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Dedicated to my mother, without whose patient and constant encouragement, this book would not have been possible.

Capt. R.D. Kohli 13th September 1981.
Extra Master,

Executive Director, Shipping Corporation of India Ltd.,

Chairman of the Council,
The Institution of Marine Technologists,

Master of the Company of Master Mariners of India,

President, Dufferin - Rajendra Old Cadets Association,

Vice Chairman, Narottam Morarjee Institute of Shipping.

FOREWORD

I have known Capt. Subramaniam for over ten years — a young enthusiastic mercantile marine officer with a dynamic personality, always giving the impression that he wants to accomplish more.

When he suddenly appeared at my office, I was surprised — a professor wanting to see me! After presenting me with a copy of his latest book 'Shipborne Radar' he said 'Sir, would you please write the foreword to my book on stability?' I was taken aback by this unusual request, more so when he went on to say that he had particularly decided, five years ago, to request me to write the foreword to his book on stability, even before he wrote the books on Navigation, Meteorology and Radar.

This set me thinking about my first voyage. I was a cadet fresh out of the training ship 'Dufferin' and the passage, trans-atlantic in winter. The ship rolled very heavily, often as much as 35°, creaking and moaning. Crashing sounds were frequently heard as various objects in the cabins broke loose, answering the call of gravity along the highly

SHIP STABILITY - I

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NUTSHELL SERIES
BOOK 4

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BY

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inclined plane. I thoroughly enjoyed myself in blissful ignorance of terms in stability such as stiff and tender ships, free surface effect, angle of vanishing stability and progressive flooding. I shudder to think what I would feel, if I was in the same circumstances today, realising the implications of such a situation.

Capt. Subramaniam has attempted, and I would say succeeded, in combining the theory and practical application of stability. The book closely follows the best approach. Starting from the very basics, or 'beginning at the very beginning,' the book brings the student steadily up to the required level in such a manner that he can study it by himself, whilst out at sea, hardly needing any other assistance.

I have specifically avoided indulging in paraphrasing about the biography of the author. He has by now become well established by his "Nutshell Series".

I understand that Capt. Subramaniam plans to include the more complex topics on this subject in his next book 'Ship Stability II' in the near future. I wish him all success.

(R.D. Kohli)

PREFACE

Like the earlier books in the Nutshell Series, this book is intended for study whilst out at sea.

Part I, this book, adequately covers the syllabuses for Second Mate (FG) and the recently proposed grade of WKO (Watch-Keeping Officer).

Part II, Nutshell Series Book 5, will contain additional topics. Master (FG) and First Mate (FG) will find that they require both the books to cover their syllabuses.

Marine Engineers also may find these two books useful.

(H. SUBRAMANIAM)

Bombay
13th September 1981.

CONTENTS

1

Density & Relative Density

Density of a substance is its mass per unit volume.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

where mass is in tonnes (t), volume is in cubic metres (m^3) and density is in tonnes per cubic metre (tm^{-3}).

Though mass may be expressed in kilogrammes (kg) and density in kilogrammes per cubic metre (kgm^{-3}), the use of tonnes is more convenient in stability. The density of fresh water is 1 tm^{-3}.

Relative density of a substance is the number of times the substance is heavier than fresh water. Being a ratio, RD has no units.

$$\text{RD} = \frac{\text{Mass of any volume of substance}}{\text{Mass of an equal volume of FW}}$$

Considering a volume of $1 m^3$,

$$\text{RD of substance} = \frac{\text{Density of substance}}{\text{Density of fresh water}}$$

Since the density of fresh water is 1 tm^{-3}, RD of a substance is numerically equal to its density, if density is expressed in tm^{-3}.

Some typical values are given below:

	Density	RD
Fresh water	1.0 tm^{-3}	1.0
Salt water	1.025 tm^{-3}	1.025
Fuel oil	0.95 tm^{-3}	0.95
Diesel oil	0.88 tm^{-3}	0.88
Dock water	1.015 tm^{-3}	1.015

Example 1

A tank has a volume of 400 m^3. Find how many tonnes of SW (density 1.025 tm^{-3}) it can hold.

Mass of SW $= \text{Volume} \times \text{density}$
$= 400 \times 1.025$
$= 410$ t

Answer: The tank can hold 410 t of SW.

Example 2

A tank can hold 320 tonnes of SW. Find how many tonnes of oil of RD 0.8 it can hold.

Mass of SW $= \text{Volume of SW} \times \text{density of SW}$
$320 = V \times 1.025$
$V = \frac{320}{1.025}$

Volume of tank $= \frac{320}{1.025}\ m^3$

Mass of oil $= \text{Volume of oil} \times \text{density of oil}$
$= \frac{320}{1.025} \times 0.8$

$= 249.8$ t

Answer: The tank can hold 249.8 tonnes of oil.

Example 3

A cylindrical tank is 10 metres high and has a radius of 3 metres. If it is filled to an ullage of 2 metres, with oil of RD 0.7, find the mass of oil.

Mass of oil $= \text{Volume of oil} \times \text{density of oil}$
$= (\frac{22}{7} \times 3 \times 3 \times 8)\ 0.7$
$= 158.4$ t

Answer : Mass of oil is 158.4 tonnes.

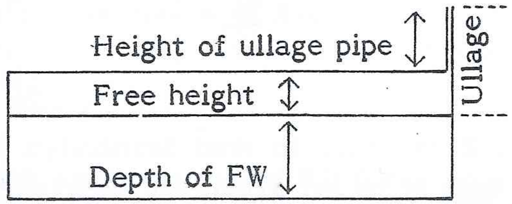
Example 4

A rectangular tank measuring 20 m x 10 m x 10 m has an ullage pipe extending to 0.5 m above the tank top. If the tank is 98% full of FW, find the mass of FW and state the ullage.

Volume of FW $= \frac{98}{100}(20 \times 10 \times 10)\ m^3$

Mass of FW $= \text{Volume of FW} \times \text{density of FW}$
$= \frac{98}{100}(20 \times 10 \times 10) \times 1$
$= 1960$ t.

Depth of FW $= \frac{98}{100} \times \text{depth of tank}$
$= \frac{98}{100} \times 10 = 9.8$ m



Free height inside tank = 10 — 9.8 = 0.2 m

Height of ullage pipe above tank top = 0.5 m

Ullage = 0.7 m

Answer : Mass of FW 1960 tonnes, ullage 0.7 metres.

Example 5

A rectangular tank is 20 m x 20 m x 12 m. Find how many tonnes of oil of RD 0.8 it can hold, if 2% of the volume of the tank is to be left for expansion. State also, the ullage on loading.

Volume of tank = 20 x 20 x 12 = 4800 m^3

Volume of tank = Volume of oil + Free space

$4800 = V + \left(\frac{2}{100} \times 4800\right)$

$4800 = V + 96$

$V = 4704\ m^3$

Mass of oil = Volume of oil x density of oil

= 4704 x 0.8

= 3763.2 t

Depth of oil $= \frac{98}{100} \times$ depth of tank

$= \frac{98}{100} \times 12 = 11.76$ m

Ullage = 12 — 11.76 = 0.24 m

Answer : Mass of oil = 3763.2 t, ullage = 0.24 m.

Example 6

In worked example 5, if it was required to leave 2% of the volume of oil loaded for expansion, find the mass of oil and the ullage on loading.

Volume of tank = Volume of oil + Free space

$4800 = V + \left(\frac{2}{100} \times V\right)$

$4800 = 1.02V$

$V = 4705.88\ m^3$

Mass of oil = Volume of oil x density of oil

= 4705.88 x 0.8

= 3764.7 t

Depth of oil $= \frac{\text{Volume of oil}}{\text{Area of tank surface}}$

$= \frac{4705.88}{20 \times 20} = 11.765$ m

Ullage = Depth of tank — depth of oil

= 12 — 11.765 = 0.235 m

Answer: Mass of oil 3764.7 t, ullage 0.235 m.

Exercise 1

Density and relative density

1. A rectangular tank measures 16 m x 15 m x 6 m. How many tonnes of oil of RD 0.78 can it hold?

2. A cylindrical tank of diameter 8 m is 10 m high. 400 t of oil of RD 0.9 is poured into it. Find the ullage, assuming π to be 3.1416.

3 A tank of 2400 m^3 volume and 12 m depth, has vertical sides and horizontal bottom. Find how many tonnes of oil of RD 0.7 it can hold, allowing 2% of the volume of the tank for expansion. State the ullage on loading.

4 A tank 10 m deep has vertical sides. Its bottom consists of a triangle measuring 12 m x 12 m x 10 m. Find the mass of oil (of RD 0.8) to be loaded, allowing 3% of the volume of oil loaded for expansion. State the ullage on completion of loading.

5 A rectangular tank measuring 25 m x 12 m x 8 m has an ullage pipe projecting 0.3 m above the tank top. Find the mass of SW in the tank when the ullage is 3.3 m.

6 A rectangular tank measures 30 m x 16 m x 14 m. It has an ullage pipe projecting .5 m above its top. Oil of RD 0.78 is to be loaded. The pipeline leading from the refinery to the ship is 10 km long and 40 cm in diameter. At the time of completion, all the oil in the pipeline has to be taken. Find at what ullage the valve at the refinery end must be shut so that the final ullage in the ship's tank would be 0.78 m. State also, the mass of oil loaded finally. (Assume π to be 3.1416).

7 A tank with a horizontal base and vertical sides is 10 m deep and has a rectangular trunkway 1 m high. The volume of the tank alone is 8000 m^3 and that of the trunkway 500 m^3. Find the ullage when 5320 t of vegetable oil of RD 0.7 is loaded.

8 A rectangular tank has a total depth of 21 m and a volume of 20 600 m^3, which includes a trunkway of depth 1 m and volume 600 m^3. Find the ullage when 16320 t of oil of RD 0.8

is loaded.

9 A rectangular tank has a total depth of 10.5 m and volume 8200 m^3, which includes a trunkway of depth 0.5 m and volume 200 m^3. Find the mass of oil of RD 0.8 loaded and the ullage, if 2% of the volume of the tank is left for expansion.

10 A rectangular tank has a total depth of 21 m and volume 10 250 m^3 which includes a trunkway of depth 1 m and volume 250 m^3. Oil of RD 0.9 is to be loaded so as to leave 3%, of the volume of oil loaded, for expansion. Find the mass of oil to be loaded and the final ullage.

2

WATER PRESSURE

Pressure is the load per unit area.

At any point in a liquid, pressure acts in all directions and is expressed in tonnes per square metre (tm^{-2}). It may, if desired, be expressed in kilo-Newtons per square metre ($kN\ m^{-2}$) where 1 tonne per square metre = 9.81 kilo-Newtons per square metre OR in bars where 1 bar = 10.2 tonnes per square metre.

At any point in a liquid,

$$\text{Pressure} = \text{depth} \times \text{density}$$
$$tm^{-2} = m \times tm^{-3}$$

Thrust is the total pressure exerted on a given surface. Thrust is expressed in tonnes (t) but may, if desired, be expressed in kilo-Newtons (kN) where 1 tonne = 9.81 kilo-Newtons.

$$\text{Thrust} = \text{pressure} \times \text{area}$$
$$t = tm^{-2} \times m^2$$

Example 1

Find the thrust on a keel plate 10 m x 2 m when the draft of the ship is 5 m in salt water.

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Pressure = depth x density
= 5 x 1.025
= 5.125 tm^{-2}

Thrust = pressure x area
= 5.125 x 10 x 2
= 102.5 t

Answer: Thrust on keel plate = 102.5 tonnes.

Example 2

A tank has a rectangular bulkhead 20 m wide and 10 m high. Find the thrust experienced by the bulkhead when the tank is full of oil of RD 0.9.

Note: For calculating the thrust on a vertical surface, the pressure is taken at the geometric centre of the immersed part of the surface and multiplied by the immersed area.

Pressure = depth x density
= 5 x 0.9
= 4.5 tm^{-2}

Thrust = pressure x area
= 4.5 x 20 x 10
= 900 t

Answer : Thrust on bulkhead = 900 tonnes.

Example 3

A lock gate is 30 m wide and 10 m high. The water inside the lock is 7 m deep and of RD 1.005 and that outside is 5 m deep and of RD 1.025. Find the resultant thrust and the direction in which it acts.

Considering the water inside,

Pressure	=	depth x density
	=	$\frac{7}{2}$ x 1.005
	=	3.5175 tm^{-2}
Thrust	=	pressure x area
	=	3.5175 x 30 x 7
	=	738.675 t

Considering the water outside

Pressure	=	depth x density
	=	$\frac{5}{2}$ x 1.025
	=	2.5625 tm^{-2}
Thrust	=	pressure x area
	=	2.5625 x 30 x 5
	=	384.375 t

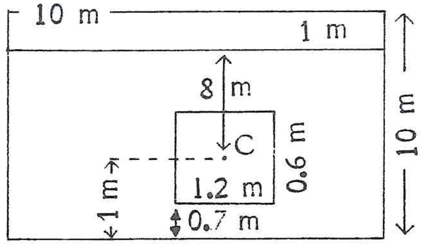
Thrust outwards	=	738.675 t
Thrust inwards	=	384.375 t

Answer : Resultant thrust = 354.3 t outwards.

Example 4

A deep tank 10 m wide and 10 m deep has a rectangular manhole (1.2 m x 0.6 m) at its forward

end. The longer sides of the manhole are horizontal and its lower edge is 0.7 m from the bottom of the tank. Find the total pressure experienced by the manhole cover when the tank is full of oil of RD 0.8 to an ullage of 1 m.

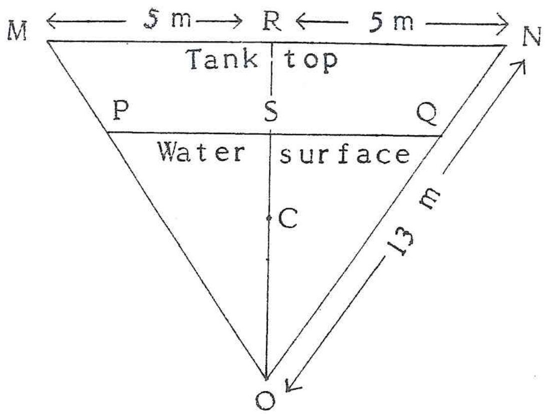


Depth of tank	=	10 m
Ullage	=	1 m
Depth of oil	=	9 m
Height of C above bottom	=	1 m
Depth of C below oil surface	=	8 m
Pressure at C	=	Depth x density
	=	8 x 0.8
	=	6.4 tm^{-2}
Thrust	=	Pressure x area
	=	6.4 x 1.2 x 0.6
	=	4.608 t

Answer : Total pressure on manhole = 4.608 tonnes.

Example 5

A collision bulkhead is in the form of a triangle 10 m x 13 m x 13 m. Find the thrust experienced by it when saltwater is run into the forepeak tank to a sounding of 9 m.



