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Problem of water flow on deck of small vessel

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Green water moving on deck of a small vessel affects its motion and can contribute to the vessel's capsizing. The phenomenon is nonlinear and its description using mathematical differential problems continues to be a challenge. The paper presents the comparison study of two simplified methods describing the water moving on deck. The first model is used in Ro-Ro ferries damage stability calculations. The model is based on an assumption that free surface of water over the deck is horizontal. The dynamic pressure caused by water on deck depends on the vessel's acceleration and changing height of water. The shallow water model is the second method. This method is used in simulation of shallow water motion along the deck of a small vessel. In this method the vertical acceleration of water is neglected and the horizontal components of water's velocity do not depend on the vertical coordinate. The paper presents verification possibilities of applying these methods in practice.

Keywords: method of shallow water flow, vessel capsizing, water on deck, irregular waves, vessel motion

1. INTRODUCTION

Figures reported by the International Marine Organization itself show that the annual loss of life on world's fishing vessels accounts for the loss of a huge number of human lives every year and that the safety of small vessels is a problem. One of the important reason for capsizing of small vessels is water moving on deck.

Correct modelling of hydrodynamic forces imposed by moving water on deck is a very complex and difficult problem if continuously changing amount of water on deck is taken into consideration. A detailed description of this problem is presented by Belenky (2002).

Dilligham (1981) presents a formulae describing water flow through scrubbers and over bulwarks. The mass of flowing water depends on the size and shape of openings, the height of sea wave and of the water height above the opening.

Numerical solution of 2D problem is obtained by Dillingham (1981). The equation used is valid for a level ship at rest. The author applies the random choice method for solving hyperbolic equations. The three-dimensional flow is described by Dillingham and Falzarano (1986) who transform equation to a coordinate system coupled to the ship's centre of gravity. Panatazapoulas (1988) presents a 3D equation of shallow water motion on deck of a ship moving in waves with yow equal to zero. His method is further developed by Huang and Hsiung (1997) who apply the flux differential splitting method to solve the non-linear three-dimensional problem describing water flow on deck. The forces and moments of water moving on deck are added to equations of ship motion.

Jankowski & Laskowski (2006) applied a simplified approach used in Ro-Ro ferries damage stability calculations in their computer programs enabling simulation of ship motion in irregular waves (Jankowski, 2007), as the first phase of modelling the water-on-deck effects. They added additional pressure acting on the deck to the model used in Ro-Ro ferries, caused by the change of water amount on the deck (Buchner, 2002).

In the second phase the problem of shallow water flow was used to model the water motion on deck, which include horizontal relative velocity of water (Zienkiewicz, 2005). The model was verified (Warmowska, 2008) testing cases of water motion:

- with constant water mass inside tank moving with constant acceleration,
- with constant water mass inside tank moving in 3D,
- trapping on non moving open deck.

The results were compare with results obtained by other authors and in other experiments (Huang Z.-J., Hsiung C., 1997).

The paper presents the comparison of these two methods for the given ship motion in time.

2 EQUATION OF VESSEL MOTION WITH WATER ON DECK IN IRREGULAR WAVES

The simulation of vessel motions in waves is based on numerical solutions of non-linear equations of motion (non-linear model). The hydrodynamic forces and moments defining the equations are determined in each time step. The accuracy of the simulation depends on the accuracy of calculating the hydrodynamic forces and moments due to waves.

It is assumed that the hydrodynamic forces acting on the vessel can be split into Froude-Krylov forces, diffraction and radiation forces as well as other forces, such as those induced by water on deck, rudder forces and non linear damping.

The Froude-Krylov forces are obtained by integrating the pressure caused by irregular waves undisturbed by the presence of the ship over the actual wetted ship surface.

The diffraction forces are determined as a superposition of diffraction forces caused by the harmonic components of the irregular wave. It is assumed that the ship diffracting the waves is in its mean position. This is possible under the assumption that the diffraction phenomenon is described by a linear hydrodynamic problem. The variables of diffraction function are separated into space and time variables with the space factor of the function being the solution of the hydrodynamic problem and the known time factor. Such an approach significantly simplifies calculations because bulky calculations can be performed at the beginning of the simulations and the ready solutions can be applied for determining the diffraction forces during the simulation.

