Floatability and stability of floating dock-docked ship system

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ABSTRACT

An analysis of floatability and stability of the floating dock- docked ship system is the subject of this paper. These properties are considered for a cubicoid box dock whose dimensions are close (almost identical) to those of SINE 212 CD dock designed by SINUS design office. The analysis is first of all aimed at determination of the above mentioned hydromechanical properties in the light of the relevant requirements of PRS dealing with minimum freeboard of the dock and its initial metacentric height. It has been concluded that the analyzed dock reveals the designed docking capability which is not constrained by the PRS requirements though the dock in question is fitted with the roofing unfavourable for dock stability. It has been shown that assessing the tranverse stability of the dock as well as of docked ship (floating object) by means of a stability factor instead of metacentric height, is reasonable. The work was performed within the frame of EUREKA – E! 2968 ECOLOGICAL DOCK research project.

Key words : floating dock, docked object, floatability, stability, stability factor.

1. INTRODUCTION

Essential conditions of usefulness (functionality) of floating dock are, among other, possibilities of maintaining the required values of its floatability and stability.

Correctly designed dock should have such floatability (immerseability and load-carrying ability) which can ensure, in the range of its allowable draughts, docking (bringing-in and lifting) the floating objects of demanded values of such parameters as weight and main dimensions. Hence the ensuring of the ability amounts to determining an appropriate design arrangement of the dock, i.e. its main dimensions and correct subdivision determining its ballasting capability.

Correctly designed and used dock must be transversely stable, i.e. both in the case of the whole floating *dock/docked object* system and the docked object itself.

Therefore the dock must have such features due to which, in every phase of its functioning, it can float in the upright position or at most with heel angle of a given allowable value. Also, it should be fitted with such technical devices and service manuals which make it possible to keep docked objects in the upright position effectively and permanently.

This paper presents results of identification and analysis of floatability and stability of a box-shaped cubicoidal dock having its main particulars and performance parameters close to those of SINE 212-CD dock described in [1].

The research task in question was realized as the part of EUREKA – E! 2968 ECOLOGICAL DOCK project, titled: „Ecological floating dock – special hydromechanical problems".

2. GEOMETRICAL AND HYDROSTATICAL CHARACTERISTICS OF FLOATING DOCK

The main hydrostatical characteristics of cubicoidal floating dock, depending on its length L, draught T and geometry of its transverse cross-section as in Fig.1, are expressed as follows:

Volumetric displacement of the dock :

$$V(T)=\begin{cases} LBT & \text{for } T\in(0;h) \\ LBh+2Lb(T-h) & \text{for } T\geq h \end{cases} \quad (1)$$

Ordinate of the centre of the volume V(T) :

$$z_B(T)=\begin{cases} 0.5T & \text{for } T\in(0;h) \\ \dfrac{h^2(B-2b)+2bT^2}{2\left[(B-2b)h+2bT\right]} & \text{for } T\geq h \end{cases} \quad (2)$$

Initial transverse metacentric radius :

$$r_0(T)=\begin{cases} \dfrac{B^2}{12T} & \text{for } T\in(0;h) \\ \dfrac{b(3B^2-6Bb+4b^2)}{6\left[Bh+2b(T-h)\right]} & \text{for } T\geq h \end{cases} \quad (3)$$

The hydrostatical characteristics V(T), $z_B(T)$ and $z_M(T) = z_B(T) + r_0(T)$ of the dock whose dimensions L, B, b and h are given in Fig.1 and Tab.1, obtain numerical values given in Tab.2 and shown in Fig.2.

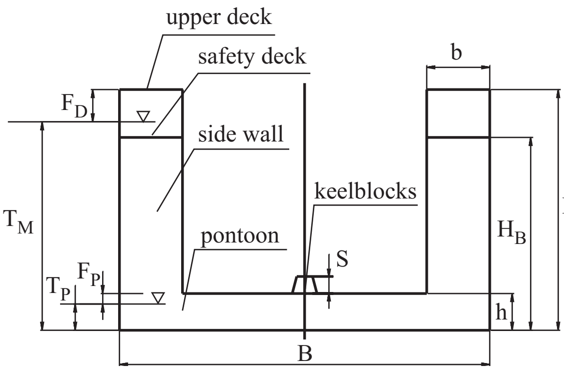


Fig.1. *Transverse cross-section of the dock .*

Tab. 1. *Main particulars of the dock .*

Item	Symbol	Value
Length of pontoon and side walls	**L**	170.00 m
Total breadth	**B**	42.00 m
Side wall breadth	**b**	4.00 m
Pontoon depth	**h**	3.375 m
Dock mass	$\mathbf{P_D}$	8200 t
Height of dock mass centre	$\mathbf{z_{G1}}$	12.90 m
Height of keelblocks	**s**	1.80 m

Tab. 2. Values of hydrostatic characteristics of the dock of the dimensions as in Tab.1.

