INVESTIGATION INTO THE EFFECTS OF SHALLOW WATER ON DECK ON SHIP MOTIONS

Tiago A. Santos, Unit of Marine Technology and Engineering Instituto Superior Técnico
Technical University of Lisbon (Portugal)
Carlos Guedes Soares, Unit of Marine Technology and Engineering Instituto Superior Técnico
Technical University of Lisbon (Portugal)

Abstract

This paper presents a numerical study in the time domain of the behaviour of ships with water on deck or water inside an enclosed vehicle deck. The water on deck is modelled using shallow water theory, which allows for the calculation of the forces that act on the ship. The differential equations describing the ship motions are then solved in the time domain taking in consideration these forces. Numerical results of this theoretical approach, regarding the motions of a fishing vessel and a tanker with a compartment partially filled with shallow water are compared with experimental results available in the literature. The same theoretical approach is used to simulate the behaviour of a passenger Ro-Ro ship with constant amounts of water inside the main vehicle deck. The results are discussed and conclusions are drawn.

1 INTRODUCTION

The operation of ships in severe seas frequently causes the shipping of water in the deck because of large waves. If closed bulwarks bound the deck, the draining openings may not be sufficient to evacuate the water, which then starts accumulating. This problem becomes particularly serious in beam seas for ships with small freeboards, closed bulwarks and large exposed decks, such as fishing vessels and offshore supply vessels.

A similar problem occurs when a Ro-Ro ship is damaged both above and below the main vehicle deck. In this case, the freeboard is reduced and the ship might start taking water in the main deck due to the action of waves. The flooding takes place through the damage opening and it has been found that water tends to accumulate inside the deck, creating a large free surface, which in turn causes the ship to list. Again, this problem is more serious when the ship is subject to beam seas.

In both cases, there is potential for very violent motions of the water on deck, especially if the water depth is small and the frequency of oscillation of the ship is close to the natural frequency of the water on deck. In this case, certain phenomena appear such as hydraulic jumps, impacts on the side walls and non-static distributions of the water. These effects may cause significant nonlinearities in the forces and moments caused by the water on deck on the ship and high impact pressures on the side walls.

The problem of predicting the behaviour of water accumulating on the deck of a moving ship is obviously very complicated and a considerable number of studies is available in the literature. Vassalos and Turan [1], while studying the motions of damaged Ro-Ro ship, used a semi-empirical approach to this problem, which continues to be improved and fine tuned to experimental results by, for example, Vassalos *et al.* [2]. Recently, Woodburn *et al.* [3] and Spanos and Papanikolaou [4] have applied CFD codes to calculate the floodwater dynamics inside a Ro-Ro ship vehicle deck, therefore partly removing the empiricism from the analysis. However, these codes involve solving the Navier-Stokes equations, which is, computationally, very time consuming.

A number of authors have concentrated in the problem of water on deck in vessels with large open decks and low freeboards such as fishing vessels and offshore supply vessels. Spanos and Papanikolaou [5] applied the ‘lump mass’ concept to model the water dynamics in a small tank on a fishing vessel. Recently, Spanos and Papanikolaou [4] have applied the same approach to the case of a Ro-Ro ship with the main deck flooded. This method has the disadvantage of the ‘lump mass’ centre being forced to move along a known path with two degrees of freedom.

De Kat [6] concentrated on the study of a large tanker with water entrapped in a large central tank. This author considers the water in the tank to be part of the ship and treats the ship-water as a single dynamical system. However, this approach is not very successful in dealing with large amounts of water inside the tank.

Other authors, such as Dillingham [7], Adee and Caglayan [8], Pantazopoulos [9] and Laranjinha *et al.* [10] calculate the water on deck behaviour using shallow water theory. This approach is appropriate since in all cases mentioned above the water depth is small compared to the radius of curvature of the water surface. According to this theory, the water flow can be described by a system of non-linear hyperbolic equations, which can then be solved using a discretization of the deck in small elements. Therefore, this approach is closely related to the CFD methods mentioned above but offers the advantage of being computationally less demanding while still being capable of yielding reliable descriptions of the water elevation and velocities across the deck.

The non-linear hyperbolic equations describing the shallow water flow can be solved using the method of characteristics, presented by Stoker [11]. However, if there are hydraulic jumps, the ship motions are large or parts of the deck become dry, the method of random choice given by Glimm [12] and perfected by Chorin [13] may be used. Other authors, like Huang and Hsiung [14], have used other numerical methods to solve the shallow water equations. In the method of random choice, the deck is divided in small elements, in each of which the depth and velocity of the water are assumed constant. It is also assumed that the normal (to the deck) component of the water velocity is zero. Under these conditions, between each two cells, there exists a Riemann problem, or “dam-breaking” problem. This problem can be solved using the method of characteristics of Stoker [11].

This paper presents the theory of shallow water waves applied to the water on deck problem. This theory, coupled to the ship equations of motion, has been coded in a time domain computer program. The water is considered to be a separate dynamical system and to act on the ship as external force and external moments. This constitutes a major difference in relation to the works of Spanos and Papanikolaou [5] and De Kat [6].

The results of this approach are presented for a fishing vessel and a large tanker with water entrapped in a tank. Comparison is made with experimental and numerical results. Some examples of the water surface shape at specific times are shown. The same approach is applied to a different problem, namely that of a Ro-Ro ship with water entrapped in the main vehicle deck. Some preliminary results are given and discussed. Finally, the main conclusions of the study are stated.

2 THEORY OF SHIP MOTIONS AND WATER ON DECK FLOW

2.1 Equations of Ship Motion

The ship motions are expressed in the coordinate system shown in Figure 1.

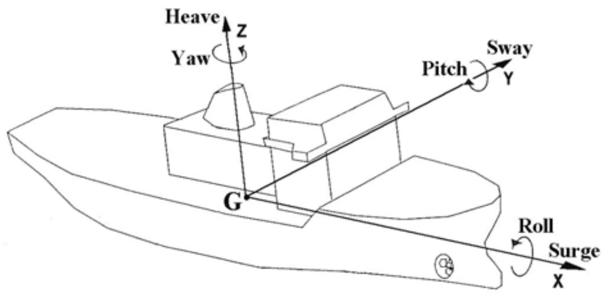

Figure 1 – Coordinate System for Ship Motions

The equations describing the ship motions are, essentially, similar to those presented by Santos *et al.* [15]:

$$\sum_{j=2}^{6}(M_{ij}+A_{ij})\ddot{X}_j(t)+B_{ij}\dot{X}_j(t)+F_j(t)=F_i^E(t)+F_i^{AC}(t) \quad (1)$$

for $i = 2,\ldots,6$. Where:

- M_{ij} represents the mass matrix,
- A_{ij} and B_{ij} represent the radiation coefficients,
- F_i represents the hydrostatic forces,
- F_i^E represents the wave excitation forces (diffraction forces plus Froude-Krylov forces),
- F_i^{AC} represents the accumulated water forces.