The radiation forces are determined by added masses for infinite frequency and by the so-called memory functions (given in the form of convolution). The memory functions take into account the disturbance of water, caused by the preceding ship motions, affecting the motion of the ship in the time instant in which the simulation is calculated.

The volume of water on deck, varying in time, depends on the difference in heights between the wave surface and the following edges: the upper edge of the bulwark, and the lower edges of openings in the bulwark.

The equations (1) of ship motion in irregular waves are written in the non-inertial reference system. The system *Q*, with axis QX directed to the ship bow, QY directed to the ship port side and QZ directed upward, is fixed to the ship in the centre of its mass and the equations of ship motion assume the following form (Jankowski, 2007):

$$\begin{aligned} &m[\dot{\mathbf{V}}_Q(t)+\mathbf{\Omega}(t)\times\mathbf{v}_Q(t)]=\mathbf{F}_W(t)+\mathbf{F}_D(t)+\mathbf{F}_R(t)+\mathbf{F}_d(t)+\mathbf{F}_A(t)+\mathbf{D}^{-1}\mathbf{G},\\ &\dot{\mathbf{L}}(t)+\mathbf{\Omega}(t)\times\mathbf{L}(t)=\mathbf{M}_{QW}(t)+\mathbf{M}_{QD}(t)+\mathbf{M}_{QR}(t)+\mathbf{M}_{Qd}(t)+\mathbf{M}_{QA}(t),\end{aligned} \qquad (1)$$

$$\begin{aligned} &\dot{\mathbf{R}}_{UQ}(t)=\mathbf{v}_Q(t)-\mathbf{\Omega}(t)\times\mathbf{R}_{UQ}(t),\\ &(\dot{\varphi}(t),\dot{\theta}(t),\dot{\psi}(t))^T=\mathbf{D}_\Omega^{-1}\mathbf{\Omega}(t)\end{aligned}$$

where m is the mass of the vessel, $\mathbf{v}_Q = (v_{Q1},v_{Q2},v_{Q3})$ is the velocity of the mass centre, $\mathbf{\Omega} = (\omega_1, \omega_2, \omega_3)$ is angular velocity, $\mathbf{L} = (l_{Q1}, l_{Q2}, l_{Q3})$ is the angular momentum, $\mathbf{R}_{UQ}= (r_{UQ1}, r_{UQ2}, r_{UQ3})$ is the position vector of the ship mass centre in relation to the inertial system U, moving with a constant speed equal to the average speed of the vessel, (φ,θ,ψ) are Euler's angles representing roll, pitch, yaw, $\mathbf{F}_W$, $\mathbf{F}_D$, $\mathbf{F}_R$ and $\mathbf{F}_d$ are Froude–Krylov, diffraction, radiation forces and forces caused by water on deck, respectively, $\mathbf{G} = (0, 0, -mg)$ – gravity force, $\mathbf{M}_{QW}$, $\mathbf{M}_{QD}$, $\mathbf{M}_{QR}$, $\mathbf{M}_{Qd}$ are their moments in relation to the mass centre, $\mathbf{D}$ is the rotation matrix, and $\mathbf{D}$ is the matrix which transforms Euler components of rotational velocity $(\dot{\varphi},\dot{\theta},\dot{\psi})$ into $\mathbf{\Omega}$. The additional forces and moments such as damping forces or those generated by the rudder are denoted by $\mathbf{F}_A$ and $\mathbf{M}_{QA}$.

The ways of solving 3D hydrodynamic problems and determining forces appearing in the equation of motion are presented by Jankowski (2007). The non-linear equations of motion (1) are solved numerically (Hamming procedure is applied) according to the method presented by Ralston (1975). The program based on equations presented above and on the numerical methods applied enables to perform simulation of vessel motion with water on deck in irregular waves. The example of simulation history of motion is presented in Figure 1.

