NUMERICAL PREDICTION OF THE DYNAMIC BEHAVIOR OF A RO-RO SHIP AFTER A HULL SIDE DAMAGE

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Abstract

Nowadays, one of the most important issues in ship stability is roll-on/roll-off ship stability after hull damage. After the dreadful sinking of "*Estonia*", regulations for this type of vessels have been modified to take into account the dynamic effects in the car deck caused by the sudden entrance of water.

In the first part of this paper, the new IMO regulations will be presented, highlighting the regulations concerning model tests. The methodology used for model testing, which will show the dynamic effects made by the entrance of water in the car deck, will be presented afterwards. We will also show the importance of correct evacuation of air and the effects of sloshing and breaking waves inside tanks.

Finally, we will propose the use of a CFD code which we consider suitable for capturing this type of phenomena. It is a particle method, which is advantageous in that it obviates the need for a computational grid and can cope in a natural way with the complex discontinuities of the free surfaces which arise in sloshing and breaking wave phenomena. Furthermore, it can deal with the interactions between two fluids with different densities (air-water), and between fluids and structures. We also will present some experiments which demonstrate the good characteristics of this method.

1. INTRODUCTION

Ferries and roll-on/roll-off vessels are very popular around the world, generating large profits. However, their continuous ro-ro deck design means that they are always at risk of flooding and a consequent loss of stability following hull damage.
After a collision where the hull sustains damage, the ingress of water will create a heeling moment that will produce a roll response. If the heel is enough to enable water to pass onto the ro-ro deck, the heeling moment can overcome the restoring one and the balance damping can cause the ship to capsize. As a result of this the IMO decided to change the stability regulations for roll-on/roll-off and ferry vessels.

Nevertheless, some roll-on/roll-off and ferry vessels which met the new design rules were damaged in the latter years of the last century. *"The Herald of Free Enterprise", "Estonia"* and the *"Doña Paz"* are examples of passenger ferry disasters which occurred in recent decades. In particular the *"Doña Paz"* tragedy led to the loss of around 4376 lives. As a result of the *"Estonia"* ferry tragedy rigorous rules referred to as the Stockholm Agreement have been applied along the Western European Coast between the North-West of Spain to the North of Norway.

A standard procedure regulated by the IMO (pages 36-37 annex SOLAS/CONF.3/46 [1]) allows hull stability to be tested for compliance with the Stockholm Agreement. This procedure is based on model tests in a hydrodynamics basin.

These tests have shown the importance of the correct evacuation of air and the effects of sloshing and breaking waves inside tanks. In order to reproduce these types of discontinuous effects using a CFD code it is advisable to use a computational method which avoids the use of grids. SPH particle methods, which are described in this paper, provide a solution which can adeptly handle these kinds of complex phenomena.

2. STABILITY REGULATIONS

The concept of "analysis of stability in a damaged condition" was introduced in the SOLAS Convention of 1948, because the application of "flooded lengths" in longitudinal subdivision was considered insufficient.

The 1960 and 1974 SOLAS Conventions [2,3] introduced important amendments to the regulation with respect to subdivision and damage stability for passenger ships (in part B of chapter II of the 1960 version [2] and chapter II-1 of the 1974 version [3]). In both, the watertight subdivision is required to be arranged in such a way that the ship should remain afloat and stable in the event of certain damage occurring. This laid down a stability standard which could be complied with and is known as the deterministic method. However, the stability curves obtained by applying the standards of 1960 SOLAS were far from practical given that even slight sea roughness could cause the ship to capsize.

The concept of "probability" began to be used after the sinking of the passenger ship "*Andrea Doria"* in 1956. The IMO Assembly adopted the resolution A.265(VIII) in 1973 [4], entitled "Regulations on Subdivision and Stability of Passenger Ships", equivalent to part B of chapter II of SOLAS 60 [3] and referred to these requirements as an alternative to those contained in part B, in the 1974 SOLAS Convention[3]. This is known as the probabilistic method.

