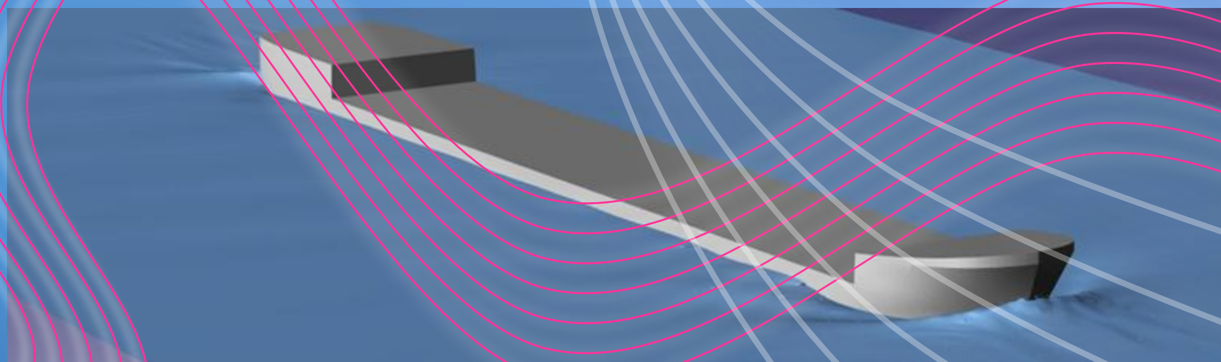
CONTROL OF SEAKEEPING

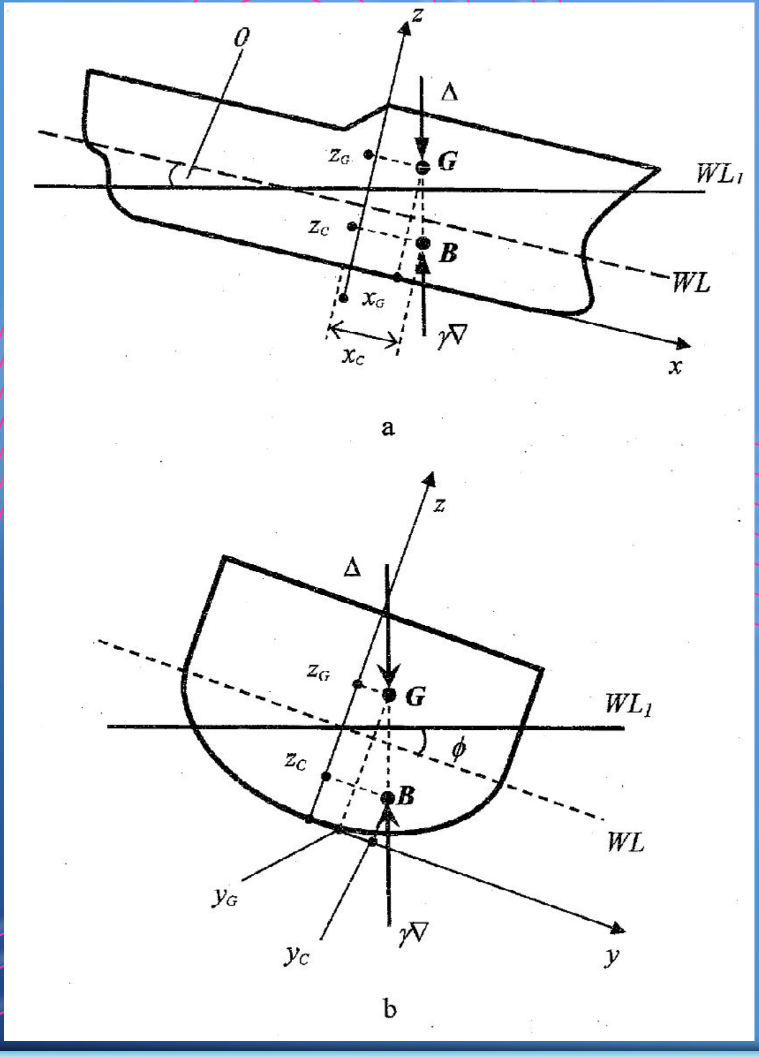


Igor F. Davydov, PhD, Associate Professor

Main seakeeping qualities:

I. Floatability
II. Stability
III. Damage trim and stability (floodability)
IV. Ship's strength
V. Ship resistance
VI. Ship propulsion
VII. Ship motion
VIII. Manoeuvrability

Ship's equilibrium position under still water condition and equilibrium equations:



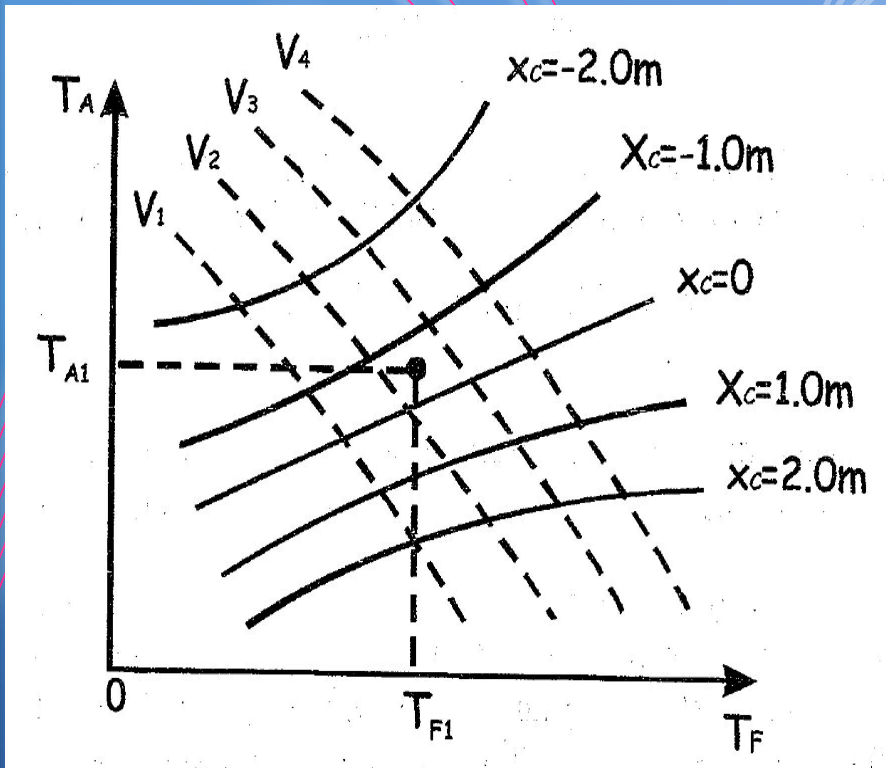
$$\left.\begin{aligned} \Delta &= \rho g V; \\ (x_c - x_g) &= (z_g - z_c)tg\Psi; \\ (y_c - y_g) &= (z_g - z_c)tg\Theta \end{aligned}\right\}$$

Where:

