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Author M.L. Kaminski and H. Bogaert

Address Delft University of Technology
Ship Hydromechanics Laboratory
Mekelweg 2, 2628 CD Delft

TUDelft
Delft University of Technology

Full Scale Sloshing Impact Tests
Part 1

by

H. Bogaert, L. Brosset and M.L. Kaminski

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Full-Scale Sloshing Impact Tests—Part I

Miroslaw Lech Kaminski and Hannes Bogaert
MARIN, Hydro Structural Services, Wageningen, The Netherlands

This paper describes the first full-scale tests on a real membrane containment system subjected to the action of breaking waves representative of sloshing impacts in LNG tanks. The waves were generated in a water flume using a wave focusing method. The tests were carried out within the Sloshel project, which is described in several accompanying papers. This paper focuses on describing the test method, the experimental setup and the post processing of the data collected in 110 tests; it explains how the project goals were translated into the design of the test setup and the instrumentation. Then it describes an extensive qualification of the data acquisition system and sensors. Emphasis is on the sensors developed within the project, such as pressure gauges and a novel optical sensor capturing the last stage of the sloshing impact. The test programme and some preliminary results are summarised. Conclusions are given regarding system performance, data quality and the use of data for achieving the project goals.

INTRODUCTION

In this paper, Brosset, Mravak, Kaminski, Collins and Finnigan (2009) introduce the Sloshel experiment, designed to collect full-scale data describing sloshing impacts and associated structural response. This data set will be used to verify different assessment methods of membrane-type containment systems subjected to sloshing.

Conventional sloshing assessments of new membrane LNG carriers traditionally follow the comparative approach that is based on small-scale model testing, numerical simulations and over 40 years of successful operating experience of LNG carriers. Model testing provides the maximum loads, based on the statistical analysis of measured pressures. The response of the containment system to these loads is numerically simulated and checked against different limit states.

However, with the filling level limitation on the current fleet, experience is lacking to support comparative methods for partially filling cargo tanks. To move forward, the industry is developing a methodology to assess membrane systems by a direct comparison of the loads and the structural capacity. To develop such a methodology, MARIN recognised the need for full-scale validation already back in 2003 (Fig. 1).

Sloshel, a confidential joint industry project, was organised. The scope of work included full- and large-scale tests being carried out by MARIN, developments of simplified numerical methods being carried out by Bureau Veritas, and validation studies being carried out by individual consortium members.

This paper describes full-scale sloshing tests successfully carried out by MARIN in the Delta flume operated by Deltares. Malenica, Korobkin, Ten, Gazzola, Mravak, De-Lauzon and Scolan (2009) described simplified numerical methods they have developed. Maguire, Whitworth, Oguibe, Radosavljevic and Carden (2009), and Wang and Shin (2009) described validation studies undertaken by LR and ABS, respectively.

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KEY WORDS: Sloshing, full-scale testing, large-scale testing, LNG, membrane containment systems, NO96, pressure sensors.

TEST METHOD

As stated in the Introduction, the sloshing assessment of a membrane LNG vessel has traditionally been carried out using small-scale model tests and additional numerical simulations. The questions are:

• How close to reality are these experimental and numerical models?

• What are the hydroelastic and scale effects?

In order to answer these questions full-scale data are needed, with simultaneous measurements of fluid dynamics and structural response. But the question was:

• How to obtain full-scale data?

So, first of all the following wish list was formulated about the way the full-scale data should be collected:

- in full scale
- with a real containment system
- with sloshing impacts such as those in LNG membrane tanks
- with many sloshing impacts
- with measurable impact conditions and structural response
- with controllable and repeatable sloshing impacts
- in cryogenic conditions
- with LNG

Then, the different concepts listed in Table 1 were proposed and evaluated. None of these concepts was accepted because of the reasons given in the table. Following that, it was concluded that the complete wish list cannot be satisfied, and it was agreed to release the list's last 2 requirements and to carry out the full-scale testing with water. In this way the allowance for cryogenic conditions was shifted to the material testing and associated acceptance criteria. The different behaviour of water with air at ambient pres-

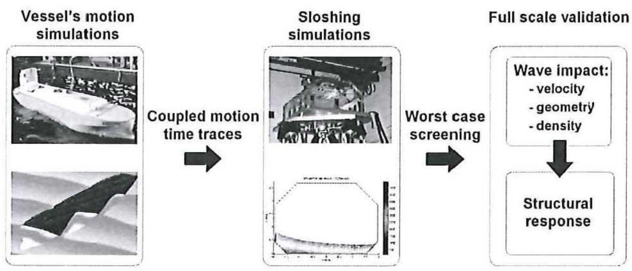


Fig. 1 Sloshing assessment and role of Sloshel project

Concept	Rejection arguments
Monitoring of LNG carrier	Small chance of sloshing events
	Difficult inspection
	No partial filling
	Unknown impact conditions
	Too long a project duration
Dedicated 3D tank 1:3 size and real CS	Different excitation & sloshing conditions
	Safety issues & too long an access time
	Too complex an auxiliary installation
Dedicated 2D tank 1:3 size and real CS	Different excitation & sloshing conditions
	Different boundary conditions of CS
	Safety issues & difficult access
	Too complex an auxiliary installation

Table 1 Different rejected concepts for full-scale testing

sure and LNG with its saturated vapour was accepted. It is considered that tools validated against such full-scale data will provide much higher confidence, and that either computational fluid dynamics (CFD) or small-scale testing with LNG would provide some correction factors.

Finally, the concept of generating breaking waves in a coastal engineering flume by a wave focusing method was selected. This concept was proposed by BV and is referred to as the Sloshel test method.

The Delta flume operated by Deltares (Fig. 2) was selected as the test facility. The open-air part of the flume is 5 m wide and 7 m deep. At the south end of the flume there is a huge piston of 800-kW power and 5-m stroke. This piston, with the 2nd-order wave steering system, was used for wave generation. A transverse test wall was placed 145.16 m from the piston's zero position; this test wall is described below.