With the sinking of the roll-on/roll-off passenger ferry *"Herald of Free Enterprise*" in March 1987 where 193 lives were lost, two packages of amendments to SOLAS Convention were adopted in 1988 to improve the security of passenger ships. One of the most important amendments in the second package (October 1988) concerned regulation 8 of chapter II-1 which referred to stability standards for damaged passenger ships. This became known as the "SOLAS 90" standard [5]. These requirements should have provided adequate protection against capsize as they implicitly take into account the effects of the entry of water into a ro-ro deck in seas where the wave height is significant (up to 1.5 m). This amendment applied to ships built after 29 April 1990.

The April 1992 amendments to SOLAS, which came into force in October 1994, introduced measurements to make the "SOLAS 90" standards [5] with slight modifications, mandatory on existing ships, under a phase-in programme. The date by which each vessel had to comply depended upon the A/Amax ratio value determined in accordance with a calculation procedure developed by the MSC [6] to assess the survivability characteristics of existing roll-on/roll-off passenger ships. This procedure is a simplified version of the probabilistic method developed in the aforementioned resolution A.265(VIII) [4].

When the "*Estonia*" disaster occurred in September 1994 the Secretary General of IMO proposed that a complete review of the safety of roll-on/roll-off and ferries should be carried out by a specially selected Panel of Experts.

In November 1995 a special Conference was held which had on its agenda a number of important resolutions and changes to SOLAS. The most important amendments concerned the requirements for the watertight integrity and stability of roll-on/roll-off passenger ships.

Two new regulations were adopted: chapter II-1, 8-1 and 8-2. The first meant that existing roll-on/roll-off passenger ships would have to fully comply with 'SOLAS 90" [5] in accordance with an agreed phase-in programme depending on the A/Amax ratio. The second regulation contained special requirements for roll-on/roll-off passenger ships carrying 400 passengers whereby they should survive with two compartments flooded following damage.
These regulations applied to all new ships built while existing ships built using a one-compartment subdivision standard were expected to be phased out.

On the other hand the Panel of Experts, influenced by the results obtained from the research work (Joint R&D Nordic Project) carried out by a group of companies, institutions and administrations of the Nordic countries, concluded that the requirements of 'SOLAS 90" [5] should be improved to explicitly include the effect of water accumulating on the ro-ro deck so as to enable the ship to survive in more rough sea conditions. The Conference adopted resolution 14 [1] that permits regional agreements on specific stability requirements which do not exceed those contained in the Annex to the resolution. These requirements include provisions that are designed to ensure that the 'SOLAS 90" [5] stability standard can be achieved even with up to 50 cm of water on the vehicle deck.

However, the Administration will be able to exempt from the application of these requirements and accept model tests according with a method specified in the Appendix of the Resolution 14 [1]. The testing procedure will be exposed in this paper.

Recently, in April 2002, the Subcommittee of Stability of the IMO proposed [7] a review of the model test method to take into account the application of new technologies and the lessons learned from previous incidents.
The Governments which had initially proposed the 'SOLAS 90" + 50 cm standard duly concluded an agreement (the Stockholm Agreement) which entered into force on 1 April 1997. Existing ferries operating between ports in the signatory countries had to be upgraded between then and 1 October 2002.

Currently a European Community Directive proposal [8] regarding the specific stability requirements for roll-on/roll-off passenger ships sailing in the south of Europe. These requirements are in accordance with the Stockholm Agreement. The proposal's objective is to obtain uniformity of stability requirements across the European Community.

3. SURVIVABILITY MODEL TESTS

As previously explained, one of the methods to determine if a vessel complies with stability regulations is by means of survivability model tests. The IMO Panel of Experts, named for the

SOLAS Conference in London November 1995, proposed a model test method in order to test compliance with the water on deck stability requirements. The approved methods are described in the appendix of the IMO Circular letter nº 1891, SOLAS/CONF.3/46/NOV95 [9] with the objective being to explain how the survivability tests must be carried out in order to prove the ability to withstand the effects of a seaway in the worst damage case scenario.

The scaled model should be a copy of the ship. Model scales are shown in Table 1. The main differences to the standard basin model are the necessary internal damaged space arrangements. Bulkheads, tanks and air ventilation tubes should be modeled properly as far as practicable. The model must also comply with other construction characteristics including a minimum length of 3 meters with a damage opening matching the SOLAS shape (regulations II-1/8.4.1 & 2) in the worst case scenario where two compartments are damaged. Additional tests are required if the damage location is outside the range ±10% Lpp from the midship.

