INSTITUTO SUPERIOR TÉCNICO

Secção Autónoma de Engenharia Naval

Comportamento de Estruturas Navais

Capítulos Seleccionados

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The objective of Resistance of Ship Structure is to understand the global behavior of ship hull structures, to know the distribution of stresses of ship hull for various modes of flexure and twisting and to recognize the importance of interaction between ship hull with other secondary structures.

The programme includes: Basic consideration. Structural response in still water. Estimation of the weight of a ship and its contents. Distribution of the weight of a ship and water buoyancy. Basic relationships: load, shear forces and vertical bending moment. Statistical analysis of still water load effects in ship structures. Wave induced load. Quasi-static approximations of wave-induced loads. Simplified estimation of dynamic effects induced by waves. Probabilistic analysis of wave induced load. Analysis of primary ship hull girder stresses and deflections. Distribution of primary stresses. Distribution of combined stresses. Composite Construction. Torsion of circular section subjected to torque moment. Torsion of thin walled sections. Distribution of shear flow and shear stresses in primary ship hull structure – single cell structure. Distribution of shear flow and shear stresses in primary ship hull structure – multicellular structure. Local strength problems. Ship hull structural component. Analysis of beam, portal frame and grillage structure.

Contents

1 Basic Consideration

In various disciplines in the course of Naval Architecture and Marine Engineering have been mainly studied wave motion and external wave forces on marine objects. It is not to the same extent that considered how structures respond to these forces, or which internal stresses are introduced into the materials. In the present subject, it will be consider the properties of structural components and how relate their behaviour to the wave forces. It will be, however, limited to a particular class of structures or elements, viz. those that may be studied by slender beam models.

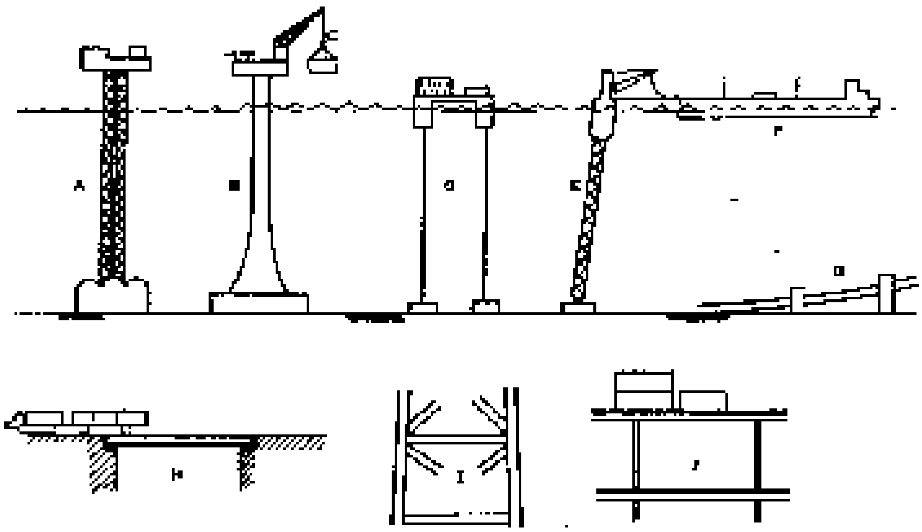


Figure 1 Structures evaluated in terms of beam models.

A) Framework tower (uniform clamped-free bar with attached mass).

B) Concrete monotower (nonuniform clamped-free bar).

C) Crane hoist rope (stretched stiff string).

D) Tendons in a tension leg platform (stretched pipes).

E) Articulated loading tower (hinged-free bar).

F) A ship's hull (free-free beam).

G) Pipeline (long beam with periodic supports).

H) Simple bridge (hinged-hinged beam).

I) Brace member in a framework structure (clamped-clamped bar).

J) Supporting pillar (bar under axial compression).

A slender beam is a bar with cross-sectional dimensions that are small compared with the length or the deformation gradients. In addition to bending and shear forces, there may also be axial forces. This may be either compression or a tension. Some examples of structures, which may be represented by slender beam models, are sketched in Figure 1.

In some of the cases shown, the beam model is a rather crude representation. The stresses obtained are global stresses averaged over great sections of the unit. There are, nevertheless, several reasons why the slender beam model is still useful. Firstly, it offers quick, preliminary calculation method to check safety and performance at an early design stage. For structures where dynamic responses may be a problem, the lowest natural frequencies may be estimated with good accuracy such that a qualitative comparison with external force spectra may be undertaken. A fine-meshed finite element model most frequently calculates local stresses numerically. It is, however, not always possible to make an element model of the complete unit. One may then calculate the global response by a coarse beam model and the local stresses by a fine-meshed finite element model of part of the model only.

Structures should be checked against two main types of failure due to overloading viz. yielding (or breaking) and buckling. Yielding occurs by excess tensional stresses, while buckling occurs by excess compression. The two types of overloading may be defined in simple terms as the limits of Hooke's law.

Global deformation of a ship's hull caused by still water, as well as wave loading, may be expanded in the vibration modes functions of a free-free bar. This modal expansion simplifies the simultaneous description of bending moments and shear forces along the hull. This also allows analytical, extreme value prediction of certain quadratic interaction formulae for yielding and buckling, such as von Misses' equivalent stress.

The zero-frequency modes for transversal and axial vibrations in ships correspond to the classical six rigid-body degrees of freedom. Symmetric and anti-symmetric modes then correspond to steady rotations and translations. Usually the ship motion components are assumed small, leading to commutative rotations and linear equations of motion. For large angular motions, however, the rigid-body rotations may be described more exactly in terms of the Eulerian angles.

Ship structural load can be divided by the loads acting on the ship structure into four categories based partly upon the nature of the load and partly upon the nature of the ships response.

A-**Static loads** are loads that change only when the total weight of the ship changes, as a result of loading or discharge of cargo, consumption of fuel, or modification to the ship itself:

- weight of the ship and its contents;
- static buoyancy of the ship at rest moving;

- thermal loads resulting from non-linear temperature gradients within the hull;
- concentrated loads caused by dry-docking and grounding.

B-**Low-frequency dynamic loads** are loads that vary in time with periods ranking from a few seconds to several minutes, and therefore occur at frequencies that are sufficiently low compared to the frequencies of vibratory response of the hull and its parts that there is no appreciable resonant amplification of the stresses induced in the structure. The stresses are called dynamic because they originate mainly in the action of the waves through which the ship moves and are therefore, always changing with time. They may be broken down into the following components:

- wave-induced hull pressure variations;
- hull pressure variations caused by oscillatory ship motions;
- internal reactions resulting from the acceleration of the mass of the ship and its contents.

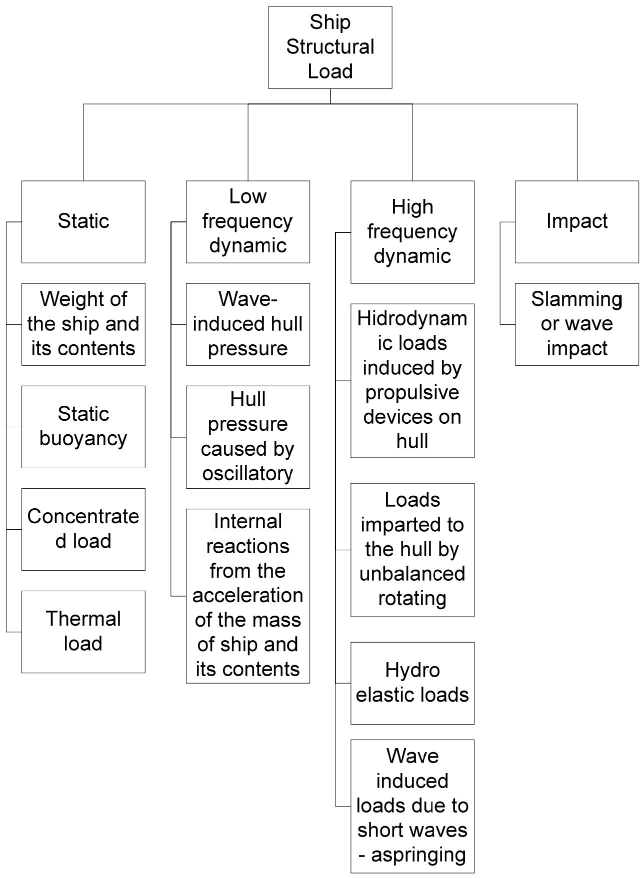


Figure 2 Classification of loads

C-High-frequency dynamic loads are time-varying loads of sufficiently high frequency that they may induce vibratory response of the ship structure. Some of the exciting loads may be quite small in magnitude, but because of resonant amplification, they can give rise to large stresses and deflections. Examples of such dynamic loads are the following:

- hydrodynamic loads induced by propulsive devices on hull or appendages;
- loads imparted to the hull by reciprocating or unbalanced rotating machinery;
- hydro-elastic loads resulting from interaction of appendages with the flow past the ship;
- wave-induced loads due primarily to short waves whose frequency of encounter overlaps the lower natural frequencies of hull vibration and which therefore may excite appreciable resonant response, termed *springing.*

D-Impact loads- are loads resulting from slamming or wave impact on the forefoot, bow flare and other parts of the hull structure, including the effects of green water on deck. In a naval ship, weapon effects constitute a very important category of impact loads. Impact loads may induce transient hull vibration that is termed *whipping*.

2 Static Loading on Ship in Still Water

The static loads acting on ship in still water consist of two parts: buoyancy forces and gravity forces, or weights.

The buoyancy is the resultant of the hydrostatic pressure distribution over the immersed external area of the ship. This pressure is a surface force whose direction is everywhere normal to the hull. The buoyant force is, however, the resultant perpendicular to the water surface and directed upwards.

The weights are body forces distributed throughout the ship and its contents, and the direction of the weight forces is always vertically downward.

If we integrate the local buoyant pressures over a unit ship length around a cross section at a given longitudinal position, the resultant is a vertical buoyant force per unit length whose magnitude is given by $\rho g A$, where ρg is the weight density of water (ρ is the mass density, or mass per unit volume) and A is the immersed sectional area. Similarly, we may add together all of the weights contained in a unit length of the ship at this section, resulting in a total weight per unit length. The net structural load per unit length is the algebraic sum of the unit buoyancy and unit weight.

The individual loads may have both local and overall structural effects. A very heavy machinery item induces large local loads at its points of attachment to the ship, and its foundations must be designed to distribute these loads over the hull structure. At the same time, the weight of this item contributes to the distribution of shear forces and bending moments acting at all locations along the length of the hull.

The geometrical arrangement and resulting stress or deflection response patterns of typical ship structures are such that it is usually convenient to divide the structure and the associated response into three components, which are labelled primary, secondary and tertiary.

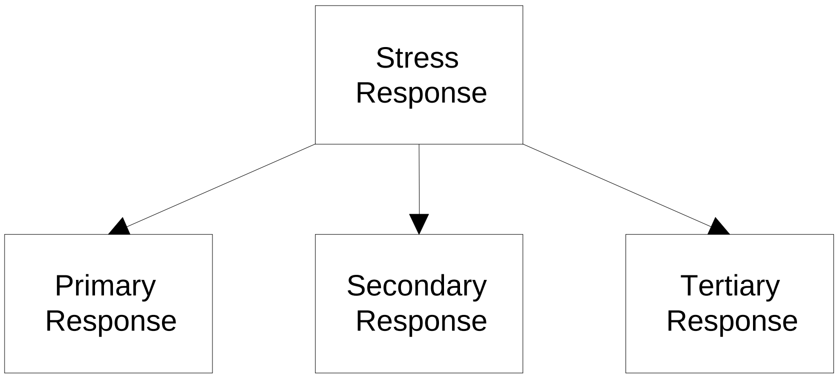


Figure 3 Stress response

Primary response is the response of the entire hull when bending and twisting are subjected to a beam as a result of external longitudinal distribution of vertical and twisting loads.

Secondary response comprises the stress and deflection of a single panel of stiffened plating e.g. the panel of bottom structure contained between two adjacent transverse bulkheads. The loading of the panel is normal to its plane and other secondary panels (side shell and bulkheads) usually form the boundaries of the secondary panel.

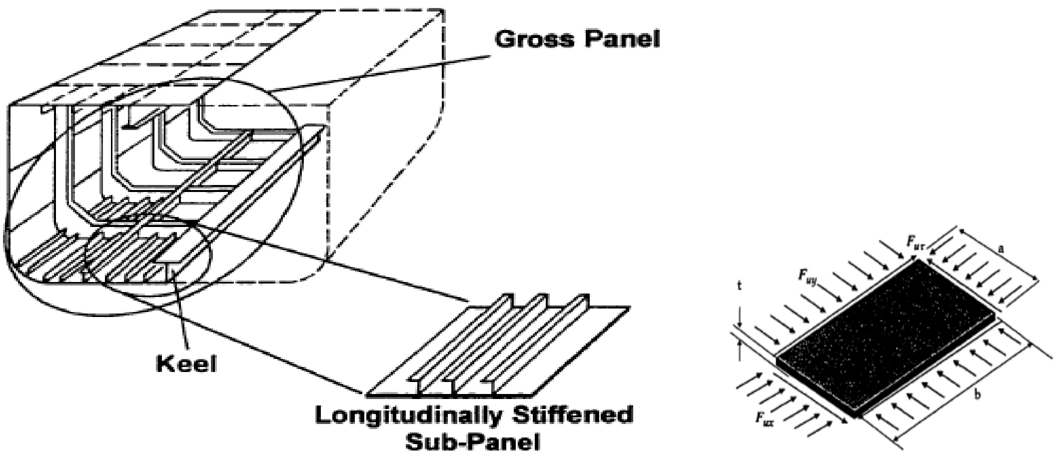


Figure 4 Structural responses

Tertiary response describes the out-of-plane deflection and associated stress of an individual panel of plating. The loading is normal to the panel, and the stiffeners of the secondary panel of which it is a part form its boundaries.

2.1 Estimation of the Weight of the Ship and its Contents

The weights in a ship fall into two main categories: those which are relatively unchanging, such as the ships own structural weight and those which do change such as cargo fuel, stores and ballast (see Figure 5). The first group constitutes the “Light-Weight” (LW) of a ship that is the weight when it is without cargo, fuel and so on. The second group is called the “Dead-Weight”, (DW). The dead-weight changes with each different cargo loading and hence there are usually several loading conditions, which need to be investigated. The two most common conditions are “full load” and “ballast”.

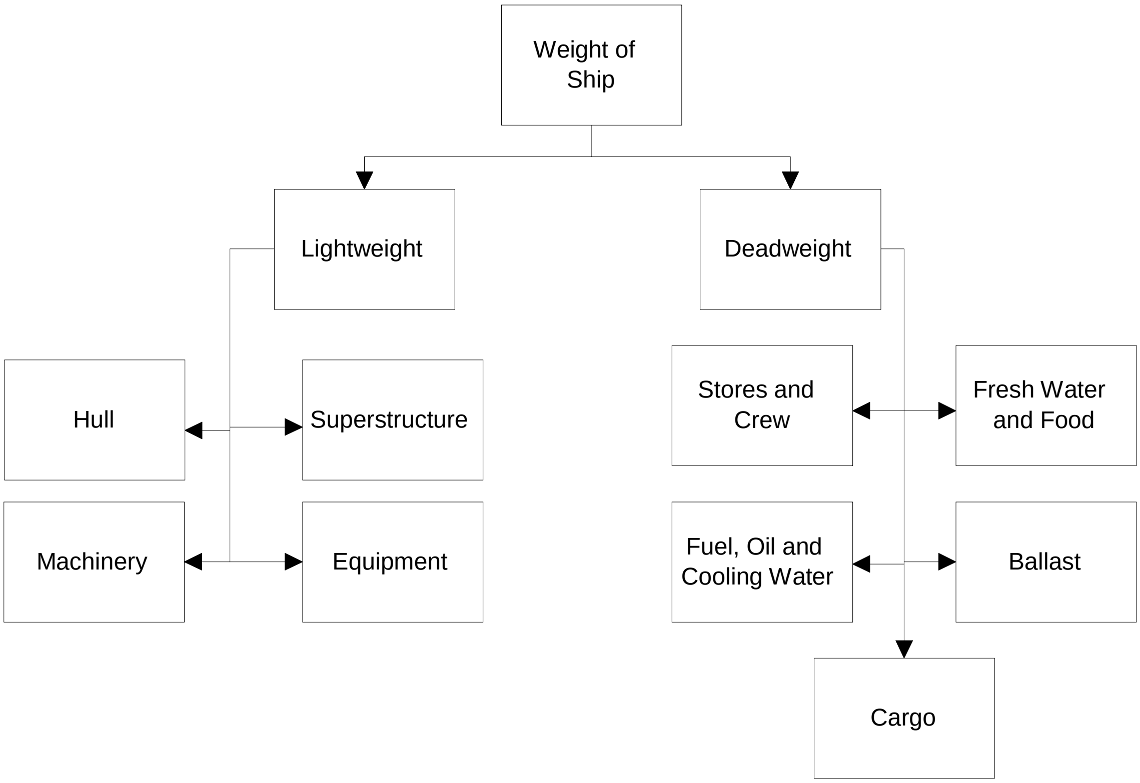


Figure 5 Weight of ship

In general, the information regarding weights is of a discrete nature and must be gathered together and entered into a “Table of Weight” or some other suitable form of information storage.

The formulations that are going to be presented here have been applied to a bulk carrier with main characteristics presented in Table 1. The midship section of bulk carrier and the main arrangement are shown in Figure 6 and Figure 7.

Table 1 Main characteristics of bulk carrier

Length of Ship, L	120.00	[m]
Breadth, B	18.00	[m]
Block Coefficient, C_B	0.68	[-]
Depth, D	10.00	[m]

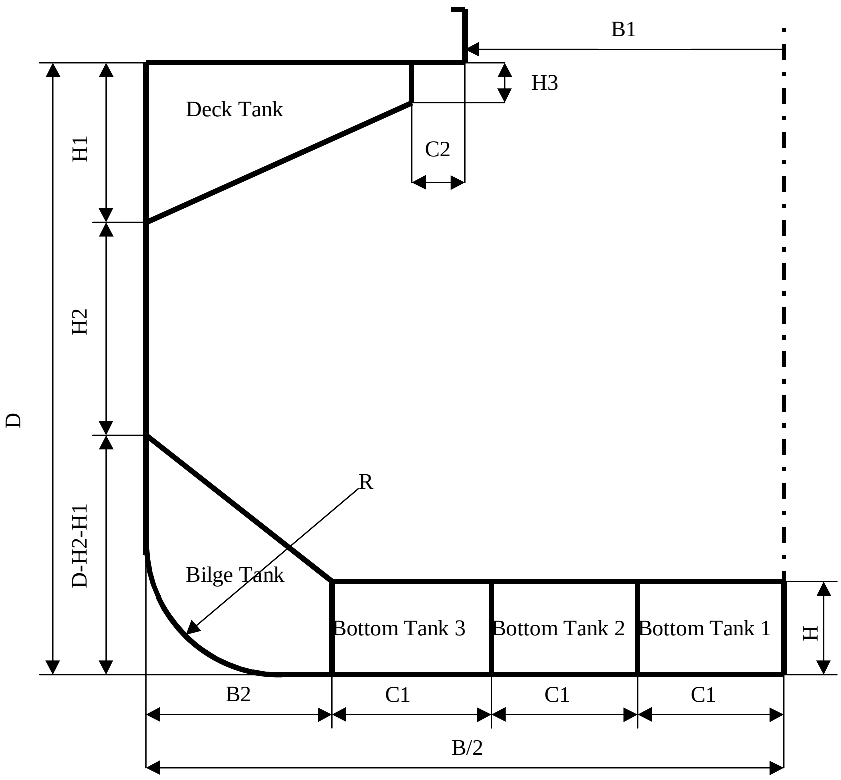


Figure 6 Midship section of bulk carrier

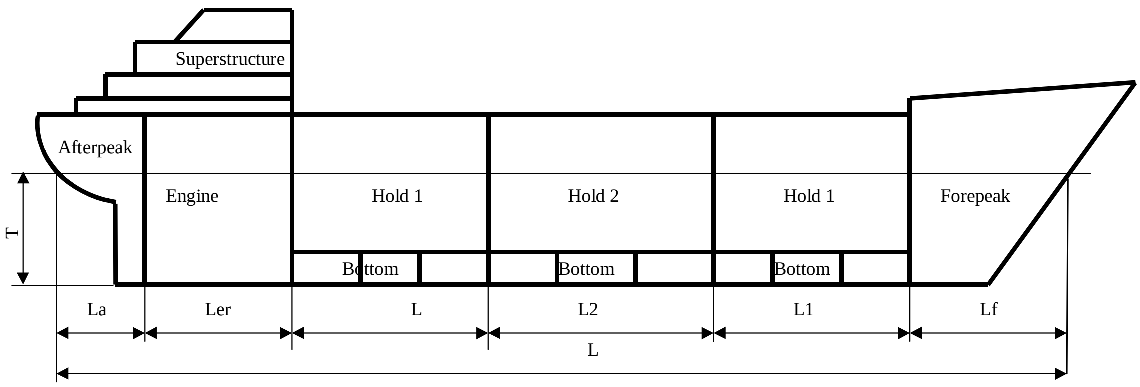


Figure 7 General arrangements

2.1.1 Lightweight

In specifying the distribution of individual weights, it is helpful and even necessary to use some approximations and idealisations. Nearly all items can be represented in terms of one or more of the three basic types of distribution: point, uniform and trapezoidal distribution. In addition, for cargo and ballast, an alternative approach is possible.

For a trapezoid with a length, *dL* the relevant information may be specified by a total mass *P*, with a specified position of centre of gravity C_1. The transforming the trapezoid into uniform distribution is shown in Figure 8.

