Effect of Decks on Survivability of Ro–Ro Vessels

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ABSTRACT

The paper describes a methodology for accounting the effect of decks above the car deck on ro–pax vessels on their survivability in the damaged condition. The methodology can be regarded as extension of the SEM for multi-deck ro–pax vessels. The effect of decks appears to be ambiguous and depends on detailed subdivision of the ship, which proves the robustness of the original SEM. For trim cases, however, the decks can be very detrimental.

Keywords: *damage stability, survivability, and criteria*

1. INTRODUCTION

The static equivalent method (SEM) was developed in 1995 for ro–ro vessels with the large open main deck (vehicle deck). The method evolved from research carried out at the University of Strathclyde (Vassalos 1996, Vassalos 1997), based on a framework presented earlier by Pawłowski (1995). The SEM defines the critical significant wave height Hs (= $Hs_{50\%}$) in terms of the median value, given damage stability. It is assumed that the damage opening is unrestricted in the vertical direction and the flow of water on the deck induced by waves is undisturbed by the presence of decks above the main deck, typical on ro–pax vessels. Now, the SEM will be extended to account for the effect of multi-decks for an unrestricted height of the damage opening. The presence of decks is believed to be detrimental for survivability of ro–pax vessels due to a greater heeling moment exerted by water accumulated on higher decks and the multi free surface effect. In particular, this is pertinent for damage cases with trim, despite some protection against flooding of the main deck provided by the higher decks.

2. THE HEELING MOMENT

Consider a damaged ro–ro vessel at the point of no return (PNR), as shown in Figure 1, called also as the critical heel. The PNR occurs at a heel angle equal to ϕmax, where the GZ-curve has a maximum. This angle, for typical ferries is less than 10 degrees. Reference is made here to the GZ-curve calculated traditionally, using the constant displacement method, allowing for free flooding of the vehicle deck when the deck edge is submerged, and corresponding to minimum stability. For compartments other than amidships, the GZ-curve should be obtained for a freely floating ship, exposed to a trimming moment of value equal to that produced by the water elevated on the decks at the PNR. This problem can be solved iteratively. In practice, however, a single iteration is normally sufficient. It is worth mentioning here that the widely used NAPA package is unable to calculate the GZ-curve of minimum stability.

The amount of water on decks at the critical heel can be predicted from stability calculations considering a flooding scenario, in which the ship is damaged only below the vehicle deck. However, there is some amount of water on the (undamaged) deck inside the upper (intact) part of the ship and on the deck above, as shown in Figure 1. The space above the vehicle deck is enclosed by the undamaged deck and the undamaged ship sides above the deck, with the damage extending from below the deck downwards. For the ship with a side casing or wing tanks, the space is enclosed by the undamaged double hull beyond the flooded part of the double hull, and by the inner shell—in way of the flooded part of the wing spaces. Consequently, the freeboard can be interpreted as the depth of immersion of the deck edge (taken with a negative sign) measured at the inner shell of the wing tanks in the middle of damage.

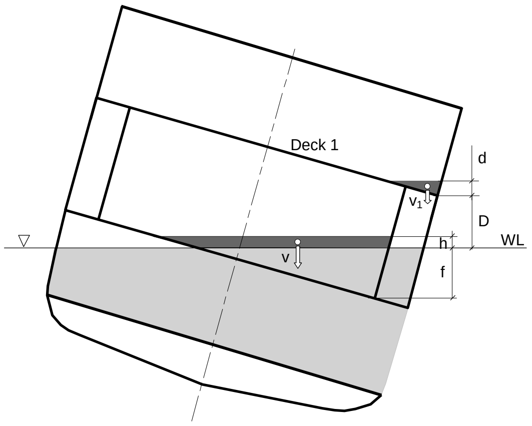

Figure 1: A damaged ro–ro vessel at the PNR with water accumulated on decks

For given height D of Deck 1 above the sea level (the same as positive freeboard for this deck) and given sea state, the water head d on this deck can be found (as discussed later) with the help of the theory regarding accumulation of water on a deck with positive freeboard. The knowledge of d defines volume v_1, accumulated on Deck 1 – the first deck above the vehicle deck (see Figure 1). This is the volume, which in general combines both the elevated water that can drain off from the deck, when the damage is opened, and the dead water that stays on deck, when the damage is opened. The latter takes place particularly for the damage cases with trim. The dead water is a result of progressive flooding of the deck induced by waves that cannot drain off from the deck. It contributes to the heeling moment produced by water on deck but has nothing to do with the dynamic elevation of water induced by waves.