Table 1. Model Scales.

Lpp. B, T (m)	λ
Hs (m)	λ
Roll, pitch, yaw (º)	1
Time (s)	$\lambda^{0,5}$
Speed (m/s)	$\lambda^{0,5}$
Surge, sway, heave (m)	λ
Displacement (m^3)	λ^3

The model must be completely free to drift in beam seas with the damage facing the oncoming waves. Five tests of at least 30 minutes, for each peak period should be carried out in a seaway defined by the JONSWAP spectrum with significant wave height (Hs) peak enhancement factor (γ) and peak period (Tp). The values used for the spectrum have to be $Tp = 4\sqrt{Hs}$ with γ=3.3, Tp can be set equal to the roll resonant period for damaged ship without water on deck but cannot exceed $6\sqrt{Hs}$ when γ=1.

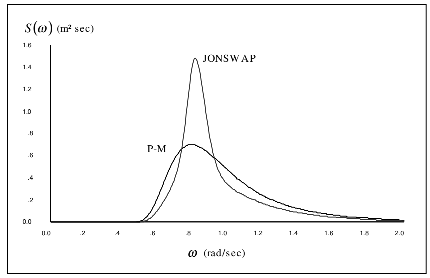


Figure 1. Bretschneider & JONSWAP γ = 3,3 spectra.

Additional tests should be repeated with additional heel if none of the tests result in final inclination towards the damage.

The survival criteria is based on the roll responses, and a ship is considered to have survived if angles of more than 30º occur on less than 20% of the cycles or if the steady heel is smaller than 20º.

The necessary instrumentation to carry out the survivability tests is as follows:

- Wave and water sensors to measure the water along the garage deck and the instantaneous freeboard.
- Optical tracking system with external cameras and light emitting diodes on the model superstructure to obtain the 6 DOF.
- Internal and external video cameras.
- Data acquisition system.

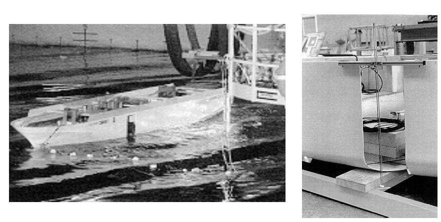
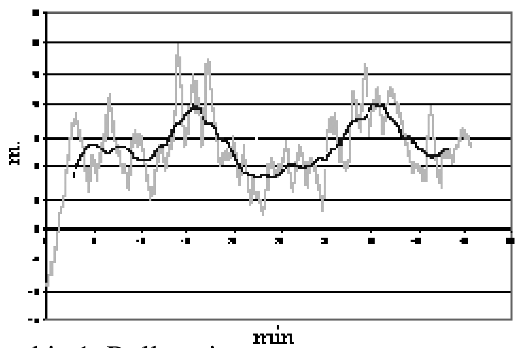
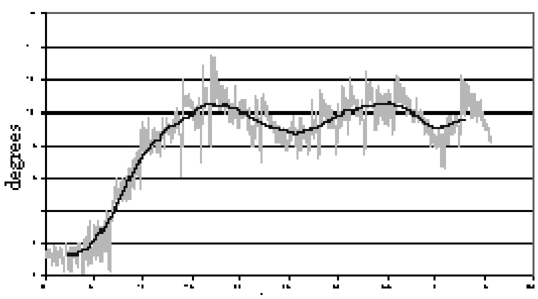


Figure 2. Model tests.

The following graphics represent the main temporary series; roll-time, water on deck-time, obtained during a survivability test.



Graphic 1. Roll vs time.



Graphic 2. Water on deck vs time.

The national Administration must approve the test program in advance and the classification society must check the model and tests.

Relevant information produced by the tests and model must be documented by means of a report and videos, which should be submitted to the IMO and the Administration.
In order to reproduce a survivability test, not only has the water ingress to be taken into account but also the air outlet must be considered. The thickness of the air outlets became relevant during the tests. If the air could not flow outside the model the water would not enter properly into the ro-ro deck. Scale effects in the air outlets have to be studied more carefully. Scale effects are very important in this kind of test and this, together with the necessity to reproduce the compartment distributions of the real vessel, is the reason why greater scales are preferable for testing.