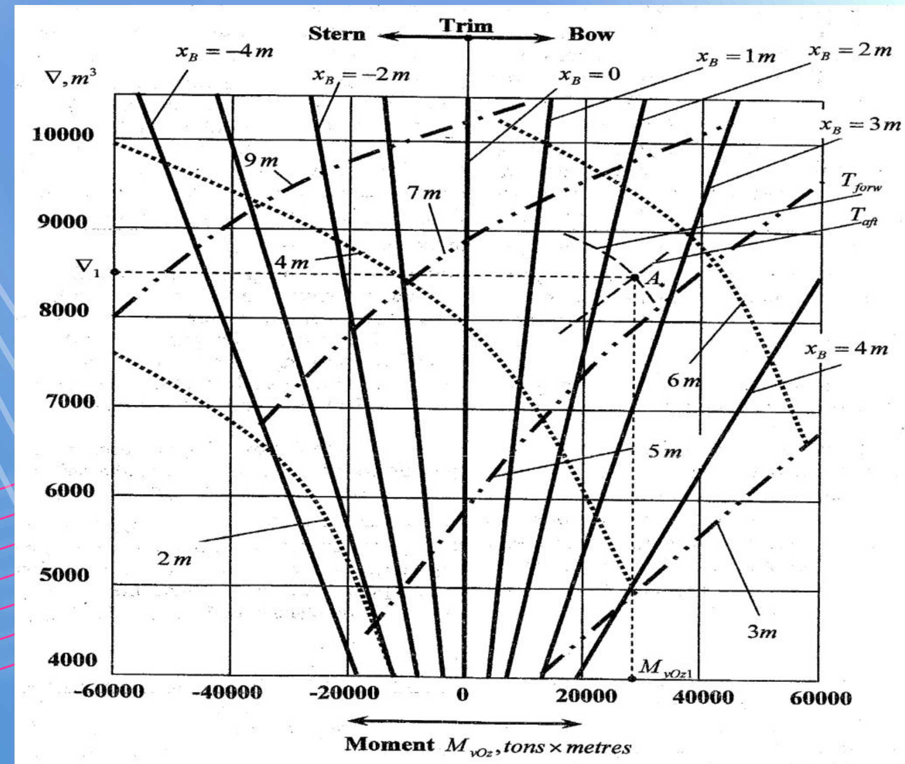
x_c, y_c, z_c – are coordinates of the center of buoyancy;

x_g, y_g, z_g – are coordinates of the center of gravity.

Types of trim diagram



Firsoff diagram



Peterson diagram

INTERNATIONAL MARITIME ORGANIZATION

IMO

Stability Requirements

INTERNATIONAL CODE ON INTACT STABILITY, 2008
(2008 IS CODE)

RESOLUTION MSC.319(89)
(adopted on 20 May 2011)

General criteria

1. Criteria regarding initial stability
2. Criteria regarding righting lever curve properties
3. Severe wind and rolling criterion (weather criterion)

IS CODE CONTAINS INTACT STABILITY CRITERIA FOR THE FOLLOWING TYPES OF SHIPS AND OTHER MARINE VEHICLES OF 24 M IN LENGTH AND ABOVE, UNLESS OTHERWISE STATED:

.1 cargo ships;
.2 cargo ships carrying timber deck cargoes;
.3 passenger ships;
.4 fishing vessels;
.5 special purpose ships;
.6 offshore supply vessels;
.7 mobile offshore drilling units;
.8 pontoons; and
.9 cargo ships carrying containers on deck and containerships.

GENERAL CRITERIA

All criteria shall be applied for all conditions of loading.
Free surface effects shall be accounted for in all conditions of loading.
Each ship shall be provided with a stability booklet, approved by the Administration, which contains sufficient information to enable the master to operate the ship in compliance with the applicable requirements contained in the Code.
Each ship shall be provided with a stability booklet, approved by the Administration, which contains sufficient information to enable the master to operate the ship in compliance with the applicable requirements contained in the Code. If a stability instrument is used as a supplement to the stability booklet for the purpose of determining compliance with the relevant stability criteria such instrument shall be subject to the approval by the Administration

Criteria regarding initial stability

The initial metacentric height GM_0 shall not be less than 0.15 m.

Criteria regarding righting lever curve properties

1 The area under the righting lever curve (GZ curve) shall not be less than 0.055 metre-radians up to Θ = 30° angle of heel and not less than 0.09 metre-radians up to ϕ = 40° or the angle of down-flooding Θ_f, if this angle is less than 40°. Additionally, the area under the righting lever curve (GZ curve) between the angles of heel of 30° and 40° or between 30° and Θ_f, if this angle is less than 40°, shall not be less than 0.03 metre-radians.

2 The righting lever GZ shall be at least 0.2 m at an angle of heel equal to or greater than 30°.

3 The maximum righting lever shall occur at an angle of heel not less than 25°. If this is not practicable, alternative criteria, based on an equivalent level of safety, may be applied subject to the approval of the Administration.

Θ_f is an angle of heel at which openings in the hull, superstructures or deckhouses which cannot be closed weathertight immerse. In applying this criterion, small openings through which progressive flooding cannot take place need not be considered as open.

Severe wind and rolling criterion (weather criterion)

The ability of a ship to withstand the combined effects of beam wind and rolling shall be demonstrated, with reference to figure presented below as follows:

.1 the ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline which results in a steady wind heeling lever (*lw1*);

.2 from the resultant angle of equilibrium (Θ_0), the ship is assumed to roll owing to wave action to an angle of roll (Θ_1) to windward. The angle of heel under action of steady wind (Θ_0) should not exceed 16° or 80% of the angle of deck edge immersion, whichever is less;

.3 the ship is then subjected to a gust wind pressure which results in a gust wind heeling lever (*lw2*); and

.4 under these circumstances, area *b* shall be equal to or greater than area *a*, as indicated in figure below:

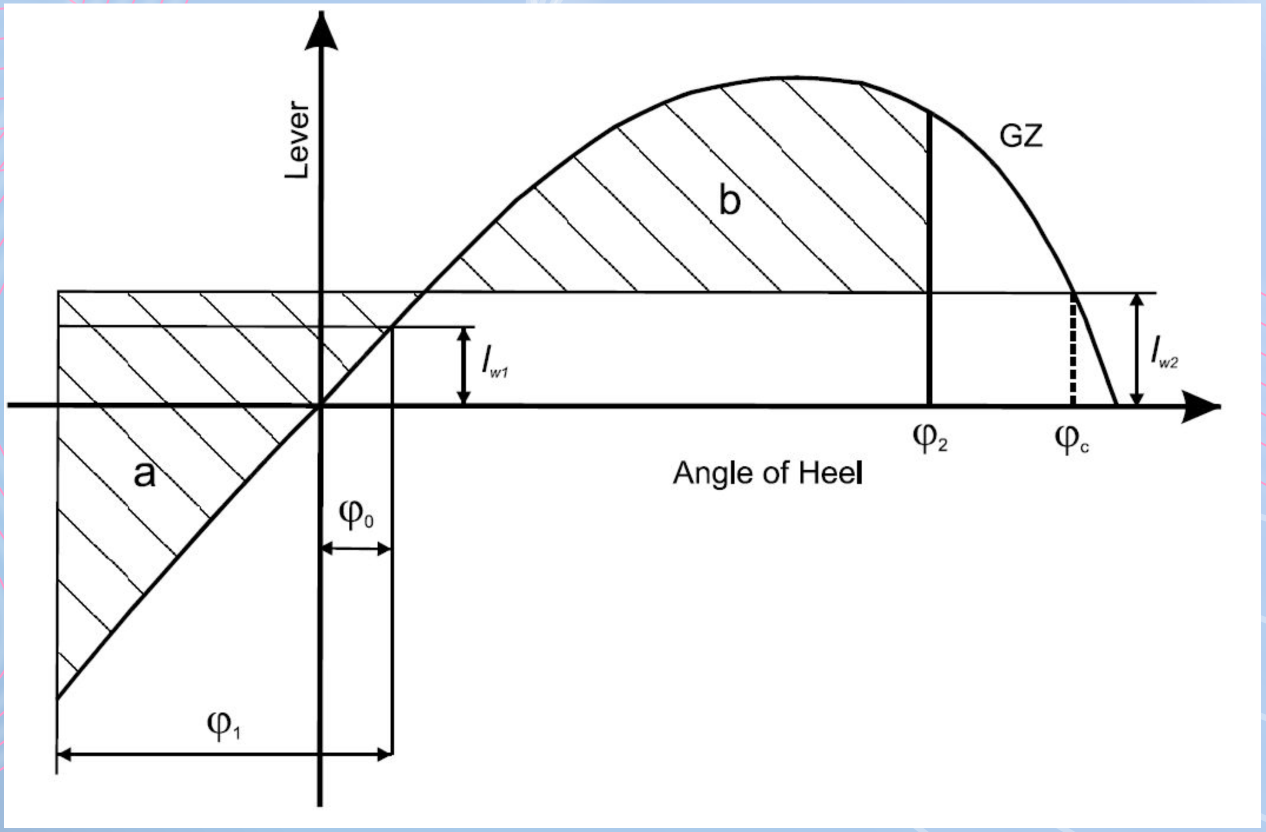


Figure Severe wind and rolling

where the angles in figure are defined as follows:
ϕ_0 = angle of heel under action of steady wind
ϕ_1 = angle of roll to windward due to wave action ϕ_2 = angle of down-flooding (ϕ_f) or 50° or ϕ_c, whichever is less,
where:
ϕ_f = angle of heel at which openings in the hull, superstructures or deckhouses which cannot be closed weathertight immerse.
In applying this criterion, small openings through which progressive flooding cannot take place need not be considered as open
ϕ_c = angle of second intercept between wind heeling lever *lw2* and GZ curves.