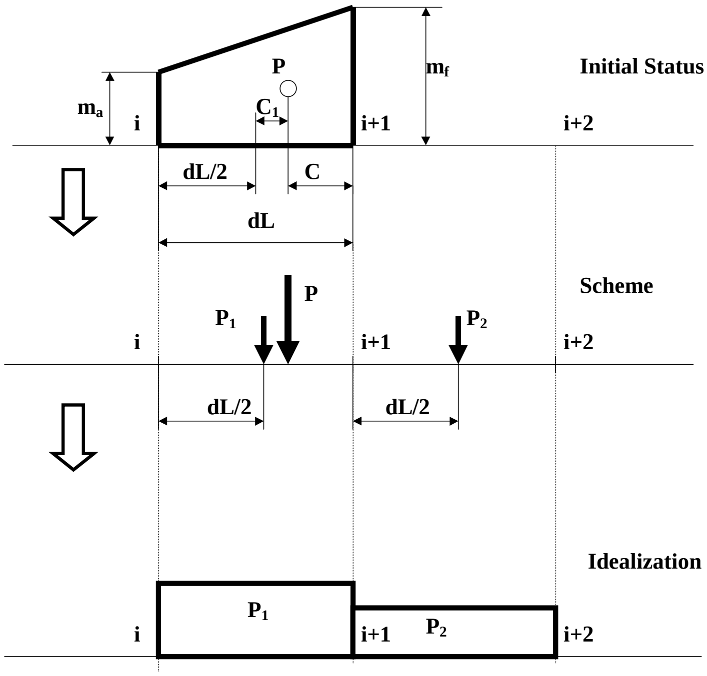


Figure 8 Trapezoidal and uniform representation of the weight

The formulas for converting from one form of distribution to another one are:

$$P = \frac{dL\left(m_f + m_a\right)}{2} \tag{1}$$

$$C_1 = \frac{dL}{6}\left[\frac{m_f - m_a}{m_f + m_a}\right] \tag{2}$$

$$C = \frac{dL}{2} - C_1 \tag{3}$$

$$P_1 = P\left(\frac{1}{2} + \frac{C}{dL}\right) \tag{4}$$

$$P_2 = P\left(\frac{1}{2} - \frac{C}{dL}\right) \tag{5}$$

$$P = P_1 + P_2 \tag{6}$$

For these items the weight per unit length is related to the cross-sectional area of the relevant cargo or ballast space, and their weight distribution may be taken as the product of the sectional area curve of the relevant space times the mass density of the cargo or ballast. The weight of LW may be presented as:

$$LW = P_{hull} + P_{ss} + P_{eq} + P_m \quad , [\mathrm{t}] \tag{7}$$

where P_{hull} is the weight of hull, P_{ss} is the weight of the superstructures, P_{eq} is the weight of the equipment and P_m is the weight of the machinery.

2.1.1.1 Weight of Machinery

Typical approximation of weight of machinery depends on the location of the engine room (see Figure 9 and Figure 10).

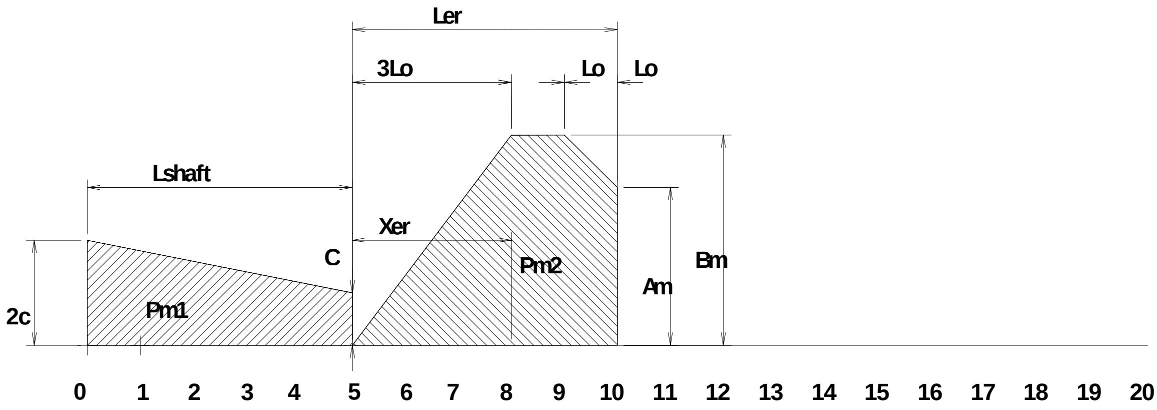


Figure 9 Weight distribution of machinery (midship)

The weight parameters are described as (Figure 9):

$$P_{m1} = 2L_{shaft} \text{ , [t]} \tag{8}$$

$$P_{m2} = P_m - P_{m1} \text{ , [t]} \tag{9}$$

$$X_{er} = (0.59 \div 0.62)L_{er} \text{ , [m]} \tag{10}$$

where P_{m1} is the weight of the shaft and the propeller, P_{m2} is the weight of the mechanisms in the engine room, L_{shaft} is the length of the shaft and X_{er} is the abscise of the centre of gravity of the weight of the mechanisms in the engine room.

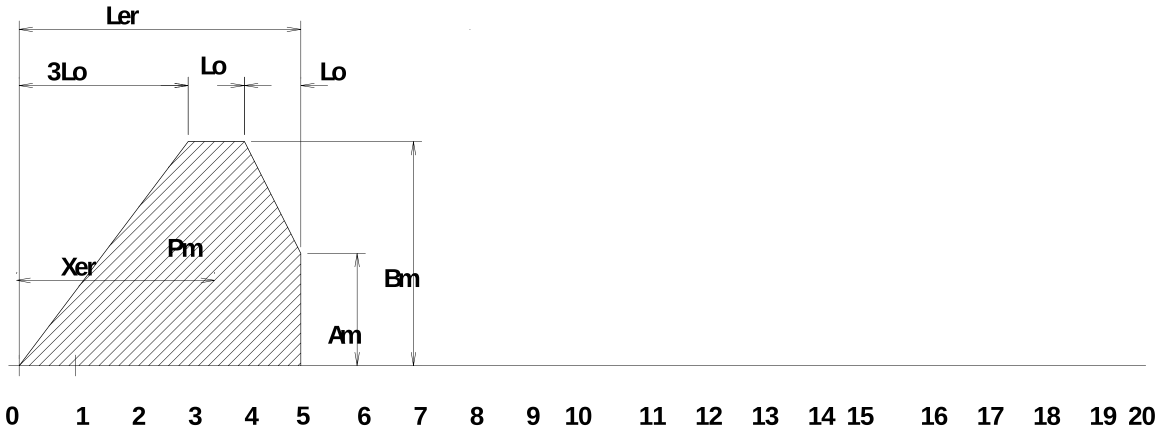


Figure 10 Weight distribution of machinery (aft of midship)

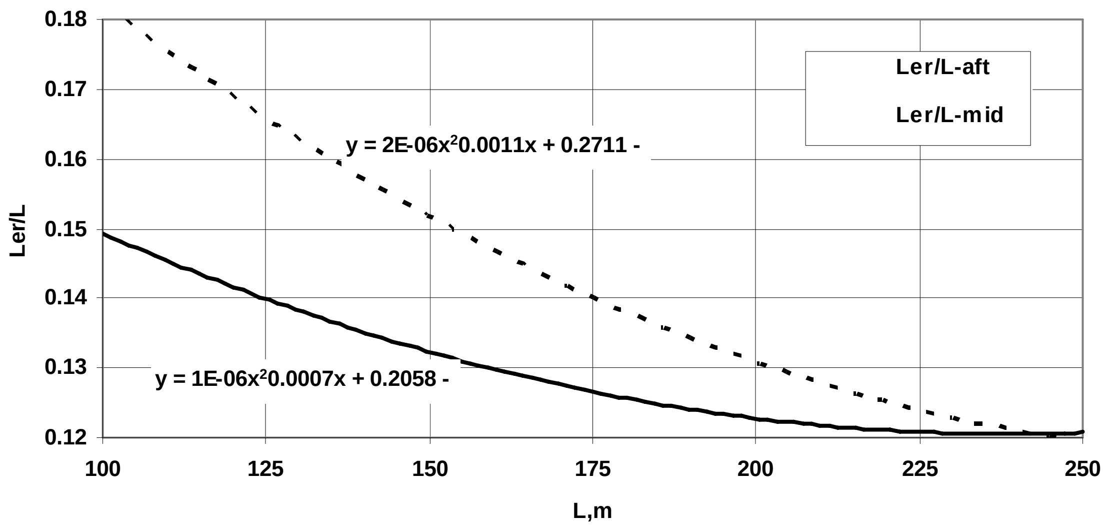


Figure 11 Relative length of main engine room

The descriptors of the weight distribution presented in Figure 9 and Figure 10 are given as:

$$A_m = \frac{5}{8}\frac{P_m}{L_{er}}\left(45\frac{X_{er}}{L_{er}} - 26\right), \text{[t/m]} \tag{11}$$

$$B_m = \frac{5}{16}\frac{P_m}{L_{er}}\left(14 - 15\frac{X_{er}}{L_{er}}\right), \text{[t/m]} \tag{12}$$

$$P_m = 0.1 N_{eff} \text{ , [t]} \tag{13}$$

where L_{er} is the length of the engine room and N_{eff} is the effective power of the main engine. The relative length of the engine room as a function of the length of ship is given in Figure 11 and the effective power of the main engine is shown in Figure 12.

The calculations performed to describe the weight distribution of the machinery are presented in Table 2. The position of the engine room was considered at the aft of ship.

Table 2 Calculation of the weight of machinery

L_{er}/L=2E-6*L^2-0.0011*L+0.2711	0.168	[-]
L_{er}	24.000	[m]
$X_{er}=0.6*L_{er}$	14.400	[m]
$N_{eff}=0.4612*L^2 - 42.254*L + 2013.3$	3584.10	[Horse]
$P_m=0.1*N_{eff}$	358.410	[t]
$A_m=5/8*P_m/L_{er}*(45*X_{er}/L_{er}-26)$	9.334	[t/m]
$B_m=5/16*P_m/L_{er}*(14-15*X_{er}/L_{er})$	23.334	[t/m]
$L_o=L_{er}/5$	4.800	[m]
$B_1=B_m*(\Delta L/(3*L_o))$	9.722	[t/m]
$B_2=B_m*((2*\Delta L)/(3*L_o))$	19.445	[t/m]
$B_3=B_m$	23.334	[t/m]
$B_4=A_m$	9.334	[t/m]
$c_1=\Delta L/3$	2.000	[m]
$m_1=B_1*\Delta L/2$	29.167	[t]
$M_{11}=m_1*(1/2+c_1/\Delta L)$	24.306	[t]
$M_{12}=m_1*(1/2-c_1/\Delta L)$	4.861	[t]
$c_2=\Delta L/2-\Delta L/6*((B_2-B_1)/(B_2+B_1))$	2.667	[m]
$m_2=\Delta L*(B_2+B_1)/2$	87.502	[t]
$M_{22}=m_2*(1/2+c_2/\Delta L)$	82.641	[t]
$M_{23}=m_2*(1/2-c_2/\Delta L)$	4.861	[t]
$c_3=\Delta L/2-\Delta L/6*((B_3-B_2)/(B_3+B_2))$	2.909	[m]
$m_3=\Delta L*(B_3+B_2)/2$	128.337	[t]
$M_{33}=m_3*(1/2+c_3/\Delta L)$	126.392	[t]
$M_{34}=m_3*(1/2-c_3/\Delta L)$	1.944	[t]
$c_4=\Delta L/2-\Delta L/6*((B_3-B_4)/(B_3+B_4))$	2.571	[m]
$m_4=\Delta L*(B_3+B_4)/2$	98.003	[t]
$M_{44}=m_4*(1/2+c_4/\Delta L)$	91.003	[t]
$M_{43}=m_4*(1/2-c_4/\Delta L)$	7.000	[t]

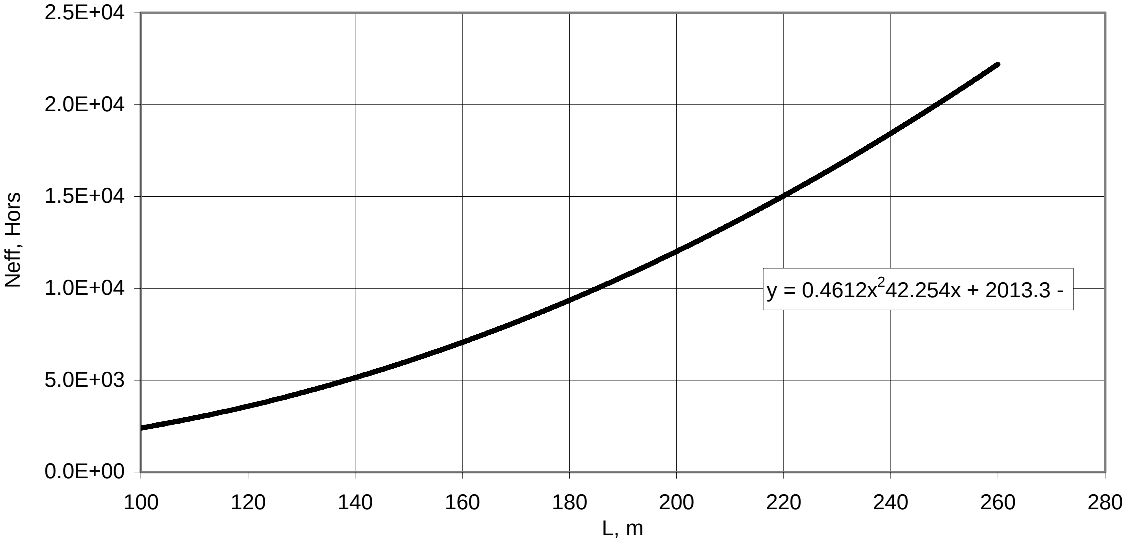
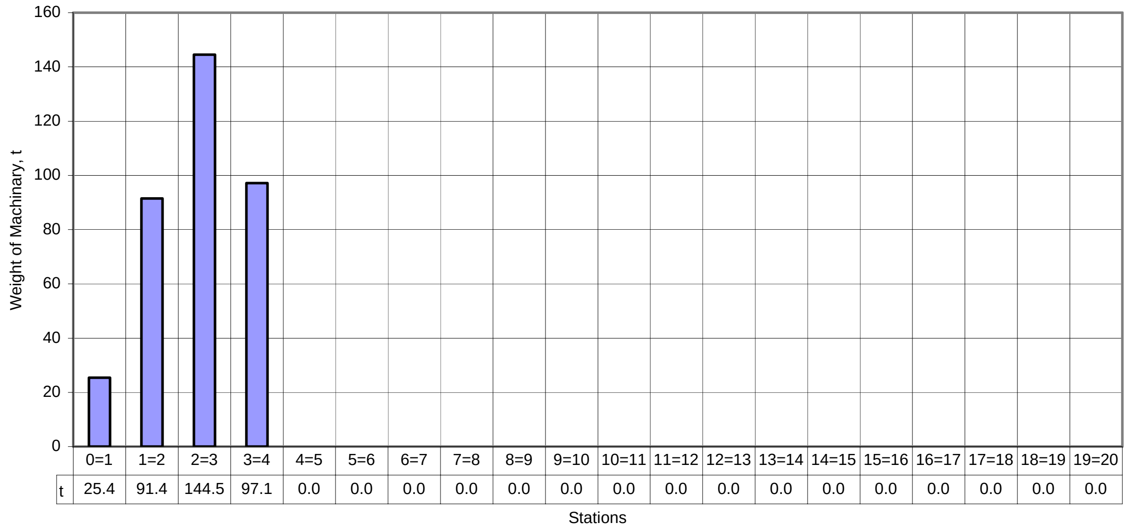


Figure 12 Effective main engine powers as a function of length of ship.

Graphical illustration of the weight distribution of the machinery is given in Figure 13.



	0=1	1=2	2=3	3=4	4=5	5=6	6=7	7=8	8=9	9=10	10=11	11=12	12=13	13=14	14=15	15=16	16=17	17=18	18=19	19=20
t	25.4	91.4	144.5	97.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 13 Weight distribution of machinery

2.1.1.2 Weight of Superstructure

The distribution function of the weight of the superstructures is presented in Figure 14 and Figure 15 and it is described by the following parameters:

$$L_{ss,1} = L_{er} + 2a \text{ , [m]} \tag{14}$$

$$L_{ss,2} = 0.05L + 3\text{, [m]} \tag{15}$$

$$a = 0.003L + 0.48\text{, [m]} \tag{16}$$

$$P_{ss,aft} = 0.5L_{er}\,B\text{, [t]} \tag{17}$$

$$P_{ss,for} = 0.008L\,B\text{, [t]} \tag{18}$$

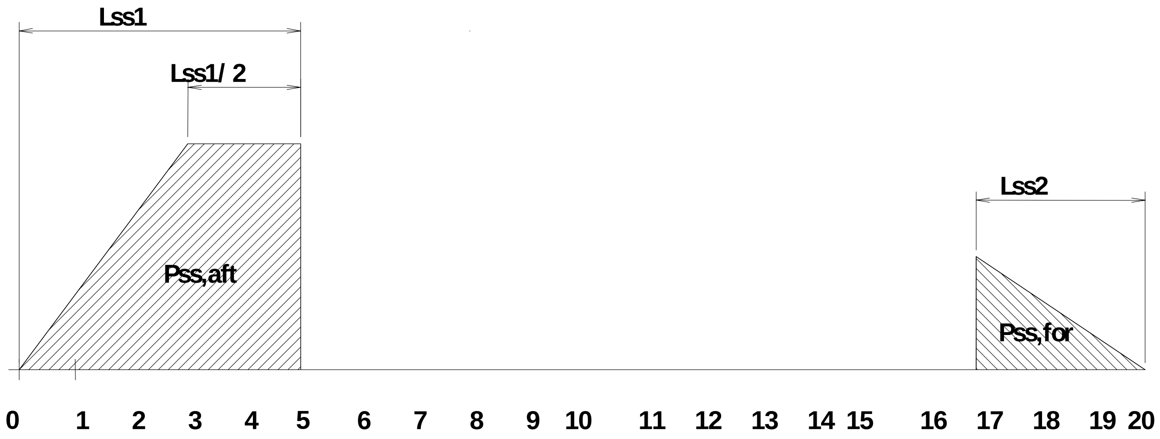


Figure 14 Weight distribution of superstructures (aft midship)

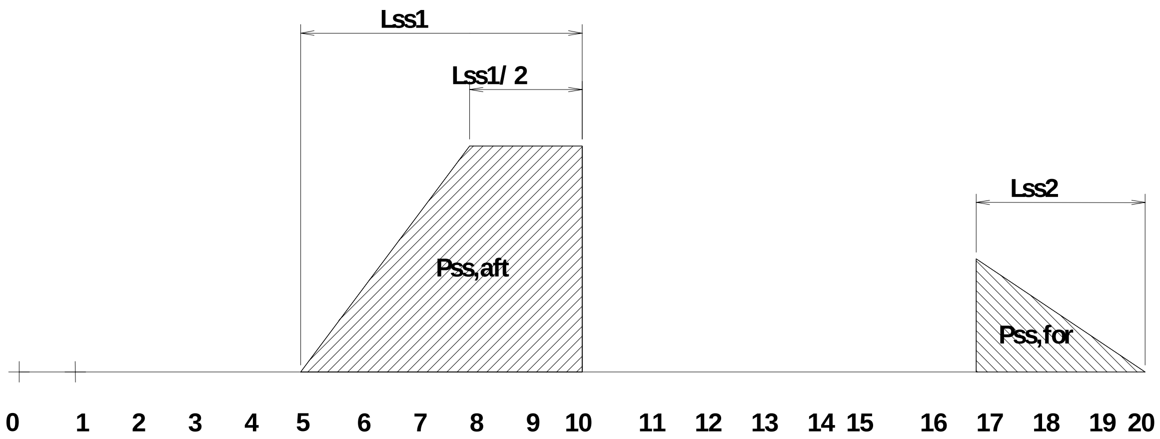


Figure 15 Weight distribution of superstructures (midship)

The calculation describing the weight distribution of superstructures is given in Table 3 and in Figure 16. The superstructures are considered to be as it is shown in Figure 14.