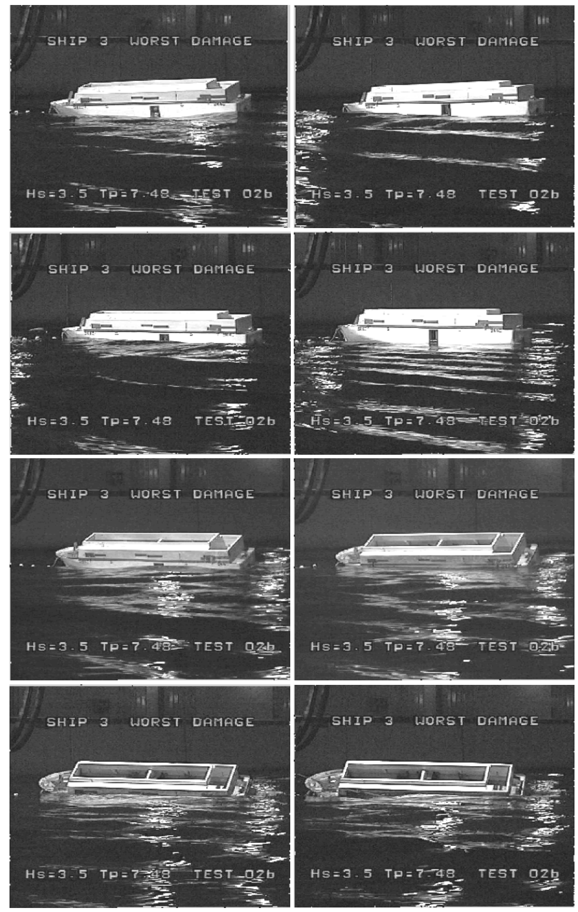


Figure 3. Survivability test sequence.

The sloshing effects are very important inside the ro-ro deck as it can be shown in the following figures.

Figure 4. Sloshing inside ro-ro deck.

4. MODEL TESTS CONCLUSIONS

Model tests are, of course, a very good way in which to ensure compliance with stability regulations, especially in existing roll on/roll off ships, but they have the following disadvantages:

¬ Models are very expensive because they have to be big enough to properly reproduce the internal arrangement of the ship.

¬ A model basin with wave generation is needed.

¬ Internal arrangement modifications are hard and time consuming because all the parts above the modification have to be dismounted and mounted again. Internal spaces have to be mounted very carefully because many of them have to be watertight.

Due to the lattermost disadvantage and the strong chaotic behaviour of the water inside the ship entailing air bubbles, sloshing, splashes and breaking waves, we firstly decided to choose and then to develop a computer code to predict the movement of the water inside the ro-ro deck of a model during survivability tests. Of all CFD codes available today, the first and most attractive feature of the SPH method, is its gridless character, which is able to elegantly handle all the non continuous effects mentioned above alongside the complex geometry inside the ship. Moreover, it is capable of simulating the mixing of two fluids of different densities (water and air). The code is not intended as a replacement for model tests but instead provides a means of testing a variety of modifications to the internal arrangement of the ship before actually building a physical model, thus saving on time and money.

5. SPH METHOD

Smoothed Particle Hydrodynamics (SPH) is a Lagrangian method [10, 11] for performing fluid dynamical simulations in which the entire fluid state is carried by a finite set of particles. This contrasts with Eulerian schemes where the space in which the fluid exists is subdivided into a collection of *fixed* grid cells which are used to maintain fluid state. The ' ' particles' ' in SPH do not represent actual particles, but rather are used to track local properties of the fluid.

