FLOODSTAND Integrated Flooding Control and Standard for Stability and Crises Management

FP7-RTD- 218532

FLOODSTAND-deliverable:

Modeltests in atmospheric and vacuum conditions

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SEVENTH FRAMEWORK PROGRAMME

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This report is about the flooding modeltests done for a simple and detailed geometry in atmospheric and scaled air pressure. Setup, methodology, results and lessons learned are described in detail.</td></tr>
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EXECUTIVE SUMMARY

This report describes the model tests done by MARIN for the FLOODSTAND project ad are related to the tasks in work package WP2.5.1. The objective of the modeltests was to investigate the influence of the detail of modelling and the influence of scaled air pressure on the flooding process.

The tests were done in the DTT (Depressurised Towing Tank) of MARIN. A simple model and a detailed PERSPEX model were created (scale 1:20) and these were flooded under atmospheric and low pressure conditions. All the tests were done with captive models that were fixed at a number of heel/trim combinations. The draft was kept constant.

These types of flooding tests were never before done on such a large model scale and under both atmospheric and low pressure conditions. The type, the amount and the required accuracy of the measurements in combination with the low pressure conditions, the model complexity and the required positioning accuracy of the model made this a very challenging project.

In view of the explorative character of these modeltests a considerable effort was spent in the preparation phase of this project. Potential risks were identified and contingency measures or design changes were made to eliminate or minimize them. Nevertheless, a number of problems surfaced in the first attempt that made it necessary to repeat the tests because the required accuracy could not be achieved..

The problems that surfaced mainly had to do with the repeatability of the positioning of the models in the facility. To be able to compare modeltest runs in atmospheric and vacuum conditions both the attitude and the draft of the models should be controlled very precise. In addition to this, there were problems with the water level measurement accuracy. Most likely those were related to the difference in water properties between vacuum and atmospheric.
Despite modifications to the facility equipment and other measures the required accuracy was not achieved. Further research will be required to unravel all the details of these problems and hopefully find solutions for future projects
.
Comparing the results of the different runs is not easy due to the uncertainty in the measurements caused by the problems described above. In general, for the model geometries used in the tests, the influence of scaled air pressure seemd not significant. The same can be said about the difference in detail of both models. In addition to these findings an important number of lessons with respect to the preparation and execution of this type of tests have been learned.

NOMENCLATURE

AC	Alternating Current
AMC	Australian Maritime College
APP	Aft Perpendicular
COG	Centre Of Gravitiy
DA	Detailed model, Atmospheric conditions
DTT	Depressurised Towing Tank
DV	Detailed model, Vacuum conditions
FPP	Fore Perpendicular
FREDYN	'FREgat DYNamica' (Non-linear Frigate Seakeeping & Manoeuvring simulation program)
h<i>.<j>	Calculated vertical distance to still water plane of the <j>th level sensor in compartment <i>
hm<i>.<j>	Measured level to still water plane of the <j>th level sensor in compartment <i>
PLC	Programmable Logic Controller
pt<i>.<j>	Measured pressure of the <j>th pressure sensor in compartment <i>
PU	Poly Urethane
S0	Coordinate system S0 (earth fixed, still water plane)
S4	Coordinate System S4 (ship fixed, centre of gravity)
SA	Simple model, Atmospheric conditions
SV	Simple model, Vacuum conditions
SWP	Still Water Plane

1 INTRODUCTION

1.1 Context & funding

FLOODSTAND is an abbreviation of "Integrated **FLOOD**ing Control and **STAND**ard for Stability and Crises Management". It is a European funded project with a "Collaborative Small or Medium Scale Focused Research Project" funding scheme and it addresses two topics of the FP7-SUSTAINABLE SURFACE TRANSPORT (SST)-2007-RTD-1 program:

- SST.2007.4.1.1 Safety and security by design
- SST.2007.4.1.3 Crises management and rescue operations

All MARIN activities will be 75% funded and 25% will be contributed by MARIN itself. For this reason, not only the project's but also MARIN's interest plays a role in the definition of the objectives to be achieved by the work done by MARIN. It was tried to align both as well as reasonably possible. The official start of the project was the 1st of March 2009.

1.2 Background

The size of new passenger ships has increased tremendously during the past decades, see Figure 1. This trend is expected to continue, as bigger size means new opportunities and economics of scale. However, with larger number of passengers on-board the same vehicle the risk to life increases, and hence new insights are required and methods to deal with this risk need to be explored.

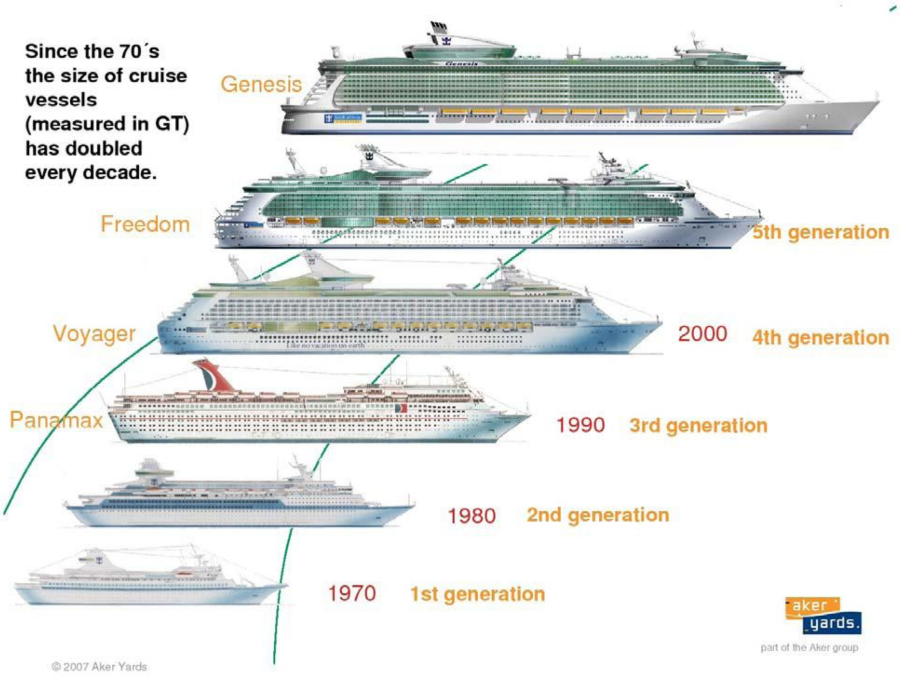

Figure 1 Growth of the passenger cruise ships during four decades

Since it is known[1] that the major risk to persons on-board is posed by the hazard of flooding, the proposed project FLOODSTAND sets to respond to this need by two differently focused approaches[2]:

- Deriving new, detailed and more reliable information and modelling principles on the process of ship flooding and develop new methods for analysing the flooding extent on-board,

[1] See e.g. EU SAFEDOR, FP6

[2] These two approaches originate from the approaches presented in the FP7-SST-2007-RTD-1 Collaborative Small or Medium Scale Focused Research project proposals FLOODCONTROL and ISTAND, which are merged together as the proposed project FLOODSTAND.

- Develop a standard for a more comprehensive measure of damaged ship stability than standards in use today.

The combination resulted in a large group of participants:

	Participant	**Abbreviation**	**Country**
1	(Coordinator) Helsinki University of Technology	TKK	Finland
2	STX Europa ASA (former Aker Yards Oy)	STX	Finland
3	Centre National de la Recherche Scientifique	CNRS	France
4	Centrum Techniki Okretowej Spolka Akcyjna	CTO	Poland
5	Det Norske Veritas AS	DNV	Norway
6	Maritime Research Institute Netherlands	MARIN	The Netherlands
7	MEC Insenerilahendused	MEC	Estonia
8	MEYER WERFT GmbH	MW	Germany
9	Napa Ltd	NAPA	Finland
10	SF Control Oy	SFC	Finland
11	University of Strathclyde The Ship Stability Research Centre	SSRC	UK
12	BMT Group	BMT	UK
13	SSPA Sweden AB	SSPA	Sweden
14	Safety At Sea Oddzial w Polsce	SaS	Poland
15	National Technical University of Athens	NTUA	Greece
16	Bureau Veritas	BV	France
17	Maritime Coastguard Agency	MCA	UK

Participants 1 to 10 originate from the FLOODCONTROL project while the participants 11 to 17 were part of the ISTAND project.

1.3 Objectives

The FLOODSTAND project is a result of the merger of two separate project proposals with some differences in approaches and objectives. Therefore, this project presents two main objectives, each with four with sub-objectives:

a) Increase the reliability of flooding simulation tools in design and on-board use by establishing modelling principles and uncertainty bounds, in particular:
    - Establishing guidelines for modelling leaking through closed doors and the critical pressure head for collapsing under the pressure of floodwater.
    - Simplified modelling of pressure losses (discharge coefficients) in flows through typical openings.
    - Feasible and realistic modelling of compartments with complex layout, such as cabin areas, for flooding simulation tools.
    - Use of flooding monitoring systems and time domain simulation for assessing the damage and flooding extent on-board the damaged ship.

b) Establish a method for instantaneous classification of the severity of ship flooding casualty, with the following key objectives:
    - Stochastic ship-response modelling: establish requirements and uncertainty bounds for methods to predict the time it takes a ship to capsize or sink after damage.
    - Rescue-process modelling:_establish requirements and uncertainty bounds for models of mustering, abandonment and rescue operations.
    - Standard for decision making in crises: establish a loss function which must reflect in a balanced manner the societal concerns pertinent to a “large” loss.
    - Demonstration:_develop and implement a system and test its effectiveness of the standard in rating different decisions for various casualty cases as well as test the approach in a design environment.

1.4 Work-packages

At the highest level the following work-packages are defined:

WP0	Management	TKK
WP1	Design and application	STX
WP2	Flooding Progression Modelling	TKK
WP3	Flooding Simulation and Measurement On-board	NAPA
WP4	Stochastic ship response modelling	SSRC
WP5	Rescue process modelling	BV
WP6	Standard for decision making in crises	SSRC
WP7	Demonstration	NTUA

MARIN will be active in WP2 (total costs 13 man-month) and WP3 (total costs 2 man-month). For a detailed description of the relevant packages for MARIN see below. For all details see reference [1].

1.4.1 Work package 2 - Task 2.5 Model tests for cabin areas

In the EC funded SAFEDOR project flooding in RoPax ferries was investigated by means of model tests on cabin arrangements and simulations for ships. This work focused on basic cabin arrangements with not too much level of detail. All available results from the previous studies (e.g. NEREUS, SAFEDOR, ESTONIA) will be used as a starting point for this new study in Task 2.5. The participants of this task are STX, MW, NAPA and MARIN (who has the lead).

*Sub-Task 2.5.1 Flooding tests on detailed cabin arrangements (Participants: **MARIN**, STX, MW)*
Flooding tests on detailed cabin arrangements of a large cruise passenger ship model will be carried out. The arrangements will contain a substantial amount of cabins while the cabins will be modelled in two levels of detail (furniture, doors, etc.).
Deliverable(s):

- Draft report on flooding tests on detailed cabin arrangements, month 11 after the start of the project (**MARIN**)

*Sub-Task 2.5.2 Scale effects (Participants: **MARIN**, STX, MW)*
Flooding tests will be performed on two identical cabin arrangements in different scale to investigate scale effects due to different sized openings, Reynolds numbers and air compressibility effects.
Deliverable(s):

- Report on flooding tests on detailed cabin arrangements and the effects of different scale, month 17 after the start of the project (MARIN)

*Sub-Task 2.5.3 Guidelines (Participants: **MARIN**, STX, MW, NAPA)*
MARIN and NAPA will perform flooding simulations with different detail levels for the modelling of the cabin area. Based on the simulations and model tests guidelines will be derived on how to model cabin arrangements in flooding simulation programs. The guidelines will address issues like the required level of detail, recommendations for the discharge coefficient values and when and how to include air compressibility effects.
Deliverable(s):

- Guidelines on modelling principles for cabin areas, month 23 after the start of the project (**MARIN**)

*1.4.2 Work package 3 - Task 3.2 Impact of ship dynamics**(Participants: MARIN, TKK)***

This task will focus on studying of the impact of the sea environment on the reliability of the system of flood sensors and simulation tools for predicting the ship response. Flooding simulations for a damaged ship in calm water and in various sea states will be performed. The motions will be evaluated for a number of ship

operating conditions and operating areas, and for different sea states. The results will be used in Task 3.1 for quantification of the requisite uncertainties. TKK has the lead, MARIN will be participant.
Deliverable(s):

- Impact of ship dynamics, month 26 after the start of the project (**TKK**, MARIN)

2 TEST PHILOSOPHY

2.1 Flooding Problem Characteristics

Researching the flow of water through a complex geometry is a challenging problem. The complexity of the problem increases when the geometry is subject to -ship- motions: there is a very tight coupling between the motions and the flow through the geometry.

The combined system is a highly non-linear process with many degrees of freedom. Because of this it is likely that it shows chaotic behaviour[3]: small changes in the initial conditions can result in a very different end result.

This chaotic behaviour has consequences for the validation of the tool and for the simulation methodology: (large) differences in the result may be found but the question will be whether the differences are caused by an inadequate simulation tool or that they are inherent to the process that is tried to be reproduced (or a combination of those). To avoid this, the focus of this test program will be at a decoupled flooding problem: the motions are left out of the equations and instead a constrained geometry will be tested.

2.2 Test objectives

The detailed test objectives for this project are:

1) Quantify the influence of the model scale on the results of flooding model tests. If the scale of the model can be quantified as a 'significant' influence this might open new markets for MARIN's depressurised towing tank (DTT) and for MARIN's flooding simulation tools. When considering flooding model tests the model scale effects can be sub-divided in two categories:

    a) Scale effects due to different Reynolds number
    b) Scale effects due to compressibility of air

    This project will be limited to the quantification of the compressibility of air. The scale effects of compressibility of air will result in a different amount of fluid mass and a different centre of gravity of this fluid (in x, y and z) over time.
2) Quantify the influence of the detail of the geometry on the results of flooding model test.
    It will be practically impossible to model all the geometry details on scale. The size of the model will probably become too large and the costs will explode. In addition, the information might simply not be there or very difficult to obtain. The question is therefore: what is the minimum level of detail and which details should never be forgotten?[4]
3) Provide measurement data for validation of flooding simulation tools.
    The sub-objectives are two-fold:

    a) The timing during the flooding process appears to be very critical in some cases. For example, does (or doesn't) the flooding of a compartment start at a certain roll angle? At the same time this illustrates one of the difficult issues when validating this process: the tight coupling between motions and the flooding process.
    b) Try to get a grip on the required level of detail that has to be used to model the geometry, and in addition, try to define guidelines for the modelling.
    The rationale is the same as for the quantification of the level of detail for the model tests because it will again be practically impossible to model the geometry into the smallest detail; it will not only be very costly also the detailed information will probably not be available.[5]

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3 Results from previous modeltests seem to confirm this.