Table 3 Calculation of the weight of superstructures

$P_{ss,aft}$=0.5*L_{er}*B	216.000	[t]
$P_{ss,for}$=0.008*L*B	17.280	[t]
a=0.03*L+0.48	4.080	[m]
$L_{ss,1}$=L_{er}+2*a	36.000	[m]
$L_{ss,2}$=0.05*L+3	12.000	[m]
m_{aft}=4/3*$P_{ss,aft}$/L_{ss1}	8.000	[t/m]
m_{for}=2*$P_{ss,for}$/L_{ss2}	2.880	[t/m]
B_1=dL/L_{ss1}/2*m_{aft}	2.667	[t/m]
B_2=2*dL/L_{ss1}/2*m_{aft}	5.333	[t/m]
B_3=m_{aft}	8.000	[t/m]
B_4=m_{aft}	8.000	[t/m]
B_5=m_{aft}	8.000	[t/m]
B_6=m_{aft}	8.000	[t/m]
c_1=ΔL/3	2.000	[m]
m_1=B_1*ΔL/2	8.000	[t]
M_{11}=m_1*(1/2+c_1/ΔL)	6.667	[t]
M_{12}=m_1*(1/2-c_1/ΔL)	1.333	[t]
c_2=ΔL/2-ΔL/6*((B_2-B_1)/(B_2+B_1))	2.667	[t]
m_2=ΔL*(B_2+B_1)/2	24.000	[t]
M_{22}=m_2*(1/2+c_2/ΔL)	22.667	[t]
M_{23}=m_2*(1/2-c_2/ΔL)	1.333	[t]
c_3=ΔL/2-ΔL/6*((B_3-B_2)/(B_3+B_2))	2.800	[t]
m_3=ΔL*(B_3+B_2)/2	40.000	[t]
M_{33}=m_3*(1/2+c_3/ΔL)	38.667	[t]
M_{34}=m_3*(1/2-c_3/ΔL)	1.333	[t]
m_4=ΔL*B_4	48.000	[t]
M_{44}=m_4	48.000	[t]
m_5=ΔL*B5	48.000	[t]
M_{55}=m_5	48.000	[t]
m_6=ΔL*B_6	48.000	[t]
M_{66}=m_6	48.000	[t]
B_{18}=m_{for}	2.880	[t/m]
B_{19}=ΔL/L_{ss2}*m_{for}	1.440	[t]
c_{19}=ΔL/3	2.000	[m]
m_{19}=B_{19}*ΔL/2	4.320	[t]
M_{1919}=m_{19}*(1/2+c_{19}/ΔL)	3.600	[t]
M_{1918}=m_{19}*(1/2-c_{19}/ΔL)	0.720	[t]
c_{18}=ΔL/2-ΔL/6*((B_{18}-B_{19})/(B_{18}+B_{19}))	2.667	[m]
m_{18}=ΔL*(B_{18}+B_{19})/2	14.640	[t]
M_{1818}=m_{18}*(1/2+c_{18}/ΔL)	13.827	[t]
M_{1817}=m_{18}*(1/2-c_{18}/ΔL)	0.813	[t]

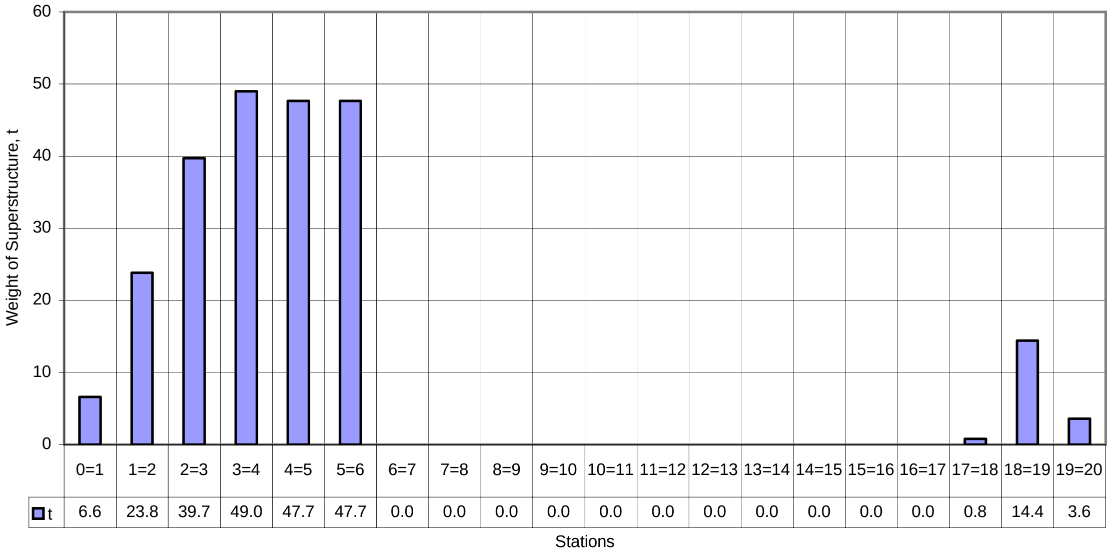


Figure 16 Weight distribution of superstructure

2.1.1.3 Weight of Hull

The major item of the weight distribution is the hull. A useful first approximation of the hull weight distribution is described in Figure 19 and Figure 20. The hull weight may be calculated as:

$$P_{hull} = P_{hull,ss} - P_{ss} \text{, [t]} \tag{19}$$

where:

$$P_{hull,ss} = \Delta \; k_{hull,ss} \text{, [t]} \tag{20}$$

$$\Delta = \frac{DW}{k_{DW}} \text{, [t]} \tag{21}$$

The coefficients $k_{hull,ss}$ and k_{DW} are presented in Figure 17 and DW as a function of length of ship is given in Figure 18.

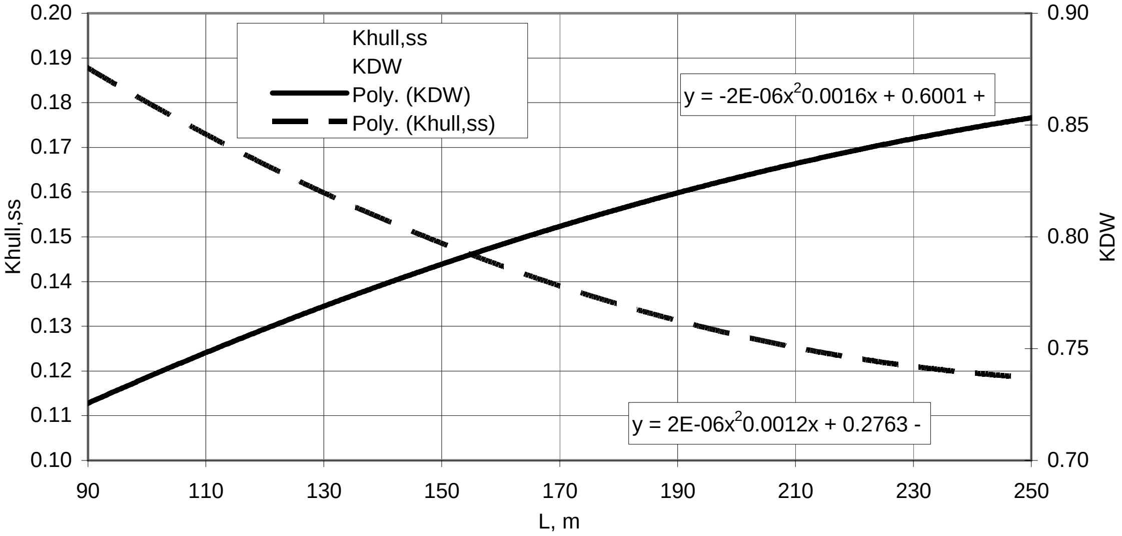


Figure 17 Coefficient $k_{hull,ss}$ and k_{DW} as a function of length of ship

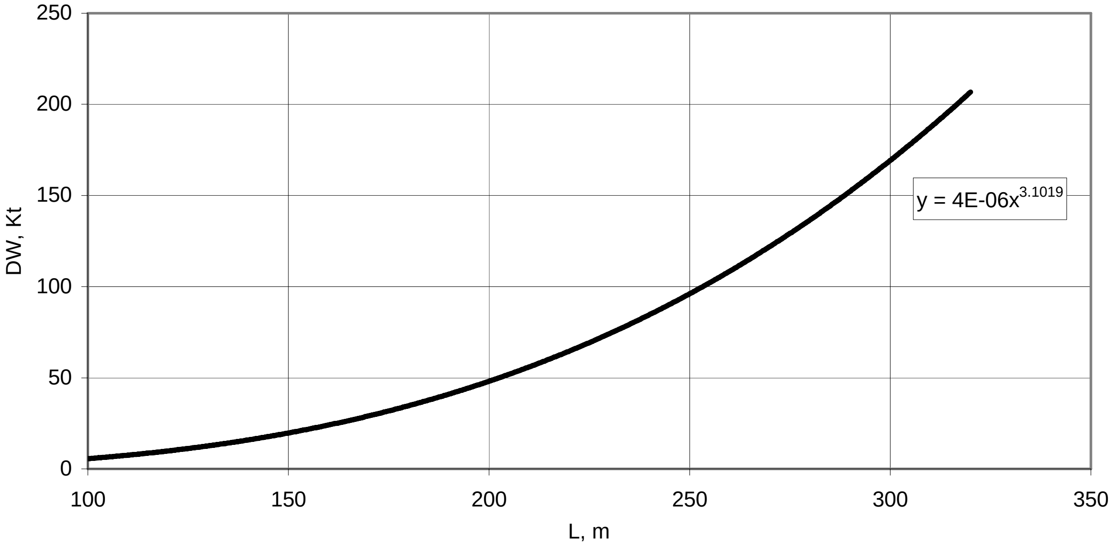


Figure 18 DW as a function of the length of ship.

The distribution of the weight may differ depending on the position of the engine room. When the engine room is located at the middle of the ship the weight distribution is given in Figure 19. The parameters determining the distribution are:

$$dA = 2\Delta L \frac{B - A}{L - L_c}, \text{ [t/m]} \tag{22}$$

$$B = \left[1 + C_b\left(1 - \frac{L_c}{L}\right)\right] P_{hull}, \text{ [t/m]} \tag{23}$$

$$dC = 2\Delta L \frac{B - C}{L - L_c}, \text{ [t/m]} \tag{24}$$

$$\frac{x_{hull}}{\Delta L} = \left[\left(\frac{L_c}{L} - 0.8\right) \div\ 0.35\right], \text{ [-]} \tag{25}$$

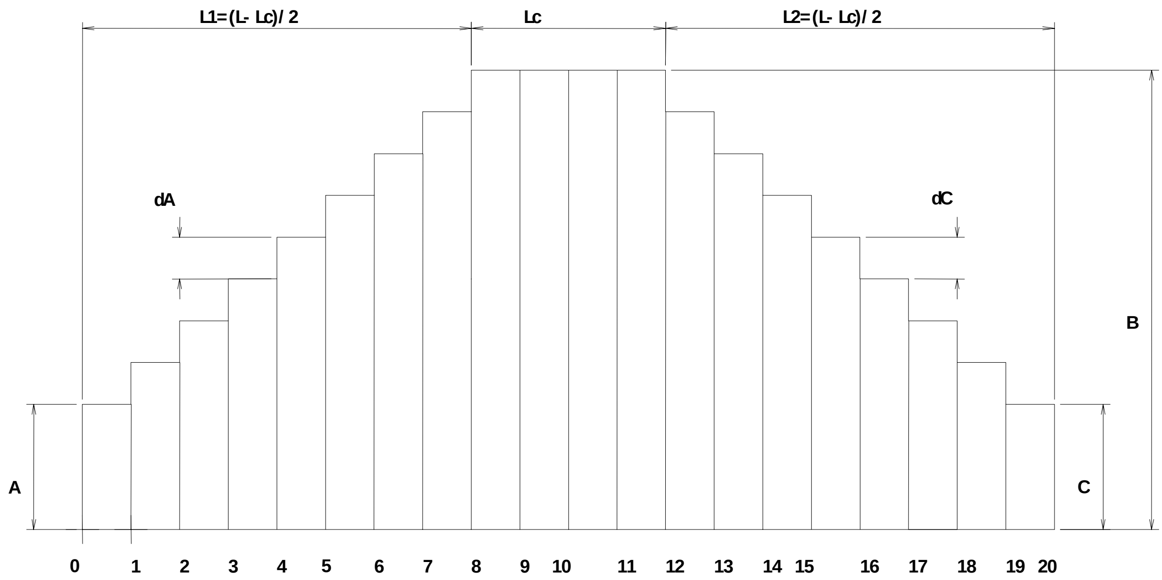


Figure 19 Hull weight distribution (midship).

Table 4 Hull weight distribution parameters (midship).

$L_c\ /\ L$	0.1	0.2	0.3
B/(P_{hull}/L)	1.27	1.24	1.21
A/(P_{hull}/L)	$0.730 - 0.293(x_{hull}/\Delta L)$	$0.707 - 0.310(x_{hull}/\Delta L)$	$0.685 - 0.333(x_{hull}/\Delta L)$
C/(P_{hull}/L)	$0.730 + 0.293(x_{hull}/\Delta L)$	$0.707 + 0.310(x_{hull}/\Delta L)$	$0.685 + 0.333(x_{hull}/\Delta L)$
$L_c\ /\ L$	0.4	0.5	0.6
B/(P_{hull}/L)	1.18	1.15	1.12
A/(P_{hull}/L)	$0.667 - 0.365(x_{hull}/\Delta L)$	$0.650 - 0.408(x_{hull}/\Delta L)$	$0.640 - 0.476(x_{hull}/\Delta L)$
C/(P_{hull}/L)	$0.667 + 0.365(x_{hull}/\Delta L)$	$0.650 + 0.408(x_{hull}/\Delta L)$	$0.640 + 0.476(x_{hull}/\Delta L)$

When the engine room is located at the aft of a midship, then the distribution of weight is presented in Figure 20 and the parameters that describe the hull weight are given as:

$$dA = 2\,\Delta L \frac{B - A}{1.1L - L_c}, \text{ [t/m]} \tag{26}$$

$$B = \left[1 + C_b\left(1 - \frac{L_c}{L}\right)\right]\frac{P_{hull}}{L}\text{, [t/m]} \tag{27}$$

$$dC = 2\,\Delta L\,\frac{B - C}{0.9L - L_c}\text{, [t/m]} \tag{28}$$

$$\frac{x_{hull}}{\Delta L} = \left[\left(\frac{L_c}{L} - 0.7\right) \div\ 0.5\right]\text{, [-]} \tag{29}$$

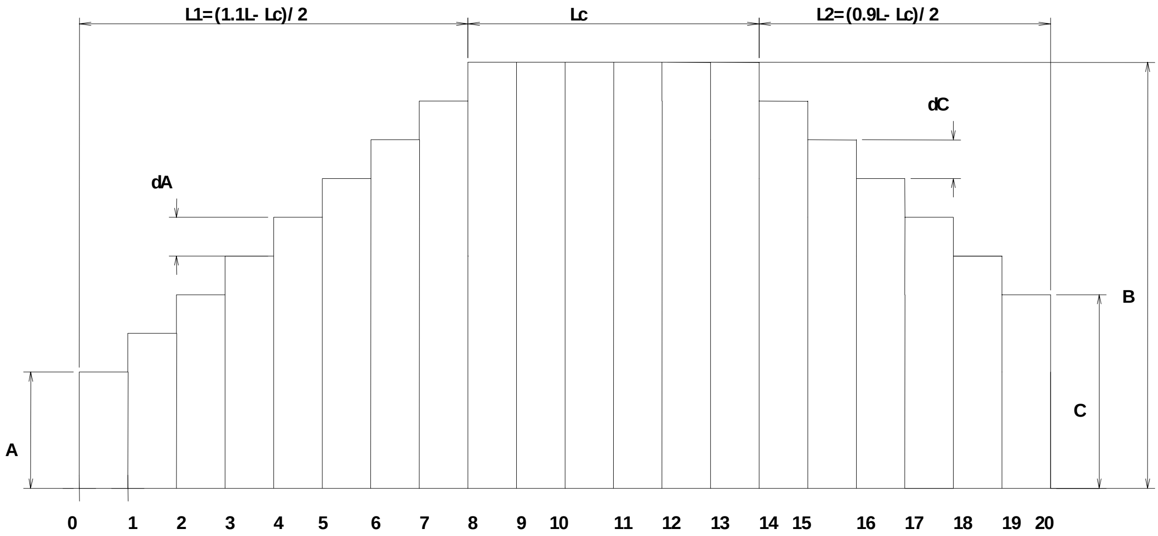


Figure 20 Hull weight distribution (aft a midship)

Table 5 Hull weight distribution parameters

$L_c\,/\,L$	0.1	0.2	0.3
B/(P_{hull}/L)	1.27	1.24	1.21
A/(P_{hull}/L)	$0.755 - 0.266(x_{hull}/\Delta L)$	$0.738 - 0.279(x_{hull}/\Delta L)$	$0.726 - 0.296(x_{hull}/\Delta L)$
C/(P_{hull}/L)	$0.699 + 0.325(x_{hull}/\Delta L)$	$0.668 + 0.349(x_{hull}/\Delta L)$	$0.637 + 0.381(x_{hull}/\Delta L)$
$L_c\,/\,L$	0.4	0.5	0.6
B/(P_{hull}/L)	1.18	1.15	1.12
A/(P_{hull}/L)	$0.711 - 0.319(x_{hull}/\Delta L)$	$0.704 - 0.350(x_{hull}/\Delta L)$	$0.704 - 0.392(x_{hull}/dL)$
C/(P_{hull}/L)	$0.606 + 0.426(x_{hull}/\Delta L)$	$0.574 + 0.490(x_{hull}/dL)$	$0.544 + 0.588(x_{hull}/dL)$

Table 6 Calculation of weight of hull

k_{DW}= -2E-6x^2 + 0.0016x + 0.6001	0.763	[-]
DW=4E-06*$L^{3.1019}$	11258.287	[t]
Δ=DW/k_{DW}	14749.491	[t]
LW=Δ-DW	3491.205	[t]
$k_{hull,ss}$= 2E-06*L^2 – 0.0012*L + 0.2763	0.161	[-]
$P_{hull,ss}$=Δ*k_{hull}	2376.14	[t]
P_{ss}	233.300	[t]
P_{hull}=$P_{hull,ss}$-P_{ss}	2142.84	[t]
L_c/L	0.500	[-]
L_1=(1.1*L-L_c)/2	36.000	[m]
L_c	60.000	[m]
L_2=(0.9*L-L_c)/2	24.000	[m]
P_{hull}/L	17.857	[m]
X_{hull}=L_c/L-0.7	-0.200	[t/m]
A=(P_{hull}/L)*((0.704-0.350*(X_{hull}/ΔL))	12.780	[t/m]
B=(P_{hull}/L)*1.15	20.536	[t/m]
C=(P_{hull}/L)*((0.574+0.490*(X_{hull}/ΔL))	9.958	[t/m]
dA=2*ΔL*(B-A)/(1.1*L-L_c)	1.293	[t/m]
dC=2*ΔL*(B-C)/(0.9*L-L_c)	2.644	[t/m]

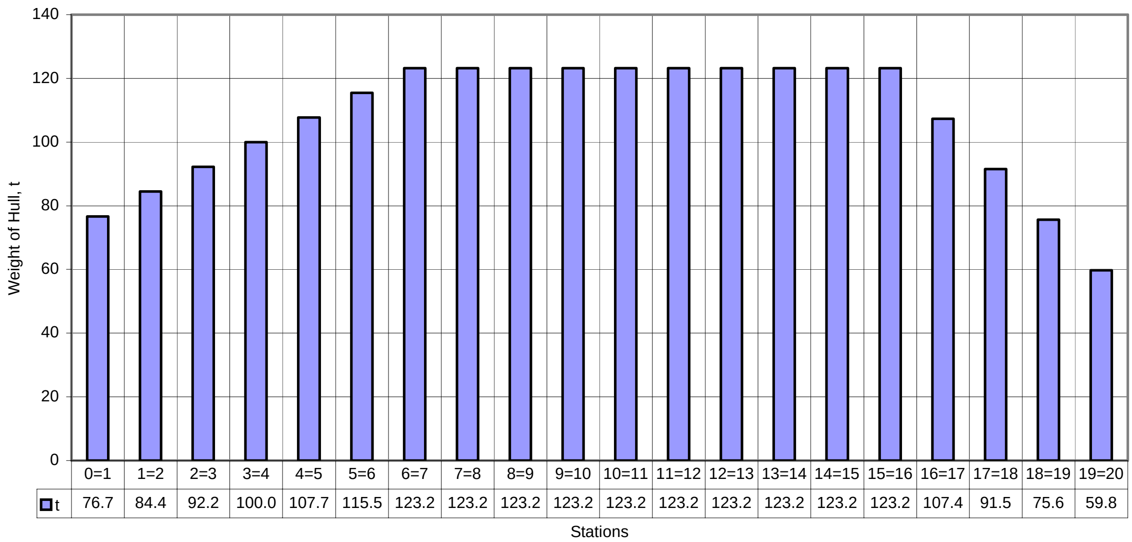


Figure 21 Weight distribution of hull

2.1.1.4 Weight of Equipment

The weight of equipment is presented as:

$$P_{eq} = P_{eq,1} + P_{eq,2} + P_{eq,3} + P_{eq,4}\text{, [t]} \tag{30}$$

$$P_{eq,1} = [0.4 \div 0.6] P_{eq}\text{, [t]} \tag{31}$$

$$P_{eq,2} = [0.02 \div 0.05] P_{eq}\text{, [t]} \tag{32}$$

$$P_{eq,3} = [0.3 \div 0.45] P_{eq}\text{, [t]} \tag{33}$$

$$P_{eq,4} = [0.05 \div 0.1] P_{eq}\text{, [t]} \tag{34}$$

$$P_{eq} = LW - P_{hull} - P_{ss} - P_m\text{, [t]} \tag{35}$$

$$LW = \Delta - DW\text{, [t]} \tag{36}$$

Depending on the location of the engine room, the distribution of the weight of equipment is shown in Figure 22 and Figure 23.