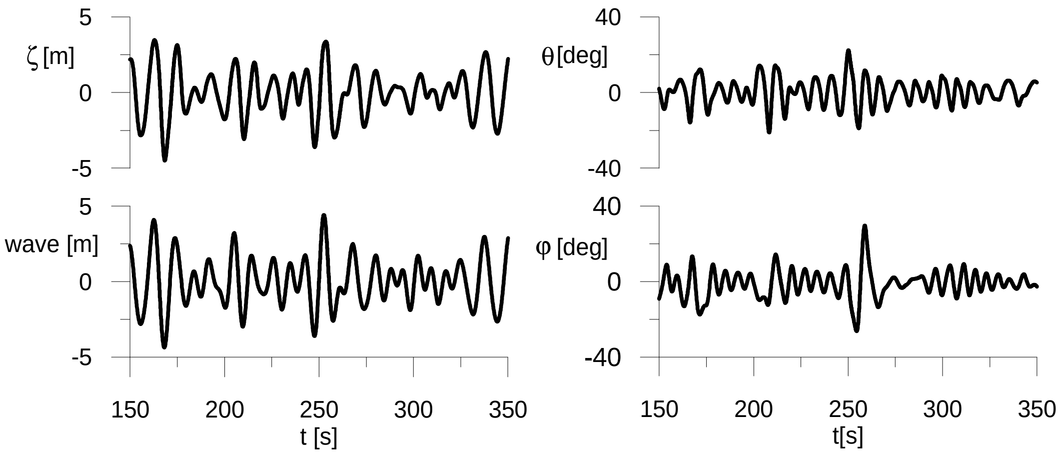

Figure 1. Time history of surface elevation, heave ζ, roll φ and pitch θ

3. THE FORCES AND MOMENTS ON DECK

The volume of water on deck, varying in time, depends on the difference in heights between the wave surface and the following edges: the upper edge of the bulwark, and the lower edges of openings in the bulwark.

It is assumed that the flow rate of water volume over the bulwark can be calculated as the flow over a weir, whereas the flow through the openings in the bulwark is modelled as a flow through a submerged orifice in a dam. The general formula for the flow rate is:

$$q = (signH)cb\sqrt{2g}\left(\tfrac{2}{3}\left|H\right|^{\frac{3}{2}} + d\left|H\right|^{\frac{1}{2}}\right) \tag{2}$$

where *c* is the correction coefficient for non-stationary flow, established experimentally, *b* is the width of the orifice or the fragment of bulwark above which the deck is flooded, *H* is the vertical distance between the wave profile and the free surface on the deck at a point considered (positive if the wave exceeds the water level on the deck), *d* is the depth of water at the orifice or the instantaneous elevation of wave profile above the deck edge at the orifice. Equation (2) assumes various forms depending on relative water levels inside and outside the deck well and on the position of the opening in the bulwark (Pawłowski, 2004). The formula (2) is applied separately for the upper edge of bulwark and the openings in the bulwark.

The forces $\mathbf{F}_d$, and moments $\mathbf{M}_{Qd}$, caused by water on deck, are calculated according to the following formula:

$$F_{di} = -\rho \int_{\Delta S} p_d n_i dS, \quad i = 1,2,..,6 \tag{3}$$

where S is the wetted surface of the deck, n_1, n_2, n_3 are components of the normal vector $\mathbf{n}$ in the considered deck surface ΔS and n_4, n_5, n_6 are the components of $\mathbf{R}\times\mathbf{n}$. Vector $\mathbf{R} = (x_d, y_d, z_d)$ is the position vector of deck point in non inertial system Q (the components of the normal vector are determined in the reference system fixed to the vessel in its centre of mass Q), p_d is the pressure in point on the deck.

3.1 Model used in Ro-Ro ferries damage stability calculations

The position of water trapped on deck is determined by the horizontal plane and the actual position of the vessel deck in the given time instant.

The dynamics of water caused by the motion of water particles in relation to the deck is neglected. The forces and moments caused by water-on-deck are obtained by integrating the hydrostatic pressure determined by water horizontal plane above the deck in the vessel's actual position (for time $t=t_i$, $i=1..n$).

Additionally, the vessel's acceleration and the changing heights of the horizontal plane above the deck have been added to the model to better replicate the phenomenon (Jankowski & Laskowski, 2006). The pressure p_d in point on the deck is equal to:

$$p_d = \rho \frac{dh}{dt} v_V + \rho(g + a_V)h \tag{4}$$

where

$$
\begin{aligned}
v_V &= d_{31} v_{P1} + d_{32} v_{P2} + d_{33} v_{P3}, \\
a_V &= d_{31} a_{P1} + d_{32} a_{P2} + d_{33} a_{P3}, \\
\mathbf{v}_P &= \mathbf{v}_Q + \mathbf{\Omega} \times \mathbf{R}_{QP}, \\
\mathbf{a}_P &\approx \dot{\mathbf{v}}_Q + \dot{\mathbf{\Omega}} \times \mathbf{R}_{QP}
\end{aligned}
$$

d_{3i}, $i = 1,2,3$, are components of the matrix D and h is the vertical distance from the horizontal plane to the point of the deck in the inertial coordinate system U. Velocity v_V and acceleration a_V are also determined in the system U.