4 This might be an impossible question to answer without knowing for example the mechanism or sequence that led to the capsizing/sinking of a vessel: see for example the MV Braer accident. The solution will likely be a combination of methodology, sound judgement and intuition.

5 However, there is more flexibility than with the scale model production.

Considering all this, the focus of the testing will be on the flooding process itself and not on the ship-model dynamics or the interaction between the flooding and the dynamics. Decoupling these two is very important to be able to reduce the complexity of the testing and the analysis and interpretation of the results.

2.3 Experimental Model(s)

2.3.1 Air compressibility effects

The effect of the model scale on the effects of air-compressibility related to the fluid flow can be investigated in two ways:

1) Build the same model on a different scale and repeat the tests.
   The disadvantage of this approach is that the Reynolds number will be different for the two models. To be able to reduce this effect the smallest model has to be relatively large (scale at least 1:20, see the Estonia report [2]). The larger model will need an even bigger scale (e.g. 1:10). This leads to large models that are costly and difficult to handle.
2) Reduce the air-pressure in relation to the scale of the model (air-pressure scales 1:1 with the scale, when scaled according to Froude’s law) and repeat the tests in both atmospheric and low pressure conditions.

For this project the second approach will be used. The main reason is that only lowering the air pressure to the correct model scale value will give the definite answer on its importance. It also eliminates the Reynolds effects which would be present when two different scaled models were used.

To assess the effects of air compressibility on up- and down flooding (which influences the vertical centre of gravity and hence the stability) at least two but preferably three decks will be mounted on top of each other. Each deck will stretch between two watertight bulkheads and it will be air-tight (apart from the up- and down-flooding openings). The compartment geometry (cabins, corridors) fitted on these decks do not have to be air-tight: in reality this will also not be the case.

2.3.2 Detail of Geometry

Two models will be built on the same scale. The difference will be the internal geometry. A ‘simple’ model and a more ‘detailed’ model will be built. The difference will be that the detailed model will have longitudinal and transverse pathways that will change the (cross) flooding process. All details are given in Appendix E. The changes in detail were chosen such that they will reflect the choices a ‘modeller’ will have to make when deciding on the level of detail.

2.3.3 Damage Opening initiation mechanism

The damage will have to be initiated in a very reproducible way. This is a tricky issue. Damage initiation shall also have to be quick: less than 1 video-frame (1/25 sec, model scale time) to open up the entire opening. In addition, it shall be reliable and watertight when closed. Reliability is essential to avoid unpredictable ruptures of the membrane. This is very time consuming, especially if this happens in the DTT low pressure part: the model(s) have to brought back through the air-lock, drained and refitted with new membranes.

The tests in the DTT will focus on the internal geometry without the hull. This poses fewer constrictions to the smoothness of the closure mechanism of the opening: for example the opening can be closed by pressing a frame with a thin rubber sheet from the outside to the damage opening. This is allowed as long as the frame does not obstruct the water flowing into the damage opening.

2.3.4 Model Construction

Video footage is an important instrument for this type of tests. Therefore, the construction material shall be transparent to provide a clear view. For earlier modeltests Perspex was used with various thickness. It will not be possible to model the thickness of decks and bulkheads to the proper scale compared to real life). The outer dimensions of the model used for the Australian Maritime College (AMC) tests was 1:45 resulting in outer dimensions of approximately 0.75 m x 0.45 m x 0.25 m.

For the tuning of the simulation model, the timing of the flooding process is important. This is determined by both the volumes of all the compartments and the thickness of the decks (in case of up-flooding). In combination both values do not scale well. In this particular case preference is given to the correct scaled thickness of the deck plating. The maximum dimensions are determined by a number of reasons:

1) The dimensions of the airlock of the DTT.
2) Ease of handling
3) Maximum vertical motion of the measurement carriage (to set the draft of the model)
4) Ease of access to the internal geometry (e.g. for draining) without taking the model apart (this could affect the air/water tightness of the model)

For ease of handling, especially in the non-accessible environment of the DTT it is paramount to limit the dimension as much as possible; on the other hand, ease of accessibility of the model is also important. If the test-model is mounted on the measurement carriage (which can move from 540 to 1140 mm above the water – 600 mm) then a scale of 1:20 was the best choice (see Table 1). This results in outer dimensions of 1.68 m x 1.02 m x 0.56 m. When fully flooded (the worst case), this represents a weight of approximately 1000 kg. A reason to use a scale as large as possible is that the second model needs to have more details and building accuracy improves with larger scale.

Special attention was given to making the model compartments air-tight. This specifically applies to those compartments that are pressurised during the flooding process. If air leaks from these compartments it will be very difficult to reproduce the results in a simulation[6].
Despite all the effort paid to this aspect it appeared that a number of compartments leaked tiny amounts of air. It was not possible to locate the leak(s) but the most likely candidates were the deck/bulkhead penetrations created for the small Perspex tubes used to guide the sensor wiring to the top of the model.

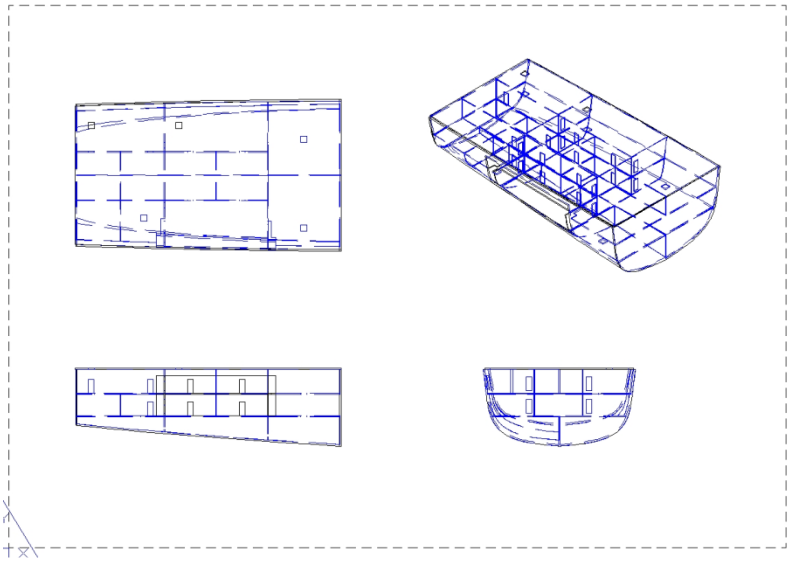


Figure 2 Model impression

The form of some tanks is determined by the curvature of the hull. To assure visibility from outside, the curvature of the hull is moulded by the Perspex.

One of the valuable experiences of the ESTONIA project was that the water pressure in full compartments exercises a large force on the decks. For the ESTONIA model (which was only a single deck) the upper deck bulged severely which had to be controlled by putting large weights on the deck. Nevertheless, it resulted in considerable air-leakage between the compartments.

[6] In the ideal situation all compartments have their air-pressure measured. That will make it possible to detect the amount of air-leakage for each compartment.

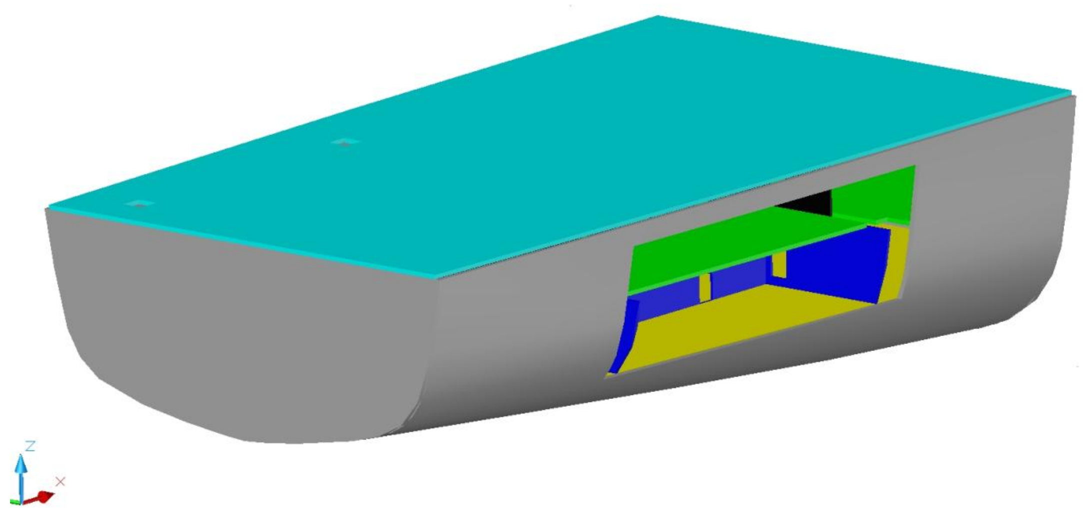


Figure 3 Geometry limits

2.3.5 Coordinate system & rotation

The model set-up is fixed witch respect to the sub-carriage. The heel, trim and draft have to be defined with respect to a coordinate system. The origin of this system is defined on the line connecting a point on the aft bulkhead, halfway the depth of the hull and a second point on the forward bulkhead also halfway the depth of the hull. The origin is located where this line intersects the vertical halfway the length of the deck. The deck is horizontal when the heel and trim are both zero. The distance from the origin to the lowest point of the model is 6.392 m (on full scale).

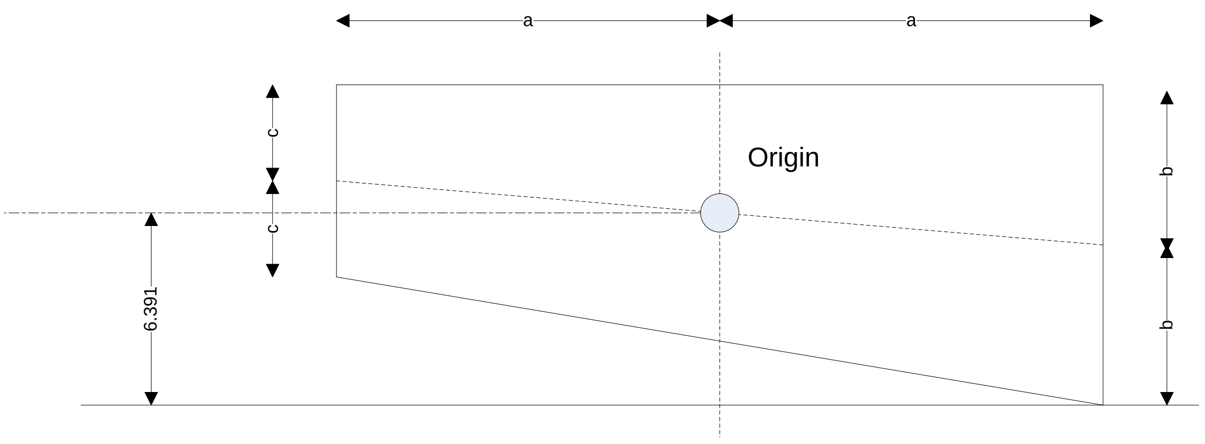


Figure 4 Coordinate system

With the most extreme roll (20 deg) and pitch angle (-3 deg), the water plane with respect to the damage opening looks like Figure 5. The water plane is defined through the origin; the coordinates of the origin are (with respect to the aft bulkhead of the model) (16.5 m, 0.0 m, 6.392 m) on full scale.

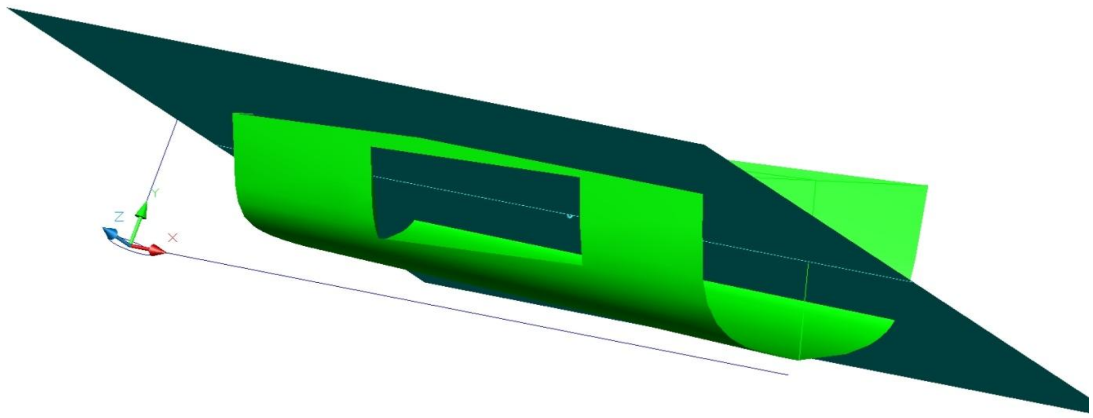


Figure 5 Water plane & Damage opening

When heeled and trimmed like this, the underwater buoyancy point is (0.654 m, -1.50 m, 2.30 m, model scale, with respect to the origin about which the rotation took place – in the original coordinate system (un-trimmed, un-heeled). The underwater displacement is about 2368 tons (or about 296 kg for the model). The rotation is done around the fixed axes: starting with a horizontal model, first the roll around the x-axis, then the pitch rotation around the fixed y-axis. The positive x-axis is pointing forward, parallel to the keel-line, the positive y-axis is pointing to port. The coordinates of the origin is of this system is given above.

2.4 Test program

As discussed, the focus of this project was be on the flooding mechanism and not on the dynamics of the vessel model. To study the effects of air compressibility the geometry was completely constrained and held at different roll and pitch angles when the flooding was initiated. A single test is completed when the levels (or the total mass) had stabilised. The ideal, rough workflow for a single test was approximately:

Nr.	Activity	Start [min]	Duration [min]	End [min]
1	Prepare the model			
	1.1 Drain the model	0	20	20
	1.2 Close the damage opening	20	20	40
	1.3 Check equipment	40	10	50
2	Install the model under the carriage	50	30	80
3	Constrain the model at heel, trim	80	10	90
4	Do a test measurement	90	5	95
5	Transport harbour->tank	95	22	117
6	Constrain the model at draft	117	10	127
7	Start measurement	127	1	128
8	Initiate the damage	128	1	129
9	Wait for the flooding to finish	129	2	131
10	Stop the measurement	131	1	132
11	Lift the model from the water	132	10	142
12	Drain some tanks	142	10	152
13	Transport tank->harbour	152	15	167

The fact that the tests were held at low pressure in the DTT made it impossible to access the model during the testing.
The heel and trim angle combinations that were tested are given in Table 1 below.

