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COMMITTEE V.2
NATURAL GAS STORAGE AND TRANSPORTATION

COMMITTEE MANDATE

Concern for the safety and design of containment systems for the storage and transportation of natural gas in connection with floating platforms and terminals, and onboard ships. This is to include assessing the performance of various containment systems for gas under compression (CNG), liquefaction under cooling (LNG), and combinations of the two methods. Particular attention shall be given to the integrity and safety aspects of containment systems under pressure and thermal loads, and the interaction between fluid and structure under static and dynamic conditions. Consideration shall be given to the installation and safety matters of gas and dual fuel propulsion systems, fitted onboard conventional vessels. Needs for revision of current codes and regulations shall be addressed.

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1. DISCUSSION

1.1 Official Discussion by Laurent Brosset

1.1.1. Introduction

The committee wrote a very comprehensive report on most aspects related to natural gas storage and transportation. I feel much honored to be asked reviewing this report but as my field of expertise is limited to sloshing, my comments and additions especially concern that part of the report.

For the sloshing section, I did not strictly follow the initial structure of the report. I tried to organize my comments and additions in order to show, as far as I know, where we are today and the distance we still have to cover in order to better master the liquid impact physics and therefore the related scaling issues. I complemented the report with aspects that initially were not or insufficiently covered according to my views but trying to keep the sloshing section as a whole that can be read separately. This exercise is necessarily subjective: I shared my point of view and sometimes my intuitions. Being in charge of the R&D related to sloshing physics within GTT, the designer of well-known membrane containment systems for LNG tanks, my views may possibly be biased, against my will.

For the other parts, I followed the initial plan and made some rare comments or suggestions.

1.1.2. Background

The text should be updated taking into account the recent crude oil price reduction which led to a reduction of the investments. The initial keen interest in LNG as a fuel has since been mitigated. Anyway, the long-term trends remain unchanged.

1.1.3. Safety and Design

Cargo Containment Systems:

In section 4.1.1, please replace bar by barg (bar gauge) for the design ullage pressure of membrane tanks (0.25–0.7 barg).

Chapter 4.1.3 intends to address New Development of CCS but concentrates primarily on the new IGC Code. This does not therefore consider the recent developments and improvements in systems to respond to market requirements in terms of insulation performance (reduction of daily boil-off) and strength. Nor is there any consideration for new systems that are being proposed. During the last three year period, several new membrane containment systems have been launched like:

- Mark III Flex, NO 96 GW & NO 96 – L03, Mark V, NO 96 Max, Mark FIT proposed by GTT
- SCA proposed by Samsung
- KC-1 proposed by KOGAS, DSME, SHI, HHI
- In Table 3, according to IGC code, the requirements should be as follows:
- for item Design Basis, full secondary barrier should be required for Type A tanks for T < –10°C (instead of –55°C ≤ T < –10°C) → §4.21.1.2 IGC.
- for item Structural Analysis, for Type C tanks, stress analysis and thickness determination to be performed as per §4.23.2.5 IGC.

Structural Integrity and Rules:

No comment.

Sloshing:

- *Long-Term Assessment*

✓ *State of the art*

Today, the only way to assess any new project of LNG tank on a floating structure with regard to sloshing is to perform sloshing model tests (see classification notes at the end, Gervaise et al. (2009), Kuo et al.

(2009)). The model tank, most of the time at scale 1:40, is partially filled with water. The ullage gas is a heavy gas, usually a mixture of SF_6 and Nitrogen, chosen in order to match the gas-to-liquid density ratio (DR) existing in LNG membrane tanks ($DR \approx 4 \cdot 10^{-3}$). The model tank is placed on the platform of a six-degree-of-freedom test rig, usually a hexapod (Stewart platform), and submitted to motions derived from full scale sea-keeping calculations by Froude-scaling. The model tank is instrumented by numerous dynamic pressure sensors (300 per tank in GTT) gathered in rectangular arrays located in the most impacted areas. A data acquisition system acquires the pressure signals at high sampling rate (≥20 kHz). All conditions the tank might experience during the ship or barge life are mimicked during a test campaign with as many repetitions as necessary for relevant pressure peak statistics.

A spatial post-processing is made in order to determine the history of the average pressure on rectangular arrays of sensors (virtual sensors) of different sizes. The pressure peaks, for all sloshing impacts, at the sensor level but also for the different sizes of the virtual sensors, are gathered in relevant bins for statistical post-processing. The pressure scaling process relies on the feed-back at sea for large scale LNG floating tanks. It means that the methodology is calibrated by mimicking the sequences for which incidents occurred at sea, like deformations of the corrugations for the Mark III membrane or indentations of the plywood cover-plate of NO96 boxes. As there is a lack of feedback for partial fillings or small scale LNG applications, the scaling is simply based on Froude similarity. Long-term pressure probability of exceedance curves are built for the different sizes of the loaded area.

Capacity curves featuring the strength versus the size of the loaded area are obtained for the different limit states of the containment system by applying static patch loads at cryogenic temperatures by successive steps of increasing magnitude until the first damage. Rectangular patches of the same size are applied at the different weak points of the structure. Different sizes are tested. The capacities are adjusted to take into account the dynamic behaviour of the structure.

Finally the loads are compared to the capacity at the right probability level for the considered limit state, for the different sizes of the loaded area. A safety margin is introduced before any validation.

✓ *Conservatism and representativeness of sloshing model tests with regard to reality*

It has been shown in a common DNV/GTT presentation in Gastech 2014 (Østvold et al. (2014), unfortunately no paper is available), thanks to pressure and strain measurements accumulated during five years on board a membrane LNG carrier, that the sloshing assessment methodology based on sloshing model tests as described above is globally conservative but not always strictly representative of the reality.

The study was performed within the Full Scale Measurement JIP led by DNV described in Lund-Johansen et al. (2011) and Pasquier et al. (2012). The 148 300 m^3 LNG IMO carrier operated by BW Gas was delivered by DSME in 2008 with instrumented NO96 boxes in the two fore top corners of tank#2. The instrumentation included eight pressure sensors embedded in the cover plates of two primary boxes below the INVAR membrane, strain gauges on both sides of the plywood bulkheads inside the primary and the secondary boxes at the vertical of the pressure sensors, and strain gauges behind the cover plate of the two fore corner boxes. The six degree of freedom ship motions were recorded by a Motion Reference Unit (MRU).

All the voyages for which sloshing events were experienced have been mimicked at scale 1:40. Some of them were also reproduced at scale 1:25. Comparison of long-term statistics has been made. The probability of exceedance of maximum pressures obtained from pressure peaks at full scale and at scale 1:40 are compared in Figure 1. The statistical distributions are representative of the ship operational profile over four years of measurements. Model test distribution proves to be more conservative than the full scale one. Comparison with the design pressure at probability 10-3 per year shows a safety margin for both curves.

Short-term statistics comparison is not as straight forward because the number of events recorded at full scale during a 3-hour sequence is generally not enough for reliable statistics. This can be compensated at model scale by relevant repetitions of the condition but obviously not at full scale. Therefore the comparison has been based on the event rate (number of sloshing events per hour). This parameter is known as quick to converge according to model tests. On the other hand it depends on a pressure threshold to be defined at both scales. In Figure 2, the thresholds have been adjusted in order to have the best match over the 2.5-day voyage. The figure illustrates general trends observed during all voyages with available data: model tests accurately predict periods with sloshing and periods without sloshing. Event rate trends are similar but differences are observed in absolute values. These differences prove to be larger than when comparing two model scales (1:40 compared to 1:25).

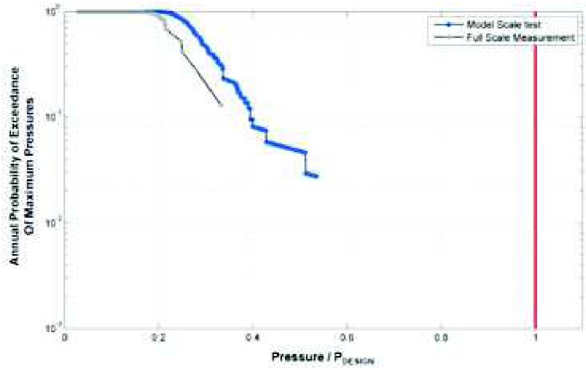


Figure 1: Long-term comparison between full scale and scale 1:40: probability of exceedance of maximum pressure.

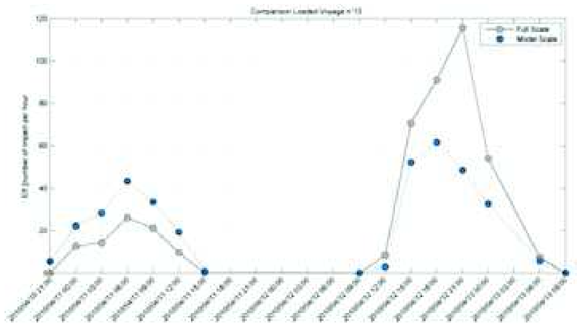
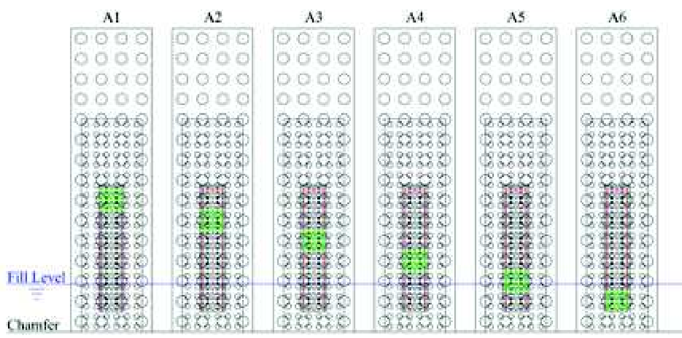
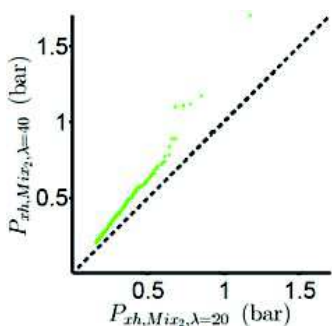


Figure 2: Short-term comparison between full scale and scale 1:40: event rate (number of event per hour for which a pressure threshold is exceeded).