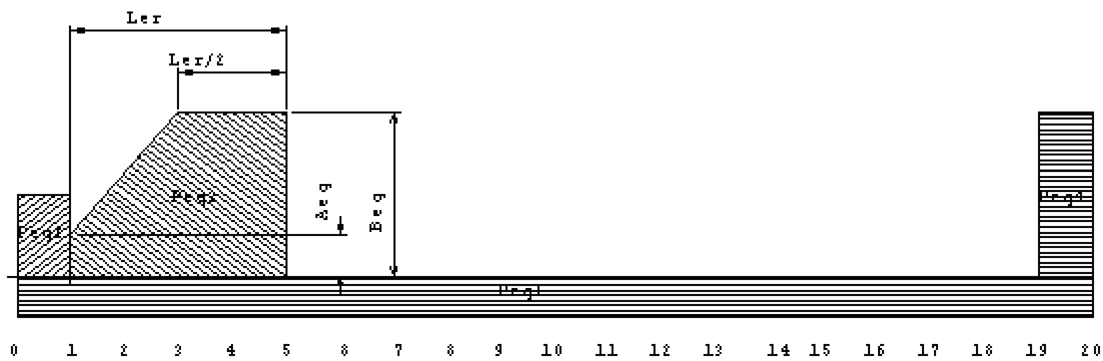


Figure 22 Weight distribution of equipment (aft of a midship)

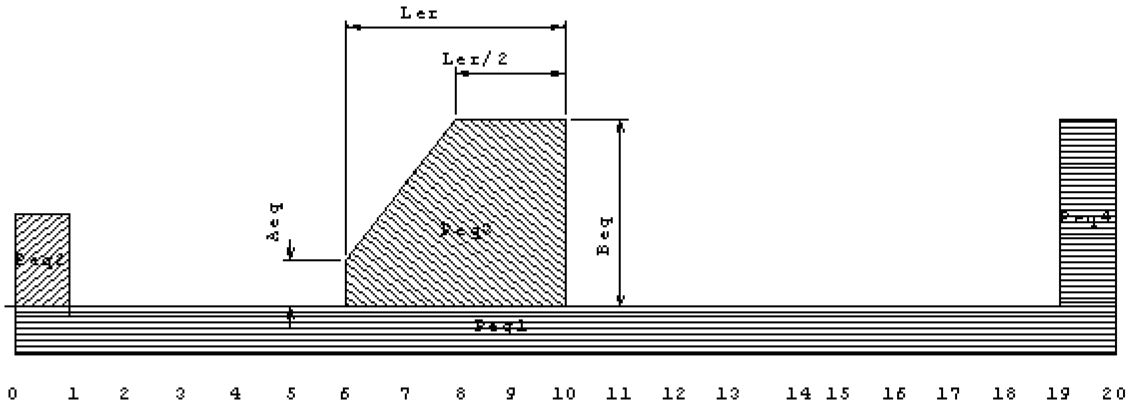


Figure 23 Weight distribution of equipment (midship)

The weight of equipment may be approximated as:

$$P_{eq,aft} = 0.5 L_{er} B \text{, [t]} \tag{37}$$

$$P_{eq,for} = 0.008 LB \text{, [t]} \tag{38}$$

Table 7 Calculation of the weight of equipment

LW	3491.205	[t]
P_{hull}	2142.848	[t]
P_{ss}	233.291	[t]
P_m	358.410	[t]
P_{eq}=LW-P_{hull}-P_{ss}-P_m	756.656	[t]
L_{er}	24.000	[m]
P_{eq1}=0.5*P_{eq}	378.328	[t]
P_{eq2}=0.03*P_{eq}	22.700	[t]
P_{eq3}=0.4*P_{eq}	302.662	[t]
P_{eq4}=0.07P_{eq}	52.966	[t]
A_{eq}=B_{eq}/3	5.044	[t/m]
B_{eq}=P_{eq3}/(10/3)/ ΔL	15.133	[t/m]
B_1=A_{eq}	5.044	[t/m]
B_2=2*B_{eq}/3	10.089	[t/m]
B_3=B_{eq}	15.133	[t/m]
B_4=B_{eq}	15.133	[t/m]
c_1=ΔL/2-ΔL/6*((B_2-B_1)/(B_2+B_1))	2.667	[m]
m_1=(B_1+B_2)* ΔL/2	38.169	[t]
M_{11}=m_1*(1/2+c_1/ΔL)	36.048	[t]
M_{12}=m_1*(1/2-c_1/ΔL)	2.120	[t]
c_2=ΔL/2-ΔL/6*((B_3-B_2)/(B_3+B_2))	2.800	[m]
m_2=ΔL*(B_3+B_2)/2	75.666	[t]
M_{22}=m_2*(1/2+c_2/ΔL)	73.143	[t]
M_{23}=m_2*(1/2-c_2/ΔL)	2.522	[t]
M_{33}=B_3*ΔL	90.799	[t]
M_{44}=B_4*ΔL	90.799	[t]

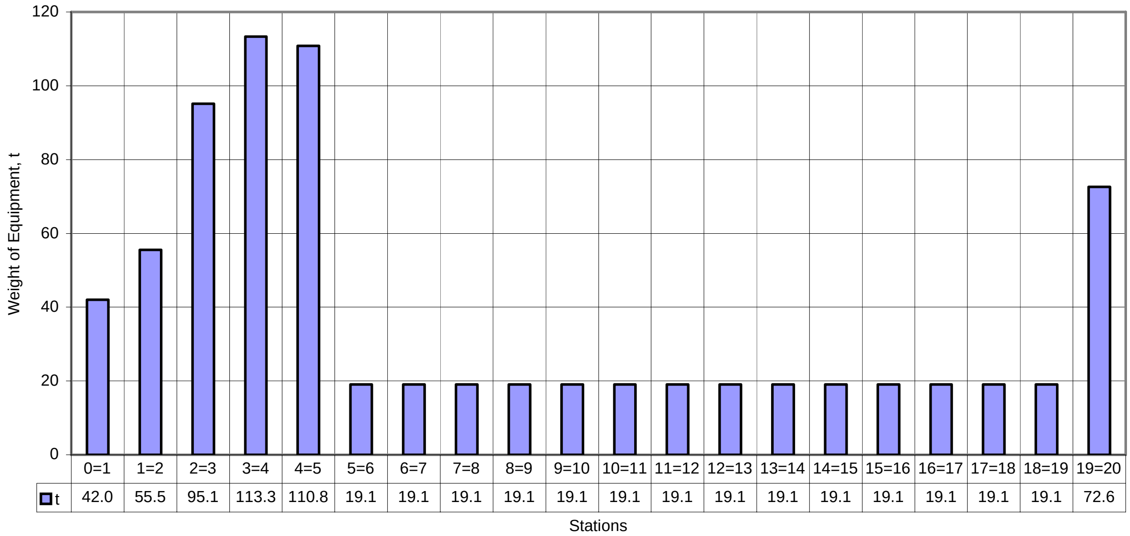


Figure 24 Weight distribution of equipment

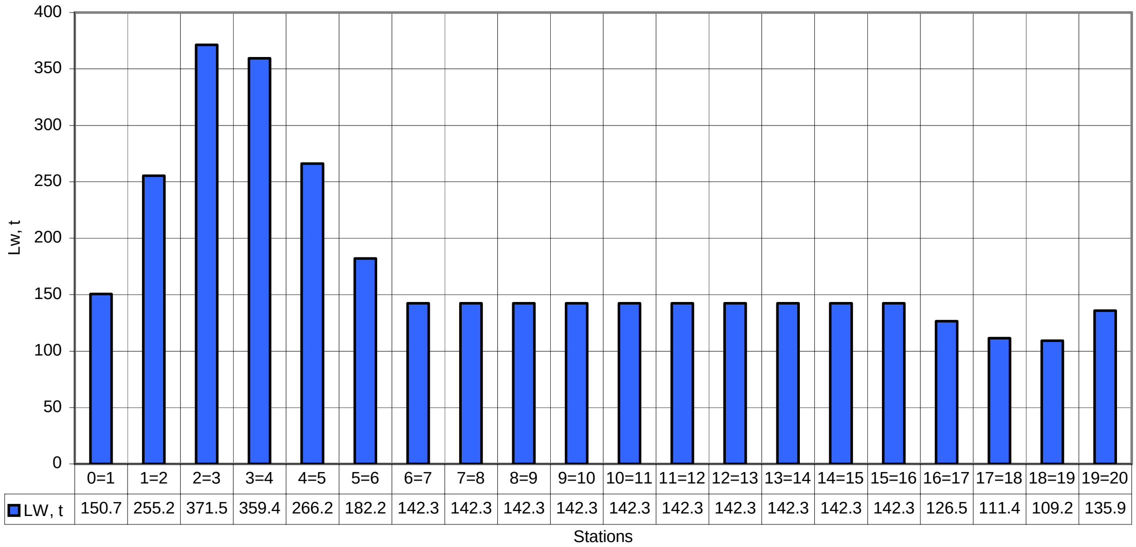


Figure 25 Weight distribution of LW

2.1.2 Cargo Dead-weight

A basic characteristic of any ship is the weight of the cargo that can be carried at full load draft or cargo dead-weight (*DW*). The *DW* of merchant ships is the difference between the full-load displacement weight Δ and the light ship weight:

$$DW = \Delta - LW \qquad (39)$$

$$\Delta = \nabla \rho \tag{40}$$

where ∇ is the volume of displacement and ρ is the mass density of the liquid in which the ship is assumed to float.

The actual cargo dead weight is obtained by deducting the weight of fuel, stories, fresh water, water (or other removable ballast), crew and stores, which the ship may carry.

$$DW = P_{sc} + P_{fw} + P_{foc} + P_b + P_c \tag{41}$$

Owners usually have defined ideas as to the amount of provisions, stores and fresh water necessary for their service. When better information is not available following equations give approximated weight.

2.1.2.1 Weight of Stores and Crew

The weight of the stores and crew may be approximated as:

$$P_{sc} = 0.15n \tag{42}$$

where n is the number of the members of the crew and the distribution function of the weight is shown in Figure 26 and Figure 27 ($A_{sc} = B_{sc} / 3$).

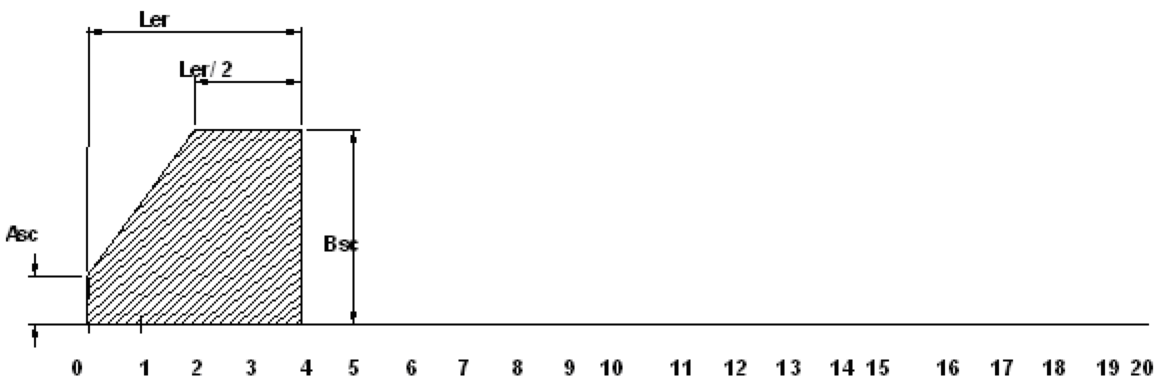


Figure 26 Weight distribution of the stores and the crew (aft midship).

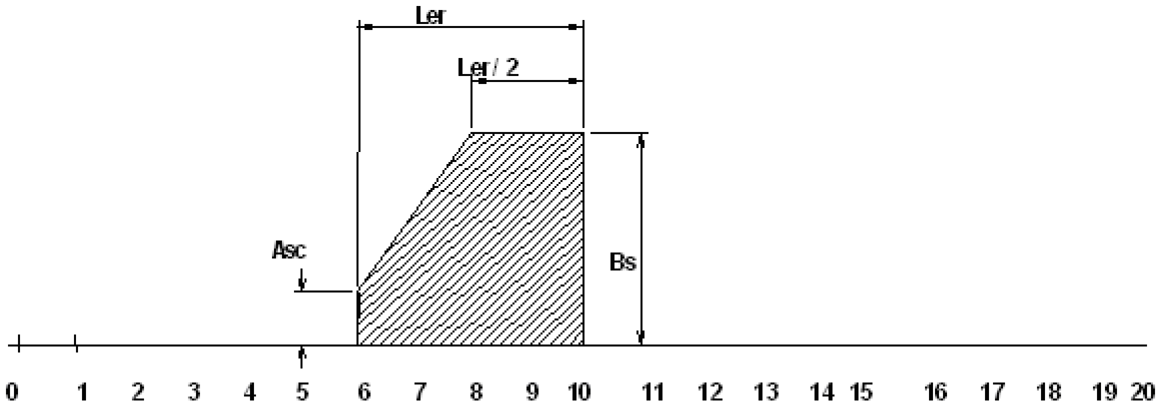


Figure 27 Weight distribution of the stores and the crew (midship).

Table 8 Calculation of the weight of the stores and the crew

n	32	[ps]
P_{sc}=0.15*n	4.800	[t]
$A_{sc}=B_{sc}/3$	24.000	[t/m]
$B_{sc}=P_{sc3}/(10/3)/\Delta L$	0.080	[t/m]
$B_1=A_{sc}$	0.240	[t/m]
$B_2=2*B_{sc}/3$	0.080	[t/m]
$B_3=B_{sc}$	0.160	[t/m]
$B_4=B_{sc}$	0.240	[t/m]
$c_1=\Delta L/2-\Delta L/6*((B_2-B_1)/(B_2+B_1))$	0.240	[m]
$m_1=(B_1+B_2)*\Delta L/2$	2.667	[t]
$M_{11}=m_1*(1/2+c_1/\Delta L)$	0.720	[t]
$M_{12}=m_1*(1/2-c_1/\Delta L)$	0.680	[t]
$c_2=\Delta L/2-\Delta L/6*((B_3-B_2)/(B_3+B_2))$	0.040	[m]
$m_2=\Delta L*(B_3+B_2)/2$	2.800	[t]
$M_{22}=m_2*(1/2+c_2/\Delta L)$	1.200	[t]
$M_{23}=m_2*(1/2-c_2/\Delta L)$	1.160	[t]
$M_{33}=B_3*\Delta L$	0.040	[t]
$M_{44}=B_4*\Delta L$	1.440	[t]

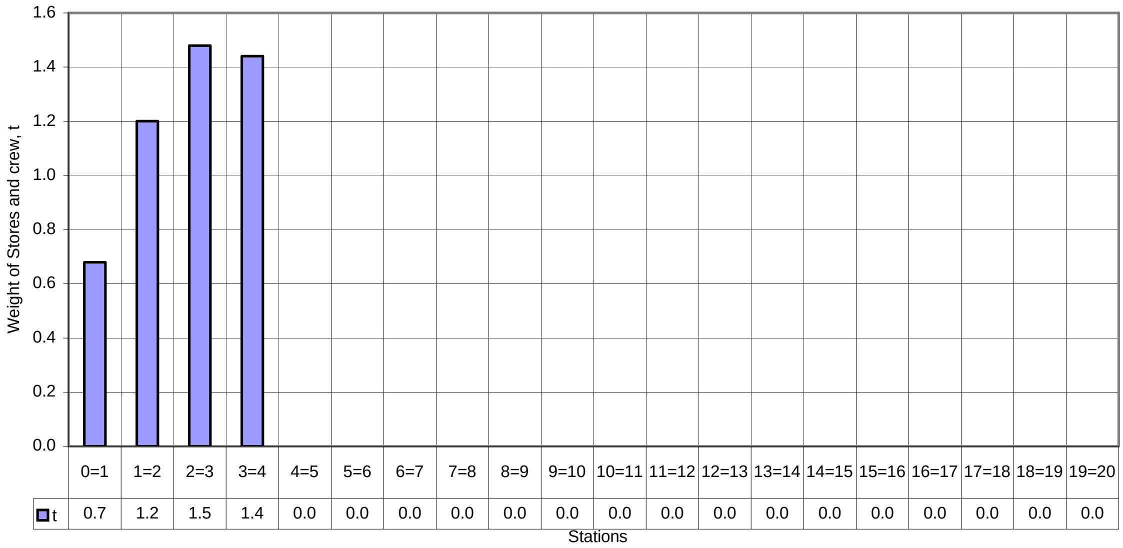


Figure 28 Weight distribution of the stores and the crew.

2.1.2.2 Fresh water capacity

Fresh water capacity will depend upon whether water is to be obtained ashore and carried for the length of the voyage or the ship's distilling plant can meet all requirements at sea. In the later case requisite capacity for fresh water will be much reduced. The weight of fresh water and food may be described as (see Figure 17):

$$P_{fw} = \left[0.015 \div 0.02\right] DW \qquad (43)$$

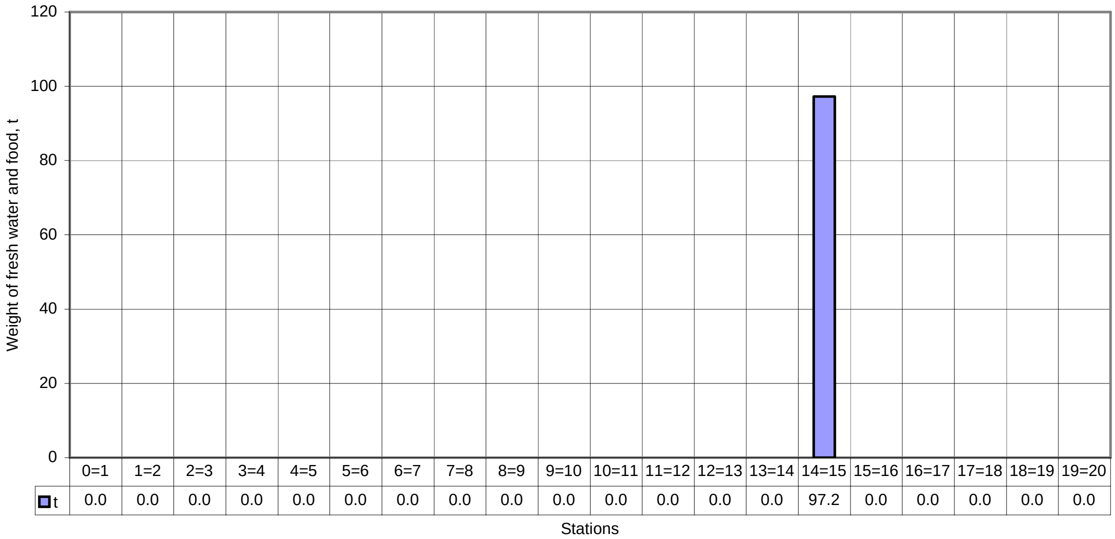


Figure 29 Weight distribution of fresh water and food

Table 9 Calculation of the weight of fresh water

n	32	[ps]
P_w	105.600	[t]
γ_{water}	1.000	[t/m^3]
$P_{w, real}$	97.200	[t]

2.1.2.3 Fuel, oil and cooling water

The necessary weight of fuel, oil and cooling water is a mater for specific estimating for the particular machinery installation. An approximated expression may be taken as:

$$P_{foc} = 0.0002 N_{eff} T \tag{44}$$

where T is the duration of the voyage in hours.

Table 10 Calculation of the weight of fuel, oil and cooling water

N_{eff}=0.4612*L^2 - 42.254*L + 2013.3	3584.100	[Horse]
T=24*A	720.000	[Hours]
A	30.000	[days]
P_{foc}=0.0002*N_{eff}*T	516.110	[t]
γ_{fuel}	1.000	[t/m^3]
$P_{foc,real}$	559.623	[t]

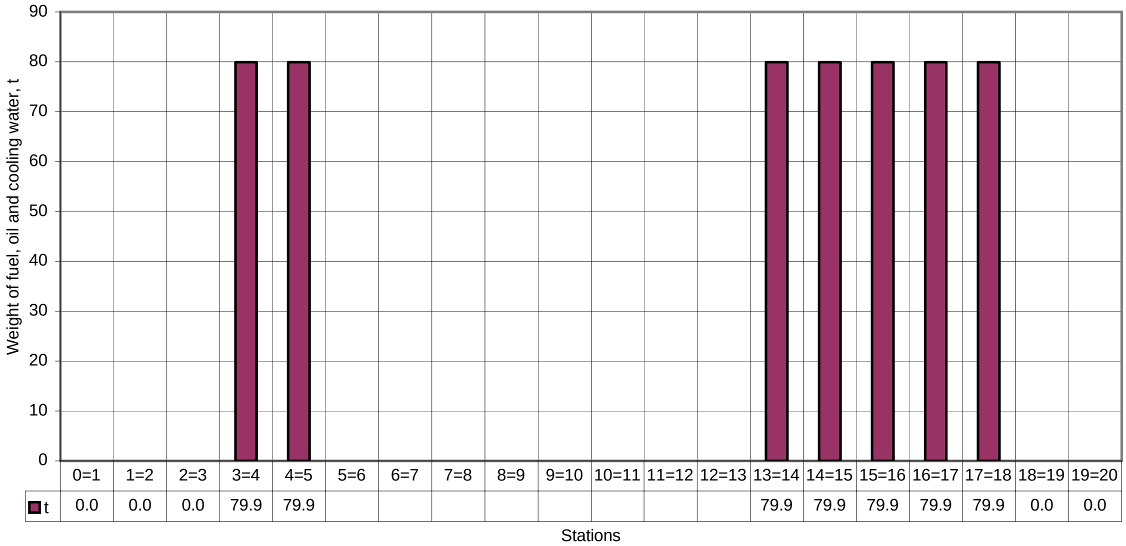


Figure 30 Weight distribution of fuel, oil and cooling water

2.1.2.4 Ballast

The required ballast will be dependent upon trim and stability consideration, which in the first approximation can be taken as:

$$P_b = (0.15 \div 0.4)DW \tag{45}$$

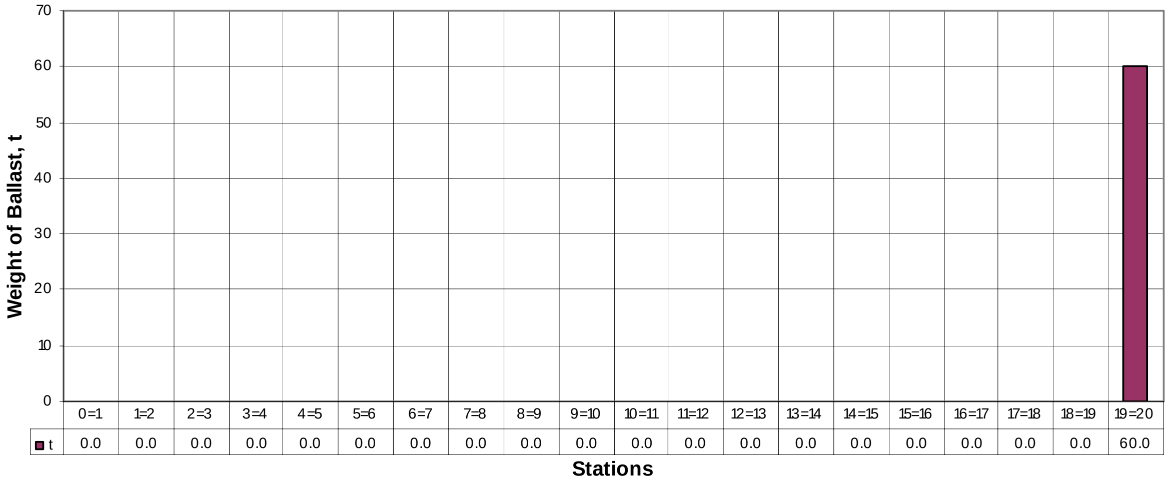


Figure 31 Weight distribution of ballast

2.1.2.5 Weight of Cargo

Detail information has to be taken to determine weight of cargo. In the preliminary design phase, approximation to weight may be adequate. When the design is finalised exact methods should be used. The cargo weight may be presented as:

$$P_c = DW - P_{wc} - P_{foc} - P_b \tag{46}$$

The distribution functions of cargo and ballast require knowing the volume capacities on ship. In order to construct the plane of the volume capacities of tanks and holds is required the information for the hull arrangement and the relative to the midship sectional floating area at different states (Eqn (48) and Figure 32) and longitudinal prismatic coefficient.

The longitudinal prismatic coefficient gives the ratio between the volume of the displacement and the prism whose length equals the length of the ship and whose cross section equals the midship sectional area:

$$C_p = \frac{\nabla}{LBdC_M} = \frac{C_b}{C_M} \tag{47}$$

For simplicity the longitudinal prismatic coefficient may be taken as $C_p = C_b + 0.1$.