The wind heeling levers *lw1* and *lw2* are constant values at all angles of inclination and shall be calculated as follows:
where:

$$l_{w1} = \frac{P \times A \times Z}{1000 \times g \times \Delta} \text{ (m)}$$

$$l_{w2} = 1.5 \times l_{w1} \text{ (m)}$$

P = wind pressure of 504 Pa. The value of P used for ships in restricted service may be reduced subject to the approval of the Administration
A = projected lateral area of the portion of the ship and deck cargo above the waterline (m^2)
Z = vertical distance from the centre of A to the centre of the underwater lateral area or approximately to a point at one half the mean draught (m)
Δ = displacement (t)
g = gravitational acceleration of 9.81 m/s^2.

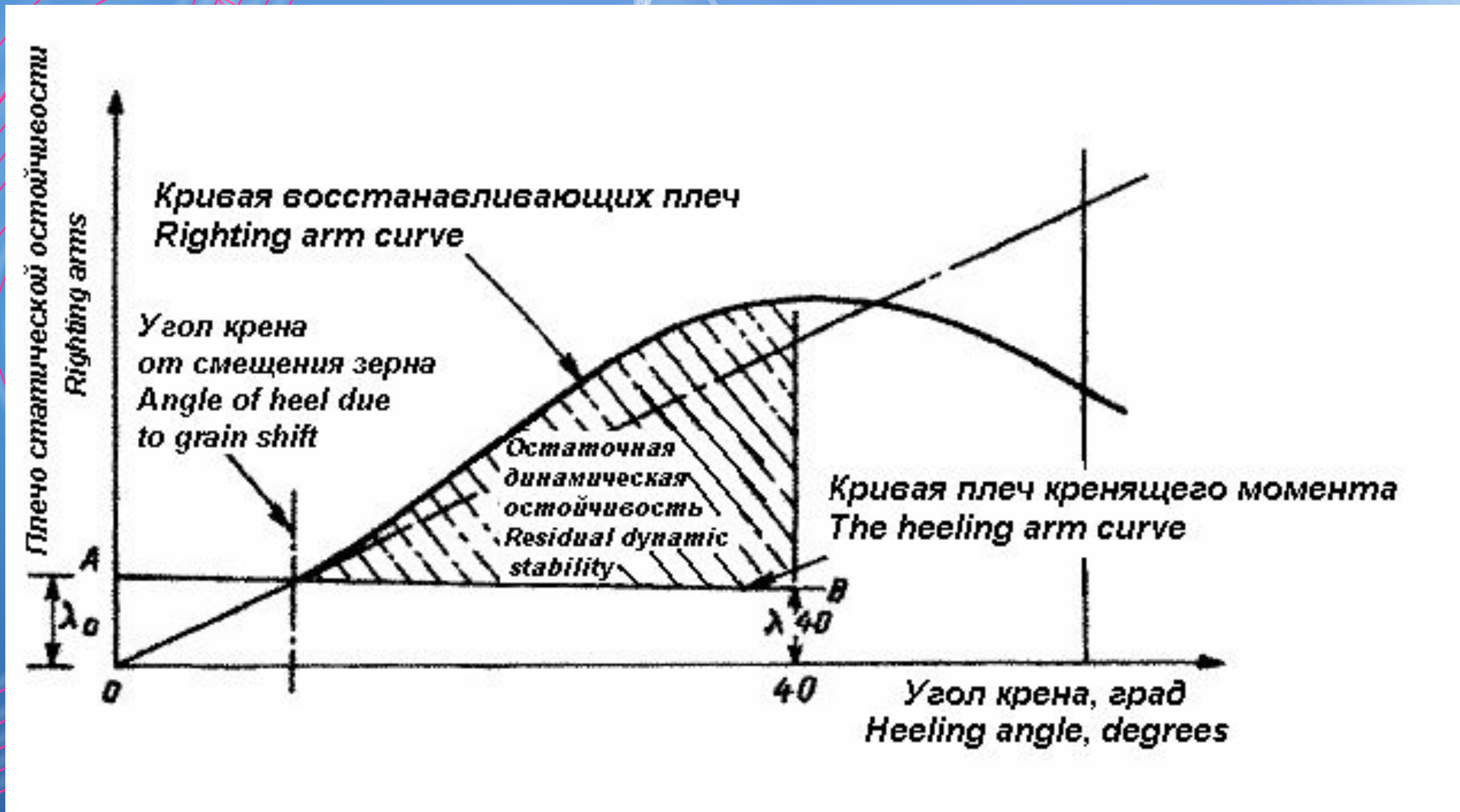
Stability Requirements

1. The initial metacentric height, after correction for the free surface effects of liquids in tanks, shall not be less than 0.3 m.

2. The angle of heel due to the shift of grain shall not be greater then 12° or the angle at which the deck edge is immersed, whichever is the lesser.

3. In the statical stability diagram, the net of residual area between the heeling arm curve and the righting arm curve up to the angle of heel of maximum difference between the ordinates of the two curves, or 40° or the angle of flooding (Θf), whichever is the least, shall in all conditions of loading be not less than 0.075 metre-radians.

INTERNATIONAL CODE
FOR THE SAFE CARRIAGE OF GRAIN IN BULK
RESOLUTION MSC.23(59)
(adopted on 23 May 1991)



(1) Where:

$$\lambda_0 = \frac{\text{assumed volumetric heeling moment due to transverse shift}}{\text{stowage factor x displacement}};$$

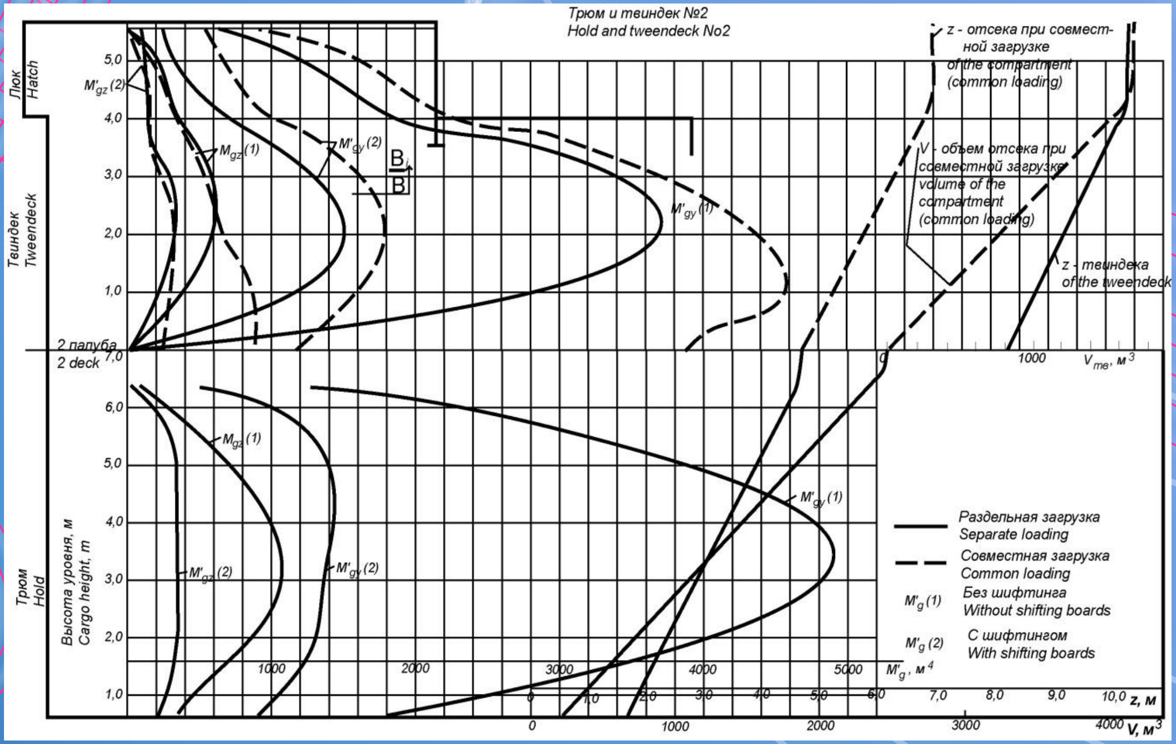
$$\lambda_{40} = 0.8 \times \lambda_0;$$