Another recent study (Karimi et al., 2014) brought insight on the conservatism of Froude-scaling with regard to statistical pressures. The authors described the comparison of sloshing model tests performed on a transverse slice (2D tank) of the tank#2 of a 152 000 m3 membrane LNG carrier at three different scales: 1:10, 1:20 and 1:40. All tests were performed with water and different ullage gases (He, N2, Air, two different mixtures of N2+SF6, SF6) for the filling rate of 20% of the tank height. A unique sequence of 5-hour transverse ship motions (three degrees of freedom in the 'plane' of the tank) was studied corresponding to a sea state with a significant wave height of 6 m. The same ship motions were Froude-scaled according to the position of the tank and the scale. Whatever the scale, the condition led to a succession of breaking wave impacts on the longitudinal walls. Each tank was instrumented by a unique rectangular array of dynamic pressure sensors located on the same side and covering the impacted area. Each condition, corresponding to a given ullage gas at a given scale, was repeated 17 times in order to gather enough pressure peaks for relevant statistics. As the same pressure sensors and the same horizontal and vertical distance between the centres of two adjacent sensors were used at different scales, the sensor lay outs were necessarily different after being displayed at the same scale. The comparison of the pressure statistics was made on average pressure calculated on six geometrically similar square areas (A1 to A6) as shown in Figure 3. Figure 4 shows a Quantile-Quantile (Q-Q) plot comparing the maximum average pressures on area A4 with the same return period at scales 1:20 and 1:40 with a ullage gas corresponding to a mixture of SF6 and Nitrogen with a gas-to-liquid density ratio of 2. 10-3. Pressures at scale 1:40 have been multiplied by 2 according to Froude-scaling. The longest return period, therefore the highest pressures, corresponds to 85 h full scale (17 x 5 hours). The trend shown by Figure 4 is observed for all studied areas (A1 to A6), for all ullage gases for all couple of scales: Froude scaling process proved to be conservative and the smaller the scale, the more conservative the results.





Comparison of sloshing model tests at three different scales

Figure 3: Six geometrically similar areas (green) defined on the three sensor modules represented at the same scale. The largest common area on the three modules is represented in red.

Figure 4: Q-Q plot comparing the maximum average pressure on area A4 with the same return period at scales 1:20 and scale 1:40 for the same condition repeated 17 times. Pressures at scale 1:40 have been scaled by a factor 2 (Froude scaling).

✓ *Reliability of sloshing model tests*

The different labs providing sloshing model tests for real LNG projects comply with some non-written and still vague minimum requirements: six-degree-of-freedom motions, heavy ullage gas in order to match the real DR, forced motions derived from 3D BEM methods taking into account the coupling between ship and cargo motions, large number of sensors, high sampling frequency (>20 kHz), etc.

It is interesting to notice that historically for all the listed parameters above, simplifications were first adopted for want of anything better. All justifications given at that time for simplifications proved to be wrong …

In addition to the parameters above mentioned or mentioned in the report and described in Pistani and Thiagarajan (2012) a special care is to be taken on:

- The exact geometry of the model tank including flatness of the walls, horizontality of the bottom and ceiling, verticality of the other walls except chamfers and main internal dimensions.
- Rigidity of the walls which should avoid any barrel shape for high fills that can significantly affect the actual fill level. As an example, 20 mm-thick walls in PMMA are clearly insufficient, if not reinforced, at scale 1:40 for usual membrane tank sizes.
- The accuracy of the motions imposed by the test rig. An accurate measurement system, independent of the actuators, should allow a verification of the effective motion. This is done in GTT by a system of six LVDTs composing a measurement hexapod imbricated in the motion hexapod. The measurement hexapod is 10 times more accurate than the motion hexapod and do not bear any load, which ensures that its accuracy does not decrease over time.
- The fill level (or the filling ratio with regard to the tank height). Sensitivity studies on the fill level have already shown the significant influence of 1 mm variations on the pressure peak statistics. Two different objectives should be distinguished during sloshing tests: the determination of the absolute value of the fill level and the fact to be able to keep exactly the same fill level even though its absolute value is not known very precisely. The first objective can theoretically been achieved by weighing the water to be poured inside the tank. For a 3D tank and usual dimensions of membrane tank at scale 1:40, 1 mm of water corresponds to a volume of several deciliters which gives an idea of the accuracy that can be theoretically be reached by weighing. However, one should keep in mind that weighing the water will only give an accurate value of a nominal fill level, assuming that the geometry is perfect. The second objective is important as most of the time a given fill level can be kept more than one week in a tank during a test campaign and the fill level can slightly vary due to evaporation. A good accuracy can be obtained with a simple camera carefully fixed to the tank, focusing on the free surface from a short distance and triggered by a remote system. Thus, a variation of 0.1 mm can easily been distinguished as corresponding to a few pixels.
- The real DR within the tank. It should be measured regularly by a density meter especially when studying high fills as the heavy ullage gas is progressively dissolved within the water until saturation. As an order of magnitude, it usually takes more than 12 hours in order to reach a stabilized DR when studying high fills with a heavy ullage gas.

This long list of sensitive parameters directly questions the reliability of sloshing model tests. Two main questions can be raised: (1) are the results repeatable within a given facility in terms of pressure peak statistics? (2) How such results compare when obtained in different facilities?

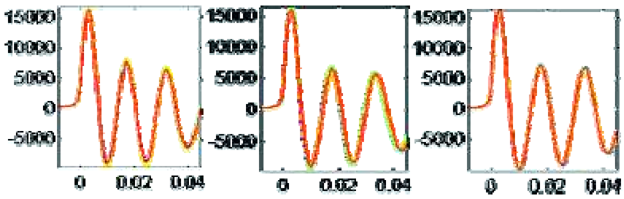
The experimental benchmarks (2012 & 2013) mentioned in the committee report have been launched to provide some answers to these questions and provide guidelines to make both answers positive. The principle is to compare measurements, especially impact pressures, from sloshing model tests performed by different laboratories involving the same nominal input conditions. The philosophy governing those benchmarks is to use as simple and as controlled conditions as possible. The choice of simple test conditions not only enables to include more participants but also helps to sort out the reasons of discrepancies between the results of the different labs.

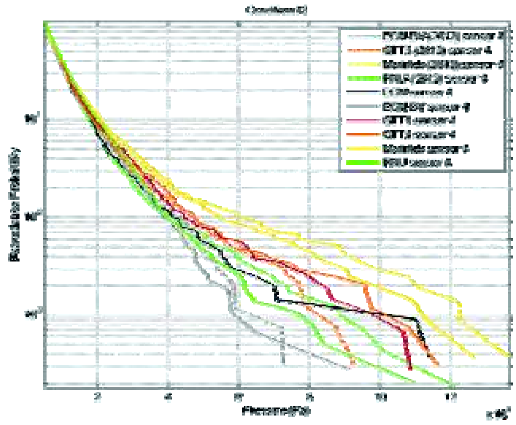
The model tank is a rectangular 2D tank representing at scale 1:40 a longitudinal slice of a real LNG tank, the tests are performed with water and air for a unique filling ratio of 85% of the tank height. Three Single Impact Wave (SIW) conditions (short duration condition leading to a single impact) and three long duration (5 hours at full scale) irregular motions derived from sea-keeping calculations have been studied in 2013. All conditions are defined with only one degree of freedom (either surge or pitch) except an irregular one defined with the three degrees of freedom within the 'plane' of the tank. The results are presented in Loysel et al. (2013).

The results obtained for the SIWs are encouraging. As an example, Figure 5 shows the pressure time traces as recorded by sensors at similar locations within an entrapped gas pocket in three different facilities. Each small graph represents the superimposition of ten signals corresponding to ten repetition of the test.

Generally the results for SIW conditions show good repeatability of the pressure signals within each facility but also good comparisons between some different facilities at least for the two simplest selected SIWs: a large gas pocket impact (all pressures compared are within the gas pocket) and a jet impact featuring a travelling pulse. These results should be used as reference results for validation of numerical simulations as already done in Neugebauer et al. (2014).

The results for irregular conditions are less satisfying. As illustrated by Figure 6, the comparison of probability of exceedance curves provided by different facilities shows significant discrepancies even for low probability levels. Therefore the benchmarking process should go on trying to reduce progressively these discrepancies by a better control of the main parameters involved.





Sloshing model test benchmark

Figure 5: Each graph represents pressure signals obtained by a given sensor located within an entrapped gas pocket for a SIW condition repeated ten times. The graphs correspond to results obtained in three different facilities for sensors at similar location.

Figure 6: Probability of exceedance obtained by pressure sensors at the same location in six different facilities for an irregular surge motion. 2012 results are presented in dashed lines when available.

