

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5.6 Flooding of a side compartment at midship.

(a) *Find the new mean draft*:

T = initial or intact draft
T_2 = new uniform draft before heeling

$$\text{Bodily increase in draft} = \frac{\text{Volume of lost buoyancy}}{\text{Area of intact W.P.}}$$

$$= \frac{15 \times 9 \times 7.5}{(100 \times 18) - (15 \times 9)} = 0.61$$

$$\text{New draft} = 7.50 + 0.61$$

$$\therefore \text{New draft} = 8.11 \text{ m} = \text{Draft } d_2 \boxed{= T_2}$$

(b) *Find the shift of the center of buoyancy*:

Total volume $= LBT = (LB - a)T_2$

$$BB_1 = \frac{a \times B/4}{LB - a}$$

$$= \frac{15 \times 9 \times 18/4}{(100 \times 18) - (15 \times 9)} = \frac{607.5}{1665}$$

$$= 0.365 \text{ m}$$

- To find the horizontal SHIFT in the CoB, after the increase in the draft but before heeling, take moments of the volume about the intact CoB and divide by the (new = old) total volume
- Method 1. New Vol. $BB_1 = \frac{aT_2\,(B/4)}{(LB-a)T_2} = \frac{aB/4}{LB-a} = \frac{15*9*(18/4)}{100*18-15*9}$ =0.36495 m

- Method 2. Original Vol. $\overline{BB_1} = \frac{aT_2(B/4)}{LBT} = \frac{15*9*8.11(18/4)}{100*18*7.5} = 0.36495$ m

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Moment of Inertia of Damaged WPA

- After parallel sinkage, the Moment of Inertia of the damaged waterplane area about the centerline can be found in many ways.
- Method 1. B&D consider the intact port-side half of the WPA and the damaged stbd-side. The MoI is found about the Centerline of the vessel. The MoI of a rectangle about the edge along the length is $I = Length\ Breadth^3/3$. For the intact side, the length is the full length, L. For the damaged side, it is $L - l$.
- MoI $= \frac{L(B/2)^3}{3} + \frac{(L-l)(B/2)^3}{3} = \frac{LB^3}{12} - \frac{lB^3}{24}$
- Method 2. Find the MoI of the original WAP about its Centerline. Subtract the MoI of the damaged part about its edge.
- MoI $= \frac{LB^3}{12} - \frac{l(B/2)^3}{3} = \frac{LB^3}{12} - \frac{lB^3}{24}$

(c) To find I_{OZ}:

$$I_{CL} = \left(\frac{B}{2}\right)^3 \times \frac{L}{3} + \left(\frac{B}{2}\right)^3 \times \frac{(L - l)}{3}$$

$$I_{CL} = \frac{9^3 \times 100}{3} + \frac{9^3 \times 85}{3} = 24{,}300 + 20{,}655$$

$$= 44{,}955 \text{ m}^4$$

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Transverse Moment of Inertia of Damaged WPA about the CoF

- The centroid of the damaged WPA (CoF) is at y = -0.365 m (ISO coordinates)
- The MoI about the CoF is (Parallel axis theorem)

(c) *To find* I_{OZ}:

$$I_{CL} = \left(\frac{B}{2}\right)^3 \times \frac{L}{3} + \left(\frac{B}{2}\right)^3 \times \frac{(L-l)}{3}$$

$$I_{CL} = \frac{9^3 \times 100}{3} + \frac{9^3 \times 85}{3} = 24{,}300 + 20{,}655$$

$$= 44{,}955 \ \text{m}^4$$

$$I_{OZ} = I_{CL} - A \times BB_1^2 \qquad A = \text{Intact area of waterplane}$$

$$= 44{,}955 - \{(100 \times 18) - (15 \times 9)\} \times 0.365^2$$

$$= 44{,}955 - 222$$

$$= 44{,}733 \ \text{m}^4$$

I_{OZ} =44,733 m^4

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5.6 Flooding of a side compartment at midship.

- After parallel sinkage, use the MoI to find the damaged BM and then the GM. Original and flooded UW Volume are the same. It is easier here to use the original UW Volume.
- At this stage, it is assumed that the flooded vessel is on even keel. The KB is half the flooded draft.
- $KM = KB + BM = 7.37$ m
- KG does not change after bilging
- $GM = KM - KG = 3.37$ m

(d) *To find GM:*

$$BM = \frac{I_{OZ}}{V}$$

$$= \frac{44{,}733}{100 \times 18 \times 7.5}$$

$$= 3.31 \text{ m}$$

$+$

$$KB = \frac{d_2}{2} \ \therefore \ KB = \underline{4.06 \text{ m}}$$

$$KM = 7.37 \text{ m}$$

$-$

$$KG = \underline{4.00 \text{ m}} \text{ as before bilging}$$

$$\text{After bilging, } GM = \underline{3.37 \text{ m}}$$

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List Angle. Approximate Analysis.

The shift in the center of buoyancy produces a listing moment.

Let θ be the resultant list. Then: $\boxed{\tan\theta = \dfrac{GX}{XM} = \dfrac{BB_1}{XM}}$

where XM represents the initial metacentric height for the bilged condition.

XM = difference between z coords of G and M. It is the initial metacentric height after bilging.

GM after parallel sinkage is approximately the GM after listing. After listing, M lies on the line joining G and B_2. See S51.

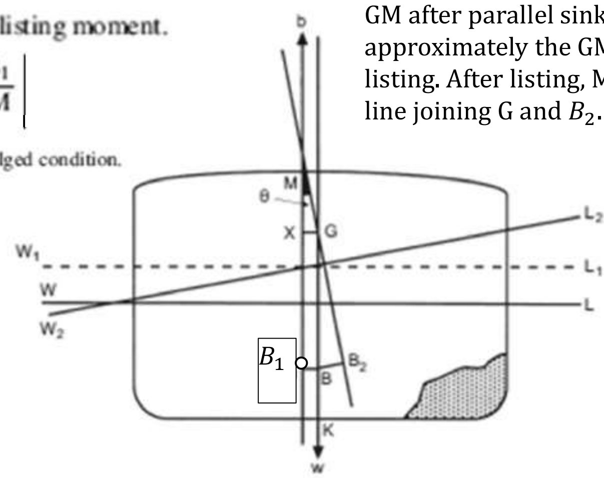

Figure 14.1

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5.6 List of flooded barge. Approximate Analysis.

- New CoF is at B_1. Check this.
- Barrass and Derrett give an expression for tan(List). In the next lecture, we will find the list for 5.7 using Archimedes principle and Stevin's Law.

(e) *To find the list*:

$$\tan \text{ List} = \frac{BB_1}{GM}$$

$$= \frac{0.365}{3.37} = 0.1083$$

Ans. List = 6° 11′.

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Name a Naval Arch book that you read in the last one week

Read books, magazines, and journals

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Stability of Ships

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Stability of Ships. Course Content. Exam question paper will be based on this.

Course Content:

1. **Module I**
   Stability terms. Potential energy. Equilibrium. Weight displacement and Volume displacement; Change of density, FWA, DWA. Equi-volume inclinations, shift of CoB due to inclinations, CoB curve in lateral plane, (*initial*) metacentre, metacentric radius, metacentric height; metacentre at large angles of inclinations, pro-metacentre. CoG, righting moment and lever; Statical, metacentric, residuary, form and weight stabilities. Surface of flotation, curve of flotation. Derivation of BM = I / V.

2. **Module II**
   Initial (*transverse*) stability: GM_0, GZ at small angles of inclinations, Wall sided ships. Sinkage and stability due to addition, removal and shift (transverse and vertical) of weight, suspended weights and free surface of liquids; Inclining Experiment; stability while docking and grounding; Stiff/ Tender ship.

3. **Module III**
   Large angle (*transverse*) stability: Diagram of statical stability (GZ curve), characteristics of GZ curve, effect of form, shift of G and super structure on GZ curve, static equilibrium criteria, Methods of calculating GZ curve (Prohaska, Krylov and from ship form), Cross curves of stability.
   Dynamical stability, diagram of dynamical stability, dynamic stability criteria.
   Moments due to wind, shift of Cargo and passengers, turning and non-symmetric accumulation of ice.
   Intact stability rules, Heel/ Load test.
   Practical: Diagram of statical stability / Cross curves of stability (Krylov's method).

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Stability of Ships. Course Content

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4. **Module IV**
   Longitudinal Stability: Trim, longitudinal metacentre, longitudinal centre of flotation, moment to change trim, trimming moment, change of trim and drafts due to addition,

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removal and longitudinal shift of weight, trim and draft change due to change of density. Rules on draft and trim.

5. **Module V**
   Damage stability: Bilging, Surface and volume permeability; Sinkage, heel, change of trim and drafts due to bilging of midship, side and end compartments.

Practical: Floodable length calculation and subdivision of ship. Stability in waves,

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Course Content

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Completed

- Module 1. Stability Terms. 06 Lectures.
- Module 2. Initial (Transverse) Stability. 07 lectures.
- Module 3. Large Angle Transverse Stability. 07 lectures.
- Module 4. Longitudinal Stability. 03 Lectures

Today

- 5. Damaged Stability

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Module 5

- 5.1 What is damaged stability?
- 5.2 Bilging
- 5.3 Surface and volume permeability
- 5.4 Two methods for assessing damaged stability
- 5.5 Bilging of a midship compartment
- 5.6 Flooding of a side compartment at midship
- 5.7 Exact analysis of a barge with an off-center full-length flooded compartment

Today

- 5.8 Flooding of a side compartment forward of CoF. General case.

Later

- 5.9 Floodable length curve
- 5.10 Damaged stability regulations
- 5.11 Stability in waves

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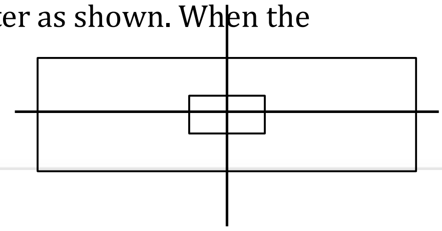
5.8 Flooding of a side compartment forward of CoF. General case.

- Read Rawson and Tupper. 5th Ed. Chap 5. pp 145-
- Lost Buoyancy method
- When a compartment with the same CoF as the ship is flooded, the CoF of the ship after parallel sinkage does not change. The CoB of such a compartment can be different from the CoB of the ship. If so, the CoBs of the ship before and after parallel sinkage will be different.
- Consider the parallelepipedic barge shown in the figure. It has a parallelepipedic compartment at the center as shown. When the compartment is flooded, the CoF, xCoB, and yCoB before and after flooding are the same. The zCoB increases.