T [m]	V [m³]	z_B [m]	r_0 [m]	z_M [m]
0.500	3570	0.250	294.00	294.25
1.000	7140	0.500	147.00	147.50
1.500	10710	0.750	98.00	98.75
2.000	14280	1.000	73.50	74.50
2.500	17850	1.250	58.80	60.05
3.000	21420	1.500	49.00	50.50
3.375	24098	1.688	43.56	45.24
*) 3.375	24098	1.688	32.01	33.69
3.375	24098	1.688	20.45	22.14
4.000	24948	1.756	19.75	21.51
4.500	25628	1.822	19.23	21.05
5.000	26308	1.898	18.73	20.63
5.175	26546	1.926	18.56	20.49
5.500	26988	1.982	18.26	20.24
6.000	27668	2.075	17.81	19.89
6.500	28348	2.175	17.38	19.56
7.000	29028	2.282	16.98	19.26
7.500	29708	2.396	16.59	18.98
8.000	30388	2.516	16.22	18.73
8.500	31068	2.641	15.86	18.50
9.000	31748	2.772	15.52	18.29
9.500	32428	2.908	15.20	18.10
10.000	33108	3.048	14.88	17.93
10.500	33788	3.193	14.58	17.78
11.000	34468	3.342	14.30	17.64
11.500	35148	3.495	14.02	17.52
12.000	35828	3.652	13.75	17.41
12.500	36508	3.812	13.50	17.31
13.000	37188	3.976	13.25	17.23

*) at the draught T = 3.375 m the functions r_0 (T) and z_M (T) are discontinuous. Their corresponding values are given in the shadowed line.

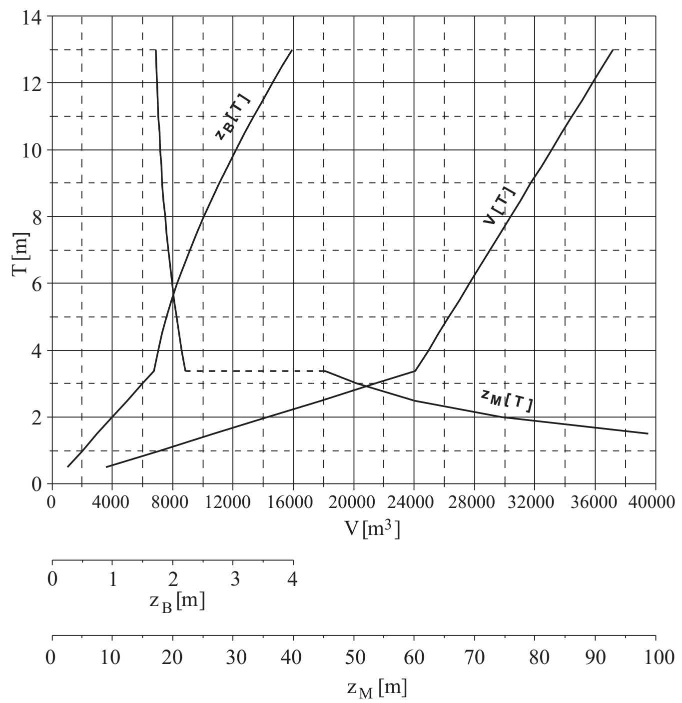


Fig.2. Hydrostatic characteristics of the dock .

3. BALLASTING CAPABILITY OF THE DOCK

Ballasting capability of the dock is determined by the data given in Tab.3 and Fig.3. Dimensions of ballast tanks and their schematic arrangement within the dock space are shown in Fig.3. In Tab.3 are given the effective volumes of the tanks, V_i , (determined with accounting for the assumed permeability factor μ = 0.97) and values of the inertia moments of their transverse cross-sections, i_x.

Tab. 3. Effective volumes of the ballast tanks and values of the inertia moments of their transverse cross-sections

Tank number acc. Fig.3.	Tank symbol acc. [1]	Effective volume		Moment of inertia i_x [m⁴]
		V [m³]	$\frac{V}{\sum V}$ [%]	
1	TK1CPS	1170.0	3.86	3605
2	TK1CSB	1170.0	3.86	3605
3	TK1SPS	1769.0	5.83	2709/174 *)
4	TK1SSB	1769.0	5.83	2709/174
Σ 1÷4		**5878.0**	19.38	12628/348
5	TK2CPS	900.3	2.97	2773
6	TK2CSB	900.3	2.97	2773
7	TK2SPS	1364.1	4.50	2083/133
8	TK2SSB	1364.1	4.50	2083/133
Σ 5÷8		**4528.8**	14.94	9712/266
9	TK3CPS	900.3	2.97	2773
10	TK3CSB	900.3	2.97	2773
11	TK3SPS	1364.1	4.50	2083/133
12	TK3SSB	1364.1	4.50	2083/133
Σ 9÷12		**4528.8**	14.94	9712/266
13	TK4CPS	900.3	2.97	2773
14	TK4CSB	900.3	2.97	2773
15	TK4SPS	1364.1	4.50	2083/133
16	TK4SSB	1364.1	4.50	2083/133
Σ 13÷16		**4528.8**	14.94	9712/266
17	TK5CPS	900.3	2.97	2773
18	TK5CSB	900.3	2.97	2773
19	TK5SPS	1364.1	4.50	2083/133
20	TK5SSB	1364.1	4.50	2083/133
Σ 17÷20		**4528.8**	14.94	9712/266
21	TK6CPS	1260.4	4.16	3882
22	TK6CSB	1260.4	4.16	3882
23	TK6SPS	1909.7	6.30	2917/187
24	TK6SSB	1909.7	6.30	2917/187
Σ 21÷24		**6340.2**	20.92	13598/374
Total for the dock		**30333.4**	100.00	65074/1786

*) Two values of the inertia moments given in the form „a/b" concern side wall tanks (and their sets) which , depending on their filling degree (water level), have different inertia moments of ballast water surface area.