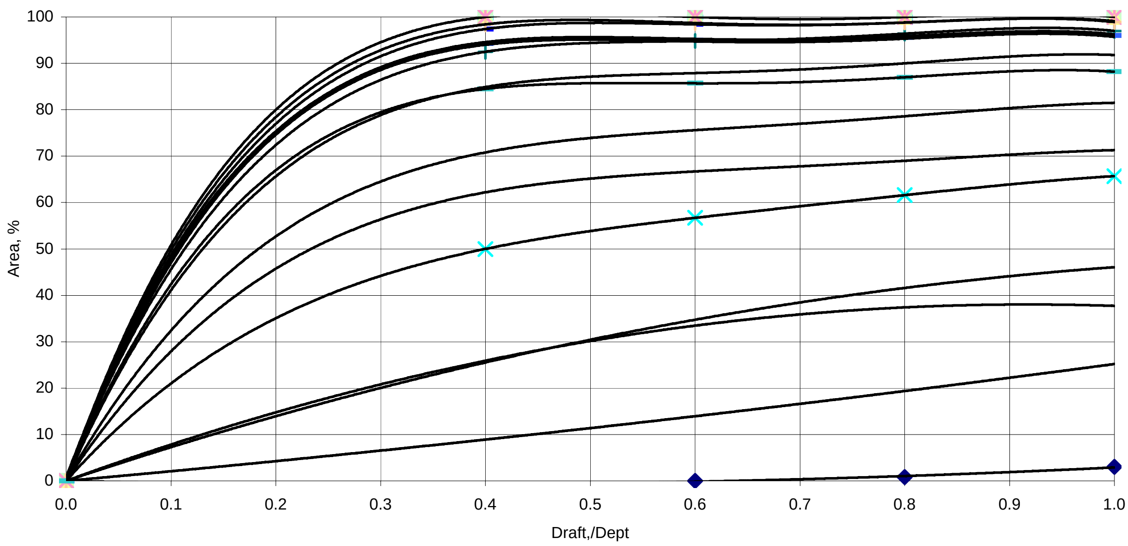


Figure 32 Relative net sectional area

$$
\begin{Bmatrix}
\bar{A}_{\%}(0)\\ \bar{A}_{\%}(1)\\ \bar{A}_{\%}(2)\\ \bar{A}_{\%}(3)\\ \bar{A}_{\%}(4)\\ \bar{A}_{\%}(5)\\ \bar{A}_{\%}(6)\\ \bar{A}_{\%}(7)\\ \bar{A}_{\%}(8)\\ \bar{A}_{\%}(9)\\ \bar{A}_{\%}(10)\\ \bar{A}_{\%}(11)\\ \bar{A}_{\%}(12)\\ \bar{A}_{\%}(13)\\ \bar{A}_{\%}(14)\\ \bar{A}_{\%}(15)\\ \bar{A}_{\%}(16)\\ \bar{A}_{\%}(17)\\ \bar{A}_{\%}(18)\\ \bar{A}_{\%}(19)
\end{Bmatrix}
=
\begin{bmatrix}
0 & 0 & 7.943 & -5.043\\
0 & 0 & 4.877 & 20.315\\
0 & 0 & -29.590 & 75.660\\
-141.670 & 417.500 & -462.330 & 252.200\\
-255.210 & 750.000 & -811.040 & 397.750\\
-384.380 & 1088.000 & -1125.400 & 512.800\\
-453.130 & 1262.500 & -1284.400 & 572.000\\
-477.080 & 1346.200 & -1381.200 & 611.100\\
-520.830 & 1458.300 & -1479.200 & 641.670\\
-520.830 & 1458.300 & -1479.200 & 641.670\\
-520.830 & 1458.300 & -1479.200 & 641.670\\
-520.830 & 1458.300 & -1479.200 & 641.670\\
-520.830 & 1458.300 & -1479.200 & 641.670\\
-520.830 & 1458.300 & -1479.200 & 641.670\\
-520.830 & 1458.300 & -1479.200 & 641.670\\
-502.080 & 1410.000 & -1435.900 & 626.900\\
-453.130 & 1262.500 & -1284.400 & 572.000\\
-433.330 & 1209.200 & -1221.900 & 534.000\\
-196.880 & 597.080 & -669.000 & 349.200\\
0 & 0 & -45.154 & 82.877
\end{bmatrix}
\begin{Bmatrix}
\left(\frac{T}{D}\right)^4\\
\left(\frac{T}{D}\right)^3\\
\left(\frac{T}{D}\right)^2\\
\left(\frac{T}{D}\right)
\end{Bmatrix}
\qquad (48)
$$

Table 11 Calculation of the weight of cargo

DW	11258.287	[t]
$P_{water,real}$	97.200	[t]
$P_{fuel,real}$	559.623	[t]
$P_{ballast,real}$	60.000	[t]
$P_{cargo}=DW-P_{water,real}-P_{fuel,real}-P_{ballast,real}$	10541.463	[t]
Δ	14749.491	[t]
$B_1=0.5*B$	9.000	[m]
$h_1=0.2*D$	2.000	[m]
$h_2=0.3*D$	3.000	[m]
$b_2=0.15*B$	2.700	[m]
$C_1=2.25*((L+30)/80)^{0.25}$	2.000	[m]
$C_2+B1=0.6*B$	12.600	[m]
$H_3=1$	1.000	[m]
H=(L-40)/0.57+40*B+3500*T/L, [mm]	1.110	[m]
γ_{cargo}	1.000	[t/m^3]
Deck tank	97.200	[m^3]
Bilge tank	77.760	[m^3]
Bottom tank 1	26.649	[m^3]
Bottom tank 2	26.649	[m^3]
Bottom tank 3	26.649	[m^3]
Area		
Deck tank	16.200	[m^2]
Bilge tank	12.960	[m^2]
Bottom tank 1	4.441	[m^2]
Bottom tank 2	4.441	[m^2]
Bottom tank 3	4.441	[m^2]

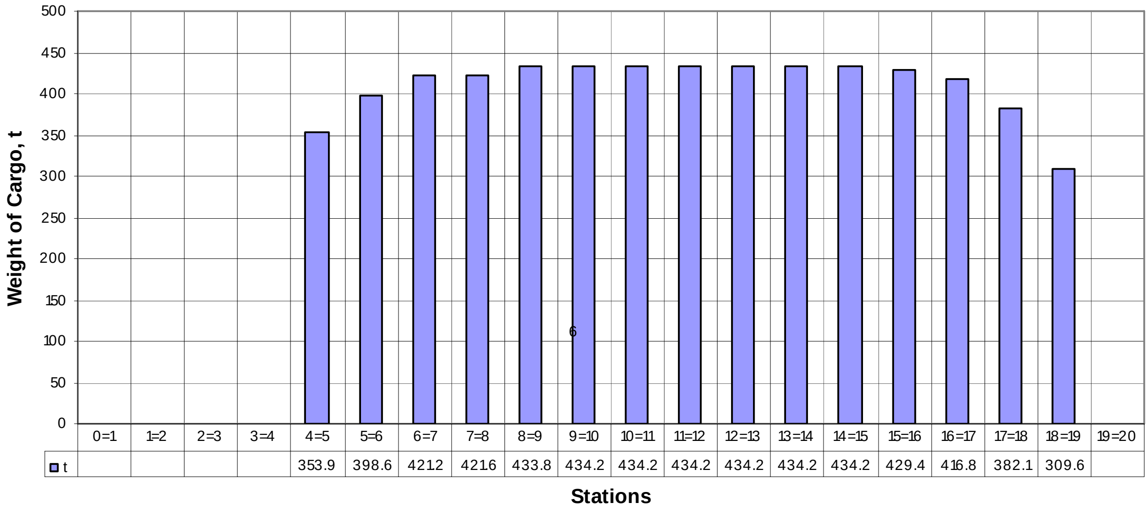
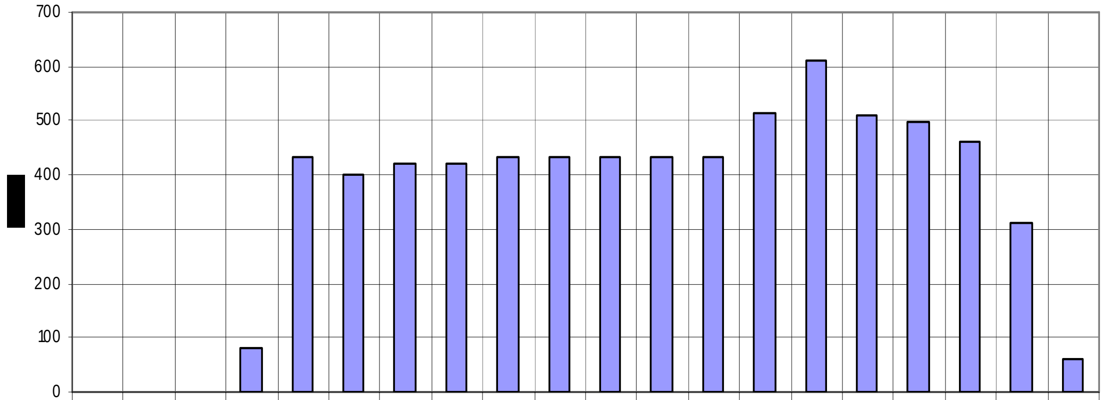


Figure 33 Weight distribution of cargo



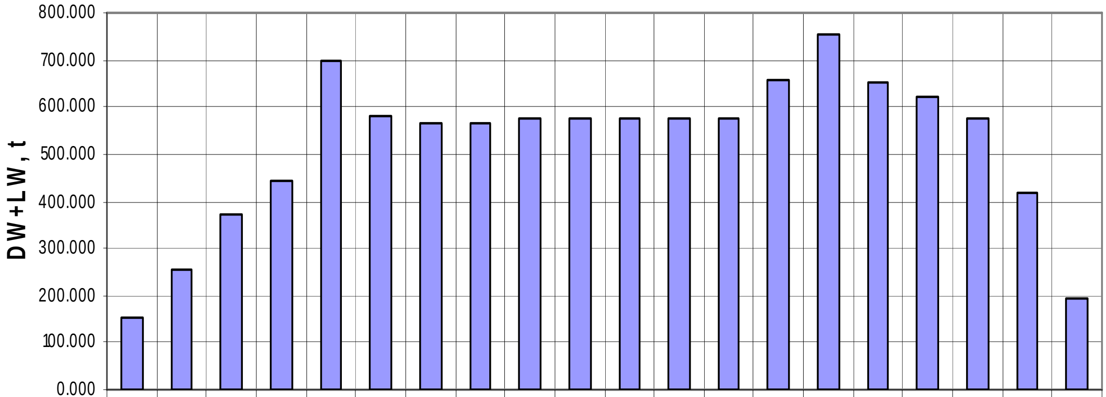
Stations	0=1	1=2	2=3	3=4	4=5	5=6	6=7	7=8	8=9	9=10	10=11	11=12	12=13	13=14	14=15	15=16	16=17	17=18	18=19	19=20
t	0.7	12	15	814	433.8	398.6	4212	4216	433.8	434.2	434.2	434.2	434.2	514.1	611.3	509.4	496.8	462.0	309.6	60.0

Stations

Figure 34 Weight distribution of DW.

2.2 Estimation of the centre of gravity of DW and LW

The calculation for the position of the centre of gravity is carried out in table form.



Stations	0=1	1=2	2=3	3=4	4=5	5=6	6=7	7=8	8=9	9=10	10=11	11=12	12=13	13=14	14=15	15=16	16=17	17=18	18=19	19=20
t	151.396	256.39	372.94	440.76	699.96	580.82	563.48	563.91	576.07	576.510	576.510	576.510	576.510	656.45	753.65	651.68	623.22	573.42	418.74	195.90

Stations

Figure 35 Weight distribution of DW+LW.

Table 12 Calculation of the centre of gravity of DW and LW

Stations	Stores	Water	Fuel	Ballast	Cargo	DW	LW	DW+LW	k	[9]*[10]
	[1]	[2]	[3]	[4]	[5]	[6]	[8]	[9]	[10]	[11]
0=1	0.680	0.000	0.000	0.000	0.000	0.7	150.716	151.396	-9.500	-1438.262
1=2	1.200	0.000	0.000	0.000	0.000	1.2	255.196	256.396	-8.500	-2179.366
2=3	1.480	0.000	0.000	0.000	0.000	1.5	371.466	372.946	-7.500	-2797.098
3=4	1.440	0.000	79.946	0.000	0.000	81.4	359.383	440.769	-6.500	-2865.001
4=5	0.000	0.000	79.946	0.000	353.867	433.8	266.152	699.965	-5.500	-3849.810
5=6	0.000	0.000	0.000	0.000	398.589	398.6	182.235	580.824	-4.500	-2613.707
6=7	0.000	0	0.000	0.000	421.167	421.2	142.317	563.484	-3.500	-1972.194
7=8	0.000	0.000	0.000	0.000	421.601	421.6	142.317	563.918	-2.500	-1409.795
8=9	0.000	0.000	0.000	0.000	433.759	433.8	142.317	576.076	-1.500	-864.113
9=10	0.000	0.000	0.000	0.000	434.193	434.2	142.317	576.510	-0.500	-288.255
10=11	0.000	0.000	0.000	0.000	434.193	434.2	142.317	576.510	0.500	288.255
11=12	0.000	0.000	0.000	0.000	434.193	434.2	142.317	576.510	1.500	864.765
12=13	0.000	0.000	0.000	0.000	434.193	434.2	142.317	576.510	2.500	1441.274
13=14	0.000	0.000	79.946	0.000	434.193	514.1	142.317	656.456	3.500	2297.596
14=15	0.000	97.200	79.946	0.000	434.193	611.3	142.317	753.656	4.500	3391.452
15=16	0.000	0.000	79.946	0.000	429.417	509.4	142.317	651.680	5.500	3584.239
16=17	0.000	0.000	79.946	0.000	416.825	496.8	126.450	623.222	6.500	4050.941
17=18	0.000	0.000	79.946	0.000	382.090	462.0	111.391	573.427	7.500	4300.706
18=19	0.000	0.000	0.000	0.000	309.580	309.6	109.161	418.740	8.500	3559.292
19=20	0.000	0.000	0.000	60.000	0.000	60.0	135.904	195.904	9.500	1861.084

$$x_p = \Delta L \frac{\sum_{11}}{\sum_{9}} \tag{49}$$

2.3 Estimation of water buoyancy

In order to calculate the still water buoyancy distribution the location of the still waterline of the vessel must be determined from the two overall equilibrium requirements. It is also necessary to define the weight distribution $m(x)$ or at least the overall weight Δ and the location of the longitudinal centre of gravity. Thus, once the line of a ship has been specified, the still water buoyancy is fixed and calculable, and the still water load, shear force and bending moment depend entirely on the weight distribution.

The overall static equilibrium requires that the total upward buoyant force equals the weight of the ship and that these two vertical forces coincide that the longitudinal centre of buoyancy (LCB) must coincide with the longitudinal centre of gravity (LCG). Using this notation, the first requirement is:

$$\rho g \int_{o}^{L} a(x) dx = g \int_{o}^{L} m(x) dx = g\Delta \tag{50}$$

where: $a(x)$ is immersed cross sectional area, $m(x)$ is mass distribution, ρ is mass density of seawater, g is gravitational acceleration and Δ is the weight displacement.

The factor g is retained on both sides to emphasise that it is forces, which are involved.

Similarly, the equilibrium of moments requires that:

$$\rho g \int_{o}^{L} x\, a(x) dx = g \int_{o}^{L} x\, m(x) dx = g\Delta\, l_G \tag{51}$$

where l_G is distance from origin to LCG.

To satisfy the above requirements must be determined the drafts at FP and AP, which needs the information about the mean moulded draft (T_m), the longitudinal centre of buoyancy (LCB), the longitudinal metacentric radius $\overline{BM_L}$ and the longitudinal centre of gravity (LCG):

$$T_{FP} = T_m + \left(\frac{L}{2} - x_f \right) \frac{LCG - LCB}{\overline{BM_L}} \tag{52}$$

$$T_{AP} = T_m - \left(\frac{L}{2} + x_f \right) \frac{LCG - LCB}{\overline{BM_L}} \tag{53}$$

Having the drafts at FP and AP and applying the Bonjean plane the floated net-section can be defined and the displacement and longitudinal centre of buoyancy may be calculated. The procedure has to be repeated until the difference between the position of the longitudinal centre of gravity and the longitudinal centre of buoyancy is in the limit of $[-0.01L,\ 0.0001L]$.

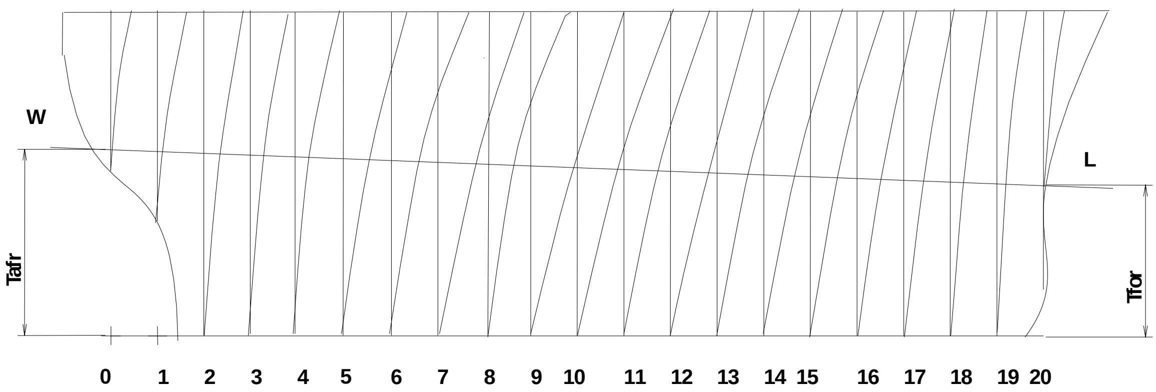


Figure 36 Bonjean plane

In the preliminary design, there is no information about the Bonjean plan then a simplified method for estimation of longitudinal centre of buoyancy and displacement can be applied. It is well known that the floated section of the Bonjean plane may be approximated by a line between two neighbour water lines with that leads on a distance of 0.1*T*. If it is considered that $LCB = x_f = 0$ and $\overline{BM}_L = L$ then an analytical method for estimating the LCB and displacement can be applied. For that purpose an additional water line WLC above the waterline WLO on a distance of $\varepsilon \in [0.05T_m,\ 0.Td_m]$ has to be plotted. If the estimated waterline takes place between WL_O and WL_C then the immersed cross sectional area at any states may be calculated as:

$$a_i = a_{oi} + \frac{a_{ci} - a_{oi}}{\varepsilon}\left(a + b\frac{x}{L}\right) \tag{54}$$

Once having information about the location of the water line then the buoyancy and its distribution and the position of the centre of buoyancy can be calculated.

Table 13 Bonjean plan- still water

Stations	T_{WLo}, m	T_{WL}, m	T_{WLc}, m	$Area_{WLo}$, %	$Area_{WL}$%	$Area_{WLc}$%	$Area_{mid}$, m^2	$Area_{WLo}$, m^2	$Area_{WL}$, m^2	$Area_{WLc}$, m^2
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
0	7.00	7.44	7.50	0.36	0.64	0.69	153.74	0.39	0.69	0.74
1	7.00	7.44	7.50	16.61	17.81	17.98	153.74	17.88	19.17	19.35
2	7.00	7.44	7.50	38.46	39.91	40.10	153.74	41.39	42.95	43.15
3	7.00	7.44	7.50	59.19	60.25	60.40	153.74	63.69	64.84	65.00
4	7.00	7.44	7.50	76.99	77.66	77.76	153.74	82.85	83.58	83.68
5	7.00	7.44	7.50	88.41	88.87	88.94	153.74	95.14	95.64	95.72
6	7.00	7.44	7.50	95.28	95.70	95.77	153.74	102.54	102.99	103.06
7	7.00	7.44	7.50	98.18	98.34	98.38	153.74	105.66	105.83	105.87
8	7.00	7.44	7.50	99.51	99.60	99.63	153.74	107.08	107.19	107.22
9	7.00	7.44	7.50	99.51	99.60	99.63	153.74	107.08	107.19	107.22
10	7.00	7.44	7.50	99.51	99.60	99.63	153.74	107.08	107.19	107.22
11	7.00	7.44	7.50	99.51	99.60	99.63	153.74	107.08	107.19	107.22
12	7.00	7.44	7.50	99.51	99.60	99.63	153.74	107.08	107.19	107.22
13	7.00	7.44	7.50	99.51	99.60	99.63	153.74	107.08	107.19	107.22
14	7.00	7.44	7.50	99.51	99.60	99.63	153.74	107.08	107.19	107.22
15	7.00	7.44	7.50	98.32	98.43	98.46	153.74	105.81	105.93	105.96
16	7.00	7.44	7.50	95.28	95.70	95.77	153.74	102.54	102.99	103.06
17	7.00	7.44	7.50	85.78	86.14	86.20	153.74	92.31	92.70	92.77
18	7.00	7.44	7.50	74.16	75.06	75.18	153.74	79.80	80.77	80.91
19	7.00	7.44	7.50	35.89	36.67	36.76	153.74	38.62	39.46	39.56
20	7.00	7.44	7.50	0.00	1.00	2.00	153.74	0.00	1.08	2.15