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5.8 Flooding of a side compartment forward of CoF. General case.

- In the following, there is there is no double bottom or watertight deck between the initial and final waterlines
- See pp 149

Where there is no such limitation and the space is free flooding, heel, trim and parallel sinkage are calculated by regarding the flooding as lost buoyancy in a manner similar to that already described for a central compartment. Now, because the ineffective area of waterplane is not conveniently central, the centre of flotation will move and the ship will not heel about the middle line. The procedure is therefore as follows:

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5.8 Flooding of a side compartment forward of CoF. General case.

- General procedure for finding final attitude of a ship when ANY compartment is flooded
- Rawson 5th Ed. Lost buoyancy method.
- 6 steps

(i) calculate permeable volume of compartment up to original waterline;
(ii) calculate TPI, longitudinal and lateral positions of CF for the waterplane with the damaged area removed; **Find CF using the first moment**
(iii) calculate revised second moments of areas of the waterplane about the CF in the two directions and hence new $\overline{BM}$s;
(iv) calculate parallel sinkage and rise of CB due to the vertical transfer of buoyancy from the flooded compartment to the layer;
(v) calculate new $\overline{GM}$s
(vi) calculate angles of rotation due to the eccentricity of the loss of buoyancy from the new CFs.

- Details of the 6 steps are in the following slides

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Rawson. 6 steps. Lost Buoyancy

- When a compartment is flooded, the ship will heel and trim so that more of the flooded side is submerged – as shown in the figure – to compensate for the lost buoyancy. The final CoB is at B_1. Note that in the 6 steps, Rawson does not present the new CoB. It is to be found by using the condition that $\overline{\boldsymbol{BG}}$ is perpendicular to the water surface.

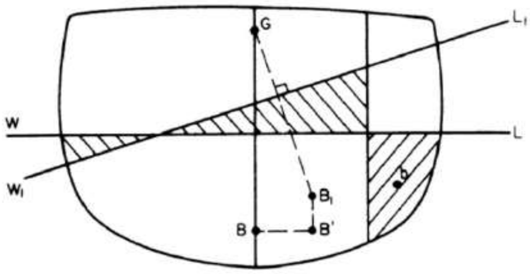

Fig. 5.6

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General Procedure

- To find the attitude of a ship after a compartment is flooded, the following procedure can be followed. It is a rephrased version of the procedure in Rawson.
- Find the lost buoyancy (volume), the CoF, and the CoB of the compartment
- Assume that the ship undergoes parallel sinkage first followed by heel and trim
- Find the draft and CoF after the parallel sinkage. The CoF after parallel sinkage and the lost compartment will lie on opposite sides of the intact CoF.
- For the simpler cases of flooding such as barges with cuboidal compartments (See L24 to L27) the CoB after parallel sinkage is also found.
- For ship with complex uw shapes, find the $\overline{BM_T}$ and the $\overline{BM_L}$. Recall that $\overline{BM} = I/V$ is easier to find than the CoB. Use them to find the $\overline{GM_T}$ and the $\overline{GM_L}$. Then, find the heel and trim angles by using the lost moment.
- After heel and trim, the final CoF and CoB will lie on the same side as the lost compartment – with respect to the original CoF and CoB.

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5.8 Flooding of a side compartment forward of CoF. General case.

150 *Basic ship theory*

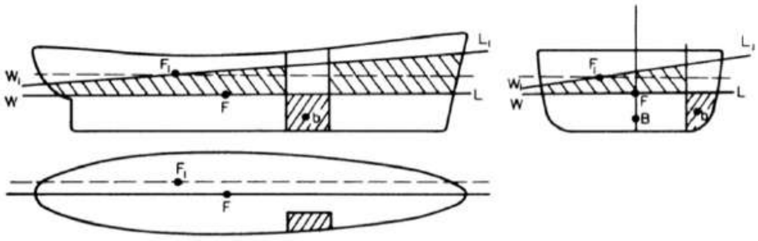

Fig. 5.5

- **Ship info**

- Compartment info is on the next slide.

Before the incident the ship was floating on an even draught of 10 m at which the following particulars obtained

Displacement mass, 30,000 tonnes	$\overline{KM}$ long, 170 m
$\overline{KG}$, 9.40 m	WP area, 4540 m^2
$\overline{KM}$ transverse, 11.40 m	CF, 1 m before midships
$\overline{KB}$, 5.25 m	LBP, 220 m

Calculate the heel and trim when the compartment is bilged.

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5.8 Flooding of a side compartment forward of CoF. General case.

EXAMPLE 1. A compartment having a plan area at the waterline of 100 m^2 and centroid 70 m before midships, 13 m to starboard is bilged. Up to the waterline obtaining before bilging, the compartment volume was 1000 m^3 with centres of volume 68.5 m before midships, 12 m to starboard and 5 m above keel. The permeability was 0.70.

- **Rawson. pp 149. Find the attitude of the ship after bilging.**

Compartment info

- **Plan area = 100 m^2. Centroid = 70 m fwd of midship and 13 m to starboard.**
- **Volume = 1000 m^3. Centroid = 68.5 fwd of midship and 12 m to starboard and 5 m above keel.**

Step (i)

- Lost Buoyancy = vol of compart. *permeability= 1000 * 0.7 = 700 m^3.

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Centre of Floatation

For a plane figure placed symmetrically about the x-axis such as a waterplane, $M_{xx} = \int x_1 y \, dy = 0$ and the distance of the centre of area, called in the particular case of a waterplane, the *centre of flotation* (CF), from the y-axis is given by

$$\bar{x} = \frac{M_{yy}}{A} = \frac{2\int xy_1 \, dx}{2\int y_1 \, dx}$$

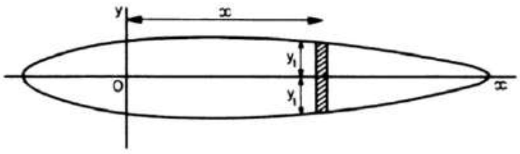

Fig. 2.15

*Note that $M_y \equiv M_{xx}$.

- Rawson 5th Ed
- Compartment vol = 1000 m^3.
- Lost buoyancy = 1000*1025 kg = 1025 t

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Overview of the Lost Buoyancy Method

- A forward compartment has been flooded.
- As in the earlier simpler cases, find the parallel sinkage, the damaged CoF, and then the inclination about the damaged CoF
- To find the inclination, the moment of inertia of the damaged WPA is needed
-
- After parallel sinkage will the damaged CoF move forward or aft? Ans. Aft
- After parallel sinkage will the damaged CoB move forward or aft? Ans. Aft
- After inclination (heel and trim), the CoF and CoB will be in the same direction as the lost compartment.

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5.8 Flooding of a side compartment forward of CoF. General case.

- Study Rawson. Understand the ideas explained by using a numerical example
- In Step (ii), consider parallel sinkage. The CoF of the damaged waterplane area moves to the aft with respect to the original CoF because a forward compartment has been bilged and it moves to the port because a starboard compartment has been bilged. See the next slide for the details.
- Step (iia). Damaged WPA. It is assumed that the ship is locally wall-sided.
- WPA after flooding = WPA before flooding – WPA of compartment = 4540 – 100 = 4440 m^2

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- Step (iib). CoF after parallel sinkage.
- With respect to the original CoF, xCoF of WPA moves = - moment of damaged WPA/damaged WPA

  = - Area of damaged WPA (Dist between centroid of compartment's WPA and CoF of intact WPA) / damaged WPA

  = - 100(70-1)/4440 = -1.554 m. The minus sign indicates that the CoF moves aft
- Wrt original CoF, yCoF of damaged WPA moves = -moment of damaged WPA / damaged WPA = - 100*13/4440 = -0.293 m. It moves to the port.

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- Rawson. 6 steps

Solution: Refer to Fig. 5.5. Use the lost buoyancy method.

5.5 Rawson. Example.

(i) Permeable volume = 0.70 × 1000 = 700 m^3

4540-100

(ii) Damaged WP area = 4440 m^2

Take moment about CF_{Int}

$$\text{Movement of CF aft} = \frac{100 \times (70-1)}{4440} = 1.55\text{ m}$$

$xCoF_I$

xCoF of flooded compt.

$$\text{Movement of CF to port} = \frac{100 \times 13}{4440} = 0.29\text{ m}$$

Displacement mass, 30,000 tonnes
$\overline{KG}$, 9.40 m
$\overline{KM}$ transverse, 11.40 m
$\overline{KB}$, 5.25 m

$\overline{KM}$ long, 170 m
WP area, 4540 m^2
CF, 1 m before midships
LBP, 220 m

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5.8 Flooding of a side compartment forward of CoF. General case.

- Moment of Inertia is the ratio between the torque applied and the resulting angular acceleration about that axis.

❖Step (iii) the transverse and longitudinal $\overline{\boldsymbol{BM}}$ are found after parallel sinkage

- Find I_{xx} of damaged WPA about the Centerline. Then, find the I_{xx} about the CoF after parallel sinkage.
- Use the parallel axis theorem to find I_{xx} of the WPA about the CoF after parallel sinkage. Use that I_{xx} to find the list.
- Intact I_{xx} = BM * Volume = (KM – KB) * Volume = (11.40 – 5.25) * 30000/1.025 = 179.89e3 m^4. Rawson uses 1/1.025 ≅ 0.975. Explain.
- The final CoF is not the CoF after parallel sinkage because the ship trims and heels and the CoF changes because of that. Recall Krylov's method.

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- Rawson. Step 3 of 6.

Displacement mass, 30,000 tonnes
$\overline{KG}$, 9.40 m
$\overline{KM}$ transverse, 11.40 m
$\overline{KB}$, 5.25 m

$\overline{KM}$ long, 170 m
WP area, 4540 m^2
CF, 1 m before midships
LBP, 220 m

(iii) Original transverse I $I = \overline{BM}$ Volume

$\overline{KM}$ - $\overline{KB}$ = $\overline{BM}$ See next slide

$$I = (11.40 - 5.25) \times 0.975 \times 30{,}000 \; \boxed{=179.89\text{e}3 \text{ m}^4}$$

Damaged transverse I Damaged I Is less than intact I

Subtract lost I. Then use Parallel axis theorem.

$$I = 179.89 \times 10^3 - 100 \times 13^2 - 4440 \times (0.29)^2 = 162{,}620 \text{ m}^4$$

(ignoring I of the damage about its own axis)

$$\text{Damaged transverse } \overline{BM} = \frac{162{,}620}{0.975 \times 30{,}000} = 5.56 \text{ m}$$

Compartment volume not subtracted as lost vol = gained vol

Original long. I

$\overline{KM}$ - $\overline{KB}$ = $\overline{BM}$ $= \overline{BM}_F$

$$I = (170.0 - 5.25) \times 0.975 \times 30{,}000 = 4.819 \times 10^6 \text{ m}^4$$

$\overline{KM}_L$ - $\overline{KB}$ = $\overline{BM}_L$

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Step (iii) continued

Damaged long. I **Subtract lost I. Then use Parallel axis theorem.**

$$I = 4.819 \times 10^6 - 100\,(69)^2 - 4440\,(1.55)^2 = 4.332 \times 10^6 \text{ m}^4$$

Damaged long. $\overline{BM}$

$$\overline{BM} = \frac{4.332 \times 10^6}{0.975 \times 30{,}000} = 148.1 \text{ m}$$

- On S19, the I of the damaged compartment about its own axis is neglected.
- On S20, the I of a damaged rectangle with a cut-out rectangle is found using two methods. The I of the damaged compartment about its own axis is included. Both methods yield the same results.