Stowage factor = volume per unit weight of grain cargo;

Displacement = weight of ship, fuel, fresh water, stores etc. and cargo.

(2) The righting arm curve shall be derived from cross-curves whicn are sufficient in number to accurately define the curve for the purpose of these requirements and shall include cross-curves at 12° and 40°.

INTERNATIONAL CODE
FOR THE SAFE CARRIAGE OF GRAIN IN BULK
RESOLUTION MSC.23(59)
(adopted on 23 May 1991)



Relations between grain level, compartment's volume *V*, CG altitude *z*, horizontal *M*gy and vertical *M*gz moments due to grain shifting in hold and tweendeck

INTERNATIONAL STABILITY REQUIREMENTS FOR THE SAFE CARRIAGE OF NON-COHESIVE SOLID BULK CARGO

1. The initial metacentric height, after correction for the free surface effects of liquids in tanks, shall not be less than 0.70 m.

2. The angle of heel due to the shift of grain shall not be greater then 12° or the angle at which the deck edge is immersed, whichever is the lesser.

3. In the statical stability diagram, the net of residual area between the heeling arm curve and the righting arm curve up to the angle of heel of maximum difference between the ordinates of the two curves, or 40° or the angle of flooding (Θ_f), whichever is the least, shall in all conditions of loading be not less than 0.120 metre-radians.

INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS

A damage stability analysis serves the purpose to provide proof of the damage stability standard required for the respective ship type. At present, two different calculation methods, the deterministic concept and the probabilistic concept are applied.

SCOPE OF ANALYSIS AND DOCUMENTATION ON BOARD

1. The scope of subdivision and damage stability analysis is determined by the required damage stability standard and aims at providing the ship's master with clear intact stability requirements. In general, this is achieved by determining *KG*-respective *GM*-limit curves, containing the admissible stability values for the draught range to be covered.

2. Within the scope of the analysis thus defined, all potential or necessary damage conditions will be determined, taking into account the damage stability criteria, in order to obtain the required damage stability standard. Depending on the type and size of ship, this may involve a considerable amount of analyses.

SCOPE OF ANALYSIS AND DOCUMENTATION ON BOARD

3. Referring to SOLAS chapter regulation 19, the necessity to provide the crew with the relevant information regarding the subdivision of the ship is expressed, therefore plans should be provided and permanently exhibited for the guidance of the officer in charge. These plans should clearly show for each deck and hold the boundaries of the watertight compartments, the openings therein with means of closure and position of any controls thereof, and the arrangements for the correction of any list due to flooding. In addition, Damage Control Booklets containing the aforementioned information should be available.

INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS

GENERAL DOCUMENTS

For the checking of the input data, the following should be submitted:

.1 main dimensions;
.2 lines plan, plotted or numerically;
.3 hydrostatic data and cross curves of stability (including drawing of the buoyant hull);
.4 definition of sub-compartments with moulded volumes, centres of gravity and permeability;
.5 layout plan (watertight integrity plan) for the sub-compartments with all internal and external opening points including their connected subcompartments, and particulars used in measuring the spaces, such as general arrangement plan and tank plan. The subdivision limits, longitudinal, transverse and vertical, should be included;
.6 light service condition;
.7 load line draught;
.8 coordinates of opening points with their level of tightness (e.g., weathertight, unprotected);

GENERAL DOCUMENTS

For the checking of the input data, the following should be submitted:

.9 watertight door location with pressure calculation;
.10 side contour and wind profile;
.11 cross and down flooding devices and the calculations thereof according to resolution MSC.245(83) with information about diameter, valves, pipe lengths and coordinates of inlet/outlet;
.12 pipes in damaged area when the destruction of these pipes

DOCUMENTATION

1 Initial data:

.1 subdivision length *Ls*;
.2 initial draughts and the corresponding *GM*-values;
.3 required subdivision index *R*; and
.4 attained subdivision index *A* with a summary table for all contributions for all damaged zones.

2 Results for each damage case which contributes to the index A:

.1 draught, trim, heel, GM in damaged condition;
.2 dimension of the damage with probabilistic values **p**, **v** and **r**;
.3 righting lever curve (including GZmax and range) with factor of survivability **s**;
.4 critical weathertight and unprotected openings with their angle of immersion; and
.5 details of sub-compartments with amount of in-flooded water/lost buoyancy with their centres of gravity.

DOCUMENTATION

3 In addition to the requirements mentioned above, particulars of non-contributing damages ($s_i = 0$ and $p_i > 0{,}00$) should also be submitted for passenger ships and ro-ro ships fitted with long lower holds including full details of the calculated factors.

DEFINITIONS

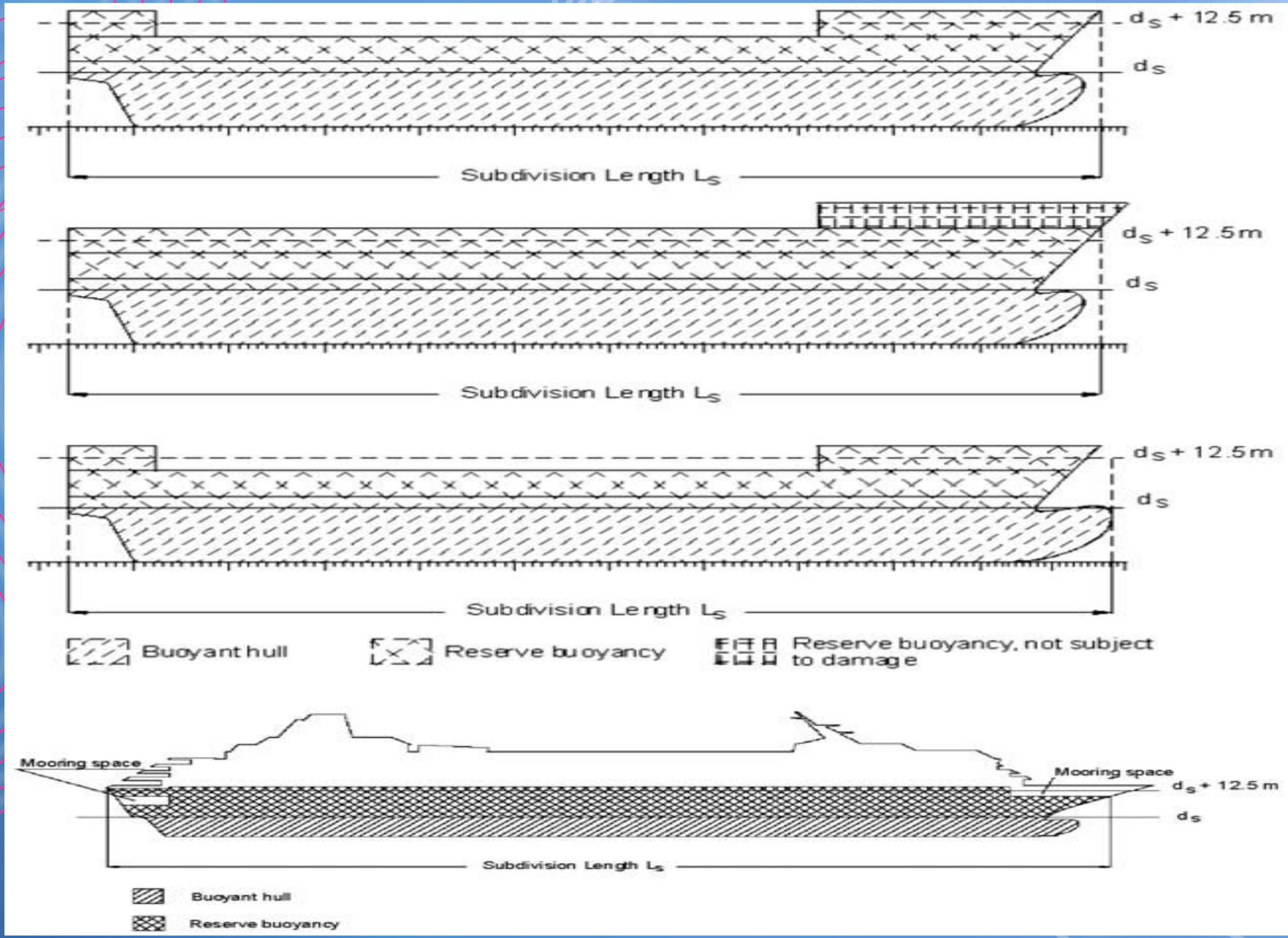
Subdivision length (L_s) – Different examples of L_s showing the buoyant hull and the reserve buoyancy are provided in the figures below. The limiting deck for the reserve buoyancy may be partially watertight.