Table 1 Test matrix

		Heel [deg]			
		0.0	5.0	10.0	20.0
Trim [deg]	0.0	x			x
	-0.5		x		
	-1.0				
	-1.5			x	
	-3.0	x		x	x

The tests specified in this matrix were done under scaled (1:20) pressure (50.0 mBar) and atmospheric circumstances.

2.4.1 Level measurements

In the tilted conditions special attention was given to the measurement of the fluid levels. Ideally, their locations have to be such that at least one of the level sensors in a compartment is in contact with the fluid surface all the time.

For example, the set-up below will require at least 3 level sensors to have a continuous level measurement range. Since for these test the tilting will always be in the same direction and hence the highest and the lowest point can easily be determined. The level sensor has to be placed at the lowest point of the compartment; fortunately this will be easy due to the constrained test set-up.

This requirement could not be fully achieved for all measurements. It would have resulted in more level sensors than were available.

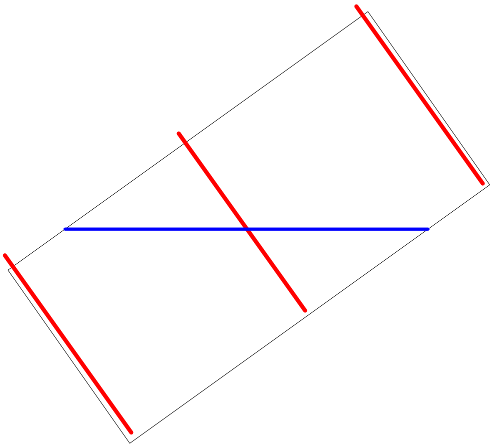


Figure 6 - Level measurement (3 locations)

2.4.2 Air pressure measurements

The air pressure was measured at selected locations where enclosed air-patches may form during the testing. Heel and trim were only in one direction so it was easy to determine the highest point where the sensor should be placed (or where a small air guidance hose could be placed connecting the compartment with the sensor). Care was taken that the sensor (and possibly its signal conditioning electronics) had to operate in low pressure circumstances. The selected sensor was a sensitive pressure difference sensor.

2.4.3 Force & Moment measurements

The whole test set-up was placed on heel and trim blocks. Between the frame holding the model and the sub-carriage a 6 component force measurement frame was placed. Using these measurements the floodwater mass, and its centre of gravity (x and y, not height) will be determined. To assess the centre of gravity in height the level measurements of the compartments need to be used in combination with tank tables which describe the relation between fluid volume, heel, trim and the centre of gravity of the fluid. This was outside the scope of this project.

3 MODELTESTS & SETUP

3.1 Planning

The modeltests were performed in three phases. Despite the thorough preparation a number of problems surfaced during the first phase in January 2010. The problems were mainly related to strange, unexplainable measurement artefacts and problems with the vertical positioning of the modules in the basin.

This required a second phase in which the same tests had to be repeated. The time between the first and second phase was used to incorporate all lessons learned:

- Design and install automatic positioning of the sub-carriage and the models
- Add three draught measurement probes on the carriage to check the vertical positioning
- Do a number of additional (laboratory) tests to try to explain the measurements
- Try to make compartments airtight (partly succeeded)
- Produce a double set of heel and trim blocks such that both models have the same heel and trim during a single test.
- Try to improve the calibration and measurement procedure

In the second phase (March 2010) only a preliminary calibration could be done. The positioning of the carriage malfunctioned and the tests had to be abandoned.

The third phase (April/May 2010) allowed for another improvement. A PERSPEX tube was fitted to the sub-carriage. The tube had a wave probe fitted on the outside and a wave probe fitted on the inside. It had a length of approximately 600 mm and was closed at the top. After run4b (see the test program in Appendix A) an additional pressure sensor was fitted at the top of the tube. When the models were lowered in the water the difference in height between the inner- and outer level measurement, together with the air pressure in the tube and the ambient air pressure on the outside of the tube makes it possible to check (or correct) the calibration factors of the level sensors in the model. This assumes that the water in- and outside of the tube has the same properties as the water inside the model.

The three phases allowed for the incorporation of the lessons learned, something which is very difficult to do during the testing itself.

3.2 Test facility

The Depressurised Towing Tank (DTT) is a unique research facility for testing cavitation of the propeller(s) operating behind the complete ship model. In addition, the facility is used as a multi-purpose model basin for hydrodynamic research related to the resistance and propulsion of ships. Cavitation and hull pressure tests are carried out in depressurised conditions, with the propeller(s) in Froude scaled condition and the model in free surface conditions (free to trim and thus creating the proper propeller inflow).

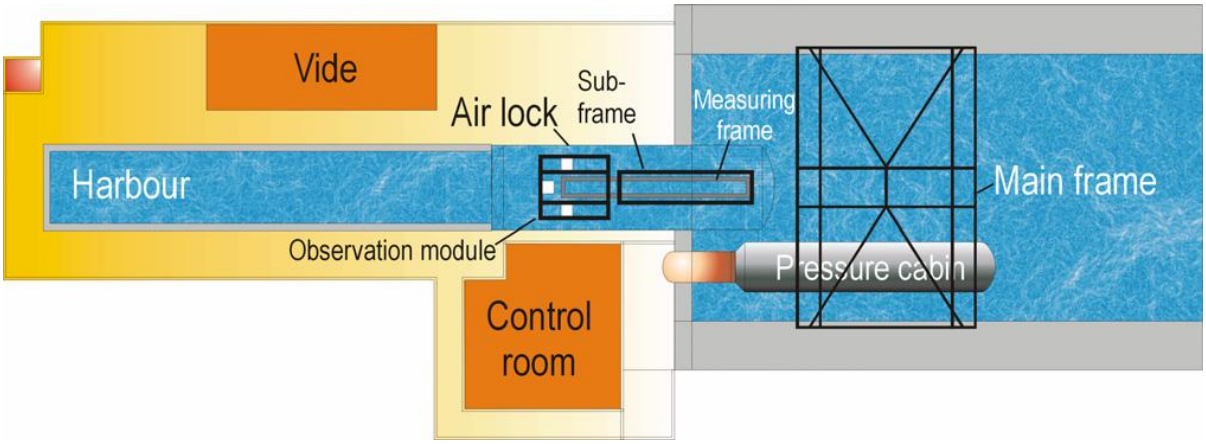


Figure 7 DTT Layout

Tank dimensions are 240 x 18 x 8 m. The harbour (preparation) area is 26 m long and 4.2 m wide. The instrumentation allows for measuring 40 channels at 5 kHz. The noise measurement system is able to test frequencies of 2 – 80 kHz.

According to the laws of similarity which apply to cavitation, the ambient air pressure in the tank must be reduced to the inverse of model scale. Through three vacuum pumps it can be lowered to a minimum of 2500-4000 Pa.

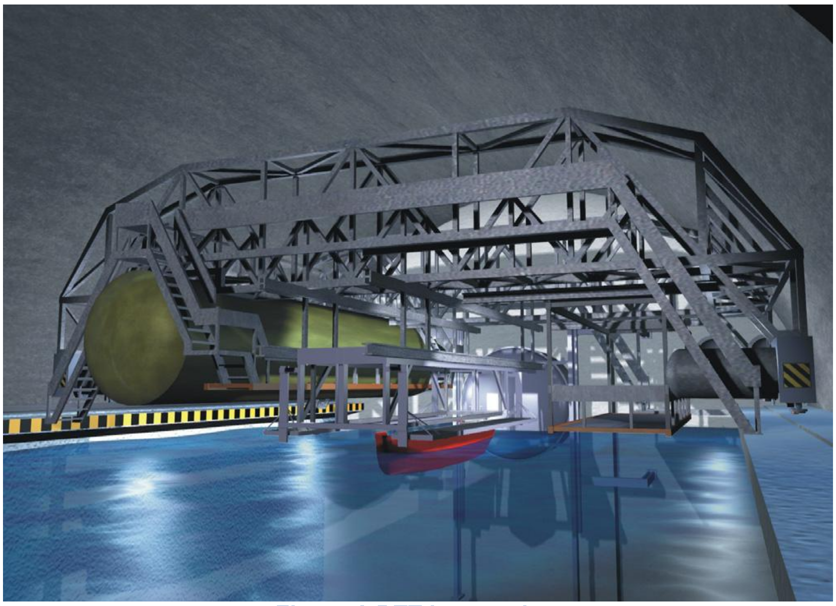


Figure 8 DTT Impression

3.3 Model Production

The models were entirely made from PERSPEX to ensure the best possible visibility of the internal flow process. The Perspex model was constructed externally by a specialised company. The installation of the measurement equipment was done by MARIN.

After the model was glued together the accessibility to the inside of the model was poor or non-existing. All the level sensors were mounted in the model during the construction. This implied that the level sensors could not be cleaned or repaired. The same applies to small internal (air) leakages: these could not be repaired. The difficult accessibility has proved to be very disadvantageous. The basin water appeared to be quite corrosive and this has probably deteriorated the quality of the level sensors. In addition, there were problems with the attachment of the level sensors to the Perspex. Both will have influenced the measurement quality in a negative way since the modeltests were split up in three phases and overall took almost three month to complete.

It appeared difficult to drain the model properly. Two drain plugs were fitted in the double bottom tanks S06 and S01, see Appendix E for the layout and tank numbering). The plug in S06 was fitted in the forward bulkhead, slightly (15 mm, model scale) above the lowest point, in S01 it was fitted in the double bottom, at the lowest point. The result was that S06 could not be drained 100% while S01 could be drained completely. When the fixation blocks were changed a portable pump was used to drain the compartments that could be reached with a hose. However, not all compartments could be drained 100%.

3.4 Basin set-up

As described above, the basin is divided in two areas:

1) The harbour (atmospheric conditions)
2) The basin (vacuum tank, controllable pressure)

The sub-frame of the measurement carriage (or Main frame), see Figure 7) can be moved from the basin to the harbour (and vice versa). Both models were mounted in two frames attached to the sub- frame. Between each model-frame and the sub-frame three force transducers were mounted each measuring the vertical force (in z-direction) and x and y forces..

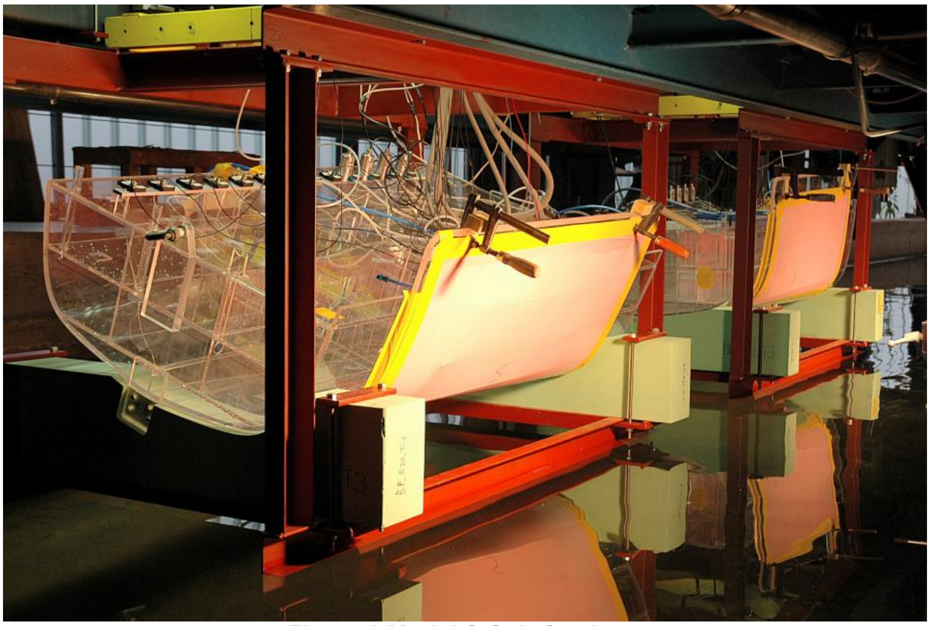


Figure 9 Model & Sub-Carriage

The whole sub-frame can be lowered in a controlled way over a range of approximately 600 mm. The models were mounted on specially constructed fixation blocks: for each heel, trim combination a dedicated set of blocks was used. The height of the blocks was chosen such that the sub-frame had to be lowered to the same position for each test. The position was determined by lowering the model in the un-heeled, un-trimmed condition to the draft line that was marked on the model. The draft line was set at 0.16 m above the level as the rotation point (at a draft of 6.392 m, see §2.3.5).

During the testing in phase I, the decoders used to display and control the vertical position proofed to be unreliable. Therefore, the required vertical position was clearly marked on the model-frames and corresponded to a draft of 6.392 meter of the un-trimmed, un-heeled model. Remark that the draft definition is with respect to the whole vessel of which the tested geometry is a slice (from 12.0 m to 45.0 m from APP). Additional complexity was that the lowering of the sub-frame in the basin had to be done without direct visual feedback; instead, video cameras pointed at the draft-mark on the sub-frame had to be used but the draft-marks were very difficult to see on the video camera (also see §6.3)

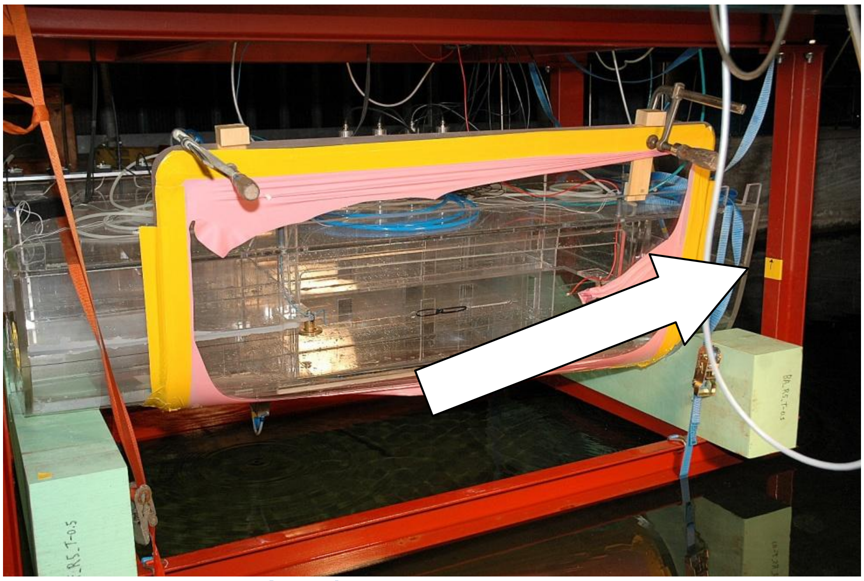


Figure 10 One of the 4 draught-marks (see arrow)

3.5 Sub- and model-frame layout

For each run with different heel and trim both models had to be removed and new heel, trim blocks had to be mounted. The detailed layout including dimensions and locations of the three draft sensors, the PERSPEX tube can be found in the appendices. Care was taken that both models kept the same position in relation to the 6 component frame measuring the x, y and z forces. However, small deviations might be possible due to the difficult positioning of both models.