The sea state that defines volume v_1 is the critical sea state obtained by the original SEM, without taking into account the effect of decks above the vehicle deck. The heeling moment produced by water on Deck 1 equals v_1l_1, where l_1 is the heeling arm with respect the axis of floatation of the damaged waterplane, passing through its centre of floatation. The critical amount of water on the car deck, which in turns defines the critical sea state is such that the resultant moment vanishes at the PNR, that is

$$VGZ_{max} = vl + v_1l_1, \tag{1}$$

where V is the volume displacement of the intact ship (before damage), v is the elevated volume of water on the vehicle deck above the sea level, as shown in Figure 1, and l is the heeling lever produced by this water with respect the axis of floatation of the damaged waterline, passing through the centre of floatation (not shown in Figure 1). Both the heeling arms l and l_1 are measured with respect to the same axis of floatation of the damaged waterline, without the parts occupied by the floodwater.

The critical amount of water on the vehicle deck can be found also with the omission of the GZ-curve, which is particularly useful for the flooding cases with trim. This characteristic value is such for which heeling moment produced by the elevated water reaches maximum.

By solving equation (1), one gets the sought volume v of elevated water on the vehicle deck and its (static) elevation h above sea level that has to be produced by the dynamic action of waves and ship motions, along with the freeboard f. Knowing the two quantities we would like to estimate now the critical sea state without resorting to model experiments. This can be achieved only by utilising the available theoretical knowledge on accumulation of water on the car deck (Pawłowski 2003, and 2004).

From equation (1) it follows immediately that the critical rise of water on the vehicle deck with the effect of a higher deck is smaller but at the same time the rate of flooding such a deck is smaller as well due to the protection provided by the deck above while the outflow rate is unchanged. Thus, on the whole it is difficult to predict beforehand how this affects the critical sea state the ship can withstand, particularly for damage cases with no trim. The outcome depends on particulars of the design.

3. ACCUMULATION OF WATER ON A PROTECTED DECK

The asymptotic dynamic elevation of water on the vehicle is defined by the equation:

$$q_{in} - q_{out} = const = q_{1.5}(t_1 = t_2), \tag{2}$$

where q_{in} is the nondimensional flow rate, ignoring the effect of the higher decks, qout is the nondimensional outflow rate, $q_{1.5}$ ($t_1=t_2$) is the inflow moment $q_{1.5}$ (t_1) calculated taking t_1 to be $t_2 = D/\sigma$, and $\sigma = H_{sr}/4$ is the standard deviation of the relative wave elevation at the damage opening (Pawłowski 2003 and 2004). The two flow rates are given by the equations:

$$q_{in} = 1.5\tau q_{0.5}(t_1) + q_{1.5}(t_1), \tag{3}$$

$$q_{out} = \tau^{3/2} F(t_0) + 1.5\tau q_{0.5}(t_0, t_1) - 0.5 q_{1.5}(t_0, t_1), \tag{4}$$

where $t_0 = f/\sigma$ is the nondimensional freeboard at orifice (the damage opening), $t_1 = h/\sigma$ is the nondimensional height of the free surface on deck above sea level, $\tau = d/\sigma$ is the nondimensional depth of water on deck at orifice; $\tau = t1-t_0$, and $F(t_0)$ is CDF of the standard density function f(t) calculated at $t = t_0$. The quantities qm (with m = 0.5 and 1.5) are in general moments of the order m of the standard density function f(t), defined as follows:

$$q_m(t_1) = \int_{t_1}^{\infty} (t - t_1)^m f(t)\,dt, \tag{5}$$

$$q_m(t_0, t_1) = \int_{t_0}^{t_1} (t_1 - t)^m f(t)\,dt. \tag{6}$$

As results from analytical studies for water on deck accumulation demonstrate (Pawłowski 2003 and 2004), if the nondimensional height t_2 of the edge of Deck 1 above sea level at the PNR is greater than ≈ 2.4, such a deck have no effect on the intensity of flooding the vehicle deck and its effect on survivability of the ship can be ignored. A smaller height $D <\approx 2.4\sigma = 0.6H_{sr}$ has obviously a positive effect on ship's survivability, increasing the critical sea state H_s.