✓ *Numerical methods*

Classically, 3D BEM methods are used to calculate the ship motions from which are derived the model tank motions to be imposed by the sloshing rig during sloshing model tests. Today, these calculations are usually made taking into account a linear coupling between the ship and the cargo motions (multi modal approach for the liquid motions inside the tank as proposed by DIODORE software for instance). It has long been observed that this coupling radically changes the sloshing behavior but for the time being there is no result showing how far the linearity assumption is relevant. Would the pressure statistics be significantly changed if the non-linear behavior of the flow (impacts onto the ceiling, breaking waves, etc.) was taken into account? In case the answer proved to be positive, the best way would be to adopt hybrid simulations mixing on real time internal hydrodynamic loads as derived from force and torque measurements directly acquired on a sloshing rig together with ship motion calculations.

Replacing Sloshing Model Test by calculations, as sometime proposed, shows a faith in numerical simulations which is surprising, considering the basic physics included in the models. Moreover, carrying a test for a given equivalent-full-scale duration is much shorter than carrying the unfortunately-not-equivalent calculation.

- *Global Flow and variability*

✓ *Experiments*

During sloshing model tests, all internal dimensions of the model tank are down-scaled from the real internal tank geometry by a geometric scale $1/\lambda$ generally chosen around 1:40. The motions of the floating structure are calculated at scale 1 and down-scaled according to a Froude similarity before being imposed by the sloshing rig to the model tank. This means that the time scale $1/\tau$ as followed by the model tank motions is the square root of the geometric scale ($\tau = \sqrt{\lambda}$). This Froude similarity is required by the fact that, whatever the scale, the tank is subjected to the same earth gravity field. This does not mean that the flow inside the model tank is rigorously in Froude similarity with the real flow for a given condition. Liquid and gas properties like their density, compressibility, viscosity or the surface tension at the interface may intervene more or less during certain sequences of the flow. The liquid and the gas inside the model tank should therefore have their properties relevantly scaled with regard respectively to those of LNG and of natural gas (NG) in order to comply with all similarity laws involved or, in other words, in order the small scale flow is described by the same dimensionless problem as the full scale flow. As this requirement can obviously not be totally fulfilled, the Froude similarity that is expected to be imposed by Froude-scaled excitations is necessarily biased.

Therefore, one can wonder whether sloshing model tests make sense. Indeed, the flow inside the model tank might diverge progressively from the Froude-scaled flow derived from scale 1. It is generally admitted that there is a global flow in a one hand, which is repeatable (deterministic) and complies with Froude similarity when changing the scale, and local effects during impacts in the other hand, biasing Froude similarity due to the involvement of unscaled fluid properties (for instance gas compressibility). But these notions are rather vaguely defined.

Moreover there is a large variability of local pressure measurements during liquid impacts that is well known and illustrated by Figure 7 from measurement during wave impact tests in a large flume performed within Sloshel JIP (Brosset et al., 2009). The maximum pressure as recorded during a test is reported by a point according to the focal point location as prescribed to the wave-maker. Types of impacts are differentiated by different point colors. For a same focal point location, the motion imposed to the wave-maker was the same. Here, the maximum pressure variation goes up to 10 times the minimum value for Flip-Through impacts. It is interesting to compare the variability of local pressure induced by liquid impacts to that of wave elevations. Figure 8 shows two stochastic samples with the same mean value. First one (green) corresponds to wave elevation peaks as measured by an instrumented oceanic buoy. Second one corresponds to pressure peaks as measured during sloshing tests. The variability of sloshing pressure is much larger than that of wave elevation.

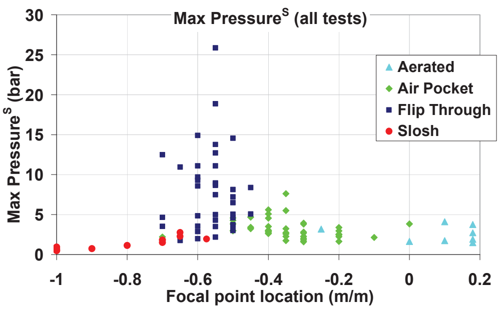


Figure 7: Variability of maximum pressure measurements as observed during wave impact tests (Sloshel JIP). A point corresponds to one impact. A column of points correspond to impact with the same wave maker prescription.

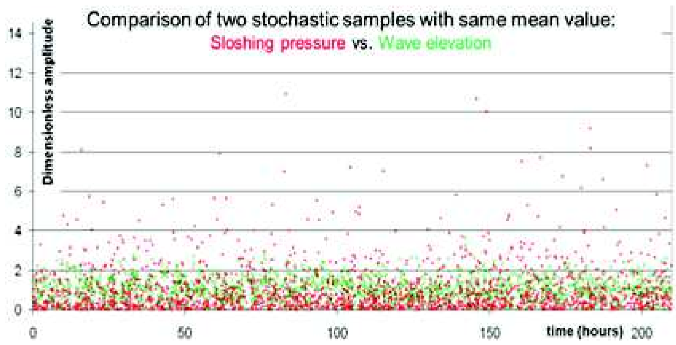


Figure 8: Comparison of two stochastic samples with the same mean value. First one (green) corresponds to wave elevation peaks as measured by an instrumented oceanic buoy. Second one corresponds to pressure peaks as measured during sloshing tests.

This variability of local loads is the malediction of liquid impact studies: It imposes to repeat many times and for long durations the different conditions studied during sloshing model tests to gather significant samples of pressure peaks for relevant statistics. It also makes the influence of any relevant parameter on impact loads more complex to discriminate experimentally. Furthermore, it prevents any serious experimental validation of numerical simulations as far as local pressures are concerned. Despite its crucial influence, the variability of local pressures has been considered as a fatality and their physical causes starts only to be studied.

Based on sloshing model tests at scales 1:40 and 1:20, the study performed by Karimi et al. (2015a) brings some new insight with regard to global flow and variability. At a given scale, if a small uncertainty window (small with regard to the shortest zero-crossing period for the six degrees of freedom, let's say around 50 ms) is introduced, impacts always happen at the same instants when the same irregular excitation is repeated. When comparing two different scales with Froude-similar excitations, the impacts happen at Froude-similar instants. Changing the ullage gas does not affect this property. This result is illustrated by Figure 9 showing the impact times and corresponding maximum recorded pressure for a short sequence of irregular tests repeated 40 times with different ullage gases at both scales.

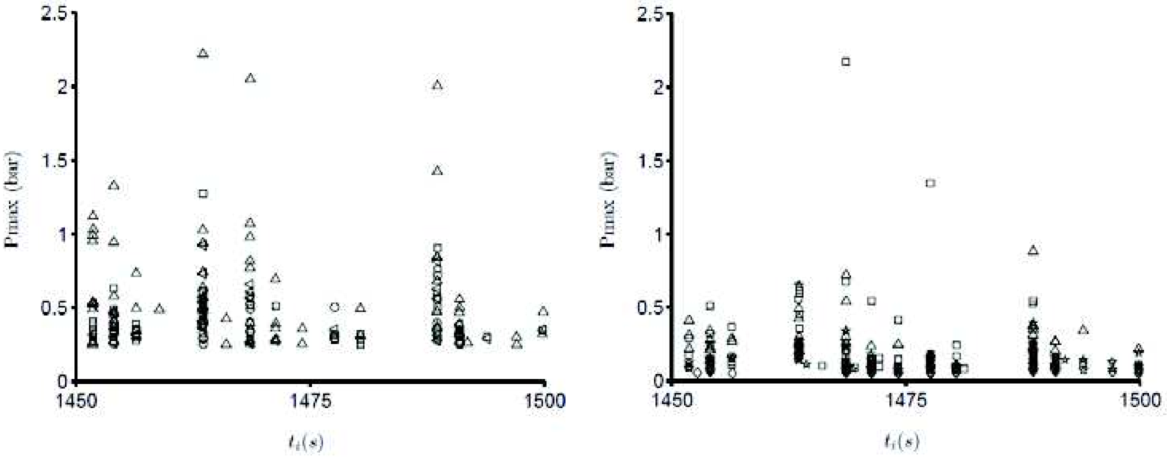


Figure 9: Impact times and corresponding maximum recorded pressure for the 50 last seconds of a 1500 s sequence of irregular tests repeated 10 times with four different ullage gases at scale 1:20 (left) and scale 1:40 (right). Each point corresponds to an impact. Each symbol correspond to a given ullage gas. Time at scale 1:40 has been scaled by $\sqrt{2}$.

This regularity does not deteriorate over time. However, in between two successive impacts, when the wave front is far from the impact areas, shape variations can be distinguished, though they are small, when repeating the same condition. As a reference, for a SIW either performed during sloshing model tests or during wave impact tests in a flume, the wave shape before impact and far from the impact area can be experimentally reproduced very precisely without any distinguishable variation and with a smooth free surface but repetitions always lead to large discrepancies between the local pressure measurements and small shape variations after impact. Thus, the sources of variability clearly occur during the impacts.

For a SIW, they directly come from the free surface instabilities that develop just before the impacts during the gas escaping phase while the wave front approaches the wall (see Figure 10). For sloshing tests, the fall of droplets after the splashing following the impact is a second source of variability. Nevertheless, the perturbations brought by these sources vanish quickly enough to prevent a progressive deterioration of the flow that would induce an increasing variability. Thus, the variability of the local loads and of the flow in between two impacts is due to the development of free surface instabilities generated by the shearing gas flow just before the impact but also to the remaining perturbations, not yet completely damped, from a few last previous impacts.