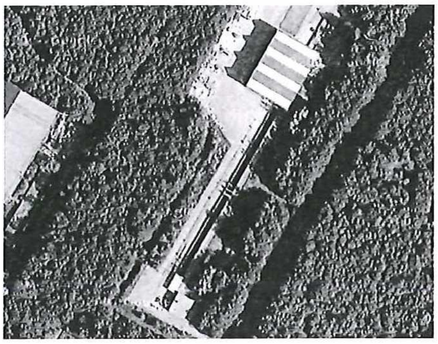


Fig. 2 The Delta flume

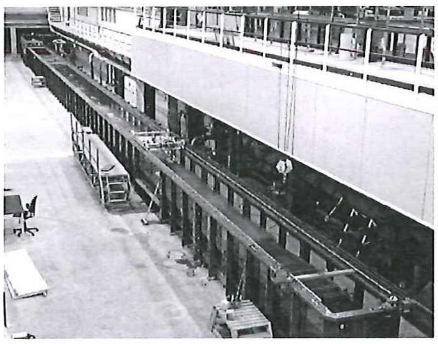


Fig. 3 The Scheldt flume

Fig. 4 Breaking wave generation, without test wall

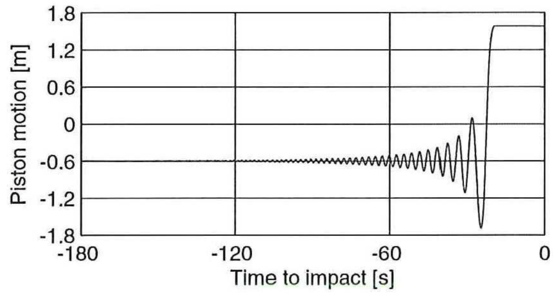


Fig. 5 Example of piston motion

Fig. 4 shows the process of generating a breaking wave by the wave focusing method. The piston generates successive waves of increasing length and height. The longer the waves, the faster they propagate. The wave train is generated in such a way that all waves converge at one longitudinal position of the flume and produce a single, large breaking wave. The position where the wave breaks is called the focal point. Fig. 5 gives an example of measured piston motion. Having selected the full-scale test method, it was necessary to prove that the waves generated by the wave focusing method and breaking on a vertical wall in a flume are representative of sloshing in membrane LNG tanks. The focus is on low filling levels. For this reason, Deltares carried out the first series of large-scale testing in the Scheldt flume shown in Fig. 3.

The Scheldt flume is a 1:5 scale copy of the Delta flume. It was found that different impact types can be obtained by changing the position of the focal point with respect to the transverse wall, and that there is no need to modify bottom bathymetry, i.e. the bottom could remain flat and horizontal contrary to real LNG membrane tanks.

The video recordings from these tests (Fig. 6) were first compared by BV and GTT with video recordings from traditional small-scale (1:40) testing, using tanks made of Plexiglas.

The authors performed additional comparisons between a third series of tests at the Scheldt flume and 1:10-scale sloshing tests carried out within the ComFLOW-2 project (Bunnik and Huijsmans, 2007). In this project, the low filling ratios were studied. Fig. 7 shows a flip-through type of the impact observed in the ComFLOW-2 tests (1:10); this impact type is introduced below. Although the kinematics has not been investigated, Figs. 6 and 7 show that the wave profiles in a flume are similar to those in a 2D sloshing tank at low filling levels. Lugni, Brocchini and Faltinsen (2006) reported similar wave profiles.

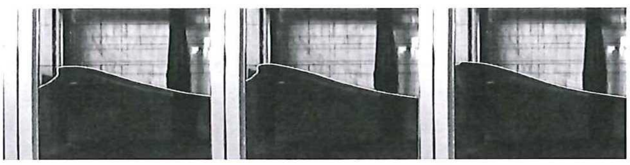


Fig. 6 A flip-through impact: Sloshel large-scale tests (1:6)

Fig. 7 A flip-through impact: ComFLOW-2 large-scale tests (1:10)

TEST SETUP

Test Wall

In order to assess hydroelastic effects it was decided to test a rigid structure and a containment system simultaneously, assuming that impacts would be predominantly 2D, i.e. constant over the wall width, as was observed during the large-scale testing in the Scheldt flume.

Anticipating that different containment systems will be tested in the future, it was decided to make a modular design of the test wall. Figs. 8 and 9 show the final design; the test wall is an assembly consisting of the front wall with the test panel, the base wall and 3 propped support steel beams (brackets).

It must be noted that available formulas for estimating loads on vertical walls subjected to breaking waves give very different answers. Thus the consortium decided to carry out a second series of large-scale tests in the Scheldt flume. Based on these tests, the design force was specified at 6.1 MN. The Delta flume had to be strengthened in order to resist this force and provide sufficient support for the test wall.

The test wall construction sequence was as follows. First, 3 brackets were bolted to the flume bottom. Then, 4 concrete slabs (depth × width × height = 0.75 × 5 × 2 m) were successively bolted to the brackets and to each other. These slabs formed the base wall. Following that, the test panel and several concrete slabs, of the same depth and width but different heights, were successively bolted to each other and to the base wall. In this way the flush front wall was formed. All bolts were pre-tensioned.

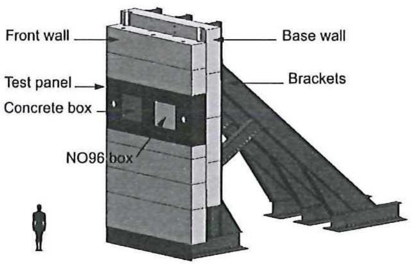


Fig. 8 Test wall design

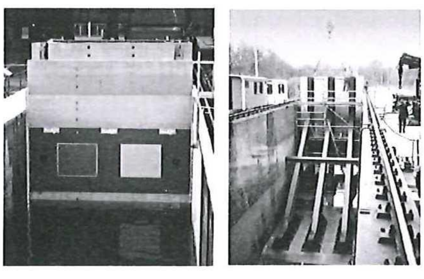


Fig. 9 Test wall as installed in Delta flume

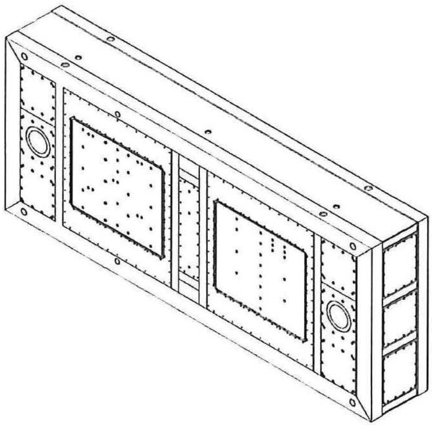


Fig. 10 Test panel design

It was intended to test different impact intensities by changing the water depth. To align the test panel with the vertical position of the impact zone, concrete slabs of different heights were applied. Vertical position changes of 0.25 m could be made. In addition, small water depth variations were made to locate the high-impact pressures on the upper part of the NO96 box.

