

# Experimental and numerical investigation of 2D sloshing: scenarios near the critical filling depth

A. Colagrossi\* F. Palladino\* M. Greco\*  
a.colagrossi@insean.it f.palladino@insean.it m.greco@insean.it

C. Lugni\* O. M. Faltinsen\*\*  
c.lugni@insean.it oddfal@marin.ntnu.no

\* INSEAN, Italian Ship Model Basin, Roma – Italy.

\*\* Centre for Ships and Ocean Structures, NTNU, Trondheim – Norway.

Sloshing is an important issue for LNG tanks and in general when partially filled tanks are on-board of a vessel. This resonance phenomenon may be connected with complex motions of the filled liquid that can couple with the ship motions and can represent a danger for the tank structure and for the stability of the ship. In this context, it is very important to identify the possible scenarios associated with the sloshing. Present analysis is a part of the research activities reported in Colagrossi *et al.* (2004) and Lugni *et al.* (2005) and uses both 2D sloshing experiments performed in a rectangular tank  $L = H = 1$  m long and  $b = 0.1$  m wide (see left sketch in figure 1), and the 2D SPH solver (Colagrossi and Landrini 2003 and Colagrossi 2005). In particular it is the logical continuation of the experimental investigation presented in Colagrossi *et al.* (2004). There, sloshing phenomena in the case of filling depth  $h/L = 0.35$ , *i.e.* slightly higher than the critical value  $h/L = 0.337$  (Faltinsen *et al.* 2000), were investigated. By varying the excitation period  $T$  of the sinusoidal horizontal motion of the tank, and by increasing its amplitude of oscillation, some peculiar phenomena were observed for  $T$  near the linear sloshing natural period  $T_1$ , *i.e.* an asymmetric behavior of the wave elevation along the tank, as well as alternation of the breaking phenomenon at the two tank sides. Such phenomena are connected with important water-wall interactions and with the vortex generation consequent to the post breaking phenomena. Because of their complex features, they can not be predicted by potential-flow models. Further, to our knowledge no documentation of them is available in the literature.

With the aim to identify the main physical mechanisms involved and responsible for the observed phenomena, a dedicated experimental and numerical investigation has been performed by choosing the excitation period near  $T_1$  and reducing it progressively. For each examined  $T$ , the excitation amplitude  $A$  was varied and the features of the resulting sloshing events have been analyzed. Within the studied region of the  $T/T_1$ - $A/L$  plane four main scenarios have been identified. They are presented in the table of figure 1 and can be listed as events: (I) without free-surface breaking, (II) with alternate breaking, (III) long-time randomic asymmetric behavior, (IV) with local splashing jets. The fundamental

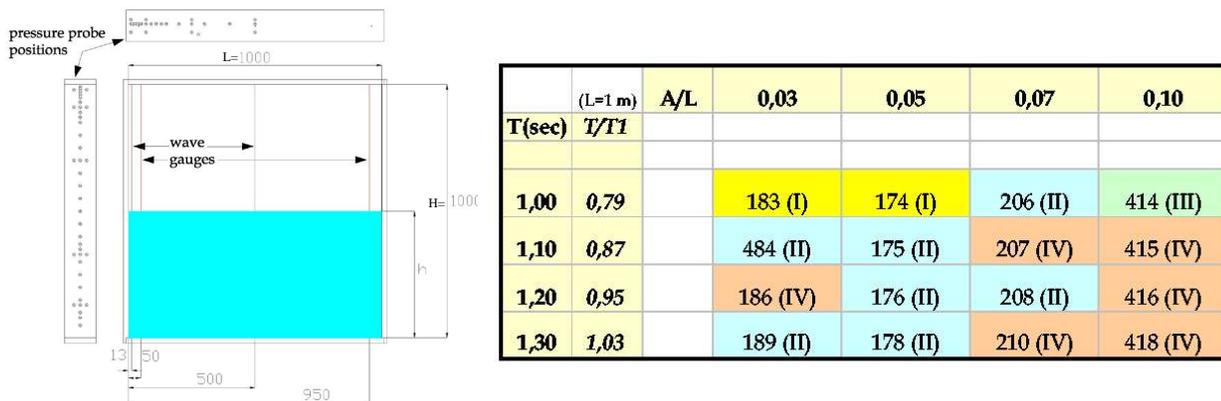


Figure 1: Left: experimental set-up. Right: cases studied and main sloshing scenarios identified as a function of the excitation period  $T$  and excitation amplitude  $A$ .  $T_1$  is the linear sloshing natural period and  $L$  is the tank length.

behavior of the water motion in the tank for each of them is given in figure 2 through experimental images recorded with a digital video camera.