The maximum possible vertical extent of damage above the baseline is d_s + 12,5 m.

Freeboard deck **Bulkhead deck**

Light service draught (d_l) – The light service draught (d_l) represents the lower draught limit of the minimum required GM (or maximum allowable KG) curve. It corresponds, in general, to the ballast arrival condition with 10 % consumables for cargo ships. For passenger ships, it corresponds, in general, to the arrival condition with 10 % consumables, a full complement of passengers and crew and their effects, and ballast as necessary for stability and trim. The 10 % arrival condition is not necessarily the specific condition that should be used for all ships, but represents, in general, a suitable lower limit for all loading conditions. This is understood to not include docking conditions or other non-voyage conditions.

INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS



INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS

ATTAINED SUBDIVISION INDEX A > REQUIRED SUBDIVISION INDEX *R*

REQUIRED SUBDIVISION INDEX *R*

In case of cargo ships greater than 100 m in length L_s: $R = 1 - \frac{128}{L_s + 152}$

In case of passenger ships: $R = 1 - \frac{5000}{L_s + 2.5N + 15255}$; were $N = N_1 + 2N_2$

N_1 – number of persons for whom lifeboats are provided;
N_2 – number of persons (including officers and crew) the ship is permitted to carry in excess of N_1

INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS

ATTAINED SUBDIVISION INDEX A

The attained subdivision index *A* is determined by a formula for the entire probability as the sum of the products for each compartment or group of compartments of the probability that a space is flooded, multiplied by the probability that the ship will not capsize or sink due to flooding of the considered space. In other words, the general formula for the attained index can be given in the form:

$$A = \sum p_i s_i$$

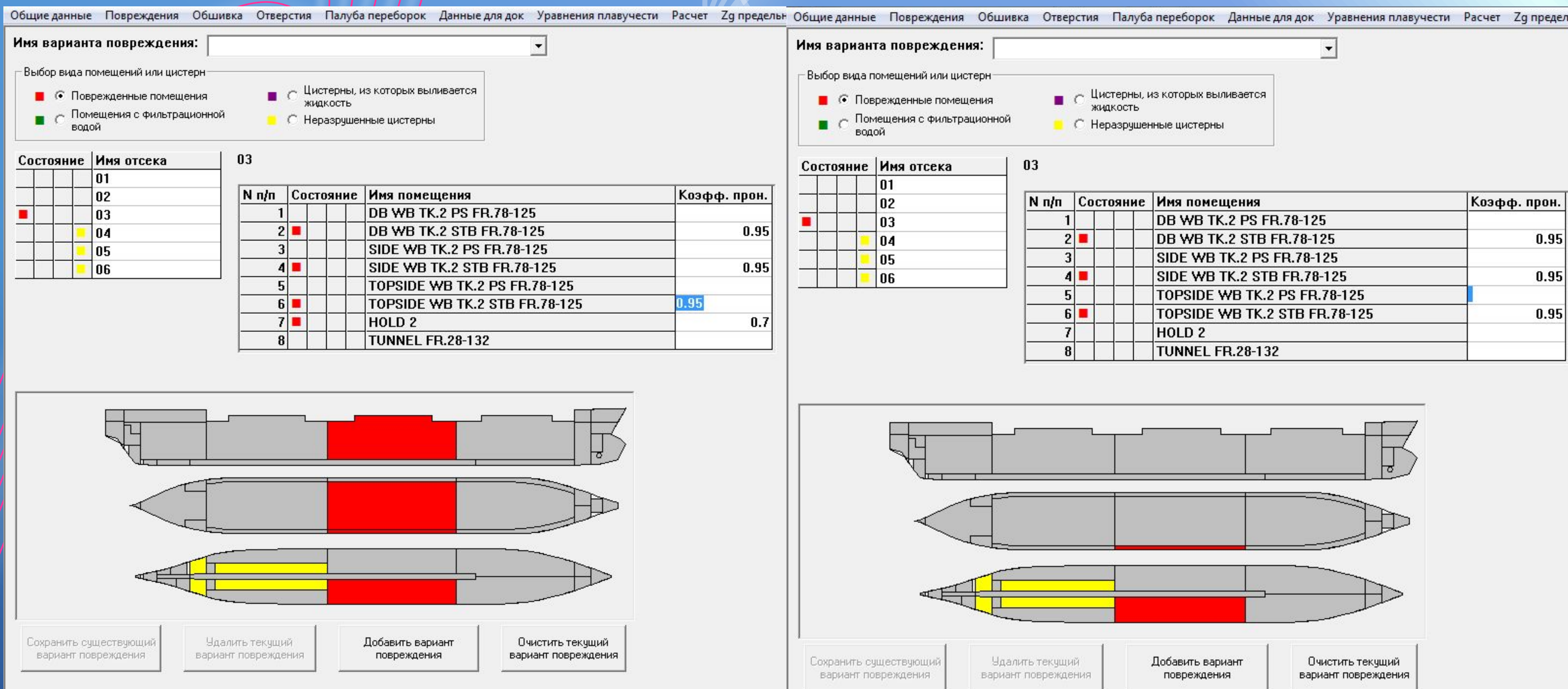
ATTAINED SUBDIVISION INDEX A

Subscript ***i*** represents the damage zone (group of compartments) under consideration within the watertight subdivision of the ship. The subdivision is viewed in the longitudinal direction, starting with the aftmost zone/compartment.