4 ACCURACY & CALIBRATION

4.1 Electronic equipment

All electronic equipment required for signal conditioning, sensor power supply etc. was tested for stability under low atmospheric pressure (50 mBar). All equipment successively passed the tests.

4.2 Pressure sensors

The differential pressure sensors were all calibrated at MARIN by exposing them to a calibrated pressure (see calibration report). The 95% accuracy of these sensors is approximately 100 Pa. There was no need to recalibrate the pressure sensors during the testing.

4.3 Level sensors

4.3.1 Sensor construction

The level sensors (a.k.a. wave probes) consisted of two stainless steel strips which were attached to the PERSPEX of the model with double sided tape. The resistance measured over both strips changes with the water level (more accurate: with the area of the strips exposed to the water). The changing resistance results in a changing current and the measured value are (after calibration) used as an indication for the water level[7]. Although MARIN had good experience with this method it proofed to be quite cumbersome in the run of the three month that it took to do the measurements: some of the strips detached from the PERSPEX. This has had a negative influence on the quality of the measurements (and the calibration).

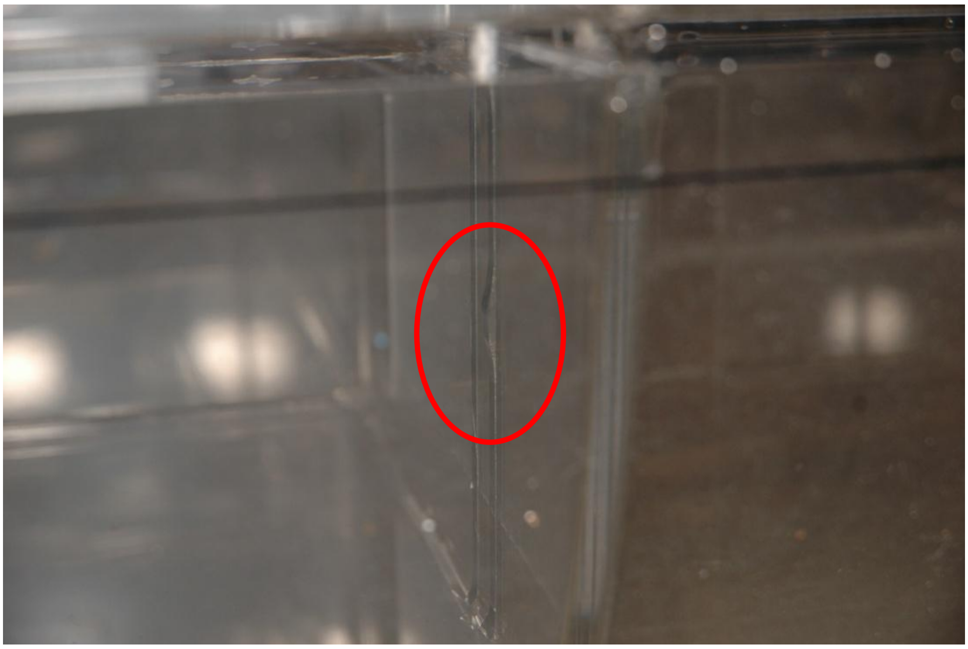


Figure 11 - Detached wave probe

Although stainless steel was used for the sensors strips, it is likely that the surface of the strips was corroded in the quite aggressive water of the basin. Again, this has had a negative and unpredictable influence of the measurement accuracy of the levels.

[7] In reality the measurement principles are more complex For example; the sensors are supplied with an AC current. When sensors are located close to each other a different AC frequency is used to minimise interference between the sensors.

4.3.2 Laboratory Calibration

The wave probe sensors were calibrated in two phases. First, under controlled laboratory circumstances a number of sensors were glued to a Perspex plate. The plate was lowered into the water of a drum in a number of steps. After lowering, it was raised with the same steps. The procedure was repeated a number of times. It gave an indication of the reproducibility/repeatability of the measurements of this sensor type.

During the preliminary calibration the reproducibility improved when the Perspex was cleaned before the strips were glued to it. The same procedure was repeated when the strips were glued in the model. From these laboratory measurements the 95% accuracy was estimated to be 2 mm over the full range.

4.3.3 Model Calibration & Checks

The second phase was calibrating the sensors once they were fitted inside the model. This step of the calibration proved to be much more time consuming than estimated beforehand. The level calibration was done under atmospheric conditions and with both models in a horizontal position (zero heel and trim). The procedure was to do the calibration per deck with both models at the same time. The platform on which both models were mounted was slowly lowered into the water (in steps of 2 cm). For the first step care was taken that all sensors had ‘wet feet’. A zero measurement was taken when the level had stabilised. After that, the platform was lowered a single step of 2 cm and care was taken that the level stabilised again. This procedure was repeated until just before the water plane touched the top deck of the compartment.

After this had been repeated for all decks, the model was drained and the procedure was repeated but now without nullifying the sensors when a new deck was reached. This was done to check the repeatability of the measurements. It was done under atmospheric conditions (in the harbour) and in the vacuum part of the facilities.

Approximately halfway during the measurement program (after run3b) an intermediate reproducibility check was done, this time only in the Atmospheric condition. At the end of the measurement program a final check was done, now with smaller steps and in the atmospheric and vacuum conditions.

4.4 Force measurements

The force transducers used for the 6 component frames are calibrated in the MARIN laboratory. The measurement uncertainty of a MARIN 1-component force transducer is typically less than 0.6% of the measured value between 10% and 100% of its full scale range. The linearity uncertainty is typically less than 0.2 % of the measured value between 10% and 100% of its full scale range. The full range for the three z transducers was from 0~200 kg. For the single y transducer the measurement range is 0~200 kg and for both x-transducers it is 80 kg.

Therefore, the weight, determined by the three z transducers has a 95% accuracy of 0.6% of 200 is approximately 2.1 kg on model scale (and ~17000 kg on full scale)

The layout of the force transducers is depicted in Figure 12.

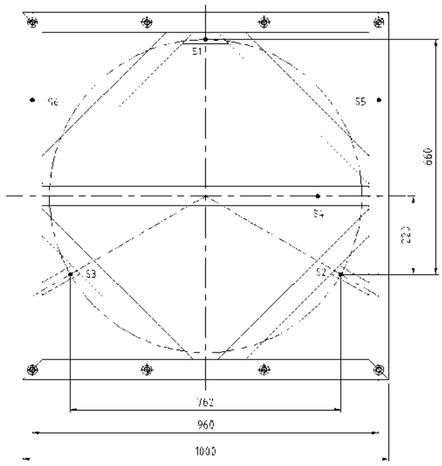


Figure 12 - Component frame

The vertical force used to assess the horizontal position of the centre of gravity, was measured with 3 force transducers: Fz_SBa, Fz_PSa and Fz_f. The schematic geometry is given in Figure 13. The upper triangle gives a top view with force sensors in each corner. The bottom triangle gives a view from aft to foreward.

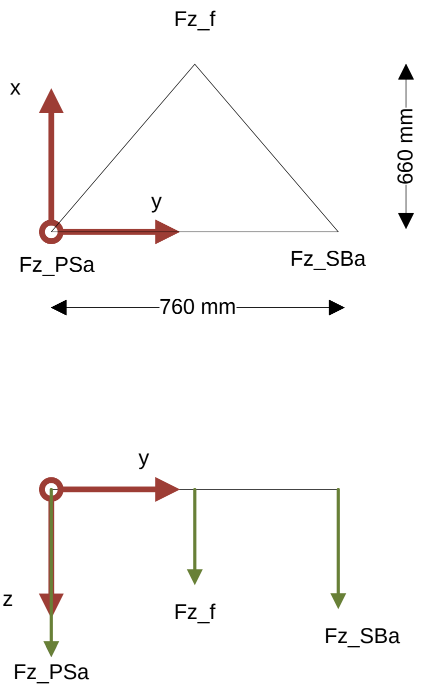


Figure 13 Vertical force measurements

Although much care was taken to position the models accurately during the change of a configuration, it cannot be guaranteed that the location of the rotation point of the models (as described in §2.3) is always in the same position relative to the measurement frame. During the change of the heel-trim blocks the models might have been slightly shifted. However, the position of the models during all runs of a single configuration did not change and therefore the COG calculations of a single run (also between detailed and simple models) can be compared. Remark the slightly unusual coordinate system used in the calculations. Also remark that the flooding process is asymmetrical and hence the COG y position will generally not be 0.0 (not even for the zero heel and zero trim case).

4.5 Positioning of the Models

The draft, heel and trim are very important input parameters for these tests. The results of the atmospheric tests have to be compared to the tests done in vacuum. In addition, the simple model has to be compared with the detailed model. To do this in a reliable manner, the positioning control should be accurately and repeatable. If this cannot be achieved then the comparison cannot be made with sufficient accuracy and no conclusions can be drawn on the influence of the scaled air pressure on the flooding process.

4.5.1 Vertical position of Measurement frame

Initially (phase I) the vertical position of the models was not directly measured. Instead the value of three pulse counters was used to manually set the vertical position of both models at the same time. The configuration of the worm wheels used to position the platform is triangular (see below). The triangle gives a schematic top view of the position of the three worm wheels used to adjust the vertical position of the sub-carriage.

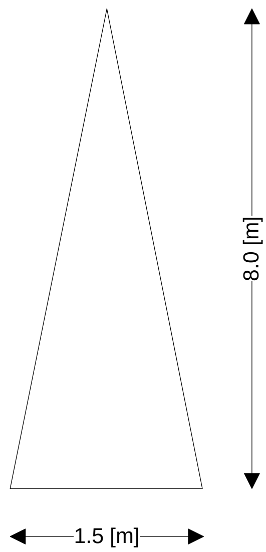


Figure 14 Sub-frame vertical positioning

The maximum allowed difference of the counters is 5 mm, both in the longitudinal and in the transverse direction. The sub-frame has to be reset (re-adjusted and calibrated) if for some reason this offset is exceeded. Given the distances between the worm wheels this is a maximum error of 0.035 deg in the longitudinal direction (trim) and 0.19 deg in the transverse direction (heel).

The initial value of the counters was determined by lowering the model at a heel and trim of 0.0 deg to its waterline. At first the values of the counters were used to position the platform. Unfortunately this gave a false indication of accuracy. The counter values were displayed in millimetres but during the manual up/down positioning pulses were lost such that the absolute value of the counter could not be used for repeatedly positioning the platform on the same draught. The draught error that was made during these runs is estimated to be 10 mm, see §6.3 for a discussion.

After this was realised the control loop was closed visually: on each corner of the sub-frame a draught mark was set and these were closely monitored while lowering the platform (either with direct sight in the harbour, or on video camera when in the basin). The 95% accuracy with which the platform could be positioned is estimated to be 10 mm. However, also this approach proofed to be problematic. In the second and third phase of the project the PLC software controlling the sub-frame was modified such that the vertical position of the sub-frame was automatically controlled to a desired value.

In addition three level sensors were mounted to the sub-frame. These were set to zero when the pulse counter value was determined (model at heel and trim of 0.0 deg). A reading of 0.0 on all these sensors (Draft_PSa, Draft_PSf and Draft_SBm) should indicate that the sub-frame was at the right draft and that there was no torque (a.k.a. it was horizontal).

4.5.2 Heel & trim

Wooden and PU Foam blocks were used to position the model on the required heel, trim and draught. The heel and trim varied but the draught was kept at the same value (full scale 6.392+0.16 m), see the discussion in §4.5. In addition to the uncertainties in heel and trim caused by positioning the sub-frame there is also uncertainty caused by the possible misalignment with which the models were placed on the blocks and with which the blocks were placed on the sub-frame.

For the heel the misalignment uncertainty is estimated to be 0.25 deg, which brings the total for the heel on 0.31 deg (95% value), see §4.5). For the trim the accuracy is a bit better: 0.10 deg (95%). The reason for the better accuracy in trim is the longer longitudinal distance between the blocks in the trim direction.

When the sub-frame is not horizontal when lowered into the water then this adds to the in-accuracy in heel and trim. Whether this is the case can be checked by the visual inspection of the draft marks and by the three draft sensors mounted to the sub-frame (which all should read zero). This problem will be addressed in §6.3.

In phase I different heel and trim values were used for both models during a single run. Thus, the detailed model was for example on the heel=20.0 deg and trim=-3.0 deg while the simple model was on the heel=0.0 deg and trim=0.0 deg blocks. This was done to limit the number of required blocks. It appeared however that the results of such a run were difficult to compare because of draft variations during the runs. Therefore, in the second and third phase the same heel and trim values were used for both models during a run.

4.6 Perspex Tube

In phase III a PERSPEX tube was fitted to the model frames. It was closed at the top and had a level sensor fitted on the inside and on the outside. From run 4 (after the calibration check, see test program) also the air pressure was measured. The length of the tube was 600 mm and the diameter 120 mm (both on model scale). When the model is positioned at its draft the bottom of the tube is submerged approximately 460 mm (on model scale). The outside level h_{out}, the inside level h_{in} and the measured air pressure difference, Δp_{air}, are directly related to each other:

$$\Delta p_{air} = \rho_{water}.g.\ h_{out} - h_{in} \tag{1.1}$$

The air pressure difference divided by the level difference multiplied with the gravity constant g and the specific weight ρ_{water} of the basin water should ideally give unity. If not, it is assumed that the level measurement did have an error. The pressure transducers are very stable and accurate and do not depend on issues like corrosion, conductivity of the water etcetera. This ratio is used to check and correct the calibration of the level sensors, see §5.1). A correction factor for the level sensors can be calculated form the measurements if it is assumed that the error of the level sensors is uniform and not depending on the location.

$$C_f = \frac{\rho_{water}.g.\ h_{out} - h_{in}}{\Delta p_{air}} \tag{1.2}$$

This factor C_f should be equal to unity. Thus when it is assumed that the level measurements are biased and have to be corrected by a factor α then:

$$\frac{\alpha.\rho_{water}.g.\ h_{out} - h_{in}}{\Delta p_{air}} = 1.0 \tag{1.3}$$

And the factor α to correct the level sensors with is:

$$\alpha = \frac{1}{C_f} \tag{1.4}$$

The factor C_f will be determined for all measurement runs but the average, equilibrium value for the atmospheric and the vacuum runs will be used to correct the measurements.