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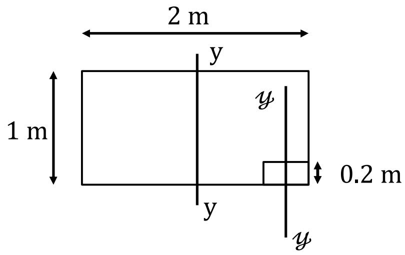
Exact I about an axis of a "Damaged" rectangle

- From a L = 2 m & B = 1 m rectangle, a $l = 0.4$ m x $b = 0.2$ m piece is cut out as shown. Find the <u>exact</u> transverse I_{yy} before and after the piece is cut.
- Before cut. $I_{yy} = BL^3/12 = 2/3$. Cut area a= 0.08 m^2. $i_{\mathcal{yy}} = bl^3/12$. Dist between CoF of cut piece and axis = $\left(\frac{L}{2} - \frac{l}{2}\right)$ = 0.8 m.
- After cut, find the I about the yy axis.



- Method 1. $I^1_{yy} = I_{yy} - a\left(\frac{L}{2} - \frac{l}{2}\right)^2 - i_{\mathcal{yy}}$
- = 0.6667 – 0.0512 – 0.11 = 0.6144 m^4
- Method 2. Use 3 rectangles.
- $I^2_{yy} = \frac{B\left(\frac{L}{2}\right)^3}{3} + \frac{B\left(\frac{L}{2} - l\right)^3}{3} + \frac{(B-b)(l)^3}{12} + (B-b)l\left(\frac{L}{2} - l\right)^2 = 0.3333 + 0.0720 + 0.0043 +$ 0.2048 = 0.6144 m^4. Both Methods yield the same result.

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0.975 m^3/t is used by Rawson

- Density of sea water is approx. 1025 kg/m^3 = 1.025 t/m^3
- The reciprocal is approx. 0.975 m^3/t. For small x, $1 - x^2 \cong 1$.
- $1 + x \cong \frac{1}{1-x}$

The ratio of the density of a solid or a liquid to the density of pure water is the *specific gravity*, γ. Since it is the basic reference for all such materials, the weight properties of pure distilled water are reproduced in Fig. 9.1.

The inverse of the weight density is called the *reciprocal weight density u*, or *specific volume*. The value for salt water is <u>0.975 m^3/tonne</u>f or 99.5 m^3/MN. Corrections are applied for variations of <u>reciprocal weight</u> density from this value. Table 3.1 gives values of mass density for common fluids and for steel, air and mahogany.

Rawson. pp 53

Table 3.1
Properties of some common materials

Material	Mass density, ρ (kg/m^3)	Reciprocal mass density (m^3/Mg)	Specific gravity, γ
Fresh water (standard)	1000	1.00	1.00
Fresh water (British preferred value)	996	1.00	1.00
Salt water	1025	0.975	1.03
Furnace fuel oil	947	1.05	0.95
Diesel oil	841	1.19	0.84
Petrol	697	1.44	0.70
Steel	7689	0.13	7.70
Mahogany	849	1.18	0.85
Air	1.293	774.775	—

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- Summary Slide of Steps (i) to (iii)

Displacement mass, 30,000 tonnes

$\overline{KG}$, 9.40 m

$\overline{KM}$ transverse, 11.40 m

$\overline{KB}$, 5.25 m

$\overline{KM}$ long, 170 m

WP area, 4540 m²

CF, 1 m before midships

LBP, 220 m

Solution: Refer to Fig. 5.5. Use the lost buoyancy method.

5.5 Rawson. Example.

(i) Permeable volume = 0.70 × 1000 = 700 m³

4540-100

(ii) Damaged WP area = 4440 m²

Take moment about CF_I

Movement of CF aft $= \frac{100 \times (70 - 1)}{4440} = 1.55\,\text{m}$ $\boldsymbol{CF_I}$

CF of flooded compt.

Movement of CF to port $= \frac{100 \times 13}{4440} = 0.29\,\text{m}$

(iii) Original transverse I **See next slide**

$\overline{KM}$ - $\overline{KB}$ = $\overline{BM}$

I = $\overline{BM}$ Volume

$I = (11.40 - 5.25) \times 0.975 \times 30{,}000$ $\boxed{=179.89\text{e}3\ \text{m}^4}$

Damaged transverse I I about new CF is lower than I about old CF

Subtract lost I. Then use Parallel axis theorem.

$I = 179.89 \times 10^3 - 100 \times 13^2 - 4440 \times (0.29)^2 = 162{,}620\,\text{m}^4$

(ignoring I of the damage about its own axis)

Damaged transverse $\overline{BM} = \frac{162{,}620}{0.975 \times 30{,}000} = 5.56\,\text{m} = \overline{BM}_F$

Compartment volume not subtracted as lost vol = gained vol

Original long. I

$\overline{KM}_L$ - $\overline{KB}$ = $\overline{BM}_L$

$I = (170.0 - 5.25) \times 0.975 \times 30{,}000 = 4.819 \times 10^6\,\text{m}^4$

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Rawson. 6 steps. Lost Buoyancy

- In Step 3, the transverse and longitudinal $\overline{\boldsymbol{BM}}$ are found.
- In Step 4, the rise in B is found. But the xCoB and yCoB are not found.
- CoB (centroid of the underwater volume) after parallel sinkage will behave like the CoF (centroid of the waterplane are) because they are both centroids. After parallel sinkage, both move away from the lost compartment. See B_P in the earlier lecture.
- The final CoB is not the CoB after parallel sinkage. It is the centroid of the new volume that is underwater after the ship has changed its attitude (draft amidship, heel, and trim) because of the flooding. It is vertically below the original CoG which has not changed.

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Rawson. 6 steps. Lost Buoyancy

- We are half-way through Step 3 in which we have to find $\overline{BM}_F$ and $\overline{BM}_{LF}$
- In Step 3, a term in the moment of inertia is neglected. What is its value?

(i) calculate permeable volume of compartment up to original waterline;
(ii) calculate TPI, longitudinal and lateral positions of CF for the waterplane with the damaged area removed;
(iii) calculate revised second moments of areas of the waterplane about the CF in the two directions and hence new $\overline{BM}$s;
(iv) calculate parallel sinkage and rise of CB due to the vertical transfer of buoyancy from the flooded compartment to the layer;
(v) calculate new $\overline{GM}$s
(vi) calculate angles of rotation due to the eccentricity of the loss of buoyancy from the new CFs.

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5.7 Sinkage, heel, and trim due to bilging. General case.

Damaged long. I

Subtract lost I. Then use Parallel axis theorem.

$$I = 4.819 \times 10^6 - 100\,(69)^2 - 4440\,(1.55)^2 = 4.332 \times 10^6\ \mathrm{m}^4$$

Damaged long. $\overline{BM}$

Lost volume = Compartment vol * Vol permeability

$$\overline{BM} = \frac{4.332 \times 10^6}{0.975 \times 30{,}000} = 148.1\ \mathrm{m}$$

Lost volume/Damaged WPA

(iv) Parallel sinkage $= \frac{700}{4440} = 0.16\,\mathrm{m}$

Lost volume(Original draft +0.5 Increase in draft – CoB flooded compt)

$$\text{Rise of B} = \frac{700(10 + 0.08 - 5)}{0.975 \times 30{,}000} = 0.12\ \mathrm{m}$$

Take Moment about Keel

$\overline{KB}$ **+ Rise in B +** $\overline{BM}_F$ **-** $\overline{KG}$

(v) Damaged transverse $\overline{GM} = 5.25 + 0.12 + 5.56 - 9.40 = 1.53\ \mathrm{m}$

Damaged long. $\overline{GM} = 5.25 + 0.12 + 148.1 - 9.40 = 144.1\ \mathrm{m}$

12 + 0.29 = 12.29 m = dist between lost buoy and new CF

(vi) Angle of heel $= \frac{700 \times 12.29}{0.975 \times 30{,}000 \times 1.53} \times \frac{180}{\pi} = 11.0°$

$\Delta\, \overline{GM}_{LF} \sin\theta$ **= Moment about CF**

$$\text{Angle of trim} = \frac{700 \times (68.5 - 1 + 1.55)}{0.975 \times 30{,}000 \times 144.1} = 0.01147\ \mathrm{rads}$$

Change of trim $= 0.01147 \times 220 = 2.52\ \mathrm{m}$ between perps.

Note that displacement and $\overline{KG}$ are unchanged.

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Rawson. 6 steps. Lost Buoyancy

- In Step 4, note that lost volume = gained volume. To find the rise in B, take moments about the original CoB. The CoB of the gained volume is approximately at original draft + 0.5*increase in draft = 10+0.08 m. Heel and trim will cause a change in the CoB of the added volume. The CoB of the lost volume is at 5 m.
- In Step 5, the new $\overline{\boldsymbol{KM}}_{\boldsymbol{F}}$ (F is for flooded) = Original $\overline{\boldsymbol{KB}}$ + rise in $\boldsymbol{B}$ + $\overline{\boldsymbol{BM}}_{\boldsymbol{F}}$. $\overline{\boldsymbol{KG}}$ does not change. Therefore, $\overline{\boldsymbol{GM}}_{\boldsymbol{F}} = \overline{\boldsymbol{KM}}_{\boldsymbol{F}}$ - $\overline{\boldsymbol{KG}}$
- In Step 6, Δ is used. The total displacement is always Δ =30,000 t. Therefore, the total underwater volume is 30,000/1.025 ≈ 0.975*30,000 before and after the flooding.