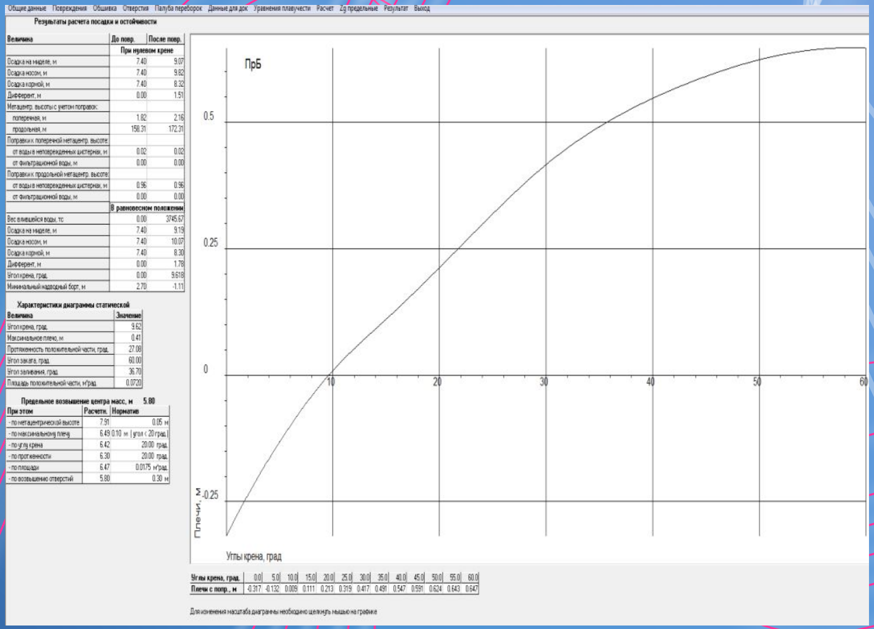
The value of p_i represents the probability that only the zone *i* under consideration will be flooded, disregarding any horizontal subdivision, but taking transverse subdivision into account. Longitudinal subdivision within the zone will result in additional flooding scenarios, each with its own probability of occurrence.

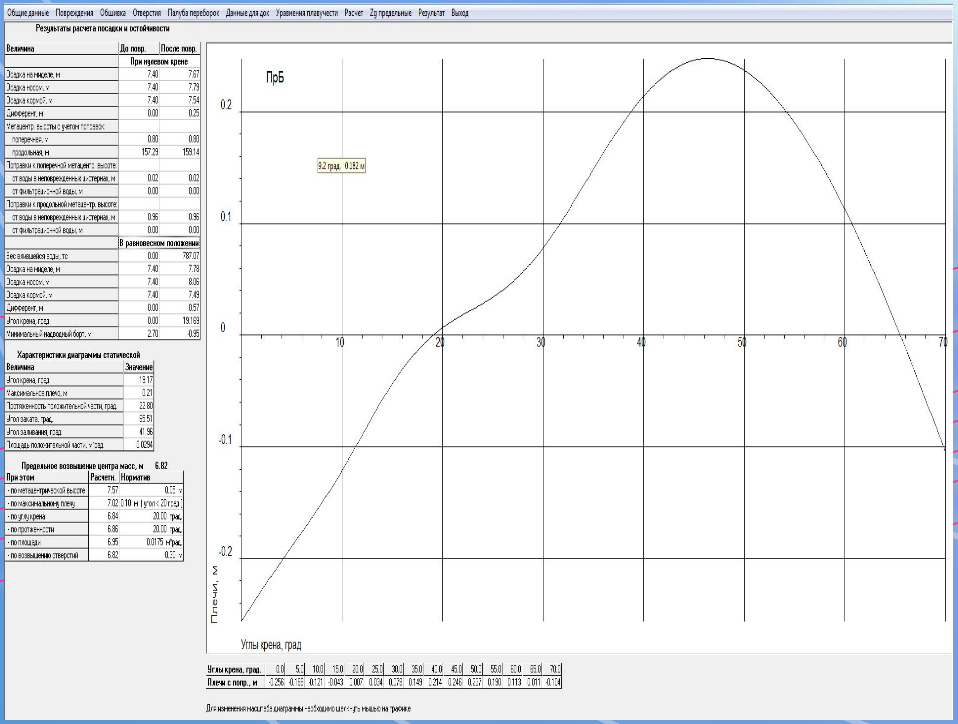
The value of s_i represents the probability of survival after flooding the zone ***i*** under consideration.

INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS



INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS





INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS

The effect of a three-dimensional damage to a ship with given watertight subdivision depends on the following circumstances:

.1 which particular space or group of adjacent spaces is flooded;

.2 the draught, trim and intact metacentric height at the time of damage;

.3 the permeability of affected spaces at the time of damage;

.4 the sea state at the time of damage; and

.5 other factors such as possible heeling moments due to unsymmetrical weights.

INTERNATIONAL DAMAGE TRIM AND STABILITY (SOLAS) REQUIREMENTS

The probability that a ship will remain afloat without sinking or capsizing as a result of an arbitrary collision in a given longitudinal position can be broken down to:

.1 the probability that the longitudinal centre of damage occurs in just the region of the ship under consideration;

.2 the probability that this damage has a longitudinal extent that only includes spaces between the transverse watertight bulkheads found in this region;

.3 the probability that the damage has a vertical extent that will flood only the spaces below a given horizontal boundary, such as a watertight deck;

.4 the probability that the damage has a transverse penetration not greater than the distance to a given longitudinal boundary; and

.5 the probability that the watertight integrity and the stability throughout the flooding sequence is sufficient to avoid capsizing or sinking.

EXTENT OF DESIGN DAMAGE

1. Longitudinal extent: 1/3 $^{2/3}$ or 14.5 m (whichever is the less).

2. Transverse extent measured inboard of ship side at right angles to the centre line at the level of the deepest subdivision load line: 1/5 of the ship breadth ***B*** or 11.5 m (whichever is the less).

3. Vertical extent: from the base line upwards without limit.

1.1 The Importance of Accurate Resistance Predictions A central problem for the practicing naval architect is the prediction of the resistance of a new design already at an early stage in the project. When a new ship is ordered, a contract containing a specification of the ship is signed between the owner and the shipyard. One of the more strict specifications is the so-called contract speed, which is the speed attained at a specified power consumption in a trial run before delivery. This trial is supposed to take place under ideal conditions (i.e., with no wind or seaway and with no influence from restricted water and currents). In reality, corrections most often have to be applied for the influence of these factors. Should the corrected speed be lower than the contract speed, the yard will have to pay a penalty to the owner, depending on the difference between the achieved speed and the contract speed. If the difference is too large, the owner might even refuse to accept the ship.

The engine power required to drive the ship at a certain speed is not only dependent on the resistance; an important factor is also the propulsive efficiency (i.e., the performance of the propeller and its interaction with the hull). Losses in the power train must also be considered. However, the resistance is the single most important factor determining the required power.

Because the resistance, as well as other forces acting on the hull, are the result of shear and normal stresses (pressures) exerted on the hull surface by the water flow, knowledge of the flow around the ship is essential for the understanding of the different resistance components and for the proper design of the hull from a resistance point of view. Further, the flow around the stern determines the operating conditions for the propeller, so in this book a large emphasis is placed on describing the flow around the hull.

1.2 Different Ways to Predict Resistance

1.2.1 Model Testing. Because of the complicated nature of ship resistance, it is natural that early recourse was made to experiments, and it is recorded that Leonardo da Vinci (1452–1519) carried out tests on three models of ships having different fore-and-aft distributions of displacement (Tursini, 1953). The next known use of models to investigate ship resistance were qualitative experiments made by Samuel Fortrey (1622–1681), who used small wooden models towed in a tank by falling weights (Baker, 1937). After this, there was a steady growth of interest in model experiment work (Todd, 1951). Colonel

The major problem encountered by the early investigators was the scaling of the model results to full scale. In what way should the measured towing force be extrapolated, and at which speed should the model be towed to correspond to a given speed at full scale?

This problem was first solved by the French scientist Ferdinand Reech (1844), but he never pursued his ideas or used them for practical purposes. Therefore, the solution to the problem is attributed to the Englishman William Froude, who proposed his law of comparison in 1868 (Froude, 1955). In Froude's own words: "The (residuary) resistance of geometrically similar ships is in the ratio of the cube of their linear dimensions if their speeds are in the ratio of the square roots of their linear dimensions." The residuary resistance referred to is the total resistance minus that of an equivalent flat plate, or plank, defined as a rectangular plate with the same area and length, and moving at the same speed as the hull.