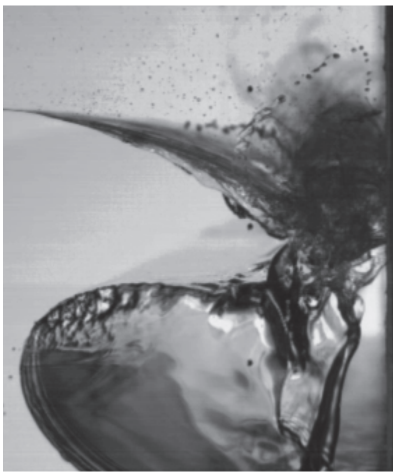


Figure 10: Free surface instabilities generated before a wave impact in a flume (Sloshel JIP)

In summary, the notion of a global flow complying with Froude similarity makes sense but there are perturbation flows, associated to every impact, generated in a one hand by phenomena that do not comply with Froude similarity because of unscaled properties of the fluids and in the other hand by free surface instabilities and splashing. These perturbation flows superimpose to the global flow but damp 'quickly' enough to not cumulate over time.

As already mentioned, free surface instabilities are generated by the gas flow in between a wave and a wall, becoming stronger and stronger as the wave approaches the wall. It induces a shear force upon the free surface which makes it unstable. These free surface instabilities especially grow in the regions where the tangent gas flow is strong, namely around the crest regions for breaking waves. It starts by irregularities on the free surface and degenerates into excrescences and finally to fragmentation. It is not clear whether they belong to Rayleigh-Plateau, Kelvin-Helmholtz or Richtmyer-Meshkov category (see Drazin, 2004).

These results suggest that the variability of sloshing loads should be considered as part of the sloshing physics related to the fluid properties: surface tension at the interface and viscosity of both the gas and the liquid. As these properties cannot be relevantly scaled, the variability at small scale and related statistics are not necessarily representative of those at full scale. It is expected that the variability is higher at full scale, especially due to larger Weber numbers and thus to more fragmentation of the liquid during the impacts.

✓ *Numerical methods*

There are three different subjects concerning global flow and variability where numerical simulation is or should be involved:

- 3D Global flow simulations in a partially filled tank under forced motions are usual today. Liquid and gas are taken into account under incompressible assumptions. The most popular numerical method for these simulations is based on finite volumes with either free surface tracking or capturing. These simulations compare pretty well, as far as global flow is concerned (far from the impact areas), with experiments as performed during sloshing model tests. It is useful to keep repeating that the pressures at wall determined by these codes do not capture the pressure peaks that are used in a sloshing assessment. This is not only a question of refinement of the grid (the most refined models used for such simulations correspond to an average cell size around 0.2 m^3 instead of a few mm3 required for capturing impact pressures) but above all the model do not integrate the minimum required physics (see Lafeber et al., 2012b). These kinds of simulation are useful to estimate the loads on the pump tower within LNG membrane tanks (Champagnac et al., 2014).
- Simulations of wave propagation in flume tanks by non-linear potential codes are very useful in order to initialize the flow conditions just before impact for bi-fluid compressible CFD codes that simulate the last stage of the impact. Such strategy is explained in Guilcher et al. (2012 and 2014) or Costes et al. (2014). Both authors rely on the same potential code, FSID (Scolan, 2010 and 2014), to initialize their wave impact calculations saving much time that way.
- The development of free surface instabilities in the context of liquid impacts has not been studied by numerical simulations yet. This is a challenging subject as it requires a numerical model including surface tension at the interface and viscosity in liquid and gas. An adaptive mesh refinement (AMR) piloted by the free surface curvature is also needed. Nevertheless, such numerical simulations would be a necessary first step for a better understanding of the variability of local liquid impact loads.

▪ *Physics of liquid impacts and scaling*

✓ *Similarity laws and Elementary Loading Processes (ELP)*

The main reason to study the physics of liquid impacts in the context of sloshing is to better understand the scaling processes. As already mentioned, sloshing model tests are performed with forced motions derived from ship motion calculations by Froude-scaling. But although the global flow follows Froude similarity, there are perturbations due to gas and liquid properties in the model tank that intervene during certain sequences of the flow, especially during the impacts, and that are not relevantly scaled with regard to those of NG and LNG. Indeed, Froude similarity would be sufficient to exactly scale an ideal flow of incompressible liquid without gas simply described by the incompressible Euler equations. But at each time an additional fluid property is involved in the physics of the flow, an associated similarity law is added, implying to relevantly scale the property for right compliance. Having an ullage gas above the liquid, even if considered as incompressible, implies to introduce a density ratio between liquid and gas into the dimensionless form of the incompressible Euler equation. If the gas compressibility is involved, a Mach similarity is to be followed to get a perfect match at different scales. Together with Froude similarity, this obviously leads to Froude-scaling the speed of sound within the gas. For the same reason, involving liquid compressibility leads to Froude-scale the speed of sound within the liquid, etc. This had already been described in Braeunig et al. (2009). The authors called the conditions for this perfect match between small scale and full scale the Complete Froude Scaling, or CFS, conditions. As the compliance with any of these similarity laws, except Froude's and density ratio's, is impossible, the conditions adopted at small scale, called Partial Froude Scaling (PFS), necessarily bias the complete similarity between the flows at both scales. Moreover, changing the scale, but keeping the same fluids at both scales, in the context of Froude scaled inflow conditions before impact is equivalent (means Froude-similar) as keeping the same scale but shifting the properties of the fluids. The larger distance between the scales, the larger the shift to be imposed to the fluid properties.

As mentioned in the report, referring to the work of Lafeber et al. (2012b), the load on the wall of a partially filled moving tank can always be analyzed as a combination of three Elementary Loading Processes (ELPs). At a wall area in contact with gas, the pressure remains constant (ullage pressure) unless the gas is accelerated and compressed, chased off by the wave approach, or the gas is entrapped (ELP3). A wall area in contact with liquid withstands both a hydrostatic and a hydrodynamic load that can generally be estimated as though the liquid were incompressible (ELP2), unless an impact locally creates a discontinuity leading to the generation of a pressure wave inside the liquid (ELP1). This general statement is true whatever the scale of the phenomena occurring at wall.

When considered alone, ELP2 simply follows Froude similarity. ELP1 and ELP3 follow their respective Mach similarity together with the Froude-similar inflow conditions. The scaling problem starts to become complex when the ELPs interact together or with other physical phenomena.

Many R&D studies have been conducted during the last years in order to better understand the physics of liquid impacts and tackle the scaling issue. They focused on various scenarios of single impacts studied either experimentally, numerically or with simple theoretical models used as surrogate models. For each scenario, parametric studies were performed by changing the gas or liquid properties, or the scale.

✓ *Experiments*

Three kinds of experiments are usually proposed: (1) drop tests of a wedge on a water surface initially at rest; (2) SIWs performed in a small-scale tank moved by a sloshing rig; (3) wave impact tests in a flume.

Drop-tests are quite repeatable for large dead-rise angles of the wedge because the gas can escape almost freely without creating free surface instabilities, but the impact load that they generate is very peculiar, following very well Froude similarity as a pure hydrodynamic load (ELP2), and do not represent the generality of liquid impact loads.

Sloshing tests can easily be performed with different gases, even different liquids or different small scales as done by (Karimi et al, 2014, 2015a and 2015b).

Wave impact tests in a flume can be made at large scale but are always performed with water and air. Thus, the only way to study the influence of liquid and gas properties during wave impact tests is to perform the tests at different scales with Froude-similar inflow conditions. Several wave impact test campaigns have been performed in different flume tanks these last years (Bredmose et al. (2009), Brosset et al. (2009), Kaminski et al. (2010), Kimmoun et al. (2010), Kaminski et al. (2011)) in order to study the physics of liquid impacts. More recently a consortium of five British universities performed such tests in Plymouth within the FROTH project. The results are not yet published.

Sloshing tests and wave impact tests present the drawbacks to show large variability of the pressure measurements, at least in the impact areas, and to have a discrete representation of the continuous loads with many large gaps due to the too large distance between pressure sensors with regards to the phenomena involved. These drawbacks lead to restrict the deterministic comparisons of pressures at different scales only to the areas where the pressure measurements are accurately repeatable. Practically, it means inside the gas pockets (ELP3).

✓ *Numerical simulations*

Important CFD works have also been done recently in order to adequately capture liquid impact loads on a rigid wall. As the problem is multi-scale (a few tens of meters for the global flow, a few millimeters for capturing impact pressures) and multi-physics (at least bi-fluid compressible), the requirements in order such simulations make sense are strong. Nevertheless, they theoretically present many advantages:

- Virtual conditions could be easily tested including unrealistic initial conditions or fluid properties;
- Changing the scale is easy, either directly or by shifting the fluid properties;
- Adding or removing some physics (gas or liquid compressibility, phase transition, etc.) is theoretically simple;
- The pressure map on the impacted wall can be as continuous as necessary by refining the grid.

Their main limitations concern the available physics (phase transition is rarely taken into account in the models yet) and the refinement of the grid (it is never dense enough to capture realistically the free surface instabilities). This last point means that the apparent stabilization of the local pressures with regard to the grid refinement should be considered as a pseudo-convergence. Nevertheless, this could be seen as an advantage as it theoretically enables to directly look at the interaction between the three ELPs in the impact area beyond the veil of variability normally brought by experiments. In particular, it enables to deterministically capture the sharp ELP1-type pressure peak in the impact area and compare at different scales, which is not possible experimentally.

The main scenarios of impacts studied numerically, include those studied experimentally: SIWs either in flume tanks or in sloshing tanks. In order to tackle the multi-scale and multi-physics challenges, a strategy is usually applied combining the use of a potential code able to quickly and accurately calculate the inflow conditions before impact (before any local compression of the gas) and a CFD code simulating the impact from these inflow conditions either in the complete domain (Guilcher et al, 2013 and 2014) or in a restricted domain close to the impact area (Costes et al., 2014).