SPH can be viewed as an approximation scheme for a function $f(r)$ defined over a set Ù based on the following approach:

$$\langle f(r)\rangle = \int_{\Omega} f(s)W(r-s,h)ds \qquad (1)$$

with h being the *smoothing* distance and W a weighting function which in SPH is known as the *kernel.* W and h both play a critical role in the SPH method. The kernel can be any continuous function that complies with the following characteristics of the Dirac Delta function $\delta(u)$.

$$\int_{\Omega} W(u,h)du = 1$$
$$W(u,h) \xrightarrow[h\to 0]{} \delta(u) \qquad (2)$$

Thus in the limit it is guaranteed that:

$$\langle f(r)\rangle = f(r) + o(h^2)$$
$$\langle f(r)\rangle \xrightarrow[h\to 0']{} f(r) \qquad (3)$$

If we assume that the function $f(r)$ is known at a set of N points r_j each with an associated mass m_j distributed according to the volumetric density, $\rho(r_j)$ we can discretize (1) as:

(4) $$\langle f(r)\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho(r_j)} f(r_j) W(r - r_j, h)$$

The particles at the points r_j do not need to be arranged in a structured way since SPH is a "gridless" method.

This method can also be applied to other operators such as the gradient:

$$\langle \nabla f(r)\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho(r_j)} f(r_j) \nabla W(r - r_j, h) \quad (5)$$

Most importantly, this relation can be applied to the equations of fluid mechanics to obtain continuity, momentum, and energy equations for each fluid particle a, as follows:

$$\begin{aligned} &\rho(r) = \sum m_i W(r - r_i) \\ &\frac{dv_a}{dt} = -\sum m_i \left(\frac{P_i}{\rho_i^2} + \frac{P_a}{\rho_a^2} \right) \cdot \nabla W_{ai} \\ &\frac{du_a}{dt} = \frac{1}{2} \sum m_i \left(\frac{P_i}{\rho_i^2} + \frac{P_a}{\rho_a^2} \right) v_{ai} \cdot \nabla W_{ai} \end{aligned} \quad (6)$$

where v is the speed of a particle, u is its internal energy and P and ρ represent the pressure and density at particles a and i respectively. In addition, W_{ai} represents the SPH kernel $W(r_a - r_i, h)$ and $v_{ai} = (v_a - v_i)$ is the relative velocity between neighboring particles.

6. APPLICATION OF THE SPH METHOD TO INCOMPRESSIBLE FLOWS

The essential features of the SPH method are:

i) its Lagrangian character, allowing self-adaptability to large fluid-domain deformations

ii) its gridless character, avoiding the burden of constructing a mesh which captures all of the 'interesting' zones in the fluid which may include complex geometry with sufficient accuracy.

It is important to be aware that in SPH liquid incompressibility is not directly enforced via the continuity equation. The reason for this is that the SPH method was originally conceived to simulate gases. Indeed, there is a significant numerical advantage in modeling incompressible flows by explicitly applying the equations in (5) instead of applying the standard fluid dynamics equations directly. In order to extend the SPH model to incompressible fluids we obtain the pressure forces by using an explicit state equation of the form $P_i = f(\rho_i)$. This equation is designed to limit density variations to ~1% so that, in practice, a very small variation of volume is observed.

The equation of state has the following form:

$$P_i = B\left[\left(\frac{\rho_i}{\rho_o}\right)^{\gamma} - 1\right] \quad (7)$$

where ρ_o is the canonical density and ρ_i is the current density value at particle i. The values of B and γ must be chosen to ensure that any density fluctuations remain within 1% of the reference value ρ_o. To strictly enforce incompressibility, a Poisson equation for the pressure can be solved, as in the MPS method [12]. However, this adds complexity to the solver, affects solver performance and is likely to make implementing the SPH approach more difficult.

SPH for incompressible flows has been

successfully applied to the study of breaking waves in shallow water and around ships. In this paper we are especially interested in the interaction between two fluids: water and air. SPH-based approaches to multi-phase flows have already been proposed in literature [13].

SPH has been applied effectively to a wide range of other fields including astrophysics, stress and breakage analysis, high velocity impacts and electromagnetism.

7. IMPLEMENTATION

A team of engineers in the Shipbuilding Technical School (Madrid Polytechnic University, Spain) and the Spanish company Next Limit Inc. are working on an SPH implementation coded in C++ which is capable of simulating the interaction between multiple fluids and solid structures. The code is being designed to accept standard file formats containing geometric information about the vessel and its internal structure.