The idea was thus to divide the total resistance in two parts: one because of the friction between the hull and the water, and the other (the residuary resistance) because of the waves generated. The friction should be obtained from tests with planks (which do not produce waves) both at model- and full-scale, whereas the residuary resistance should be found from the model test by subtraction of the friction. This residuary resistance should then be scaled in proportion to the hull displacement from the model to the ship and added to the plank friction at full scale. A prerequisite for this scaling was that the ratio of the speeds at the two scales was equal to the square root of the length ratios, or, in other words, the speed divided by the square root of the length should be the same at both scales.

William Froude made his first model experiments in 1863 in a large rainwater tank using a falling weight to tow the hull. This was the technique used by most earlier investigators, but he soon became dissatisfied with the limitations of these experiments and turned his mind to the use of a larger tank. He made proposals to the British Admiralty in 1868, which were accepted, and a new tank was completed near his home in Torquay in 1871 (Froude, 1955). This tank had a length of 85 m, a width at the water surface of 11 m, and a depth of water along the centerline of 3 m. It was equipped with a mechanically propelled towing carriage to tow the models, in place of the gravitational device, and because of this and its size may be considered as the forerunner of the tanks so common today.

Froude's hypothesis paved the way for modern resistance prediction techniques, but a major weakness was the formula suggested for the friction of the equivalent plate. The correct way of scaling friction was not known until Reynolds (1883) found that the scaling parameter is a dimensionless number, which later became known as the Reynolds number. The Reynolds number was introduced in model testing by Schoenherr (1932), who proposed a plank friction formula, but it was not until 1957 that the International Towing Tank Conference (ITTC) recommended the use of Reynolds number scaling of the friction, then by a different formula.

1.2.2 Empirical Methods. Model tests are rather time-consuming, particularly if a large number of alternative designs are to be evaluated at a very early design stage. There is thus a need for very fast, but not necessarily as accurate, methods for resistance estimates. Such methods are of two different types: systematic series and statistical formulas based on unsystematic data.

1.2.3 Computational Techniques. Thanks to the rapid development of computer technology during the past 50 years, computational techniques in ship hydrodynamics have developed over a shorter time span than the experimental ones. However, the first method which may be considered as computational hydrodynamics was presented in a landmark paper by the Australian mathematician Michell more than a century ago

1.2.4 Use of the Methods. The three different methods for determining resistance are used at different stages of the ship design process. At the very early basic design stage, the main parameters of the hull are often varied and the design space explored with respect to length, beam, draft, block coefficient, and longitudinal position of the center of buoyancy. Because the entire design of the ship depends on these parameters, time is often short, and a reasonable estimate is required rapidly. Then the empirical methods come into play. A large design space may be explored with little effort and the main particulars of the ship determined at least approximately. Because the shape variation is very much linked to computer-aided design (CAD), most CAD packages for ship design contain a module for predicting ship resistance, in most cases based on the Holtrop-Mennen method.

During the past couple of decades, the numerical methods have made their way into design offices. Thus, having a good idea of the hull main dimensions, they may be further optimized using these methods. More important, however, is the possibility of optimizing the local shape of the hull, not only the main parameters. Forebody optimization using potential flow methods is now a standard procedure used by most ship designers. Particular features to look at are the size and shape of the bulb and the radius of the fore shoulder. The purpose is normally to minimize wave resistance (Valdenazzi et al., 2003).

To obtain a very accurate prediction of resistance and power, model testing is still used for the majority of new ships. Typically, optimization is first carried out using numerical methods, whereas the final decision about the hull shape is taken only after model tests of a few of the best candidates have been carried out. This is so because numerical predictions have not yet reached the reliability of model test results. There is no question, however, that the regular testing of ship models will be replaced by numerical predictions, sooner or later. Towing tanks and other test facilities will then be used more for more advanced investigations and for validation of new computational techniques.

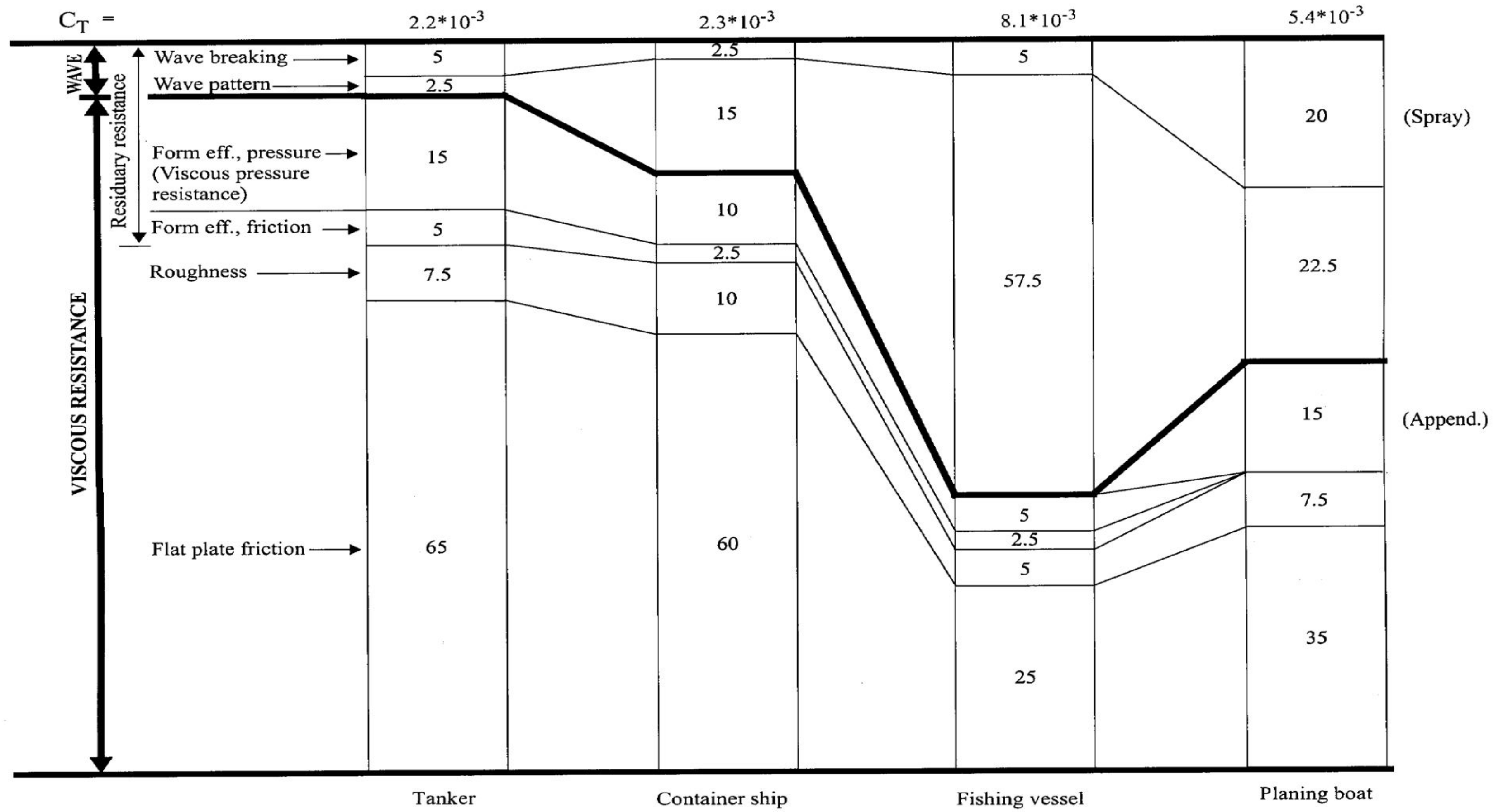


Figure 4.1 Resistance components for four vessels (%).