The pressure maps - p(z, t), z being the coordinate along the vertical wall and t the time – obtained through 2D numerical simulations by a SPH software of breaking wave impacts in a flume with water and air (Guilcher et al., 2014) materialize time-space distributions of the ELPs. Whatever the wave, the different areas on the map are well identified with (1) a sharp peak following the first liquid contact at wall and the induced pressure wave (ELP1); (2) two ridges corresponding to the significant hydrodynamic loads (ELP2) at (a) the wave trough and (b) the root of the building jet downwards after the crest impact; (3) the compression and expansion of the gas (ELP3), the former starting during the gas escaping phase. Figure 11 and Figure 12 show respectively a typical pressure map obtained with the SPH code for a gas-pocket impact and a symbolic representation of a liquid impact with the space and time distribution of the ELPs (impact chart).

The sharp peak caused by ELP1 is difficult to experimentally capture because of the complexity of the real local flow with all excrescences or droplets in the vicinity of the crest and the poor density of pressure sensors on the wall with regard to this complexity, not to mention the too large diameter of the sensors with regard to the tiny size of the phenomena to capture. It may be replaced in the reality by a more complex representation mixing many micro combinations of the ELPs for each micro impact.

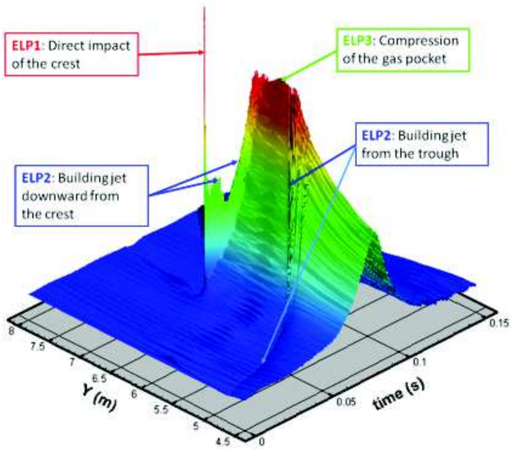


Figure 11: Typical pressure map for a gas pocket impact with description of its different elements by reference to the ELPs.

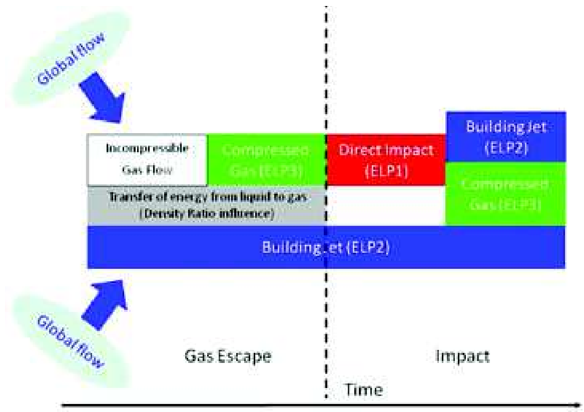
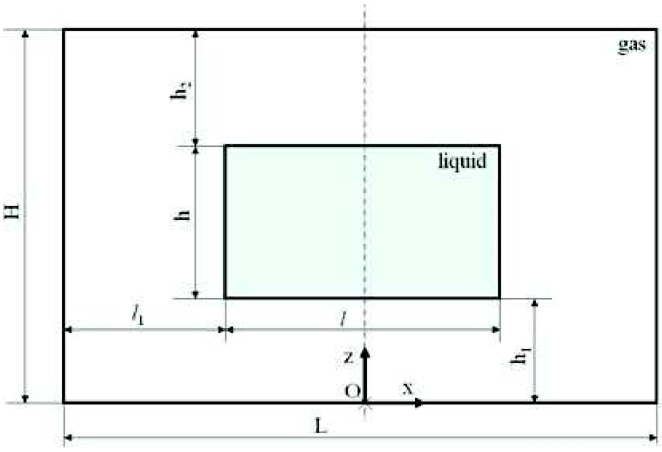


Figure 12: Symbolic representation of the time-space distribution of the load induced by a liquid impact.

As already written, numerical simulations enable to study very simple initial conditions that could not be experimentally carried out. Taking benefit of this advantage, a very simple 2D impact case has been defined, that progressively became a numerical benchmark, piloted by both University College Dublin (UCD) and GTT under the auspices of ISOPE. The case, initially studied by Braeunig et al. (2009), features the free fall of a liquid patch, initially at rest with a rectangular shape, completely surrounded by a gas, also initially at rest, within a rectangular vertical tank subjected to gravity. The different dimensions at scale 1 are given in Figure 13. This test is very simple to implement but nevertheless challenging to simulate as it includes the multi-scale and multi-physics aspects of any liquid impact. It can easily be declined at a given scale with variations of the liquid and gas properties, or at different scales with PFS or CFS conditions. It is wise to start with this simple case and compare with existing results before trying any wave impact simulations.



Parameter	Scale 1 value (m)
H	15
h	8
h_1	2
h_2	5
L	20
l	10
l_1	5

Figure 13: Initial conditions for the numerical benchmark case (liquid patch impact).

Actually, this impact case leads to an interaction between ELP3 and ELP1. The balance between the two ELPs depends on the gas-to-liquid density ratio DR: the smaller DR, the more important the influence of ELP1; the larger DR, the more important the influence of ELP3.

Two successive comparative studies were organized based on this test case. The results of the last one, concerning 9 different codes, were presented during ISOPE conference in 2013 (no paper available). Three variations of the test case were proposed: (a) scale 1 with LNG + NG; (b) scale 1:40 with LNG + NG (PFS conditions); (c) scale 1:40 with scaled properties for the fluids (CFS conditions). When comparing all results together, large variations of the central pressure peak are observed. When restricting to those who performed a convergence study with regard to the grid refinement, a much better comparison is observed with a pressure peak at scale 1 around 16 bars. Anyway, whatever the absolute values calculated by the different codes, each of them obtained the same dimensionless pressures when comparing results at scale 1 (a) and at scale 1:40 (c) with CFS conditions.

✓ *Results*

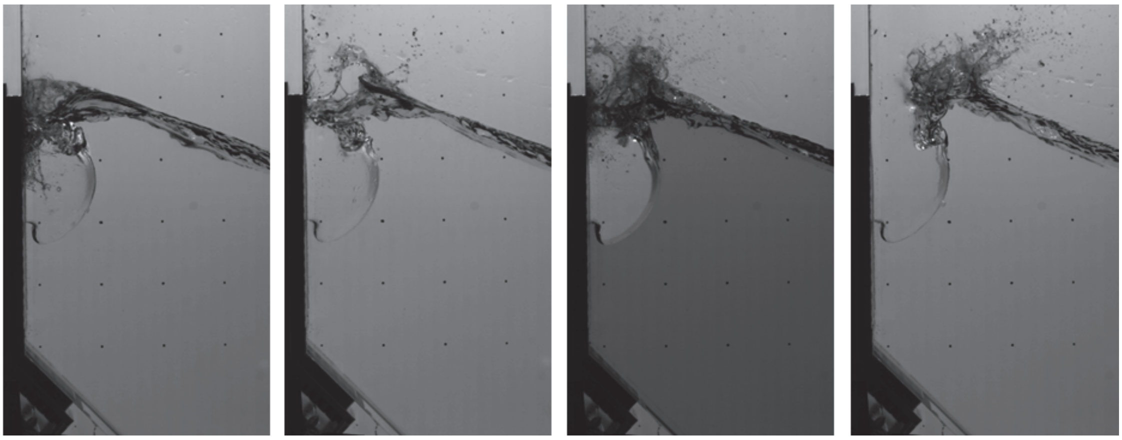
– Gas-to-liquid density ratio (DR)

From sloshing model tests performed with water and different ullage gases (Kuo et al. (2009), Maillard et al. (2009), Ahn et al. (2012)), it has been shown that, statistically, the heavier the ullage gas, the smaller the pressures. Based on this result, sloshing model tests for any project of LNG floating tank are now performed with a heavy gas (usually SF6 + N2) with the same DR as in real LNG tanks. Actually, this result combines the influences of all properties of the ullage gas, not only DR. As the compressibility of a heavier gas tends to be larger and as any gas at small scale is far too stiff with regard to the CFS conditions, having a heavier gas is more representative of the reality also from the gas compressibility point of view.

Karimi et al. (2015b) performed sloshing model tests with a 2D tank representing a transverse slice of the tank#2 of a LNG carrier filled at 20% of the tank height. They tested several SIW conditions (short sway motions inducing a unique impact) with two different liquids and many ullage gases. They compared the wave shapes before impact, before any compression of the gas, in the area of the wave front where the free surface keeps smooth and repeatable, unaffected by any development of free surface instabilities, namely from the trough to the base of the crest.

When repeating the same SIW excitation with two different liquids (water and a 1.8 kg/m3-density solution of Sodium Polytungstate (PST)) and choosing the respective ullage gases in order to get matching DRs, the wave front shape remains precisely the same. Therefore, this shape is independent of the liquid density and only depends on DR (see Figure 14 (b), (c)).

When comparing the same SIW condition with water and different ullage gases, the larger the DR, the less advanced the breaking process is (see Figure 14). The gas seems to impede the breaking process. For larger DRs, the speed of the upward building jet from the trough is slightly reduced.



(a) Water + Helium (DR=0.0003) *(b) Water + air (DR=°0.001)* *(c) Sol. of PST + (SF_6+N_2) (DR=0.001)* *(d) Water + (SF6+N2) (DR=0.004)*

Figure 14: Sloshing tests in a 2D tank filed at 20%H and exited with a SIW condition. Wave shape before impact at the same instant for increasing density ratios from left to right. The two central pictures correspond to the same DR with liquid of different densities.