The hydrostatic forces are calculated over the instantaneous wetted surface taking into account the ship's motions. These forces are calculated using an hydrostatic pressure integration technique described by Santos and Guedes Soares [16].

The viscous roll damping is approximated by a linearized coefficient, which is estimated using the results of model experiments given by the authors in the literature.

2.2 Formulation of Water-on-Deck Problem

The motion of the water on deck is expressed in the coordinate system shown in Figure 2. The *x* axis is perpendicular to the ship section shown in that figure.

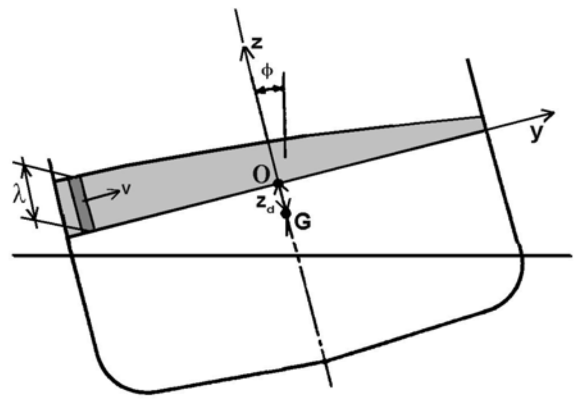

Figure 2 – Coordinate System for Water-on-Deck

The water motion is governed by a system of non-linear hyperbolic equations. These are derived from the continuity equation:

$$\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (2)$$

by integrating this equation over the depth while imposing the cinematic, dynamic and bottom boundary conditions.

The equations that describe the motion of the water in a stationary and level deck are:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial y} = -g\frac{\partial \eta}{\partial x}$$
$$\frac{\partial[v(\eta+h)]}{\partial y} = -\frac{\partial \eta}{\partial t} \tag{3}$$

Extending the same approach to a two dimensional deck, the following equations are obtained:

$$\begin{aligned}
&\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial \eta}{\partial x}\\
&\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial \eta}{\partial y}\\
&\frac{\partial[u(\eta+h)]}{\partial x} + \frac{\partial[v(\eta+h)]}{\partial y} = -\frac{\partial \eta}{\partial t}
\end{aligned} \tag{4}$$

where $\eta = \eta(x,y,t)$ represents the elevation of the water surface, h is the depth of the water and u and v are the velocity components in the x and y directions.

If the ship is moving, the water equations of motion may be represented by:

$$\begin{aligned}
&\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -a_z\frac{\partial \lambda}{\partial x} + f_1(x)\\
&\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -a_z\frac{\partial \lambda}{\partial y} + f_2(y)\\
&\frac{\partial \lambda}{\partial t} + u\frac{\partial \lambda}{\partial x} + v\frac{\partial \lambda}{\partial y} + \lambda\frac{\partial u}{\partial x} + \lambda\frac{\partial v}{\partial y} = 0
\end{aligned} \tag{5}$$

where $f_1(x)$, $f_2(y)$ and a_z represent the accelerations acting on the fluid in the x, y and z direction. Equations for these accelerations may be found in Pantazopoulos [9].

2.3 Numerical Solution by Random Choice Method

The water equations of motion (5) can be solved eficiently using the fractional step method proposed by Yanenko [17]. This method decomposes the three-dimensional problem in two bi-dimensional problems, one in the x direction, the other in the y direction. The relevant equations in each case are obtained by dropping the derivatives in the other direction. For example, in the x direction:

$$\begin{aligned}
&\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -a_z\frac{\partial \lambda}{\partial x} + f_1(x)\\
&\frac{\partial \lambda}{\partial t} + u\frac{\partial \lambda}{\partial x} + \lambda\frac{\partial u}{\partial x} = 0\\
&\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} = 0
\end{aligned} \tag{6}$$

This system of equations configures a one-dimensional problem. The solutions of each one-dimensional problem can be combined as described by Dillingham [7].

The first step in the numerical solution of equations (6) consists in removing the inhomogeneous terms on the right hand side. The equations can then be solved using the random choice method presented by Glimm [12]. The inhomogeneous terms can be included at a later stage using the following equations:

$$\frac{\partial u}{\partial t} = f_1(x) \tag{7}$$

$$\frac{\partial v}{\partial t} = f_2(y) \tag{8}$$

The deck is divided in rectangular elements measuring Δx by Δy. In each cell the depth is λ and the water velocity components in the x and y direction are u and v. Time is divided in small steps Δt. It is then assumed that the velocity components and depth in each cell are constant and known in time t as indicated by the following:

$$\begin{Bmatrix} u \\ v \\ \lambda \end{Bmatrix}_{i,j}^{n} \text{ in } \begin{cases} (i-1/2)\Delta x < x < (i+1/2)\Delta x \\ (i-1/2)\Delta y < y < (i+1/2)\Delta y \\ t = n\Delta t \end{cases} \tag{9}$$

The flow characteristics are sought in time $t+\Delta t$. It may be seen that, at each cell boundary, a discontinuity exists. For example, for a bi-dimensional problem, at *(i+1/2)Δx*:

$$\begin{Bmatrix} u \\ \lambda \end{Bmatrix}_{i+1}^{n} \text{ se } x > (i+1/2)\Delta x \qquad (10)$$

$$\begin{Bmatrix} u \\ \lambda \end{Bmatrix}_{i}^{n} \text{ se } x < (i+1/2)\Delta x \qquad (11)$$

Equations (10), (11) and (6) represent the well-known Riemann problem, also known as the "dam-breaking" problem. This problem may be solved analytically, over each two cells, as shown by Stoker [11] and Toro [18]. In this solution care has to be taken to ensure that the Courant-Friedrichs-Levy condition is satisfied:

$$\frac{\Delta x}{2\Delta \tau} > \left(|u| + C\right) \qquad (12)$$

The random choice method consists in approximating the analytical solution of the Riemann problem centred in i+1/2 given by:

$$f_u\left[x,(n+1/2)\Delta\tau\right], f_\lambda\left[x,(n+1/2)\Delta\tau\right] \qquad (13)$$

through piecewise constant functions:

$$\begin{aligned} (u)_{i+1/2}^{n+1/2} &= f_u\left[(i+1/2+r_n)\Delta x,(n+1/2)\Delta\tau\right] \\ (\lambda)_{i+1/2}^{n+1/2} &= f_\lambda\left[(i+1/2+r_n)\Delta x,(n+1/2)\Delta\tau\right] \end{aligned} \qquad (14)$$

where r_n is a random number with a uniform distribution in the interval [0,+1/2]. This advances the solution to time *(n+1/2)Δτ*. To advance the solution to *(n+1)Δτ* a similar procedure is applied but this time with the random number r_n picked from a uniform distribution between [-1/2,0]. In this way, the field of water heights, *λ*, and the fluid velocities, *u* and *v*, can be calculated over the ship's deck. These properties can then be used to calculate the forces and moments caused by the water on the deck and bulwarks.