Test Panel

The test panel was designed modularly and can accommodate 2 test structures, the data acquisition system, 2 high-speed cameras and auxiliary systems such as the leak detection system and the camera surveillance system. Fig. 10 shows the test panel design; Fig. 11, the panel just after placement during the front wall erection.

In the full-scale tests, 2 test structures were tested: a concrete block (1500 kg) and a containment system of the N096 type. The N096 box consisted of primary and secondary plywood boxes. Standard reinforced boxes were tested. The front area of both tested structures was the same: 1.2 m in width, 1 m in height. The intention is to keep the concrete block in future tests as a reference. The tested structures were first placed in their test cubes, which were then installed in the test panel and sealed. A considerable effort was made to select a proper sealing method that would not affect the measurements and would sustain multiple impacts. An inflatable sealing did not pass qualification tests. Finally, flexible mastic was used (Fig. 21).

The consortium decided to test the NO96 boxes without their primary and secondary 0.7-mm invar membranes; this was because the main function of both membranes is to assure gas and fluid tightness, which was irrelevant for the reported tests. Further, neither membrane affects the interaction between the impacting

Fig. 11 Test panel

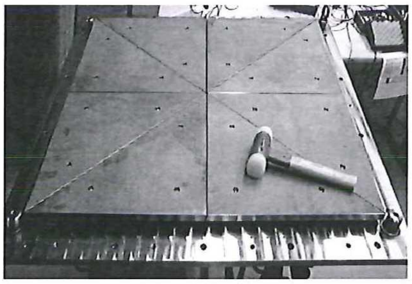


Fig. 12 Force plate

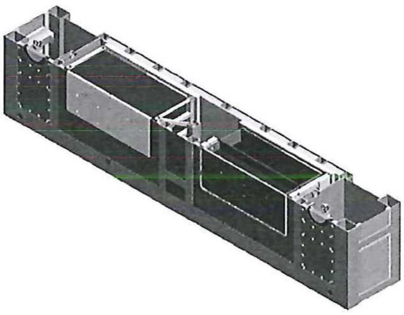


Fig. 13 NO96 and concrete cubes' designs

water and the boxes. The effect of invar tongues on the flow was disregarded.

Test Cubes

A test cube was designed for each tested structure. The test cubes provided adequate boundary conditions for the tested structures and allowed the contact forces between and accelerations of the tested structures and their support to be measured. The contact forces and accelerations were measured by the force plate shown in Fig. 12. Fig. 13 shows designs of the NO96 and the concrete cubes placed in the test panel.

The NO96 boxes were mounted in the cube just as they are mounted in a real LNG tank. First, a paper sheet and then resin ropes were applied on the force plate. Second, the boxes were placed and pre-tensioned on their corners against the supporting frame by couplers. The 4 pre-tensioning forces were measured by load cells. The concrete block was similarly installed.

NO96 boxes

The NO96 boxes were delivered by a manufacturer from Spain. The bottom plywood plates were not stapled in order to allow for internal instrumentation (Fig. 14). After the instrumentation, the boxes were closed by GTT engineers just as they would be closed by the manufacturer (Fig. 15). The boxes were not filled with perlite granules. The invar tongue slits in the cover plate of

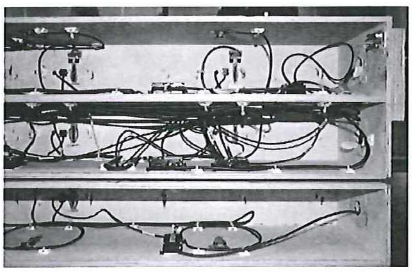


Fig. 14 Interior of primary box

Fig. 15 Closing primary box

the primary box were filled with flexible mastic. The cover plate was then painted. The mass of NO96 boxes was 94 kg.

INSTRUMENTATION

General

The Sloshel project focuses on a direct link between impact conditions and structural response. However, because the present design methods use pressures as a governing parameter, the Sloshel consortium decided to measure pressures on the interface surface between the fluid and the impacted structure. This allows for correlating the new and existing methods. Fig. 16 shows schematically different media involved in a sloshing event. The behaviour of each medium and the interaction surface were measured.

Table 2 gives an overview of measured quantities and sensors. MARIN was responsible for the measurement of all quantities. Deltares provided the sensors and signals marked by an asterisk in the table; MARIN provided all remaining sensors and signals. The data acquisition system (DAS), the iCAM sensor and the pressure sensors, only, are described below. The systems performance was very good; over 99% of all sensors were working at the end of testing.

Data Acquisition System

MARIN used a high-tech, state-of-the-art, shock-resistant, modular, compact and 16-bits DAS for 300 channels with a sampling rate of 50 kHz per channel. A single Ethernet cable connected the system seating in the test panel with an external computer in the control room. This system was the single-shot system with a circular data buffer and was set to keep data 1 s before and 2 s after one of the pressure sensors reached a predefined threshold level. The system was qualified using the shooting apparatus shown in Fig. 19. All systems were synchronised with an accuracy of 20 μs. The pressures measured by Deltares were sampled with 25 kHz.

iCAM Sensor

A very important aspect of the hydrodynamic impacts is their type. In the small-scale tests using Plexiglas tanks or in the large-scale tests in the Scheldt flume, the type of impact can be observed and recorded visually because the tank walls are transparent.

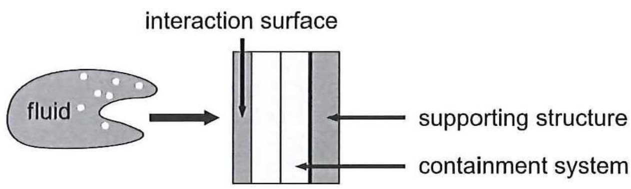


Fig. 16 Media involved in sloshing event

Medium	Quantity	Sensor description
Air	Wind direction	Anemometer*
	Wind speed	Anemometer*
	Temperature	Thermometer*
Water	Piston motion	Displacement sensor*
	Wave elevation	3 wave probes*
		2 video cameras*
		5 video cameras
	Wave velocity	5 video cameras (idem)
		iCAM (640 sensors)
	Impact type	iCAM (idem)
	Impact aeration	iCAM (Idem)
	Water depth	Manual gauge*
	Temperature	Thermometer*
NO96 box		
Interaction surface	Pressures	20 pressure gauges
	Velocities	20 accelerometers
Response	Strains	142 strain gauges
	Accelerations	24 accelerometers
Supporting structure	Forces	24 load cells
		4 couplers with load cells
	Accelerations	5 accelerometers
Concrete block		
Interaction surface	Pressures	10 pressure gauges
	Velocities	5 accelerometers
Supporting structure	Forces	24 load cells
		4 couplers with load cells
	Accelerations	5 accelerometers
Test panel		
	Pressures	2 pressure gauges*
	Accelerations	3 accelerometers
	Integrity	2 internal video cameras
	Leak	2 leak tapes
Test wall		
Front wall	Pressures	11 pressure gauges*
Base wall	Accelerations	2 accelerometers*
	Accelerations	6 accelerometers
Brackets	Forces	4 strain gauges

Table 2 Overview of instrumentation

Because this is not the case in the Delta flume, an alternative way of capturing the impact evolution had to be applied.