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Rawson. 6 steps. Lost Buoyancy

- In Step 6, the heeling moment is caused by a loss of buoyancy. It is equal to lost volume * CoB of lost volume with respect to the CF. The damaged CF is at port 0.29 m (See Step 2). The CoB of the lost volume is at 12 m starboard. Therefore, the lever arm is 12.29 m.
- The longitudinal distance between the lost CoB and the damaged CF = lost CoB – (Original CF + change in CF) = 68.5 – (1 – 1.55) m. Note that change in CF is negative as it moves aft. This is used in Step 6.

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Attitude and Damaged Stability

- Recall that the attitude of a ship is fully defined when the draft amidship and the angles of heel and trim are known.
- These 3 have been found approximately for the flooded ship but the new CoB has not been found.
- The Damaged Stability curves are to be computed.
  - The damaged initial righting moment is found in Step 6

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5.8 Flooding of a side compartment forward of CoF. General case.

- Read Rawson. 5th Ed.
- When a compartment is flooded, the waterplane area changes. It has a new Center of Floatation. The Principal Axes are, in general, not along the centerline of the ship and perpendicular to the centerline. They are to be found.

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Watertight Deck. Reserve Buoyancy

- Tupper 4th Ed. pp 121
- In any analysis, pay special attention to the assumptions. The results, in general, are not valid when the assumptions are not valid.
- Tupper. The watertight deck is above the original and damaged waterplanes.

In the description of both methods it is assumed that the compartment that has been breached extends above the original and the final waterlines. If it does not then the actual floodable volumes must be used, and the assumed waterplane characteristics amended accordingly. It will be clear that it is highly desirable for the ship to have reasonable amounts of potential buoyancy above the intact waterplane as a 'reserve'. This is termed *reserve of buoyancy*.

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Watertight Deck

- Rawson and Tupper. 5th Ed. pp 149

Often, a watertight deck will limit flooding of a compartment below the level of the new waterline. But for a possible free surface effect due to entrapped air, the compartment may be considered pressed full and its volume calculated. In this case, the new waterline, heel and trim are best calculated by regarding the flooding as a known added weight whose effects are computed by the methods described in Chapters 3 and 4.

- This means that even though the compartment is assumed to be fully flooded, the free-surface effect is to be considered as air may be entrapped
- Example. Double bottom

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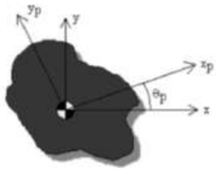
Principal Axes and Principal Moments of Inertia: The principal axes are those for which the product of inertia is zero. For any arbitrary shape there exists a set of axes which result in zero product of inertia. The orientation of principal axes with respect to the centroidal coordinates x and y can be obtained using



$$\boxed{\theta_p = \frac{1}{2}\tan^{-1}\left[\frac{2I_{xy}}{I_y - I_x}\right]} \qquad (10)$$

where I_x, I_y, and I_{xy} represent the moments of inertia about the x-axis, moment of inertia about the y-axis, and the product of inertia with respect to x and y axes, respectively. The angle θ_p is measured positive counter clockwise from the centroidal x-axis.

Based on the above definition, if either x or y is an axis of symmetry, then they both are considered as principal axes as I_{xy} and hence θ_p would be zero in that case.

The moments of inertia about the principal axes are expressed as

$$\boxed{I_{x_p} = I_x \cos^2\theta_p + I_y \sin^2\theta_p - I_{xy}\sin 2\theta_p} \qquad (11)$$

$$\boxed{I_{y_p} = I_x \sin^2\theta_p + I_y \cos^2\theta_p + I_{xy}\sin 2\theta_p} \qquad (12)$$

Key Observations:

A key factor to remember is that the sum of moments of inertia about any two perpendicular axes in the plane of the area is constant. This implies the following:

$$I_x + I_y = I_{x_p} + I_{y_p} = \text{constant}$$

Another important fact to remember is that between I_{xp} and I_{yp} one represents the minimum while the other represents the maximum moment of inertia for the shape considered. This fact is crucial in design of beams for minimum deflection. If the load on a beam is applied perpendicular to the cross-sectional axis with the largest moment of inertia, then the resulting deflection is the minimum for that shape and size beam.

- https://www.ae.msstate.edu/vlsm/shape/area_moments_of_inertia/papmi.htm
- See next slide for the use of Principal Axes

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The principal axes of the waterplane, as well as moving parallel to their original positions, also rotate. The effects of this rotation are not great until a substantial portion of the waterplane has been destroyed.

This approach to the flotation calculations is satisfactory for trim which does not intersect keel or deck and for heel up to about 10 degrees. Thereafter, it is necessary to adopt a trial and error approach and to calculate the vertical, athwartships and longitudinal shifts of the centre of buoyancy for several trial angles of waterplanes. That angle of waterplane which results in the new centre of buoyancy being perpendicularly under the centre of gravity is the correct one. This is illustrated for the transverse plane in Fig. 5.6, in which the transfer

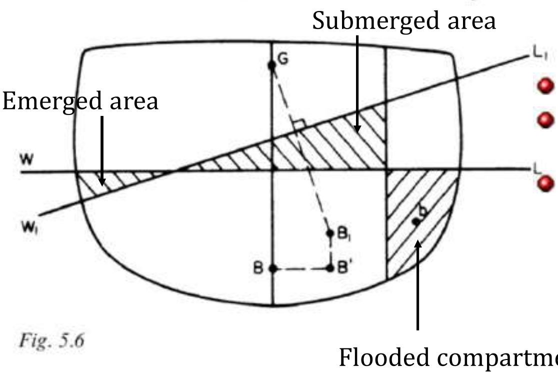

Fig. 5.6

- **Rawson**
- **6 step approach is ok for upto 10 deg heel angle**
- **For higher angles, use trial and error or successive approximation method to find the attitude of the ship**

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Rawson. Very large angles of heel.
Trial and Error method.

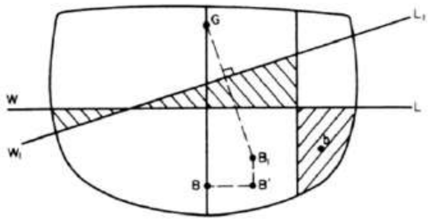

Fig. 5.6

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of buoyancy from b to the two wedges (one negative) results in a move of the centre of buoyancy of the whole from B to B_1. $\overline{B_1G}$ must be perpendicular to W_1L_1. To ensure that the displacement is unaltered, several waterlines parallel to W_1L_1 will be necessary at each angle as described presently under 'Damaged Stability Calculations', Fig. 5.8.

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Semyonov. Method of Successive Approximations

- Read Semyonov pp 321-331. Damaged Stability
- This method is to be used when the ship is not wall-sided
- In modern computer programs the method of successive approximations is used. So you should understand this well.
- The next few slides are for self-study by students. It is not a part of Module V.

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Semyonov. Method of Successive Approximations

72. FLOODING CALCULATION BY THE METHOD OF SUCCESSIVE APPROXIMATIONS Students should read Semyonov

The methods of calculation of flooding developed in Sections 66 through 70 are approximate, as has already been noted, since in the derivation of computing formulas we have assumed that the sides of the ship are straight and that it is permissible to use the metacentric formulas. If the changes in position and stability of the ship due to flooding are small, these assumptions do not entail serious errors in calculations. This obviously happens if the flooded compartment is small, i.e., the quantity of water admitted to the ship is not great.

In practice when compartments and especially when groups of compartments are flooded the quantity of admitted water is often great. In this case it is necessary to make use of a method of calculation providing more accurate results. Among the known methods of more accurately calculating the position and stability of the ship consequent upon the unsymmetrical flooding of a compartment a consideration must be given to the method of successive approximations since it can give the final result with any degree of accuracy depending on the number of approximations.

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Semyonov. Method of Successive Approximations

In Sec. 34 the method of successive approximations has been developed with reference to the calculation of the position and stability of the ship consequent upon the addition of a large weight. We shall apply this method to the calculation of the position and stability of the ship consequent upon the flooding of a large compartment with free communication with the sea. To reduce the number of approximations necessary for obtaining the desired accuracy in the final result the calculation of the first approximation should be effected in such a manner as to increase, as far as possible, its accuracy. To do this it is necessary to eliminate, in part at least, the sources of errors which make the calculation of the first approximation inaccurate. One of these sources is the assumption that the sides of the ship are straight which is used in the calculation of the change in mean draught. Hence for the determination of the change in mean draught δT we use the displacement curve as follows.

In addition to the ordinary displacement curve of the ship we plot the "displacement curve" of the flooded compartment for the upright position of the ship, i.e., a curve of quantity of water admitted to a compartment in relation to water level in it reckoning from the base plane. Next we plot on the displacement curve of the ship $D(T)$ a horizontal line corresponding to the original draught T and a vertical line corresponding to the

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original displacement D (Fig. 120). From this vertical we plot the displacement curve of the compartment $p(z)$ to the scale adopted for draught T and displacement D. We treat the water admitted to the compartment as an added weight. Then to the intersection of the two displacement curves $D(T)$ and $p(z)$ there correspond the following equalities

$$D+p_1=D_1;$$
$$T_1=z_1,$$

where D_1 is the displacement of the ship after flooding the compartment which corresponds to the draught T_1, p_1 is the weight of water admitted to the compartment which corresponds to the depth of the water z_1.

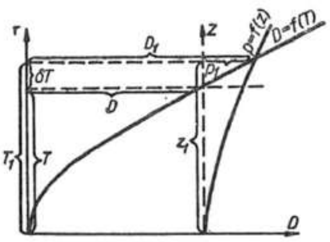

Fig. 120

Thus we find the change in mean draught to a first approximation

$$\delta T=T_1-T.$$

To determine the angles of heel and trim to a first approximation we make use of the formulas derived in Sec. 67. We choose that group of formulas

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Semyonov. Method of Successive Approximations

Fig. 120

We choose that group of formulas which takes account of the mutual effect of heel and trim. We write these formulas in the form

$$\tan\psi=\frac{p\left[x_p-x_f+(x_s-x_f)\frac{s}{S-s}\right]}{\gamma(I_{f_2}-Va_1)}[(k_\theta-1)k+1]; \quad (72.1)$$

$$\tan\theta=\frac{p\left(y_p+y_s\frac{s}{S-s}\right)}{\gamma(I_{x_2}-Va_1)}\left(\frac{k_\psi-1}{k}+1\right). \quad (72.2)$$

In these formulas

$$\left.\begin{array}{ll} k_\theta=1+\dfrac{sy_s^2}{Vh_2}k_T; & k_\psi=1+\dfrac{s(x_s-x_f)^2}{VH_2}k_T; \\ k_T=1+\dfrac{s}{S-s}; & k=\dfrac{\dfrac{y_p}{y_s}+(k_T-1)}{\dfrac{x_p-x_f}{x_s-x_f}+(k_T-1)} \end{array}\right\} \quad (72.3)$$

$$\left.\begin{array}{l} I_{f_2}=I_f-i_y-s(x_s-x_f)^2k_Tk_\theta \\ I_{x_2}=I_x-i_x-sy_s^2k_Tk_\psi \end{array}\right\} \quad (72.4)$$

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Semyonov. Method of Successive Approximations

and further

$$VH_2 = I_{f_1} - Va_1; \quad Vh_2 = I_{x_1} - Va_1, \tag{72.5}$$

where

$$I_{f_1} = I_f - i_y - s(x_s - x_f)^2 k_T; \qquad I_{x_1} = I_x - i_x - sy_s^2 k_T, \tag{72.6}$$

$$a_1 = a - \frac{p}{D}\left(T + \frac{\delta T}{2} - z_p\right). \tag{72.7}$$

To increase the accuracy of the calculation of the first approximation it is permissible to take the elements of the upright waterline S, x_f, I_x, I_f, s, x_s, y_s, i_x and i_y in all the foregoing formulas as the values of the same elements of waterlines corresponding to the draught T_1.