In triangle ORN,

$$OR^2 = ON^2 - RN^2$$
$$= 13^2 - 5^2$$
$$= 144$$
$$OR = 12 \text{ m}$$

Depth of tank $= 12$ m

Triangles OSQ and ORN are similar.

$$\frac{SQ}{RN} = \frac{OS}{OR} \quad \text{or} \quad SQ = \frac{5 \times 9}{12} = 3.75 \text{ m}$$

Area of triangle OPQ $= \frac{1}{2}$ (PQ . OS) $=$ SQ . OS

$= 3.75 \times 9$

$= 33.75 \text{ m}^2$

Area of immersed part of bulkhead $= 33.75 \text{ m}^2$

Depth of C below water line $= \frac{1}{3} \times 9 = 3$ m

Pressure at C = depth x density

= 3 x 1.025

= 3.075 tm^{-2}

Thrust = pressure x area

= 3.075 x 33.75

= 103.781 t

Answer : Thrust on bulkhead = 103.781 tonnes.

Example 6

A double bottom tank measures 20 m x 20 m x 1 m. Its air pipe extends 12 m above its top. Find the thrust on the tank top when it is pressed up with salt water.

Pressure at tank top = depth x density

= 12 x 1.025

= 12.3 tm^{-2}

Thrust on tank top = pressure x area

= 12.3 x 20 x 20

= 4920 t

Answer : Thrust on tank top = 4920 tonnes.

Exercise 2

Water pressure

1. Find the thrust experienced by a flat keel plate 10 m x 2 m when the draft is 8 m in SW.

2. A box-shaped vessel 150 m x 20 m x 12 m is floating in a dock of RD 1.010 at an even

keel draft of 10 m. Find the total water pressure experienced by the hull.

3 A submarine has a surface area of 650 m^2 and can withstand a total water pressure of 1332500 t. Find at what approximate depth in SW she would collapse.

4 A rectangular lock gate 40 m wide and 20 m high has water of RD 1.010 12 m deep on one side and water of RD 1.020 11 m deep on the other. Find the resultant thrust experienced and the direction in which it acts.

5 A rectangular lock gate 36 m wide and 20 m high has FW on one side to a depth of 16 m. Find what depth of SW on the other side will equalize the thrust.

6 A collision bulkhead is triangular in shape. Its maximum breadth is 12 m and its height 15 m. Find the thrust experienced by it if the forepeak tank is pressed up to a head of 3 m of SW.

7 A collision bulkhead is triangular shaped, having a breadth of 14 m at the tank top and a height of 12 m. As a result of a collision, the forepeak tank gets ruptured and SW enters the tank to a sounding of 9 m. Calculate the thrust on the bulkhead.

8 A tank has a triangular bulkhead, apex upwards. Its base is 14 m and its sides, 15 m each. It has a circular inspection hole of radius 0.5 m. The centre of the manhole is 0.8 m above the base and 1.6 from one corner. Find the thrust on the manhole cover when the tank contains oil of RD 0.95 to a sounding of 10 m. (Assume π to be 3.1416).

9 A rectangular deep tank is 22 m x 20 m x 10 m. Above the crown of the tank is a rectangular trunkway 0.2 m high, 5 m long and 4 m wide. Find the thrust on the tank lid when the tank is pressed up with SW to a head of 2.64 m above the crown of the tank.

10 A double bottom tank measures 25 m x 20 m x 2 m. Find the thrust on the tank top when pressed up to a head of 16 m of SW. Also find the resultant thrust on the tank bottom, and the direction that it acts, if the ship's draft in SW is 10 m.

3

FLOTATION

Archimedes' Principle states that when a body is wholly or partially immersed in a fluid, it suffers an apparent loss of weight which is equal to the weight of fluid displaced.

Since the word fluid includes both, liquids and gases, and the fact that merchant ships are only expected to be partially immersed in water, a modified version of Archimedes' Principle may be called the Principle of flotation.

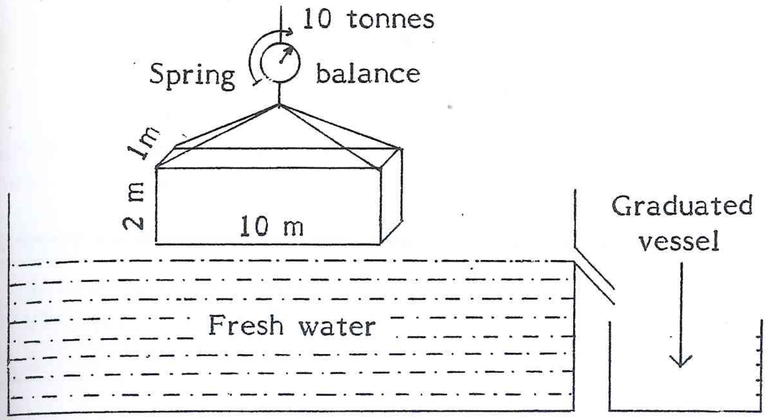
Principle of flotation: When a body is floating in a liquid, the weight of liquid displaced equals to the weight of the body.

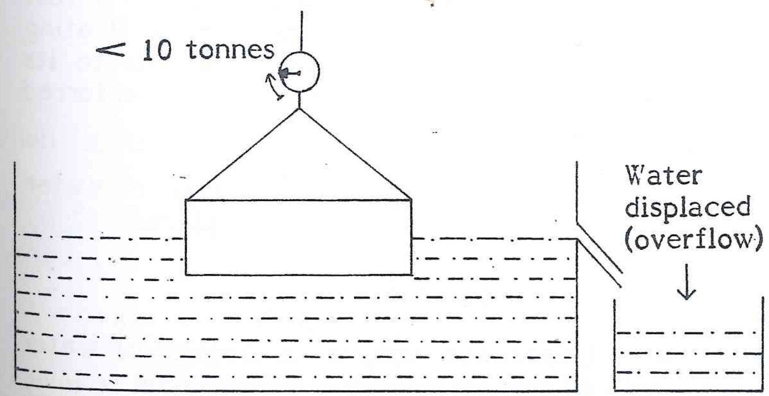
Experimental explanation

Consider a rectangular watertight box 10 m x 1 m x 2 m, weighing 10 t. If this was lifted by a crane and gradually lowered into a pool full of FW, the volume of water displaced can be collected and measured.

It will be noticed that as the box is lowered more and more into the water, the load registered by the spring balance becomes less and less. Consider the case when the draft becomes 0.1 m. The underwater volume of the box is then 1.0 m^3 i.e. the volume of water displaced (overflow) is 1.0 m^3. The weight of water displaced or displacement is 1 t. So the apparent loss of weight or buoyancy experienced

by the box is 1 t. The spring balance now shows a reading of only 9 t whereas it showed 10 t before the box reached the water surface. Similarly when the draft becomes 0.2 m, the displacement (or buoyancy) is 2 t and the load registered by the spring balance is 8 t.





The following would be the results, expressed as a table :

Draft	Volume of displacement	Displacement or buoyancy	Load registered by spring balance
0.00 m	0.0 m^3	0.0 t	10 t
0.05	0.5	0.5	9.5
0.1	1	1	9
0.2	2	2	8
0.4	4	4	6
0.6	6	6	4
0.8	8	8	2
1.0	10	10	0

At a draft of 1.0 m, it is noted that the spring balance registers zero indicating that the buoyancy equals to the weight so that the body is now floating freely.

From the foregoing it is clear that:

(i) The volume of water displaced is the underwater volume of the ship.

(ii) Buoyancy or displacement is the upward thrust experienced by the ship. When the ship is floating freely, its displacement (or buoyancy) equals to its weight. The weight of the ship is therefore referred to as displacement (W).

W = Volume of water displaced x Density of water displaced

OR

W = Underwater volume of ship x Density of water displaced

While doing stability calculations, density should preferrably be in tm^{-3}, volume in m^3 and displacement in t.

Example 1

A homogeneous rectangular log 6 m x 1 m x 0.8 m floats in SW at a draft of 0.5 m, with its largest face parallel to the water. Find its mass.

W = u/w volume x density of water displaced

W = 6 x 1 x 0.5 x 1.025 = 3.075 t

Since the log is floating freely, its displacement and mass are equal.

Answer : Mass of log = 3.075 tonnes.

Example 2

A homogeneous rectangular log 6 m x 1.5 m x 1 m has RD 0.7. Find its draft in FW. (Assume that the log will float with its largest face parallel to the water).

Mass of log = Volume x density

= 6 x 1.5 x 1 x 0.7

= 6.3 t

When floating freely, mass = displacement.

W = u/w volume x density of water displaced

6.3 = 6 x 1.5 x d x 1

d = 0.7 m

Answer : Draft in FW = 0.7 metres.

Example 3

A homogeneous log of 0.5 m square section has RD 0.8. Find its draft in water of RD 1.02, assuming that it will float with one face horizontal.

Let the length of the log be L metres.

Mass of log = Volume x density

= L x 0.5 x 0.5 x 0.8 tonnes

W = u/w volume x density of water displaced

W = L x B x d x 1.02

= L x 0.5 x d x 1.02 tonnes

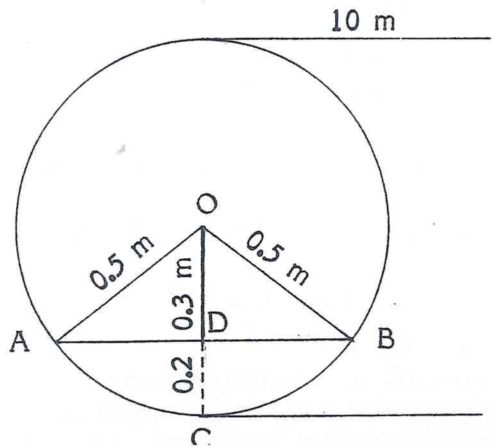
When floating freely, Displacement = Mass

L x 0.5 x d x 1.02 = L x 0.5 x 0.5 x 0.8

$$d = \frac{0.5 \times 0.8}{1.02} = 0.392 \text{ m}$$

Answer : Draft of log = 0.392 metres.

Figure for example 4



Example 4

A hollow, plastic cylinder of 1 m diameter and 10 m length floats in FW at a draft of 0.2 m, with its axis horizontal. Find its mass.

OA = OB = OC = 0.5 m radius

CD = 0.2 m draft

OD = OC — CD = 0.3 m

In triangle ODB,

$DB^2 = OB^2 - OD^2$

$= 0.5^2 - 0.3^2$

$= 0.16$

DB = 0.4 m

$$\text{Sin BOD} = \frac{.4}{.5} = 0.8$$

Angle BOD = 53.13°

Angle AOB = 106.26°

$$\frac{\text{Area of segment AOBC}}{\text{Area of circle}} = \frac{\text{AOB}}{360°}$$

$$\text{Area of segment AOBC} = \frac{\pi r^2 \times \text{AOB}}{360}$$

$$= \frac{3.1416 \times 0.5^2 \times 106.26}{360}$$

$= 0.232 \text{ m}^2$

Area of triangle AOB $= \frac{1}{2} \times 0.8 \times 0.3$

$= 0.120 \text{ m}^2$

Area of segment ABC = 0.232 — 0.120
= 0.112 m^2

Underwater volume = 0.112 x 10
= 1.12 m^3

W = u/w volume x density of water displaced

W = 1.12 x 1
= 1.12 t

Answer : Mass of cylinder = 1.12 tonnes.

Example 5

A cylindrical drum of radius 40 cm and height 2 m weighs 200 kg. Lead pellets are put in it until it floats with its axis vertical, at a draft of 1.4 m in SW. Find the mass of lead pellets in it, in kilogrammes.

W = u/w volume x density of water displaced

W = $\pi . r^2 d$ x 1.025
= 3.1416 x .4 x .4 x 1.4 x 1.025
= 0.7213 t

Total mass of drum and lead = 0.7213 t
Mass of drum = 0.2 t
Mass of lead = 0.5213 t

Answer: Mass of lead pellets = 521.3 kilogrammes.

Example 6

A rectangular lidless box 6 m x 2 m x 1.5 m floats in water of RD 1.005 at a draft of 0.6 m. Find the

maximum mass of iron that can be put in it without sinking it, when it is floating in SW.

W = u/w volume x density of water displaced

Maximum W = 6 x 2 x 1.5 x 1.025 = 18.450 t
Present W = 6 x 2 x 0.6 x 1.005 = 7.236 t
Difference of displacement = 11.214t

Answer: In SW, it can hold 11.214 tonnes of iron.

Example 7

A rectangular barge 10 m x 5 m x 4 m, floating in SW at a draft of 2 m, is being lifted out of the water by a heavy-lift crane. Find the load taken by the crane when the draft becomes 1.2 m.

W = u/w volume x density of water displaced

W at 2.0 m draft = 10 x 5 x 2.0 x 1.025 = 102.5 t
W at 1.2 m draft = 10 x 5 x 1.2 x 1.025 = 61.5 t
Load taken by crane = difference = 41.0 t

Exercise 3

Flotation

1. A rectangular log of wood 8 m long, 2 m wide and 2 m high floats in FW at a draft of 1.6 m with one face horizontal. Find its mass and RD.

2. A rectangular log of wood 5 m x 1.6 m x 1.0 m weighs 6 t and floats with its largest face horizontal. Find its draft in SW and its RD.

3 A rectangular log 3 m broad and 2 m high floats with its breadth horizontal. If the density of the log is 0.7 tm^{-3}, find its draft in water of RD 1.01.

4 A cylinder 2 m in diameter and 10 m long floats in FW, with its axis horizontal, at a draft of 0.6 m. Find its mass.

5 A barge of triangular cross section is 20 m long, 12 m wide and 6 m deep. It floats in SW at a draft of 4 m. Find its displacement.

6 A cylindrical drum of 1.2 m diameter and 2 m height floats with its axis vertical in water of RD 1.016 at a draft of 1.4 m. Find the maximum mass of lead shots that can be put in it without sinking it.

7 A rectangular barge 10 m long and 5 m wide, floating in SW at a draft of 3 m, is being lifted out of the water by a heavy-lift crane. Find the load on the crane when the draft has reduced to 1 m.

8 A rectangular box 2.4 m long, 1.2 m wide and 0.8 m high, floats in water of RD 1.012 at an even keel draft of 0.2 m. Find the maximum mass of SW that can be poured into it without sinking it.

9 A box-shaped vessel of 18450 t displacement is 150 m long and 20 m wide. Find its draft in SW.

10 A box-shaped vessel 120 m long and 15 m wide is floating in DW of RD 1.005 at a draft of 5 m. If her maxmium permissible draft in SW is 6 m, find how much cargo she can now load.

4

Some Important Terms

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Displacement is commonly used to denote the mass of a ship in tonnes. Technically, it is the mass of water displaced by a ship and, when floating freely, the mass of water displaced equals to the mass of the ship, as explained in Chapter 3.

Light displacement is the mass of the empty ship — without any cargo, fuel, lubricating oil, ballast water, fresh and feed water in tanks, consumable stores, and passengers and crew and their effects.

Load displacement is the total mass of the ship when she is floating in salt water with her summer loadline at the water surface.

Present displacement is the mass of the ship at present. It is the sum of the light displacement of the ship and everything on board at present.