The numerical results presented in Scolan et al. (2014), based on calculations with a bi-fluid potential code, and in Guilcher et al. (2013) based on a SPH code, fit qualitatively well with these experimental conclusions.

Changing the DR modifies the impact conditions and therefore the nature of impact. The trends that have been listed above could as well magnify the impact pressures or mitigate them when increasing the DR depending on the initial wave shape chosen. Therefore, the conclusions listed here are not sufficient to explain why, statistically, the higher the DR, the smaller the pressure are. The best explanation remains that which was brought by Braeunig et al. (2009): the influence of DR on the wave shape before any compression of the gas is due to a transfer of mechanical energy from the liquid to the gas. The higher the DR, the larger this transfer is, therefore, the smaller the remaining energy of the liquid is. This has been checked during Guilcher's SPH calculations.

– Gas compressibility (GC)

Many recent works, both numerical (Guilcher et al. (2013), Bredmose et al. (2015)) and experimental (Bogaert et al. (2010), Kimmoun et al; (2010), Lafeber et al. (2012a)), have studied at different scales the pressure within gas pockets entrapped by breaking waves impacting a vertical wall for Froude-similar inflow conditions with the same fluids at both scales (PFS conditions). As the same fluids are used at both scales, DR is obviously the same but the gas compressibility at small scale is much too small compared to ideal CFS conditions.

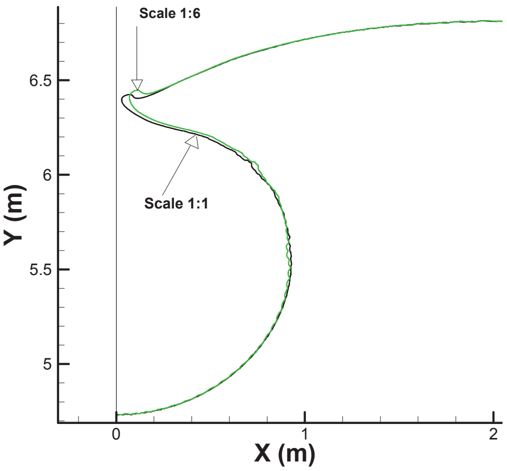
Tests as well as simulations show that pressure can be considered as uniform within the entrapped gas pockets. They also show that the too high stiffness of the gas at small scale leads to higher frequency pulsations of the gas pockets after Froude-scaling. All these studies led to the same conclusion concerning the scaling law for the pressure inside the gas pockets: Bagnold scaling law (Bagnold, 1939) is much closer to the reality than Froude scaling law. Bagnold scaling law is based on the analogy between a gas-pocket entrapped by a breaking wave and a gas pocket piston. This analogy is not perfectly exact. Indeed, in the piston problem, whatever the scale, all the initial kinetic energy of the piston is given to the piston when looking at the maximum pressure inside the pocket, whilst only a part of the mechanical energy of the wave is transferred to the gas pocket and this part has no reason to follow Froude similarity (Brosset et al., 2013).

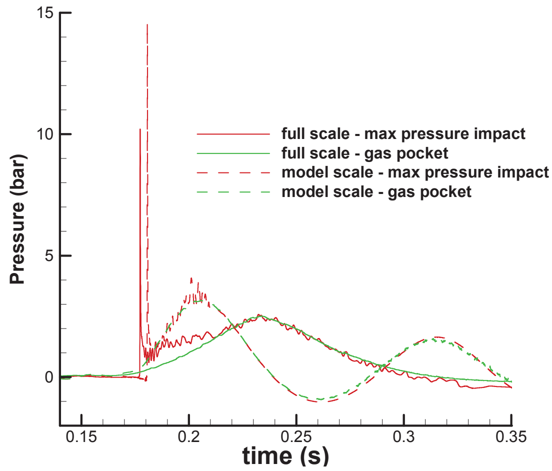
– Liquid compressibility (LC)

The effects of liquid compressibility (ELP1) are expected in the wave impact regions where the free surface instabilities are well developed, inducing a large variability of pressure measurements. Therefore, numerical simulations are best suited for such studies as they simplify the free surface behavior, at least with the level of discretization that is achievable today.

Guilcher et al. (2014) compared the simulations of three breaking wave impacts in a flume at two different scales (scale 1 and scale 1:6) with a SPH code. Their results were presented in ISOPE'2014 conference but without any paper. The simulations were performed with water and air at both scales, therefore with the right DR but with biased (too stiff) gas and liquid compressibility at small scale with regard to CFS conditions.

For the three gas-pocket impacts, the pressure peak due to the impact of the crest onto the wall (ELP1) is significantly larger at scale 1:6, after Froude-scaling, than at scale 1 and the time of maximum pressure is always slightly delayed, after Froude scaling, at scale 1:6 compared to the corresponding time at scale 1. The location where this maximum pressure occurs is also slightly modified as the crest is deviated upwards at small scale. Figure 15 shows the comparison of the wave shapes just before impact at both scales for the largest gas pocket studied. Figure 16 shows the comparison of the pressures at first contact point (ELP1) and in the gas cavity (ELP3) at both scales for the same wave impact as in Figure 15.





Large gas-pocket impact as simulated by SPH-Flow (HydrOcean, Nantes(Fr)) at scale 1 and scale 1:6

Figure 15: Comparison of wave shapes before impact at scale 1 (black) and at scale 1:6 (green) after scaling geometry and time.

Figure 16: Pressure histories at first contact point (red) and in the gas cavity (green).Results at scale 1:6 in dashed lines are Froude-scaled.

As the density ratio is the same at both scales (same fluids are used), the delay and the deviations are only due to the influence of gas compressibility. Whatever the gas-pocket impact, a too stiff gas at scale 1:6 compared to CFS conditions leads to a stronger gas flow during the gas escaping phase which delays the impact and deviates the crest upward. Consequently, the horizontal impact velocity is slightly smaller at scale 1:6, after Froude-scaling, than at scale 1. This leads to a mitigation of the impact and therefore should lead to a smaller pressure peak at scale 1:6 after Froude-scaling. As the opposite is observed, another influence is to be involved: obviously, this is the liquid compressibility, which is involved for any ELP1-type of load. Thus, the too stiff liquid at scale 1:6 leads to a pressure peak which is higher than at scale 1, after Froude-scaling, although the too stiff gas slowed down the crest. The liquid compressibility magnifying influence more than compensates the gas compressibility mitigating influence: Froude-scaling the ELP1-type peak pressures obtained at small scale is conservative.

– <u>Phase Transition (PT)</u>

PT (evaporation and liquefaction) is likely to happen during impacts in LNG floating tanks as the fluid is close to thermo-dynamical equilibrium. Unfortunately, its influence on the loads as not been much studied yet in the context of sloshing.

Sloshing tests have been performed with boiling water and vapor in conditions close to the phase boundary (Maillard et al. (2007), Yung et al. (2010)). Varying the temperature within the tank, therefore the ullage pressure, enabled to study a large range of DRs, moving along the saturation curve. Some of these conditions were repeated with the same DRs as initially but with non-condensable gases. Statistically, the pressure proved to be smaller with PT than without PT.

Moreover, at each time that a vapor pocket was entrapped, the pressure oscillations - that are typically observed with non-condensable gases - were absent. The vapor pocket seemed to behave like a punctured ball without any stiffness.

Ancellin et al. (2012) proposed an extension of Bagnold model for the piston problem, including the energy and mass transfers occurring between a liquid and its vapor during a liquid impact with a vapor pocket entrapped, when the two phases are close to a thermodynamic equilibrium. The model is based on Non-Equilibrium Thermodynamics (NET) and enables to simulate the relaxation phase for a pure fluid in between initial unbalanced thermodynamic conditions and the final equilibrium along the phase boundary.

The model uses the three Onsager's transport coefficients. The values for these parameters are controversial. The large range offered by experimental or theoretical results for these values brings a large uncertainty on the fluid properties used in the model. Nevertheless, whatever the exact values of the Onsager's coefficients in the whole reasonable range for them, phase transition always leads to a reduction of the maximum pressure in the gas pocket and to oscillation damping. These results are qualitatively in line with the experimental results from Maillard et al. (2009).

Now the question is: what happens in the impact area? Behruzi et al. (2014) performed simulations of the liquid patch impact with Flow3D software for the initial conditions recalled in Figure 13 with and without phase change but keeping the same DR. Some results showed an increase of the impact pressure in the center of the impacted tank floor when PT was taken into account.

– Free surface instabilities

As already mentioned the variability of sloshing loads is due to the development of free surface instabilities before impacts and splashing after impacts. It should be considered as part of the sloshing physics related to the surface tension at the interface and viscosity of both the gas and the liquid. As these properties cannot be relevantly scaled, the variability at small scale and related statistics are not necessarily representative of those at full scale. It is expected that the variability is higher at full scale due to larger Weber numbers and thus to more fragmentation of the liquid before the impacts.

Figure 17 shows wave shapes before impact obtained during wave impact tests in two different flume tanks, with water and air, at two different scales (scale 1 on the left and scale 1:6 on the right). The tests were performed during the Sloshel JIP. The pictures are taken before any compression of the gas.