2.4 Forces Caused by the Water-on-Deck

The forces and moments acting in the ship as a result of the water-on-deck are given by:

$$F^{AC} = -\iint_S pn\,ds \qquad (15)$$

$$M^{AC} = -\iint_S p\vec{r} \times \vec{n}\,ds \qquad (16)$$

where:

$$p(x,y,z) = \rho a_z(x,y)z \qquad (17)$$

3 RESULTS

3.1 Effects of Water on Deck on a Fishing Vessel

The equations of motion of the ship and water on deck presented in the previous section have been coded in a computer program. This section presents the results concerning ship motions in the time domain obtained with that program.

The first ship selected for this study is a small fishing vessel, which behaviour was previously studied numerically and experimentally by Amagai *et al.* [19]. The main particulars of the fishing vessel are shown in Table 1.

Table 1 – Main particulars of fishing vessel

Displacement, *Δ* (t)	59.80
Length between perpendiculars, L_{pp} (m)	15.20
Beam, *B* (m)	3.80
Draught, *T* (m)	1.33
Trim, *d* (m)	1.01
Depth to main deck, D_{md} (m)	1.56
Metacentric height, *GM* (m)	0.44
Roll natural period, T_s (s)	4.14

Figure 3 shows the lines plan of the fishing vessel.

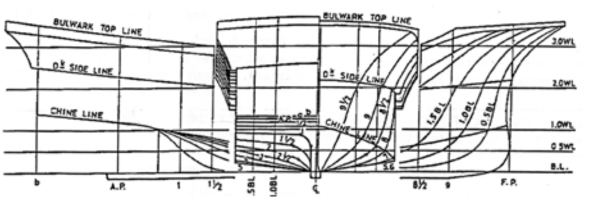

Figure 3 – Body plan of the fishing vessel (extracted from ref. [5])

The ship is fitted with a small tank in the deck. The tank is used to contain water, which depth will be varied. The tank has 2.28m in length and 3.80m in breadth. Figure 4 shows the location of the tank.

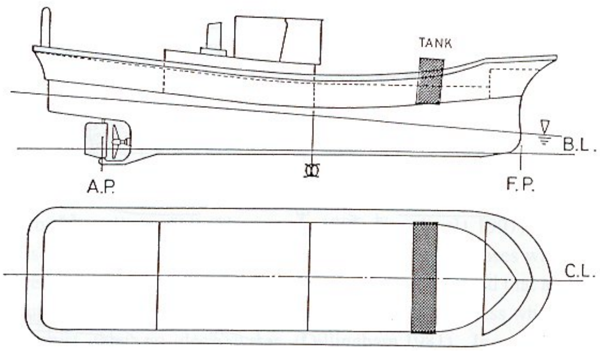

Figure 4 – General arrangement of the fishing vessel model (extracted from ref. [19])

Figures 5 to 9 show the roll behaviour of the fishing vessel with various different depths of water in the tank. The roll amplitude is shown in each figure for various different adimensional wavelengths. The roll motion is also adimensionalized by the wave steepness. The figures show both numerical and experimental results. The numerical results are obtained in the time domain using the computer program. The experimental results were given by Amagai *et al.* [19].