The implementation uses a space partitioning scheme to perform fast calculation of the interactions between particles and their neighbors. A method for handling boundary conditions is included which detects collisions between fluids and parts of the structure.
Finally, the particles are integrated forward in time using a second order scheme. A rigid body engine has also been included to allow the displacement and collision of solid structures.

The goal of this project is to calculate the interaction of water masses entering a damaged ship. The long-term evolution of the ship may depend upon the initial conditions. The complex and sometimes chaotic behavior of water and its interaction with internal fixed and moving solid structures suggest that the SPH method is an ideal approach for solving this problem.

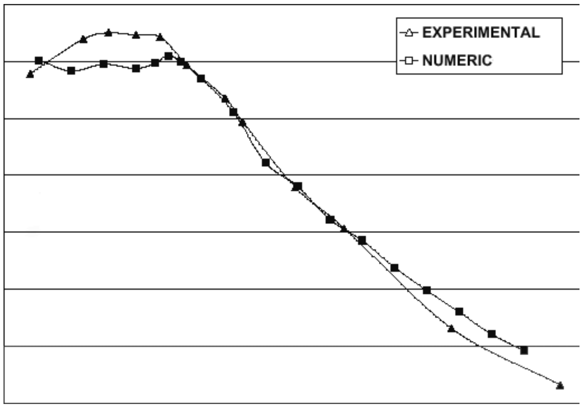
7.1. Case example

A numerical simulation of passive stabilizer tanks for fishing vessels using the SPH method has been carried out at the Shipbuilding Technical School (Madrid Polytechnic University, Spain) [14].

Passive stabilizer tanks are used successfully in fishing and cable-laying vessels to dampen their roll movement. To date these tanks have been successfully designed using experimental tests. While problems have not arisen with this approach a numerical model to evaluate their behavior would be an invaluable tool. In particular, the need to build real test tanks would be delayed until much later in the design cycle saving on cost and time. Moreover, such a model would also increase the number of new designs that could be evaluated within the timescale of a project.

A comparison between the results predicted by the SPH method and the experimental tests revealed a positive correlation which we show in graph 3.

We believe (and our preliminary experimental results demonstrate) that SPH techniques can be useful for simulating a broad range of phenomena involving interactions between air, water and dynamic structures, especially in those cases where strong deformations and complex free surfaces arise. Typically, traditional CFD codes encounter difficulties when attempting to model these kinds of phenomena.



Graphic 3. Roll angle in degrees vs out of phase angle period in seconds.

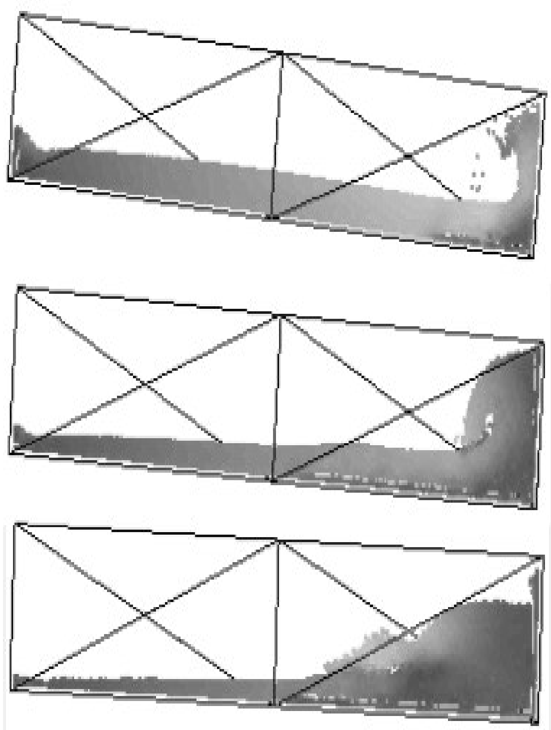


Figure 5. Simulation data: wave interaction at different angles

8. CURRENT RESEARCH

We are currently studying the motion of water inside a car deck of a roll-on/roll-off ship with a forced sinusoidal rolling motion. In the first case, the car deck is empty, whereas in the second case it is filled with vehicles, cars and trailers of standard dimensions.