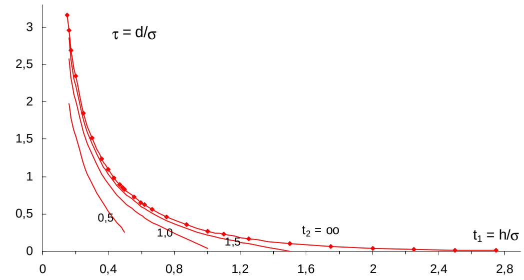

Figure 2: Nondimensional depth of water on deck $\tau = d/\sigma$ at opening versus nondimensional height of free surface above sea level $t_1 = h/\sigma$, depending on nondimensional clearance $t_2 = D/\sigma$

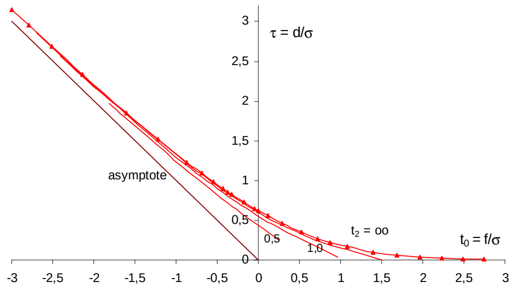

Figure 3: Nondimensional depth of water on deck $\tau = d/\sigma$ at opening versus nondimensional freeboard at opening $t_0 = f/\sigma$, depending on parameter nondimensional clearance $t_2 = D/\sigma$

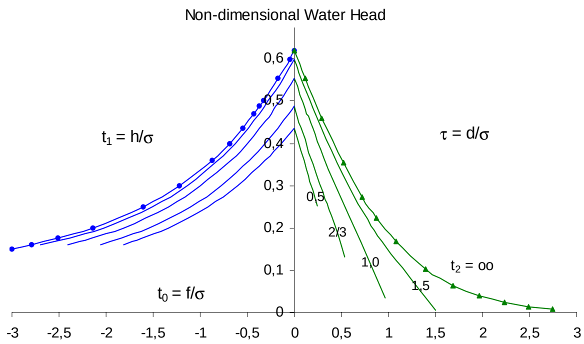

Figure 4: Nondimensional water head versus nondimensional freeboard at opening $t_0 = f/\sigma$, depending on nondimensional clearance $t_2 = D/\sigma$

The nondimensional height of the deck above sea level $t_2 = D/\sigma$ plays the role of a parameter in equation (2). Due to the physics, the variable t_1 is equal to or less than t_2. Numerical solutions of this equation are shown in Figure 2 to Figure 4, equivalent one to another. Note that all the curves in these figures are terminated just at points corresponding to $t_1 = t_2$. It is clear from them that a restricted clearance above the vehicle deck reduces the water head, which is positive for ship survivability – the same elevation on a protected deck has to be induced by a higher sea state.

We would like now to describe quantitatively the effect of clearance on the elevation of water on deck. The curves on the left-hand side in Figure 4 (for negative freeboard) decay asymptotically as the inverse of the nondimensional freeboard t_0. To overcome this inconvenience, a transformation can be used in which the abscissa axis x = f/(3h–f), where the variable x ∊ ⟨−1, 0⟩, while the ordinate axis presents $y = t_1/(1+x)^{1/2}$. Such curves are shown in Figure 5.

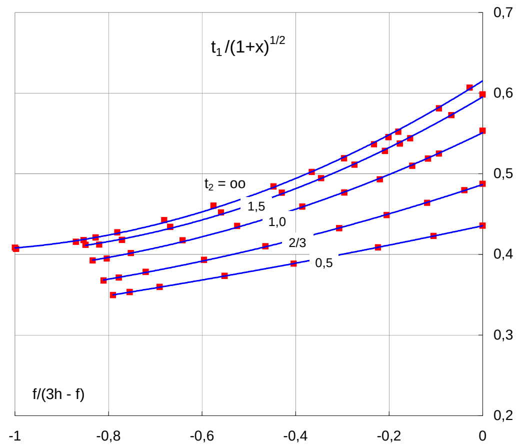

Figure 5: Nondimensional water elevation versus the ratio *f*/(3*h* – *f*), depending on nondimensional clearance $t_2 = D/\sigma$ and its parabolic approximations