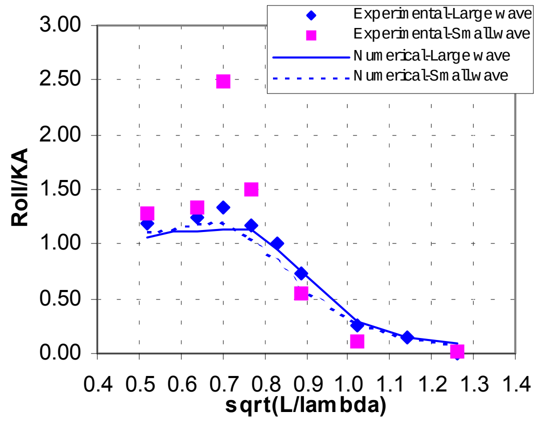

Figure 5 – Roll amplitude without water in tank

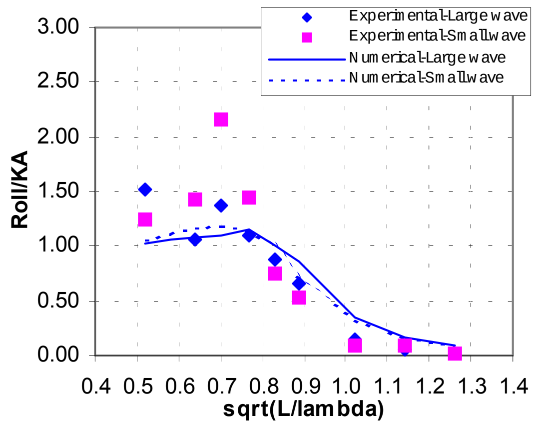

Figure 6 – Roll amplitude with 0.076m water depth

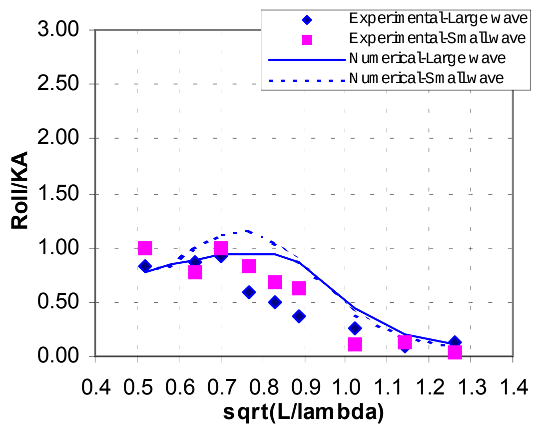

Figure 7 – Roll amplitude with 0.152m water depth

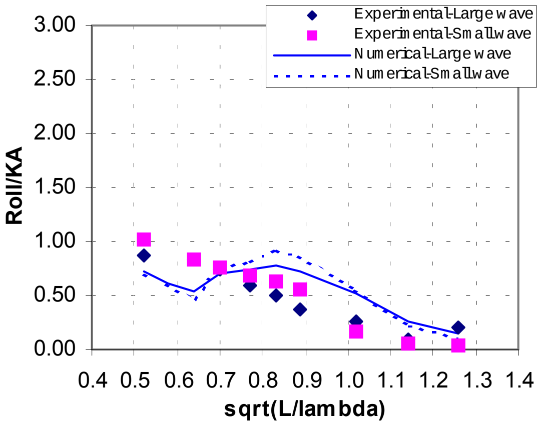

Figure 8 – Roll amplitude with 0.228 water depth

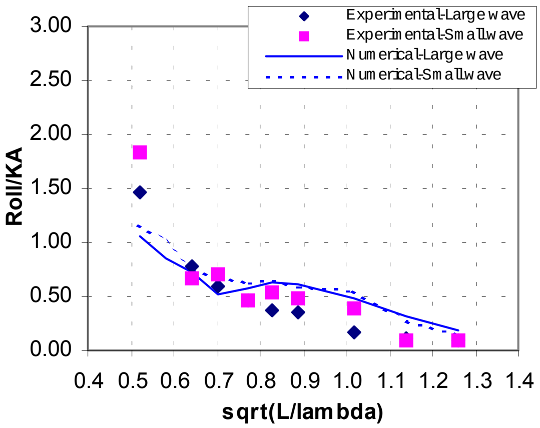

Figure 9 – Roll amplitude with 0.304m water depth

Table 2 shows the mass of water and the natural frequency of the water for each water depth. It may be seen that as the water depth increases the adimensional water natural frequency also increases. For the largest water depth, this adimensional frequency is very near the fishing vessel roll natural frequency. This explains the very significant decrease in roll motion experienced by the fishing vessel for most wave frequencies.

Table 2 – Characteristics of the water in the tank

Water depth (m)	Water mass (t)	Water mass (%Δ)	Water natural frequency (adim)
0.000	0.00	0.00	0.00
0.076	0.68	1.13	0.38
0.152	1.35	2.26	0.53
0.202	1.79	3.00	0.61
0.304	2.70	4.52	0.75

Figure 10 shows an example of the water distribution throughout the tank at a given instant of time. The tank is partially dry and an accumulation of water may be seen on the right part of the figure. The depth of water in the tank at rest, for this particular case, is 0.08m.

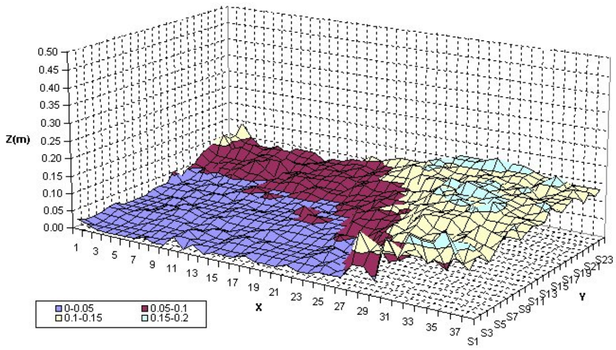

Figure 10 – Water Surface inside the tank

3.2 Effects of Water on Deck on a Tanker

The second ship selected for this study is a large tanker, which behaviour was previously studied numerically and experimentally by De Kat [6]. The main particulars of the tanker are shown in Table 3.

Table 3 – Main particulars of tanker

Displacement, Δ (t)	202600.00
Length between perpendiculars, L_{pp} (m)	310.20
Beam, B (m)	47.20
Draught, T (m)	16.00
Trim, d (m)	0.00
Depth to main deck, D_{md} (m)	26.07
Metacentric height, GM (m)	9.50
Roll natural period, T_s (s)	10.00

Figure 11 shows the body plan of this large tanker. The ship is fitted with a rectangular tank measuring 82.0m in length by 31.76m in breadth. The base of this tank is located 5.2m above the baseline. The tank, as shown in Figure 12, is located amidships in the centreline and was filled with different depths of water during the model tests carried out by De Kat [6].

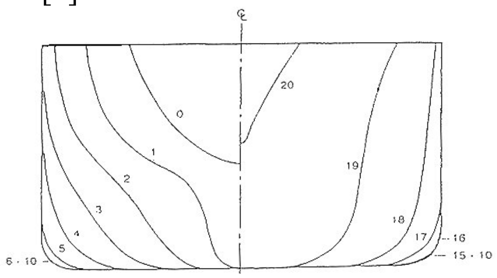

Figure 11 – Body plan of the tanker (extracted from ref. [6])

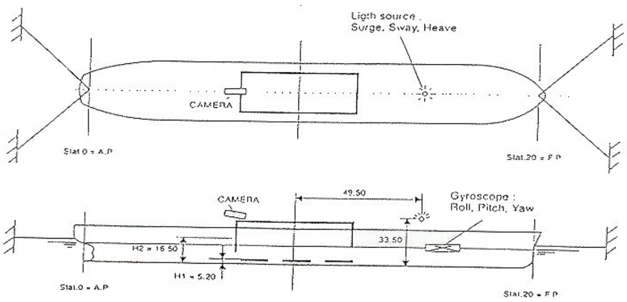

Figure 12 – General arrangement of the tanker model (extracted from ref. [6])

Figures 13 and 16 show the motion response of the tanker with a dry tank. A good correlation between all sets of results may be observed. Figures 14 and 17 show the results for the ship with 1m water depth in the tank. The correlation between present numerical results and the experimental results is very good except in the peaks of the heave and roll response where some minor differences appear. The amplitudes of both motions are not significantly affected by the presence of water.

Figures 15 and 18 show numerical results for 2m water depth. The amplitudes of the motions remain unaffected by the presence of water except for the roll, which is slightly larger at the peak.

Figures 19 and 23 show the ship motions with 3m water depth. It may be seen that the roll motion has substantially decreased in the peak region. The heave motion remains unaffected.

Figures 20 and 24 show the results for the heave and roll motions with a water depth of 4m. It may be seen that the heave motion is not very affected by the water. The correlation of present numerical results for heave with the experimental results is very good except for the lower frequencies. Concerning the roll motion, it may be seen that the roll motion has decreased substantially because of the water on deck. The peak of the response has practically disappeared. The correlation between the experimental results and the current numerical results is significantly better than the correlation with the numerical results by De Kat [6].