Deadweight (DWT) of a ship is the total mass of cargo, fuel, freshwater, etc., that a ship can carry, when she is floating in salt water with her summer loadline at the water surface.

DWT of ship = load displ − light displ

Deadweight aboard is the total mass of cargo, fuel, ballast, fresh water, etc., on board at present.

DWT aboard = present displ − light displ

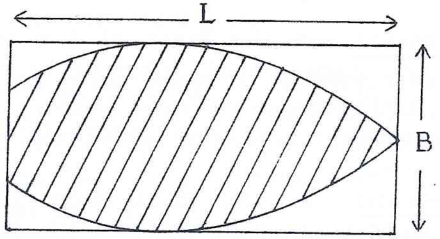
Deadweight available is the total mass of cargo fuel, fresh water, etc., that can be put on the ship at present to bring her summer loadline to the water surface in salt water.

DWT available = load displ — present displ.

Waterplane coefficient (C_w), or coefficient of fineness of the water-plane area, is the ratio of the area of the water-plane to the area of a rectangle having the same length and maximum breadth.

$$C_w = \frac{\text{Area of water-plane}}{L \times B}$$

$$\text{Area of water-plane} = L \times B \times C_w$$



Block coefficient (C_b), or coefficient of fineness of displacement, at any draft is the ratio of the underwater volume of the ship at that draft to a rectangular box having the same extreme dimensions.

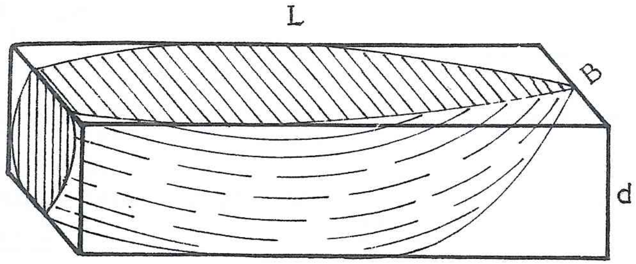
$$C_b = \frac{\text{Underwater volume}}{L \times B \times d}$$

$$\text{Underwater volume} = L \times B \times d \times C_b$$

The term block coefficient may also be used with respect to a tank in which case it would be the ratio of the volume of the tank to the volume of a rectangular box having the same extreme dimensions as the tank.

$$C_b \text{ of tank} = \frac{\text{Volume of tank}}{L \times B \times D}$$

$$\text{Volume of tank} = L \times B \times D \times C_b$$



Reserve buoyancy (RB) is the volume of the enclosed spaces above the waterline. It maybe expressed as a volume in m^3 or as a percentage of the total volume of the ship.

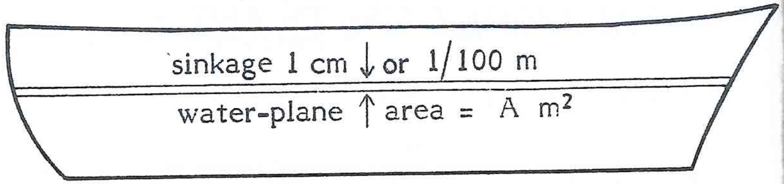
$$RB = \text{Total volume} - \text{underwater volume}$$

$$RB\ \% = \frac{\text{Above water volume}}{\text{Total volume}} \times 100$$

Reserve buoyancy is so called because, though it is not displacing any water at that time, it is available for displacement if weights are added or if bilging takes place. Bilging is the accidental entry of water into a compartment, due to underwater damage and is discussed in volume II.

Tonnes per centimetre (TPC) is the number of tonnes required to cause the ship to sink or rise by one centimetre. In SI units TPC is indicated as t cm^{-1}.

Considering 1 cm sinkage



Increase in underwater volume $= A \times \frac{1}{100} \text{ m}^3$

Increase in W $= \frac{A}{100} \times$ density of water displaced.

Or TPC $= \frac{A}{100} \times$ density of water displaced

TPC in SW $= \frac{A}{100} \times 1.025 = \frac{1.025A}{100}$

TPC in FW $= \frac{A}{100} \times 1.000 = \frac{A}{100}$

TPC in DW RD 1.017 $= \frac{A}{100} \times 1.017 = \frac{1.017A}{100}$

In the foregoing formulae, the area of the water-plane of a ship-shape has been considered constant since the sinkage or rise being considered is only 1 cm. However, the area of the water-plane of a ship-shape usually increases as draft increases. Hence, its TPC also increases as draft increases. In view of this, calculations involving TPC should generally be confined to small values of sinkage or rise, say less than about 20 cm, in the case of ship-shapes. Otherwise, the accuracy of the calculation will tend to suffer.

In the case of a box-shaped vessel, the area of the water-plane is the same at all drafts and hence its TPC does not change with draft.

Example 1

A box-shaped vessel is 120 m long and 16 m wide and has a load draft of 8 m. If her present draft is 6 m, find the DWT available.

W = u/w volume x density of water displaced.

Load W $= 120 \times 16 \times 8 \times 1.025 = 15744$ t

Present W $= 120 \times 16 \times 6 \times 1.025 = 11808$ t

DWT available $= 15744 - 11808 = 3936$ t

Example 2

The length and breadth of the water-plane of a ship are 100 m and 12 m. If the coefficient of fineness of the water-plane is 0.7, find her TPC in SW and in FW.

Water-plane area $= L \times B \times C$

$= 100 \times 12 \times 0.7$

$= 840 \text{ m}^2$

TPC $= \frac{A}{100} \times$ density of water

In SW, TPC $= \frac{840}{100} \times 1.025 = 8.610 \text{ t cm}^{-1}$

In FW, TPC $= \frac{840}{100} \times 1 = 8.400 \text{ t cm}^{-1}$

Example 3

A ship floating in DW of RD 1.010 at a draft of 5 m, is 90 m long and 10 m wide at the water-line. If her block coefficient is 0.72 and her light displacement is 1200 t, find the DWT aboard.

W = u/w volume x density of water displaced.

Present W = 90 x 10 x 5 x 0.72 x 1.010
= 3272.4 t

Light W = 1200.0 t

DWT aboard = 2072.4 t

Example 4

A box-shaped vessel is 120 m long and 14 m wide and 12 m high. If her displacement is 13776 t, find her reserve buoyancy % in SW.

W = u/w volume x density of water displaced.

$$13776 = V \times 1.025$$

$$V = \frac{13776}{1.025} = 13440 \text{ m}^3$$

Total volume = 120 x 14 x 12 = 20160 m^3

RB = Total vol — underwater vol
= 20160 — 13440 = 6720 m^3

$$\text{RB \%} = \frac{\text{Above water volume}}{\text{Total volume}} \times 100$$

$$= \frac{6720}{20160} \times 100 = 33.333\%$$

Example 5

A ship is floating in FW at a draft of 6.8 m. If her maximum FW draft is 7.0 m, and her SW TPC is 40, find the DWT available.

$$\text{SW TPC} = \frac{A}{100} \times 1.025$$

$$40 = \frac{A}{100} \times 1.025$$

$$\text{Or } A = \frac{40 \times 100}{1.025} = 3902.4 \text{ m}^2$$

$$\text{FW TPC} = \frac{A}{100} = \frac{3902.4}{100} = 39.024 \text{ t cm}^{-1}$$

Sinkage required = 7.0 — 6.8 = 0.2 m = 20 cm.

Cargo to load = Sinkage x TPC = 20 x 39.024
= 780.48 t.

DWT available = 780.48 t.

Exercise 4

Displacement, DWT, RB, TPC, etc.

1 A box-shaped vessel 120 m long and 15 m wide has a light draft of 4 m and a load draft of 9.8 m in SW. Find her light displacement, load displacement and DWT.

2 A box-shaped vessel 100 m long and 14 m wide is floating in SW at a draft of 7.6 m. Her light draft is 3.6 m and load draft 8.5 m. Find her present displacement, DWT aboard and DWT available.

3 A ship is 200 m long and 20 m wide at the waterline. If the coefficient of fineness of the water-plane is 0.8, find her TPC in SW, FW and DW of RD 1.015.

4 A double bottom tank 20 m x 10.5 m x 1.0 m has a block coefficient of 0.82. Calculate how much fuel oil of RD 0.95 it can hold.

5 A ship floating in SW at a draft of 8 m is 110 m long and 14 wide at the waterline. If her block coefficient is 0.72, find her displacement.

If her load displacement is 12000 t, find the DWT available.

6 A vessel of 14000 t displacement is 160 m long and 20 m wide at the waterline. If she is floating in SW at a draft of 6.1 m, find her block coefficient.

7 A box-shaped vessel 18 m x 5 m x 2 m floats in SW at a draft of 1.4 m. Calculate her RB%.

8 A box-shaped vessel of 2000 t displacement is 50 m x 10 m x 7 m. Calculate her RB% in FW.

9 The TPC of a ship in SW is 30. Calculate her TPC in FW and in DW of RD 1.018.

10 A ship is floating at a draft of 8.2 m in DW of RD 1.010. If her TPC in SW is 40, find how much cargo she can load to bring her draft in DW to 8.4 m.

5

EFFECT OF DENSITY ON DRAFT & DISPLACEMENT

Part I: When displacement is constant

When a ship goes from SW to FW, her draft would increase and vice versa. This can be illustrated by a simple example. Consider a ship of 10000 tonnes displacement.

W = u/w volume x density of water displaced

In salt water

$$10000 = V_{SW} \times 1.025$$

$$\text{or } V_{SW} = \frac{10000}{1.025} = 9756 \text{ m}^3$$

Underwater volume in SW = 9756 m^3

In fresh water

$$10000 = V_{FW} \times 1$$

$$\text{or } V_{FW} = 10000 \text{ m}^3$$

Underwater volume in FW = 10000 m^3

From the foregoing example it is clear that when a ship goes from SW to FW her underwater volume (and hence her draft) increases, and vice versa, though her displacement is constant.

FRESH WATER ALLOWANCE

FWA is the increase in draft when a ship goes from SW to FW and vice versa.

$$FWA = \frac{W}{40\ TPC}$$

Where W is the displacement of the ship in salt water, expressed in tonnes.

TPC is the tonnes per centimetre immersion in salt water.

FWA is the fresh water allowance in centimetres.

FWA of a ship usually increases as draft increases. This is because W depends on underwater volume whereas TPC depends on waterplane area. As draft increases, both W and TPC increase but W increases at a faster rate. Hence FWA, as calculated by the foregoing formula, also increases as draft increases. The table on the next page is taken from the hydrostatic particulars on an actual ship in service.

The FWA calculated, by the foregoing formula, for the summer load condition is called the FWA of the ship. This FWA is mentioned in the loadline certificate and is considered constant for those loadlines marked on the ship's sides — T, S, W and WNA. When a ship is loading down to her marks in FW, she can immerse her loadline by the FWA of the ship so that when she goes to SW, she would rise to her appropriate loadline.

If it is desired to find the FW draft of the ship when she is not immersed upto the loadline marked on the ship's sides, the FWA must be calculated by

the formula and added to the SW draft of the ship at that time.

Draft m	W t	TPC tcm^{-1}	$\frac{W}{40\ TPC}$	=	FWA cm
3.000	5478	20.90	$\frac{5478}{40 \times 20.9}$	=	6.6
5.000	9788	22.08	$\frac{9788}{40 \times 22.08}$	=	11.1
7.000	14299	22.95	$\frac{14299}{40 \times 22.95}$	=	15.6
9.000	19051	24.14	$\frac{19051}{40 \times 24.14}$	=	19.7
9.233 (load draft)	19617	24.28	$\frac{19617}{40 \times 24.28}$	=	20.2

DOCK WATER ALLOWANCE

DWA is the increase in draft when a ship goes from saltwater to dockwater, and vice versa, where the dockwater is neither fresh not salt i.e., RD between 1 and 1.025. When loading in a dock, the ship can immerse her loadline by the DWA so that when she goes to sea, she would rise to her appropriate loadline.

When a ship goes from SW to FW (change of RD of .025) she increases her draft by FWA. So for any change of RD between 1.025 and 1.000, linear interpolation may be done. For example:-

			Change of RD	Change of Draft
SW 1.025	to	FW 1.000	.025	FWA
SW 1.025	to	DW 1.017	.008	$\frac{.008}{.025}$ x FWA
SW 1.025	to	DW 1.020	.005	$\frac{.005}{.025}$ x FWA
FW 1.000	to	DW 1.016	.016	$\frac{.016}{.025}$ x FWA
DW 1.017	to	DW 1.005	.012	$\frac{.012}{.025}$ x FWA

From the foregoing example, it is clear that:-

$$\text{Change of draft} = \frac{\text{change of RD}}{.025} \times \text{FWA}$$

The change of draft, so obtained, would be in the same units as the FWA — mm, cm or m.

This formula holds good for any change of RD. However, when the change of draft is calculated between SW and DW, it is called DWA. The term dock water is used here only symbolically to represent water whose RD is between 1.000 and 1.025 and, for stability purposes, includes the water of rivers, harbours, etc., even though they may not have enclosed docks.

Part II: When draft is constant

When a ship floats at the same draft, on different occasions, in water of different RD, her displacement each time would be different. This is illustrated by a simple example.

Suppose the underwater volume of a certain ship at 7 m draft is 14000 m^3.

In SW, at 7 m draft, W = 14000 x 1.025 = 14350 t.

In FW, at 7 m draft, W = 14000 x 1.000 = 14000 t.