Type I refers to the less severe sloshing phenomena (see run 183 in figure 2), with smooth free-surface. Such events can be studied by means of a potential flow model.

As the nonlinearities involved increase, a threshold condition is reached above which wave breaking phenomena characterize the sloshing and alternate at the two sides of the tank. The related sloshing belongs to category II (see runs 484, 176 and 208 in figure 2). An example is given in the top plot of figure 3 in terms of the wave-elevation time history at a wire probe that is 1 cm from the left. For such events, in addition to the super-harmonics, the steady-state water motion shows a sub-harmonic with period three times greater than the excitation period. This is documented by the evolution of the wave-elevation spectrum reported in the left plot of figure 4 for the case discussed. The latter is not very energetic,

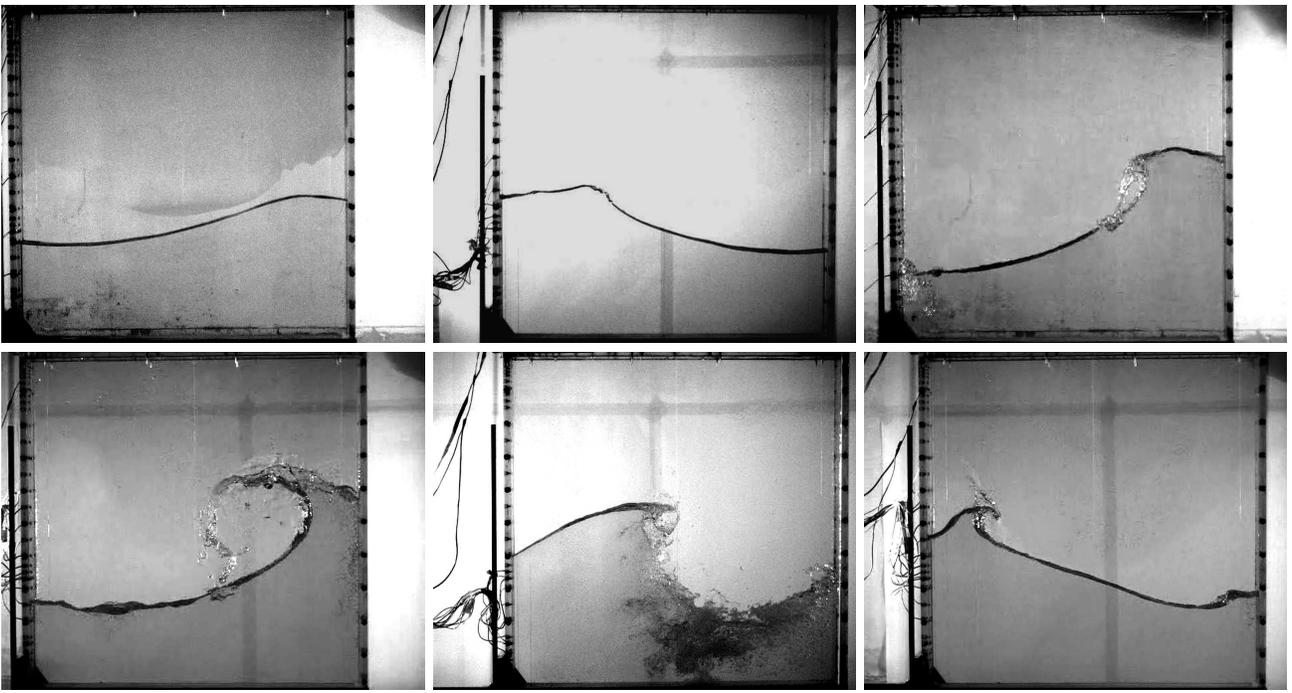


Figure 2: Snapshots of the water in the tank recorded during the tests with a digital video camera. From left to right and from top to bottom: cases 183 (I), 484 (II), 176 (II), 208 (II), 414 (III) and 207 (IV).