Figures 21 and 25 show numerical results for 5m water depth. It may be seen that the roll motion is still severely damped but the response peak tends to re-appear in the lower frequency range. The heave motion is not very affected.

Figures 22 and 26 show the numerical results for 6m water depth. This water depth, taking in consideration the tank breadth, is at the limit of the range of applicability of the shallow water theory. The results are still sound, showing the re-appearance of the roll peak. The heave motion remains unaffected.

The most severe roll reduction shown in Figure 24 can be explained taking in consideration Table 4, which shows the natural frequencies of the water in the tank. It may be observed that the natural frequency of the water in the tank for 4m depth is 0.62rad/s, matching approximately with the ship's roll natural frequency.

Table 4 – Characteristics of the water in the tank

Water depth (m)	Water natural frequency (rad/s)	Water mass (t)	Water mass (%Δ)
1.00	0.31	2669	1.32
2.00	0.44	5338	2.64
3.00	0.54	8008	3.95
4.00	0.62	10677	5.27
5.00	0.69	13347	6.59
6.00	0.76	16016	7.91

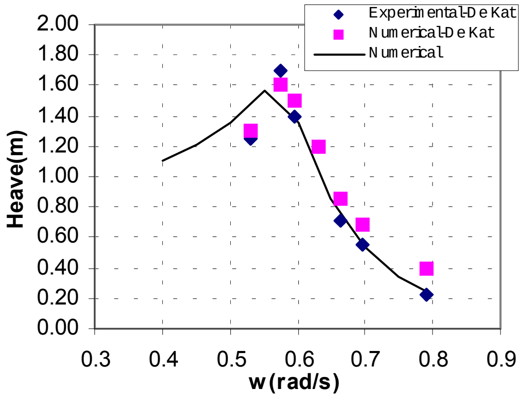

Figure 13 – Heave amplitude with no water on deck

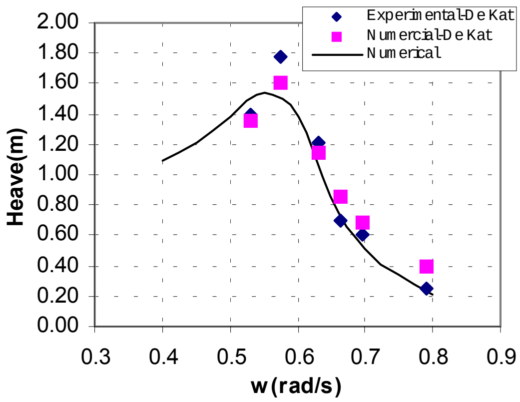

Figure 14 – Heave amplitude with 1m water depth

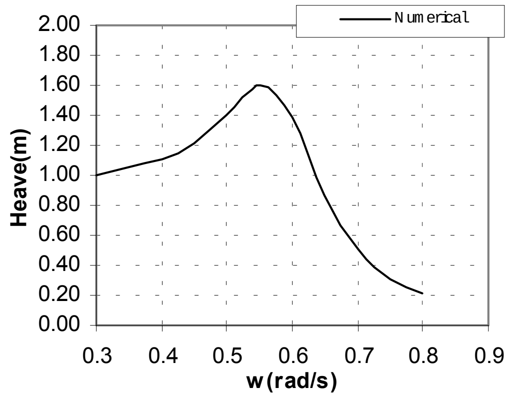

Figure 15 – Heave amplitude with 2m water depth