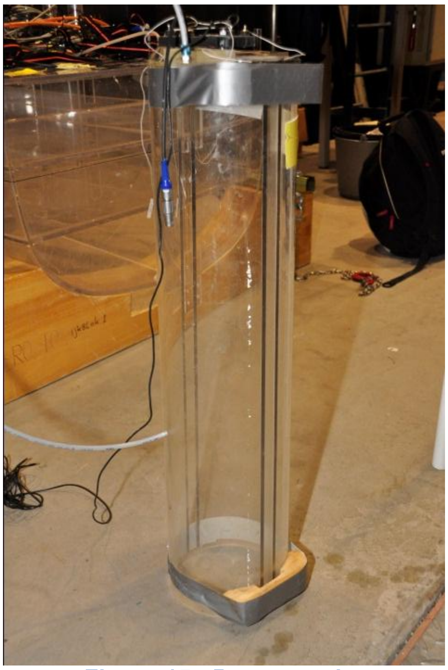


Figure 15 - Perspex tube

The outer level of the tube is also used as a fourth draft sensor. This value is not zeroed when the model was at its draft (for zero heel and trim) as was done with the other draft sensors. Therefore, when the other draft sensors have a reading of approximately zero, the tube outer level has a value of 460 mm (model scale).

4.7 Measurement Procedure

For a given test set-up (a certain heel-trim combination) a measurement in the harbour was done and a measurement in the basin (at 50 mBar). During this cycle the fixation blocks and the models remained mounted to the sub-frame.

For the first measurement of a test-setup the model was drained as good as possible. After the draining the level was estimated in those compartments having a level measurement and that contained a little water. This level (when it touched the level-sensor) was noted down as the initial level. After that all the sensors (level, pressure and force) were zeroed. The next measurement therefore only takes into account the weight increase due to the flooding and not the amount of initial water.
After the first measurement the model was drained as good as possible and the levels were noted again (as described above). Prior to the next measurement only the force sensors were zeroed.

Each run was saved to a separate file. Therefore, for each heel, trim combination there 4 files with raw measurements were created:

- Detailed model, Atmospheric
- Simple model, Atmospheric
- Detailed model, vacuum
- Simple model, vacuum

However, the measurements were not necessarily done in that order. The measurement order is given by the filenames containing the raw measurements, see Appendix A. (121003.txt was done first, followed by 121004.txt, etcetera).

When, for example, the detailed model was measured in vacuum also the simple model measurements were logged in the same file. When the simple model had been flooded prior to the detailed model these measurements give the equilibrium situation of the, already flooded, simple model. If the simple model had not yet been tested then these measurements give the zero measurements of the simple model. These additional measurements sometimes gave an indication of the stability of the equilibrium, in other cases the measurements indicated that the model that had not yet been measured was leaking (either via the drain valves or via the latex path covering the opening).

5 MEASUREMENTS & DATA ANALYSIS

5.1 Post-processing of raw-measurements

The steps in the post-processing are described in the next paragraphs. A large part of the post processing is focussed on the calibration of the level sensors, to check and correct it when required.
The calculations described are all carried out during the post-processing of the raw measurement data. In addition to calculating a number of new signals the raw measurement files were also split in a measurement file containing the data of the ‘active’ model (which was flooded during that run) and the ‘passive’ model that either had been flooded or still had to be flooded. The format of the name of the data files contains all required information, e.g.:

run1a_d[d]_121003_H000_T000.dat

run1a	Run 1 in atmospheric atmosphere (see test program)
d[d]	Measurements of the detailed model while the detailed model was active.
121003	Based on raw data in file 121003.txt
H000	heel of 0 deg
T000	trim of 0 deg

Or another example:

run3b_d[s]_121019_H000_T-30.dat

run3b	Run 3 in vacuum atmosphere (see test program)
d[s]	Measurements of the simple model while the detailed model was active.
121019	Based on raw data in file 121019.txt
H000	heel of 0 deg
T-30	trim of -3.0 deg

The common signals (such as heel, trim, heave, 3xdraft, tube measurements – 2x draft, 1x air pressure) were stored in both files.
In addition, the names of the raw measured signals were also renamed to facilitate comparison. The relation between the signals names is given in Appendix C - Sensor names & Locations.

The following table illustrates this:

Run3	Run3a Atmospheric	Detailed Model active	Run3a_d[d]_121018_H000_T-30.dat
			Run3a_d[s]_121018_H000_T-30.dat
		Simple Model active	Run3a_s[s]_121017_H000_T-30.dat
			Run3a_s[d]_121017_H000_T-30.dat
	Run3b Vacuum	Detailed Model active	Run3b_d[d]_121019_H000_T-30.dat
			Run3b_d[s]_121019_H000_T-30.dat
		Simple Model active	Run3b_s[s]_121020_H000_T-30.dat
			Run3b_s[d]_121020_H000_T-30.dat

5.2 Propagation of uncertainty

Comparing measurements and calculations based on measurement data is of limited value if no insight is given into the uncertainties involved. For example, to calculate the distance between the equilibrium level in a compartment and the SWP (still water plane) the following data (and their uncertainty values are required:

- Level measurement in the compartment
- Heel, trim and draft of the vessel
- Possible deviations of the heel, trim and draft (if they can be assessed)
- Position of the lowest point of the level sensor inside the model
- Point of rotation

During the post-processing of the measurement data the full propagation of all these uncertainties was taken into account for some of the level measurements. These were the measurements that were used to check the “law of communicating vessels”: three compartments (S11, S15 and S16) always have a free flooding connection to each other (and the SWP) and they are fully ventilated during all model tests. The consequence is that the levels inside these compartments should have a zero distance to the SWP.
The uncertainty values are specified in §5.6.

5.3 Calibration Check

Immediately after the first calibration the models were lowered into the water with small steps of 50 mm. The damage opening was left open. After each step the water was given time to settle and when the levels inside the model were stable a measurement cycle of 2 minutes was started. The average level value of each sensor over this 2 minute period was logged. Ideally this would produce a relation between the vertical position of the model and the level of each sensor (provided it is wet and the compartment is not full) which has a slope of 1 (a 50 mm draft step gives a 50 mm level rise). This check was done for both models right after the calibration (prior to the test) in atmospheric and vacuum, after run 3b as an intermediate check (only atmospheric) and after the last test – run 7b -, atmospheric and vacuum. For this last check steps of 25 mm were taken.

1. Calculate the average slope of the level calibration check runs and plot these for each level sensor.
2. Compare this with the expected value of 1.0, see Figure 16 for an example:

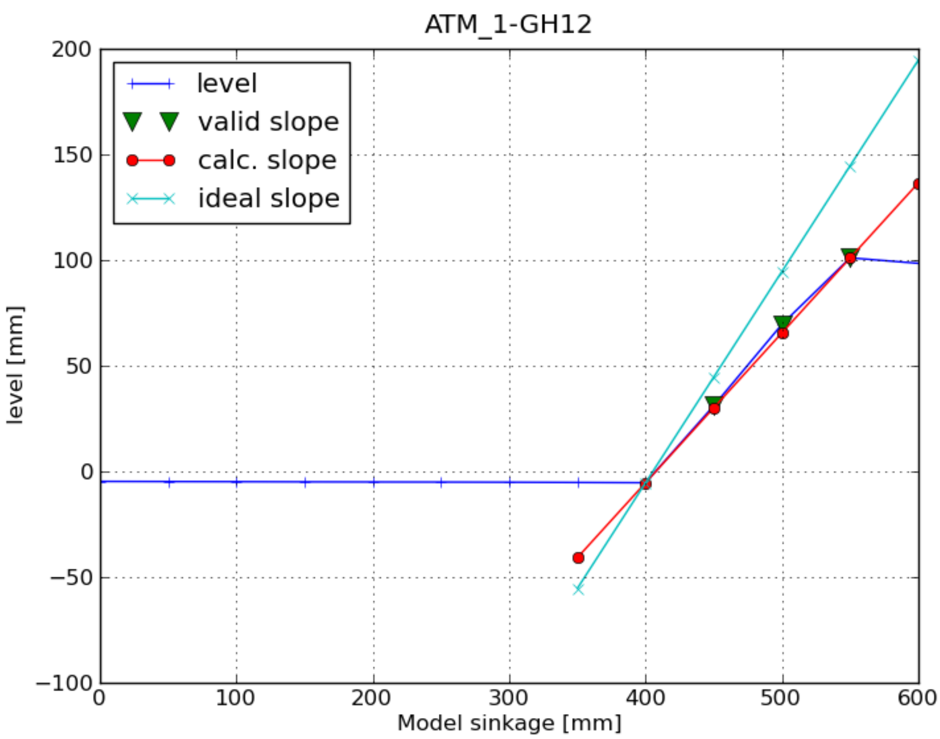


Figure 16 Calibration results (Sensor GH12, simple model, atmospheric)

In this plot the 'level' line gives the relation between the (simple) model draft steps and the measured level of compartment 12. If the sensor behaves correctly then the slope of the line is 1.0 (given by 'ideal slope'). In this particular case the calculated slope differs significantly (see 'calc. slope' line). The points used in the slope calculation are indicated by the green triangles ('valid slope'). These points are determined by limiting the calculated slope between 0.5 and 1.5. The reason to do this is to filter out erroneous measurement points caused by for example compression effects. See Figure 17 where the last measurement was excluded. All results can be found in Appendix B – Calibration Check results.
When inspecting the table in the appendix it is evident that quite large deviations from the desired value of 1 exist. The largest deviations are found during the first calibration check which was done immediately after the calibration itself: values as large as 0.64 for the slope (GH12, see Figure 16) and 0.55 for GH16.

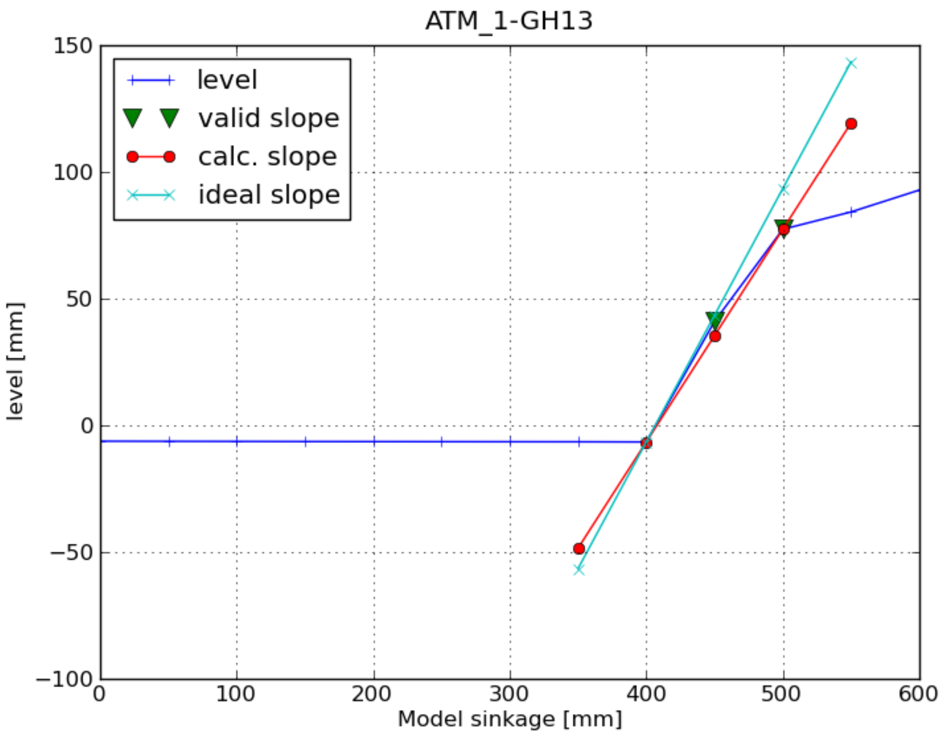


Figure 17 Calibration results (Sensor GH13, simple model, atmospheric)

It is also interesting that all slope values are too low and that the results for the final check show an improvement. When comparing the average values between both models (GH sensors of the simple model and W sensors for the detailed model) then it shows that there are differences, but also the standard deviation is quite high.
When comparing the values between atmospheric and vacuum the differences become larger: the average vacuum slope is lower. However, the standard deviation is quite high. A plot is shown in Figure 18: it shows the average calculated slope and the standard deviation for al calibration checks (simple model 1-5, detailed model 6-10). The horizontal axis gives the calibration measurement run index. The sequence was 1 & 2 (6 & 7): calibration checks immediately after the initial calibration of the level sensors, 3 (8) calibration check after completion of run 3, 4 & 5 (9 & 10) Calibration check at the end of the program. See the test program in Appendix A.

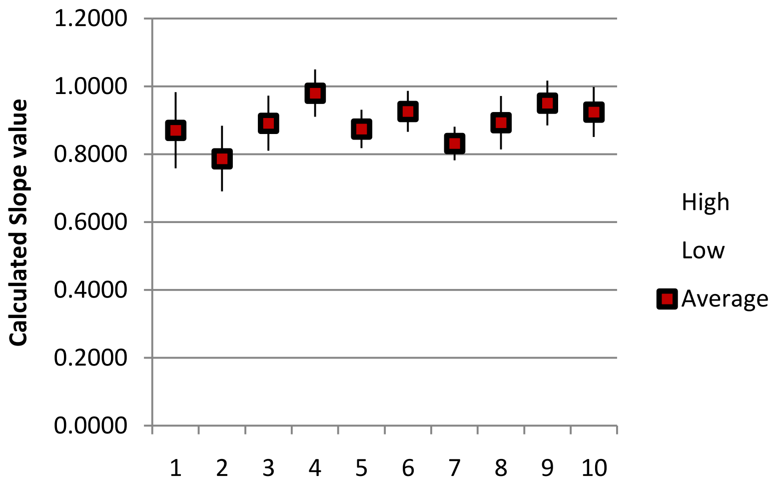


Figure 18 Calculated Average Slope (no correction)

3. Use the calibration-tube data to correct these calibration check measurements when required. This can be done for the intermediate and the final calibration check that were respectively done after run 3b (atmospheric only) and the final calibration check after run 7b (atmospheric and vacuum). For the first calibration check measurements the pressure in the tube was not measured and hence the correction cannot be calculated, see Appendix B. When inspecting the table and the plot it is clear that the average slope values are all overestimated.