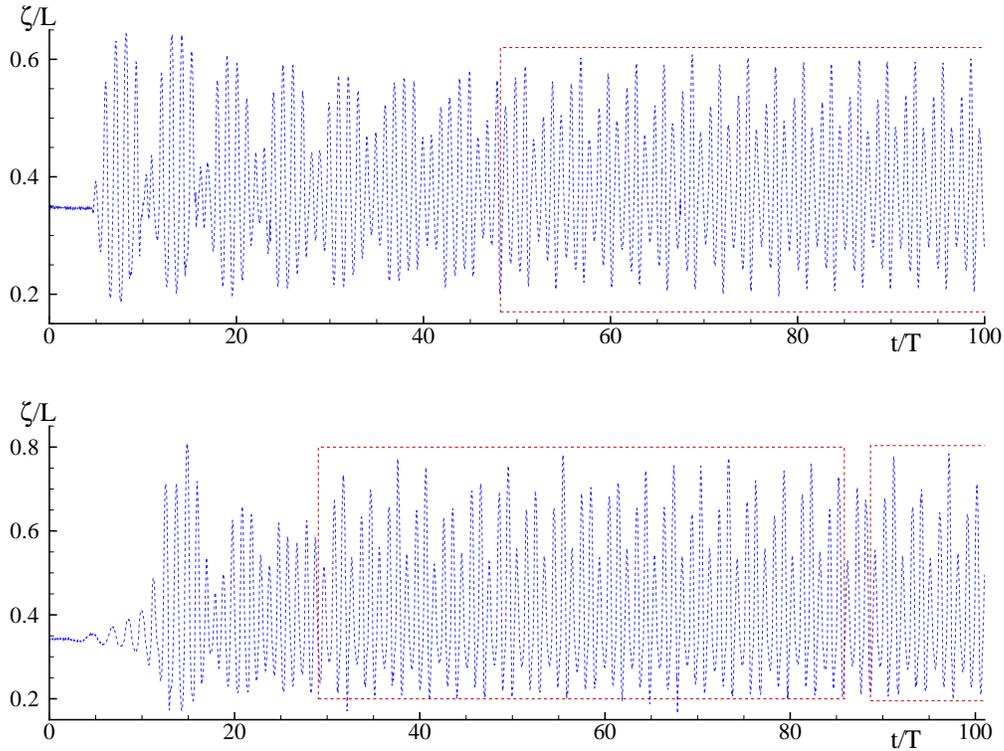


Figure 3: Case II: time history of the wave elevation at a wire probe 1 cm from the left tank side. Top: run 484. Bottom: run 176. The dashed boxes enclose the time regions with regular breaking sequences inside the tank.

the different harmonics characterize the spectrum during the whole time history (except for the  $T/T_1$  component which is damped out) and result in a sloshing phenomenon with spilling breakers continuously alternating inside the tank.

As the breaking phenomena become more energetic their alternate sequences are not able to characterize the entire sloshing event. Time intervals during which the breaking can occur with unpredictable features are also recorded experimentally, see example in the bottom plot of figure 3. The duration of regular breaking sequences, *i.e.* with alternate occurrence (inside the dashed boxes in the figure), reduces as the energy involved in the wave motion increases. Conversely the intervals of the wave-elevation time history with irregular behavior enlarge. This trend is handled by the SPH, see right-top plot of figure 4. However the numerical results predict much shorter regions of alternate breaking sequences.