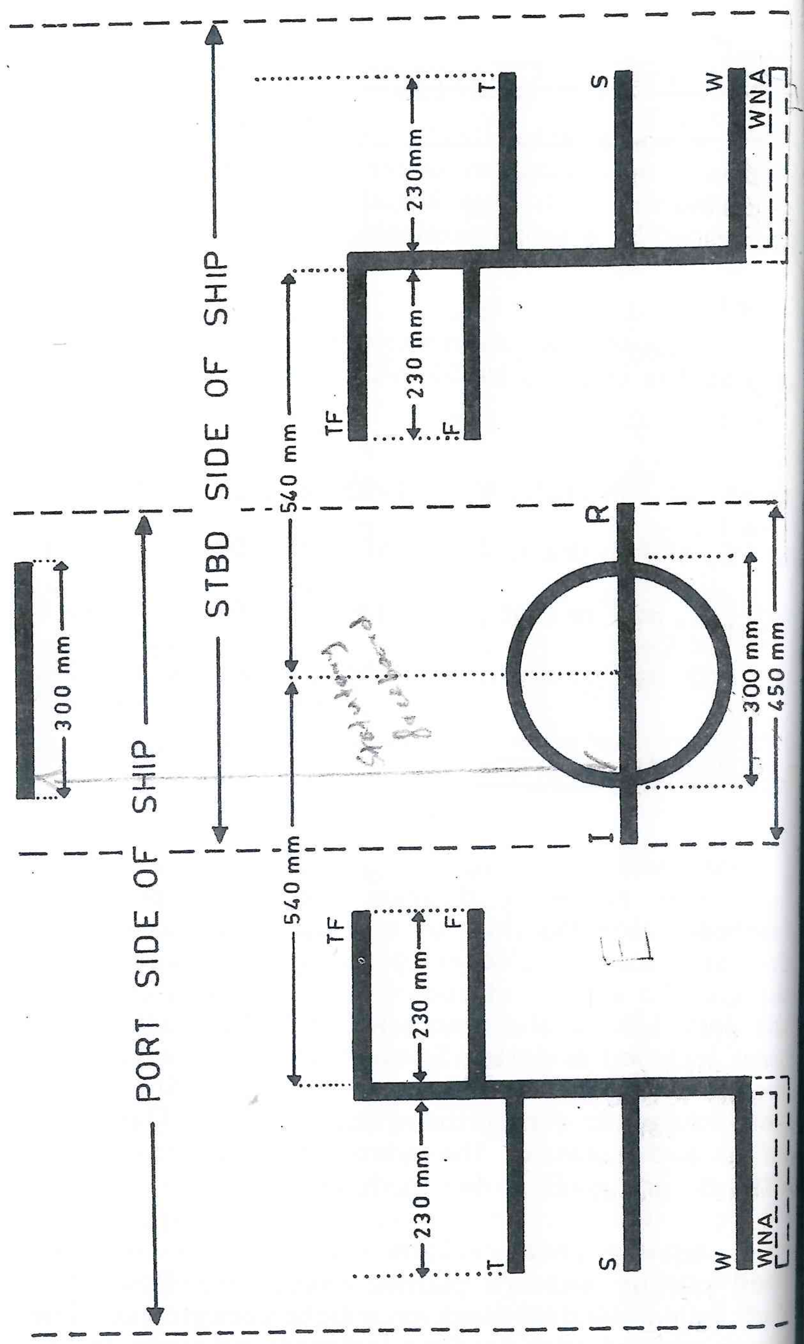
RD 1.01, at 7 m draft, W = 14000 x 1.010 = 14140 t.

RD 1.02, at 7 m draft, W = 14000 x 1.020 = 14280 t.

LOADLINES OF SHIPS

The following diagram shows the port and starboard side loadlines of a cargo ship. To see the port side loadlines, cover up the the right 1/3 of the sketch. To see the starboard side loadlines, cover up the left 1/3 of the sketch. The WNA loadline has been included in dotted lines as it is only required by vessels less than 100 metres in length, trading in the North Atlantic during the winter season. The exact limits and dates of the winter zone in the North Atlantic are given in the loadline rules.

All the lines are 25 mm thick, are cut into the shell plating and are painted white or yellow on a dark background or black on a light background. The upper edge of each loadline indicates its exact level.



The top of the deck line indicates where the top of the freeboard deck would meet the outer side of the shell plating, if produced. Directly below the deck line is the Plimsoll mark (or loadline disc) and the vertical distance between them is called the Statutory Summer Freeboard. The centre of the loadline disc is at the middle of the upper edge of its 25 mm thick, painted, diametric line. The deck line and the Plimsoll mark are situated exactly amidships.

Exactly 540 mm forward of the disc is a vertical line 25mm thick with horizontal lines, measuring 230 mm x 25 mm, on each side of it. On its forward side the lines are marked S, T and W (also WNA if applicable). The lines on the after side are marked F and TF.

The upper edge of the line marked S is in line with the horizontal line of the Plimsol mark. In summer zones, the ship can load up to this line in salt water. The vertical distance between the upper edges of S and T (and also between S and W) is 1/48 of the summer draft of the vessel. The dates and limits of winter, summer and tropical zones are given in the loadline rules. The WNA mark, if applicable, if situated exactly 50 mm below the W mark (measured between their upper edges).

The vertical distance between the upper edges of the lines marked S and F, and also between T and TF, is the FWA of the ship.

Example 1

A ship's load displacement is 16000 t and TPC is 20. If she is in DW of RD 1.010, find by how much she may immerse her loadline so that she will not be overloaded when she goes to sea.

$$FWA = \frac{W}{40 \, . \, TPC} = \frac{16000}{40 \times 20} = 20 \text{ cm}$$

DWA $= \frac{(1.025 - dd)}{.025} \times FWA = \frac{(1.025 - 1.010)}{.025} \times 20$

$= 12$ cm

Hence, ship can immerse her SW loadline by 12 cm.

Example 2

A vessel of FWA 200 mm goes from water of RD 1.018 to water of RD 1.006. Find the change in draft and state whether it will be sinkage or rise.

Change of draft $= \frac{\text{Change of RD} \times FWA}{.025}$

$= \frac{(1.018 - 1.006) \times 200}{.025}$

$= 96$ mm.

Since the RD of water has decreased the draft will increase.

Hence, the vessel will sink by 96 mm.

Example 3

A box-shaped vessel 24 x 5 x 3 m has a mean draft of 1.2 m in DW of RD 1.009. Calculate her draft in DW of RD 1.019.

W = u/w volume x density of water displaced.

In DW RD 1.009, W = 24 x 5 x 1.2 x 1.009

In DW RD 1.019, W = 24 x 5 x d x 1.019

Since displacement is constant,

$24 \times 5 \times d \times 1.019 = 24 \times 5 \times 1.2 \times 1.009$

$d = \frac{1.2 \times 1.009}{1.019} = 1.188$ m

Hence, draft in DW of RD 1.019 = 1.188 m.

Note: This problem could also be worked by calculating the displacement, SW TPC, FWA and then the change of draft, all by various formulae. However such a method would be unduly tedious.

Example 4

A box-shaped vessel 20 x 6 x 4.5 floats in DW of RD 1.010 at a draft of 2.4 m. Calculate her percentage reserve buoyancy in DW of RD 1.020.

W = u/w volume x density of water displaced.

In DW RD 1.010, W = 20 x 6 x 2.4 x 1.010

In DW RD 1.020, W = V x 1.020

Since displacement is constant,

$V \times 1.020 = 20 \times 6 \times 2.4 \times 1.010$

$V = 285.176 \text{ m}^3$

Total volume $= 20 \times 6 \times 4.5 = 540 \text{ m}^3$

Above water volume = Total volume - u/w volume

$= 540 - 285.176 = 254.824 \text{ m}^3$

$RB\% = \frac{\text{Above water volume}}{\text{Total volume}} \times 100 = \frac{254.824}{540} \times 100$

$= 47.19\%$

Hence, RB% in DW of RD 1.020 = 47.19%

Example 5

A vessel displaces 5000 t at a certain draft in DW of RD 1.018. Find her displacement when floating at the same draft in DW of RD 1.012.

W = u/w volume x density of water displaced.

In DW RD 1.018, 5000 = V x 1.018

or V = $\frac{5000}{1.018}$ = 4911.591 m^3.

Hence, u/w vol of ship at that draft = 4911.591 m^3.

In DW RD 1.012, W = 4911.591 x 1.012

= 4970.53 t

= 4971 t

Example 6

A vessel displaces 16000 t at her summer load draft in SW. If she is now floating in DW of RD 1.015 with her summer loadline on the water, calculate how much DWT is available.

W = u/w volume x density of water displaced.

At Summer load draft, 16000 = V x 1.025

or V = $\frac{16000}{1.025}$ = 15609.756 m^3

Hence, underwater volume of ship at summer draft =

= 15609.756 m^3

Present disp = 15609.756 x 1.015 = 15843.9 t

DWT available = Maximum disp — present disp

= 16000 — 15843.9

= 156.1 t

= 156 t

Example 7

A vessel is in SW with her summer loadline 60 mm above the water on the port side and 10 mm above the water on the starboard side. Find the DWT available, if her TPC is 40.

Obviously, the vessel is listed to starboard. Since both, port and starboard loadlines are of same name (above water), mean distance from water will be half the sum of the distances.

Mean distance of loadline = $\frac{60 + 10}{2}$ = 35 mm

Hence, when upright, loadlines will be 3.5 cm above water.

DWT available = Sinkage x TPC = 3.5 x 40

= 140 t

Example 8

A vessel is in SW with her port summer loadline 80 mm below water and her starboard, 200 m above. Find the DWT available if TPC is 30.

Obviously the vessel is listed to port. Since the loadline on one side is above the water and the other, below the water (different names), the mean distance of the loadline from the water will be half the difference between the distances. The name (above or below) of the mean distance will be the same as that of the larger of the two distances.

Mean distance of loadline = $\frac{200 - 80}{2}$ = 60 mm

Hence, when upright, loadline will be 6.0 cm above water.

DWT avaialable = Sinkage x TPC = 6 x 30
= 180 t

Example 9

A vessel floats in DW RD 1.016 with her winter loadline 100 mm below water on the port side and 180 mm below water on the starboard side. If her FWA is 200 mm, TPC is 24 and summer load draft is 9.6 m, find DWT available.

Port winter loadline is 100 mm below water

Stbd winter loadline is 180 mm below water

Mean distance from water $= \frac{1}{2}(180 + 100)$
$= 140$ mm below

Hence, when upright, winter loadline will be 14 cm below water.

Distance W to S $= \frac{1}{48} \times$ Summer draft
$= \frac{1}{48} \times 9.6 = 0.2$ m
$= 20$ cm

Hence, distance from present waterline to S
$= 20 - 14 = 6$ cm

$$DWA = \frac{(1.025 - 1.016)}{.025} FWA = \frac{.009}{.025} \times 200 = 72 \text{ mm}$$

DWA = 7.2 cm

Hence, total sinkage permissible $= 6 + 7.2 = 13.2$ cm

$$TPC = \frac{A}{100} \times \text{density of water}$$

Note: TPC given is always SW TPC unless specifically stated otherwise.

$$\text{In SW, } 24 = \frac{A}{100} \times 1.025 \text{ or } \frac{A}{100} = \frac{24}{1.025}$$

$$\text{In DW, TPC} = \frac{A}{100} \times 1.016 = \frac{24}{1.025} \times 1.016$$
$$= 23.79 \text{ tcm}^{-1}$$

DWT available = sinkage x TPC = 13.2 x 23.79 = 314t

Example 10

A vessel arrives at port X at the mouth of a river. Her displacement is 12000 t and arrival draft 5.77 m in RD 1.020. She is to cross a bar upriver before entering port Y. The depth at the bar is 6.0 m and RD 1.005. If her TPC is 25, find the minimum quantity of cargo to off-load at port X so that she may cross the bar with an under-keel clearance of 0.5 m.

$$FWA = \frac{W}{40 \times TPC} = \frac{12000}{40 \times 25} = 12 \text{ cm}$$

$$\text{Change of draft} = \frac{\text{Change of RD}}{.025} \times FWA$$
$$= \frac{(1.020 - 1.005)}{.025} \times 12$$
$$= 7.2 \text{ cm} = .072 \text{ m}$$

Depth of water over bar = 6.0 m
Under-keel clearance = 0.5 m
Max draft to arrive at bar = 5.5 m
Change of draft due to RD = 0.072 m

Max draft on dep port X	=	5.428 m
Draft on arrival port X	=	5.770 m
Required mean rise at port X	=	0.342 m
	=	34.2 cm

TPC at Port X $= \frac{25}{1.025} \times 1.020 = 24.88$ tcm^{-1}

Cargo to discarge	=	rise x TPC
	=	34.2 x 24.88
	=	850.9 t

Hence, required to discharge 851 t at port X.

Note: The TPC given is always the SW TPC unless clearly stated otherwise. The TPC used in the final stage of this problem is the TPC at RD 1.020 because the cargo lightening operation is being carried out at port X whose RD is 1.020. This is purely of academic interest because any cargo calculation involving TPC is approximate only. If the SW TPC was used in this problem, the answer would be only 4 tonnes different. In actual practice at sea, the displacement of the ship at the required draft of 5.5 m in RD 1.005 would be found out (using the hydrostatic particulars of the ship) and that, subtracted from the present displacement, would give the quantity of cargo to off-load at port X. This is explained in Chapter 17.

Exercise 5

1. A ship of 16000 t displacement and TPC 20 is floating in SW at a draft of 8.0 m. Find her draft in FW.

2. A ship goes from water of RD 1.008 to SW. Find the change in draft, if her FWA is 180 mm, and state whether it would be sinkage or rise.

3. A vessel goes from water of RD 1.010 to FW. If her FWA is 160 mm, state whether she would sink or rise and by how much.

4. A ship of FWA 175 mm goes from water of RD 1.006 to water of RD 1.018. Find the amount of sinkage or rise.

5. A ship's stability data book gives her load displacement to be 18000 t and TPC to be 25. If she is now loading in DW of RD 1.018, by how much may her loadline be immersed so that she would not be overloaded?

6. A box-shaped vessel 20 x 4 x 2 m has a mean draft of 1.05 m in SW. Calculate her draft in DW of RD 1.012.

7. A box-shaped vessel 18 x 5 x 2 m floats in DW of RD 1.000 at a draft of 1.4 m. Calculate her percentage reserve buoyancy when she enters SW.

8. The hydrostatic particulars of a ship indicate that her displacement in SW at a draft of 5 m is 3000 t. Find her displacement when floating at 5 m draft in water of RD 1.018.

9 A vessel displaces 4500 t of FW at a certain draft. Find her displacement at the same draft in water of RD 1.020.

10 A ship 100 m long and 20 m wide, block coefficient 0.8, floats in SW at a mean draft of 8.0 m. Calculate the difference in displacement when floating at the same draft in FW.

11 A vessel displaces 14 500 tonnes, if floating in SW upto her winter load-line. If she is in a dock of RD 1.010, with her winter load-line on the surface of the water, find how much cargo she can load, so that she would float at her winter load-line in SW.

12 A vessel of 12000 t displacement arrives at the mouth of a river, drawing 10.0 m in SW. How much cargo must she discharge so that her draft in an upriver port of RD 1.012 would be 10.0 m.

13 A vessel floating in DW of RD 1.005 has the upper edge of her summer loadline in the waterline to starboard and 50 mm above the waterline to port. If her FWA is 180 mm and TPC is 24, find the amount of cargo which the vessel can load to bring her to her permissible draft.

14 A vessel is floating at 7.8 m draft in DW of RD 1.010. TPC is 18 and FWA is 250 mm. The maximum permissible draft in SW is 8.0 m. Find the DWT available.

15 A vessel's statutory freeboard is 2.0 m. She is loading in DW of RD 1.015 and her freeboard is 2.1 m. TPC = 24. FWA = 200 mm. Find the DWT available.

16 A vessel is lying in a river berth of density 1.010 tonnes per m^3, with her summer loadline 20 mm above the water on the starboard side and 50 mm above the water on the port side. Find how much cargo she can load to bring her to her summer loadline in SW, if her summer displacement is 15000 tonnes and TPC is 25.

17 A vessel is floating in dock water of RD 1.005 with her starboard WNA mark 30 mm below, and her port WNA mark 60 mm below the water line. If her summer SW draught is 8.4 m, TPC is 30 and FWA is 160 mm, calculate how much cargo can be loaded to bring the vessel to her summer draught in SW.

18 A vessel is loading in a SW dock and is lying with her starboard Winter loadline 60 mm above and her port Winter loadline 20 mm below the surface of water. If her summer draught in SW is 7.2 m and TPC is 20, find how many tonnes of cargo the vessel can load to bring her down to her Tropical loadline in SW.