4. FLOATABILITY OF THE DOCK

For the intended use of the dock first of all two its floatability states determined by its characteristic draughts, are of importance (see Fig. 1), i.e.:

- ✶ by the draught T_M, i.e. the draught at which effective bringing - in – the dock operation of the ship (object) at its draught T_S, is possible.

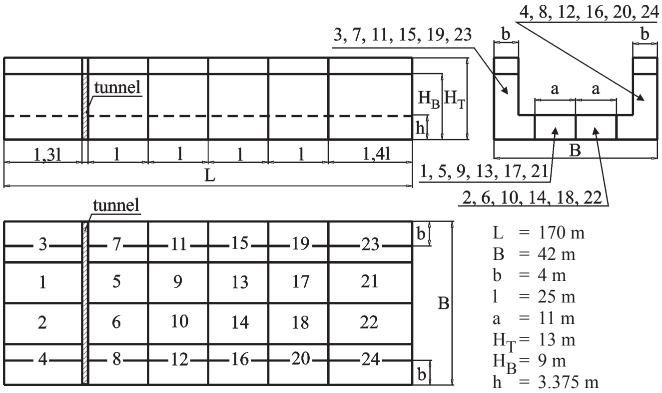


Fig.3. *Ballast water compartments of the dock .*

- ✶ by the operational draught T_P, i.e. such a draught of the emerged dock at which safe realization of repair work on the docked ship (object), is possible.

4.1. Nominal (design) draught T_M

The design draught of the dock, T_M , is directly determine as a result of simultaneous fulfillment of two requirements :

- ♦ the requirement, resulting from the classification society rules, that the minimum freeboard value F_P^* defined as $F_D = H_T - T_M$, (see Fig. 1), is to be maintained, which means that :

$$H_T - T_M = F_D \geq F_D^* \tag{6}$$

- ♦ the fundamental design requirement which determines the maximum draught T_S of the ships (objects) intended for docking in the designed dock. The draughts T_M and T_S are mutually connected by the obvious relation:

$$T_M \geq T_S + h + s + w \tag{7}$$

in which the remaining quantities have the following meanings :

- **h** and **s** – pontoon depth and height of keelblocks, respectively (see Fig.1)
- **w** – distance between keel of the ship brought into the dock and the bed of keelblocks, in which some margin for ship trim is also included.

Assuming that the dock of the dimensions given in Tab.1 has to satisfy the freeboard regulations determined in PRS rules [2], i.e. that its design freeboard value F_D cannot be smaller than $F_P^* = 1$ m , one can determine, using the relationships (6) and (7) and under assumption that the distance $w \cong 0.30$ m is sufficient [3], that :

- ✶ the maximum draught of the dock, T_M , can be $T_{M1} = 12$ m and that
- ✶ at the draught T_M it is able to receive ships (objects) of the maximum draught $T_S = 6.525$ m.

The above determined immersability features of the dock are merely potential ones as they result only from the linear dimensions of the dock and they at most determine extreme (inexceedable) values of the draughts T_M and T_S . Ballasting capability of the dock, i.e. the maximum mass of water ballast which can be intentionally and effectively put into the dock, decides whether the draught values may be really reached.

Hence the water ballast mass, M_R (or its volume V_R), necessary to immerse the dock to the draught $T = T_M = 12$m should be determined and compared with the dock's ballasting capacity, i.e. the maximum ballast mass M_M (or its volume V_M) which can be taken in and distributed in its designed ballast tanks.

The dock of the draught T will remain in equilibrium of floatation if for that draught the following inequality is satisfied :

$$P_D + P_W + M_R = \rho V(T) \tag{8}$$

where :

$P_D + P_W$	–	total mass of the dock and its required working stores
$M_R = \rho V_R(T)$	–	the required mass of water ballast of the volume V_R (T)
V(T)	–	volumetric displacement of the dock
ρ	–	density of ballast and overboard water.

Hence the water ballast volume V_R, necessary to reach the draught T, is as follows :

$$V_R(T) = V(T) - \frac{P_D + P_W}{\rho} \tag{9}$$

Assuming that :

$P_D = 8200$ t (see Tab.1)
$P_W = 150$ t (acc. [1])
$\rho = 1.005$ t/m^3 (with accounting for hull plating thickness)

one can state on the basis of the expression (9) that :

- ➢ the dock can be effectively immersed to the draught $T = T_M = 12$ m and at the draught
- ➢ some ballast volume margin amounting to $V_M - V_R = 2814$ m^3 , equivalent to about 9.3% of the dock ballasting capacity $V_M = 30333$ m^3 (see Tab.3), still remains.