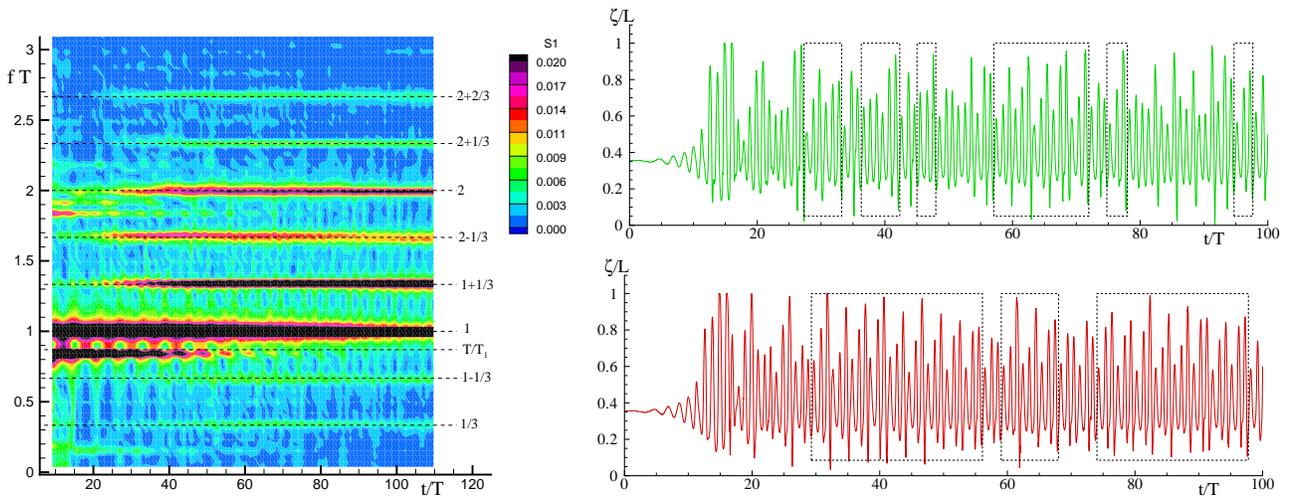


Figure 4: Case II. Left: experimental time history of the wave-elevation spectrum for run 484.  $S1$  is the spectral amplitude,  $f$  the frequency and  $t$  the time. Right: SPH wave-elevation time evolution at 1 cm from the left side of the tank for two numerical damping levels. The highest value is used in the bottom simulation. The dashed boxes enclose the time regions with regular breaking sequences inside the tank.

A possible explanation is connected with viscous effects in the physical tank, that are not accounted for by the numerical solver. This is supported by the results given in the right-bottom plot of the same figure, obtained with a higher level of the numerical damping Colagrossi and Landrini (2003). This parameter smooths out the spray connected with the breaking phenomena and leads to a longer duration of the regular sequence of breaking inside the tank. The numerical solution with larger damping level is more consistent with the experiments. The comparisons will be detailed discussed at the workshop.

During type III of sloshing the free-surface fragmentation is rather pronounced and complex, and is not connected with the features of classical wave breaking phenomena (see run 414 in figure 2). In this case, the water-elevation sub-harmonics become more complicated. Their periods are  $N$ -times higher than  $T$ , with  $N$  a large integer varying in time during the sloshing evolution (see example in figure 5). The wave motion inside the tank has an asymmetric behavior

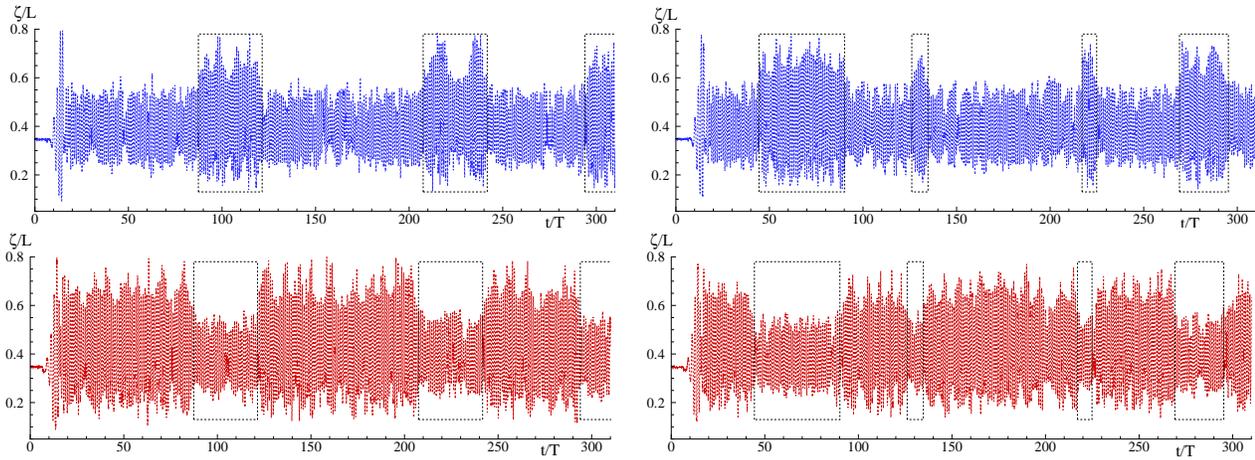


Figure 5: Case III: time history of the wave elevation at a wire probe 5 cm from the left (top plots) and right (bottom plots) tank sides. Experimental runs 414 (left plots) and 426 (right plots). The dashed boxes enclose the time regions with a wave impact against the left side wall only. The remaining time regions are characterized by wave impacts against the right side wall only.

with wave impacts occurring either against the left or the right tank side (see also Landrini *et al.* 2003, Colagrossi *et al.* 2004). This feature can be detected also numerically by the SPH, see figure 6. However it is hard to reproduce correctly the time evolution of such sloshing phenomena. The reason is that they are very sensitive to the initial conditions. To the purpose, figure 5 gives two test runs formally with the same test conditions. As we can see both of them show an asymmetric behavior but the occurrence and features are different. According to the numerical analysis, the asymmetric behavior disappears for sufficiently high damping level (see right plots of figure 5).