19 From the following details, calculate the DWT available:– Present freeboards: port 3.0 m, starboard 2.9 m in water of RD 1.020. FWA 200 mm. TPC 30. Statutory summer freeboard 2.8 m.

20 From the following information, calculate the DWT available upto the Tropical loadline in SW:-

Present freeboards: port 1.68 m, starboard 1.79 m in RD 1.017.

Tropical SW freeboard : 1.63 m
Tropical SW draft : 9.6 m
FWA 150 mm, TPC 20.4

6

Centre Of Gravity

The centre of gravity (G or COG) of a ship is that point through which the force of gravity may be considered to act vertically downwards, with a force equal to the weight of the ship.

The position of the COG of a ship is indicated by its distance in metres from three reference lines:

(i) Its height above the keel. This distance is referred to as KG where K represents the keel. KG affects the stability of the ship.

(ii) Its distance from the after perpendicular (A) of the ship. This distance is referred to as AG. AG affects the trim of the ship.

Note: The after perpendicular (A) of a ship is the after part of the stern post. If the vessel does not have a stern post, then it is the axis of the rudder stock.

Some shipyards use midships (H) for reference instead of the after perpendicular (A). The distance of the COG is then referred to as HG, in this book, but then it must be stated whether the COG is forward or abaft midships in each case. HG affects the trim of the ship.

Note: Midships is taken to be the line drawn at right angles to the keel, midway between the forward and after perpendiculars.

(iii) Its distance from the centre line of the ship. This distance causes the ship to list. Since mariners like to keep their ship upright at all times, this distance should preferably be zero.

The position of the COG of a ship depends on the distribution of weights on board and not on the total weight.

When a weight is added (loaded), the COG of the ship moves directly towards the COG of the added weight.

When a weight is removed (discharged), the COG of the ship moves directly away from the COG of the removed weight.

When a weight already on board is shifted, the COG of the ship moves in a direction parallel to that moved by the weight.

The foregoing statements are illustrated by the following figures wherein G is the COG of the ship before loading/discharging/shifting and G_1 is the COG of the ship after the loading/ discharging/ shifting is completed.

So far, only the direction of shift of COG has been considered. The distance through which the COG would move is given by the following formula:

$$GG_1 = \frac{wd}{W}$$

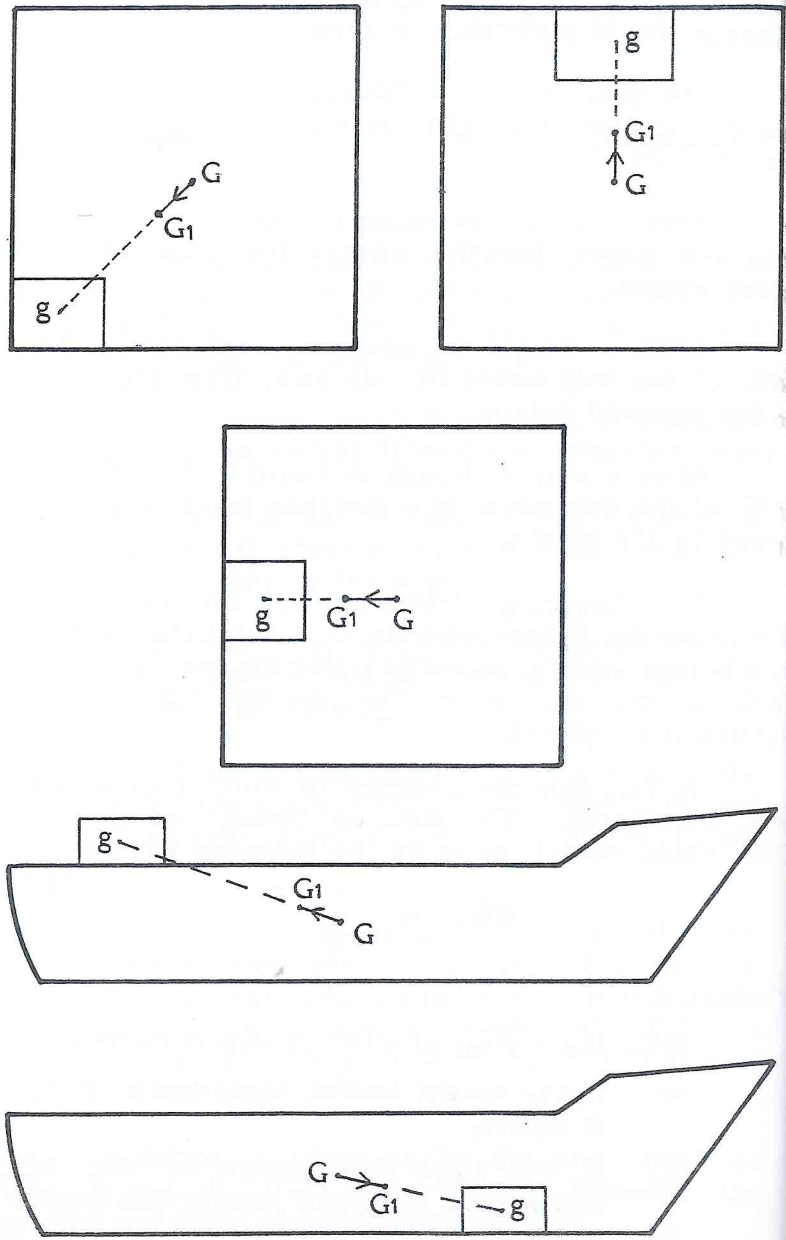
Wherein,

GG_1 is the shift of COG of ship in metres.

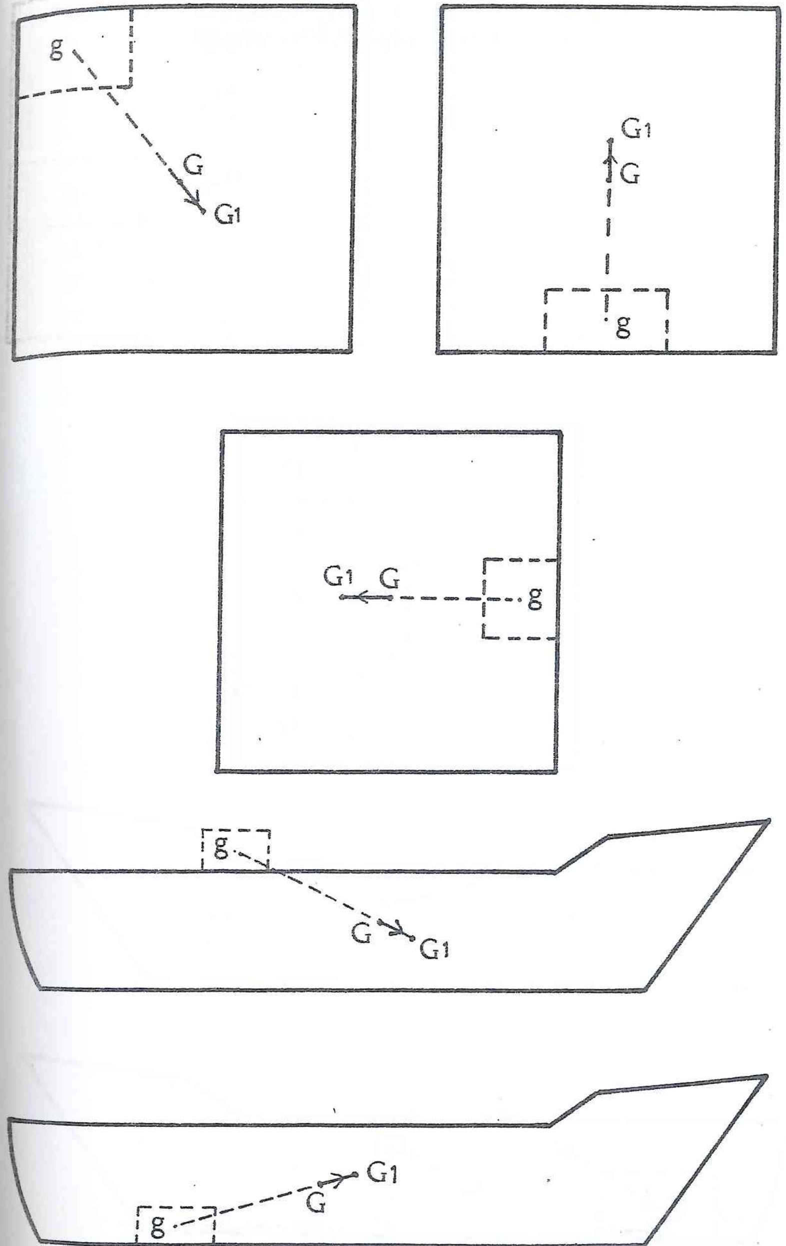
w is the weight loaded/discharged/shifted, in tonnes.

W is the final displacement of ship in tonnes i.e., after the weight has been

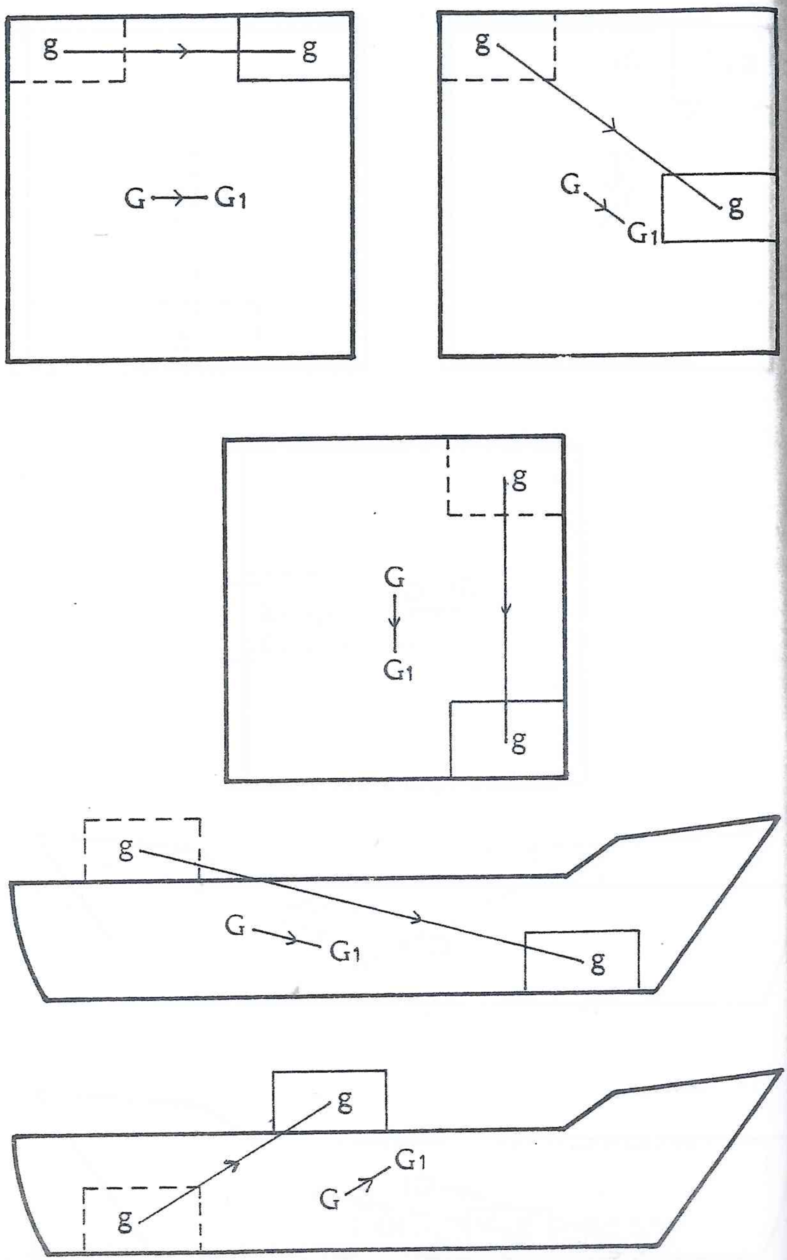
Effect of adding a weight



Effect of removing a weight



Effect of shifting a weight



loaded/discharged/shifted.

d When loading/discharging, d is the distance in metres betwen the COG of the ship and the COG of the weight.

When shifting a weight, d is the distance moved by the weight.

In stability calculations, the vertical, longitudinal and transverse movements of COG are calculated separately. In other words, the actual movement of COG is split into its three components and each component is calculated separately, as shown in later chapters.

7

FINAL KG

Part I: Considering a single weight only.

When loading, discharging or shifting a single weight, the vertical shift of the COG of a ship is given by the formula:-

$$GG_1 = \frac{wd}{W}$$

Wherein,

- GG_1 : Vertical shift of COG of ship in metres.
- w : Weight loaded/discharged/shifted in tonnes.
- W : Final displacement of ship in tonnes.
- d : When loading or discharging, 'd' is the vertical distance between the COG of the ship and the COG of the weight.

  When shifting a weight already on board, 'd' is the vertical distance moved by the weight.

Example 1

In a vessel of 12000 t displacement, KG 9 m, 200 t of cargo was shifted from the upper deck (KG 12 m) to the lower hold (KG 2 m). Find the new KG.

KG of cargo while on UD = 12 m

KG of cargo when in LH = 2 m

Hence d = 10 m downwards

$$GG_1\downarrow = \frac{wd}{W} = \frac{200 \times 10}{12000} = 0.167 \text{ m}$$

Original KG	=	9.000 m
$GG_1\downarrow$	=	0.167 m
KG_1 or new KG	=	8.833 m

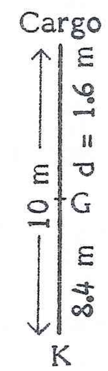
Example 2

In a vessel of 7850 t displacement, KG 8.4 m, 150 t of cargo is loaded on the UD (KG 10 m). Find the final KG.

Final W = 7850 + 150 = 8000 t

w = 150 t, d = 1.6 m

$$GG_1 = \frac{wd}{W} = \frac{150 \times 1.6}{8000} = 0.03 \text{ m}$$



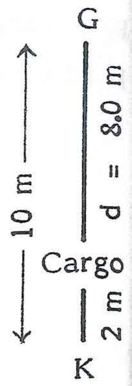
Since the cargo was loaded above the COG of the ship, GG_1 will be upwards.

Original KG	=	8.400 m
$GG_1\uparrow$	=	0.030 m
KG_1 or new KG	=	8.430 m

Example 3

In a ship of 12300 t displacement, KG 10 m, 300 t of cargo was discharged from the lower hold (KG 2 m). Find the final KG.

Final W = 12300 − 300 = 12000 t.



w = 300 t, d = 8 m

$GG_1 = \frac{wd}{W} = \frac{300 \times 8}{12000} = 0.2$ m

Since cargo was discharged from below the COG of ship, GG_1 will be upwards.

Original KG	=	10.0 m
$GG_1 \uparrow$	=	0.2 m
KG_1 or new KG	=	10.2 m

Example 4

On a vessel of 6000 t displacement KG 7.4 m, how many tonnes of cargo may be discharged from the lower hold (KG 2.0 m) in order to have a final KG of 8.0 m ?