For this reason MARIN, in co-operation with Optel in The Netherlands, developed the impact capturing matrix sensor (iCAM). The iCAM sensor consisted of 640 single optical sensors covering an area 3 m high and 1.5 m wide. The distance between sensors was 7.5 cm and 10 cm in the vertical and horizontal direction, respectively. Each sensor was able to distinguish air, aerated water and solid water whether its surface was dry or covered by a water film. The iCAM sensor was placed on the east wall of the Delta flume (Fig. 17) just in front of the test panel.

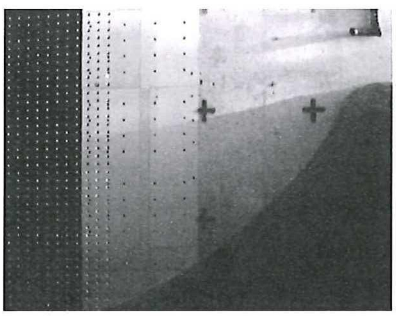


Fig. 17 iCAM sensor mounted on flume's east wall

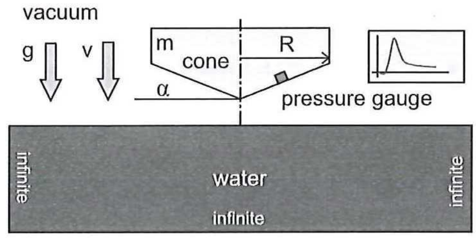


Fig. 18 Verification conditions of pressure sensors

The disturbing effect of iCAM on the breaking wave was minimized by its thickness of only 25 mm. The water tightness of the iCAM sensor was monitored by a separate leak-detection system. The iCAM sensor was sampling with 3 or 15 kHz, and the high-speed video cameras ran at 100 Hz.

The iCAM sensor performed very well and delivered crucial data that allowed the investigating the type of each impact and validation of hydrodynamic computations. For example, Figs. 26~29 were obtained from the iCAM data.

Pressure Sensors

The measurement of pressures exerted by a fluid on a structure during hydrodynamic impact is not straightforward because:

- the impact can be of very short duration and hence the pressure gauge should have a very high natural frequency;
- during an impact, the gauge experiences a thermal shock because it and the supporting structure are immersed in a medium of different thermal conductivity'
- during an impact, the gauge experiences a high acceleration;
- the gauge has a sensing area with finite dimensions;
- the pressure is affected by vibrations of the supporting structure; and
- the data acquisition system may have a limited sampling rate and different filters that may change the actual pressure.

Thus, in general, the recorded pressures differ from actual pressures. Aware of this, the consortium decided to qualify the whole chain of pressure measurement including pressure sensors and the DAS in hydrodynamic conditions that are representative of sloshing events. The qualification process included selection of representative conditions, prediction of actual pressures, experiments and evaluation. Fig. 18 shows the selected condition which could be numerically and experimentally realised. It was a cone with mass (m), radius (R) and rise angle (α) that impact perpendicularly a flat water surface at a certain initial velocity (v) in a vacuum in the gravitational field (g).

On the one hand, based on the modified Wagner theory, ECM developed software predicting pressures at an arbitrary point on the cone as a function of cone parameters, varying penetration velocity and small deviations from perpendicular conditions (Scolan and Korobkin, 2001). On the other hand, MARIN designed and carried out experiments that as far as possible mimicked the selected condition. The most important condition was that the cone had to penetrate the water as a free body. For this reason, a dedicated shooting apparatus (Fig. 19) was designed, manufactured and tested within the project. The apparatus could shoot a cone of a maximum 80 kg with a radius of maximum 200 mm into water with an initial velocity of maximum 12 m/s and angular deviation of maximum 2°. The pressure gauges were tested in air using a cone weighing 50 kg and with a 75° rise angle and 200-m radius. Each pressure gauge was tested 10 times. The pressure gauges were mounted at a 100-mm radius.

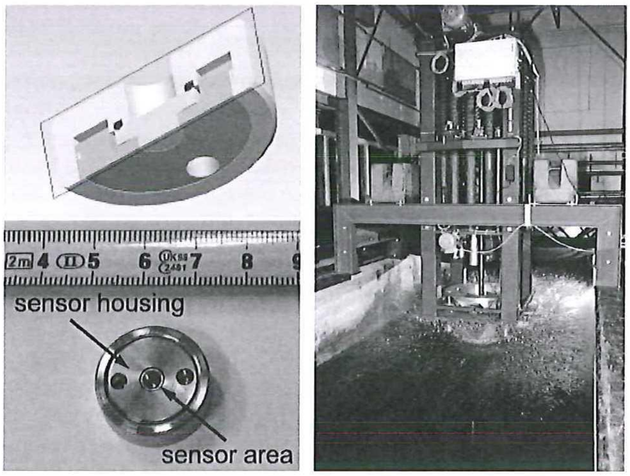


Fig. 19 Pressure gauge including housing and shooting apparatus

Originally the selected pressure gauges did not match numerical predictions. This helped, however, to identify these gauges' weak points and resulted in new requirements, namely insensitivity to accelerations and a low power use of the sensor in combination with thermal isolation of the membrane to reduce its thermal sensitivity. Because no standard gauge could meet the new requirements, a dedicated gauge was designed and manufactured for the project. The new pressure gauges showed good agreement between the measurement data and the numerical predictions. The results were also repeatable, as illustrated in Fig. 20. It should be noted that when comparing the numerical and experimental pressures, the numerical pressures have to be first obtained for the numerical time step that corresponds with the experimental sampling rate, and then the numerical pressures have to be integrated over the sensor area (1.3 mm in diameter).