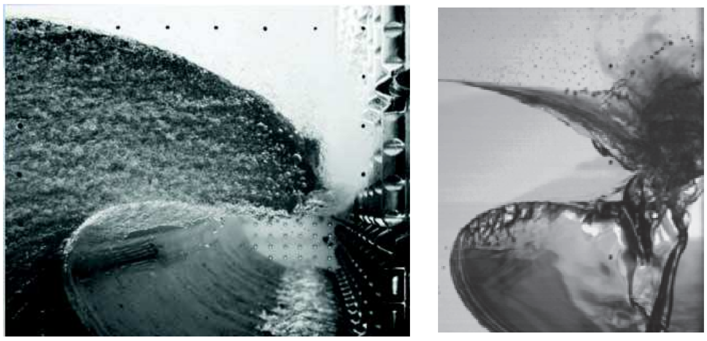


Figure 17: Wave shapes before impact as obtained during wave impact tests in two different flumes (Sloshel JIP). Left: tests at scale 1; right: tests at scale 1:6.

As expected, free surface instabilities develop very differently around the wave crest at both scales: the fragmentation is much more important at larger scale. Indeed, while long water filaments remain connected to the crest at scale 1:6, a spray of droplets wraps the crest at scale 1.

Leakage:

It is referred to a study of Choi et al. (2013) who analysed the flow and thermal characteristics of leaked LNG in glass wool for the Mark III CCS: there is no glass wool in Mark III CCS.

Fatigue: No comment.

Collision, grounding, flooding: No comment.

Sloshing Control:

The membrane containment systems benefit from extremely positive safety track records in conventional operating filling ranges (liquid heel below 10%H or laden condition above 70%H), which enforces the model tests based sloshing assessment as performed by GTT and Classification Societies. Results of the Full Scale Measurement JIP, as presented by DNV-GL & GTT during the last Gastech also show that comparison of sloshing measurement in operating conditions and model test sloshing loads show very satisfying safety margins in these conventional filling ranges (see sloshing section and Figure 1). In non-conventional filling ranges, where a lack of experience prevents any correlation to model test sloshing assessment, ship-owners have expressed their interest for a sloshing monitoring solution in order to allow operational management of sloshing phenomenon by ship crews.

Until recently, the only method the crew had to estimate the sloshing activity were basic and mostly relied on observation of banging noises, which excluded tanks 1 to 3 as they are too remote from the accommodation. There was then a need for a reliable real time indicator of sloshing activity inside all the tanks, to support the decisions from the crew. At least two sloshing monitoring solutions have been proposed recently to meet these requirements: Sens-FibTM developed and commercialized by Light-Structure and GTT's SloShieldTM solution.

To enable installation as a retrofit, the instrumentation of SloShieldTM is simple, light, and non-intrusive. Thanks to advanced analysis of the vibration of the tanks structures, a unique sensor per tank is used. A signal processing has been designed to discriminate sloshing impacts from other noises. It has been correlated to reality onboard a LNGC in operations.

This kind of system supports the decision process of the crew and helps them building up their own sloshing understanding and therefore developing their skills. Through post voyage analysis, it also supports the knowledge capitalization on sloshing.

Fire safety, temperature control of hull structures: No comment.

1.1.4. LNG as a fuel

In addition to the different drivers provided in the report for switching to LNG as ship fuel, such use also helps two-stroke engines to reduce the amount of NOx generated and in some case allowing them to be Tier III compliant.

The third driver, related to price, exhibited in the report is a bit outdated already. LNG prices in Europe and Asia are currently quite low as they are correlated to the crude oil price. However crude oil which was trading at 110 USD/bbl 12 months ago has gone through a low point at less than 50 USD/bbl at the beginning of 2015 but has now recovered to 70 USD/bbl already, which will make the LNG price delivered onboard client ships more competitive.

In addition to the remark on scrubber vs. LNG as fuel: actually, what has been observed since 1st January 2015 when new SOx emissions limitation at 0.1% entered into force in North European and North American SECA, is that a majority of ship-owners shifted to MDO (becoming suddenly relatively cheap as a direct effect of crude oil price reduction), the rest retrofitting their ships to scrubbers and only few making the choice of LNG and only for new buildings.

No bunker ship has been delivered yet but it is worth mentioning that at least four are on order today: One by GDF-SUEZ in Hanjin in Korea (5,100 m3 capacity), another one for Shell in STX Korea (6,300 m3 capacity), another one for Sirius Shipping, a joint venture between Skangass and Anthony Veder in Royal Bodewes in the Netherlands (5,800 m3 capacity), an LNG bunker barge in the US for TOTE/WESPAC (2,200 m3 in membrane). Others are currently under consideration in many places including Southern Europe, Russia, Middle East and Asia.

The text listing the LNG-fueled ships on order has likely been written in 2013 and should be updated. Since then, all the ships mentioned have been delivered and 63 in total are in operation today (3rd June 2015). Another 50 are on order or under construction and several others are planned either as LNG-ready or as LNG-fueled from the beginning. However it can be noticed that the very optimistic view delivered by DNV-GL in 2013 with an expected number of 1000 LNG-fueled ships in operation in 2020 or 2025 will have to be revised probably at half this number or less. But still the number will be significant.

As a comment to the last sentences of the section (However, the engineering works are limited to the design safety construction of LNG tank without risk of collision. The specific research in collision issue for LNG tanks is needed in the future): GTT has already produced number of designs of LNG-fueled very large container ships, addressing the various issues discussed at the IMO (discussions and drafting of the future IGF code) as well as assessment of collisions etc. Most of these studies were carried out jointly with ship-owners, ship designers, Class Societies and have led to Approval in Principle. Membrane containment technologies demonstrating extremely good behavior for use as LNG fuel tanks on such large ships. They look particularly well adapted both from an economic perspective as well as from a safety and operational point of view.

1.1.5. Safety and Design for Special Applications

No comment.

1.1.6. Conclusions

In the implications of the new IGC code, please note that Part F is dedicated to Cargo Containment Systems of Novel Configuration. More precisely §4.27 defines the limit state design for novel concepts.

1.1.7. References

Classification Notes

American Bureau of Shipping, Strength Assessment of Membrane-type LNG Containment systems under Sloshing Loads, Guidance Notes, April 2006 updated July 2009.

Bureau Veritas, Design Sloshing Loads for LNG Membrane Tanks, Guidance Note NI 554 DT R00 E, May 2011.

Det Norske Veritas, Sloshing analysis of LNG membrane tanks. DNV Classification Notes No. 30.9, August 2014.

Lloyds Register, Sloshing Assessment Guidance Document for Membrane Tank LNG Operations, Version 2, May 2009.

Publications

Y. Ahn, S. Y. Kim, K. H. Kim, S. W. Lee, Y. Kim, and J. J. Park (2012). Study on the Effect of Density Ratio of Liquid and Gas in Sloshing Experiment. Proceedings of the 22nd International Offshore and Polar Engineering Conference (ISOPE), Rhodes, Greece. Vol. 3, pages 311 – 317.

M. Ancellin, L. Brosset, and J.-M. Ghidaglia (2012). Influence of phase transition on sloshing impact pressures described by a generalized Bagnold's model. in Proceedings of 22nd International Offshore and Polar Engineering Conference (ISOPE), Rhodes, Greece. Vol. 3, pages 300-310.

Bagnold, R (1939). Interim Report on Wave-Pressure Research, J. Inst. Civil Eng., Vol. 12, pp 201–226.

Bogaert, H, Léonard, S, Brosset, L, and Kaminski, M (2010). Sloshing and Scaling: Results from Sloshel Project, Proc. 20th International Offshore and Polar Engineering Conference (ISOPE), Beijing, China, Vol. 3, pp 88-97.

J.-P. Braeunig, L. Brosset, F. Dias, J.-M. Ghidaglia (2009). Phenomenological study of liquid impacts through 2D compressible two-fluid numerical simulations. Proceedings of the 19th International Offshore and Polar Engineering Conference (ISOPE), Osaka, Japan. vol. 3, pages 21 - 29.

P. Behruzi, M. Konopka, F. de Rose, G. Schwartz (2014), Cryogenic Slosh Modeling in LNG Ship Tanks and Spacecrafts, Proceedings of the 24th International Offshore and Polar Engineering Conference (ISOPE), Pusan, South Korea, Vol. 3, pp. 209-217.

Bredmose, H., Peregrine, D.H., Bullock, G.N. (2009). Violent breaking wave impacts. Part 2: modeling the effect of air, Journal of Fluid Mechanics, vol. 641, pp 389-430.

H. Bredmose, G. N. Bullock, A. J. Hogg (2015). Violent breaking wave impacts. Part 3. Effects of scale and aeration. Journal of Fluid Mechanics, Vol. 765, pp 82-113.

Brosset, L., Mravak, Z., Kaminski, M., Collins, S. and Finnigan, T., (2009). Overview of Sloshel project, Proc. of the 19th International Offshore and Polar Engineering Conference (ISOPE), Osaka, Japan, Vol. 3, pp 115-124.

Brosset, L., Ghidaglia, J.M., Guilcher, P.M., Le Tarnec, L. (2013). Generalized Bagnold Model, Proc. 23rd International Offshore and Polar Engineering Conference (ISOPE), Anchorage, (AK), USA, Vol. 3, pp 209-223.

M. Champagnac, E. Gervaise (2014), Pump Tower – GTT Methodology for Load Determination for Strength Assessment. Proceedings of the 24th International Offshore and Polar Engineering Conference (ISOPE), Pusan, South Korea, Vol. 3, pages 143-149.

Costes, J., Ghidaglia, J.-M., Mrabet, A. A. (2014), On the simulation of liquid impacts on a flat rigid wall by a 2D parallel finite volume solver. Proceedings of the 24th International Offshore and Polar Engineering Conference (ISOPE), Pusan, South Korea, Vol. 3, pages 246-256.