The changes in draught forward and aft are calculated by the formulas

$$\delta T_f = \delta T + \tan\psi\left(\frac{L}{2} - x_{f_1}\right); \qquad \delta T_a = \delta T - \tan\psi\left(\frac{L}{2} + x_{f_1}\right), \tag{72.8}$$

where

$$x_{f_1} = x_s - (x_s - x_f)\, k_T. \tag{72.9}$$

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Semyonov. Method of Successive Approximations

Thus we have the improved formulas for the calculation of insubmersibility to a first approximation. If the results furnished by them are not sufficiently accurate, it is necessary to make the calculation to a second approximation.

To begin with we write the parameters of the waterline of the first approximation. By the use of formulas (72.1) and (72.2) we can calculate two parameters ψ and θ and for the third parameter we can write

$$T_{\text{II}} = T_1 - x_{f_1}\tan\psi - y_{f_1}\tan\theta. \tag{72.10}$$

Here x_{f_1} is given by formula (72.9) and for y_{f_1} we have the expression

$$y_{f_1} = -y_s\frac{s}{S-s}. \tag{72.11}$$

For the calculation of the second approximation it is necessary to have the integral curves of ω, b and c for the flooded compartment. Since the calculation of the second approximation is required in the case of large quantities of water admitted to the ship's hull a reference to the flooded compartment implies in the present case a compartment equivalent to the flooded group of compartments. The curves of ω, b and c for such a compartment can be

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Semyonov. Method of Successive Approximations

calculated and plotted for a series of equidistant cross-sections in the same way as they are plotted for a ship. The number of cross-sections must be reduced to the minimum and in many cases the consideration may be restricted to just the middle cross-section. If the compartment is unsymmetrical with respect to the diametral plane and is wholly situated to one side thereof, it is necessary to plot only one branch of the curves of ω, b and c in relation to the trace of the diametral plane. If, however, the unsymmetrical compartment is situated on both sides thereof, it is necessary to plot both branches of the curves of ω, b and c in relation to the diametral plane. If the compartment is symmetrical with respect to the diametral plane, it is sufficient to plot only the curves of ω and c as there is no heel in this case. The curves of ω, b and c need not be plotted for the flooded compartment if it has such outlines that its elements may be calculated with sufficient accuracy by replacing the true lines by the lines of elementary geometrical bodies.

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When the lines of the cross-sections of the compartment and the curves of ω, b and c for them are available it is possible for the first approximation to plot the displacement curve of the compartment and to calculate the weight p of the admitted water to the original waterline as well as the co-ordinates of the centre of gravity x_p, y_p and z_p. For the second approximation it is possible to determine p_1, x_{p_1}, y_{p_1} and z_{p_1} by the use of the same curves reckoning to the waterline of the first approximation which is defined by the parameters $T_{\text{ж}}$, ψ and θ. The necessary plottings and calculations should be carried out in accordance with the formulas of Sec. 14 by using for the determination of the elements of the flooded compartment the formulas derived for the immersed portion of the ship.

For the calculation of the second approximation it is necessary to evaluate for the flooded compartment from the appropriate ordinates y the projection of the lost area s of the waterplane on the plane XOY, the co-ordinates of its centroid x_s and y_s and the moments of inertia i_x and i_y of this area about centroidal axes parallel to the planes XOZ and YOZ.

After the elements of the flooded compartment to the waterline of the first approximation have been calculated, it is necessary to determine the elements of the ship for the same waterline. The displacement of the ship V_1 and the co-ordinates of the centre of buoyancy x_c', y_c' and z_c' can be calculated according to the formulas of Sec. 14 by using the integral curves plotted for the ship. In addition it is necessary to calculate the following elements of the projection of the area of the waterplane of the first approximation on the plane XOY:

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The co-ordinates of its centroid are expressed as

$$x_{f_1}=\frac{S'x'_f-s_1x_{s_1}}{S_1};\quad y_{f_1}=\frac{S'y'_f-s_1y_{s_1}}{S_1}. \tag{72.20}$$

The centroidal moments of inertia of the area S_1 about axes parallel to the planes XOZ and YOZ are represented by

$$\left.\begin{aligned} I_{fx}&=I_x-i_{x_1}-s_1y_{s_1}^2-S_1y_{f_1}^2\\ I_{fy}&=I_y-i_{y_1}-s_1x_{s_1}^2-S_1x_{f_1}^2\\ I_{fxy}&=I_{xy}-i_{xy_1}-s_1x_{s_1}y_{s_1}-S_1x_{f_1}y_{f_1} \end{aligned}\right\} \tag{72.21}$$

Determine the unbalanced force. If the waterline of the first approximation is not a waterline of equilibrium, then

$$\delta V=\frac{D}{\gamma}-V \tag{72.22}$$

is not zero, and in order to have the forces balanced it is necessary to sink the ship parallel to herself by the amount

$$\delta T=\frac{\delta V}{S_1}. \tag{72.23}$$

Because of this sinkage there are consequent alterations in the static moments of the displacement and we have

$$M'_{yz_1}=M_{yz_1}+\delta V x_{f_1}; \tag{72.24}$$

$$M'_{xz_1}=M_{xz_1}+\delta V y_{f_1}; \tag{72.25}$$

$$M'_{xy_1}=M_{xy_1}+\delta V\,(T_H+x_{f_1}\tan\psi+y_{f_1}\tan\theta). \tag{72.26}$$

By the use of formulas (34.23) and (34.24) it is now possible to calculate the corrections of the second approximation to the tangents of the angles of heel and trim. In the present case these formulas are written as

$$\frac{\delta\theta}{\cos^2\theta}=\frac{-M'_{xz_1}+\left(\frac{D}{\gamma}z_g-M'_{xy_1}\right)\tan\theta}{(1+\tan^2\theta)\,I_{fx}+\tan\theta\tan\psi I_{fxy}-\left(\frac{D}{\gamma}z_g-M'_{xy_1}\right)}; \tag{72.27}$$

$$\frac{\delta\psi}{\cos^2\psi}=\frac{\frac{D}{\gamma}x_g-M'_{yz_1}+\left(\frac{D}{\gamma}z_g-M'_{xy_1}\right)\tan\psi}{(1+\tan^2\psi)\,I_{fy}+\tan\theta\tan\psi I_{fxy}-\left(\frac{D}{\gamma}z_g-M'_{xy_1}\right)}. \tag{72.28}$$

The correction to the third parameter determining the position of the waterline is

$$\delta T_H=\frac{\delta V}{S_1}-x_{f_1}\frac{\delta\psi}{\cos^2\psi}-y_{f_1}\frac{\delta\theta}{\cos^2\theta}. \tag{72.29}$$

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The parameters of the waterline of the second approximation are

$$\tan\psi_1=\tan\psi+\frac{\delta\psi}{\cos^2\psi}; \tag{72.30}$$

$$\tan\theta_1=\tan\theta+\frac{\delta\theta}{\cos^2\theta}; \tag{72.31}$$

$$T_{H_1}=T_H+\delta T_H. \tag{72.32}$$

If the corrections to the parameters of the first approximation are found to be appreciable, it is necessary to make the calculation of the third approximation in the same order as the second. In practice two approximations usually suffice.

After the waterline of equilibrium has been determined with sufficient accuracy, it is necessary to assess the initial stability of the ship with the flooded compartment by the foregoing method of successive approximations. The problem is that of calculating the metacentric heights h and H for the waterline of equilibrium. It is necessary first to make use of formulas (21.33), (21.34) and (21.35) and to calculate the moments of inertia of the waterline of equilibrium I_{fx}, I_{fy} and I_{fxy}. It is then necessary to substitute in these formulas the values of I_{fx}, I_{fy} and I_{fxy} calculated by formulas (72.21) and the values of $\tan\psi_1$ and $\tan\theta_1$ calculated by formulas (72.30) and (72.31). Next it is necessary to calculate I_ξ and I_η by formulas (34.30) and (34.31) and the metacentric radii r_1 and R_1 by formulas (34.28) and (34.29). For the calculation of the height of the centre of gravity above the centre of buoyancy a_1 use should be made of formula (34.33) which is, in the present case, to be rewritten in the form

$$a_1=\left(z_g-\frac{\gamma M'_{xy_1}}{D}\right)\sqrt{1+\tan^2\psi_1+\tan^2\theta_1}. \tag{72.33}$$

Finally, the metacentric heights and the coefficients of stability are obtained by using formulas (34.34) and (34.35). If the flooding is symmetrical with respect to the diametral plane, it is sufficient to have the Bonjean scale for the calculation of flooding by the method of successive approximations.

For the calculation of flooding by the method of successive approximations see Appendix IV, Art. 2.

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Read books, magazines, and journals

and become outstanding Naval Architects

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28 Mar 2025

Stability of Ships

B. Tech. NA&SB. 2021-25. 20-215-0406
Department of Ship Technology
CUSAT, Kochi 682022
3 credits

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Stability of Ships. Course Content. Exam question paper will be based on this.

Course Content:

1. **Module I**
   Stability terms. Potential energy. Equilibrium. Weight displacement and Volume displacement; Change of density, FWA, DWA. Equi-volume inclinations, shift of CoB due to inclinations, CoB curve in lateral plane, (*initial*) metacentre, metacentric radius, metacentric height; metacentre at large angles of inclinations, pro-metacentre. CoG, righting moment and lever; Statical, metacentric, residuary, form and weight stabilities. Surface of flotation, curve of flotation. Derivation of BM = I / V.