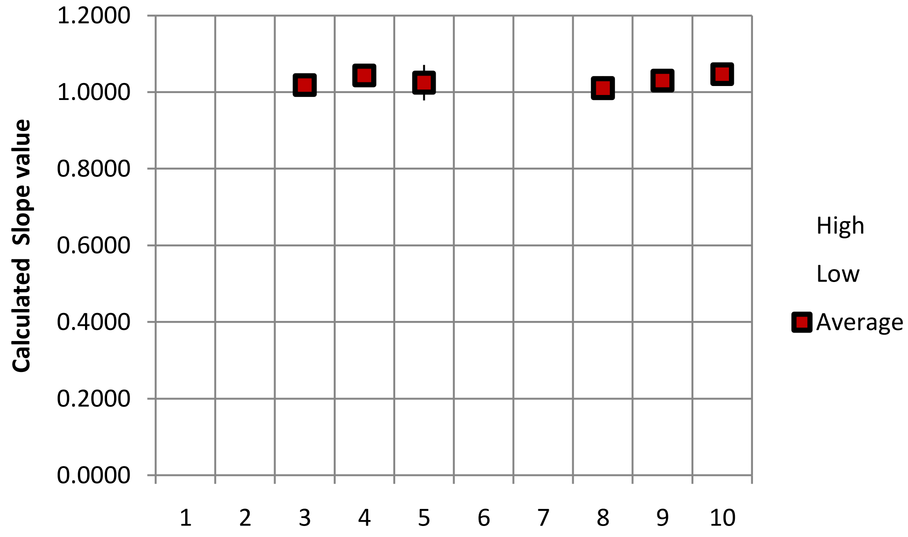


Figure 19 - Calculated slope value (with correction)

The values are much closer to the desired value of 1 and the standard deviation is also much lower.

Eventually it was decided not to apply step 3. The choice was made that when corrections are applied the same corrections (based on the same information) should be applied to all measurements. In this case this could not be done since the air pressure measurements were not available for 1 & 2 and 6 & 7.

5.4 Zero level corrections

To be sure that all sensors give the correct increase in value it has to be ensured that for example the measured water level value of an empty tank is zero. Due to measurement uncertainties it is highly unlikely that this is the case and almost always a small initial value might be measured. To correct for this the average of the first 60 sec of each signal is determined (this is before the damage is initiated) and this is subtracted from the rest of the signal.

However, this is quite tricky in case there is some initial water inside a compartment (e.g. due to leakage). In that case the zero value cannot be determined and the signal is not corrected.
The same applies to the weight sensors (three Fz force transducers). All the weight sensors were zeroed after the models were positioned at the correct draft marks and before the first model was flooded. It is the intention to measure the weight difference between the simple and detailed model, between atmospheric and vacuum conditions.

The draft sensors and the tube sensors were not zeroed between the tests. They have to give the reference signal for the constant draught of the measurement frame.

The adapted procedure is therefore as follows. A simple and the detailed model are always tested together in either atmospheric or in vacuum conditions. Between the two tests the models are kept at the same draught and they are flooded one by one. The 'raw' measurement file of a single run contain the measurements signals of the active model that is being flooded and the passive model that is either already flooded or still has to be flooded. The run sequence can be determined from the 'raw' filenames. See the test program.

Thus the data for, for example, Run1a_s (Run1 in atmospheric conditions with the simple model active) is saved in '121004.txt'. this file contains the signals of the 'active' simple model and the 'passive' detailed model. The 'passive' detailed model was already flooded which data was stored in '121003.txt' (Run1a_d). In this example the zero corrections for Run1a_d (to correct the detailed measurements) is taken from the same file ('121003.txt'), while the corrections for Run1a_s are also taken from the file '121003.txt', but in that case the measurement signals of the simple model. This can be illustrated by a plot.

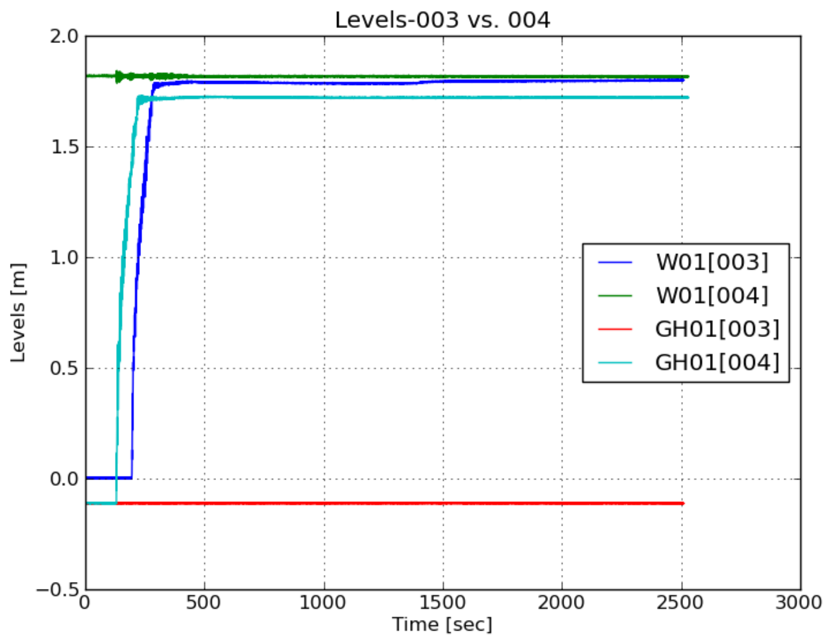


Figure 20 Water levels of run 121003 and run 121004

In the plot the levels of the S01 compartment of the simple model and the detailed model are plotted. The data comes from the –uncorrected- raw measurement file '121003.txt' and '121004.txt'. As can be seen in the plot, first the detailed model is flooded, see W01[003] that has a step response, while the level in the simple model (GH01[003]) remains constant. In the next test (saved in '121004.txt') the simple model is flooded. Now the level in the detailed model (shown by W01[004]) remains constant and the GH01[004] shows a step response. The zero corrections are now applied as follows: the average value of the first 60 sec of GH01[003] is used to correct the whole signal GH01[004] and the first 60 sec of W01[003] are used to correct W01[003].
The reason to apply this procedure is that in this way accumulated leakage water (leaked into the simple model while the test for the detailed model was done) is not eliminated from the measurements: this would indicate an erroneous difference between both models.

5.5 All Sensors

The data for each run (containing four values for slope and four values for the average of the equilibrium) are summarised for all sensors in a table. The values on a single row give the sensor values for the measurement of the detailed model in atmospheric pressure, Slope(DA), for the detailed model in vacuum, Slope(DV), the simple model in atmospheric pressure, Slope(SA) and the simple model in vacuum, Slope(SV). A similar logic is used for the average values.

1. Determine y=a.x+b for all sensors. This is used to judge the equilibrium state (the slope which should ideally be very small) and the quality of the measurement, the air tightness etc. It is done for the last 500 seconds of each run.
2. Also the average of the data over this interval is determined. This is used as the equilibrium value of the sensor.

5.6 Level Sensors

For the level sensors a number of corrections were applied to the raw measurements. Also additional signals were calculated:

1. Check and possibly correct the calibration using the tube measurements or the calibration check measurements.
2. Subtract the zero level from whole level signal (use average of first 30 sec). However, this is a tricky operation: to be able to do this the compartment has to be empty. This cannot be assumed for all compartments since during some runs for example the damage opening leaked prior to the start of the test.
3. Calculate the S0 value of the whole signal. This is the distance between the measured level in the compartment and the still water plane. It is influenced by the draft of the model, the heel and trim, the point of rotation and the location of the sensor. In addition to this value also the calculated 95% (2Sigma) upper and lower limit is stored in the data file. These values are calculated using propagation of errors throughout the calculation.
4. Calculate the equilibrium S0 values.
   If compartment ventilated and connected to the SWP, h_s0 shall be zero (taking into account the measurement uncertainties).
5. Calculate the propagation of uncertainty for the sensors in compartment S11, S12, S15 and S16. These equilibrium values of these sensors will be compared and hence uncertainty data is required to give an indication of the qualitative value of the comparison.

For those compartments that are ventilated and connected to the basin water the water level should be equal to the basin water, thus the calculated distance should be zero (law of communicating vessels). The calculation of this signal involves the use of a number of signals each having its own uncertainty. Propagating this uncertainty in the calculated signal is essential to be able to draw conclusions whether these levels are indeed the same. Uncertainties that play a role (and their estimated values) are:

Name	Uncertainty (95%)	Units	Comment
Trim	0.2	deg	
Heel	0.2	deg	
Draft	0.01	m	Includes measurement & control.
Heave	0.002	m	To express the uncertainty in draft corrections.
Level	0.004	m	Level measurement
Geometry	0.002	m	To express the uncertainty in the location of the sensors.

Unfortunately the uncertainties have to be scaled: the measurements are done on model scale and therefore the uncertainties apply to the measurements on model scale. Multiplying them with the scale factor can lead to substantial values, especially when propagated through the calculations.

5.7 6 Component Frames

The post-processing of the force measurements consisted of four actions:

1. Use the first 30 seconds as the zero level and subtract that from the rest of the whole signal
2. Calculate the total Fx, Fy and Fz forces
3. Calculate the Mx, My (prior to the flooding and after the flooding)
4. Calculate the x and y of the floodwater only.

The 6-component measurements will be the most reliable measurements. They are quite accurate (see §4.4) and independent of media properties (such as air and water) that played a role in the other measurements. As such they will be the primary measurements used to assess the differences between the models and the influence of air pressure on the flooding process.

6 MEASUREMENT & POST-PROCESSING RESULTS

6.1 Introduction

The results discussed here are limited to the average equilibrium values only. In chapter 5 it is discussed how they are determined. Considering the amount of data not all signals will be treated in detail: the most interesting phenomena were identified and the discussion will mainly focus on these. However, the plots of the other signals are delivered in binary format.

Comparisons between tests will mainly be limited to the weight and centre of gravity calculations. These measurements are the not influenced by the problems that plagued the level sensors. However, also the weight measurements are subject to the uncertainties in attitude control and measurement.

6.2 Calibration Results

After the first 4 tests were done the results were inconsistent which made it necessary to redo the whole calibration process. An additional complexity was the compartments S10, S13 and S14. All ventilation openings (the doors, height 1.70 m, full scale) of these compartments were closed by the water before the water level reached the upper deck of these compartments. Consequently, an air pocket formed which prevented the compartments to fill until the maximum possible level (the upper deck). This made it impossible to calibrate the sensors in these compartments over the full measurement range.

During the calibration it also showed that these compartments (S10, S13 and S14 of the simple model and S13, S14 of the detailed model) were not entirely airtight. This especially showed for S14. It resulted in a very slowly rising water level when it should have been stable. The rate varied from compartment to compartment but S14 showed the fasted level rise (13 mm in 150 sec, model scale), see Figure 21. In vacuum the level eventually stabilised for S14.The measurement time was increased from approximately 2 minutes to 5 minutes to check whether the level stabilised and although the rate decreased the level did not reach equilibrium in those 5 minutes model time.

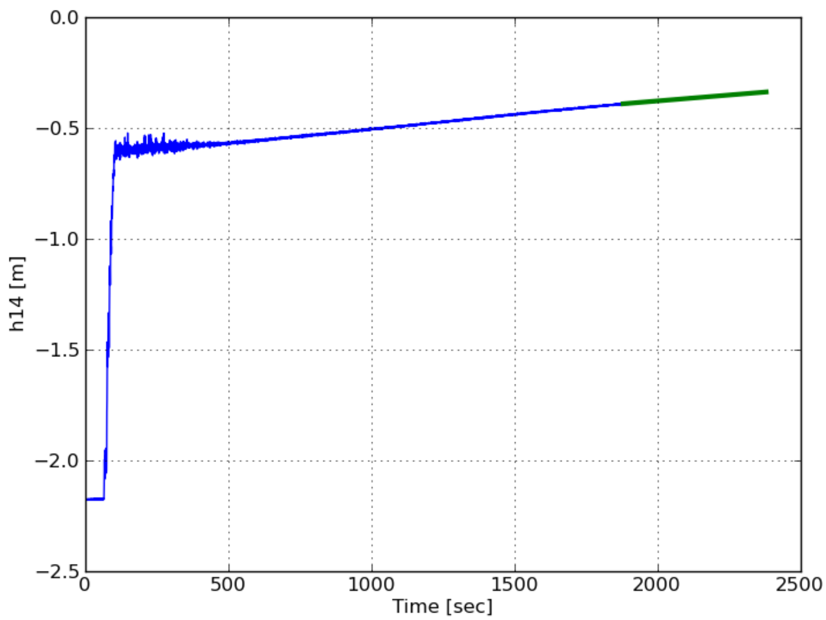


Figure 21 – Distance to SWP of compartment S14 (detailed, atmospheric, full scale)

These phenomena occurred for Run1, Run3, Run7 and Run6b (detailed model only). In general for the smaller roll angles (with the exception of Run6b). For the larger roll and trim angles the air pocket might have formed, but the maximum water level that could be measured had already been reached.

During the calibration in phase I under vacuum conditions another problem surfaced. After giving sufficient time to stabilise the level in the fully ventilated compartments S12, S16, S15 and S11 started to drop. Initially, they had been stable under atmospheric conditions. The worst was the level in compartment S12: a drop of approximately 20 mm of 110 mm measured in 330 seconds (model scale, zero trim and zero heel). This is physically not possible when the draught and attitude of the model is constant: S12 is connected via the large damage opening to the basin and should have a constant level almost from the start of the flooding.

Possible sources of this problem could be the increased effect of electrolyse of the water in vacuum at the level sensor. Under low atmospheric pressure the gas-bubbles formed at the level strips will increase in size. This will over time decrease the measured current and thus result in a seemingly lower measurement of the level. To reduce this effect the level sensor is supplied with an AC current of 6 kHz. To find the cause of the problem several additional tests were done, including a test with DTT basin water in the vacuum test tank at MARIN. However, the problem could not be reproduced in this way.

6.3 Attitude control & measurements

The three draft measurements were added in phase III to be able to check the submergence of the models. Ideally, the submergence should have been equal for all runs. This would make it easy to compare the results of the models and the difference between the atmospheric and the vacuum tests for any heel, trim combination. As described, the vertical position of the sub-frame and thus the model-frames were automatically controlled by a PLC. The desired position set point was slightly varied. The reason is that visual inspection of the draft marks on the frame seemed to indicate a drift in the vertical position of the models.

In the DTT the models were roughly positioned at the correct draft (by using the same PLC set point 485 value, the same as used in the harbour). The counter value should approximately indicate the number of millimetres above the waterline, thus the higher this value the further the sub-frame is from the water plane (and the smaller the draft). After setting sub-frame to the 485 value visual inspection of the draft marks showed that these were well above the waterline and hence, the model had to be lowered further. It seemed that 478 (thus assumed to be approximately 7 mm lower) was the correct value (again checked by visual inspection of the draft mark with the video camera).

After that, a measurement was taken with the 3 draft level sensors attached to the sub-frame and the tube outer level sensor. The measurements indicate a twist of the sub-carriage. This was confirmed by using an underwater camera for inspection of the draft marks.