4.2. Dock's operational draught T_P

The range of possible values of the dock's operational draught T_P (see Fig.1) is in particular determined by the condition of maintaining the minimum freeboard value $F_P^* = 0.20$ m compliance with the PRS rules [2] :

$$F_P = h - T_P \geq F_P^* \tag{10}$$

The resulting maximum value of the draught $T_P = T_P^* = 12$ m determines the maximum lifting capacity of the dock, U , or/and its maximum load-carrying ability N equal to the maximum mass of the ship (object) which can be docked in it.

And, in accordance with the obvious equation :

$$U + P_D = N + P_W + M_{RE} + P_D = \rho V(T_P^*) \tag{11}$$

where :

$M_{RE} = \rho V_{RE}$ - residual ballast mass

the following can be stated :

the maximum buoyancy of the dock is :

$$\rho V(T_P^*) = 22783 \text{ t}$$

its maximum lifting capacity is :

$$U = N + M_R + P_W = 14583 \text{ t.}$$

5. TRANSVERSE STABILITY OF THE FLOATING DOCK - DOCKED SHIP SYSTEM

The problem of transverse stability of floating dock is here considered in two practically distinct aspects. Two cases of the stability are analyzed and assessed, namely :

- ✦ of the entire dock-ship system when the docked ship rests with its whole length on keelblocks of the floating dock
- ✦ of the ship itself in every phase of its docking in/out process.

In both the cases only the so called initial stability, i.e that considered only within the range of small heel angles, is investigated, that, in real dock working conditions, fully covers practical problems of its stability.

An initial stability measure is assumed the *stability factor w* defined in Appendix I and identified as w_{SD} factor for the dock-ship system and w_{SS} factor for the ship itself.

Positive values of the factor (w > 0) mean that the considered object is unconditionally stable; whereas negative ones (w < 0) show its initial absolute unstability.

The unconditional stability of docked object (ship) is here assumed the sufficient and unique criterion of its stability. Whereas the stability of the dock-ship system is assessed from the point of view of formal (legal) requirements , i.e. the criteria w^*_{SD} whose values for the considered system are determined on the basis of the relevant PRS rule requirements [2]. It means that in this case, is of importance the relative stability of the object, which takes place and is acceptable only when the following inequality is satisfied : $w_{SD} > w^*_{SD}$.

The so defined stability is here determined and assessed for the dock-ship system in which :

- the dock characterized in Ch.2 and 3 operates within the range of draughts $T_D \in$ < 3.00m ; 12m >
- the ship of the dimensions and hydrostatic features described in Appendix II , is the docked object.

5.1. Stability requirements

Stability of the dock-ship system is here assessed in the light of the relevant rule requirements (criteria) of PRS [2].

They mainly amount to the following regulations :

1) During ship lifting/launching operation the initial metacentric height of the dock, GM_0 , cannot be smaller than 1.4 m. However for the docks of the load-carrying capacity $N \geq 8000$ t is recommended the height GM_0 to be not smaller than 3.0 m, that can be expressed as follows :

$$GM_0(T) \geq GM_0^{(1)} \qquad (12)$$

where :

$GM_0^{(1)}$ is the corresponding limiting value $GM_0^{(1)} = \{1.4m ; 3.0m \}$

2) The static heel angle ϕ of the dock-ship system, caused by the heeling moment, M_w , resulting from the wind pressure p = 490 Pa , should not be greater than 1.5°, that can be written as follows :

$$\mathrm{tg}\,\phi = \frac{M_W}{9.81 GM_0(T)\rho V(T)} \leq 0.0262 \qquad (13)$$

where :

$\rho V(T_D)$ [t] – dock mass (buoyancy) pertinent to its draught T_D

$M_W(T_D) = 0.001 p A_W(T_D) h_W(T_D)$ [kNm]

$A_W(T_D)$ [m^2] – dock side windage area

$h_W(T_D)$ [m] – height of centre of the area A_W over dock waterline.

For use of the requirements (12) and (13) in this work they have been transformed into the form of an equivalent criterion of stability, i.e. the factors w^*_{SD} (see comments in App.I).

Hence :

the requirement (12) obtains the form :

$$w_{SD}(T_D) = \rho V(T_D)\, GM_0(T_D) \geq \geq w^{(1)}_{SD} = GM_0^{(1)} \rho V(T_D) \qquad (14)$$

the requirement (13) obtains the form :

$$w_{SD}(T_D) \geq w^{(2)}_{SD} = 1.906 A_W(T_D) h_W(T_D) \qquad (15)$$

The limiting values of the dock stability factors $w^{(1)}_{SD}$ and $w^{(2)}_{SD}$ are presented in Tab.4, and the values $w^{(2)}_{SD}$ are given for three variants of the dock design :

- for the dock without any roofing (a hypothetical one only)
- for the dock half covered by a movable roofing whose side windage area, a part of the entire windage area $A_W(T_D)$, is equal to A_{W1} = 3230 m^2 and spread over the length l equal to the dock's half length L = 170 m [1]
- for the dock fully covered by the roofing whose side windage area is A_{W2} = (3230 + 2975) = 6205 m^2 and spread over the full length of the dock.