2. **Module II**
   Initial (*transverse*) stability: GM_0, GZ at small angles of inclinations, Wall sided ships. Sinkage and stability due to addition, removal and shift (transverse and vertical) of weight, suspended weights and free surface of liquids; Inclining Experiment; stability while docking and grounding; Stiff/ Tender ship.

3. **Module III**
   Large angle (*transverse*) stability: Diagram of statical stability (GZ curve), characteristics of GZ curve, effect of form, shift of G and super structure on GZ curve, static equilibrium criteria, Methods of calculating GZ curve (Prohaska, Krylov and from ship form), Cross curves of stability.
   Dynamical stability, diagram of dynamical stability, dynamic stability criteria.
   Moments due to wind, shift of Cargo and passengers, turning and non-symmetric accumulation of ice.
   Intact stability rules, Heel/ Load test.
   Practical: Diagram of statical stability / Cross curves of stability (Krylov's method).

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Stability of Ships. Course Content

4. **Module IV**
Longitudinal Stability: Trim, longitudinal metacentre, longitudinal centre of flotation, moment to change trim, trimming moment, change of trim and drafts due to addition,

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removal and longitudinal shift of weight, trim and draft change due to change of density. Rules on draft and trim.

5. **Module V**
Damage stability: Bilging, Surface and volume permeability; Sinkage, heel, change of trim and drafts due to bilging of midship, side and end compartments.

Practical: Floodable length calculation and subdivision of ship. Stability in waves,

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Course Content

Completed

- Module 1. Stability Terms. 06 Lectures.
- Module 2. Initial (Transverse) Stability. 07 lectures.
- Module 3. Large Angle Transverse Stability. 07 lectures.
- Module 4. Longitudinal Stability. 03 Lectures

Today

- 5. Damaged Stability

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Module 5

- 5.1 What is damaged stability?
- 5.2 Bilging
- 5.3 Surface and volume permeability
- 5.4 Two methods for assessing damaged stability
- 5.5 Bilging of a midship compartment
- 5.6 Flooding of a side compartment at midship
- 5.7 Exact analysis of a barge with an off-center full-length flooded compartment
- 5.8 Flooding of a side compartment forward of CoF. General case.

Today

- 5.9 Floodable length curve
- 5.10 Damaged stability regulations

Later

- 5.11 Stability in waves

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IMO Statement on Subdivision

- https://www.imo.org/en/OurWork/Safety/Pages/ShipDesignAndStability-default.aspx
- “Ships shall be as efficiently subdivided as is possible having regard to the nature of the service for which they are intended. The degree of subdivision shall vary with the subdivision length of the ship and with the service, in such manner that the highest degree of subdivision corresponds with the ships of greatest subdivision length, primarily engaged in the carriage of passengers.”

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Biran. International Regulations

- Students should read this introduction

The need for international regulations governing the **subdivision** of the hull into watertight compartments became clear after the *Titanic* disaster, in April 1912. A meeting was convened in London leading to the adoption on 20 January 1914 of an **International Convention of the Safety of Life at Sea**. The convention is better known under its acronym, **SOLAS**. The first convention should have been applied in July 1915, but the First World War stopped the process. In 1929 a new conference was held in London. The adopted text entered into force in 1933. Technical developments made necessary a new conference; it was held in 1948. The next edition was the 1960 SOLAS Convention, organized this time by IMO (about IMO see Section 8.2). Several amendments were adopted in the following years. The 1974 SOLAS Convention was again held in London. Since then many important amendments were issued, some of them influenced by major marine disasters, such as those of the roll-on/roll-off passenger ferries *Herald of the Free Enterprise*, near Zeebrugge, in March 1987, and *Estonia*, on 28 September 1994. The latest major amendment has been the harmonization of the provisions on subdivision and damage stability for passenger and cargo ships based on the *probabilistic* method of determining damage stability. The new regulation has taken into account the results of the *Harder* research project (Harmonisation of Rules and Design Rational), a project undertaken by a consortium of European industrial, research, and academic institutions to study the probabilistic approach for assessing the ship's damage stability and to develop new criteria and indexes of subdivision based on probability of survival. At the moment of this publication SOLAS 1974 together with all its amendments is the convention in force (see SOLAS, 2009, and de Juana and Garcia, 2009). The provisions are meant for merchant ships and not for warships or ships transporting troops. However, in the last years a number of navies have cooperated with classification societies also in this direction. This implies problems some of which are discussed by Riola and Pérez (2009).

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Students should read these

- https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx
- https://www.imo.org/en/KnowledgeCentre/ConferencesMeetings/Pages/SOLAS.aspx
- https://www.google.co.in/books/edition/SOLAS_consolidated_text_of_the_Internati/YKGeyAEACAAJ?hl=en
- https://www.imo.org/en/KnowledgeCentre/ConferencesMeetings/Pages/Marpol.aspx

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5.8 SOLAS. RoRo Ships

- “Roll-on/roll-off ships are considered by the maritime profession … as the most unsafe ships in operation”
- Some of you may design a RoRo ship in the final year

Flooding and Damage Condition 261

SOLAS prescriptions cover many aspects of ship safety, among them fire protection, life boats and rafts, radars, radio equipment, and emergency lighting. What interests us in this book are the prescriptions referring to subdivision and damage stability. A detailed history of SOLAS activities can be found on a website organized by *Metal Safe Sign International Ltd*, http://www.mss-int.com, or in the IMO website, http:www.imo.org. A short history of damage regulations appears in Gilbert and Card (1990). A commented history of the SOLAS achievements can be read in Payne (1994). Because of the overwhelming importance of the

Roll-on/roll-off ships, shortly Ro/Ro, are particularly sensitive to damage. To enable easy loading and unloading of vehicles these vessels are provided with a deck space uninterrupted by bulkheads. Damage can easily cause deck flooding with consequences like $\overline{KG}$ increase, large free-surface effect and added weight. Little and Hutchinson (1995) quote, ‘Over the past 14 years, 44 RO/RO vessels have capsized.’ Pawlowski (1999) appreciates, ‘Roll-on/roll-off (RO/RO) ships are considered by the maritime profession … as the most unsafe ships in operation.’ Statistics on loss of life due to RO/RO disasters are simply frightening. For example, Ross et al. (1997) quote 193 casualties in the case on the *Herald of Free Enterprise*, 910 in the *Estonia* disaster. A few RoRo’s sank in one and a half minutes after an accident. No wonder that many studies have been dedicated to this type of vessel. As some of them refer to constructive measures, we think that their treatment belongs to books on Ship Design, not here. We cite, however, in this chapter, the papers whose contents are close to the subject of this chapter. Based on SOLAS 90 deterministic damage stability methodology, a requirement for damage stability was agreed for RoRo ships in 1993 among North West European nations to account for the risk of accumulation of water on deck. This requirement, known as the Stockholm Agreement, was discussed in the SOLAS Conference 1995. An upgraded version of this regulation is currently in force in Europe (see EC directive 2003/25/EC).

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5.8 Basic Definitions

The *bulkhead deck* is the uppermost weathertight deck to which transverse watertight bulkheads are carried.

The *margin line* is a line at least 76 mm below the upper surface of bulkhead deck at side.

The *floodable length* at any point in the length of a ship is the length, with that point as centre, which can be flooded without immersing any part of the margin line when the ship has no list.

After flooding of a prescribed number of compartments the ship shall not submerge beyond a line situated at least 76 mm (3 in.) below the bulkhead deck at side (for an exception to this requirement see the regulations of the German Navy, Section 11.6.5). The said line is called in English **margin line**, in four other languages

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maximum allowable submergence

- In earlier classes, the effect of flooding on the attitude of the ship was presented.
- Today, we consider the maximum allowable submergence of the damaged ship – at the design stage.

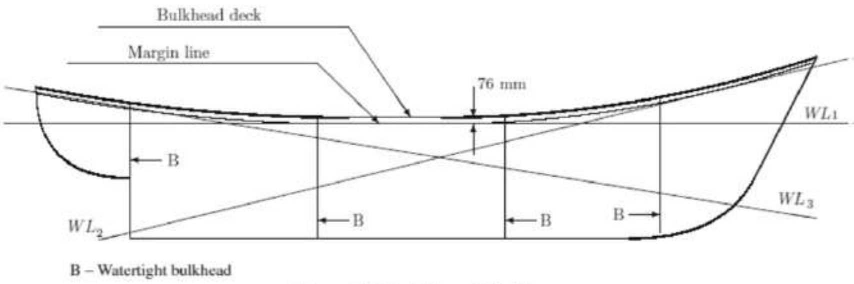

Figure 11.1 A few definitions

In Figure 11.1 we see the sketch of a ship subdivided by four bulkheads. The three waterlines WL_1, WL_2, and WL_3 are tangent to the margin line. They are examples of limit lines beyond which no further submergence of the damaged ship is admissible. If the bulkhead deck is not continuous, a continuous margin line can be assumed such as having no point at a distance less than 76 mm below the deck at side.

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Margin Line

- Note the angle at which the margin line is submerged

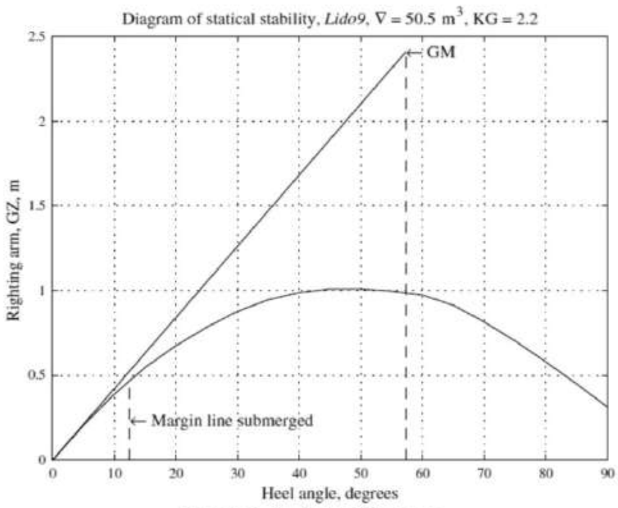

Figure 5.4 Statical-stability curve

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Damage Conditions Assessment

11.4 Damage Conditions Assessment

The survivability in damage condition can be assessed in different ways. In this section, we will review the three main approaches that have been considered in international regulations. In Section 11.6 we will outline their application.

11.4.1 Assessment of Floodable Length

11.4.2 Deterministic Assessment of Damaged Stability

11.4.3 Probabilistic Assessment of Floodable and Damaged Stability

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5.8 Floodable Lengths

11.4 Damage Conditions Assessment

The survivability in damage condition can be assessed in different ways. In this section, we will review the three main approaches that have been considered in international regulations. In Section 11.6 we will outline their application.