When the signals of the three draft sensors are compared during the 14 runs done then a similar picture emerges. The three measurements are ‘reasonably’ close but significantly different from the expected maximum difference value of 1.0 mm from an expected value of 0.0 mm during the harbour run in atmospheric circumstances. There is a very significant difference from zero during the vacuum runs. This is clear from the 2 tables below. They show the equilibrium values of the 7 runs in atmospheric circumstances (Table 2) and the 7 runs in vacuum circumstances (Table 3) (both tables are given on model scale):

Table 2 - Draft sensors (Atmospheric)

Atmospheric	Name	PLC	Avg(DA)	Avg(SA)
		[mm]	[m]	[m]
Run1	Draft_PSa	485	-0.001	-0.002
Run2	Draft_PSa	485	-0.008	-0.004
Run3	Draft_PSa	485	-0.007	-0.006
Run4	Draft_PSa	485	-0.010	-0.009
Run5	Draft_PSa	488	-0.017	-0.017
Run6	Draft_PSa	485	-0.014	-0.015
Run7	Draft_PSa	485	-0.014	-0.014
Run1	Draft_PSf	485	-0.001	-0.002
Run2	Draft_PSf	485	-0.010	-0.004
Run3	Draft_PSf	485	-0.010	-0.009
Run4	Draft_PSf	485	-0.019	-0.019
Run5	Draft_PSf	488	-0.027	-0.026

Run6	Draft_PSf	485	-0.019	-0.019
Run7	Draft_PSf	485	-0.024	-0.023
Run1	Draft_SBm	485	-0.001	-0.003
Run2	Draft_SBm	485	-0.010	-0.005
Run3	Draft_SBm	485	-0.009	-0.009
Run4	Draft_SBm	485	-0.017	-0.015
Run5	Draft_SBm	488		
Run6	Draft_SBm	485	-0.016	-0.018
Run7	Draft_SBm	485	-0.021	-0.021

The small difference between the Avg(DA) and Avg(SA) – the average value of the last 500 sec for the draft values of the detailed and the simple model in atmospheric conditions – is an indication of the stability of the measurements. The values of Run 5a Draft_SBm are not valid: the sensor failed during the run.

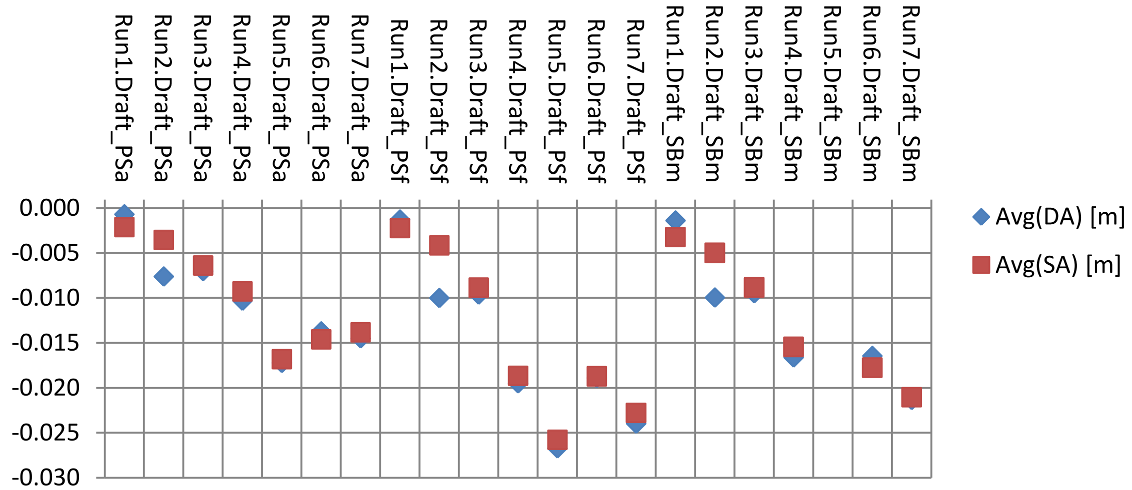


Figure 22 – Measured Drafts (Atmospheric)

All differences are negative, meaning that the draft of the models was less than required. The mean value over all measurements is about -0.012 m. When the values from Table 2 are plotted, see Figure 22, then a trend is visible: the average draft is becoming more negative in the time period of the test program. There is a clear trend in the measurements. It is not clear what caused this.

Table 3 - Draft Sensors (vacuum)

Vacuum	Name	PLC	Avg(DV)	Avg(SV)
		[mm]	[m]	[m]
Run1	Draft_PSa	485	-0.034	-0.035
Run2	Draft_PSa	478	-0.036	-0.036
Run3	Draft_PSa	478	-0.035	-0.035
Run4	Draft_PSa	478	-0.032	-0.032
Run5	Draft_PSa	478	-0.035	-0.034
Run6	Draft_PSa	478	-0.035	-0.034
Run7	Draft_PSa	478	-0.030	-0.032
Run1	Draft_PSf	485	-0.051	-0.051
Run2	Draft_PSf	478	-0.052	-0.052
Run3	Draft_PSf	478	-0.052	-0.051
Run4	Draft_PSf	478	-0.050	-0.051
Run5	Draft_PSf	478	-0.052	-0.052

Run6	Draft_PSf	478	-0.051	-0.050
Run7	Draft_PSf	478	-0.051	-0.051
Run1	Draft_SBm	485	-0.043	-0.043
Run2	Draft_SBm	478	-0.043	-0.043
Run3	Draft_SBm	478	-0.042	-0.042
Run4	Draft_SBm	478	-0.041	-0.040
Run5	Draft_SBm	478	-0.041	-0.042
Run6	Draft_SBm	478	-0.040	-0.039
Run7	Draft_SBm	478	-0.035	-0.040

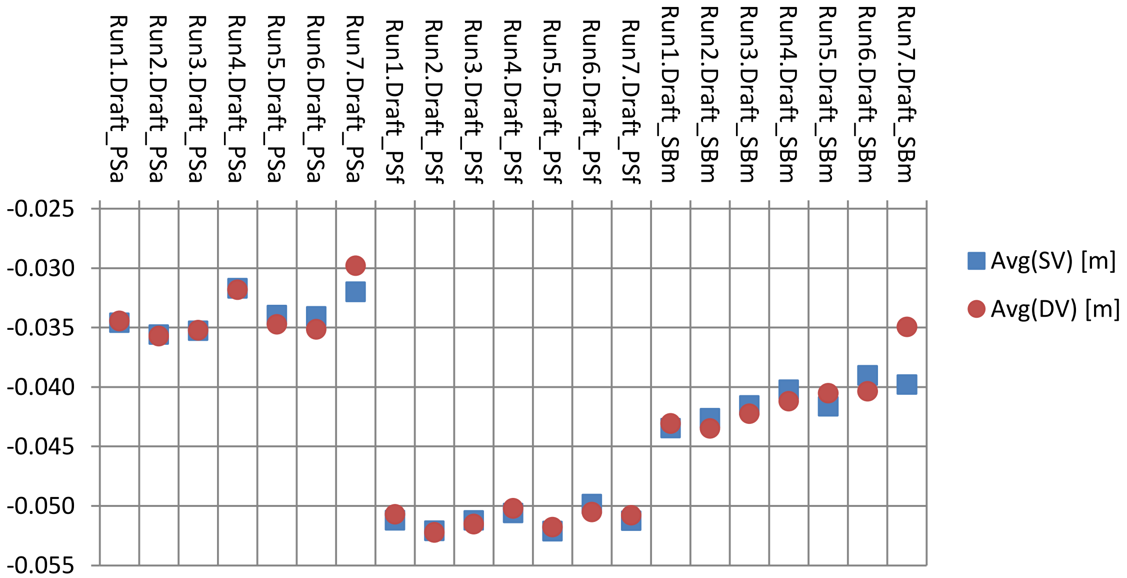


Figure 23 - Measured Drafts (Vacuum)

In Figure 23 the differences between the draft sensors are clearly visible: they are also quite consistent over all the runs. The values are again all negative and in absolute sense much higher than the values in atmospheric conditions. The average value is about 0.042 m. In addition, the measurements also indicate a substantial twist of the whole sub-frame. This twist results in an error in heel and trim value of the models. An assessment is given further on in this paragraph.

When the PERSPEX tube levels of these runs are compared (see Table 4) it shows that the measured level is quite constant over the course of a single run (a simple and a detailed measurement, either in atmospheric or vacuum circumstances). Although the same counter value was used (except for run 1b vacuum and run 5a atmospheric) there is a significant difference of approximately 30 mm between the atmospheric and the vacuum runs. What is surprising is that the increase in the counter value between run 4a and 5a is reproduced in the measurements: this is at least an indication that relative changes can be identified from the measured values.

Table 4 – Tube Level Outside (Atmospheric & Vacuum)

Atmospheric	Name	PLC	Avg(DA)	Avg(DV)	Avg(SA)	Avg(SV)
		[mm]	[m]	[m]	[m]	[m]
Run1	Tube_Out	485	0.461	0.426	0.461	0.425
Run2	Tube_Out	485	0.432	0.408	0.436	0.407
Run3	Tube_Out	485	0.436	0.405	0.436	0.406
Run4	Tube_Out	485	0.431	0.408	0.432	0.409
Run5	Tube_Out	488	0.428	0.407	0.428	0.408
Run6	Tube_Out	485	0.430	0.407	0.431	0.407
Run7	Tube_Out	485	0.427	0.409	0.427	0.408

Although the value of the PLC counter has been the same for all atmospheric runs, the value of the tube outer level of the first run is significantly different. The other values are closer to each other but still a variation of about 0.005 m can be observed.
The vacuum runs show a difference of 20 mm. Run 1 is different because of the different PLC counter value, the difference of 7 ticks (assumed to be 7 mm) can however not be related to the difference in measured values which is much bigger: the change in PLC counter value is 7 but the measured difference is 18 mm.

To get an indication of the heel and trim errors when these draft measurements are assumed correct and accurate can be achieved by fitting a plane through the draft measurements. The angles of this plane with the x-axis and y-axis are the errors in trim and heel respectively. In addition, the z-coordinate at the point of rotation of both models is calculated. This should give an indication of the error in draft.

The plane equation fitted to the draft measurements was:

$$z = f\left(x, y\right) = a.x + b.y + c \tag{1.5}$$

The expression above gives the equation for a plane in 3D. $f\left(x, y\right)$ is the z-value, x and y the x and y coordinates and a, b the plane's slope in x and y direction respectively and finally c the intercept with the z-axis. The coefficients a, b, and c were determined using the three draught measurements and the PERSPEX tube measurement in combination with the method of least squares. The origin of the coordinate system is starboard, aft of the sub-carriage, see appendix D. The origin for the z-axis is the draft plane (measurement of exact zero of the draft sensors). Negative values mean that the model's origin is <u>above</u> the plane determined by the draft measurements. The results are given in Table 5.

Table 5 - Calculated Roll/Pitch/Draft errors (Model Scale)

	Roll Error	Pitch Error	Draft Error Detailed	Draft Error Simple
	[deg]	[deg]	[m]	[m]

Run1a	0.060	-0.005	-0.001	-0.001
Run2a	-0.096	0.012	-0.007	-0.008
Run3a	0.039	0.007	-0.008	-0.008
Run4a	0.078	0.039	-0.014	-0.016
Run5a	*-9.221*	*-0.328*	*-0.110*	*-0.094*
Run6a	0.149	0.011	-0.015	-0.016
Run7a	0.057	0.038	-0.018	-0.020
Run1b	0.251	0.068	-0.040	-0.044
Run2b	0.319	0.068	-0.041	-0.044
Run3b	0.259	0.072	-0.041	-0.044
Run4b	0.237	0.085	-0.039	-0.043
Run5b	0.322	0.077	-0.040	-0.044
Run6b	0.294	0.071	-0.040	-0.043
Run7b	0.320	0.096	-0.038	-0.042

Run 5a of the atmospheric runs did have two draught sensors with faulty readings and therefore these values have to be ignored.
There is a clear difference between the Atmospheric runs (upper half of the table) and the vacuum runs (lower half of the table). Both the heel and pitch error are substantially bigger in the vacuum part of the facility. The same applies for all draft errors.

The time trace of the draft signal seems to indicate that the flooding of the model also causes a decrease of the draft of approximately 0.01 m full scale (or 0.5 mm model scale) of the model(s) , see Figure 24. The highest decrease is shown by Draft_SBm, the draft sensor in the middle of the sub-frame (~1.5 mm model scale).

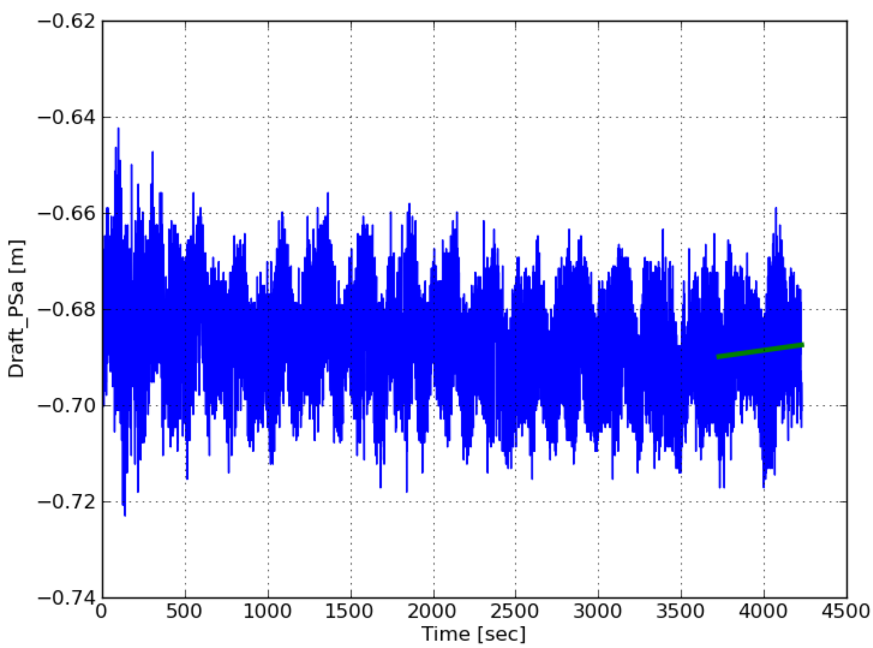


Figure 24 - Draft increase due to flooding (example, full scale)

The reason is probably the deformation of the sub-carriage and the frames holding the model(s). This trend is the reverse of what can be expected. If the model fills up it is obviously getting heavier and hence it is expected that the deformation of the model-frame and sub-frame together results in an increase of the draft measurements. It is not clear what has caused this contradiction in the measurements.