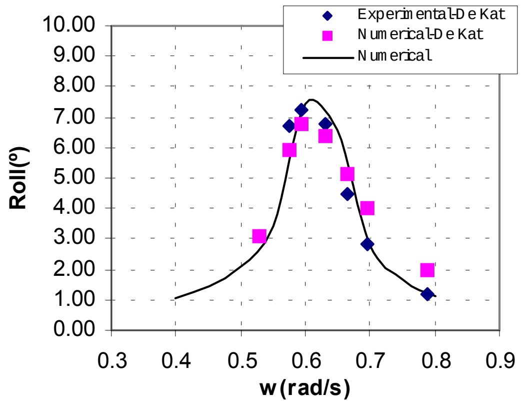

Figure 16 – Roll amplitude with no water on deck

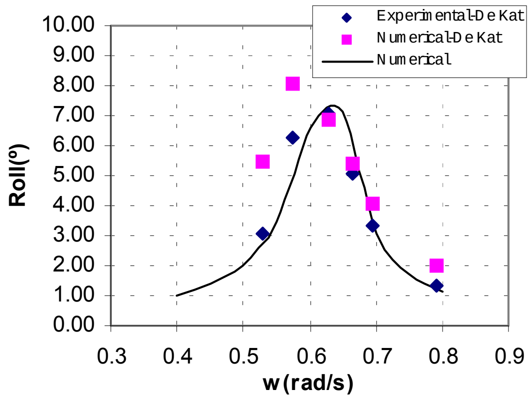

Figure 17 – Roll amplitude with 1m water depth

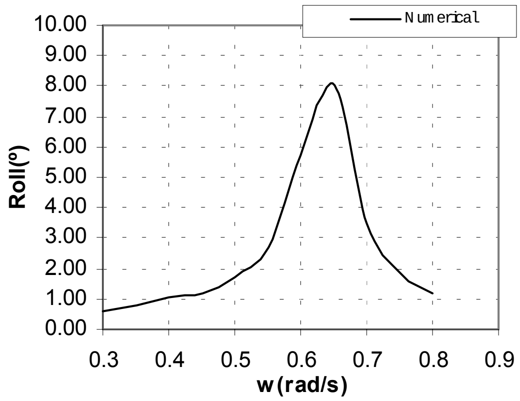

Figure 18 – Roll amplitude with 2m water depth

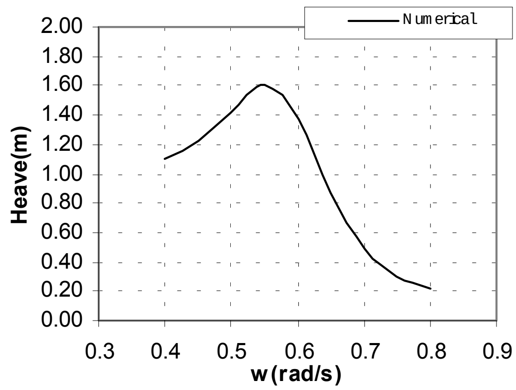

Figure 19 – Heave amplitude with 3m water depth

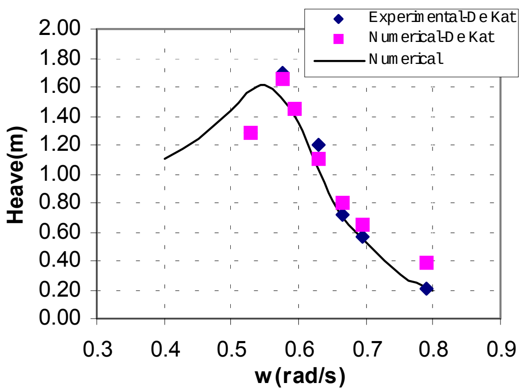

Figure 20 – Heave amplitude with 4m water depth

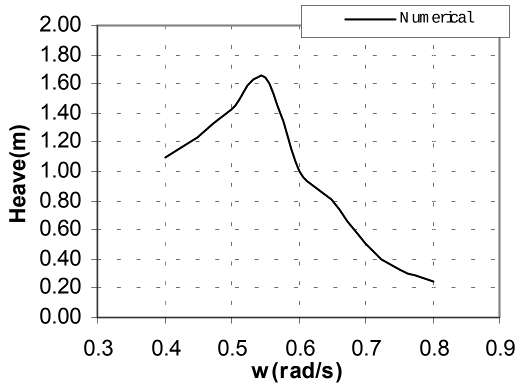

Figure 21 – Heave amplitude with 5m water depth

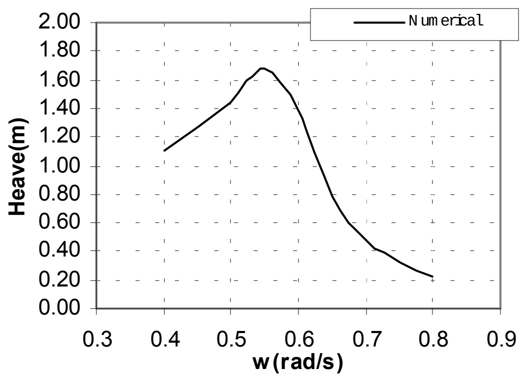

Figure 22 – Heave amplitude with 6m water depth

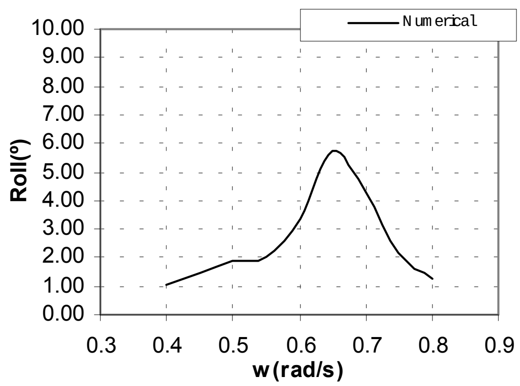

Figure 23 – Roll amplitude with 3m water depth

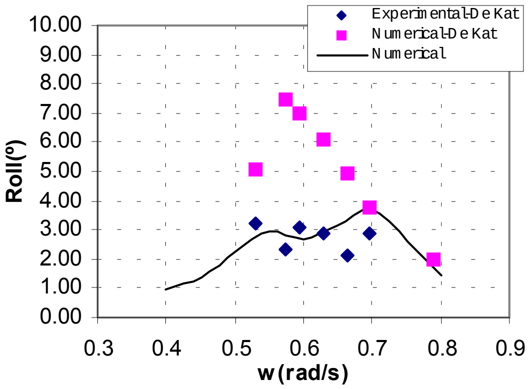

Figure 24 – Roll amplitude with 4m water depth

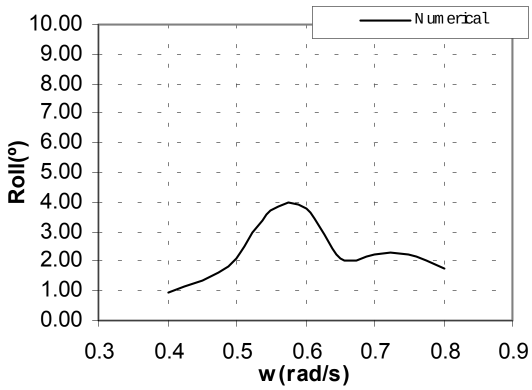

Figure 25 – Roll amplitude with 5m water depth

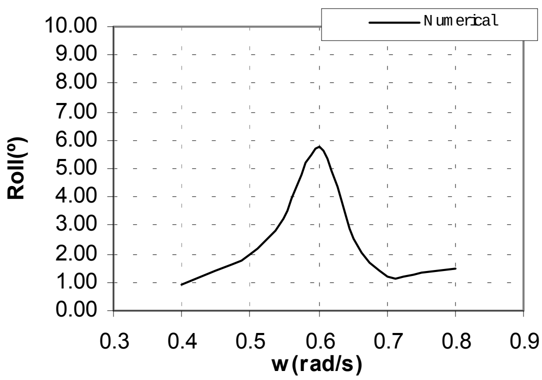

Figure 26 – Roll amplitude with 6m water depth

Figure 27 shows the roll decay curve when the ship has no water on deck.

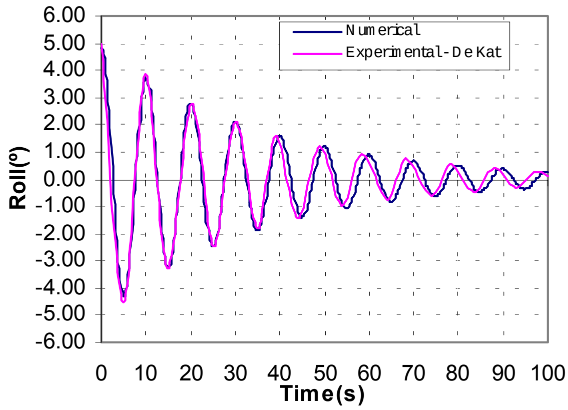

Figure 27 – Roll decay with no water on deck

Figure 28 shows the roll decay curve with 1m water depth in the tank.

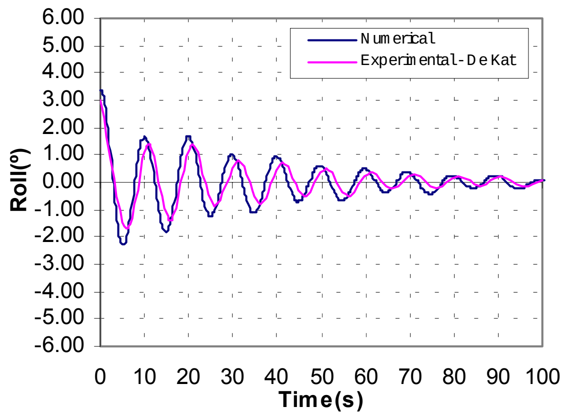

Figure 28 – Roll decay with 1m water depth

Figure 29 shows the roll decay curve with 4m water depth in the tank.