The cross sections of the ship and vehicles in this car deck are simplified. In addition, vehicles are lifted from the deck floor a suitable distance to take into account the size of their wheels. The rolling motion is forced with a sinusoidal movement of period 10.0 seconds and amplitude 10 degrees.

The dimensions of the simulation are:

B_{deck}=21.20m
h_{deck}=5.5m
$h_{deck\_above\_keel}$=7.5m
$B_{trailer}$=2.60m
B_{car}=1.70m
$h_{trailer}$=0.65m
h_{car}=0.30m.

The roll axis is located 5m above the keel.

In both cases, 12,800 particles are used, corresponding approximately to an initial water height of 50cm (SOLAS 90 stability standard).

As the quantity of water is constant, the influence of the openings through which the trapped air could escape is not considered, although their influence will be taken into account in later implementations of the solver.

While the vehicles currently have fixed positions on the deck the simulation could easily be arranged to allow them to move according to gravitational and buoyancy forces.

In both cases, calculations were performed using real scale dimensions for time and lengths. The free surface of water is clearly defined even though only a modest number of particles have been used in the simulations. This effect being studied is of greater importance as the violence of the sloshing phenomena increases, notably when there are no obstacles that interfere with the fluid flow, as in the empty deck test. As has been said before, particle methods are ideal for situations where the free surface is not smooth and continuous. The simulations described here which include breaking waves are good examples of where these methods are most suitable. This can be fully appreciated by considering the first four frames of Test #1 on figure 7.

The obstacles in the second case prevent the water from reaching high speeds and from breaking violently against the sides of the ship. While the behavior is smoother in these circumstances particle methods are equally well suited for studying this behavior.

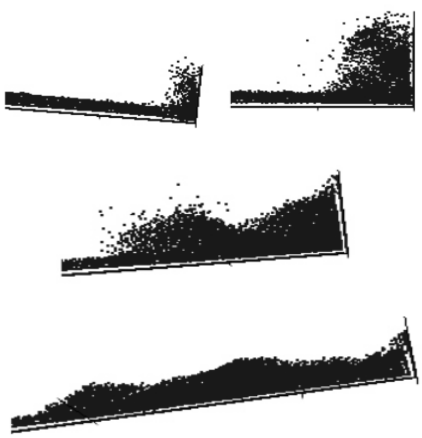


Figure 6. Detail of breaking wave.