Tab. 4. *Limiting values of stability factors* $w^{(1)}_{SD}$ *and* $w^{(2)}_{SD}$

Dock draught T_D [m]	Dock volumetric displacement V [m^3]	Limiting values $w^{(1)}_{SD}$ [tm]		Limiting values $w^{(2)}_{SD}$ [tm]		
		Required values ($GM_0^{(1)}$ = = 1 .40 m)	Recommended values ($GM_0^{(1)}$ = = 3.00m)	Dock without roofing	Dock covered: over half length	Dock covered: over full length
3.0	21420	30138	64581	16205	186680	350754
3.175	22670	31897	68350	15643	185321	348121
3.375	24098	33906	72655	15012	183774	345125
4.0	24948	35102	75218	13126	178982	335845
5.0	26308	37015	79319	10371	171447	321261
5.175	26546	37350	80036	9922	170145	318742
6.0	27668	38929	83419	7940	164074	307001
7.0	29708	41799	89570	5834	156863	293065
8.0	30388	42756	91620	4051	149814	279452
9.0	31748	44669	95720	2593	142927	266164
10.0	33108	46583	99821	1458	136202	253201
11.0	34468	48496	103921	648	129639	240561
12.0	35828	50410	108021	162	123238	228245

It can be observed (see Tab.4) that for maintaining the required relative stability of the dock the following criteria are decisive :

- the criterion (15) of the limiting values $w^{(2)}_{SD}$, in the case of either fully or partly covered dock
- the criterion (14) of the limiting values $w^{(1)}_{SD}$, in the case of not covered dock (hypothetical only).

5.2. Assessment of stability of the floating dock-docked ship system

In Tab.5 are contained values of the stability factors $w_{SD}(T_D)$ and $w_{SS}(T^*_S)$ together with their limiting values $w^{(2)}_{SD}$ and $w^*_{SS} \geq 0$, calculated and presented in App. I (Tab.1.1).

Tab. 5. *Comparison between* $w_{SD}(T_D)$ *and* $w_{SD}^{(2)}$ *values, and the values* $w_{SS}(T_S^*)$ *and* $w_{SS}^* \geq 0$

Dock's draught T_D		3.000	3.175	3.375	4.000	5.175	6.000	7.000	8.000	9.000	10.000	11.000	12.000
Stability factor $10^4\, w_{SD}(T_D)$		79.55	79.82	24.14	24.29	24.69	27.86	31.70	34.87	38.10	4.68	48.15	49.73
Limiting values $10^4 w_{SD}^{(2)}$	Half covered dock	18.67	18.53	18.38	17.90	17.01	16.41	15.69	14.98	14.29	13.62	12.96	12.32
	Fully covered dock	35.08	34.81	34.51	33.58	31.87	30.70	29.31	27.95	26.62	25.32	24.06	22.82
Ship's draught T_S^*		-	-	-	-	-	0.825	1.825	2. 825	3. 825	4. 825	5.800	5.800
Stability factor $10^4\, w_{SS}(T_S^*)$							- 6.80	- 5.05	- 3.78	- 2.66	- 1.48	0.89	0.89
Stability criterion		$w_{SS}(T_S^*) > w_{SS}^* > 0$											

*) the shadowed values show a shortage of the relative stability – in the case of dock, and the unconditional stability – in the case of ship.

From the above presented data the following results:

1) the considered dock, when lifting the example ship of the draught T_S = 5.8 m and total mass F_{GS} = 10032 t, i.e that close to the largest ship (see p.4.1 and 4.2) permitted to be docked in it,

- does not satisfy the PRS stability requirements, if fully covered and the docking phase corresponds to the dock's draught values from the interval : 7.000 m $\geq T_D \geq$ $\geq$ 3.375 m
- always satisfies (for every allowable dock draught $T \in \leq T_P;T_M \geq$) the requirements if only covered over its half length.

Taking into account that in the course of bringing the ship into the dock and lifting it, the dock is not entirely covered (as there is no need of doing so) one can assume that **the so used dock covered only over its half length can be always (in every phase of ship docking) safe as far as its stability is concerned at least in the light of the PRS rule requirements**.

It can be all the more so assumed that docking operation is also not carried out due to many other reasons, e.g. at strong wind, and surely no longer at the wind force of about 30 m/s.

2) the example docked ship loses its transverse stability (w_{SS} $\leq$ 0) practically in the instant when its keel rests along its full length on the dock's keelblocks. More precisely, the instant happens at the dock draught $T_D \cong$ 10.8 m and the ship draught $T_S^* \cong$ 5.6 m (see App. I). It means that the ship is to be additionally supported in the dock in every moment of its docking process.