Finally type IV of sloshing is characterized by the formation of a local splashing jet at a certain distance from the wall, leading to a continuous fragmentation of the free surface. As a consequence, this time, the nonlinear interactions do not induce any well defined sub-harmonic.

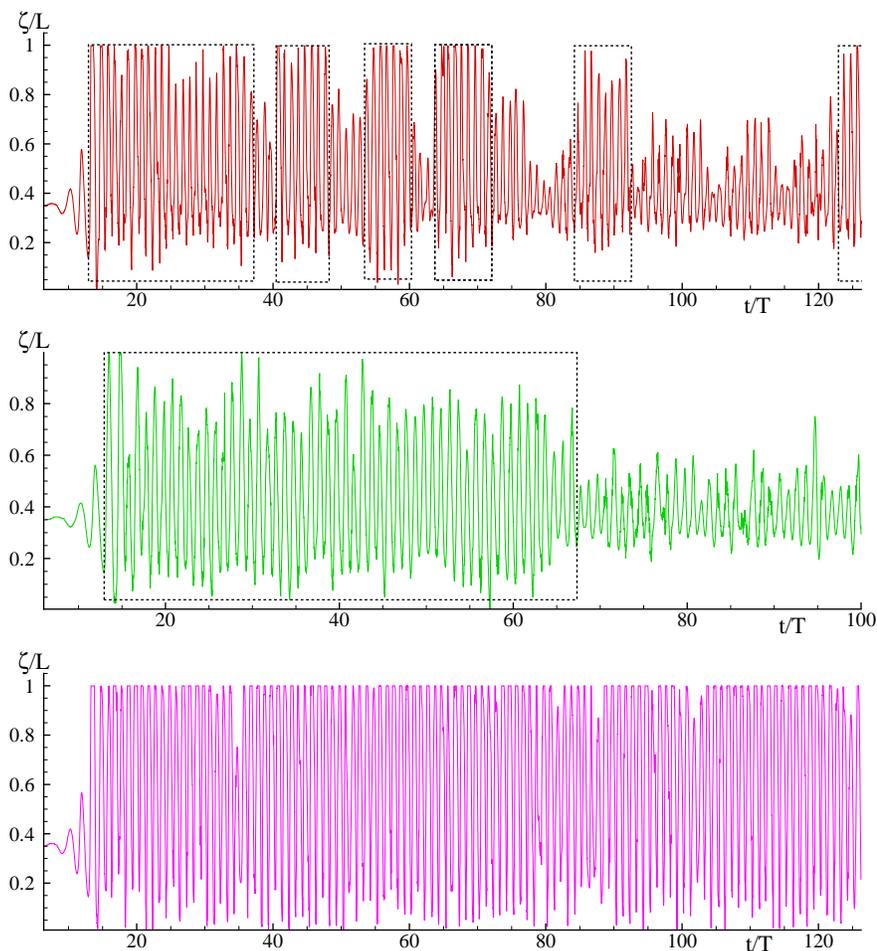


Figure 6: Case III: time history of the wave elevation at a wire probe 5 cm from the left tank side. SPH simulations with increasing damping level going from top to bottom.

The combined numerical-experimental analysis suggests that the damping mechanisms inside the tank are important for the features of the sloshing, and should be adequately investigated. These aspects will be discussed at the workshop. The different sloshing regimes will be detailed analyzed, in particular in terms of the evolution of the energy spectrum inside the tank and of the resulting sub- and super-harmonics content.

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**Colagrossi, A., Palladino, F., Greco, M., Lugni, C., Faltinsen, O. M.  
'Experimental and numerical investigation of 2D sloshing: scenarios near  
the critical filling depth'**

**Discussor - M. Longuet-Higgins:**

The triple instability that you have observed is similar to that found when steep waves are reflected from a vertical barrier; see Longuet-Higgins, M.S. and Drazen, D. (2002) 'On steep gravity waves meeting a vertical wall', *Journal of Fluid Mechanics*, 466, 305-318. Above a certain incident-wave steepness the rate of growth is almost a constant, independent of the steepness.

**Reply:**

Thank you for the useful suggestion. Your paper is extremely interesting to highlight some physical mechanisms involved in. In our experiments we observed some preliminary similarity with the period tripling phenomenon observed by Jiang and Perlin (JFM 98). Nevertheless, as in your experiment the mechanism we used to obtain the quasi-standing waves is a consequence of the reflection of the progressive waves from the end wall of the tank. Then the sentences highlighted in your investigation could be confirmed from our studies, and even in this sense we will address our research. Thank you again!