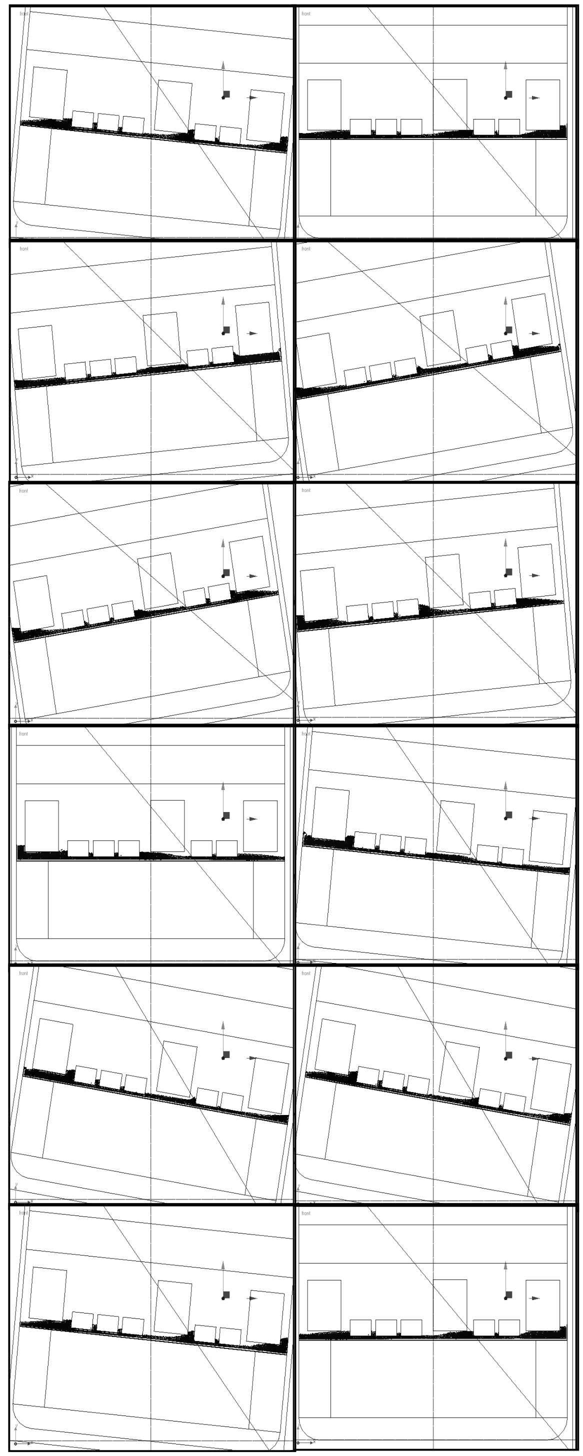


Figure 7. Test #1: empty deck.
$T_0 = 9$ s
$T_1 = 20$ s

Step: 1 s

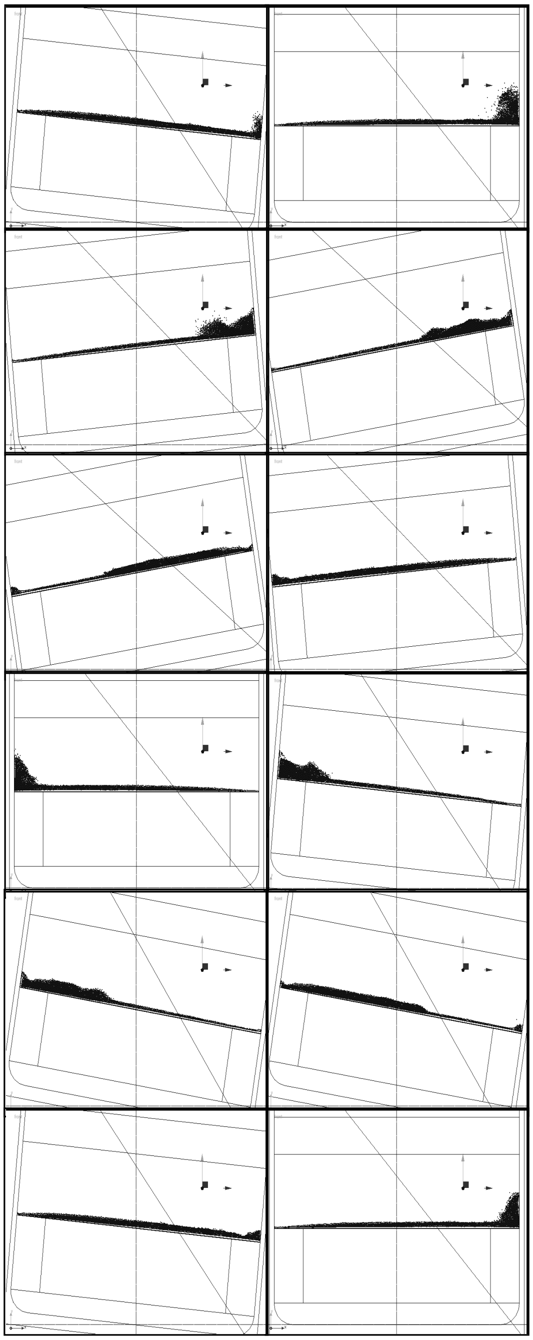


Figure 8. Test #2: with vehicles.
$T_0 = 9$ s
$T_1 = 20$ s
Step: 1 s

9. CONCLUSIONS

An adaptation of the SPH method to study the behavior of shallow water in flooded car decks has been presented. The method is very promising because it overcomes one of the principal weaknesses of conventional grid methods: the difficulty in generating a computational grid which can adeptly handle splashes and breaking waves and which can adapt to capture the irregular and frequently non-continuous water surface The resolution of the SPH method can easily be adjusted by simply varying the size of particles. Furthermore, three dimensional problems can be studied. Two test cases are presented to demonstrate the suitability of the method for these types of problems.

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