APPENDIX I

Models for calculation of initial stability of the dock-ship system and docked ship itself

The necessary condition of transverse stability (appropriate stable equilibrium) of every free-floating object is its capability to generate „automatically" such moment $M_R(\phi)$ which, in the case of inclining the object by the angle ϕ, will so act as to restore its initial position, back from the heel angle ϕ. It means that the free-floating object will be stable then and only then if all its immanent (internal) forces and moments generate such resultant moment $M_R(\phi)$ whose derivative is :

$$\frac{\partial M_R(\phi)}{\partial \phi} < 0 \tag{1.1}$$

The moment M_R (ϕ) which satisfies the condition (1.1), is righting moment.

1. Stability of the dock-ship system

Internal forces and moments which act on a free-floating dock loaded with a ship, are the following (comp. Fig.1.1a) :

- the total weight of the dock (together with stores and ballast) : $F_{GD}(T_D)g$
- buoyancy of the dock :

$$F_{BD}(T_D)g = \rho g V(T_D)$$

- pressure resultant–load exerted on the dock by the ship :

$$R_D(T_D)g = [F_{GS} - F_{BS}(T_S^*)]g \tag{1.2}$$

- the moment M_{RS} resulting from the forces F_{GS} and F_{BS} acting on the ship :

$$M_{RS}(T_S^*) = [F_{BS}(T_S^*) z_{MS}(T_S^*) - F_{GS} z_{GS}^*]g$$

- the moment :

$$Q_{RD}(T_D) = \rho g \sum i_D(T_D)$$

generated by free surfaces of water in ballast tanks.

The quantities appearing in the expressions (1.2) have the following meaning :

- ✶ F_{GS} and F_{BS} – ship mass and buoyancy, respectively
- ✶ z_{GS}^* = KG and z_{MS} = KM – ordinates of ship mass centre and its initial metacentric point, defined in the ship – fixed reference frame (with respect to the point K – see. Fig.1.1)
- ✶ T_D and T_S^* – draughts of the dock and ship, respectively, for which the following relation is valid : $T_D = T_S^* + a$, where a = h + s =5.175 m (see Fig.1 and Tab.1).

If the dock is inclined by a small positive angle ϕ the moment $M_{RD}(\phi,T_D)$ due to the above specified internal forces and moments, acting on it and defined with respect to the point K_D (see Fig.1.1a), is expressed as follows :

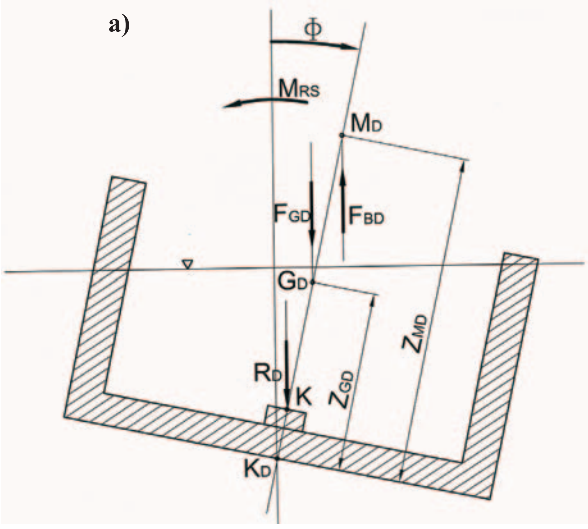
$$M_{RD}(\phi,T_D) = -\, w_{SD}(T_D) g \phi \tag{1.3}$$

where :

g > 0 – gravity acceleration

$w_{SD}(T_D)$ – moment factor of $M_{RD}(\phi,T_D)$ equal to :

$$w_{SD}(T_D) = F_{BD}(T_D)\, z_{MD}(T_D) - F_{GD}(T_D)\, z_{GD}(T) + \\ - F_{GS}(z_{GS} + a) + F_{BS}(T_S^*)[z_{MS}(T_S^*) + a] - \rho \sum i_D(T_D) \tag{1.4}$$



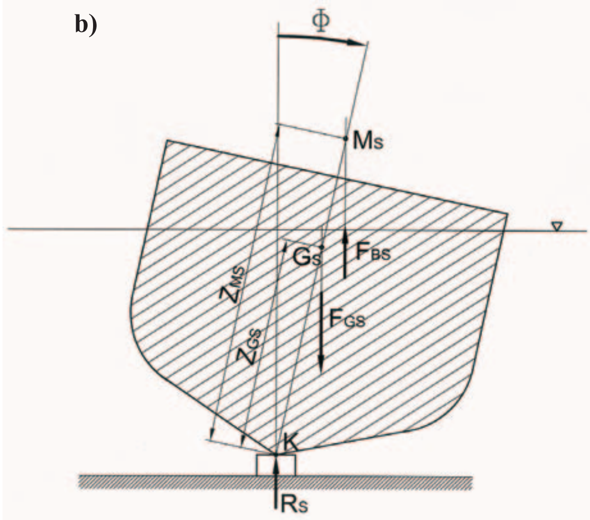


***Fig. 1.1. a)** Loads applied to the dock - ship system .* ***b)** Loads applied to the docked ship .*

The so determined values of the factor $w_{SD}(T_D)$ for the investigated dock loaded by the ship described in App. II, are presented in Tab.1.1.