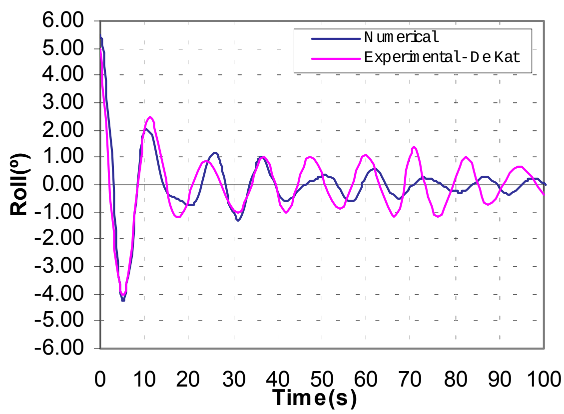

Figure 29 – Roll decay with 4m water depth

3.3 Effects of Water on Deck on a Ro-Ro Ship

This section presents some preliminary numerical results for the motions in the time domain of a Ro-Ro ship with water in the main vehicle deck.

Table 5 – Main particulars of Ro-Ro ship

Displacement, Δ (t)	15020.00
Length between perpendiculars, L_{pp} (m)	170.00
Beam, B (m)	25.00
Draught, T (m)	6.60
Trim, d (m)	0.00
Depth to main vehicle deck, D_{md} (m)	9.50
Depth to weather deck, D_{wd} (m)	19.30
Metacentric height, GM (m)	1.41
Roll natural period, T_s (s)	18.50

For this study, the ship considered by Fujiwara and Haraguchi [20] has been selected. Table 5 shows the main particulars of that Ro-Ro ship. Figure 30 shows the body plan of the Ro-Ro ship.

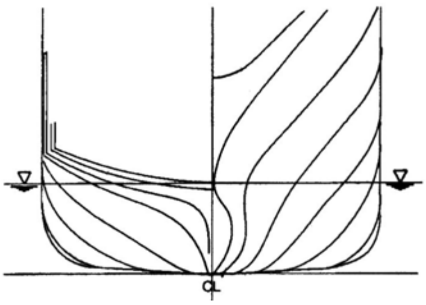

Figure 30 – Body plan of the Ro-Ro ship (extracted from ref. [20])

The results below will consider the effects on this ship's motions of a two-compartment damage below the main deck and of two different and constant amounts of water inside the main deck. The damage opening below the main deck, shown in Figure 31, is rectangular and has a length of 8.55m. No damage opening exists above the main vehicle deck.

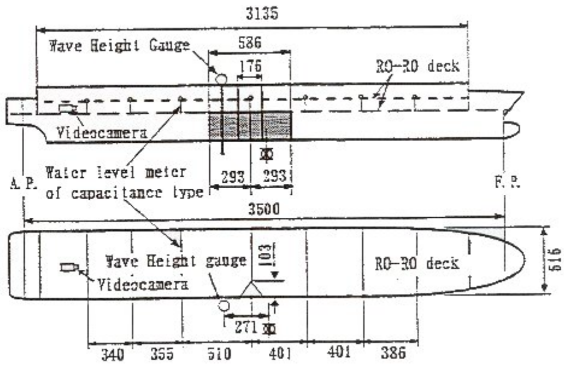

Figure 31 – General arrangement of the Ro-Ro ship model (extracted from ref. [20])

Figures 32 and 33 show the roll decay curves of the ship in intact and damaged condition. It is worth pointing out that in Figure 33 the flooding is actually taking place while the ship is rolling, but the last nine cycles occur when the ship's compartment is already completely flooded. This allows the observation that the rolling period for the intact ship is 18.5s and for the damaged ship is 16s. This fact is linked with the increase in the GM from 1.41m to 1.81m. Figure 33 also shows the sharp increase in the ship's draught.

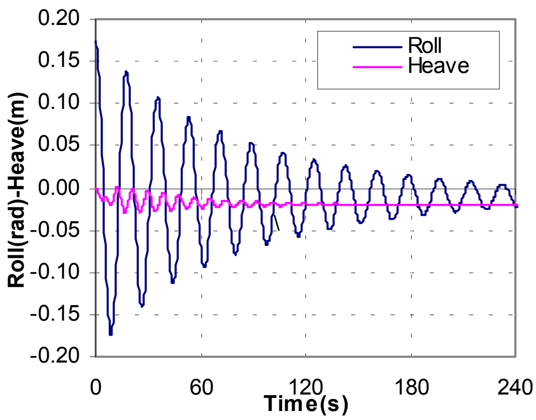

Figure 32 – Decay curve for the intact ship (without water below or above the main vehicle deck)

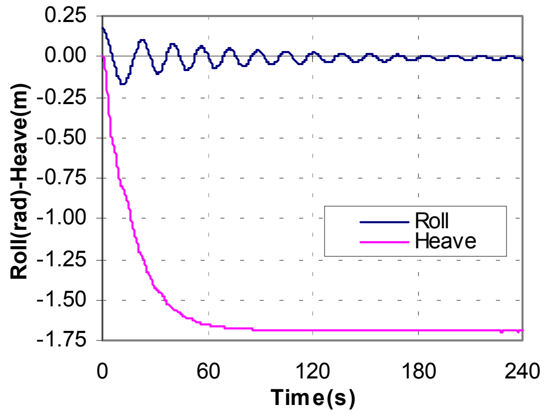

Figure 33 – Decay curve for the damaged ship (without water on the main vehicle deck)

Figures 34 and 35 show roll decay curves for the ship damaged below the main deck and with fixed quantities of water inside the main vehicle deck. These quantities of water amount to 5% and 8%, respectively, of the intact ship displacement. It may be seen that with either of these two quantities of water inside the main deck the ship is unstable in the upright position and, therefore, assumes a steady heel angle. It may also be seen that the roll response in Figure 35 exhibits non-linear characteristics. Figure 34 and, partially, Figure 35 show that the roll motion never stops completely. This is caused by the method used to model the motion of the water on deck, which does not consider any form of viscosity.