This formula has been derived, basing on the evaluation of Newton's momentum relation for a control volume on deck, in the following way (Buchner, 2002):

$$
\Delta F_{d3} = \frac{d(\Delta m v_V)}{dt} = \frac{d(\Delta m)}{dt} v_V + \frac{dv_V}{dt} \Delta m \qquad (5)
$$

where ΔF_{d3} is the force acting on the area ΔS of the deck. The mass in the control volume is equal to: $\Delta m = \rho h \Delta S$. Substituting this to equation (5), dividing by ΔS and taking into account gravitational acceleration g, formula (4) is obtained.

3.2 The shallow water model

The problem is described in the system Q, fixed to the ship in the centre of mass m. The vessel has six degrees of freedom. The force $\mathbf{F}_d$, with components (f_{Qx}, f_{Qy}, f_{Qz}) in the system Q, acts on the water particle. The gravity forces, centrifugal forces, Coriolis and tangential forces contribute to the force $\mathbf{F}_d$.

The shallow water problem is solved in four steps (Warmowska, 2008), determining:

1. domain Ω occupied by water,
2. pressure field,
3. horizontal velocities u_x, u_y,
4. vertical velocity u_z.

The motion of the free surface S_F is described by the following equations:

$$
\begin{aligned}
&\frac{dx}{dt}(t) = u_x(t,x,y,z),\\
&\frac{dy}{dt}(t) = u_y(t,x,y,z), \quad (x(t),y(t),z(t)) \in S_F(t)\\
&\frac{dz}{dt}(t) = u_z(t,x,y,z).
\end{aligned}
\tag{6}
$$

Equations (6) are integrated using the Runge-Kutta method. The nodes of the net determining the free surface moving in time are updated in each time step by interpolating the function describing free surface over nodes (x_{di}, y_{di}, z_{di}) of constant Euler grid of deck.

It is assumed that the velocity field around the ship is the velocity of the undisturbed ocean wave. In the case of the deck submerged in the wave, the water particle velocity over the deck, occurring in equations (6), is calculated taking into account the velocity field being the average of the deck water velocity field and the wave velocity field.

It is assumed that viscosity forces can be neglected. The motion of water is described using Euler equations. The shallow water model approximating the motion of water on vessel deck assumes that the vertical acceleration a_z can be neglected: $a_z(t,x,y,z) \approx 0$. These assumptions results in following equation:

The motion of the free surface S_F is described by the following equations:

$$
\frac{\partial p}{\partial z}(t,x,y,z) \cong -\rho f_{Qz}(t,x,y,z), \quad (x(t),y(t),z(t)) \in \Omega(t).
\tag{7}
$$

Equation (7) determines the pressure in the water domain over the vessel deck. The pressure field on deck p_d is obtained integrating equation (7):

$$
p_d(t,x,y,z_d) \cong p_a + \rho \int_{z_d + h(t,x,y,z_d)}^{z_d} f_{Qz}(t,x,y,s)ds, \quad (x(t),y(t),z_d(t)) \in \Omega(t).
\tag{8}
$$

where p_a is the pressure on the free surface S_F corresponding to atmospheric pressure.

Horizontal components of the velocity field in the domain Ω are determined from the Euler equations:

$$\begin{aligned}
&\frac{du_x}{dt}(t,x,y,z) = f_{Qx}(t,x,y,z) - \frac{1}{\rho}\frac{\partial p}{\partial x}(x,y,z),\\
&\frac{du_y}{dt}(t,x,y,z) = f_{Qy}(t,x,y,z) - \frac{1}{\rho}\frac{\partial p}{\partial y}(x,y,z), \quad (x(t),y(t),z(t)) \in \Omega,
\end{aligned} \tag{9}$$

for pressure determined by formula (8).

The vertical component u_z of the velocity field in the domain Ω is determined from the equation of mass conservation. Additionally, in the shallow water model it is assumed that horizontal velocities u_x and u_y do not depend on the vertical coordinate z. Basing on this assumption, the equation determining vertical component u_z takes the form:

$$u_z(t,x,y,z) = \left(-\frac{\partial u_x}{\partial x}(t,x,y) - \frac{\partial u_y}{\partial y}(t,x,y) + q \right)(z - z_{deck}) \tag{10}$$

where q represents the changes of water's mass on deck.