***Tab. 1.1.** Stability characteristics of the floating dock- docked ship system and the docked ship itself.*

Characteristics	Symbol	Unit	Values at the system draught T_D											
			3.000	3.175	3.375	4.000	5.175	6.000	7.000	8.000	9.000	10.000	11.00	12.000
for the floating dock- docked ship system														
Buoyancy of the system	F_{BD}	[t]	21527	22783	24218	25073	26678	27806	29173	30540	31907	33274	34640	36007
Ordinate of the system metacentric point	z_{MD}	[m]	50.50	47.89	22.14	21.51	20.49	19.89	19.26	18.73	18.29	17.93	17.64	17.41
Ship weight loading the dock	R_D	[t]	10032	10032	10032	10032	10032	8993	7417	5686	3849	1933	0	0
Ballast mass	M_b	[t]	3145	4401	5836	6691	8296	10463	13406	16504	19708	22991	26290	27657
Ordinate of the ballast mass centre	z_b	[m]	0.44	0.61	0.81	0.93	1.16	1.46	1.53	1.24	1.04	0.89	0.78	0.74
Mass of the dock together with ballast	F_{GD}	[t]	11495	12751	14186	15041	16646	18813	21756	24854	28058	31341	34640	36007
Ordinate of the centre of the mass F_{GD}	z_{GD}	[m]	9.47	8.64	7.91	7.56	7.03	6.52	5.88	5.15	4.56	4.08	3.69	3.55
Stability factor of the system	$\overline{w}_{SD}$	[tm]	832942	835596	558380	280297	284297	315815	345052	376822	409094	444701	483228	499057
Correction to the factor $\overline{w}_{SD} = \sum i_x$	$\Delta\overline{w}_{SD}$	[tm]	37457	37364	37296	37359	37349	37260	28006	28097	28078	27950	1732	1800
Stability factor $\overline{w}_{SD} - \Delta\overline{w}_{SD}$	w_{SD}	[tm]	**795485**	**798232**	**241366**	**242938**	**246948**	**278555**	**317046**	**348725**	**381016**	**416751**	**481496**	**497257**
for the docked ship														
Ship draught	T_S^*	[m]	-	-	-	-	-	0.825	1.825	2,825	3.825	4.825	5.800	5.800
Ship buoyancy	F_{BS}	[t]	-	-	-	-	-	1039	2615	4346	6183	8099	10032	10032
Ordinate of the ship metacentric point	z_{MS}^*	[m]	-	-	-	-	-	24.40	16.40	12.80	10.80	9.80	10.20	10.20
Ship stability factor	w_{SS}	[tm]	-	-	-	-	-	**- 68046**	**- 50512**	**- 37769**	**- 26622**	**- 14838**	**8928**	**8928**

From the condition (1.1) it results that the moment $M_{RD}(\phi,T_D)$ determined by the expressions (1.3) and (1.4) will be really the righting moment of the dock if and only if the following inequality is satisfied :

$$\frac{\partial M_{RD}(\phi, T_D)}{\partial \phi} = -w_{SD}(T_D) < 0 \qquad (1.5)$$

It means that the dock will be really (unconditionally) stable if the factor $w_{SD}(T_D)$, called here **the mass factor of stability**, is positive :

$$w_{SD}(T_D) > 0 \qquad (1.6)$$

In the case of unconditional assessment of stability (with respect to formal legal criteria), its condition determined in the domain of the factor w_{SD} amounts to the inequality :

$$w_{SD}(T_D) > w_{SD}^*(T_D) \qquad (1.7)$$

in which $w_{SD}^*(T_D)$ is the appropriate limiting value (see. Ch.5.1).

Commonly used measure of initial transverse stability of surface floating objects is **the initial metacentric height**

$h_0 = GM_0 = z_{M0} - z_G$, where : M_0 - initial metacentric point, and G - centre of mass of the object. The relevant stability factor is then expressed as follows : $w_{SD} = F_B h_0 = F_G h_0$, where F_B and F_G are values of buoyancy and weight of the floating object, respectively, and, as defined, positive and equal to each other ($F_B \equiv F_G$). The absolute stability condition $w_{SD} > 0$ amounts then to the following : $h_0 > 0$.

However the interchangeable and equivalent application of the conditions : $w_{SD} > 0$ and $h_0 > 0$ is limited to the cases in which values of F_B and F_G can be easily and unambiguously determined, and first of all it concerns the metacentric height h_0. This is always possible when the quantities F_B and F_G are homogeneous and location of the point G of the considered object is unquestionable. Otherwise if at least one of the quantities F_B and F_G is not homogeneous, the metacentric height h_0 usually is a conventional quantity and its value – relative and ambiguous. However the factor w_{SD} remains objective and unambiguous. Therefore this factor should be used to obtain an objective and right assessment of stability.