The consortium decided to integrate the pressure gauges directly in the cover plate of the primary reinforced NO96 box. In order to do this, a housing for the pressure gauge needed to be designed and qualified. The same housing (Fig. 19) was used when the pressure gauge was mounted in the cone. The housing of the pressure gauge was glued in the cover plate. Two tests were carried out to qualify the mounting procedure. The first test was the pull test till failure; the design passed the test as the pulling force was much larger than the force associated with the housing's 200-g acceleration. Fig. 21 shows the pressure gauge housing integrated in a mini box which was placed in a cylinder for the second test. This cylinder was dropped 10 times using the shooting apparatus with a speed of 8 m/s against the water surface; the photo was taken after the second test. The same test was used to qualify the painting and sealing of both tested structures.

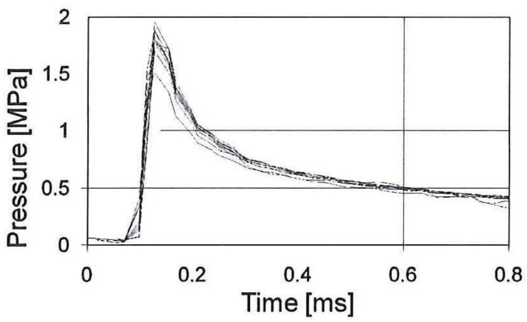


Fig. 20 Cone pressures recorded in 10 different tests

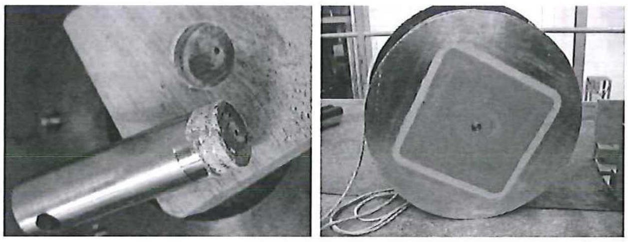


Fig. 21 Qualification tests of pressure gauge housing, paint and seal

SYSTEM IDENTIFICATION

In order to interpret measurements and validate numerical simulations, the static calibration tests and the dynamic system identification were carried out. The static tests with a water-filled bladder (up to 520 kPa) and with rubber strips (up to 250 kN) were carried out in cooperation with CEBTP-Solen in France. Fig. 22 shows the NO96 boxes just before the calibration test using 2 rubber strips at both ends; strain measurements from these calibration tests were used to validate different Finite Element models of the boxes. In another static test the Young's modulus of the plywood was estimated to be 9.85 GPa.

The dynamic system identification was carried out by defining the frequencies and shapes of several of the lowest natural vibration modes of the test wall and the primary reinforced NO96 box. Table 3 shows the first natural frequency of the test wall (installed in the Delta flume) depending on the water depth and the test panel position. Fig. 23 shows the first 2 mode shapes; the lower 2 nodes are assumed to be fixed. As expected, the natural frequencies of the test wall were low and insured that the test panel

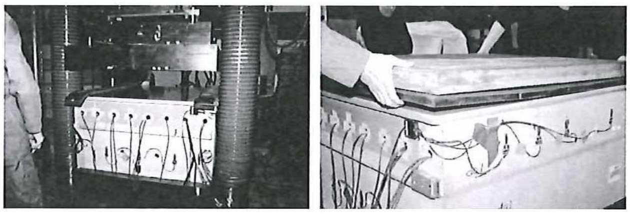


Fig. 22 NO96 boxes before static calibration tests at CEBTP

Test panel position	Water depth	First natural frequency
m	m	Hz
3.5	3.50	13.1
3.5	3.30	13.9
3.5	4.25	11.7
4.5	4.00	12.0

Table 3 Test wall's first natural frequencies

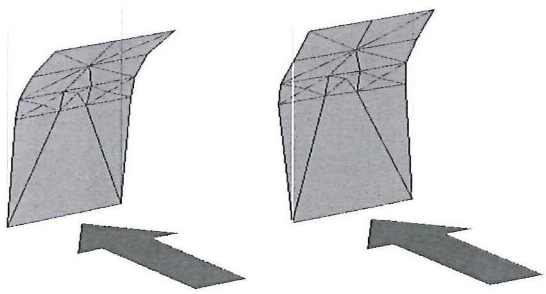


Fig. 23 Test wall's first and second vibration modes

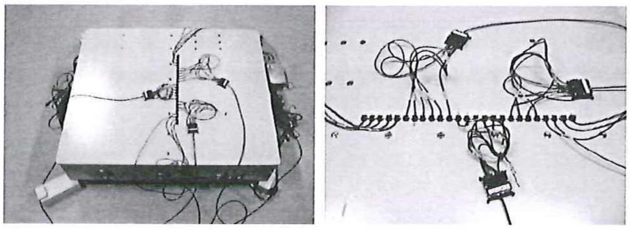


Fig. 24 Primary NO96 box with external accelerometers

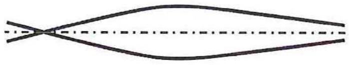
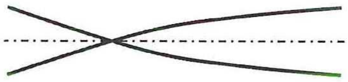
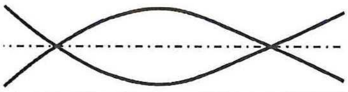
Frequency Hz	Damping ratio %	Shape (along accelerometers)
135	5.9	
171	3.2	
225	3.6	

Table 4 First 3 natural frequencies of primary NO96 box

with the test structures was properly supported, i.e. the maximum impact on the test panel was gone before the wall started to move.

The dynamic system identification for the primary reinforced NO96 box was carried out after the full-scale testing at MARIN. The box was resting on its 4 corners as shown in Fig. 24. Table 4 summarizes obtained results that were used to verify dynamic FE models of the primary box.

TEST PROGRAMME

The goals were to assess the hydroelastic effects and to collect data for the validation of the numerical tools used by the industry to verify containment systems in partially filled LNG tanks. Further, it was also planned to estimate scale effects by repeating the same tests in 1:6 scale. The original test programme included repeated tests of 3 impact types at 3 impact intensities (i.e. 3 water depth levels associated with different vertical positions of the test panel). Fig. 25 shows the originally considered impact types; for these impact types, BV was developing simplified numerical methods.

However, after several tests it became clear that achieving these goals would require more effort than originally anticipated. It was found that the same piston settings were resulting in different responses. Hence, the tests were not satisfying the repeatability condition. The tests were not repeatable because of 2 effects that were amplifying each other.