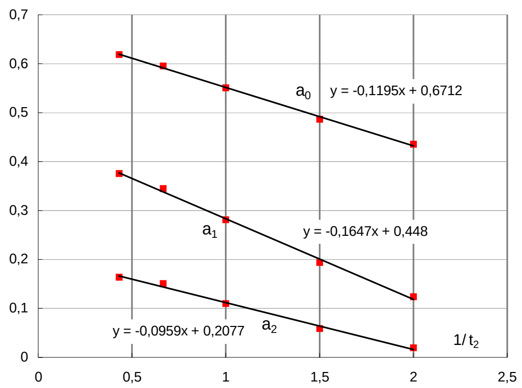

Figure 6: Coefficients of the fitting polynomials as functions of nondimensional clearance $t_2 = D/\sigma$

They are regular and can be accurately approximated by parabolic curves in the form: $y = a_0 + a_1x + a_2x^2$, where the coefficients a_0, a_1 and a_2 are found with the help of the least squares method. They are linear functions of the inverse of t_2, as shown in Figure 6,which provides also their equations.

Using graphs shown in Figure 5, the critical sea state can be easily found with the help of the so-called reduction coefficient κ. Knowing the two particulars for water on the vehicle deck h and f from static calculations, the abscissa x = f/(3h–f) can be calculated. For given x-value, the following straightforward relationships hold:

$$\kappa = \frac{y(x,t_2)}{y(x,\infty)} = \frac{t_1}{t_{1\infty}} = \frac{\sigma_\infty}{\sigma} = \frac{t_2}{t_{2\infty}}, \tag{7}$$

which defines the reduction coefficient κ, where y = y(x, t_2) is shown in Figure 5 in graphical form or provided by approximations discussed earlier. As can be seen, the reduction coefficient κ is the same as the ratio of the standard deviations of relative ship motion at opening for unrestricted opening with no protection and for the opening with a protection. As $\kappa \le 1$, the critical sea state for the ship with a protected vehicle deck is larger than without a protection, which is obviously beneficial.

Because the quantity $t_{2\infty} = D/\sigma_\infty$ is known, t_2 can be found from equation (7) by iterations. Doing so, $t_2 = t2(x, t_{2\infty})$ can be obtained as function of x and $t_{2\infty}$. Hence, the ratio $t2/t_{2\infty}$, equal to σ_∞/σ, defines the reduction coefficient $\kappa = \kappa(x, t_{2\infty})$. With its help, finding the critical sea state is straightforward, as:

$$\sigma = \sigma_\infty/\kappa, \tag{8}$$

which follows from equation (7). The reduction coefficient κ is shown in Figure 7.

The coefficient κ approximates well by parabolic curves, whose coefficients are functions of $(1/t_{2\infty})^2 = (\sigma_\infty/D)^2$, shown in Figure 7. Because $\sigma = ¼H_{sr}$ and $H_{sr} = 0.76H_s^{1.36}$, this leads to the critical sea state given by the equation

$$H_s = (4\sigma/0.76)^{1/1.36} = 3.39\sigma^{1/1.36}. \tag{9}$$

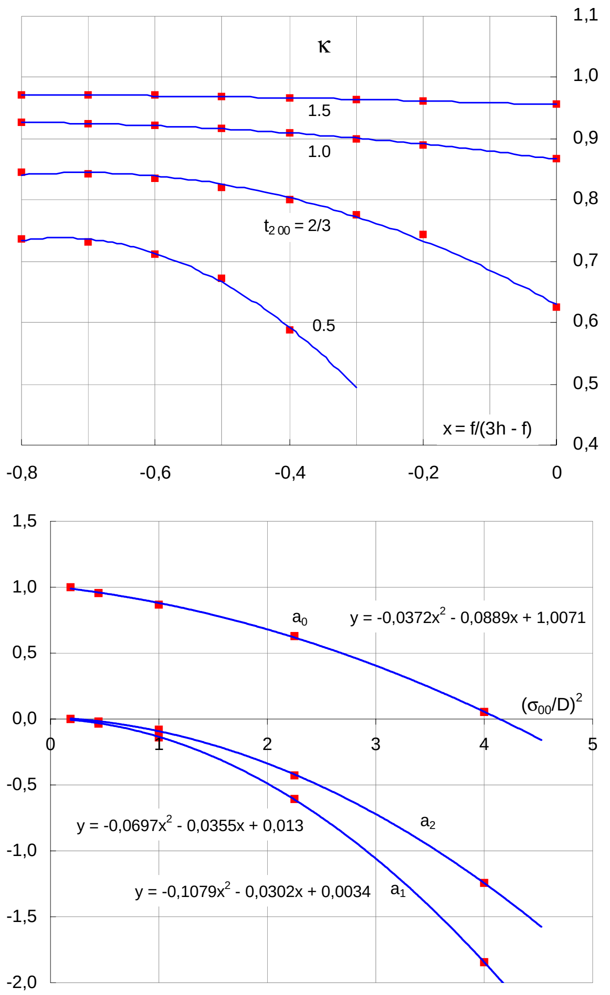

Figure 7 The reduction coefficient κ for negative freeboard along with parabolic fit (top), and coefficients of the fitting parabolas as functions of nondimensional clearance $t_{2\infty} = D/\sigma_\infty$ (bottom)

Regarding positive freeboard, curves on the right-hand side in Figure 4 have a different nature – the curve for unrestricted height of the opening decays exponentially with the nondimensional freeboard t_0, whilst the remaining curves, particularly for a smaller clearance look almost as segments of straight lines. To overcome the inconvenience of handling curves of various patterns, a similar transformation as before could be used for the abscissa axis $x = f/(3d+f)$, where this time $x \in \langle 0, 1\rangle$, while the ordinate axis is unchanged. However, in the case of positive freeboard such a transformation, although mathematically efficient, is not very handy, as the quantity d is unknown.

For positive freeboard, in order to find elevation of water on a deck above the vehicle deck, as can be seen in Figure 4, the nondimensional water head $\tau = d/\sigma$, corresponding to unrestricted height of opening with $t_2 = \infty$, is known function of the nondimensional freeboard $t_0 = f/\sigma$, where $f = D$. Hence, the following results:

$$d = \sigma\tau(t_0). \tag{10}$$

It may be assumed, for the sake of simplicity, that $\sigma = \sigma_\infty$, where σ_∞ is the standard deviation of relative wave motion when ignoring decks above the vehicle deck. We err in such a case on the side of safety. All the quantities on the right-hand side of equation (10) are then known; therefore this equation is a formulation. The function $\tau(t_0)$ up to $t_0 \approx 2.8$ is given by a polynomial of the third degree:

$$\tau = 0.6207 - 0.6205 t_0 + 0.215 t_0^2 - 0.0256 t_0^3. \tag{11}$$

4. TWO DECKS

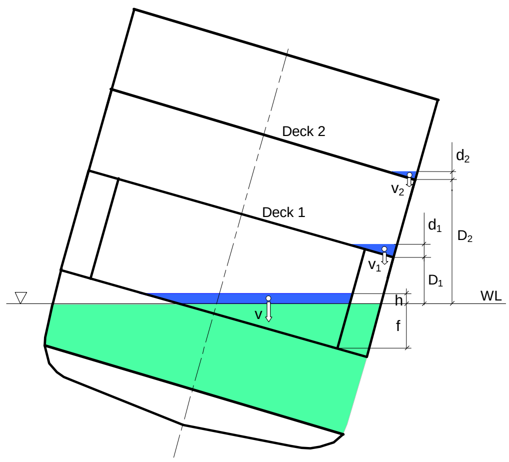

Figure 8. A damaged ro–ro vessel at the PNR with water accumulated on decks

It is easy to extend the method for two or more decks above the vehicle deck, if that proves necessary. For given height D_1 of Deck 1 and D_2 of Deck 2 above sea level (see Figure) and given sea state, the water heads d_1 and d_2 on these decks can be found using graphs regarding accumulation of water on a deck with positive freeboard, as shown in Figure 4. Water head d_2 is defined by equation (10), in which freeboard $f = D_2$. Regarding Deck 1, as this deck is protected by Deck 2, water head d_1 is defined by a similar equation:

$$d = \sigma\tau(t_0, t_2), \tag{12}$$

where in general $t2 = D/\sigma$. In this case, $f = D_1$, whereas $D = D_2$. And this should be taken as a rule: freeboard f is understood as height of the given deck above sea level, whereas D is a height of the deck above the deck under consideration relative to sea level, all measured at the PNR. The actual deck flooded and the next deck above, providing protection, form a kind of independent window – what happens below and above this window is of no interest for flooding the deck under consideration.