From the relations described by the expressions (1.2) ÷ (1.4) it results that the righting moment $M_{RD}(\phi, T_D)$ for the dock loaded by a part of weight of the docked ship, is sum of several very different components. First of all for this reason it was decided to measure stability of the dock, but also that of the docked ship (see p.2 , App. I), by using the stability factor instead of metacentric height.

2. Stability of docked ship

On the ship resting with its full length on dock's keelblocks, and inclined by a small positive angle ϕ, acts the righting moment $M_{RS}(\phi, T^*_S)$ taken with respect to the point K (see Fig.1.1b) and equal to :

$$M_{RS}(\phi, T^*_S) = [F_{GS} z^*_{GS} - F_{BS}(T^*_S) z_{MS}(T^*_S)] g \phi \qquad (1.8)$$

where the particular quantities are denoted in the same way as in the expressions (1.2), and the following relationship between the buoyancy of the ship, R_{BS} , and its mass F_{GS} and supporting force $R_S(T^*_S)$ due to reaction of keelblocks, occurs :

$$R_S(T^*_S) = [R_{BS}(T^*_S) - F_{GS}] = -R_D(T_D) \qquad (1.9)$$

Hence the mass factor of ship stability $w_{SS}(T^*_S)$, determined in accordance with the principle (1.3), is expressed as follows :

$$w_{SS}(T^*_S) = F_{BS}(T^*_S)\, z_{MS}(T^*_S) - F_{GS} z^*_{GS} \qquad (1.10)$$

Its values for the ship described in App. II are presented in Tab.1.1.

To illustrate the problem discussed in p.1, concerning the question in which way to measure stability of floating objects, either by means of the stability factor w or the metacentric height h_0, it's worth mentioning that the factor w_{SS} determined by the expression (1.10) may be presented in two ways :

$$w_{SS}(T^*_S) = w^{(1)}_{SS} = F_{BS}\left[z_{MS} - \frac{F_{GS}}{F_{BS}} z^*_{GS}\right] = F_{BS} h^{(1)}_0 \qquad (1.11)$$

or :

$$w_{SS}(T^*_S) = w^{(2)}_{SS} = F_{GS}\left[\frac{F_{BS}}{F_{GS}} z_{MS} - z^*_{GS}\right] = F_{GS} h^{(2)}_0 \qquad (1.12)$$

The obvious equality of the factors $w^{(1)}_{SS} = w^{(2)}_{SS}$ leads to generally different values of the metacentric height :

$h^{(1)}_0$ and $h^{(2)}_0$

which fulfill the relation :

$$\frac{h^{(1)}_0}{h^{(2)}_0} = \frac{F_{GS}}{F_{BS}}$$

and can be equal to each other only in two following cases :

- when $F_{GS} = F_{BS}$, i.e. for free-floating ship, not resting on keelblocks, or
- when $w_{SS} = w^{(1)}_{SS} = w^{(2)}_{SS} = 0$, i.e. in the instant when the ship loses its stability.

Therefore the following statement should be accepted :

In all the cases in which floatation equilibrium of objects is not determined only by the equality of mass and buoyancy of the objects, their stability should be measured by means of the stability factor.

APPENDIX II

Characteristics of docked ship

In this work a general cargo ship of the main dimensions given in the table below, was assumed the docked object.

Dimension	Unit	Value
Length b.p. L_{PP}	[m]	150.00
Total length L_C	[m]	161.00
Breadth **B**	[m]	22.92
Hull depth **H**	[m]	13.30
Design draught T_K	[m]	8.75
Docking draught T_d	[m]	5.80
Docked ship mass F_{GS}	[t]	10032
Ordinate of ship mass centre z_{GS}	[m]	9.31

In Fig.2.1 are presented the following hydrostatic characteristics of the ship : the ship hull volumetric displacement $V_S(T^*_S)$ and the ordinate of initial metacentric point $z_{MS}(T^*_S)$.

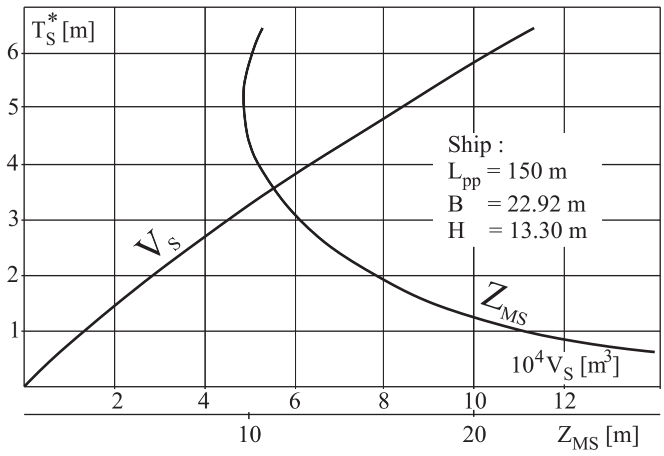


Fig. 2.1. *Hydrostatic characteristics of the docked ship .*

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