Old KG	=	7.4 m	Original W	=	6000 t
New KG	=	8.0 m	Discharged	=	w
$GG_1 \uparrow$	=	0.6 m	Final W	=	6000 - w

$GG_1 = \frac{wd}{W}$ or $0.6 = \frac{w\,(5.4)}{6000-w}$ or w = 600 t

Hence, cargo to discharge = 600 tonnes.

Example 5

A vessel of 11 000 t displacement has KG 6.3 m. A jumbo derrick is used to shift a weight of 250 t from the lower hold (KG 3 m) to the UD (KG 8.5 m). The head of the derrick is 19.5 m above the keel. Find the KG of the ship:

(a) When the weight is hanging by the derrick and

(b) When the shifting is over.

This problem is to be worked in two stages.

Stage 1: As soon as the weight is lifted off the tank-top, the COG of the weight shifts from the LH to the derrick head.

KG of weight when in LH	=	3.0 m
Height of derrick head above keel	=	19.5 m
Hence, d	=	16.5 m

$GG_1 \uparrow = \frac{wd}{W} = \frac{250 \times 16.5}{11\,000} = 0.375$ m

Original KG	=	6.300 m	+
$GG_1 \uparrow$	=	0.375 m	
KG_1 or new KG	=	6.675 m	

Hence KG at the end of stage 1 = 6.675 m answer (a).

Stage 2: As soon as the weight is placed on the upper deck, the COG of the weight shifts from the derrick head to the UD.

Height of derrick head above keel	=	19.5 m	−
KG of weight when on UD	=	8.5 m	
Hence, d	=	11.0 m	

$GG_1 \downarrow = \frac{wd}{W} = \frac{250 \times 11}{11\,000} = 0.250$ m

New KG (end of stage 1)	=	6.675 m	−
$GG_1 \downarrow$	=	0.250 m	
Final KG (end of stage 2)	=	6.425 m	

KG when shifting is over = 6.425 m answer (b).

Example 6

A vessel of 6000 t displacement, KG 7.1 m, loads a heavy lift weighing 150 t by her jumbo derrick whose head is 16 m above the keel. If the weight is placed on the tween deck (KG 8 m) find:

(a) the KG when the weight is hanging 1 m above the tween deck and

(b) the KG when the loading is over.

Stage 1: As soon as the jumbo derrick takes the heavy lift off the wharf, the COG of the weight acts on the derrick head — equivalent to loading the weight 16 m above the keel. The height of the weight above the deck is of no importance.

$$\text{Final } W = 6000 + 150 = 6150 \text{ t}$$
$$d = 16 - 7.1 = 8.9 \text{ m}$$

$$GG_1 \uparrow = \frac{wd}{W} = \frac{150 \times 8.9}{6150} = 0.217 \text{ m}$$

Original KG	=	7.100 m +
$GG_1 \uparrow$	=	0.217 m
KG_1 or new KG	=	7.317 m

Hence, KG at the end of stage 1 = 7.317 m ans (a).

Stage 2: As soon as the weight is placed on the TD, the COG of the heavy lift shifts from the derrick head (KG 16 m) to the TD (KG 8 m). i.e., d = 16 - 8 = 8 m downwards

$$GG_1 \downarrow = \frac{wd}{W} = \frac{150 \times 8}{6150} = 0.195 \text{ m}$$

New KG (at end of stage 1)	=	7.317 m −
$GG_1 \downarrow$	=	0.195 m
Final KG (at end of stage 2)	=	7.122 m

Hence, KG after shifting is over = 7.122 m ans (b).

Exercise 6

Final KG by GG_1 formula

1. In a vessel of 8800 tonnes displacement and KG 6.2 m, 200 tonnes of cargo was loaded in the lower hold, 1.7 m above the keel. Find the final KG.

2. 600 tonnes of cargo were discharged from a vessel from the upper deck 11 m above the keel. If the original KG and displacement were 6 m and 12 600 tonnes, calculate the final KG.

3. In a vessel of 9900 tonnes displacement and KG 4 m, a heavy lift of 100 tonnes is loaded on the UD (KG 15 m). Find the final KG.

4. 500 tonnes of cargo was discharged from the lower hold (KG 3 m) of a vessel whose displacement and KG before discharging were 11500 tonnes and 6.3 m. Find the final KG.

5. 500 tonnes of cargo was shifted 15 metres vertically downwards in a vessel of 10 000 tonnes displacement. Find the effect it has on the KG of the vessel and state whether KG increases or decreases.

6. In a vessel of 9000 tonnes displacement, KG 10.5 m, 300 tonnes of cargo was shifted from the LH (KG 2.5 m) to the UD (KG 11.5 m). Find the resultant KG of the vessel.

7. In a vessel of 9009 tonnes displacement, KG 8.7 m, how many tonnes of cargo can be loaded on the upper deck (KG 15 m) so that the final KG would be 9 m?

8 A heavy lift derrick, whose head is 20 m above the keel, is to shift a locomotive weighing 300 tonnes from the UD (KG 8 m) to the LH (KG 2 m). If the displacement and initial KG of the vessel were 12000 tonnes and 7.6 m, find the KG of the vessel (a) when the derrick has taken the weight off the UD and (b) after shifting is over.

9 On a vessel of 4,950 tonnes displacement, KG 9.2 m, the ship's jumbo derrick is used to load a weight of 50 tonnes from the wharf, on to the UD (KG 8 m). If the head of the derrick is 25 m above the keel, calculate the KG of the vessel (a) when the weight is hanging by the derrick on the centre line but 2 m above the UD; and (b) after loading.

10 A ship's derrick, whose head is 22 m above the keel, is used to discharge a weight of 20 tonnes (KG 5 m), lying on the centre line. If the vessel's displacement and KG before discharging were 6000 tonnes and 8 m, calculate the KG (a) as soon as the derrick lifts the weight and (b) after discharging.

Part II: Considering several weights

The GG_1 formula, which seems adequate when considering a single weight at a time, becomes impracticable for general use of ships because several weights are loaded, discharged and/or shifted, at a time. In such cases, the calculation of final KG is done by taking moments about the keel.

The initial moment of the weight of the ship about its keel plus the moments about keel of all weights loaded minus the moments about keel of all weights discharged gives the final moment. This final moment about keel divided by the final displacement of the ship gives the final KG. In cases where

weights have been shifted vertically, the weight multiplied by the vertical distance shifted gives the change in moment, to be added if the shift is upwards; to be subtracted if the shift is downwards.

Calculation of final KG by taking moments about keel can be done even when only a single weight is being loaded, discharged or shifted.

Example 7

On a ship of 10 000 t displacement, KG 7.75 m, the following changes took place:

1000 t of cargo discharged from No.2 LH, KG 4.0 m.
2000 t of cargo discharged from UD, KG 9.8 m.
500 t of FW taken into peak tanks, KG 6.5 m.
500 t of fuel oil taken into No.4 DBT, KG 0.5 m.
500 t of cargo shifted from No.2 TD to No.2 LH, through a vertical distance of 8 m.

Find the final KG of the ship.

Remarks	Weight (t) Loaded	Weight (t) Disch	KG (m)	Moment by Keel (tm) Loaded	Moment by Keel (tm) Disch
Ship	10,000	-	7.75	77,500	-
2LH Cargo	-	1,000	4.0	-	4,000
UD Cargo	-	2,000	9.8	-	19,600
Peaks FW	500	-	6.5	3,250	-
HFO 4 DBT	500	-	0.5	250	-
Total	11,000	3,000		81,000	23,600
	3,000			23,600	
Final W =	8,000			57,400	
500 t shifted 8 m down (-)				4,000	
Final moment =				53,400	

$$\text{Final KG} = \frac{\text{Final moment}}{\text{Final W}} = \frac{53{,}400}{8{,}000} = 6.675 \text{ m.}$$

Exercise 7

Final KG by moments about keel

1. A ship of displacement 2000 t and KG 4.2 m, loads 300 t of cargo (KG 2.0 m), 200 t of cargo (KG 3.2 m) and 500 t of bunkers (KG 1.0 m). Find her final KG.

2. A ship of displacement 3000 t and KG 3.9 m, loads cargo as follows:- 200 t in No.1 LH (KG 3.0 m), 300 t on deck (KG 6.4 m), 150 t in No.3 TD (KG 5.2 m) and 350 t in No.4 LH (KG 4.0 m). Find the final KG.

3. A ship of load displacement 10,000 t, KG 6.0 m, discharges cargo of 250 t (KG 3.0 m) and 150 t (KG 4.0 m). Find her final KG.

4. A ship of displacement 12,000 t, KG 4.3 m, discharges cargo as follows:- 200 t from No.1 LH (KG 2.6 m), 250 t from No.2 TD (KG 3.4 m), 1000 t from No.3 LH (KG 4 m) and 550 t from UD near No.5 (KG 8 m). Find final KG.

5. Ship of 2000 t displacement and KG 3.66 m, loads 1500 t (KG 5.5 m), 3500 t (KG 4.60 m), and takes 1520 t of bunkers (KG 0.60 m). She discharges 2000 t cargo (KG 2.44 m) and consumes 900 t of bunkers (KG 0.40 m). Find the KG at the end of the voyage.

6. A ship of 3200 t displacement, KG 6.2 m, loads 5200 t of cargo (KG 4.8 m). Find the amount of deck cargo (KG 10.4 m) that can be loaded so that the KG shall be 6.0 m when loading is completed.

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7. A ship of 2600 t displacement, KG 4.88 m, loads 4600 t of homogeneous cargo (KG 5.0 m). Find how much deck cargo (KG 10 m) may be loaded to obtain a final KG of 5.11 m.

8. A heavy-lift derrick is used to discharge a 100 t package from a ship of displacement 8000 t, KG 8.2 m. If the KG of the weight while on board is 3 m and if the derrick head is 25 m above the keel, find the KG of the ship (a) while discharging and (b) after discharging.

9. On a ship of 15000 t displacement KG 7.9 m, a weight of 200 t is loaded on the UD (KG 12 m) using the ship's Stulken derrick whose head is 30 m above the keel. Find the KG of the ship (a) while loading and (b) after loading.

10. On a ship of 11000 t displacement KG 7.2 m, a shore crane is used to shift a 180 t heavy-lift from the UD (KG 12 m) to the LH (KG 3 m). Find the KG of the ship (a) during shifting and (b) after shifting.

8

Centre Of Buoyancy

The centre of buoyancy (B or COB) of a ship is that point through which the force of buoyancy may be considered to act vertically upwards, with a force equal to the weight of water displaced by the ship. It is the geometric centre of the water displaced i.e., the geometric centre of the underwater volume of the ship.

The position of the COB of a ship is indicated by:

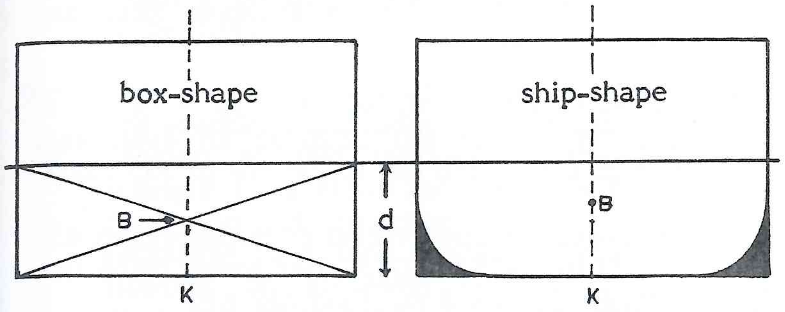
(i) Its height above the keel. This distance is referred to as KB.

(ii) Its distance from the after perpendicular of the ship. This distance is referred to as AB. Some shipyards use midships (H) for reference instead of the after perpendicular (A). The distance of the COB is then referred to as HB, in this book, but then it must be stated whether the COB is forward or abaft midships in each case.

Note: Definitions of the after perpendicular and midships are given in chapter 6.

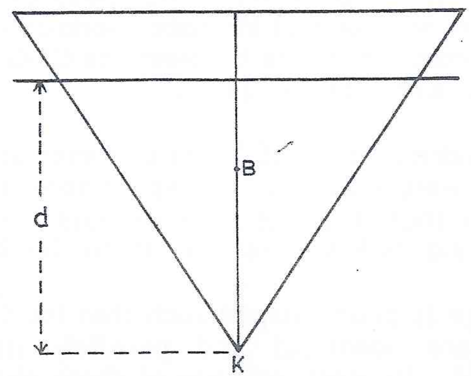
Both KB and AB depend on the shape and volume of the underwater portion of the hull and are therefore dependant on the ship's draft. KB and AB (or HB) are given in the hydrostatic particulars of the ship in the form of curves or tables against draft. Further explanation of AB is given in volume II under the heading 'Trim'.

The KB of a box-shaped vessel would be exactly half the draft, if the vessel is upright and on an even keel. The KB of a ship-shape will, however, be a little greater than half draft, as illustrated by the following figures:



From the above figure, it is obvious that if the shaded part of the box-shaped figure is removed, the figure becomes ship-shaped. The KB of a ship-shape would, therefore, be about five to ten percent more than half its draft.

KB of a triangular-shaped vessel would be two-thirds of its draft, when on an even keel and upright, as shown in the following figure:



Exercise 8

Centre of buoyancy

1 A box-shaped vessel of displacement 1640 t is 50 m long, 10 m wide and 8 m high. Find her KB in SW, if she is on an even keel and upright.

2 A box-shaped vessel 60 m x 10 m x 10 m floats in DW of RD 1.020 at an even keel draft of 6 m. Find her KB in DW of RD 1.004.

3 A triangular-shaped vessel of displacement 650 t floats in DW RD 1.015. Her water plane is a rectangle 30 m x 8 m. Find her KB.

4 A triangular-shaped vessel floats in SW. Her water plane is a rectangle 40 m x 12 m. If her KB is 3.6 m, find her displacement.

5 A homogeneous log of wood 3 m x 0.75 m x 0.75 m floats in SW with one face horizontal. If the RD of the log is 0.8 m, calculate the vertical distance between its COG and its COB.

6 A homogeneous log of wood of 0.5 m square section floats in water of RD 1.005 at a draft of 0.4 m with one of its faces horizontal. Find the vertical distance between its COG and its COB in water of RD 1.020.

7 A cylindrical drum of 0.8 m diameter and 1.5 m height weighs 10 kg. 490 kg of steel is put in it such that it floats with its axis vertical in FW. Find its KB. (Assume π to be 22/7).

8 A barge is prism-shaped such that its deck and keel are identical and parallel; its sides vertical. Its deck consists of three shapes — triangular bow of 12 m each side; rectangular mid-part 80 m long and 12 m wide; semi-circular stern of radius 6 m. If the light displacement of the barge is 500 t and it has 5000 t of cargo in it, find its KB when floating on an even keel in SW. (Assume π to be 3.142).