P. G. Drazin and W. H. Reid (2004). Hydrodynamic stability. Cambridge University Press.

Gervaise, E., P.-E. de Sèze, and S. Maillard (2009), Reliability-based methodology for sloshing assessment of membrane LNG vessels. International Journal of Offshore and Polar Engineering, . 19(4): p. 254-263.

Guilcher, P.-M. , Couty, N., Brosset, L. and Le Touzé, D., (2013). Simulations of breaking wave impacts on a rigid wall at two different scales with a two-phase fluid compressible SPH model, Int. Journal of Offshore and Polar Eng. Vol. 23, N° 4, 241-253.

P.-M. Guilcher, Y. Jus, N. Couty, L. Brosset, Y.-M. Scolan, D. Le Touzé (2014). 2D Simulations of breaking wave impacts on a flat rigid wall – Part 1: influence of the wave shape. Proceedings of the 24th International Offshore and Polar Engineering Conference (ISOPE), Pusan, South Korea, Vol. 3, pages 232 - 245.

Kaminski, M.L. and H. Bogaert (2010), Full-Scale Sloshing Impact Tests—Part I. International Journal of Offshore and Polar Engineering, Vol. 20(1), p. 24.

Kaminski, M.L., Bogaert, H., Brosset, L. (2011), Full and large scale wave impact tests for a better understanding of sloshing - Results of the Sloshel project. Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Rotterdam, The Netherlands.

Karimi, M.-R., Brosset, L., Ghidaglia, J.-M., Kaminski, M.-L. (2014), A Study on Conservatism of Froude Scaling for Sloshing Model Tests, in Proc. 24th Int. Ocean and Polar Eng. Conf., (ISOPE), Busan, South Korea, Vol. 3, pp. 306-313.

Karimi, M.-R., Brosset, L., Ghidaglia, J.-M., Kaminski, M.-L. (2015a), Effect of ullage gas on sloshing – Part I: global effects of gas-liquid density ratio. European Journal of Mechanics B/Fluids, Vol. 53, pages 213-228.

Karimi, M.-R., Brosset, L., Ghidaglia, J.-M., Kaminski, M.-L. (2015b), Effect of ullage gas on sloshing – Part II: local effects of gas-liquid density ratio. European Journal of Mechanics B/Fluids, under review. Submitted on March 31, 2015.

O. Kimmoun, A. Ratouis, and L. Brosset (2010). Sloshing and scaling: experimental study in a wave canal at two different scales. Proceedings of the 20th International Offshore and Polar Engineering Conference (ISOPE), Beijing, China, Vol. 3, pp. 33-43.

J. F. Kuo, R. B. Campbell, Z. Ding, S. M. Hoie, A. J. Rinehart, R. E. Sandström, T. W. Yung, M. N. Greer and M. A. Danaczko (2009), LNG tank sloshing assessment methodology - the new generation. International Journal of Offshore and Polar Engineering. 19(4) p. 241.

Lafeber, W., L. Brosset, and H. Bogaert (2012a). Comparison of wave impact tests at large and full scale: Results from the sloshel project. in Proceedings of the 22nd International Offshore and Polar Engineering Conference (ISOPE). Rhodes, Greece, Vol 3, pp 285-299.

Lafeber, W., H. Bogaert, and L. Brosset (2012b). Elementary Loading Processes (ELP) involved in breaking wave impacts: findings from the Sloshel project. in Proc. of the 22nd International Offshore and Polar Engineering Conference (ISOPE). Rhodes, Greece. Vol. 3, pp 265-276.

T. Loysel, E. Gervaise, S. Moreau, L. Brosset (2013). Results of the 2012-2013 Sloshing Model Test Benchmark. Proc. 23rd Int. Offshore and Polar Eng. Conf. (ISOPE), Anchorage, (AK), USA, Vol. 3, pp 141-152.

Lund-Johansen, Ø., Østvold, T.-K., Berthon, C.-F. and Pran, K. (2011), Full Scale Measurements of Sloshing in LNG Tanks, Technical Paper Gastech, Amsterdam, The Netherlands, 2011.

S. Maillard, L. Brosset (2009). Influence of density ratio between liquid and gas on sloshing model test results. International Journal of Offshore and Polar Engineering, 19(4): pages 271 - 279.

Neugebauer, J., Ould el Moctar, B., Potthoff, R. (2014), Experimental and Numerical Investigations of Single Impacts in a 2D Tank, in Proc. 24th Int. Ocean and Polar Eng. Conf. (ISOPE), Busan, South Korea, Vol. 3, pp 286-295.

Østvold, T.-K., Fredriksen, O., Pasquier, R., Nota, C. (2014), Full scale measurement of sloshing on the LNG IMO: summary of findings after 5 years in service, Presentation in Gastech conference, Seoul, Mars 2014.

Pasquier, R., Berthon, C.-F. (2012), Model Scale Test vs. Full Scale Measurement: findings from the Full Scale Measurement of Sloshing project, in Proceedings of the 22nd International Offshore and Polar Engineering Conference (ISOPE). Rhodes, Greece, Vol. 3, pp 277-284.

F. Pistani, K. Thiagarajan (2012), Experimental measurements and data analysis of the impact pressures in a sloshing experiment. Journal of Ocean Engineering Vol. 59, pp. 60-74.

Scolan, Y.-M., (2010). Some aspects of the flip-through phenomenon: A numerical study based on the desingularized technique, Journal of Fluids and Struct. Vol. 26, pp 918-953.

Scolan, Y.-M., Karimi, M.R., Dias, F., Ghidaglia, J.-M., Costes, J., (2014). Highly Nonlinear Wave in Tank with Small Density Ratio, Int. Workshop on Water Waves and Floating Bodies (IWWWFB), March 30- April 2, 2014, Osaka, Japan.

T. W. Yung, R. E. Sandström, H. He, and M. K. Minta, (2010). On the Physics of Vapor/Liquid Interaction During Impact on Solids. Journal of Ship Research, 54(3): pages 174 –183.

1.2 Floor and Written Discussions

1.2.1 Tetsuo Okada (Yokohama National University)

Thank you for your presentation on natural gas storage and transportation.

With regard to the newly revised IGC Code, the report does touch upon it briefly, but considering the committee' s mandate saying "Needs for revision of current codes and regulations shall be addressed", I think that the review on the new IGC Code is not sufficient.

The new IGC Code has introduced many good progresses, but in my opinion, there still remain some points to be further investigated. One example is the limit state methodologies introduced in the APPENDIX of the new IGC Code, to deal with development of a novel cargo containment system. The content of this APPENDIX seems to be rather calibration of partial safety factors with the existing code, than being true reliability based design code.

Secondly, filling limit was more explicitly restricted to 98% when vapor pocket is formed, but technical background is not clear.

Critical review of the revision of the IGC Code by the committee would be appreciated.

2. REPLY BY COMMITTEE V.2

2.1 Answers to the Official Discusser Dr. Laurent Brosset

Official Discusser: Cargo Containment system only addresses new IGC code
Answer: Agreed, new developments were not put forward abundantly
Official Discusser: Typos and additions in IGC code

Answer: Typos and additions corrected

Official Discusser: Sloshing all related issues. The OD presents a whole monograph on Sloshing development
Answer V.2: We welcome the in-depth analysis of the recent developments on the part of sloshing, As the mandate of the committee was not fully embracing all sloshing related issues, since majority parts are covered in ISSC Committee I.2 Loads

Official Discusser: Very stringent requirement for sloshing test, like exact geometry tank walls ceiling etc, motion excitation (through e.g. hexapod)
Answer V.2: We support therefore the bi-annual benchmarking initiative of ISOPE testing SIW and long duration impacts.

Official Discusser: Numerical methods partially well developed especially 'far' from the impact. Need for development numerical techniques to to into account the free surface instabilities
Answer V.2: Agree. It will be a very challenging task to both describe the large scales as well as the small instability scales

Official Discusser: Experiments, SIW tests and sloshing tests show large variability of pressure measurements, thus difficult to use for deterministic comparison
Answer V.2: Agree. New developments are on the horizon with e.g. the SLING project.(Sloshing of Liquid Natural Gas).

Official Discusser: Sloshing Control Development of Sloshing indicator for crew, also as a retrofit
Answer: Acknowledged

Official Discusser: LNG as fuel: Ship owners now shift to MDO with retro fittings. Only few make step to LNG
Answer V.2: We acknowledge that the recent steep price drop in oil a considerable delay is foreseen in the shift to LNG as fuel.

Official Discusser: Collision issue. Nowadays at GTT made several designs of LNG fueled Containerships
Answer V.2: As a committee we were not fully aware of these developments

Official Discusser: Several ISOPE published papers brought to our attention
Answer V.2: We welcome the addition of the papers, some of them were not within the deadline of our report schedule.

2.2 Answers to Prof. Tetsuo Okada (Yokohama National University)

Answer V.2: From the committee's mandate also the new IGC code should be further investigated, we agree on that with the discusser.

On the second part. For the special case of membrane containment systems, we can refer to DNV report No. 30.9 Sloshing Analysis of LNG Membrane Tanks, AUGUST 2014 which includes a discussion on the fill level and the types of loads that can be expected at each level. Furthermore and in practice (see BV notes) Standard Fill Levels are from 70% of tank height to 98% of tank height and from 0% to 10% of tank height. If for any reason intermediate fill levels are to be used, a dedicated study on the possible sloshing loads should be carried out.

2.3 References

Det Norske Veritas Class Notes No. 30.9: (2014). Sloshing Analysis of LNG Membrane Tanks.
Bureau Veritas: (2011). Design Sloshing Loads for LNG Membrane Tanks, Guidance Note NI 554 DT R00 E.