First, the sloshing impacts were generated in an open-air flume using the wave focusing method. The waves of increasing height and length generated at one flume end had to travel about 145 m before coming together and impacting the wall at the opposite flume end. As the flume is an open-air flume, the travelling waves were subjected to wind action which varied in force and direction. So, the wind was changing the wave focusing process and was consequently responsible for producing different impact types and associated responses for the same piston settings. Hereafter, this effect is called the wind effect.

Second, the first full-scale tests showed that the flip-through type of impact (described below), which was originally not considered, was producing not only the largest pressures on both tested structures but the largest response of the NO96 boxes as well. The physics of the flip-through impact captured by the iCAM sensor revealed that the impact is very sensitive to the breaking wave's surface perturbations. These perturbations were in the range of iCAM resolution, i.e. 10 cm. Hereafter, this second effect is called the perturbation effect.

The consortium decided to deal with both effects in the following way. The wind effect was specific to the way the full-scale tests were carried out and was accepted because the actual impact types were captured by the iCAM sensor. The challenge was to select piston settings that at actual wind conditions resulted in a desired impact type. For future tests it is planned to cover the flume. The perturbation effect resulted in a different test programme. It was decided to repeat the flip-through impact type as much as possible. For this reason the tests were carried out for only 2 impact intensities (i.e. 2 vertical positions of the test panel).

In total, 110 full-scale tests were carried out. Each test lasted approximately 5 min starting from the wave generation to impact. Fig. 26 shows 4 stages of full-scale impact. After each test the water in the flume was stabilised for 25 min; this time was used to download and process the measured data. A measuring report was produced 20 minutes after each test, and one could decide about the next test. Approximately 250 GB of data was recorded. MARIN developed dedicated analysis software with a quick data access and visualisation.

Based on the iCAM, video and pressure data, the full-scale tests were classified into 4 impact types: aerated, air pocket, flip-through and slosh. For each impact type the tests were further subdivided into several groups depending on the water depth and the vertical position of the test panel (Table 5).

These impacts have the following characteristics:

Aerated impact: The wave breaks before reaching the wall, curls over and strikes the free surface, entrapping an air pocket which breaks up into a cloud of bubbles. The aerated wave front hits the wall and deflects upwards. This front is compressed by the following impacting water. Fig. 27 illustrates the wave shape and the pressure profile during an aerated impact. Fig. 31 gives the pressure time series along the centreline of the concrete block.

Air pocket impact: The wave breaks closer to the wall, curls over and strikes the wall before collapsing. A large air pocket is entrapped. Two pressure distributions are present: higher pressures with shorter durations due to the impinging wave crest, and smaller pressures with longer durations acting on a larger area due to compression of the air pocket. The frequency of the resulting oscillations shows the size of the air pocket. The higher the frequency, the smaller the entrapped air (Figs. 28 and 31).

Flip-through: When the wave approaches the wall at the moment the wave—in the absence of the wall—would have just

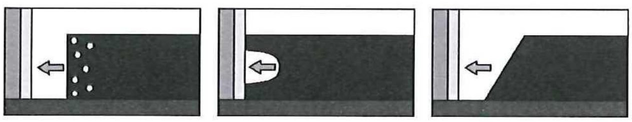


Fig. 25 Schematic representation of originally considered impacts

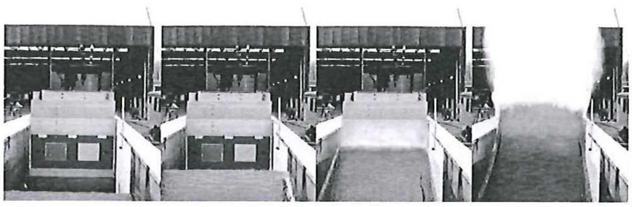


Fig. 26 Example of full-scale test

Impact type	Panel position	Water depth	Test numbers
—	m	m	—
Aerated	3.5	3.50	4, 7, 10, 14, 18
	4.5	4.25	49, 61, 65
	4.5	4.00	86
Air pocket	3.5	3.50	2, 8, 15, 19, 20, 21, 22, 28, 29, 42, 43, 44, 45, 46, 47
	3.5	3.30	33, 36
	4.5	4.25	50, 58, 59, 60, 62, 63, 64
	4.5	4.00	66, 67, 68, 69, 70, 71, 72, 79, 80, 81, 89, 90, 91, 92, 93, 94, 95, 96, 98, 101, 102
Flip-trough	3.5	3.50	1, 5, 11, 25, 26
	3.5	3.30	30, 31, 32, 34, 35, 37, 38, 39, 40, 41
	4.5	4.25	51, 52, 53, 54, 55, 56, 57
	4.5	4.00	73, 74, 75, 76, 77, 78, 82, 85, 88, 97, 99, 100, 103, 104, 107, 108, 109, 110
Slosh	3.5	3.50	3, 6, 9, 12, 13, 16, 17, 23, 24, 27
	4.5	4.25	48
	4.5	4.00	83, 84, 87, 105, 106

Table 5 Overview of full-scale tests

started overturning, the wave through fills up rapidly. The wave crest moves forward while the through rapidly accelerates at the wall, converging toward a point. At some point during convergence, the water at the wall accelerates the crest, turns it to form a vertical jet. The accompanying high accelerations require high pressure gradients, resulting in very localised high pressures with short rise times (Figs. 29 and 31). This impact produces not only the highest pressures but the highest response of the NO96 boxes as well.

Slosh: This impact is a transition between a flip-through and a standing wave. When the wave approaches the wall, the wave through fills up rapidly and reaches the anticipated impact zone way before the wave crest. The impact results in small pressures with long durations (Figs. 30 and 31).