11.4.1 Assessment of Floodable Lengths

The survivability in damage condition is directly related to the main watertight subdivision below the bulkhead deck. As previously defined, the floodable length at a given point of the ship length is the maximum length, with the centre at that point, that can be flooded without submerging the ship beyond the margin line. A first approach to the assessment of the damage condition is to find the floodable length at a given point of the ship length, multiplied by a number called *factor of subdivision*. A factor of subdivision equal to 1 means that the margin line should not submerge if one compartment is submerged, while a factor of subdivision equal to 0.5 means that the margin line should not submerge when two adjacent compartments are flooded. This assessment had been included in the SOLAS provisions, but was finally superseded by the last 2009 amendments. This approach is still used for design purposes in order to identify any issues regarding the location of bulkheads before carrying on further and more complex calculations. The assessment is based on two assumptions:

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Assessment of Floodable Length

- The floodable length curve addresses only the buoyancy but not the stability after damage. New rules address stability.

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- The ship is subject to symmetrical flooding only as the hull is subdivided only by transverse bulkheads. This is a simplification as the ship subdivision is usually more complex and includes also longitudinal bulkheads that play a very important role in the flooding process.
- The method takes into consideration only floatability without checking the residual stability after damage. It may happen that for certain waterlines tangent to the margin line the residual stability is insufficient.

For the above considerations, SOLAS added an additional requirement regarding the deterministic assessment of damage stability, on top of the floodable-length requirement. As shown in Section 11.6.5, the German BV 1030-1 regulations include requirements for the stability in damage conditions, as their older versions also did.

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11.4.2 Deterministic Assessment of Damage Stability

11.4.2 Deterministic Assessment of Damage Stability

The actual ship compartimentation and all possible damage scenarios should be taken into account. The *standard damage dimensions* are defined by a damage length, a vertical extent and a penetration (the transverse extension from the shell inwards). These dimensions depend on the respective application. For example, the Offshore Supply Vessel Code specifies a penetration of 760 mm as the damage of this kind of vessel in an offshore scenario and low speeds is very limited. Passenger ships, however, are more likely to suffer damage with larger penetrations. Therefore, the old SOLAS 90 requirements specified a penetration equal to $B/5$, while the new SOLAS provisions changed the value to $B/10$. The US, UK, and German Navy regulations consider penetrations up to the centreline plane, that is $B/2$, as warships are likely to sustain major damages in their mission. Minor damage that may be more onerous should also be considered. The location of damage may be anywhere along the ship length, including positions between transverse bulkheads.

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11.4.2 Deterministic Assessment of Damage Stability

The applicable residual stability criteria consist of a set of requirements on the $\overline{GZ}$-curve, such as to heel angle, range of positive $\overline{GZ}$-values, or maximum $\overline{GZ}$, but may also consider other properties like margin line immersion. The criteria depend on the application. For example, a heel angle of 25° after damage may be acceptable for a cargo vessel with professional crew aboard that is able to evacuate the vessel if need arises. For passenger vessels, however, the criteria may limit the heel angle to 7°. On the other hand, for warships there may be limitations that allow the use of damage control equipment such as watertight doors or pumps. The deterministic approach to damage stability is meant to ensure minimum safety in all foreseen scenarios. The approach should also provide the ship Master with information on the damage scenarios the ship can survive. This approach is considered very reliable and is used in many regulations and design standards, as exemplified later in this chapter. On the other hand, if two ships comply with the deterministic approach, we would not be able to know which is the safest one. Therefore, the deterministic approach does not provide a measure of ship safety against capsize.

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11.4.3 The Probabilistic Assessment of Flooding and Damage Stability

The probabilistic approach uses the concept of probability of survival after damage as a measure of ship safety in damage condition. This probability is referred to by SOLAS as the **attained subdivision index A**. The philosophy behind the probabilistic approach is that *two different ships with the same attained index are of equal safety*. Therefore, this attained index should be based on all possible damage scenarios. An **attained subdivision index** shall be calculated as

$$A = \Sigma p_i s_i$$

where p_i represents the probability that the ith compartment or group of compartments may be flooded, and s_i is the probability of survival after flooding the ith compartment or group of compartments. The attained subdivision index, A, should not be less than the required subdivision index, R. This attained index usually depends on the ship length and the number of passengers.

Early details of the standard for subdivision and damage stability of dry cargo ships are given by Gilbert and Card (1990). A critical discussion of the IMO 1992 probabilistic damage criteria for dry cargo ships appears in Sonnenschein and Yang (1993). The probabilistic SOLAS regulations are discussed in some detail by Watson (1998) who also exemplifies them numerically. Ravn et al. (2002) exemplify the application of the rules to Ro-Ro vessels.

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Curve of Floodable Length

11.7 The Calculation of the Curve of Floodable Lengths

Today computer programmes receive as input the descriptions of the hull surface and of the internal subdivision. In the simplest form, the input can consist of offsets, bulkhead positions and compartment permeabilities. Then, it is possible to check in a few seconds what happens when certain compartment combinations are flooded. If the results do not meet the criteria relevant to the project, we can change the positions of bulkheads and run flooding and damage stability calculations for the newly defined subdivision. Before the advent of digital computers the above procedure took a lot of time; therefore, it could not be repeated many times. Just to give an idea, manual flooding calculations for one compartment combination could take something like three hours. Usually, the calculations were not purely manual because most Naval Architects used slide rules, adding machines and planimeters. Still it was not possible to speed up much of the work. To improve efficiency, Naval Architects devised ingenious, very elegant methods; one of them produces the **curve of floodable lengths**. To explain it we refer to Figure 11.8. In the lower part of the figure we show a ship outline with four transverse bulkheads; above it we show a curve of floodable lengths and how to use it.

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Floodable Length

- The permeability is usually less than 100%. So, a large compartment can be flooded
- If the waterline should be tangent to the margin line even if two compartments are flooded, the floodable length of each compartment ≅ half the floodable length

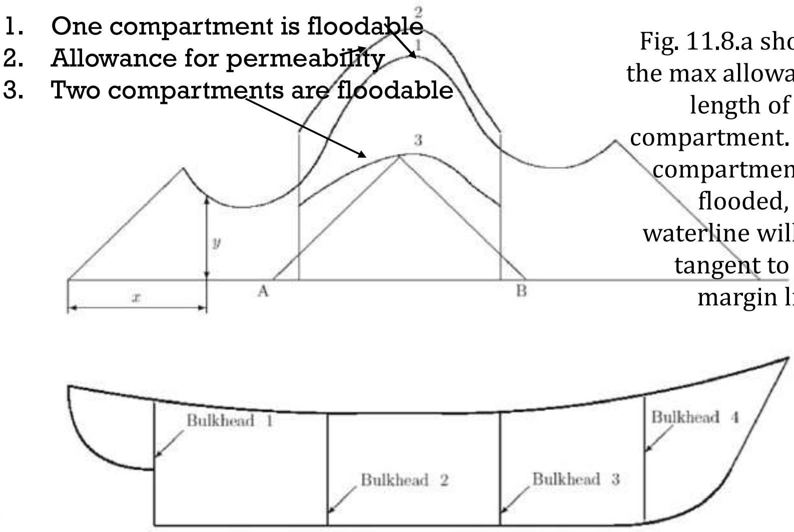

Figure 11.8 The curve of floodable lengths

Fig. 11.8.a shows the max allowable length of the compartment. If a compartment is flooded, the waterline will be tangent to the margin line.

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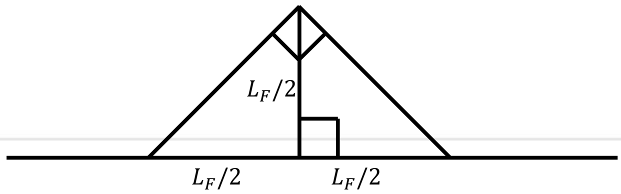
Boundaries of the floodable length compartment

- The x axis is drawn using 1:100 scale. The y axis is drawn using 1:200 scale.
- In effect, floodable length/2 is on the y axis. Example: if the local floodable length is 20 m, the y coordinate will be 10 cm.
- If 45 deg to the vertical lines are drawn, the left and right halves are both equal to floodable length/2, $L_F/2$.
- This geometric method to mark the limits of the compartment is easy. That is why the y axis scale (1:200) is half the x axis scale (1:100).



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Curve of Floodable Length

Let us consider a point situated a distance x from the aftermost point of the ship. Let us assume that we calculated the maximum length of the compartment having its centre at x and

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that will not submerge the margin line, and that length is L_F. In other words, if we consider a compartment that extends from $x - L_F/2$ to $x + L_F/2$, this is the longest compartment with centre at x that when flooded will not submerge the ship beyond the margin line.

Now, we plot a point with the given x-coordinate and the y-coordinate equal to L_F measured at half the scale used for x values. For example, if the ship outline is drawn at the scale 1:100, we plot y values at the scale 1:200. There were Naval Architects that used the same scale for both coordinates; however, the reader will discover that there is an advantage in the procedure preferred by us. Plotting in this way all $[x, L_F]$ pairs, we obtain the curve marked 1; this is the curve of floodable lengths.

As explained in Section 11.4.1, following the old SOLAS regulations the *maximum permissible length* of a compartment having its centre at a given point of the ship length is obtained as the floodable length multiplied by the factor of subdivision.

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Curve of Floodable Length

Now, let us check if the middle compartment meets the submergence-to-the-margin-line requirement. Counting from aft forward, we talk about the compartment limited by the second and the third bulkhead. Let us assume that this is a machinery compartment with permeability $\mu = 0.85$. Therefore, within the limits of this compartment we can increase the floodable lengths by dividing them by 0.85. The resulting curve is marked 2. Let us further assume that we are dealing with a ship subject to a "two-compartment" standard (factor of subdivision $F = 0.5$). Then, we divide by 2 the ordinates of the curve 2, obtaining the curve marked 3. This is the curve of permissible lengths. On the curve 3 we find the point corresponding to the centre of the machinery compartment and draw from it two lines at 45° degrees with the horizontal. The two lines intercept the baseline at A and B. Both A and B are outside the bulkheads that limit the machinery compartment. We conclude that the length of this compartment meets the submergence criterion. Indeed, as the y-coordinate of the curve of floodable lengths is equal to half the length L_F, we obtain on the horizontal axis a length $\overline{AB} = L_F/(\mu F)$, that is the permissible length. It is larger than the length of the compartment. To draw the lines at 45° we can use commercially available set squares (triangles). If we plot both x and y values at the same scale we must draw check lines at an angle equal to arctan 2; there are no set squares for this angle.