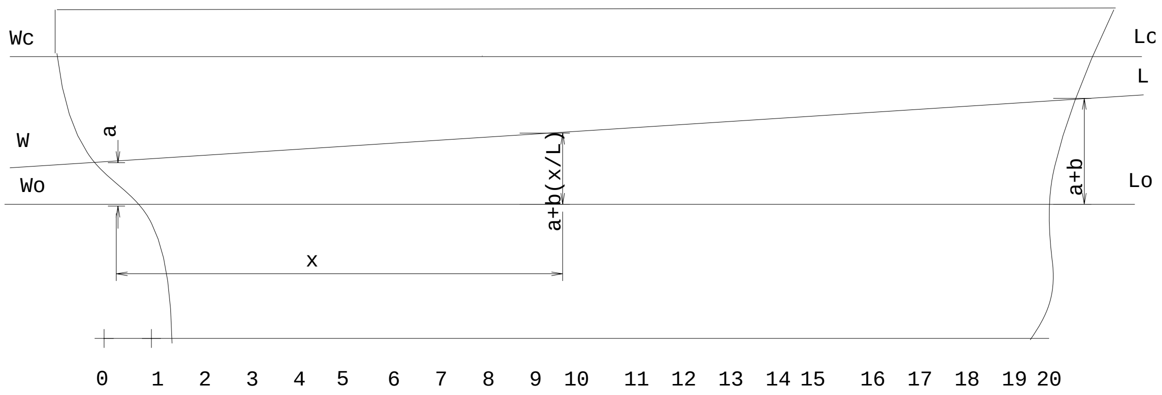


Figure 37 Estimation of LCB

Table 14 Immersed sectional area- still water

Stations	k	$Area_{WLo}$	[2]*[3]	$Area_{WLc}$	[5]-[3]	[6]*[2]	[7]*[2]	a/ +b/ *k/20	[6]*[9]	[3]+[10]	[11]*[2]
	-	m^2	m^2	m^2	m^2	m^2	m^2	-	m^2	m^2	m^2
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
0	0.0	0.2	0.0	0.4	0.2	0.0	0.0	0.9	0.2	0.3	0.0
1	1.0	17.9	17.9	19.3	1.5	1.5	1.5	0.9	1.3	19.2	19.2
2	2.0	41.4	82.8	43.2	1.8	3.5	7.0	0.9	1.6	42.9	85.9
3	3.0	63.7	191.1	65.0	1.3	3.9	11.7	0.9	1.1	64.8	194.5
4	4.0	82.9	331.4	83.7	0.8	3.3	13.2	0.9	0.7	83.6	334.3
5	5.0	95.1	475.7	95.7	0.6	2.9	14.4	0.9	0.5	95.6	478.2
6	6.0	102.5	615.2	103.1	0.5	3.1	18.8	0.9	0.5	103.0	618.0
7	7.0	105.7	739.6	105.9	0.2	1.5	10.3	0.9	0.2	105.8	740.9
8	8.0	107.1	856.7	107.2	0.1	1.1	8.4	0.9	0.1	107.2	857.6
9	9.0	107.1	963.8	107.2	0.1	1.2	10.7	0.9	0.1	107.2	964.8
10	10.0	107.1	1070.8	107.2	0.1	1.3	13.2	0.9	0.1	107.2	1072.0
11	11.0	107.1	1177.9	107.2	0.1	1.4	15.9	0.9	0.1	107.2	1179.2
12	12.0	107.1	1285.0	107.2	0.1	1.6	19.0	0.9	0.1	107.2	1286.4
13	13.0	107.1	1392.1	107.2	0.1	1.7	22.2	0.9	0.1	107.2	1393.6
14	14.0	107.1	1499.2	107.2	0.1	1.8	25.8	0.9	0.1	107.2	1500.8
15	15.0	105.8	1587.1	106.0	0.2	2.3	34.9	0.9	0.1	105.9	1589.2
16	16.0	102.5	1640.7	103.1	0.5	8.3	133.4	0.9	0.5	103.0	1648.0
17	17.0	92.3	1569.4	92.8	0.5	7.7	131.3	0.9	0.4	92.7	1576.1
18	18.0	79.8	1436.5	80.9	1.1	19.9	358.6	0.9	1.0	80.8	1454.0
19	19.0	38.6	733.8	39.6	0.9	17.8	338.1	0.9	0.8	39.4	749.5
20	20.0	0.0	0.0	1.1	1.1	21.5	430.5	0.9	0.9	0.9	18.9

Table 15 Verification of equilibrium

$\Delta=\gamma*\Delta L*\Sigma_{11}$	10384.90	[t]
$x_b=\Delta L*\Sigma_{12}/\Sigma_{11}-L/2$	3.11	[m]
x_p	3.10	[m]
P	10384.90	[t]

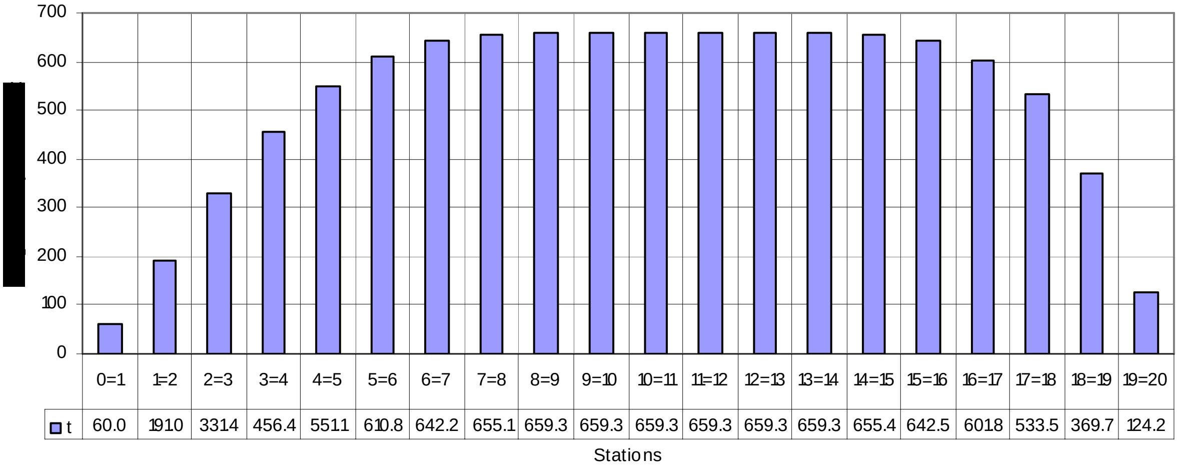


Figure 38 Weight distribution of displacement

2.4 Basic relationships: Load, Shear Force, Bending Moment

For the sake of clarity the principal assumption are listed here under:

- There is only one independent variable, longitudinal position where loads and deflection have only a single value at any cross section.

- The hull girder remains elastic, its deflection is small, and the longitudinal strain due to bending varies linearly over the cross section, about some transverse axis of zero strain (neutral axis).

- Dynamic effects may be either neglected or accounted for by equivalent static loads. Hence, static equilibrium may be invoked.

- Since the bending strain is linear, the horizontal and vertical bending of the hull girder may be dealt with separately and superimposed.

In elastic, small-deflection beam theory the governing equation for the bending moment $M(x)$ is:

$$\frac{d^2M}{dx^2} = q(x) \tag{55}$$

in which the right hand side, $q(x)$ is the loading on the beam, expressed as a distributed vertical force. For a ship, this is a net distributed force that is resultant of the buoyancy force *b(x)* and the weight force $p(x) = m(x)g$. In the sign convention adopted herein, forces are positive upward, but an exception is made for the weight force, which is conventionally regarded as positive. Hence the net force is:

$$q(x) = b(x) - p(x) \tag{56}$$

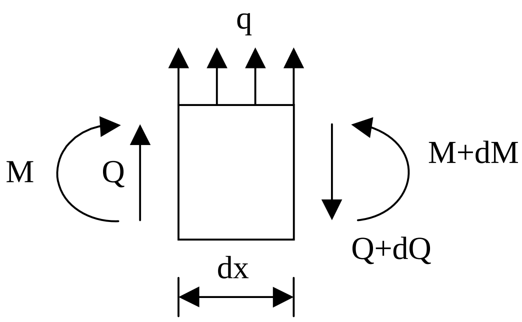


Figure 39 Hull girder bending

The solution for $M(x)$ requires two integrations. The first yields the transverse shear force $Q(x)$, and it is obtained by imposing vertical force equilibrium of a differential element considered as a free body.

$$Q + qdx - Q - dQ = 0 \tag{57}$$

$$q = \frac{dQ}{dx} \tag{58}$$

from which

$$Q(x) = \int_o^x q(x)dx + \lambda \tag{59}$$

For ships the constant of integration is always zero because the hull girder is a "free-free" beam, with zero shear force at the ends $Q(0) = 0$.

The equilibrium of moments yields:

$$M + Qdx + q\,dx\,\frac{dx}{2} - M - dM = 0 \qquad (60)$$

Table 16 Calculation of shear forces and still water bending moment

Stations	Area	Sum-par of [2]	Displ [t], 0.5*γ*[3]* ΔL	Weight, [t]	Loadings, [t], [5]-[4]	Sum from up	Integration of [7]	dQ, [t], -[7]$_{20}$*[1]/20	Q, [t], [7]+[9]	0.5*ΔL*[8]	dMsw=-[11]$_{20}$*[1]/20	Msw=[11]+[12]
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
0						0	0	0	0	0	0	0
1												
2												
3												
4												
…												
18												
19												
20						[7]$_{20}$		-[7]$_{20}$	0.0	[11]$_{20}$	-[11]$_{20}$	0

The dx^2 term of second order is neglected and therefore:

$$Q = \frac{dM}{dx} \qquad (61)$$

from which

$$M(x) = \int_o^x Q(x)dx + \lambda \qquad (62)$$

In order to calculate the load on the hull girder it is necessary to calculate both the distributed buoyancy force and the distributed weight force. The still water buoyancy is a completely static quantity and it depends mainly on the shape of immersed hull. It therefore most logically forms part of the hydrostatic calculation. The additional buoyancy force due to waves is markedly different from the buoyancy force in still water, being essentially both dynamic and probabilistic.

Table 17 Shear forces and bending moment in still water

Stations	Area	Sum-par	Displ [t]	Weight, [t]	Load, [t]	Sum from up	Integration	dQ, [t]	Q, [t]		dMsw, [t.m]	Msw, [t.m]
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
0	0.3	19.5	60.0	151.4	91.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0E+00
1	19.2	62.1	191.0	256.4	65.4	91.4	91.4	-0.2	91.2	274.1	-12.1	2.6E+02
2	42.9	107.8	331.4	372.9	41.5	156.8	339.5	-0.4	156.4	1018.6	-24.3	9.9E+02
3	64.8	148.4	456.4	440.8	-15.6	198.3	694.6	-0.6	197.7	2083.7	-36.4	2.0E+03
4	83.6	179.2	551.1	700.0	148.8	182.7	1075.5	-0.8	181.9	3226.6	-48.6	3.2E+03
5	95.6	198.6	610.8	580.8	-30.0	331.5	1589.7	-1.0	330.5	4769.1	-60.7	4.7E+03
6	103.0	208.8	642.2	563.5	-78.7	301.5	2222.7	-1.2	300.3	6668.1	-72.9	6.6E+03
7	105.8	213.0	655.1	563.9	-91.2	222.8	2747.0	-1.4	221.4	8240.9	-85.0	8.2E+03
8	107.2	214.4	659.3	576.1	-83.2	131.6	3101.4	-1.6	130.0	9304.1	-97.1	9.2E+03
9	107.2	214.4	659.3	576.5	-82.8	48.4	3281.3	-1.8	46.6	9844.0	-109.3	9.7E+03
10	107.2	214.4	659.3	576.5	-82.8	-34.4	3295.3	-2.0	-36.4	9886.0	-121.4	9.8E+03
11	107.2	214.4	659.3	576.5	-82.8	-117.2	3143.8	-2.2	-119.4	9431.3	-133.6	9.3E+03
12	107.2	214.4	659.3	576.5	-82.8	-199.9	2826.7	-2.4	-202.3	8480.0	-145.7	8.3E+03
13	107.2	214.4	659.3	656.5	-2.8	-282.7	2344.0	-2.6	-285.3	7032.1	-157.9	6.9E+03
14	107.2	213.1	655.4	753.7	98.2	-285.5	1775.8	-2.8	-288.3	5327.3	-170.0	5.2E+03
15	105.9	208.9	642.5	651.7	9.2	-187.3	1302.9	-3.0	-190.3	3908.8	-182.1	3.7E+03
16	103.0	195.7	601.8	623.2	21.4	-178.1	937.5	-3.2	-181.3	2812.5	-194.3	2.6E+03
17	92.7	173.5	533.5	573.4	39.9	-156.7	602.7	-3.4	-160.1	1808.0	-206.4	1.6E+03
18	80.8	120.2	369.7	418.7	49.1	-116.8	329.2	-3.6	-120.4	987.5	-218.6	7.7E+02
19	39.4	40.4	124.2	195.9	71.7	-67.7	144.7	-3.8	-71.5	434.1	-230.7	2.0E+02
20	0.9					4.0	81.0	-4.0	0.0	242.9	-242.9	0.0E+00

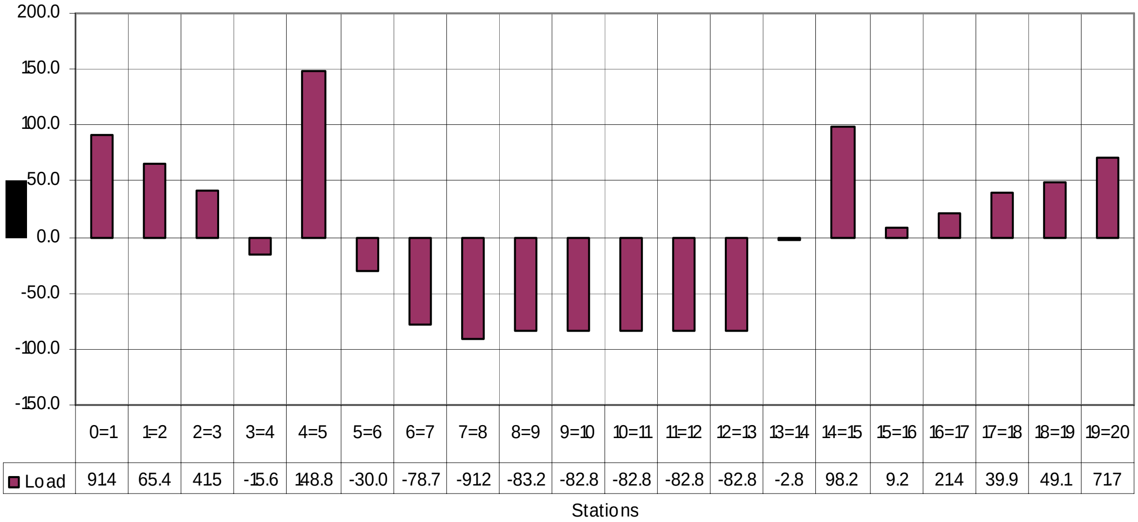


Figure 40 Load distribution

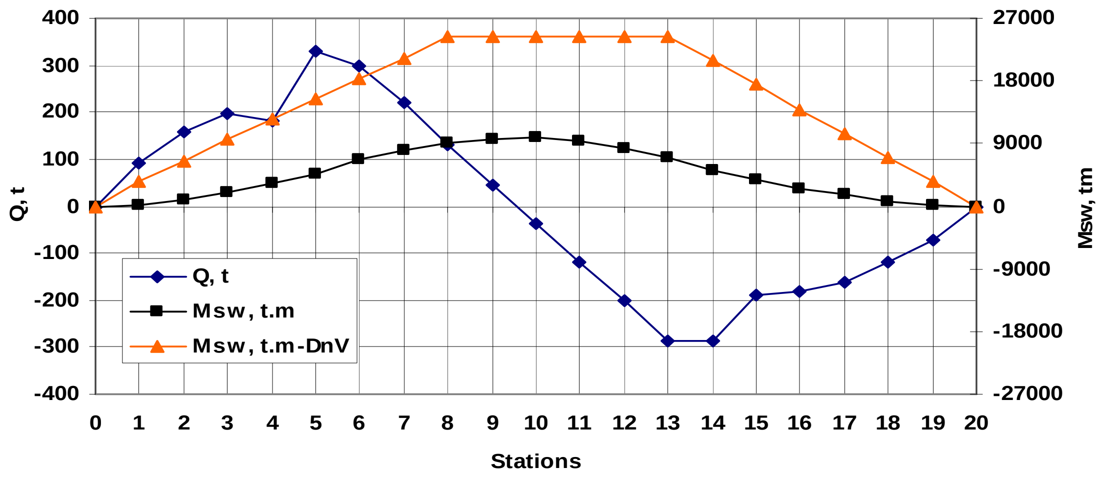


Figure 41 Distribution of shear forces and still water bending moment.

2.5 Correction of Vertical Bending Moment in Still Water as a Result of Changes in Weight

Because of the variety of possible loading conditions, the ship will rarely be in the same condition as was assumed for the still water bending moment calculation. It is therefore important to be able to calculate as simply as possible the effect of addition or removal of weight on the hull girder bending moment. A useful technique for this is to construct an influence line diagram. The influence line shows the effect of the maximum bending moment of the addition of a unit weight at any position x along the ship length. The height of the line at x represents the effect of $M_{SW,\max}$ of the addition of a unit weight at x. Two influence lines are normally drawn, one for the maximum hogging and one for the maximum sagging condition.

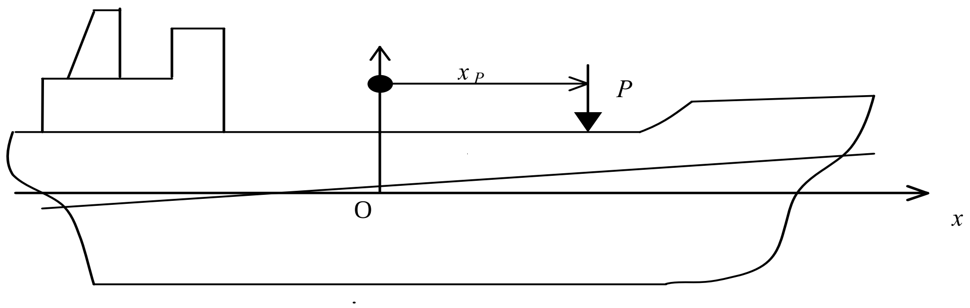


Figure 42 Changes due to added weight

As a result of the addition of some weight P the additional vertical bending moment is calculated as:

2.7.2 Effect of governing parameters on load

3 Quasi-Static Approximations ("Standard Wave") of Wave-Induced Moments and Shear Forces

3.1 Introduction

The outstanding visible characteristic of waves in the open ocean is their irregularity. Study of wave records confirms this irregularity of the sea, both in time and space. However, one is equally impressed by the fact that over a fairly wide are and often for a period of a half-hour or more the sea may maintain a characteristic appearance, because record analyses induce it is very nearly statistically steady or stationary. At other time or place the sea condition will be quite different and yet there will again be a characteristic appearance, with different but steady statistical parameters. For the most problems of behaviour of ships and floating structures at sea attention can be focused on describing mathematically the surface waves as a random or stochastic process under short-term statistically stationary conditions. Analysis of wave records has also shown that under such conditions they are approximately Gaussian in character, i.e., wave elevations read at random or at regular intervals of time have roughly a Gaussian, or normal, probability density function. This characteristic greatly simplifies the application of statistics, probability theory and Fourier analysis techniques to the development of suitable models. However for an overall understanding as well as for solving some sea keeping problems, the variation in waves over long periods of time and over great distances cannot be overlooked.

Storm waves are generated by the interaction of wind and the water surface. There are at least two physical processes involved, these being the friction between air and water and the local pressure fields associated with the wind blowing over the wave surface. Although a great deal of work has been done on the theory of wave generation by wind. It seems reasonable to assume that the total storm wave system is the result of many local interactions distributed over space and time. These events can be expected to be independent unless they are very close in both space and time. Each event will add a small local disturbance to the existing wave system.

Within the storm area, these will be wave interactions and wave-breaking processes that will affect and limit the growth propagation of waves from the many local disturbances. Wave studies show that if wave amplitudes are small the principle of linear superposition governs the propagation and dispersion of the wave systems outside the generating area. If $\zeta_1(x,y,t)$ and $\zeta_2(x,y,t)$ are two wave systems, $\zeta_1(x,y,t)$ + $\zeta_2(x,y,t)$ is also a wave system. This implies that one wave system can move through another wave system without modification.

A second important characteristic of water waves that affects the propagation of wave systems is that in deep water the phase velocity, or celerity, of a simple regular wave, such as can be generated in an experimental tank is a function of wave length. Longer wave travel faster than shorter waves. It was shown that any local system could be resolved into a sum of component regular waves of various length and directions using Fourier Integral techniques.

By an extension of the principle of superposition the subsequent behaviour of the sum of these component regular wave systems will determine the visible system of waves. Since these component waves have different celerities and directions the propagating pattern will slowly change with time.

If the propagating wave system over a short period is the sum of a very large number of separate random contributions, all essentially independent the surface elevation is $\zeta(x,y,t)=\sum_i \zeta_i(x,y,t)$ and the laws of statistics yield some very useful conclusions. Since water is incompressible, the average value of vertical displacement at any instant t in a regular component wave $\zeta_i(x,y,t)$ is zero (if is assumed to be of sinusoidal form, as discussed subsequently) and therefore the average value for the wave system $\overline{\zeta(x,y,t)}$ is also zero. However the variance of $\zeta(x,y,t)$ is written $\overline{\zeta(x,y,t)}^2$ is a positive quantity that measures severity of the sea. A fundamental theorem of statistics states that the variance of the sum of a set of independent random variable tends asymptotically to the sum of the variances of the component variables. Thus for a very large (infinite) number of components assumed to be independent $\overline{\zeta(x,y,t)}^2 = \sum_i \overline{\zeta_i(x,y,t)}^2$.

A final statistical conclusion is a consequence of the central limit theorem of statistics. This theorem implies that $\zeta(x,y,t)$ will have a normal (or Gaussian) density function even if the component variables are not distributed normally. Therefore if the variance of the surface elevation in the multi-component wave system can be estimated its probability density as a random variable is known.

The short-term descriptive model that has been described leads to a mathematical technique for describing the irregular sea at a given location and time, while condition remain steady or stationary. Each sea condition can for short periods of time be as unique as a fingerprint, and yet as with a fingerprint, it has order and pattern, as defined by its directional spectrum.

3.2 Quasi-static Approximation of Vertical Bending Moment

The nominal wave-induced vertical bending moments were customarily determined by poising the ship on a $L/20$ trochoidal wave. Since this standard wave had been considered as too conservative for larger vessels, the standard wave height was then expressed either $0.6L^{0.6}$ or $1.1\sqrt{L}$, where L is the length of the vessel.

It must be emphasised that stresses obtained by a “standard wave” calculation are useful only for comparative purposes, and that for this comparison to be valid the same standard wave must be used in both cases.

The buoyancy curve in waves is predicated on the following assumptions:

The wave is trochoidal in form.

The wavelength between crests is equal to the length of the vessel (L).

The wave height is equal to $0.6L^{0.6,}$ $1.1\sqrt{L}$, $L/20$ or other desired standard height.

The vessel is perpendicular to the wave.