9 The deck and keel of a flat-bottomed barge are identical. Its sides are vertical. The deck consists of two sections — the bow is a triangle 12 m broad and measures 12 m in the fore and aft direction; the mid-body is a rectangle 50 m long and 12 m broad. If it is floating on an even keel in SW with a displacement of 3444 t, find the position of its COB with reference to the keel and with reference to its after end.

10 A barge 45 m long has a uniform transverse cross-section throughout, which consists of a rectangle above a triangle. The rectangle is 8 m broad and 4 m high. The triangle is apex downwards, 8 m broad and 3 m deep. If the displacement of the barge is 1620 t, find the position of its COB with reference to the keel and also with reference to the after end, if it is upright and on an even keel in FW.

9

Transverse Statical Stability

While studying statical stability it is important to distinguish between list and heel.

List

List is the transverse inclination caused by unequal distribution of weights on either side of the centre line of the ship. In other words, list is caused when the COG of the ship is not on the centre line — an internal cause. A ship with a list will become upright only if the COG is brought to the centre line.

Heel

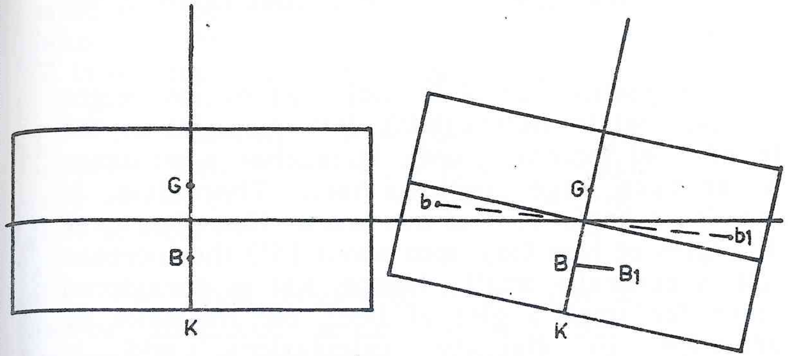
Heel is the transverse inclination of the ship, caused by external forces such as wind, waves, centrifugal force during course alterations, over-tight moorings in port, etc. Since no transverse shift of weights has taken place on board, the position of the COG of the ship remains unaffected by heel.

Transverse Shift of B

When a ship is floating in still water, her COG and COB will be in a vertical line. The forces of gravity and buoyancy, being equal and opposite, will cancel each other out and the ship will be in static equilibrium.

When a ship is heeled over to one side, say to starboard, her underwater volume increases on the

starboard side and decreases on the portside. The COB, being the geometric centre of the underwater volume of the ship, will shift to the lower side (starboard side in this case), as shown in the following figure:-



In the foregoing figure :

b	is the geometric centre of the emerged wedge (of the part that came out of the water due to heeling).
b_1	is the geometric centre of the immersed wedge (of the part that went underwater due to heeling).
B	is the COB before heeling.
B_1	is the COB after heeling.
BB_1	is the shift of COB caused by heeling.

Note: BB_1 is parallel to bb_1 . BB_1 is not parallel to the water line. BB_1 is not parallel to the keel. Angle GBB_1 is not a right angle.

Transverse metacentre (M)

When a vessel is heeled (inclined by an external force), the force of buoyancy, acting vertically upwards through the new position of COB, cuts the centre line of the ship at a point called the transverse metacentre (M). This is illustrated in the next figure.

The position of M is indicated by its height above the keel in metres (KM). KM increases as the angle of heel increases, until it reaches a maximum value at some large angle of heel. Thereafter, it decreases as angle of heel increases. However, over small angles of heel (say upto about 15°) the increase of KM is generally small. Hence, KM is considered constant for small angles of heel, for the sake of convenience in stability calculations, and is sometimes referred to as initial KM.

KM is calculated by adding KB and BM, each of which is calculated separately. The initial KM is, therefore, a function of the draft of the vessel. On board a ship, the initial KM is obtained by consulting a table or graph, supplied by the shipyard, wherein KM is indicated against draft.

Metacentric height (GM)

It is the vertical distance between the centre of gravity and the metacentre. GM is termed positive when G is below M i.e., when KG is less than KM and negative when G is above M i.e. when KG is greater than KM. GM is illustrated in the next figure.

Over small angles of heel, wherein KM may be considered constant, GM also is considered constant and is referred to as initial GM.

Righting lever (GZ)

When a vessel is heeled (inclined by an external force), the force of buoyancy, acting vertically upwards through the new position of COB, becomes separated from the force of gravity, acting vertically downwards through the COG, by a horizontal distance called the righting lever (GZ). GZ is illustrated by the following figure.

GZ normally increases as angle of heel increases until it reaches a maximum value at some large angle of heel. Thereafter, GZ decreases as angle of heel increases.

For small angles of heel (upto about 15°), wherein KM, and hence GM, may be considered constant, $GZ = GM \cdot \sin\theta$ in which θ is the angle of heel and GM is the initial GM, as is apparent in the following figure.

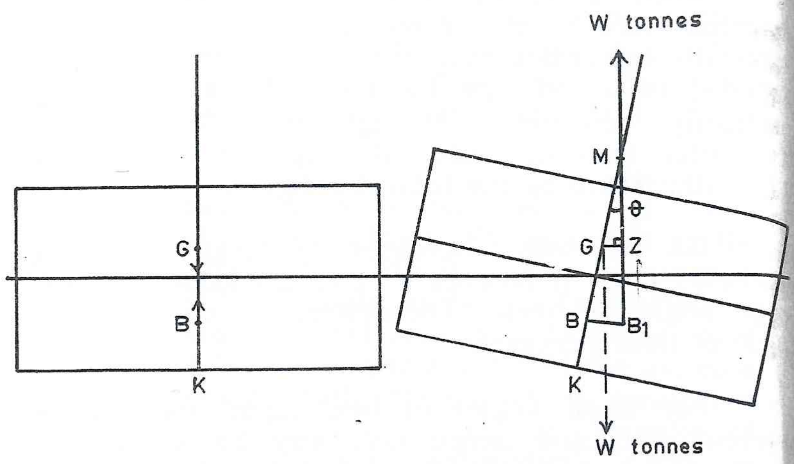
For large angles of heel, GZ can be calculated by the wall-sided formula:

$$GZ = \sin\theta\,(GM + \tfrac{1}{2}\,BM\,\tan^2\theta)$$

This formula can be used whenever the ship's sides within the immersed wedge and the emerged wedge are parallel i.e., until the deck edge goes under water. θ is the angle of heel, GM the initial GM, and BM is the height of the initial metacentre above the COB before heeling, as shown in the following figure.

On board ships, the value of GZ can be obtained for various angles of heel by use of cross curves of stability (GZ curves or KN curves) described in volume II. These curves are supplied by the shipyard.

FIGURE ILLUSTRATING BM, KM, GM, GZ, etc.



K	:	Keel. G : COG.
θ	:	Angle of heel.
B	:	COB before heeling.
B_1	:	COB after heeling.
BB_1	:	Shift of COB due to heel.
M	:	Transverse metacentre.
GM	:	Metacentric height.
GZ	:	Righting lever.
W	:	Displacement in tonnes.
W . G Z	:	Righting moment.

Righting moment

When a vessel is heeled (inclined by an external force), the forces of gravity and buoyancy, being equal and opposite, become separated by a horizontal distance called the righting lever and form a couple which tends to return the vessel to upright. The moment of this couple is a measure of the tendency of the vessel to return to upright and is hence called the righting moment or 'Moment of statical stability'.

RM = W . GZ for all angles of heel.

For small angles of heel, where GM may be considered constant, GZ = GM . Sin θ and hence

RM = W . GM . Sin θ for small angles of heel.

Exercise 9

Moment of statical stability

1. A ship of 10 000 t displacement has a GM of 0.4 m. Calculate the moment of statical stability when she is heeled by 5°.

2. A ship of 12 000 t displacement is heeled by 6°. If her righting lever is then 0.1 m, find the moment of statical stability. If her KM is 8.2 m, find her KG.

3. When a ship of 14000 t displacement is heeled by 8°, her moment of statical stabiity is 400 tm. If KG is 7.3 m, find KM.

4. A ship of 8000 t displacement has KB 3.5 m, KM 6.5 m, and KG 6 m. Find her moment of statical stability at 20° heel, assuming that her deck edge remains above water (i.e. she is still wall-sided at that angle of heel).

5. A ship of 4000 t displacement has KG 5.1 m, KB 2.1 m, KM 5.5 m. Find the moment of statical stability when she heels 24°, assuming that she is wall-sided.

10

Equilibrium Of Ships

Stable equilibrium

When a vessel is heeled (inclined by an external force), if she tends to come back to her original condition, she is said to be in stable equilibrium.

For a vessel to be stable, her GM must be positive i.e. KG must be less than KM, as shown in the figure on the next page.

Note COG As explained in Chapter 9, the position of COG remains unaffected by heel whereas the COB shifts to the lower side. The forces of gravity and buoyancy form a couple which tends to return the vessel to her original condition. A vessel with a list also may be stable.

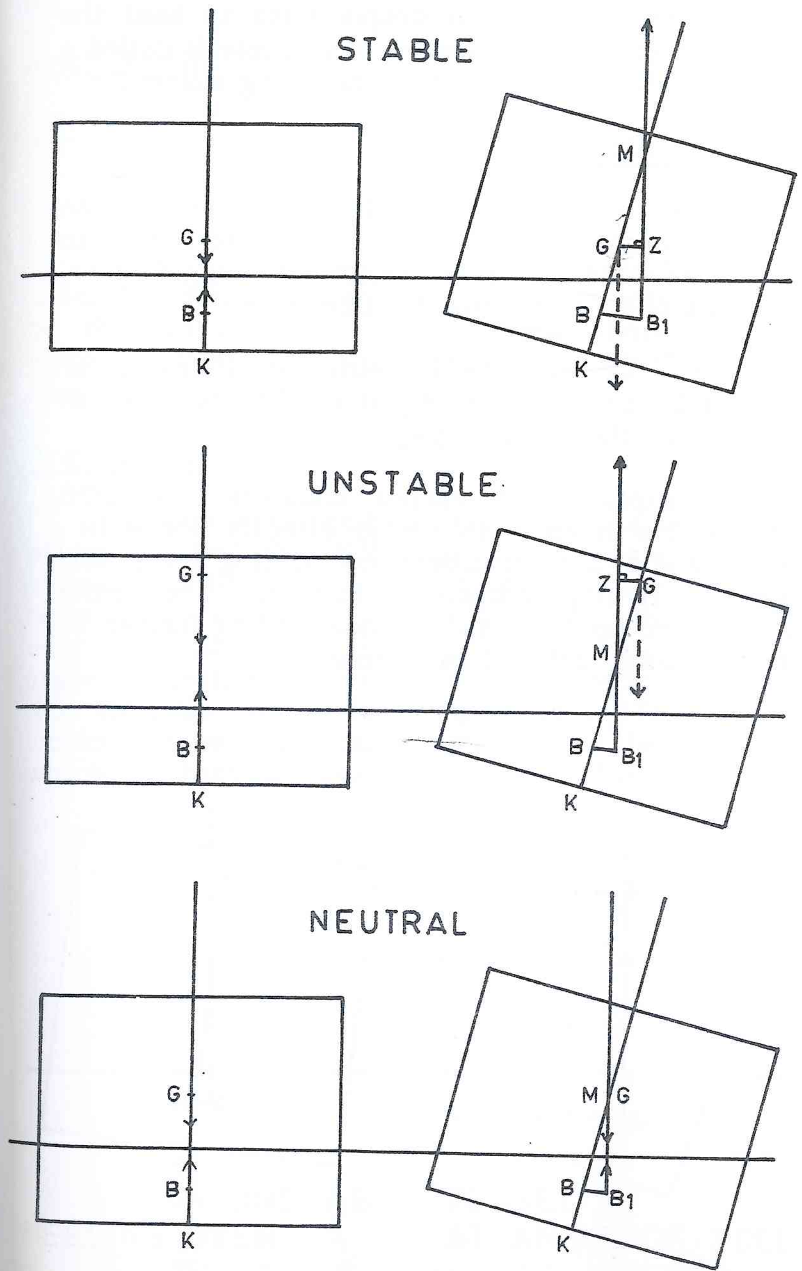
Unstable equilibrium

When a vessel is heeled (inclined by an external force), if she tends to continue heeling further, she is said to be in unstable equilibrium.

For a vessel to be unstable, her GM must be negative i.e., KG must be greater than KM, as shown in the figure on the next page.

Note As explained in earlier chapters, the COB shifts to the lower side. M is directly above B_1. The

EQUILIBRIUM OF SHIPS



forces of gravity and buoyancy form a couple but, G being higher than M, this couple tries to heel the vessel further. The moment of this couple is called a 'negative righting moment' or a 'capsizing moment'.

Neutral equilibrium

When a vessel is heeled (inclined by an external force), if she has no tendency to return to her original condition or to continue heeling further, she is said to be in neutral equilibrium.

For a vessel to be in neutral equilibrium, her GM must be zero i.e., KG equal to KM, as shown in the figure on the previous page.

Note As explained in earlier chapters, the COB shifts to the lower side. M is directly above B_1. Since G and M are coincident, no righting lever, and hence no righting moment, is formed. The vessel thus has no tendency to continue heeling further or to return to her original condition.

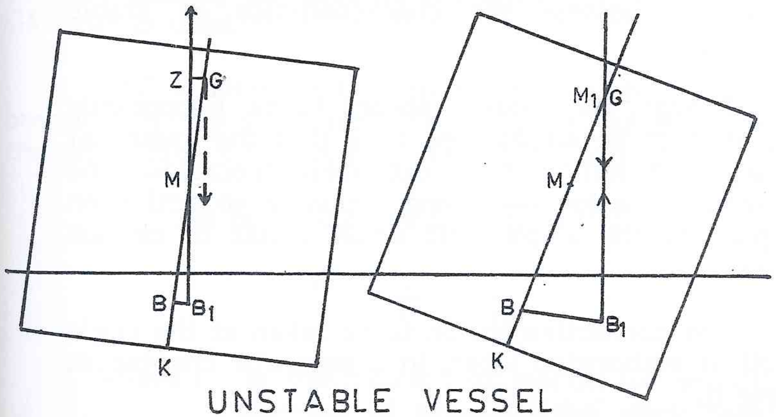
11

More About Unstable Equilibrium

The impression obtained by reading about unstable equilibrium, in the previous chapter, would be that an unstable vessel would continue heeling more and more until she capsized. Though this could happen, this is not always the case.

Angle of loll

It was mentioned earlier, under the definition of metacentre, that KM increases as angle of heel increases until it reaches a maximum value at some large angle of heel. As the unstable vessel heels over more and more, it may happen that, at some angle of heel, KM increases sufficiently to equal to KG. (see M_1 in the following figure). The vessel would then be in neutral equilibrium and the angle at which this happens is called the angle of loll.



UNSTABLE VESSEL

HEELING OVER AT ANGLE OF LOLL

In other words, when an unstable vessel heels over to progressively increasing angles of heel, it may happen that, at some angle of heel, the COB may come vertically below the COG. The vessel would then be in neutral equilibrium. The angle of heel at which this happens is called the angle of loll.