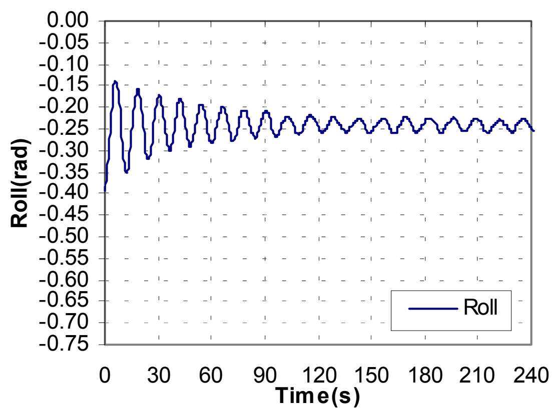

Figure 34 – Decay curve for the damaged ship with 5% water on deck

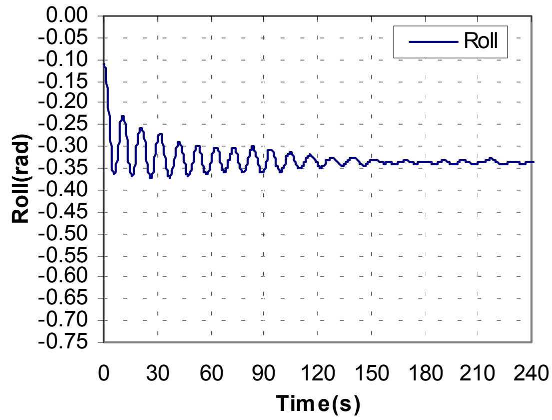

Figure 35 – Decay curve for the damaged ship with 8% water on deck

Figure 36 shows an example of a time domain simulation of the Ro-Ro ship roll motion in regular beam waves with 1m amplitude. It may be seen that the ship rolls around a steady heel angle because of the water in the main vehicle deck.

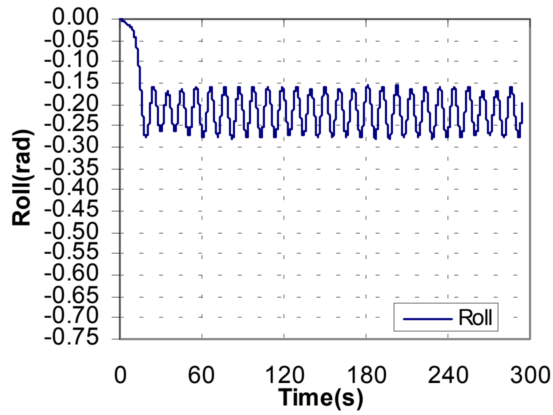

Figure 36 – Time domain simulation of roll motion in regular waves with 5% water on deck

Figure 37 shows an example of a time domain simulation of the Ro-Ro ship roll motion in irregular beam waves described by a Jonswap spectrum with 2m significant wave height. The Ro-Ro ship contains water in the main vehicle deck (5% of its intact displacement), which may be seen to cause a steady heel angle. Therefore, the ship roll motion consists in rolling about this angle under the action of the irregular beam waves. The motion of the water in the main vehicle deck is being calculated using the shallow water approach.

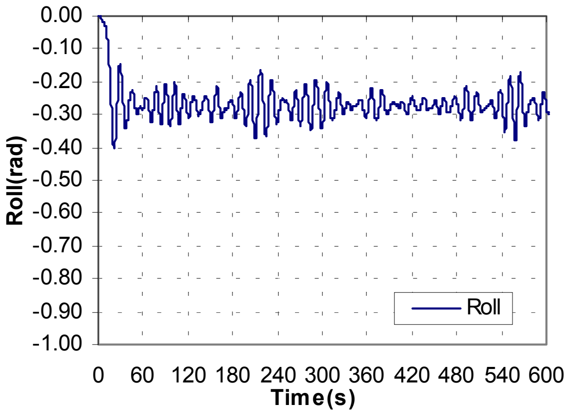

Figure 37 – Time domain simulation of roll motion in irregular waves with 5% water on deck

Figure 38 shows an instantaneous image of the water (5% of the ship's intact displacement) inside the vehicle deck when the ship is heeled to 15.5º. It may be seen that the water is accumulated in the aft part on the starboard side of the main vehicle deck and that most of the deck is dry.

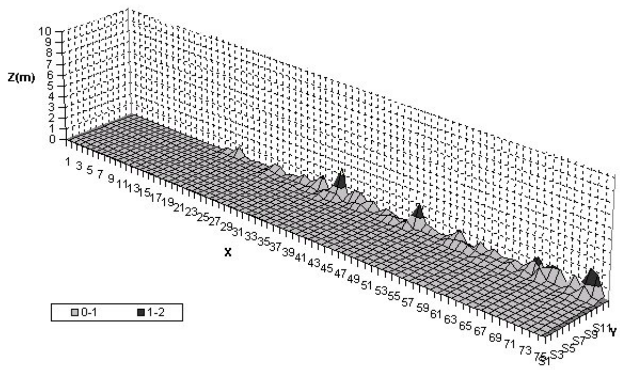

Figure 38 – Instantaneous free-surface inside the main vehicle deck

4 CONCLUSIONS

This paper has briefly described several approaches to calculate the effects on ship motions of the presence of water on deck. Shallow water theory has been described, in some detail, and applied to the study of the effect of water on deck on fishing vessel, tanker and Ro-Ro ship motions.

It was found that the numerical results obtained with the present approach to model the effect of the water on deck are satisfactory for all water depths considered in the studies. The results for the fishing vessel and tanker compared favourably with other numerical and experimental results, allowing the conclusion that the roll response shows a significant decrease when the natural frequency of the water in the tank approximately matches the roll natural frequency of the ship.

In the specific case of the Ro-Ro ship, the shallow water theory allowed the simulation of the free-surface effect inside a large vehicle deck, which causes the steady heeling of the ship and the accumulation of water on one side of the deck. Preliminary results were also shown for the Ro-Ro ship roll motion in regular and irregular waves, showing the applicability of the adopted approach when the flooded space is much larger than that of the ships previously considered. The computational method was able to effectively deal with the much-increased number of elements required to model the ship's deck.

The shallow water theory and random choice method proved to constitute a practical method to analyse the effects of water on deck. This approach has the advantage of not involving the specification of the path of the water centre of mass or involving complicated changes to the inertia of the ship because of the added water. Another major advantage of this approach is the fact that the computational time is not very large, allowing a significant number of runs to be carried out using a personal computer. This is in sharp contrast with the large computational effort involved in solving the Navier-Stokes equations, while still avoiding the inconveniences of the simplified or empirical methods for treating the water on deck.

5 ACKNOWLEDGEMENTS

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