Laying out the wave profile on that of the ship so that heights for reading the Bonjean curves may be obtained makes the buoyancy curve. The trochoidal-wave profile may be constructed as is shown in Figure 60.

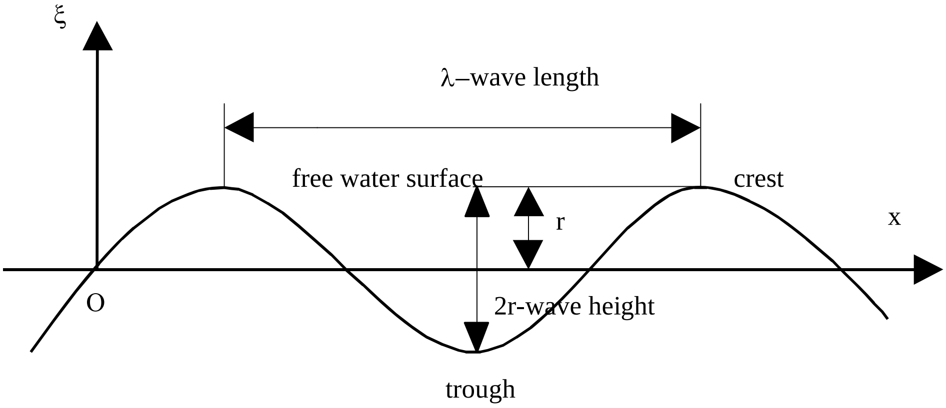


Figure 60 Parameters of a regular wave.

The wave profile must be adjusted vertically by trial and error to obtain the correct displacement, and it must be trimmed longitudinally to bring the centre of buoyancy in vertical line with the centre of gravity.

Since the area under a trochoid is less than the length times half the height, the line of centres should be placed above the vessels draft line. The area under a trochoid is that of a rectangle up to a line $\varepsilon = r^2 / 2R$ below the line of centres, where r is the radius of tracing circle equals to the half of wave height h_w and R is the radius of rolling circle equals to $L_w / 2\pi$

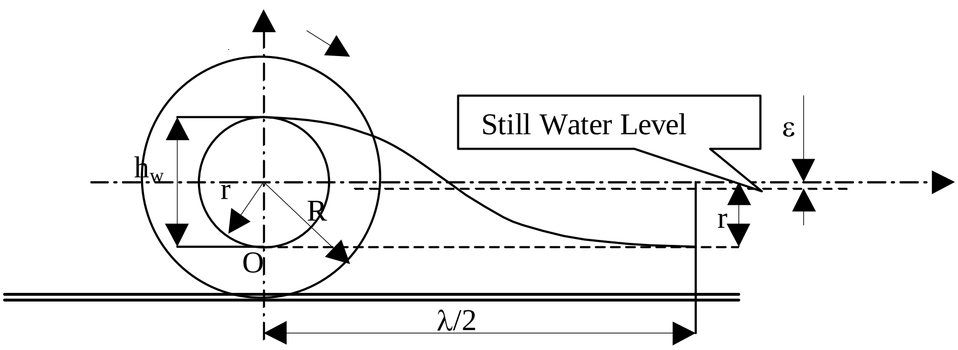


Figure 61 Trochoidal-wave profile

The shape of wave can be presented as:

$$\xi = \pm r \cos\frac{2\pi x}{\lambda} \tag{121}$$

where (+) is for a wave crest (hogging) and (-) is for wave trough (sagging), r is wave amplitude measured from the mean water surface, λ is wave length, which is the horizontal distance between successive crests or troughs.

Table 22 Relative wave ordinates ξ / r

Stations	10	9; 11	8; 12	7; 13	6; 14	5; 15	4; 16	3; 17	2; 18	1; 19	0; 20
Hogging	-1.0	-0.932	-0.742	-0.470	-0.158	0.154	0.441	0.677	0.854	0.963	1.0
Sagging	1.0	0.963	0.894	0.677	0.441	0.154	-0.158	-0.470	-0.742	-0.932	-1.0

The variation of the load of ship as a result of the wave profile is:

$$q = -\gamma B(x)\left(\varsigma \mp r\cos\frac{2\pi x}{\lambda}\right) \tag{122}$$

The condition of equilibrium is written as:

$$\int_{-L/2}^{L/2} q dx = 0 \tag{123}$$

Substituting Eqn (122) into (123):

$$\varsigma = \pm \frac{r\int_{-L/2}^{L/2} B(x)\cos\frac{2\pi x}{\lambda}dx}{A_{WP}} \tag{124}$$

Introducing

$$\int_{-L/2}^{L/2} B(x)\cos\frac{2\pi x}{\lambda}dx = \varphi BL \tag{125}$$

Taken into account that the water plane area can be calculated as:

$$A_{WP} = \alpha_{WP} BL \tag{126}$$

then Eqn (124) can be rewritten as:

$$\varsigma = \pm\frac{\varphi}{\alpha_{WP}} \tag{127}$$

The additional vertical bending moment as a result of redistributing the buoyancy is:

$$M_W = \int_{-L/2}^{x} \int_{-L/2}^{x} q dx dx \tag{128}$$

Making superposition of additional load for the vertical bending moment is written:

$$M_W \mp \gamma r B L^2 \int_{-L/2}^{x} \int_{-L/2}^{x} \left(\frac{\varphi}{\alpha_{WP}} - \cos\frac{2\pi x}{\lambda} \right) \frac{B(x)}{B} \left[d\left(\frac{x}{L} \right) \right]^2 \tag{129}$$

The sign (-) present the wave is for a wave trough (sagging) and (+) is for a wave crest (hogging).

Finally the additional vertical bending moment that is taken into consideration of static lading of the ship on the wave surface is:

$$M_W \mp \gamma r B L^2 k \left(\frac{L}{\lambda}, \alpha_{WP}, x \right) \tag{130}$$

where

$$k = \int_{-L/2}^{x} \int_{-L/2}^{x} \left(\frac{\varphi}{\alpha_{WP}} - \cos\frac{2\pi x}{\lambda} \right) \frac{B(x)}{B} \left[d\left(\frac{x}{L} \right) \right]^2 \tag{131}$$

The additional vertical bending moment at the midship section (x=0) may be calculated as:

$$M_W(0) = -\int_{-L/2}^{0} x q dx \tag{132}$$

or

$$M_W(0) = \mp \gamma r B L^2 k_0 \tag{133}$$

where coefficient k_0 is given in Table 23 and Figure 62 as a function of $\frac{\lambda}{L}$ and α_{WP}.

Table 23 Coefficient k_0 as a function of $\frac{\lambda}{L}$ and α_{WP}

λ/L; α_{WP}	0.667	0.75	0.8	0.833	0.857	0.875	0.9	1
0.5	0.0125	0.015	0.0125	0.0125	0.0125	0.01	0.01	0.01
0.67	0.0275	0.03	0.0325	0.035	0.035	0.035	0.0375	0.0375
0.75	0.0275	0.0325	0.0325	0.0375	0.04	0.04	0.0425	0.0475
0.83	0.0275	0.035	0.0375	0.0375	0.04	0.04	0.0425	0.05
1	0.025	0.03	0.0325	0.035	0.0375	0.0375	0.04	0.05
1.2	0.02	0.025	0.0275	0.03	0.03	0.0325	0.0325	0.045
1.5	0.015	0.0175	0.02	0.02	0.0225	0.0225	0.025	0.035

The vertical bending moment has maximum when $\lambda < L$ and $r = const$. If r increases with increases of L the maximum is achieved when $\lambda = L$, which is fact the pseudo-static formulation of calculation of the vertical bending moment.

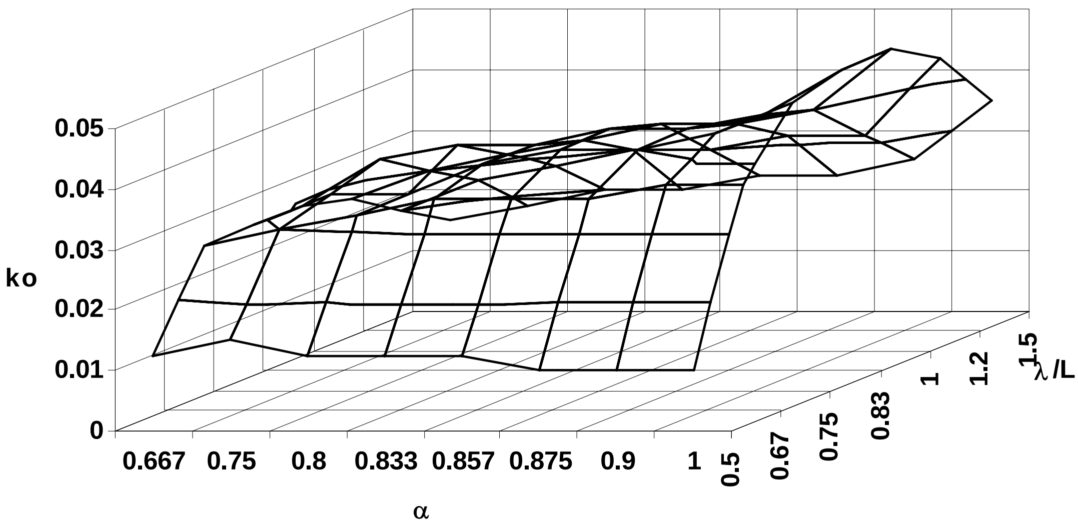


Figure 62 Coefficient k_0 as a function of $\frac{\lambda}{L}$ and α_{WP}

3.3 Wave-induced Load – Sagging (Calculation)

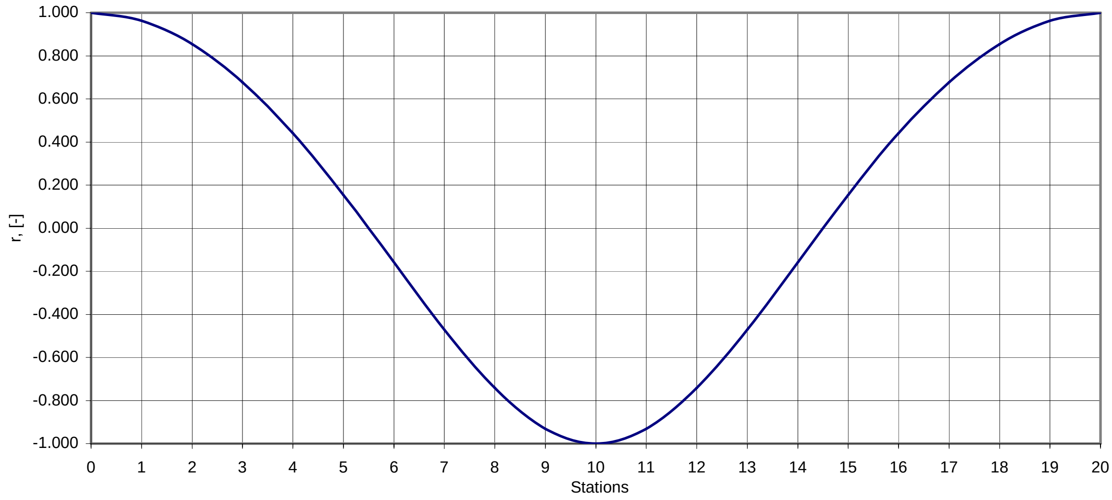


Figure 63 Wave ordinates - sagging

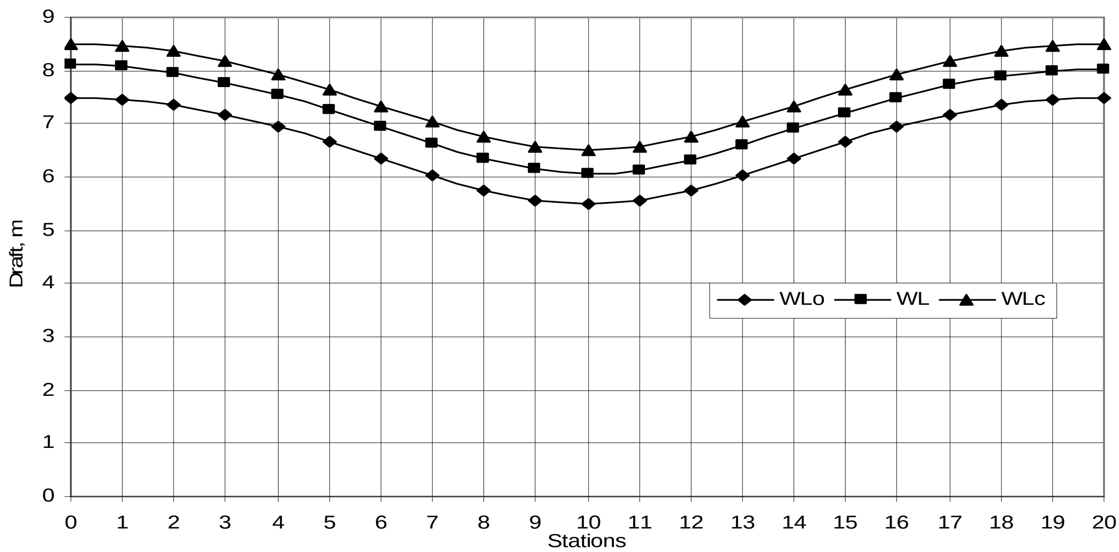


Figure 64 Waterline positions – sagging

Table 24 Bonjean plan - sagging

	Relative wave draft	T_{Wave}, [m]	T_{WLo}, [m]	T_{WL}, [m]	T_{WLc}, [m]	$Area_{Wlo}$, [%]	$Area_{WL}$, [%]	$Area_{WLc}$, [%]	$Area_{Mid}$,[m^2]	$Area_{Wlo}$, [m^2], [10]*[7]*[4]/D/100	$Area_{WL}$, [m^2], [10]*[8]*[5]/D/100	$Area_{WLc}$, [m^2], [10]*[9]*[6]/D/100
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
0	1.00	1.00	7.50	8.12	8.50	6.11	7.71	8.80	153.74	7.04	9.62	11.50
1	0.96	0.96	7.46	8.07	8.46	17.88	19.58	20.69	153.74	20.51	24.31	26.91
2	0.85	0.85	7.35	7.96	8.35	39.64	41.48	42.56	153.74	44.81	50.77	54.65
3	0.68	0.68	7.18	7.78	8.18	59.62	61.07	62.02	153.74	65.78	73.05	77.97
4	0.44	0.44	6.94	7.54	7.94	76.90	77.82	78.50	153.74	82.06	90.21	95.83
5	0.15	0.15	6.65	7.25	7.65	88.12	88.66	89.13	153.74	90.15	98.80	104.88
6	-0.16	-0.16	6.34	6.93	7.34	94.90	95.23	95.60	153.74	92.53	101.50	107.91
7	-0.47	-0.47	6.03	6.62	7.03	98.36	98.18	98.19	153.74	91.19	99.87	106.12
8	-0.74	-0.74	5.76	6.34	6.76	100.20	99.73	99.54	153.74	88.69	97.22	103.42
9	-0.93	-0.93	5.57	6.15	6.57	100.37	99.86	99.61	153.74	85.91	94.37	100.58
10	-1.00	-1.00	5.50	6.08	6.50	100.43	99.92	99.64	153.74	84.92	93.32	99.57
11	-0.93	-0.93	5.57	6.14	6.57	100.37	99.87	99.61	153.74	85.91	94.26	100.58
12	-0.74	-0.74	5.76	6.33	6.76	100.20	99.74	99.54	153.74	88.69	96.98	103.42
13	-0.47	-0.47	6.03	6.59	7.03	99.96	99.59	99.51	153.74	92.66	100.95	107.54
14	-0.16	-0.16	6.34	6.90	7.34	99.73	99.51	99.56	153.74	97.23	105.58	112.38
15	0.15	0.15	6.65	7.21	7.65	98.36	98.35	98.55	153.74	100.62	109.00	115.97
16	0.44	0.44	6.94	7.49	7.94	95.24	95.76	96.31	153.74	101.63	110.30	117.57
17	0.68	0.68	7.18	7.72	8.18	85.91	86.45	87.04	153.74	94.79	102.66	109.42
18	0.85	0.85	7.35	7.90	8.35	74.88	76.03	77.05	153.74	84.66	92.31	98.95
19	0.96	0.96	7.46	8.00	8.46	36.70	37.41	37.80	153.74	42.11	46.02	49.18
20	1.00	1.00	7.50	8.04	8.50	0.00	1.00	2.00	153.74	0.00	1.24	2.61

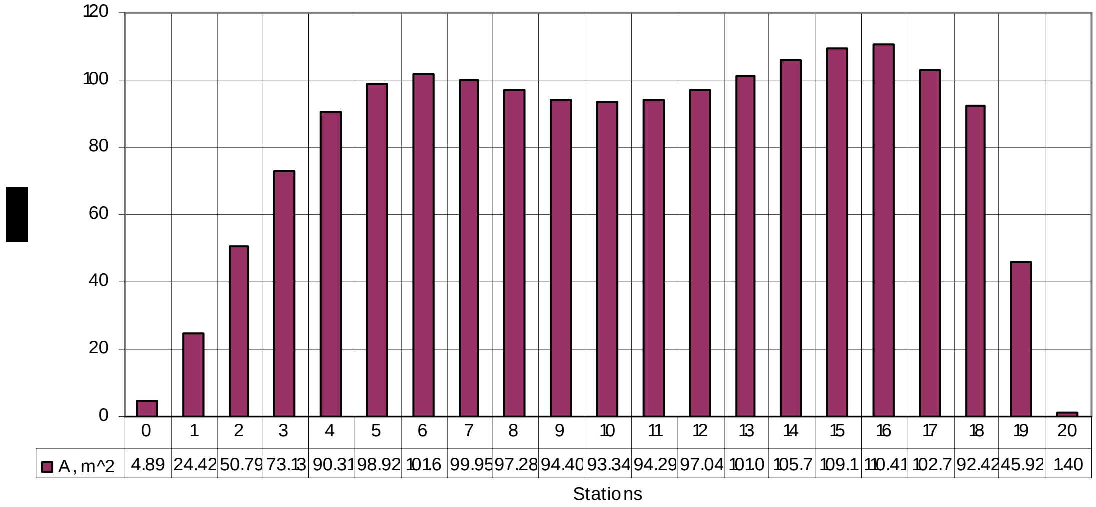


Figure 65 Immersed section area – sagging

Table 25 Immersed sectional area - sagging

Stations	Coefficient	$Area_{WLo}$	[2]*[3]	$Area_{WLc}$	[5]-[3]	[6]*[2]	[7]*[2]	a/ε+b/e*[1]/20	[6]*[9]	[3]+[10]	[11]*[2]
	-	m^2	m^2	m^2	m^2	m^2	m^2	-	m^2	m^2	m^2
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
0	0.00	3.52	0.00	5.75	2.23	0.00	0.00	0.62	1.37	4.89	0.00
1	1.00	20.51	20.51	26.91	6.40	6.40	6.40	0.61	3.91	24.42	24.42
2	2.00	44.81	89.63	54.65	9.84	19.68	39.37	0.61	5.97	50.79	101.57
3	3.00	65.78	197.33	77.97	12.19	36.57	109.72	0.60	7.35	73.13	219.39
4	4.00	82.06	328.25	95.83	13.77	55.08	220.31	0.60	8.25	90.31	361.24
5	5.00	90.15	450.73	104.88	14.74	73.68	368.42	0.60	8.77	98.92	494.58
6	6.00	92.53	555.17	107.91	15.38	92.27	553.61	0.59	9.09	101.62	609.70
7	7.00	91.19	638.30	106.12	14.93	104.52	731.64	0.59	8.76	99.95	699.66
8	8.00	88.69	709.56	103.42	14.72	117.77	942.18	0.58	8.58	97.28	778.22
9	9.00	85.91	773.23	100.58	14.66	131.96	1187.61	0.58	8.49	94.40	849.63
10	10.00	84.92	849.15	99.57	14.65	146.51	1465.15	0.58	8.42	93.34	933.40
11	11.00	85.91	945.06	100.58	14.66	161.28	1774.08	0.57	8.37	94.29	1037.15
12	12.00	88.69	1064.34	103.42	14.72	176.66	2119.90	0.57	8.35	97.04	1164.50
13	13.00	92.66	1204.64	107.54	14.88	193.43	2514.62	0.56	8.38	101.04	1313.54
14	14.00	97.23	1361.28	112.38	15.15	212.05	2968.75	0.56	8.47	105.70	1479.82
15	15.00	100.62	1509.29	115.97	15.35	230.22	3453.30	0.56	8.52	109.14	1637.06
16	16.00	101.63	1626.05	117.57	15.94	255.11	4081.72	0.55	8.79	110.41	1766.61
17	17.00	94.79	1611.39	109.42	14.63	248.71	4228.04	0.55	8.00	102.79	1747.44
18	18.00	84.66	1523.82	98.95	14.29	257.29	4631.18	0.54	7.76	92.42	1663.53
19	19.00	42.11	800.08	49.18	7.07	134.31	2551.92	0.54	3.81	45.92	872.47
20	20.00	0.00	0.00	2.61	2.61	52.27	1045.41	0.54	1.40	1.40	27.96

Table 26 Loading condition - sagging

Δ=ΔL*Σ[11]*γ	10389	[t]
Xc=ΔL*Σ[12]/Σ[11]-L/2	3.16	[m]