If any opening goes underwater, at this stage, progressive flooding would take place and the vessel would capsize. The angle of loll could be on either side of the vessel. If she is at her angle of loll to one side, and a wave was to roll her sufficiently to the other side, she would flop over to her angle of loll on the other side.

When at the angle of loll, if a wave causes the vessel to heel a little more, KM would increase and become more than KG. A small righting moment, so formed. would return the vessel to the angle of loll.

When at the angle of loll, if a wave causes the vessel to heel less, KM would decrease and become less than KG. A small capsizing moment, so formed, would return the vessel to the angle of loll.

The vessel at the angle of loll, therefore, appears to possess the characteristics of stable equilibrium.

Though the vessel appears to be temporarily safe, it must be emphasized here that the vessel at the angle of loll is in an extremely precarious and dangerous situation — wrong action or no action on the part of the ship's staff would result in certain disaster.

The corrective action to be taken at the angle of loll is elaborated later, in a separate chapter in volume II.

12

Free Surface Effect

When a vessel with a slack (partly full) tank rolls at sea, the liquid in the slack tank would move towards the lower side during each roll, thereby causing the angle of roll and the period of roll to increase. Because the vessel behaves as if her GM has been reduced, we say that a slack tank causes a virtual (imaginary) loss of GM. This is called free surface effect (FSE).

The virtual loss of GM can be calculated quite easily and is called free surface correction (FSC). In order to indicate whether FSC has been applied or not, the GM before subtracting FSC is called 'Solid GM' and after subtracting FSC it is called 'Fluid GM.' In all stability calculations involving GM, it is fluid GM that is used.

FSC depends on the length and breadth (mainly breadth) of the slack tank. The quantity of liquid in the slack tank makes only a very small difference.

FSC can be calculated by the formula:

$$FSC = \frac{i}{V} \times \frac{d_i}{d_o}$$

Where i is the moment of inertia (or second moment of area) of the slack tank surface about its centre line, in m^4.

V is the volume of displacement of the ship, in m^3.

d_i is the density of liquid in the slack tank, in tm^{-3}

d_o is the density of water outside (in which the ship is floating), in tm^{-3}.

FSC is the free surface correction in m, caused by this slack tank.

Since displacement = volume of displacement x density of water displaced, the denominator in the foregoing formula may be substituted by W, the displacement of the ship in tonnes. The formula then becomes:

$$FSC = \frac{i\,d_i}{W}$$

Since 'i' is in m^4 and 'd_i' is in tm^{-3}, '$i\,d_i$' would be in tm and is hence called the free surface moment or FSM.

When several tanks are slack on a ship, the FSM of each tank is calculated separately and then added together to obtain the total FSM. This total FSM divided by the final W of the ship would give the total FSC of all the slack tanks.

On a ship, the 'i' of each tank about the tank's centre-line is readily available in the stability particulars supplied by the shipyard.

Example 1

Given the following particulars of a ship, calculate her fluid GM:

W = 10000 t, KG = 9.0 m, KM = 9.8 m, moment

of inertia of surface of tank about its centre line = 1242 m^4, RD of heavy fuel oil in the tank = 0.95.

$$FSC = \frac{i\,d_i}{W} = \frac{1242 \times 0.95}{10,000} = 0.118 \text{ m}$$

KM	=	9.8 m
KG	=	9.0 m
Solid GM	=	0.8 m
FSC	=	0.118m
Fluid GM	=	0.682m

Example 2

The stability particulars of a ship indicate that, for her present condition, her W = 5532 t, KM = 8.7 m, 'i' of No.3 DBT about its centre line = 1428 m^4. If No. 3 DBT is partly full of DO of RD 0.88, and the ship's KG is 8.5 m, calculate her fluid GM.

$$FSC = \frac{i\,d_i}{W} = \frac{1428 \times 0.88}{5532} = 0.227 \text{ m}$$

KM	=	8.7 m
KG	=	8.5 m
Solid GM	=	0.2 m
FSC	=	0.227
Fluid GM	=	–.027m

Note The ship has a negative fluid GM and is hence unstable.

Example 3

A vessel has a displacement of 16635 t, KM 8.25 m, KG 7.4 m. She has the following tanks slack:

No 1 DBT	containing	SW, i = 400 m^4
No 3 Centre	"	HFO, i = 1200 m^4

No 4 Stbd	containing	HFO	$i = 270\ m^4$
No 5 Port	"	DO	$i = 180\ m^4$
No 8 Port	"	FW	$i = 25\ m^4$
No 8 Stbd	"	FW	$i = 15\ m^4$

If RD of HFO is 0.95, DO is 0.88 and SW is 1.025, find her final fluid GM.

Tank	Contents	i x di	=	FSM
No. 1 DBT	SW	400 x 1.025	=	410
No 3 Centre	HFO	1200 x 0.95	=	1140
No 4 Stbd	HFO	270 x 0.95	=	256.5
No 5 Port	DO	180 x 0.88	=	158.4
No 8 Port	FW	25 x 1	=	25
No 8 Stbd	FW	15 x 1	=	15
		Final FSM	=	2004.9 tm

$$FSC = \frac{FSM}{W} = \frac{2004.9}{16635} = 0.121\ m$$

KM = 8.250 m
KG = 7.400 m

Solid GM = 0.850 m
FSC = 0.121 m

Fluid GM = 0.729 m

Example 4

On a vessel of 18000 t displacement KM 8.9 m, KG 8.3 m, a DB tank is partly full of FW. If the tank surface is rectangular, 20 m long and 18 m wide, calculate her fluid GM.

'i' of rectangular tank about its centre line $= \frac{lb^3}{12} = \frac{20 \times 18^3}{12}\ m^4$

$$FSC = \frac{i\ di}{W} = \frac{20 \times 18^3}{12} \times \frac{1.0}{18000} = 0.54\ m$$

KM = 8.90 m
KG = 8.30 m

Solid GM = 0.60 m
FSC = 0.54 m

Fluid GM = 0.06 m

Example 5

On a vessel of 5000 t displacement, KM 7.8 m, KG 7.0 m, No.2 port DB tank is partly full of FW. If this tank is 15 m long and 9 m broad, find the fluid GM.

'i' of rectangular tank about its centre line

$$= \frac{lb^3}{12} = \frac{15 \times 9^3}{12}\ m^4$$

$$FSC = \frac{i\ di}{W} = \frac{15 \times 9^3}{12} \times \frac{1.0}{5000} = 0.182\ m$$

KM = 7.800 m
KG = 7.000 m

Solid GM = 0.800 m
FSC = 0.182 m

Fluid GM = 0.618 m

EFFECT OF TANK-BREADTH ON FSC

The breadth of a slack tank has an enormous effect on the FSC caused. This is illustrated simply by worked examples 6, 7, 8 and 9.

Example 6

On a ship of 10000 t displ, No 3 DB tank is partly full of SW. If the tank is 20 m long and is 18 m wide from shipside to shipside, calculate the FSC caused.

$$FSC = \frac{i\,d_i}{W} = \frac{lb^3}{12} \times \frac{d_i}{W}$$

$$= \frac{20 \times 18^3 \times 1.025}{12 \times 10\,000}$$

$$= 0.996 \text{ m}$$

Example 7

Same ship as example 6, except that No.3 DB tank has a watertight centre girder dividing it into port and starboard tanks of equal breadth. Find the FSC when both, P & S tanks are slack.

FSC for No 3 Stbd tank $= \frac{i\,d_i}{W} = \frac{lb^3}{12} \times \frac{d_i}{W}$

$= \frac{20 \times 9^3}{12} \times \frac{1.025}{10\,000}$

$= 0.1245$ m

FSC for No 3 Port tank $= 0.1245$ m (tanks are identical)

Total FSC for No 3 P & S $= 0.249$ m

Example 8

Same ship as example 6, except that No 3 DB tank is divided into three watertight tanks — P, S & C — of equal breadth. Find the FSC when all three tanks are slack.

FSC for No 3 Port tank $= \frac{i\,d_i}{W} = \frac{lb^3}{12} \times \frac{d_i}{W}$

$= \frac{20 \times 6^3 \times 1.025}{12 \times 10\,000}$

$= 0.0369$ m

FSC for No 3 Stbd tank $= 0.0369$ m (because all three tanks are identical)

FSC for No 3 Centre tank $= 0.0369$ m

$= 0.1107$ m

Example 9

Same ship as example 6, except that No 3 DB tank is divided into four identical watertight tanks — Port Outer, Port Inner, Stbd Inner, Stbd Outer. Find the FSC when all four tanks are slack.

FSC for No 3 PO tank $= \frac{i\,d_i}{W} = \frac{lb^3}{12} \times \frac{d_i}{W}$

$= \frac{20 \times 4.5^3 \times 1.025}{12 \times 10\,000}$

$= 0.01557$ m

FSC for No 3 PI tank $= 0.01557$ m (because all four tanks are identical)

FSC for No 3 SI tank $= 0.01557$ m

FSC for No 3 SO tank $= 0.01557$ m

Total FSC for all 4 tanks $= 0.0623$ m

Analysis of results of examples 6, 7, 8 & 9

Single undivided DB tank,	FSC	= 0.996 m
Divided into 2 tanks of equal breadth, both slack,	total FSC	= 0.249 m
Divided into 3 tanks of equal breadth, all 3 slack,	total FSC	= 0.111 m
Divided into 4 tanks of equal breadth, all 4 slack,	total FSC	= 0.062 m

From the foregoing it is clear that when a tank is divided, in breadth, into a number of identical watertight compartments (n), the total FSC when all the compartments are slack is $1/n^2$ of the FSC that would have occured if the slack tank was undivided. This is elaborated below:-

Example 6

Single undivided DB Tank FSC = 0.996 m

Example 7

n = 2, So FSC = $\frac{.996}{n^2}$ = $\frac{.996}{4}$ = 0.249 m

Example 8

n = 3, So FSC = $\frac{.996}{n^2}$ = $\frac{.996}{9}$ = 0.111 m

Example 9

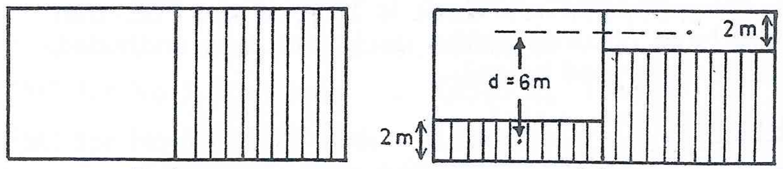
n = 4, So FSC = $\frac{.996}{n^2}$ = $\frac{.996}{16}$ = 0.062 m

Note: The answers arrived at above are the same as the answers obtained in each example wherein the FSC was calculated separately for each compartment and then added together.

The effect of the breadth of a slack tank on the FSC is a very important factor to consider when deciding on the action to take when a ship has a very small, or even negative, GM.

Example 10

A vessel of 10000 t displacement, KM 9.3 m, KG 7.3 m, has two rectangular, identical deeptanks, Port and Stbd, each 15 m long, 10 m wide and 8 m deep. The starboard deep tank is full of SW while the port deep tank is empty. Calculate the GM of the ship when one quarter of the water in the starboard deep tank is transferred to the port deep tank.



Before After

Mass of SW in tank = Volume of SW x density of SW

= 15 x 10 x 8 x 1.025

= 1230 t

Mass of water transferred = $\frac{1}{4}$ x 1230 = 307.5 t

$GG_1\downarrow = \frac{dw}{W} = \frac{6 \times 307.5}{10\,000} = 0.185$ m

Old KG	=	7.300 m
$GG_1\downarrow$	=	0.185 m
New KG	=	7.115 m
KM	=	9.300 m
Solid GM	=	2.185 m

FSC for port tank = $\frac{i\,d_i}{W} = \frac{lb^3}{12} \times \frac{d_i}{W}$

$= \frac{15 \times 10^3}{12} \times \frac{1.025}{10\,000}$

= 0.128 m

FSC for stbd tank = 0.128 m

Total FSC for P & S = 0.256 m

OR

FSC if tank is undivided = $\frac{lB^3}{12} \times \frac{d_i}{W}$

$= \frac{15 \times 20^3}{12} \times \frac{1.025}{10\,000}$

= 1.025 m

FSC when n = 2, both sides slack = 1.025 x $\frac{1}{n^2}$

$= \frac{1.025}{4} = 0.256$ m

Solid GM = 2.185 m

FSC = 0.256 m

Fluid GM = 1.929 m

Exercise 10

Free surface effect

1 On a ship of 5000 t displacement, a tank is partly full of DO of RD 0.88. If the moment of inertia of the tank about its centre line is 242 m^4, find the FSC.

2 If the tank in question 1 was partly full of SW instead of DO, find the FSC.

3 On a ship of W 6000 t, KM 7.4 m, KG 6.6 m, a double bottom tank of i 1200 m^4 is partly full of FW. Find the GM fluid.

4 Given the following particulars, find the GM fluid: W = 8800 t, tank of i = 1166 m^4 is partly full of HFO of RD 0.95, KM 10.1 m, KG 9.0 m.

5 On a vessel of W 16000 t, No 4 port DB tank 20 m long and 8 m wide is partly full of DW ballast of RD 1.010. Find the FSC.

6 A vessel has a deeptank on the starboard side 12 m long 9 m wide which is partly full of coconut oil of RD 0.72. If W = 12000 t, KM = 9 m and KG = 8.5 m, find the GM fluid.

7 A vessel displacing 8000 t, has a rectangular deep tank 10 m long 8 m wide and 9 m deep full of SW. The KM is 7 m and KG 6.2 m. Find the GM when 1/3 of this tank is pumped out.

Note: Since dimensions of tank are given, change of KG of tank due to change of sounding has to be considered.

8 A ship of W 5000 t has a tank 16 m long, 10 m wide and 4 m deep which is empty. KM is 7.2 m and KG 7.0 m. Find the GM fluid if 400 t of oil of RD 0.95 are received in it. (See note under previous question).

9 A vessel has two deep tanks, port and starboard, each 12 m long, 5 m wide and 8 m deep. The port side is full of SW while the starboard side is empty. W = 9840 t, KM = 8.5 m, KG = 8.0 m. Calculate the GM fluid if SW is transferred from P to S until each tank has equal quantity of ballast.

10 A Ship displacing 10000 t has KM 9.9 m. The following is her present condition:

Tank	KG (m)	i (m^4)	Contents	RD	Remarks
FP Tank	6.3	10	SW	1.025	Full
No 1 DBT	1.15	420	HFO	0.95	Slack
No 2 P or S	0.65	720	HFO	0.95	Port slack stbd empty
No 3 P or S	0.65	240	SW	1.025	Port full stbd slack
No 3 C	0.60	1200	HFO	0.95	Full
No 4 P or S	0.70	300	FW	1.00	Both slack
No 5 P	0.85	180	DO	0.88	Slack
No 5 S	0.85	100	HFO	0.95	Full
AP Tank	8.80	20	SW	1.025	Empty

If the final KG is 8.954 m, find the final GM fluid.