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Characteristics of the Floodable Length Curve

In Figure 11.8 we can identify the properties common to all curves of floodable lengths and give more insight into the flooding process.

1. At the extremities the curve turns into straight-line segments inclined 45° with respect to the horizontal. Let us choose any point of the curve in that region. Drawing from it lines at 45°, that is descending along the first or the last curve segment, we reach the extremities of the ship. These are indeed the limits of the floodable compartments at the ship extremities because there is no vessel beyond them.
2. The straight lines at the ship extremities rise up to local maxima. Then the curve descends until it reaches local minima. Usually the ship breadth decreases toward the ship extremities and frequently the keel line turns up. Thus, compartment volumes per unit length decrease toward the extremities. Therefore, floodable lengths in that region can be larger and this causes the local maxima.
3. As we go toward the midship the compartment volumes per unit length increase, while still being remote from the midship. Flooding of such compartments can submerge the margin line by trimming the vessel. Therefore, they must be kept short and this explains the local minima.
4. The curve has an absolute maximum close to the midship. Flooding in that region does not cause appreciable trim; therefore, floodable lengths can be larger.

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Home Work

- One compartment in a ship with port-starboard symmetry but no forward-aft symmetry is flooded. The ship remains upright and does not heel or trim. What can you say about the flooded compartment?
- A cuboidal barge has L, B, T, D. Find the floodable length at amidships.
- A cuboidal barge has L, B, T, D. There are only transverse bulkheads. The length of the midship compartment is equal to the floodable length. Then, a longitudinal bulkhead is added at the centerline. The starboard side compartment at midship is flooded. Find the attitude of the barge. Will the margin line be submerged?

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The Flooding Process

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Free-Surface

Recall

- Heeling moment ≅ Mass of liquid in the tank × transverse distance its CoG has moved
- Transverse distance CoG of entire liquid in tank has moved = $B^2 \tan\phi/(12T) = \overline{b_0 m_0} \tan\phi$
- $\overline{b_0 m_0} = i_B/v$. See the next slide for notation.

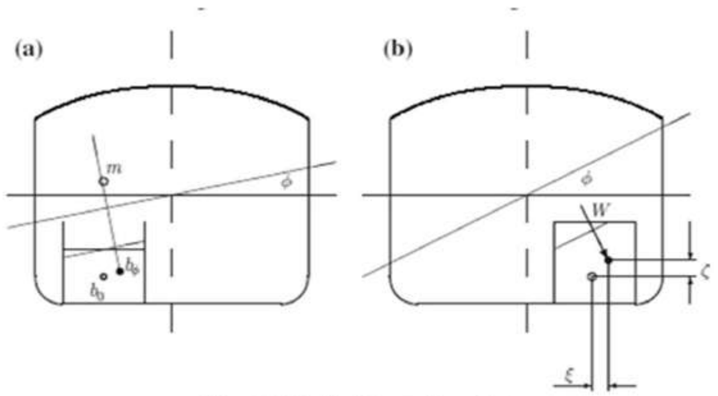

Figure 6.12 The free-surface effect

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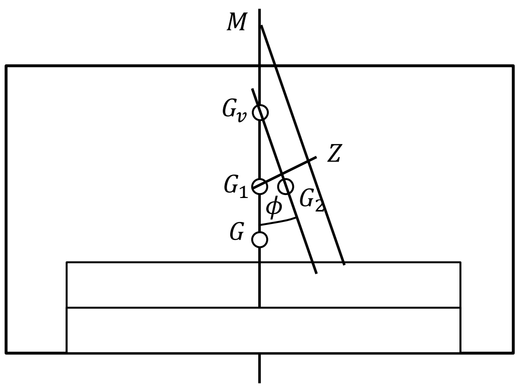
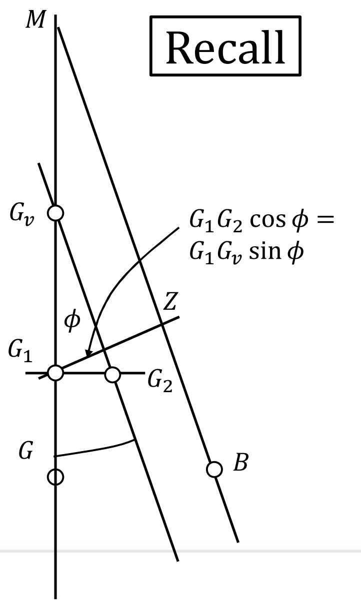
G_v = Effective or virtual CoG because of the free surface effect





- G = Original CoG
- G_1 = CoG after half the tank is emptied w/o considering the free surface effect
- G_2 = CoG after the ship heels
- G_v = Effective or virtual CoG because of the free surface effect

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liquid density, the heeling moment produced by the inclination of the liquid surface is

$$M_l = \rho v \frac{i_B}{v} \tan\phi = \rho i_B \tan\phi$$

where M_l has the dimensions of mass times length

As a result, the ship centre of gravity moves transversely a distance equal to

$$\overline{GG_1} = \frac{\rho \cdot i_B}{\Delta} \tan\phi \qquad (6.35)$$

By comparison with the preceding subsection we conclude that the **effective metacentric height** is

$$\overline{GM_{eff}} = \overline{GM} - \frac{\rho \cdot i_B}{\Delta} \qquad (6.36)$$

See L12S22

and the **effective righting arm**,

$$\overline{GZ_{eff}} = \overline{GZ} - \boxed{\frac{\rho \cdot i_B}{\Delta} \sin\phi} \qquad (6.37)$$

$= \overline{GG_1} \cos\phi$

Instead of considering the free-surface effect as a virtual reduction of the metacentric height and of the righting lever, we can take it into account as the heeling lever of free movable liquids. Its value is

$$\ell_F = \frac{\rho \cdot i_B}{\Delta} \qquad (6.38)$$

Recall

Free surface effect can be thought of as reduction in GM, reduction in righting lever, or a heeling lever

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Free-Surface

Recall

- "Effect does not depend on the position of the tank" because only the change in the CoG is important.

and the respective curve is proportional to $\sin\phi$. The latter approach is that adopted in the stability regulations of the German Navy.

The reduction of stability caused by the liquids in slack tanks is known as **free-surface effect**. Two of its features must be emphasized:

- the mass of the liquid plays no role, only the moment of inertia of the free surface appears in equations;
- the effect does not depend on the position of the tank.

In general, ships have more than one tank, and different tanks can contain different liquids. The destabilizing effects of all tanks must be summed up when calculating the effective metacentric height

$$\overline{GM_{eff}} = \overline{GM} - \frac{\sum_{k=1}^{n} \rho_k \cdot i_{Bk}}{\Delta} \qquad (6.39)$$

and the effective righting arm,

$$\overline{GZ_{eff}} = \overline{GZ} - \frac{\sum_{k=1}^{n} \rho_k \cdot i_{Bk}}{\Delta} \sin\phi \qquad (6.40)$$

where n is the total number of tanks.

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Details of the Flooding Process

11.5 Details of the Flooding Process

The free surface in a compartment open to the sea behaves differently than that in an intact tank. In Figure 11.5a $W_I L_I$ is the waterline in upright position, $W_\phi L_\phi$ the waterline in a heeled position. We assume that the water level in the side tank is the same as the external water level. In the heeled position the water surface in the tank changes to FS, a line parallel to $W_\phi L_\phi$. The volume of water in the tank remains constant. In Figure 11.5b the side tank is damaged and in open communication with the sea. If the waterline in the heeled position is $W_\phi L_\phi$, this is also the water level in the damaged tank. The water volume is no longer constant, but varies with the heel angle. For the case shown in the figure, the volume increases by the slice comprised between the lines $W_\phi L_\phi$ and FS. This change of volume must be taken into account in the added-weight method.

Figure 11.5b shows a case of **unsymmetrical flooding**. This kind of flooding can easily submerge the deck. The consequences may be a drastic reduction of stability and the submergence of openings such as vents. Therefore, care must be exercised when placing longitudinal bulkheads. Sometimes, to compensate unsymmetrical flooding it is necessary to open a connection between the damaged tank and a tank situated symmetrically on the other

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Cross Flooding

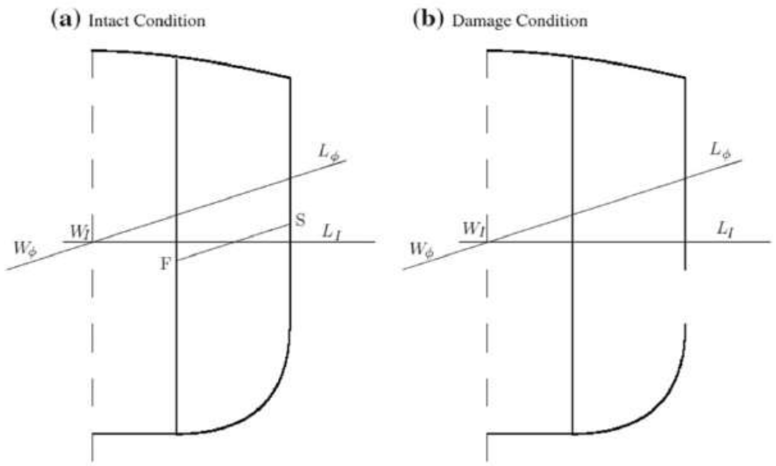

Figure 11.5 Free surface in intact and in damaged tank

side of the ship. This action is called **cross-flooding**. The UK-Navy document SSP 24 warns against the potential danger presented by longitudinal bulkheads.

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Cross Flooding

Cross-flooding takes some time and can cause a slow change of the ship position. Söding (2002) lists other slow-flooding processes such as occurring 'through open or non-watertight doors, hatches with non-watertight or partly open hatch covers, through pipes, ventilation ducts ...' In his paper Söding describes the mathematics of such water flows. Air can be trapped above the flooding-water surface. If the top envelope of the compartment is airtight, flooding is stopped. If not, it is only slowed down. Between the position of intact condition and the final damage position (provided that an equilibrium position can be found) the vessel can pass through intermediate positions more dangerous than the final one. According to some regulations it is necessary to check if such positions exist and if the ship can survive them. For instance, SOLAS considers that there is no need to study intermediate stages of flooding when the final stage is reached in less than 60 s (instantaneous flooding). However, if the damaged area contains decks, inner bulkheads, or structural, non-watertight elements of sufficient tightness and strength to seriously restrict the flow of water, intermediate-stage flooding calculations should be performed. To apply the above approach in a uniform manner, IMO has developed a standard method for evaluating cross-flooding arrangements IMO (2007a). This methodology enables the calculation of the time required from commencement of cross-flooding to the final equilibrium position, and provides a guide for dimensioning pipes that do not delay cross-flooding.

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