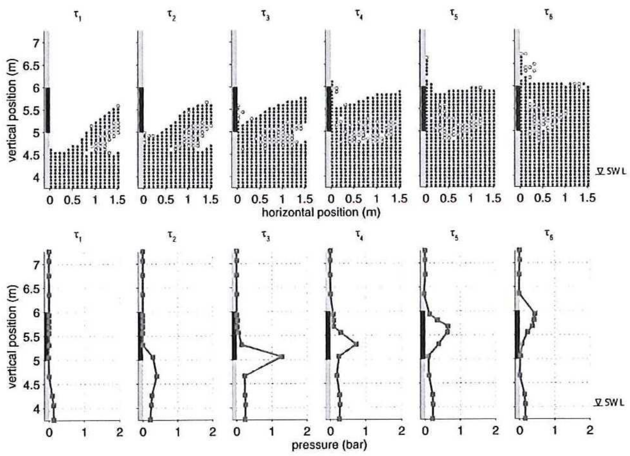


Fig. 27 Aerated impact (test 86), wave shape and pressure profile at 6 time instants, maximum pressure at τ_3 and $\Delta\tau = 50$ ms

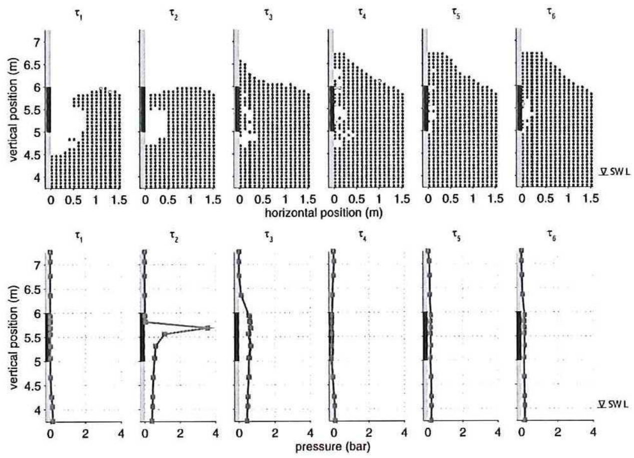


Fig. 28 Air pocket impact (test 79), wave shape and pressure profile at 6 time instants, maximum pressure at τ_2 and $\Delta\tau = 50$ ms

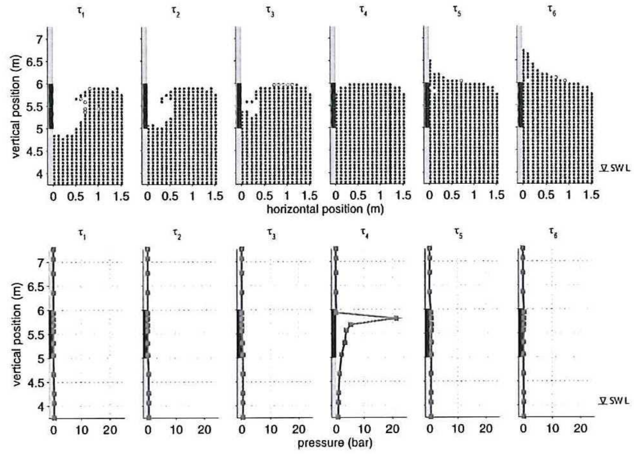


Fig. 29 Flip-through impact (test 74), wave shape and pressure profile at 6 time instants, maximum pressure at τ_4 and $\Delta\tau = 25$ ms

The analysis is still in progress and will be published by the authors in the near future. Directly below is discussed the use of these data for achieving the project goals and some preliminary results are presented.

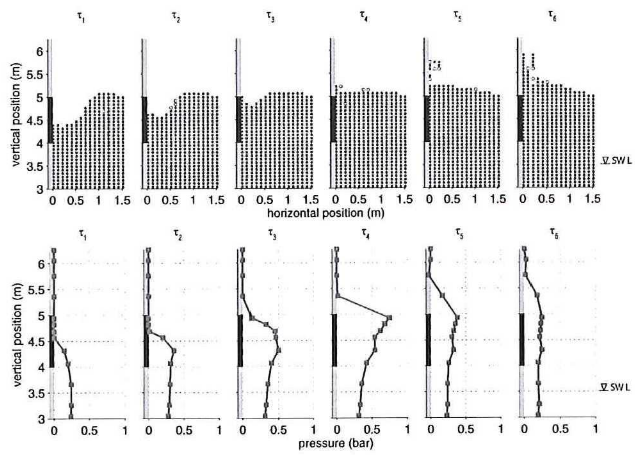


Fig. 30 Slosh (test 24), wave shape and pressure profile at 6 time instants, maximum pressure at τ_4 and $\Delta\tau = 25$ ms

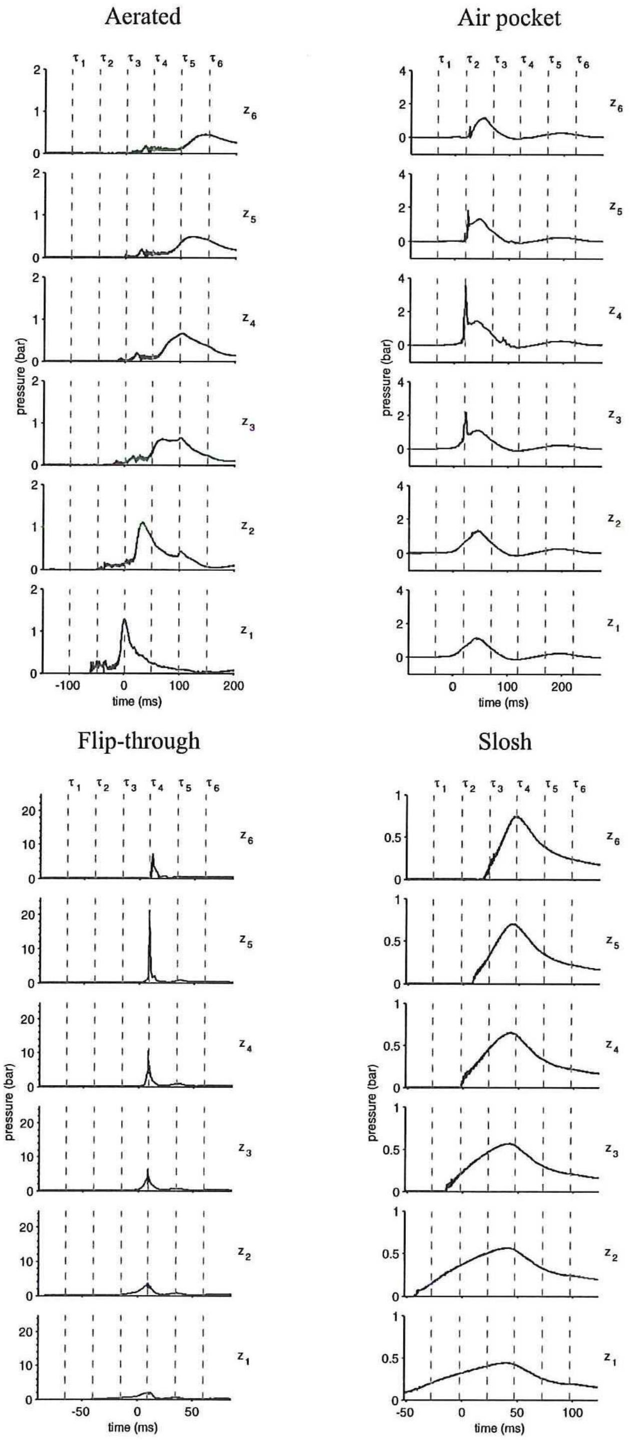


Fig. 31 Pressure time series along centreline of concrete block for aerated, air pocket, flip-through and slosh impact

DISCUSSION

General

Here is discussed how achieving each project goal was affected by the fact that the same piston settings did not result in the same impact types and associated responses. The project goals were assessment of hydroelastic and scale effects, and validation of simplified hydrostructural methods and numerical hydrostructural tools.