Table 27 Calculation of shear forces and vertical bending moment - sagging

Stations	Immersed sectional area, still water, m^2	Immersed sectional area, wave, m^2	[2]-[3]	$[4]_i+[4]_{i-1}+[5]_{i-1}$	$[5]_i+[5]_{i-1}+[6]_{i-1}$	$0.5\gamma\Delta L[5]$	$dQw=-[7]_{20}*[1]/20$, t	$Qw=[7]+[8]$, t	$0.25\gamma\Delta L^2[6]$	$dMw=-[10]_{20}*[1]/20$, tm	$Mw=[10]+[11]$, tm
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
0	0.35	4.89	-4.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	19.17	24.42	-5.25	-9.79	-9.79	-30.12	-0.59	-30.70	-90.35	-102.22	-192.57
2	42.94	50.79	-7.84	-22.89	-42.48	-70.39	-1.17	-71.56	-391.87	-204.43	-596.31
3	64.84	73.13	-8.29	-39.03	-104.40	-120.00	-1.76	-121.76	-963.05	-306.65	-1269.70
4	83.58	90.31	-6.73	-54.04	-197.47	-166.19	-2.35	-168.53	-1821.62	-408.87	-2230.49
5	95.65	98.92	-3.27	-64.04	-315.55	-196.93	-2.93	-199.86	-2910.98	-511.09	-3422.06
6	103.00	101.62	1.38	-65.93	-445.52	-202.73	-3.52	-206.25	-4109.96	-613.30	-4723.26
7	105.84	99.95	5.89	-58.65	-570.10	-180.35	-4.10	-184.46	-5259.20	-715.52	-5974.72
8	107.20	97.28	9.92	-42.84	-671.59	-131.72	-4.69	-136.41	-6195.43	-817.74	-7013.17
9	107.20	94.40	12.80	-20.12	-734.54	-61.86	-5.28	-67.13	-6776.16	-919.95	-7696.11
10	107.20	93.34	13.86	6.54	-748.12	20.12	-5.86	14.25	-6901.38	-1022.17	-7923.55
11	107.20	94.29	12.91	33.32	-708.26	102.45	-6.45	96.00	-6533.69	-1124.39	-7658.07
12	107.20	97.04	10.16	56.39	-618.55	173.40	-7.04	166.36	-5706.14	-1226.61	-6932.75
13	107.20	101.04	6.16	72.71	-489.46	223.58	-7.62	215.95	-4515.22	-1328.82	-5844.04
14	107.20	105.70	1.50	80.37	-336.38	247.12	-8.21	238.91	-3103.13	-1431.04	-4534.17
15	105.94	109.14	-3.19	78.67	-177.35	241.91	-8.80	233.12	-1636.01	-1533.26	-3169.27
16	103.00	110.41	-7.41	68.06	-30.61	209.30	-9.38	199.91	-282.39	-1635.47	-1917.86
17	92.71	102.79	-10.08	50.57	88.03	155.52	-9.97	145.55	812.05	-1737.69	-925.64
18	80.78	92.42	-11.64	28.86	167.46	88.73	-10.56	78.18	1544.80	-1839.91	-295.11
19	39.45	45.92	-6.47	10.74	207.05	33.03	-11.14	21.88	1910.08	-1942.13	-32.05
20	0.95	1.40	-0.45	3.81	221.61	11.73	-11.73	0.00	2044.34	-2044.34	0.00

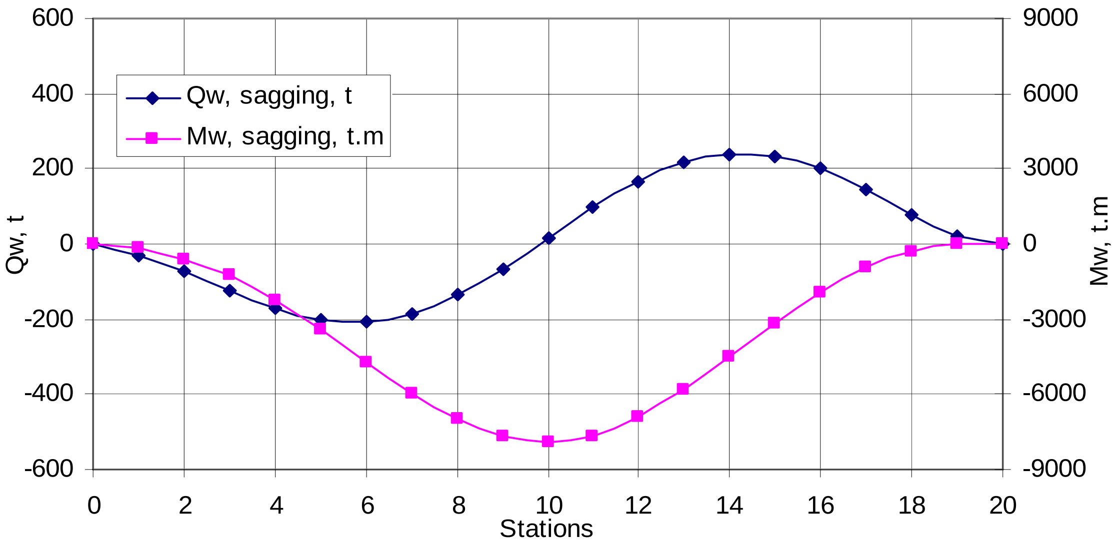


Figure 66 Distribution of shear forces and wave induced bending moment, sagging

3.4 Wave-induced Load – Hogging (Calculation)

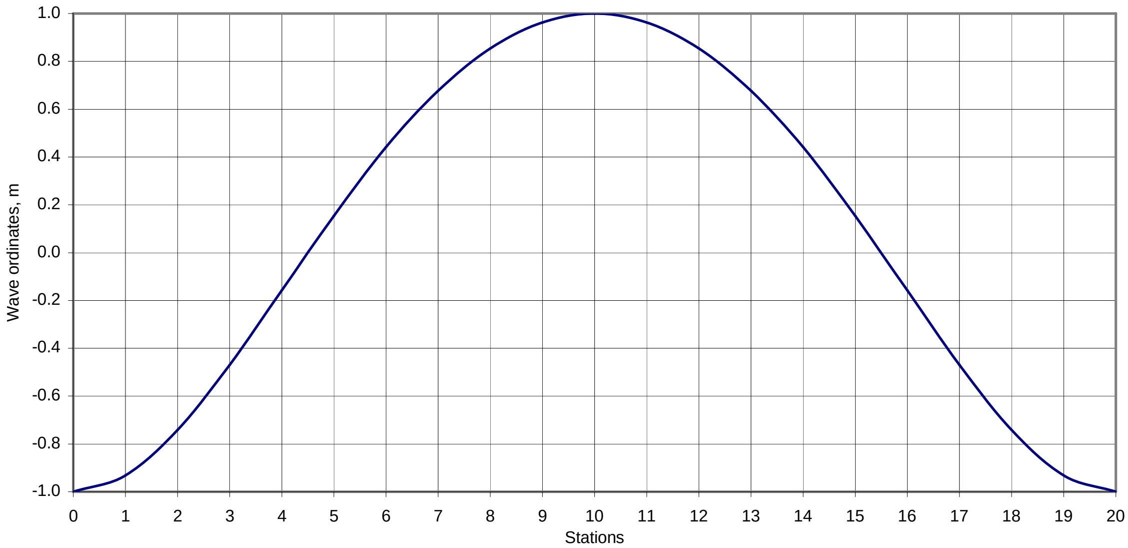


Figure 67 Wave ordinates, hogging.

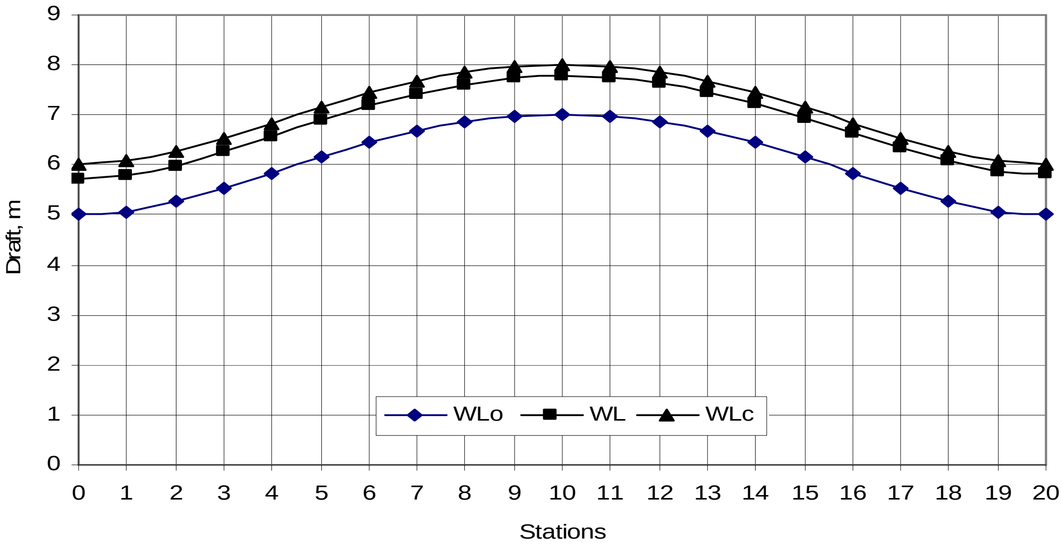


Figure 68 Waterline positions, hogging

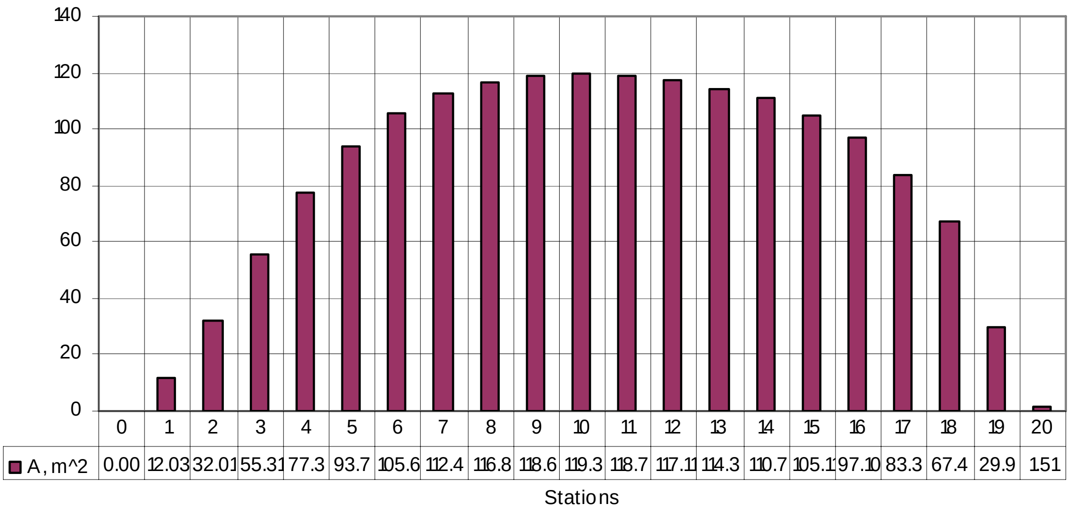


Figure 69 Immersed sectional area, hogging

Table 28 Bonjean plan, hogging

Stations	Relative draft of Wave	T_W, m	T_{WLo}, m	T_{WL}, m	T_{WLc}, m	$Area_{WLo}$, [%]	$Area_{WL}$, [%]	$Area_{WLc}$, [%]	$Area_{Mid}$, m^2	$Area_{WLo}$, m^2, [10]*[7]*[4]/D/100	$Area_{WL}$, m^2, [10]*[8]*[5]/D/100	$Area_{WLc}$, m^2, [10]*[9]*[6]/D/100
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
0	-1.00	-1.00	5.00	5.72	6.00	0.00	0.00	0.00	153.74	0.00	0.00	0.00
1	-0.93	-0.93	5.07	5.79	6.07	11.55	13.41	14.12	153.74	9.00	11.94	13.17
2	-0.74	-0.74	5.26	5.99	6.26	31.60	34.70	35.76	153.74	25.54	31.94	34.40
3	-0.47	-0.47	5.53	6.27	6.53	55.44	57.38	58.04	153.74	47.13	55.26	58.26
4	-0.16	-0.16	5.84	6.58	6.84	75.38	76.40	76.76	153.74	67.70	77.31	80.74
5	0.15	0.15	6.15	6.90	7.15	87.81	88.32	88.56	153.74	83.08	93.67	97.40
6	0.44	0.44	6.44	7.19	7.44	94.94	95.45	95.70	153.74	94.01	105.52	109.48
7	0.68	0.68	6.68	7.43	7.68	98.17	98.34	98.49	153.74	100.77	112.36	116.25
8	0.85	0.85	6.85	7.61	7.85	99.52	99.69	99.85	153.74	104.86	116.69	120.56
9	0.96	0.96	6.96	7.73	7.96	99.51	99.76	99.94	153.74	106.52	118.52	122.34
10	1.00	1.00	7.00	7.77	8.00	99.51	99.79	99.97	153.74	107.08	119.20	122.95
11	0.96	0.96	6.96	7.74	7.96	99.51	99.77	99.94	153.74	106.52	118.69	122.34
12	0.85	0.85	6.85	7.63	7.85	99.52	99.70	99.85	153.74	104.86	117.01	120.56
13	0.68	0.68	6.68	7.46	7.68	99.56	99.61	99.73	153.74	102.20	114.27	117.70
14	0.44	0.44	6.44	7.23	7.44	99.67	99.53	99.60	153.74	98.69	110.65	113.94
15	0.15	0.15	6.15	6.95	7.15	98.60	98.32	98.34	153.74	93.29	105.04	108.16
16	-0.16	-0.16	5.84	6.64	6.84	94.75	95.04	95.17	153.74	85.10	97.05	100.10
17	-0.47	-0.47	5.53	6.34	6.53	85.60	85.55	85.58	153.74	72.77	83.31	85.91
18	-0.74	-0.74	5.26	6.07	6.26	70.40	72.28	72.67	153.74	56.91	67.42	69.91
19	-0.93	-0.93	5.07	5.88	6.07	30.40	33.13	33.66	153.74	23.69	29.96	31.40
20	-1.00	-1.00	5.00	5.82	6.00	0.00	1.00	2.00	153.74	0.00	0.89	1.84

Table 29 Immersed sectional area, hogging

Stations	Coefficient	$Area_{WLo}$	[2]*[3]	$Area_{WLc}$	[5]-[3]	[6]*[2]	[7]*[2]	a/ε+b/e*[2]/20	[6]*[9]	[3]+[10]	[11]*[2]
	-	m^2	m^2	m^2	m^2	m^2	m^2	-	m^2	m^2	
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.72	0.00	0.00	0.00
1	1.00	9.00	9.00	13.17	4.18	4.18	4.18	0.73	3.03	12.03	12.03
2	2.00	25.54	51.09	34.40	8.86	17.72	35.44	0.73	6.47	32.01	64.02
3	3.00	47.13	141.39	58.26	11.13	33.40	100.19	0.74	8.18	55.31	165.94
4	4.00	67.70	270.79	80.74	13.05	52.18	208.73	0.74	9.65	77.35	309.40
5	5.00	83.08	415.39	97.40	14.32	71.61	358.03	0.75	10.67	93.75	468.73
6	6.00	94.01	564.08	109.48	15.47	92.81	556.85	0.75	11.60	105.61	633.68
7	7.00	100.77	705.39	116.25	15.48	108.33	758.31	0.76	11.68	112.45	787.18
8	8.00	104.86	838.91	120.56	15.70	125.60	1004.81	0.76	11.93	116.80	934.37
9	9.00	106.52	958.68	122.34	15.82	142.40	1281.56	0.77	12.10	118.62	1067.61
10	10.00	107.08	1070.85	122.95	15.86	158.62	1586.24	0.77	12.21	119.30	1192.99
11	11.00	106.52	1171.72	122.34	15.82	174.04	1914.43	0.78	12.26	118.78	1306.60
12	12.00	104.86	1258.37	120.56	15.70	188.40	2260.82	0.78	12.25	117.11	1405.32
13	13.00	102.20	1328.62	117.70	15.50	201.51	2619.69	0.79	12.17	114.37	1486.81
14	14.00	98.69	1381.71	113.94	15.25	213.45	2988.24	0.79	12.04	110.74	1550.34
15	15.00	93.29	1399.29	108.16	14.87	223.05	3345.81	0.80	11.82	105.11	1576.61
16	16.00	85.10	1361.55	100.10	15.01	240.09	3841.52	0.80	12.00	97.10	1553.63
17	17.00	72.77	1237.16	85.91	13.14	223.35	3796.97	0.81	10.58	83.35	1416.96
18	18.00	56.91	1024.34	69.91	13.00	234.07	4213.31	0.81	10.53	67.44	1213.94
19	19.00	23.69	450.10	31.40	7.71	146.58	2785.06	0.82	6.29	29.98	569.56
20	20.00	0.00	0.00	1.84	1.84	36.90	737.94	0.82	1.51	1.51	30.26

Table 30 Loading status - hogging

$\Delta=\gamma*\Delta L*\Sigma[11]*\gamma$	10132.35	[t]
$Xc=\Delta L*\Sigma[12]/\Sigma[11]-L/2$	3.05	[m]

Table 31 Calculation of shear forces and vertical wave bending moment - hogging

Stations	Immersed area, still water, m^2	Immersed area, wave, m^2	[2]-[3]	$[4]_i+[4]_{i-1}+[5]_{i-1}$	$[5]_i+[5]_{i-1}+[6]_{i-1}$	$0.5\gamma\Delta L[5]$	dQw=-[7]20[1]/20, t	Qw=[7]+[8], t	$0.25\gamma\Delta L^2[6]$	dMw=-[10]20[1]/20, tm	Mw=[10] +[11], tm
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
0	0.35	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	19.17	12.03	7.15	7.49	7.49	23.04	0.00	23.05	69.12	39.37	108.50
2	42.94	32.01	10.93	25.57	40.56	78.62	0.01	78.63	374.12	78.75	452.87
3	64.84	55.31	9.53	46.03	112.15	141.53	0.01	141.54	1034.58	118.12	1152.69
4	83.58	77.35	6.23	61.78	219.96	189.98	0.02	190.00	2029.10	157.49	2186.59
5	95.65	93.75	1.90	69.91	351.65	214.98	0.02	215.00	3243.98	196.86	3440.85
6	103.00	105.61	-2.61	69.20	490.76	212.79	0.03	212.81	4527.28	236.24	4763.52
7	105.84	112.45	-6.61	59.97	619.94	184.42	0.03	184.45	5718.90	275.61	5994.51
8	107.20	116.80	-9.60	43.77	723.68	134.59	0.03	134.62	6675.92	314.98	6990.91
9	107.20	118.62	-11.42	22.75	790.20	69.95	0.04	69.99	7289.55	354.36	7643.91
10	107.20	119.30	-12.10	-0.77	812.17	-2.37	0.04	-2.33	7492.29	393.73	7886.02
11	107.20	118.78	-11.58	-24.45	786.95	-75.19	0.05	-75.14	7259.62	433.10	7692.72
12	107.20	117.11	-9.91	-45.94	716.56	-141.27	0.05	-141.22	6610.24	472.47	7082.71
13	107.20	114.37	-7.17	-63.02	607.59	-193.79	0.06	-193.73	5605.05	511.85	6116.90
14	107.20	110.74	-3.54	-73.73	470.84	-226.71	0.06	-226.65	4343.54	551.22	4894.76
15	105.94	105.11	0.84	-76.43	320.69	-235.02	0.06	-234.96	2958.32	590.59	3548.92
16	103.00	97.10	5.90	-69.70	174.56	-214.32	0.07	-214.25	1610.31	629.97	2240.27
17	92.71	83.35	9.36	-54.43	50.43	-167.38	0.07	-167.31	465.21	669.34	1134.55
18	80.78	67.44	13.34	-31.73	-35.74	-97.58	0.08	-97.51	-329.69	708.71	379.02
19	39.45	29.98	9.47	-8.93	-76.40	-27.46	0.08	-27.38	-704.82	748.08	43.27
20	0.95	1.51	-0.57	-0.03	-85.36	-0.09	0.09	0.00	-787.46	787.46	0.00

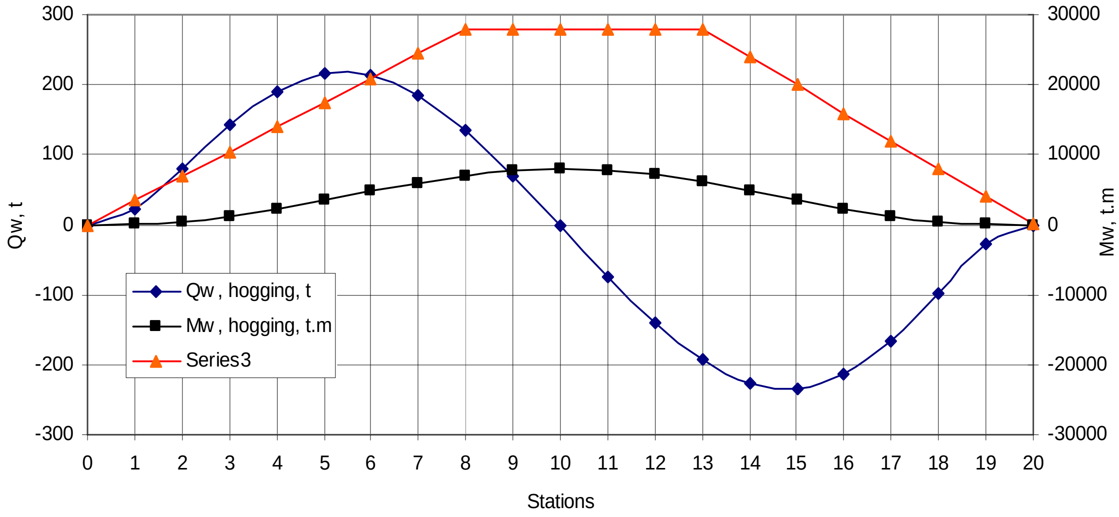


Figure 70 Distribution of shear forces and wave induced bending moment, hogging

4 Dynamic Wave-induced Load

4.1 Wave-induced Load

The wave-induced structural loading cannot be idealised as a simply redistribution of buoyancy as the ship moves through the waves. Rather, because of the strong mutual dependency between the forces and the ships motion, the wave-induced structural loads on a ship can only be determined as a part of the complete ship motion problem. To make the solution possible, several simplifications are introduced in the theory of ship motion. The principal simplification is that the ship is subdivided into a number of prismatic segments, and the various forces are calculated separately for each segment using two-dimensional flow theory, thus neglecting the longitudinal component of relative velocity and any type of interaction between adjacent segments. The shear force and bending moment along the ship are then obtained by integration of the vertical forces on the various segments. Since the ship is being represented as a series of prismatic strips of hull, this approach is usually referred to as strip theory or the strip method.

The longitudinal motion of pitch, heave and surge of a symmetrical ship in regular waves can be considered separately from the transverse models of motions. Furthermore it has been found that for most comparatively long and slender ship surge has a minor effect and can be neglected. This implies that forward speed is constant. The future simplification is considering only the case of head seas or wave from directly ahead. It is assumed that both the wave excitation forces and the resultant oscillatory motion are linear and harmonic.

The equation of motion for heave and pitch of a vessel in regular head seas are: