# Analytical Studies for Water on Deck Accumulation

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*ABSTRACT*

*A mathematical model is presented for the accumulation of water on the vehicle deck of a damaged ro-ro vessel. The model leads to a simple relationship between the mean depth of water accumulated on deck, freeboard at opening (including negative freeboard) and significant height of relative motion due to heave. The two characteristic values may potentially help with the identification of the so-called point of no return for a damaged ro-ro vessel.*

## 1. Introduction

Described in this paper are the efforts to develop a simple mathematical model for water accumulation on the vehicle deck of a damaged ro-ro ship. The theory is much the same as presented in Reference [1] but the results obtained are quite different, though the same model for water ingress has been used in both cases, as described in References [2–5]. The paper makes use of the pressure head formulation—as termed in Reference [1]—for flow rate through opening, the same as through a weir.

## 2. Relative motion

Consider a ro-ro ship inclined to a quasi-static angle of heel by water accumulated on the vehicle deck, as shown in Figure 1. In such a case, because of the inseparable free surface effect and a large reduction of the metacentric height, roll motion is strongly subdued and the ship can be regarded as having almost no roll at this position, performing chiefly heave in beam irregular seas. In terms of relative motions, the ship can be regarded as stationary. Therefore, the same mathematical model for accumulation of water on deck can be adopted as that developed by Hutchison for a stationary ship [1]. The only difference is that the significant wave height $H_S$ should be replaced by a significant height of relative motion at opening $H_{Sr}$. The relative motion is the difference between wave elevation (at the opening) and vertical displacement of

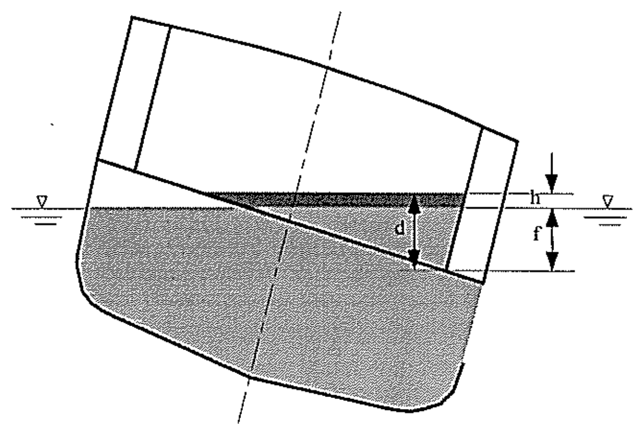


Figure 1. A damaged ro-ro ship at the point of no return

the ship, resulting both from heave and roll. Although the latter is small, it contributes significantly to relative motion, owing to large breadth of the ship.

The significant height of relative motion $H_{Sr}$ is mainly a function of significant wave height $H_S$, affected also (to some extent) by tuning factors for heave and roll, described by the ratio $T_o/T_z$ and $T_o/T_\phi$, where $T_z$ is the natural heave period, $T_\phi$ is the natural roll period at the point of no return, and $T_o$ is the modal period of irregular waves. If the modal period $T_o$ was constant, then $H_{Sr}$ would be strictly proportional to $H_S$ for given tuning factors. This is not the case since $T_o$ is proportional to $H_S^{0.5}$. Therefore, $H_{Sr}$ is a non-linear function of $H_S$, as shown in Table 1.

Table 1. A typical relation between significant height of relative motion $H_{Sr}$ and significant wave height $H_S$.

| $H_S$ (m) | 1,5 | 2 | 3 | 4 | 5 | 6,5 |
|---|---|---|---|---|---|---|
| $H_{Sr}$ (m) | 2,6 | 3,9 | 5,2 | 5,5 | 5,5 | 5,3 |

For practical applications, $H_{Sr}$ can be considered as a function of $H_S$ only, as the effect of tuning factors is not strong. The best fit of experimental data is normally achieved by a power formulation $H_{Sr} = H_S\, p$, where the exponent $p = 1.3$ has been found by regression [4] and assumed to be constant for the sake of simplicity. All experimental data show, however, that the exponent $p$ does depend on $H_S$, as shown in Figure 2 and Figure 3.

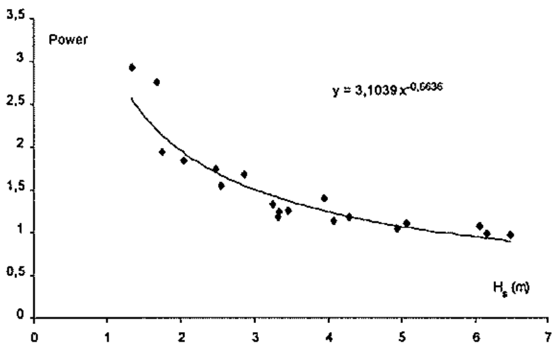


Figure 2. Regression of power $p$ on $H_S$ according to IMD's data, Canada, Ref. [6]. Average $p = 1.49$.

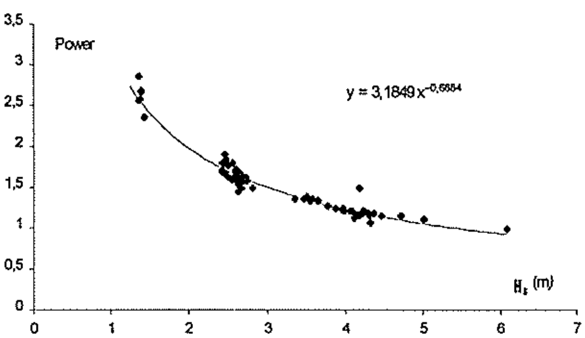


Figure 3. Regression on power $p$ according to DMI data, Denmark. Average $p = 1.54$.

There is a surprising agreement between the IMD and DMI data—the two regression lines are almost identical, although they were derived for different ships at different experimental facilities. The $p$ exponent for the two regression lines can be very well approximated by the equation

$$p = 3.144\, H_S^{-0.676}$$

where $H_S$ is in meters. The average value of $p$ for these data equals roughly 1.5, instead of 1.3 which is the effect of various regressions employed.

To improve further regression of $H_{Sr}$ on $H_S$, the tuning factors for heave and roll motion would have to be accounted for. For practical application, however, the exponential formulation is sufficient enough.

## 3. Basic flow model

At each instant the flow rate of water through opening is given by the relationship

$$Q = (\operatorname{sgn} H)\, cb\sqrt{2g}\left(\tfrac{2}{3}|H|^{3/2} + d_1|H|^{1/2}\right) \quad (1)$$

where: $c$ – correction coefficient for non-stationary flow and resistance established experimentally
- $b$ – width of opening,
- $g$ – acceleration due gravity,
- $H = \zeta - h$ – relative distance between wave profile and the free-surface at opening (positive if wave exceeds the level of water inside the ship),
- $d$ – depth of water at opening, and
- $d_1$ – height at opening with water on both sides. The height $d_1 = d$ if $H > 0$, otherwise $d_1 = \zeta - f = d - |H|$ (the instantaneous draught of the deck edge at opening), but not less than zero.

In general, $\zeta$ is relative wave elevation, $h$ is a height of free surface of water on deck above sea level, and $f$ is freeboard at opening understood as distance between the deck edge and sea level, measured at the centre of damage at the inner shell of wing spaces, if any (+ if the deck is above sea level and – if it is below)—see Figure 1. For negative freeboard $f$, shown in this figure, the height of the free-surface on deck above sea level, $h$, is the same as elevation of water on deck above sea level (water head). By definition, $h > f$. The difference $h$ and $f$ can be interpreted as depth of water on deck, $d$, measured at the centre of damage at the inner shell of wing spaces, if any. Hence, $d = h - f$.

The first term in Eq. (1) is the same as for a weir, whereas the second corresponds to the flow rate through opening in the dam below the water level. At a given instant there is either inflow of water on deck with the rate:

$$Q_{in} = \tfrac{2}{3} cb\sqrt{2g}\left(1.5dH^{1/2} + H^{3/2}\right) \qquad (2)$$

if $\zeta > h$, or outflow with the rate:

$$Q_{out} = \tfrac{2}{3} cb\sqrt{2g}\left(1.5d|H|^{1/2} - 0.5|H|^{3/2}\right) \quad (3)$$

if $\zeta < h$, where $|H| = h - \zeta$. A value of $\zeta$ in Eq. (2) cannot be greater than a height of the upper edge of opening above sea level measured at the centre of damage, $D$, while in Eq. (3) — smaller than the freeboard at opening $f$. If $\zeta > D$ then

$$Q_{in} = \tfrac{2}{3} cb\sqrt{2g}\left[1.5dH^{1/2} + H^{3/2} - (\zeta - D)^{3/2}\right] \quad (4)$$

If $\zeta < f$, the quantity $|H|$ in Eq. (3) assumes a maximum value $h - f = d$ and the expression in the parenthesis reduces to $d^{3/2}$. Hence, $Q_{out}$ is then constant and independent of $\zeta$.

## 4. Average global flow rate

In applications it is handy to use the flow rate averaged with respect to time, denoted by $Q_{av}$. If the time of averaging is long enough, then the mean value of the time averaged $Q_{av}$ can be replaced by averaging with respect to the relative wave elevation $\zeta$. Hence, the mean averaged flow rate through opening is given by:

$$\overline{Q} = \int_h^\infty Q_{in}\, d\zeta - \int_{-\infty}^h Q_{out}\, d\zeta \qquad (5)$$

where the first integral is $\overline{Q}_{in}$—average inflow rate, while the second one is $\overline{Q}_{out}$—average outflow rate. Applying Eqs. (2–4), yields

$$\overline{Q}_{in} = \frac{2}{3} cb\sqrt{2g}[1.5d\int_h^D H^{1/2} f(\zeta)d\zeta + \int_h^D H^{3/2} f(\zeta)d\zeta$$
$$+ \int_D^\infty [H^{3/2} - (\zeta - D)^{3/2}] f(\zeta)d\zeta]$$

$$\overline{Q}_{in} = \frac{2}{3} cb\sqrt{2g}[1.5d\int_h^\infty H^{1/2} f(\zeta)d\zeta + \int_h^\infty H^{3/2} f(\zeta)d\zeta$$
$$- \int_D^\infty (\zeta - D)^{3/2} f(\zeta)d\zeta] \qquad (6)$$

$$\overline{Q}_{out} = \frac{2}{3} cb\sqrt{2g}[d^{2/3}\int_{-\infty}^f f(\zeta)d\zeta + 1.5d\int_f^h |H|^{1/2} f(\zeta)d\zeta$$
$$- 0.5\int_f^h |H|^{3/2} f(\zeta)d\zeta] \qquad (7)$$

Since depth of water $d$ at opening is constant over a period of time, it can be taken in front of the integrals. If height of opening is unlimited in the vertical direction (i.e., if $D \to \infty$), then the last integral in Eq. (6) vanishes. Hence, the following finally result for the average inflow and outflow rates:

$$\overline{Q}_{in} = \frac{2}{3} cb\sqrt{2g}[1.5d\int_h^\infty H^{1/2} f(\zeta)d\zeta + \int_h^\infty H^{3/2} f(\zeta)d\zeta] \quad (8)$$

$$\overline{Q}_{out} = \frac{2}{3} cb\sqrt{2g}[d^{3/2} F(\zeta = f) + 1.5d\int_f^h |H|^{1/2} f(\zeta)d\zeta$$
$$- 0.5\int_f^h |H|^{3/2} f(\zeta)d\zeta] \qquad (9)$$

where $H = \zeta - h$ while $f(\zeta)$ and $F(\zeta)$ are the normal distribution density and cumulative distribution of the relative wave elevation $\zeta$. The normal distribution density is given by

$$f(\zeta) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2}\left(\frac{\zeta}{\sigma}\right)^2}$$

where $\sigma = H_{sr}/4$ is the standard deviation (dispersion) of the relative wave elevation $\zeta$. Integrals occurring in Eqs. (6–9) are valid for any freeboard, both positive and negative. The averaging process applied above is correct if freeboard, depth of water on deck, both measured at opening, and height of water above sea level vary slowly in the course of time which is true when a large scale flooding occurs through a relatively small opening—a typical situation for ro-ro vessels in a damaged condition.

Introducing the nondimensional random variable $t = \zeta/\sigma$, the following is obtained for the mean inflow and outflow rates:

$$\overline{Q}_{in} = Q_o q_{in}$$
$$\overline{Q}_{out} = Q_o q_{out} \qquad (10)$$

where $Q_o$ is a constant, given by

$$Q_o = \tfrac{2}{3} c\sqrt{2g}\, b\sigma^{3/2} \qquad (11)$$

corresponding to flow rate through a weir of breadth $b$ and depth of water $\sigma$ at the weir, while $q_{in}$ and $q_{out}$ are nondimensional mean flow rates, given by

$$q_{in} = 1.5\tau \int_{t_1}^{\infty} (t - t_1)^{1/2} f(t)dt$$
$$+ \int_{t_1}^{\infty} (t - t_1)^{3/2} f(t)dt \qquad (12)$$

$$q_{out} = \tau^{3/2} F(t = t_0) + 1.5\tau \int_{t_0}^{t_1} (t_1 - t)^{1/2} f(t)dt$$
$$- 0.5 \int_{t_0}^{t_1} (t_1 - t)^{3/2} f(t)dt \qquad (13)$$

where: $f(t)$ and $F(t)$ – standard normal density function and cumulative distribution of the nondimensional relative wave elevation $t = \zeta/\sigma$;
$t_o = f/\sigma$ – nondimensional freeboard at opening;
$t_1 = h/\sigma$ – nondimensional height of the free surface on deck above sea level;
$\tau = d/\sigma$ – nondimensional depth of water on deck at opening, $\tau = t_1 - t_o$.

The mean net inflow rate $\overline{Q} = \overline{Q}_{in} - \overline{Q}_{out}$ can be presented finally in a short form:

$$\overline{Q} = Q_o \left( q_{in} - q_{out} \right) \qquad (14)$$

The two quantities $q_{in}$ and $q_{out}$ reflect the effect of random variations of water elevation at opening on the resultant mean flow rates. The integrals in Eqs. (12) and (13) represent moments of the order of 0.5 and 1.5 of the density function $f(t)$ with respect to $t = t_1$. These moments can be easily calculated by numerical integration, either directly or by applying the substitution $dF = f(t)dt$, and terminating integration for the inflow case when $t \approx 3.3$ or $F \approx 0.9995$. The quantities $q_{in}$ and $q_{out}$ are well defined since the freeboard at opening $f$ and the height of water on deck above sea level $h$ are known at each position of the damaged ship—see Figure 1, and the same applies to their nondimensional counterparts $t_o = f/\sigma$ and $t_1 = h/\sigma$.

With the help of moments of the density function $f(t)$, Eqs. (12) and (13) for the nondimentional flow rates can be further abbreviated, namely

$$q_{in} = 1.5\tau\, q_{0.5}(t_1) + q_{1.5}(t_1) \qquad (15)$$

$$q_{out} = \tau^{3/2} F(t_0) + 1.5\tau q_{0.5}(t_0, t_1)$$
$$-0.5 q_{1.5}(t_0, t_1) \qquad (16)$$

where, in general, moments of the order $m$ are defined as follows

$$q_m(t_1) = \int_{t_1}^{\infty} (t - t_1)^m f(t)dt \qquad (17)$$

$$q_m(t_o, t_1) = \int_{t_o}^{t_1} (t_1 - t)^m f(t)dt \qquad (18)$$

As can be seen, since $\tau = t_1 - t_o$, both nondimensional flow rates $q_{in}$ and $q_{out}$ are functions of two variables. These are: $t_o = f/\sigma$ – the nondimensional freeboard at opening, and $t_1 = h/\sigma$ – the nondimensional height of the free surface on deck above sea level, where $t_o \le t_1$ and $t_1 > 0$. The variable $t_1$ can also be negative. Negative $t_1$ is, however, out of interest as it occurs when the ship is inclined beyond the angle of vanishing stability.

Moments of the standard normal density function $f(t)$ can be expressed by moments of the complements of the cumulative distribution function $1 - F(t)$ that are smaller by one order. Applying integration by parts yields

$$q_m(t_1) = m \int_{t_1}^{\infty} (t - t_1)^{m-1} (1 - F)dt$$

$$q_m(t_o, t_1) = \tau^m (1 - F_0) - m \int_{t_o}^{t_1} (t_1 - t)^{m-1} (1 - F)dt$$

## 5. Inflow moments

The nondimensional inflow rate $q_{in}$ depends on two special functions of one variable $q_{0.5}(t_1)$ and $q_{1.5}(t_1)$. These are the moments of the order 0.5 and 1.5 of the standard normal density function with respect to $t = t_1$ for $t > t_1$, given by Eq. (17). Their values, obtained numerically, are shown in Table 2 and plotted in Figure 4. Excellent approximations of these functions up to about $t_1 = 3$ are polynomials of the 3rd degree, shown in this figure.

Besides regression, the inflow moments $q_m(t_1)$ can be approximated in a more analytical way, based on the mean value theorem. Namely, integration by parts in Eq. (17) yields

$$q_m(t_1) = \int_{F_1}^{1}(t-t_1)^m dF = [(t-t_1)^m F(t)]_{t_1}^{t_{max}}$$

$$-\int_{t_1}^{t_{max}} F d(t-t_1)^m$$

Now, applying the mean value theorem to the integral yields a simple equation

$$q_m(t_1) \approx \delta^m[1 - F(t_1 + k\delta)] \qquad (19)$$

where: $\delta = t_{max} - t_1$ – practical extent of the integration range;
$t_{max}$ – value of $t$ for which $F \approx 1$, and
$k$ – coefficient dependent on the moment $\in \langle 0, 1 \rangle$.

Table 2 Values of inflow moments $q_m$ in terms of nondimensional height of free surface on deck above sea level $t_1 = h/\sigma$.

| $t_1 = h/\sigma$ | $q_{1.5}$ | $q_{0.5}$ | $t_1 = h/\sigma$ | $q_{1.5}$ | $q_{0.5}$ |
|---|---|---|---|---|---|
| 0 | 0.4300 | 0.4107 | 1.75 | 0.0131 | 0.0228 |
| 0.25 | 0.2951 | 0.3102 | 2 | 0.0066 | 0.0124 |
| 0.5 | 0.1952 | 0.2250 | 2.25 | 0.0032 | 0.0064 |
| 0.75 | 0.1241 | 0.1564 | 2.5 | 0.0014 | 0.0031 |
| 1 | 0.0756 | 0.1039 | 2.75 | 0.0006 | 0.0015 |
| 1.25 | 0.0441 | 0.0659 | 3 | 0.0002 | 0.0006 |
| 1.5 | 0.0246 | 0.0398 | 3.25 | 0.0000 | 0.0003 |

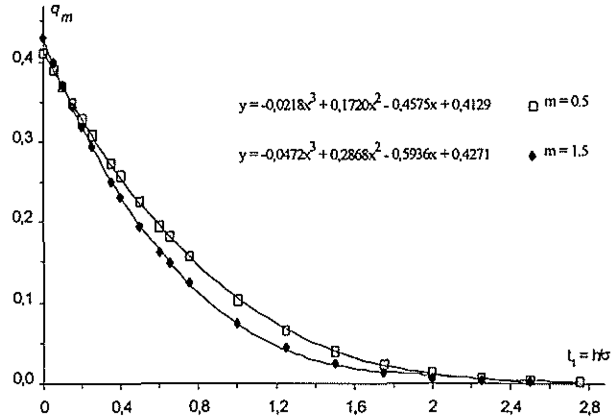


Figure 4. Inflow moments $q_m$ for $m = 0.5$ and 1.5 versus nondimensional height of free surface on deck above sea level $t_1 = h/\sigma$.

The two constants $t_{max}$ and $k$ occurring in Eq. (19) can be found with the help of the least squares method. A value of $t_{max}$ = 2.7 is assumed the same for all moments. On the other hand, the coefficients $k$ is dependent on the moment, as shown in Table 3.

Table 3. Values of the coefficient $k$ for moments of different orders $m$

| $m$ | $k$ | $m$ | $k$ |
|---|---|---|---|
| .5 | 0.246 | 2.5 | 0.604 |
| 1 | 0.385 | 3 | 0.646 |
| 1.5 | 0.481 | 4 | 0.705 |
| 2 | 0.551 | 5 | 0.741 |

Equation (19) is amazingly accurate, as accurate as the approximations shown in Figure 4 — differences between the two types of approximations are invisible in this figure. Now, since the calculation of moments $q_m(t_1)$ is simple and accurate, the same applies to the nondimensional inflow rate $q_{in}$, given by Eq. (15). For a given value of $t_1$, $q_{in}$ is a linear function of $\tau$, starting at a value $q_{1.5}(t_1)$ for $\tau = 0$.

## 6. Outflow moments

As it can be seen from Eq. (16), the nondimensional outflow rate $q_{out}$ depends on two special functions $q_{0.5}(t_o, t_1)$ and $q_{1.5}(t_o, t_1)$. These are the moments of the order 0.5 and 1.5 of the standard normal density function with respect to $t = t_1$ but for $t \in$

$\langle t_o, t_1\rangle$, as given by Eq. (18). The outflow moments $q_m(t_o, t_1)$ as functions of two variables are difficult to approximate by sheer regression. Fortunately, we can overcome this difficulty with the help of the mean value theorem. Integration by parts in Eq. (18) yields now

$$q_m(t_0,t_1) = \int_{F_0}^{F_1}(t_1-t)^m dF = [(t_1-t)^m F(t)]_{t_0}^{t_1}$$

$$-\int_{t_0}^{t_1} F d(t_1-t)^m$$

Applying again the mean value theorem to the integral, we get

$$q_m(t_o, t_1) = \tau^m [F(t_o + \kappa_m\tau) - F(t_o)] \qquad (20)$$

where the factor $\kappa_m \in \langle 0, 1\rangle$. The expression in square brackets represents the area under the density function $f(t)$ between $t_o$ and $t_o + \kappa_m\tau$. It is obvious that to get the same moment only part of the whole area can be located on the full lever $\tau$. Contrary to the inflow case, the factor $\kappa_m$ is no longer a constant—in addition, it is affected by the limits of integration $t_o$ and $t_1$ which makes the approximation much more involved. In such a case, regression methods are of little use. To get versatile approximations, analytical methods have to employed.

One immediate possibility is to expand $f(t)$ in Eq. (18) into a series around $t = t_1$ and perform integration directly. We get

$$q_m(t_o, t_1) = \tau^m\left(\frac{f_1\tau}{m+1} - \frac{f_1'\tau^2}{m+2} + \frac{f_1''\tau^3}{m+3} \mp \cdots\right) \qquad (21)$$

where $f_1$, $f_1'$ and $f_1''$ are the density function $f$ and its derivatives $f'$ and $f''$ calculated for $t = t_1$. Since $f'/f = -t_1$ and $f''/f = t_1^2 - 1$, therefore

$$q_m(t_o, t_1) = \tau^{m+1} f_1\left[\frac{1}{m+1} + \frac{t_1\tau}{m+2} + \frac{(t_1^2-1)\tau^2}{m+3} + \cdots\right]$$

The above approximation works well only for small $\tau$. Much better results can be obtained with Eq. (20) if $\kappa_m$ is approximated analytically. The easiest way, none the less still quite involved, is to compare the expressions for area inside the brackets in Eqs. (20) and (21).

$$f(1-\kappa) = \frac{f}{m+1}$$

$$f'(\kappa^2-1) + f2\kappa' = -\frac{2f'}{m+2}$$

$$-f''(\kappa^3-1) - f'6\kappa'\kappa + f3\kappa'' = c\frac{3!f''}{m+3}$$

where $1-\kappa$, $\kappa'$, and $\kappa''$ are the factor $\kappa_m$ and its first two derivatives at $\tau = 0$ (notation $1-\kappa$ for the initial value is used here just for convenience), while $c$ is a coefficient to be established by regression. The above system defines the three initial quantities of $\kappa_m$

$$\kappa = \frac{m}{m+1}$$

$$2\kappa' = t_1\left(\frac{2}{m+2} + \kappa^2 - 1\right)$$

$$3\kappa'' = (t_1^2-1)\left(\frac{6c}{m+3} + \kappa^3 - 1\right) - 6t_1\kappa'\kappa$$

These quantities are obviously independent of $\tau$ and depend on $m$ and $t_1$ only. For that reason, the factor $\kappa_m$ can be approximated by a trinomial square:

$$\kappa_m = (1-\kappa) + \kappa'\tau + 0.5\,\kappa''\tau^2 \qquad (22)$$

where the initial value $(1-\kappa) = 1/(m+1)$. A temporary guess for the fitting coefficient is 0.5. As can be seen, the factor $\kappa_m$ is a function of all the three independent quantities. Despite the complexity, the parabolic approximation, with the coefficient $c = 0.5$, appears to be amazingly accurate, as illustrated in Figure 5.

Now, with the help of outflow moments, as given by Eq. (20), the nondimensional outflow rate $q_{out}$ takes the form

$$q_{out} = \tau^{3/2}[1.5F(t_o + \kappa_{0.5}\tau) - 0.5F(t_o + \kappa_{1.5}\tau)] \qquad (23)$$

where the factors $\kappa_{0.5}$ and $\kappa_{1.5}$ are calculated by Eq.(22). Since $q_{out} < \tau^{3/2}$, therefore the expression in square brackets is less than 1 and the outflow rate can be finally presented in a short form $q_{out} = \tau^{3/2} F(t_o + \kappa_{out}\tau)$ where the factor $\kappa_{out}$ is now a function of two variables $t_o$ and $t_1$ and belongs to the interval $\langle 0, 1\rangle$. As can be seen, $q_{out}$ is a non-linear function of $\tau$, varying roughly as $\tau^{3/2}$. The highest value of $t_o$ equals obviously $t_1$ for which $\tau$ and $q_{out}$ vanish (no water on deck). On the other side, the smallest value of $t_o$

corresponds to a maximum asymptotic depth of water $\tau_\infty$ for which the mean outflow and inflow rates equalise. The asymptotic depth $\tau_\infty$ defines the aforementioned range of interest for flow calculations.

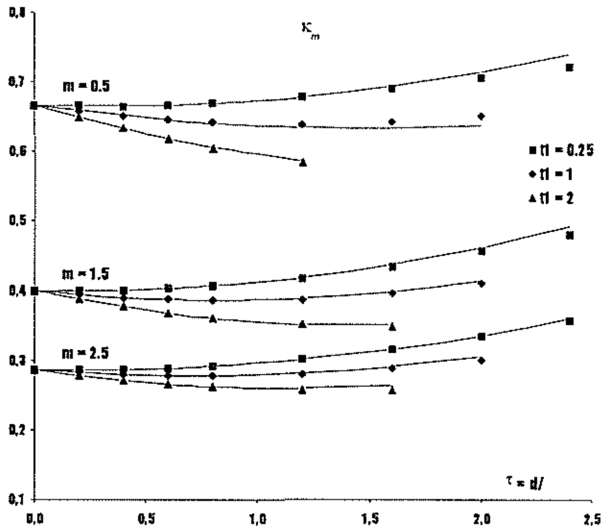


Figure 5. Factor $\kappa_m$ and its parabolic approximation.

## 7. Asymptotic depth of water on deck

Asymptotic values of the nondimensional depth of water on deck at opening are obtained from the solution of the equation $q_{out} = q_{in}$. As follows from the previous discussion, given a value of $t_1 = h/\sigma$, the equation always yields a unique root for $\tau = d/\sigma$. Further, when $t_1$ approaches zero, then $\tau$ tends to infinity as the inverse of $t_1$. The asymptotic values of $\tau_\infty$ are shown in Table 4 and Figure 6. They were obtained numerically using exact values for $q_{out}$ given by Eqs. (18). An excellent approximation for the nondimensional depth of water $\tau_\infty$ at the entire range of $t_1$ as shown in Figure 6, despite the singularity at zero. It is noteworthy that the quasi-static balance of water on deck can be achieved only for $t_1>0$.

The vertical segments between lines $y = t_1$ and $y = \tau(t_1)$ in represent the nondimensional freeboard $t_o$ (= $t_1 - \tau$ ) as a function of $t_1$. Hence, a point of intersection between the two lines determines point $A$ with $t_1 \approx 0.6185$ in which freeboard $f$ and its nondimensional counterpart $t_o = f/\sigma$ change the sign (i.e., where the deck edge at opening immerses). Below point $A$, freeboard is negative and $h$ is the same as elevation of water on deck above sea level, termed also as water head.

Table 4. Maximum mean nondimensional depth of water on deck $\tau = d/\sigma$ (at opening) versus nondimensional height of free surface on deck above sea level $t_1 = h/\sigma$.

| $t_1 = h/\sigma$ | $\tau = t_1 - t_o$ | $t_1 = h/\sigma$ | $\tau = t_1 - t_o$ |
|---|---|---|---|
| 0 | ∞ | 0,75 | 0,460 |
| 0,05 | 9,768 | 1 | 0,274 |
| 0,1 | 4,800 | 1,25 | 0,167 |
| 0,15 | 3,154 | 1,5 | 0,103 |
| 0,2 | 2,340 | 1,75 | 0,064 |
| 0,25 | 1,852 | 2 | 0,037 |
| 0,3 | 1,521 | 2,25 | 0,018 |
| 0,4 | 1,093 | 2,5 | 0,008 |
| 0,5 | 0,831 | 2,75 | 0,003 |

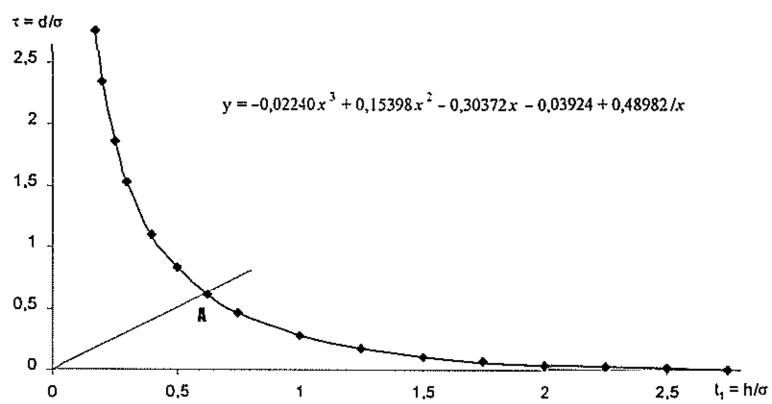


Figure 6. Maximum mean nondimensional depth of water on deck $\tau = d/\sigma$ at opening versus nondimensional height of free surface on deck above sea level $t_1 = h/\sigma$

## 8. Conclusions

In this paper, the problem of asymptotic depth of water on deck has been solved as a function of the height of the free surface on the deck above sea level non-dimensionalized with respect to the standard deviation of relative motion. As these two quantities are the key parameters in the Static Equivalency Method (Ref. 7), a major expansion of the method is now possible to include additional effects such as irregular dimensions of the opening, the presence of water draining devices, etc.. Now, it is also feasible to deal analytically with the fact that deck flooding is a random phenomenon and its mean value is not sufficient to describe it.

## 9. Disclaimer

The content of this paper reflect the views of the authors and not necessarily the official views of the Canadian Coast Guard.

## 10. Acknowledgements

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