Hydroelastic Effects

As explained above, the consortium decided to test the concrete (rigid) block and the NO96 boxes simultaneously. The plan was to compare the pressures on both structures at symmetrical positions, and to attribute possible differences to the hydroelastic effects. So, the fact that the tests were not repeatable does not affect achieving the goal of assessing the hydroelastic effects. For each test, the hydroelastic effect can be defined. After that, in order to assess the mean hydroelastic effects, a stochastic analysis can be carried out per impact type identified in Table 5. This assessment has not yet been completed because the video observation and measured accelerations gave evidence of 3D effects. These have to be investigated before final conclusions can be drawn. The planned third series of large-scale tests in the Scheldt flume is expected to help assess these effects. Still, a preliminary investigation indicated that the mean hydroelastic effects for extreme pressures can reduce the pressures by 10%.

Scale Effects

The consortium plans to repeat the full-scale tests in the Scheldt flume; these will be the third series of large-scale (1:6) tests. The test setup will look like the full-scale setup, but the NO96 boxes will not be modelled. Instead, 2 rigid blocks will be installed.

An attempt will be made to assess the scale effects for pressures and forces. The original plan was to do this by comparing characteristic pressures and forces of probability distributions obtained from full- and large-scale tests. This approach would work providing full- and large-scale tests were affected by the perturbation effect only; this is not the case because the full-scale tests were affected by the wind effect as well. However, the impact classification (Table 5) based on the iCAM data is independent of the wind effect. So, the scale effects can be assessed per impact type. Hence, the fact that the tests were not repeatable because of the wind effect does not affect achieving the goal of assessing the scale effects. This assessment awaits results of the third series of large-scale tests.

Validation of Simplified Hydrostructural Methods

The simplified hydrostructural methods being developed by BV are based on schematisations shown in Fig. 25. No flip-through impact type is considered. For each considered schematisation, i.e. impact type, a different method is being developed. Each schematisation is associated with several parameters, such as impact speed, water depth, free-surface level prior to impact, and aeration level. The original plan was to validate these methods in the following way. First, for each test, the representative impact type can be defined. Second, an associated set of parameters can be estimated based on the iCAM data. Then the structural response can be predicted by the simplified method and compared with the measured response. Following that, a bias factor can be established. Finally, a stochastic analysis of bias factors for each method, i.e. impact type, can be defined and characteristic bias factors can be established for further use of the methods. Hence, because of impact classification based on the iCAM data, the fact that the tests were not repeatable does not affect achieving the goal of validating the simplified hydrostructural methods.

Validation of Nmerical Hydrostructural Tools

Different numerical hydrostructural tools are being used by the consortium partners which were intended to be validated. In general, the following approach was planned. First, a hydrodynamic analysis is carried out. This analysis includes two steps. In the first step, the wave generation and propagation are calculated using potential theory solvers with the recorded piston motions as input. Then, the fluid state is defined at a moment when the potential theory fails to represent the process of forming a breaking wave. In the second step, this fluid state is used as an input to a programme, like Comflow, to calculate wave breaking against the test wall and associated pressures on it. Second, a structural analysis (neglecting the hydrostructural interaction) is carried out using these pressures as input. Finally, it was planned to compare the numerical and experimental responses.

The fact that the planned validation process starts with the piston motions made this validation impossible, because the tests were not repeatable for the same piston motions. However, it is still possible to validate the tools in a stochastic way. It is proposed to define the bias factors per impact types (Table 5). These factors would transform results of numerical tools into characteristic values. The bias factors are defined as the ratio between the characteristic values obtained from the full-scale tests and the values predicted by the numerical tools for the impact with a minimal wind effect.

Some Preliminary Results

This paper focuses on the description of the Sloshel test method, experimental setup and the post processing of the data collected in 110 tests. Here are some limited preliminary results which are released by the consortium. It is expected that more results will be published in the future and in associated papers.

The NO96 boxes have sustained all 110 impacts without damage and experienced the following maxima:

- 15 m/s impacting water horizontal velocity
- 2.6 MPa local pressure
- 535 kN force on NO96 box area
- 2500 micro strain (= 25 MPa stress) in the cover plate
- 46 g acceleration.

CONCLUSIONS

With regard to the test setup, the following conclusions have been drawn by the authors:

- The full-scale sloshing test method based on wave focusing in a coastal engineering flume was selected after evaluation of different testing concepts, and it has been recognised by the industry.
- A modular test setup was designed and manufactured that allowed for testing of different structures subjected to sloshing impacts.
- An extensive qualification process of the whole measuring system was carried out providing high confidence in the quality of the obtained results.
- A novel optical sensor (iCAM) capturing the last stages of sloshing impacts was designed, manufactured and applied.
- A shooting device for the hydrodynamic calibration of pressure gauges was designed, manufactured and applied.
- Pressure measurements are reliable when properly prepared.
- The performance of the setup and the measuring system was very good.
- System identification allowing for interpretation of measured data was carried out.

With regard to achieving the project goals, the following conclusions have been drawn by the authors:

- The first full-scale sloshing tests on a real LNG containment system were successfully carried out.
- The Sloshel test method produced sloshing impacts which were representative of sloshing in NO96 membrane LNG tanks.
- The iCAM sensor gave crucial data allowing for impact classification.
- The flip-through type of sloshing impact caused the most intensive action on the impacted structure and was very sensitive to small variations of the wave shape.
- The tests were not repeatable for the same settings of wave generation due to effects of wind and small water surface perturbations.
- The unsatisfied repeatability condition changed the way the project goals will be achieved.
- The project goals will be achieved per identified impact type by stochastic analysis of full-scale results and results from planned large-scale tests.
- The analysis is still in progress and the conclusions regarding the hydroelastic and the scale effects, and validation of MARIN's numerical tools will be published by the authors in the near future.

ACKNOWLEDGEMENTS

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