4. COMPARISON OF THE RESULTS OBTAINED BY THE MODELS PRESENTED

The forces $\mathbf{F}_d = (F_{d1},F_{d2},F_{d3})$ and moments $\mathbf{M}_{Qd} = (F_{d4},F_{d5},F_{d6})$ caused by water on deck are calculated with the use of formula (3) where the pressure p_d is determined by:

- formula (4) for the model used in Ro-Ro ferries damage stability calculations;
- formula (8) for the shallow water model.

The comparison was made in the following way:

- vessel motion in waves and forces generated on deck, affecting the vessel motion, is determined with the use of Ro-Ro ferry model, and

– forces generated on deck with the use of the shallow water model are calculated for the same vessel motion.

It means that forces generated on the vessel deck were calculated with the use of two different models for the same vessel motion making the comparison of the forces possible.

The irregular wave, determined by significant wave height H_s=6m and mean period T_z=8s, followed the vessel moving with the forward speed u=6m/s. The angle between the vector of forward vessel velocity and the wave vector was 30 degree.

Figure 2 presents force F_{d3} generated by water on deck, which increases the vessel draught, and Figure 6 – the rolling moment F_{d4}, responsible for vessel capsizing.

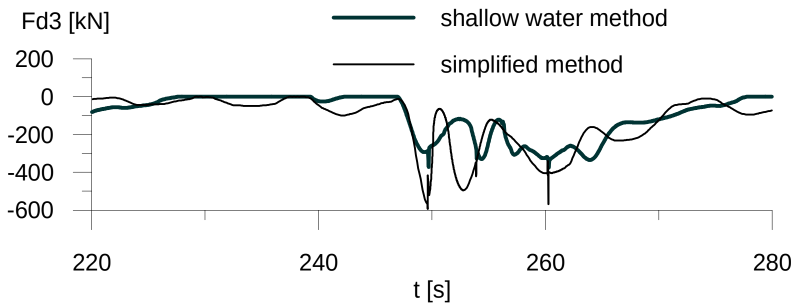

Figure 2. Time history of vertical force F_{d3} (increasing the draught)

The comparison of the forces determined by both methods shows the following:

– in the period [240s, 248s) force F_{d3} matches quite well for both methods – it is the case of the inflow of wave water on deck (Figure 3), when the vessel is in a relatively calm wave trough and the free surface on deck is almost horizontal plane (therefore both methods match well);

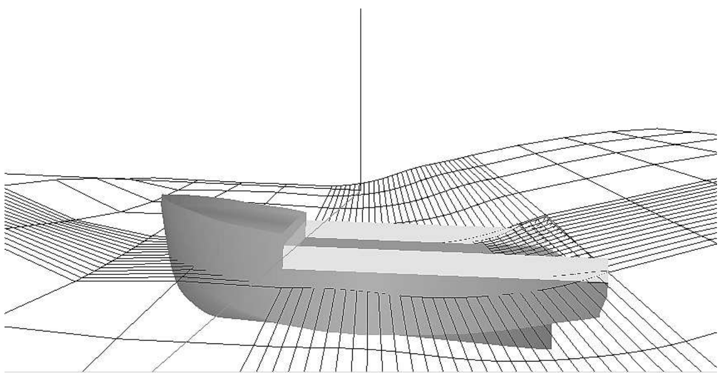

Figure 3. Inflow of wave water on deck

– in the period [248s, 260s) the water surface on the deck is still below the wave surface (Figure 4); the shallow water method models water motion on deck and the changes of water level on the deck are not as quick as in the simplified method as in this method the volume of water on deck depends only on the difference between the wave surface and deck water surface and does not depend on the velocity field on the deck;