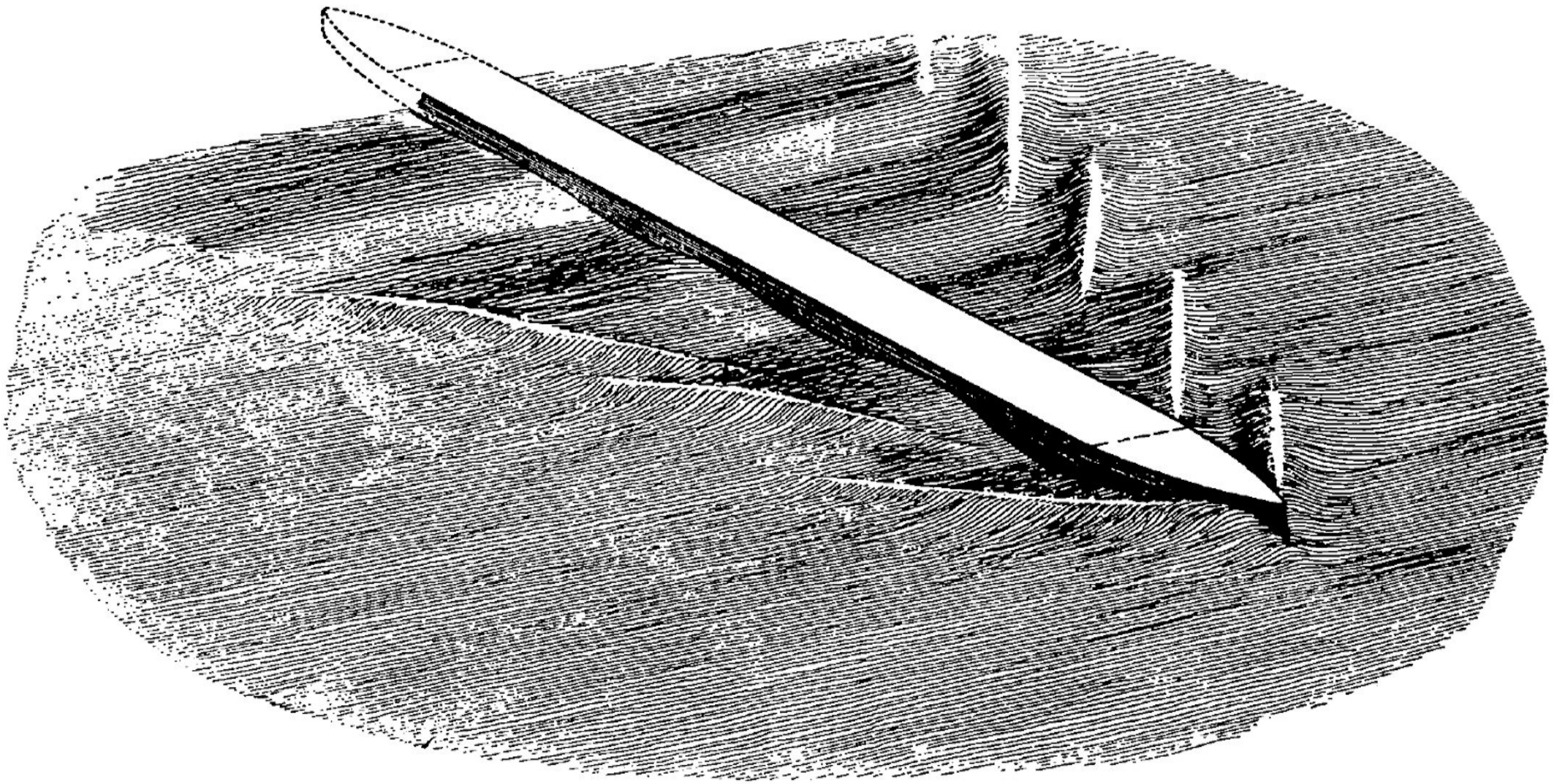


Figure 5.15 W. Froude's sketch of characteristic bow wave train (Froude, W., 1877).

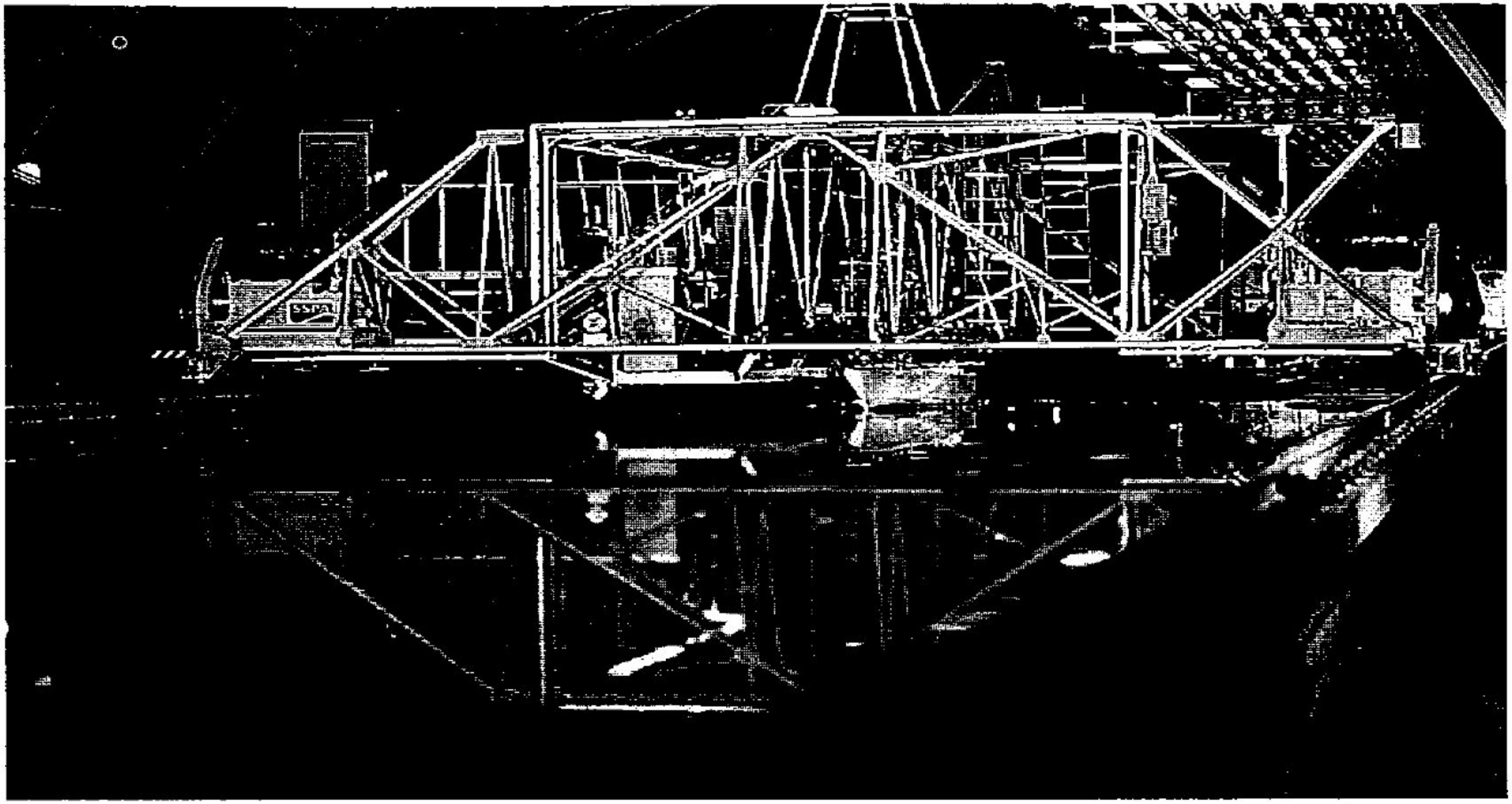


Figure 8.1 Model basin and towing carriage. (Photo: Sven Wessling. Courtesy of SSPA.)

SPECIFIC FEATURES OF SHIP STRUCTURES

1. Nature of Ship Structures
2. Size and Complexity of Ships
3. Multipurpose Function of Ship Structural Components
4. Probabilistic Nature of Ship's Structural Loads
5. Uncertainty Associated with Ship's Structural Response
6. Modes of Ship Strength and Structural Failure
7. Design Philosophy and Procedure

Thank you for attention!