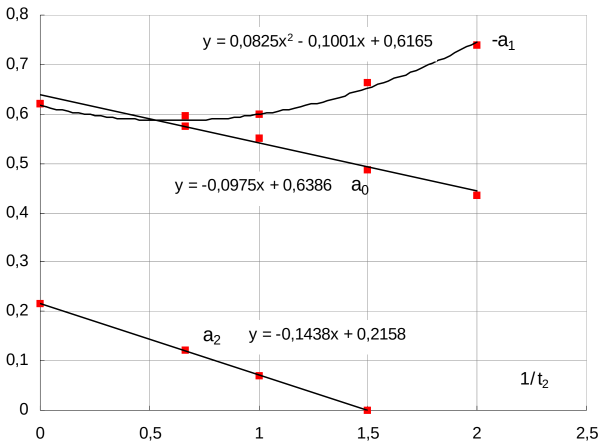

Figure 9. Coefficients of the fitting parabolas as functions of $t_2 = D/\sigma$

Assuming again that $\sigma = \sigma\infty$, all the quantities on the right-hand side of equation (12) are known; therefore this equation becomes a formulation that defines d. What is needed only is the knowledge of the nondimensional water head $\tau = \tau(t_0, t_2)$ as function of two variables t_0 and t_2. Graphs shown in Figure 4, except for $t_2 = \infty$, can be neatly approximated by parabolas, whose coefficients depend on the inverse of t_2, as shown in Figure.

The knowledge of water heads d_1 and d_2 on Deck 1 and Deck 2 defines volumes v_1 and v_2, accumulated on these decks (see Figure). The critical amount of water on the vehicle deck, which defines the critical sea state is such that the resultant moment vanishes at the PNR, i.e.

$$VGZ_{max} = vl + v_1 l_1 + v_2 l_2, \tag{13}$$

where V is volume displacement of the intact ship (before damage), v is the elevated volume of water on the vehicle deck above the sea level, as shown in Figure, and l is the heeling lever produced by this water with respect the axis of floatation of the damaged waterline, passing through the centre of floatation (not shown in Figure). All the heeling arms l, l_1 and l_2 are measured with respect to the same axis of floatation of the damaged waterline, without the parts occupied by the floodwater.

By solving equation (13), one gets the sought volume v of elevated water on the vehicle deck and its (static) elevation h above sea level that has to be produced by the dynamic action of waves and ship motion, along with the freeboard f. Knowing the two quantities, the critical sea state can be found by exactly the same way, as described earlier for the case of one deck above the vehicle deck, with $D = D_1$.

Having found the critical standard deviation of the relative wave elevation at the damage opening σ, the whole methodology can be repeated, if necessary, starting with $\sigma_\infty = \sigma$.

5. CONCLUSIONS

From equation (13) it follows immediately that the critical elevation of water on the vehicle deck is smaller in comparison to one deck. However, due to the protection provided by Deck 1 it is difficult to predict beforehand how this per capita affects the critical sea state the ship can withstand, unless the ship has a trim. The outcome depends on particulars of the design. Trim is dangerous as it opens space for "dead" water, which stays on deck, once it entered there. Draining off the decks is therefore very beneficial for ship safety.

The knowledge of water elevation on the vehicle deck and the immersion of the deck edge at the PNR along with the clearance to Deck 1 are sufficient for finding the critical sea state Hs (in terms of the median value) the ship is capable of withstanding at given flooding. The methodology is embedded at the SEM.

6. ACKNOWLEDMENTS

Main body of the paper was developed during the author's visit at The Ship Stability Research Centre of the University of Strathclyde, Glasgow from July to September 2005. Prof. D. Vassalos, the Director of the Centre, supported the visit.

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