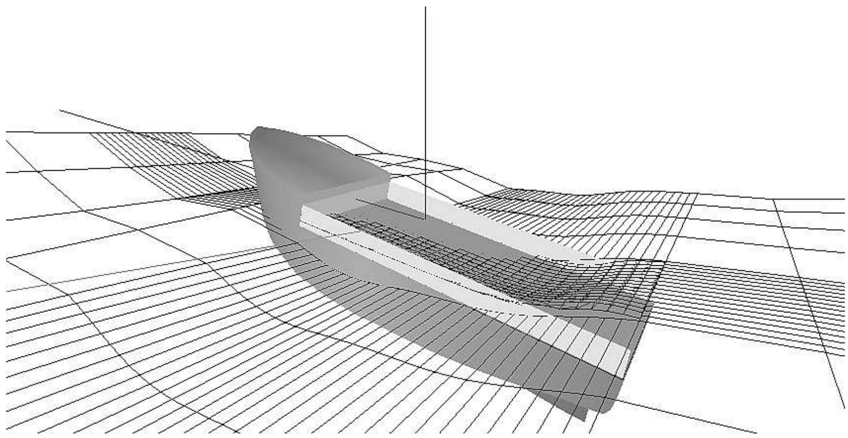

Figure 4. The relation between wave surface and water surface on deck at t=256s

– in the period [260s, 265s] the water surface drops immediately in the simplified method when the vessel bow climbs upwards while in the shallow water method the velocity field in the water on deck slows down the process (Figure 5)

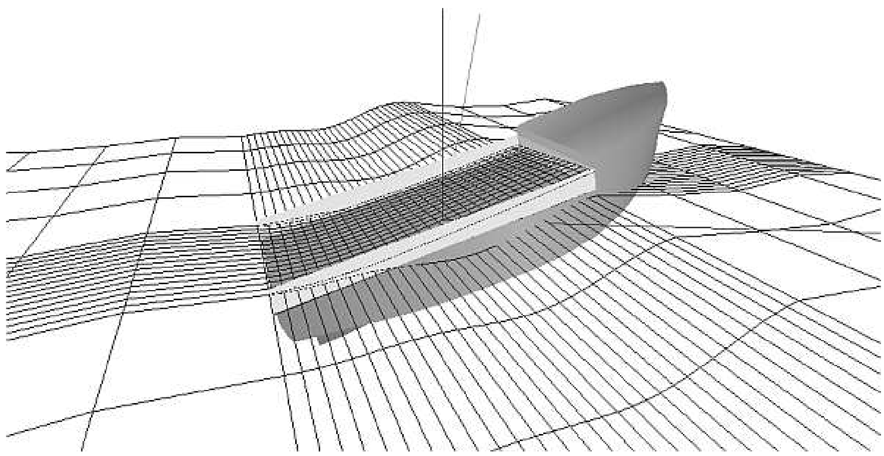

Figure 5. Outflow of water from deck (t=262s)

– in the period considered the rolling moment matches very well for both methods (Figure 6); this is probably because the following wave is considered which, for this conditions, does not generate significant water motion across the deck.

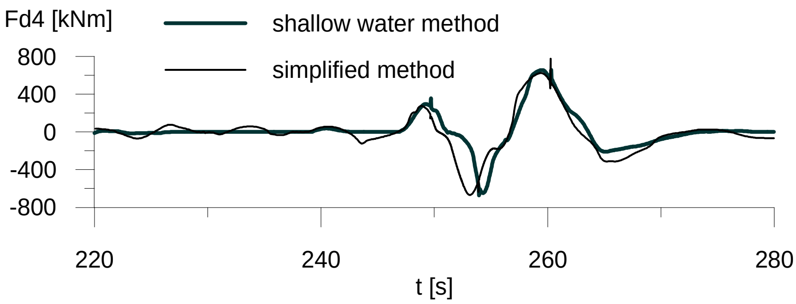

Figure 6. Time history of rolling moment F_{d4}

5. CONCLUSIONS

The study covered small vessel motion with water on deck (taking also into account the phenomenon of deck in water) in significant irregular waves. In such waves the vessel is positioned, according to good seamanship practice, in the head or following sea. The relatively rapid outflow of water from the deck due to the openings in the bulwark, means that the phenomenon of water flow on deck differs from that of sloshing in a tank as the water motion is not restricted to rebound between the bulwarks as in the tank between tank walls and the free surface of the water does not deform significantly as in the sloshing phenomenon. Maybe, this results from the observed fact that the simplified method (assuming the free surface of the water on deck to be horizontal plane) is used to model the water on deck.

However, the study shows that the velocity field in the water on deck, generated by water inflow and outflow on and off the vessel deck and the vessel motion in waves, influences the forces generated on the deck.

In the next step, studies will focus on the beam sea (wave form vessel side) for lower wave height and rolling moment.

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