For some of the runs a visual inspection of the draft marks on the model frame was performed. One of the runs was measurement run 45 (Run4a detailed, atmospheric). The footage clearly shows that the draft mark is below_the waterline (marked blue) indicating that the model was too deep in the water and hence, a positive draft measurement was expected. The upper side of the yellow tape is the draft line (remark that the yellow tape is mirrored in the SWP.

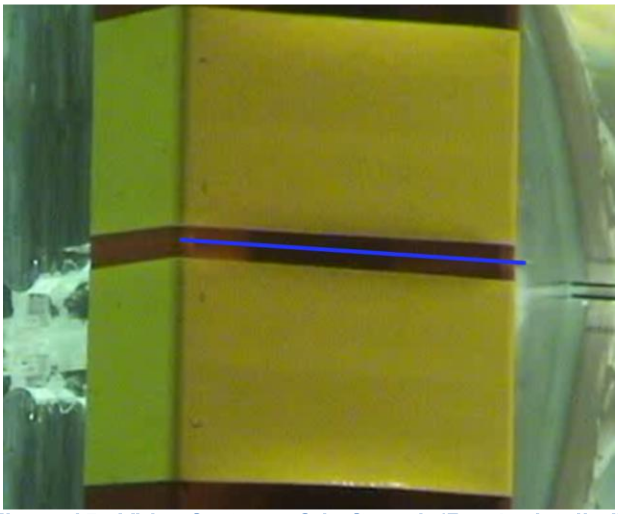


Figure 25 - Video footage of draft mark (Run4a detailed)

When the draft measurement data for this run are checked then it is apparent that all three draft measurements give a negative value (model scale):

Run4a_d	Avg(DA)
Name	[m]
Draft_PSa	-0.010
Draft_PSf	-0.020
Draft_SBm	-0.017

The negative values and the visual check that the draft of the model is too high (thus the model is too deep in the water) is confirmed by Run4b of the detailed model in vacuum:

Figure 26 - Video footage of draft mark (Run4b detailed)

Run4b_d	Avg(DV)
Name	[m]
Draft_PSa	-0.032
Draft_PSf	-0.050

Draft_SBm	-0.041

Although the draft marks are not exactly at the location of the draft sensors, the average value of the sensors (around -0.04 m) seems to be significantly more than the value that can be estimated from the video footage (the width of the yellow tape is 90 mm). The sign of all the measurements is again the opposite of what is expected.

Prior to the testing it was assumed that the vertical positioning of the sub-carriage had a repeatable accuracy of about 1 mm (both in atmospheric and vacuum conditions). The measurements appear to be indicating a much higher value. Especially the differences between the harbour location and the vacuum (basin) location are a problem since this makes the comparison between the tests in Atmospheric pressure and vacuum pressure more difficult and less accurate.

6.4 Air tube results

The correction factor (see the discussion in §4.6) is calculated for all runs and a clear difference is found between the atmospheric and vacuum runs. In addition, the difference is very similar for all runs, see Figure 27.

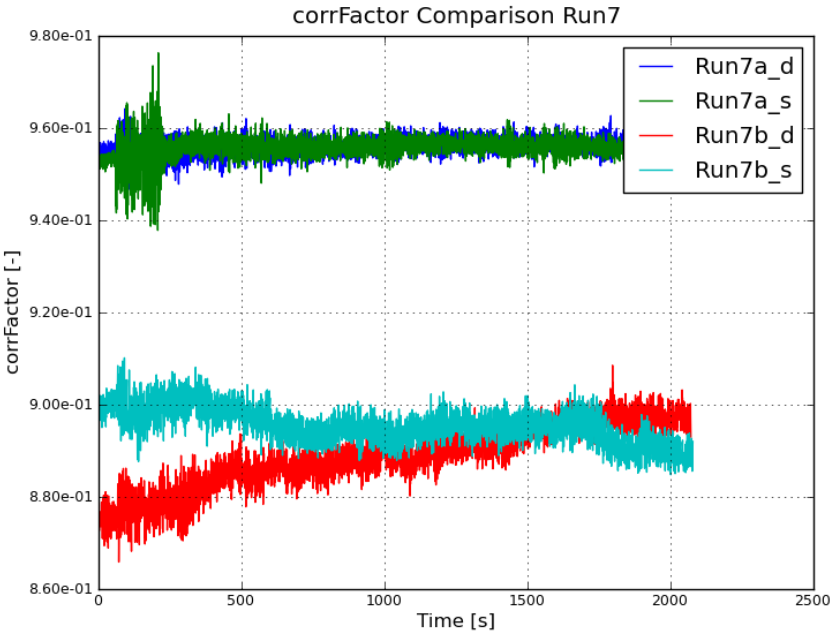


Figure 27 PERSPEX Tube correction factor Run7

The values for the atmospheric runs are very stable and vary between 0.96 and 0.98. The fluctuations in vacuum are larger, probably caused by the percentage wise lower values of the pressure difference in vacuum while the absolute fluctuations in pressure were the same. The pressure difference of the tube was not measured for the Run1a, Run1b and Run2a and hence a correction factor could not be calculated for these runs. In view of the similarity of the data of all the other runs it is assumed that the same correction factor can be applied. These factors are calculated by taking the average value of the last 500 seconds for the atmospheric and for the vacuum runs. This resulted in Table 6.

Table 6 Averaged correction factors

Id	C_f
Atmospheric	0.966
Vacuum	0.901

The correction applied to the level sensors inside the model (thus not the draft sensors) is the inverse value (as described in §4.6). The correction is applied prior to calculating the derived quantities (e.g. the distance between compartment level and the SWP).

These measurements also give a clear insight in the potential effect that scaled air-pressure might have on the flooding of a geometry. When the height difference between the outer and inner level of the PERSPEX tube are compared then a clear difference in visible between the atmospheric and vacuum runs. Remark that the orientation of the tube is the same for all runs and hence the difference in height is (approximately) the same for all runs. What is shown in the plot below is:

$$Level\ Difference = \left(Tube\_Out - Tube\_In\right)_{Atmospheric} - \left(Tube\_Out - Tube\_In\right)_{Vacuum} \qquad (1.6)$$

The average difference between atmospheric and vacuum is approximately 3.75 m (full scale) which is a clear indication of the effect of scaled air pressure, see Figure 28..

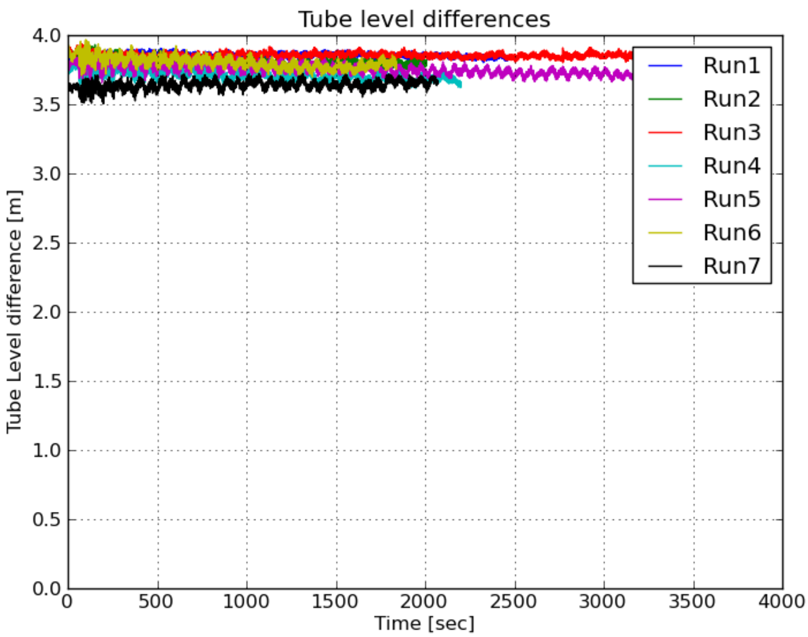


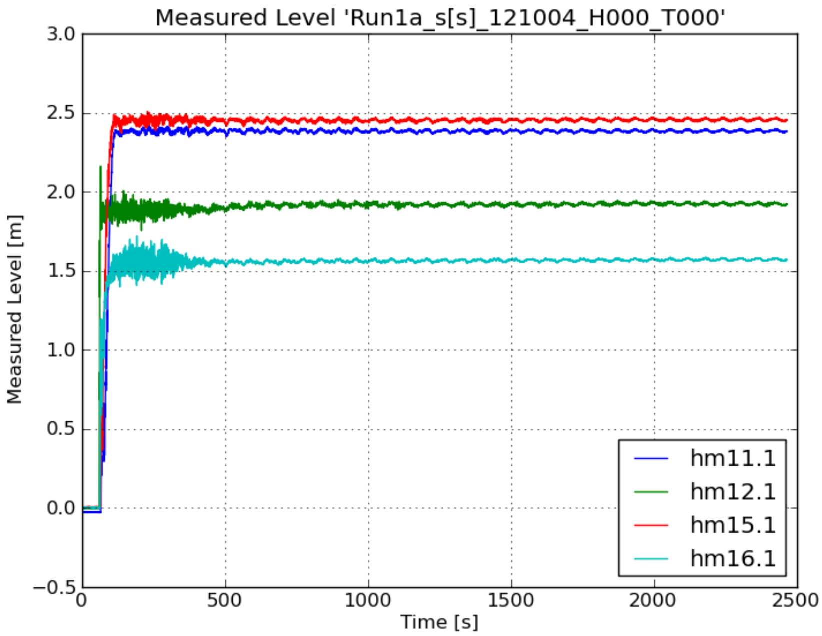
Figure 28 PERSPEX Tube level differences

6.5 Run 1 Comparison (heel = 0.0 deg, trim = 0.0 deg)

In the atmospheric runs compartment S06 of the simple model has leaked prior to the start of the test and the same applies to S06 of the simple model during the vacuum run. In the last case S06 contained a significant amount of leak water prior to the start of the flooding tests (which started with the membrane rupturing).

All the tests in Run 1 have a heel and trim of zero degrees. At this draft the compartments S17, S18 and S24 do not flood. Both the detailed and the simple model experience air leakage in S10, S13 and S14 (as discussed in 6.2). This is visible in the weight which slightly increases over time. The calculated slope of the equilibrium signal for the total weight gives a value of around 8 kg/s for the Atmospheric, and around 3 kg/s for the vacuum runs.

In this horizontal configuration the levels of the ventilated, connected compartments S11, S12, S15 and S16 should have the same value. The draft of the model should be 6.392 m increased with a heave of 0.16 m, the deck height of this deck is 4.216 m, and hence the expected water level should be 2.34 m. The situation is however different:



What strikes the most is that the levels of all compartments are significantly different from the expected level. If the draft sensors are assumed to be reliable then the draft error for both models is negligible (see Table 5) and the error should be in the calibration of the level sensors which matches the measured voltage to the level of water touching the sensor. If the values of Run1a for the simple model in atmospheric conditions are taken:

Table 7 – Run1a (simple model) Level deviations

Sensor Id.	hm	h	hmax
	[m]	[m]	[m]
11.1	2.41	0.08	2.34
12.1	1.92	-0.41	2.34
15.1	2.45	0.11	2.34
16.1	1.57	-0.77	2.34

In Table 7 'hm' is the measured value in each compartment (corrected for zero), 'h' is the calculated distance from the level in each compartment to the still water plane (upward positive). the maximum expected value for each sensor, 'hmax' is the distance between the bottom of the sensor and the still water plane: 2.34 m (assuming the draft sensors were correct and hence, the model is at its required draft of 6.392 m increased with 0.16 m as discussed in §3.4).

There is no consistent deviation for the sensors. The values for sensor 11.1 and sensor 15.1 are close together, which was expected as they are on adjacent sides of the same bulkhead in connected compartments. They are both too high. The value for sensor 12.1 and sensor 16.1 have a large error: the damage opening takes care that the level in these connected compartments is equal to the SWP at all times. This situation could already be expected after the strange effects that were identified during the first phase of the calibration, see §5.3.

For the horizontal situation of Run 1 it is comparatively easy to calculate the distance between the measured level in the compartments and the still water plane (SWP). In the case of Run1 it should apply to S12, S11, S15 and S16. The sensor in S16 (hm16.1) was giving a faulty reading: this confirms the calibration value determined in the first calibration check (immediately after the first calibration and prior to this test).

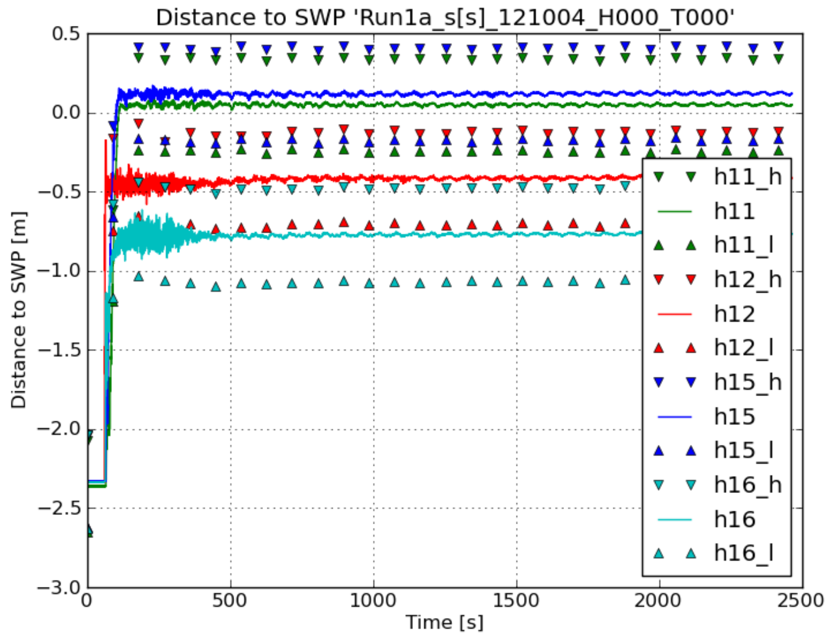


Figure 29 Distance to SWP Run 1a

Included in Figure 29 are the 95% uncertainty limits (green lines): the range of approximately two times 0.40 m (full scale, or two times 0.02 m model scale) is substantial. Using these ranges, the measurement of S16 can be identified as an outlier. The same applies for the S12 measurement. Apart from the S16 measurement the differences could partly be related to a different heel angle than the assumed value of 0.0 deg.

The weight and centre of gravity calculations are independent of the level measurement and can be used as a reliable reference for comparison of the four runs. The gradual slope caused by leaking air is clearly visible. It is about 8 kg/s on full scale and it is approximately the same value for all runs in this group (see Figure 30).

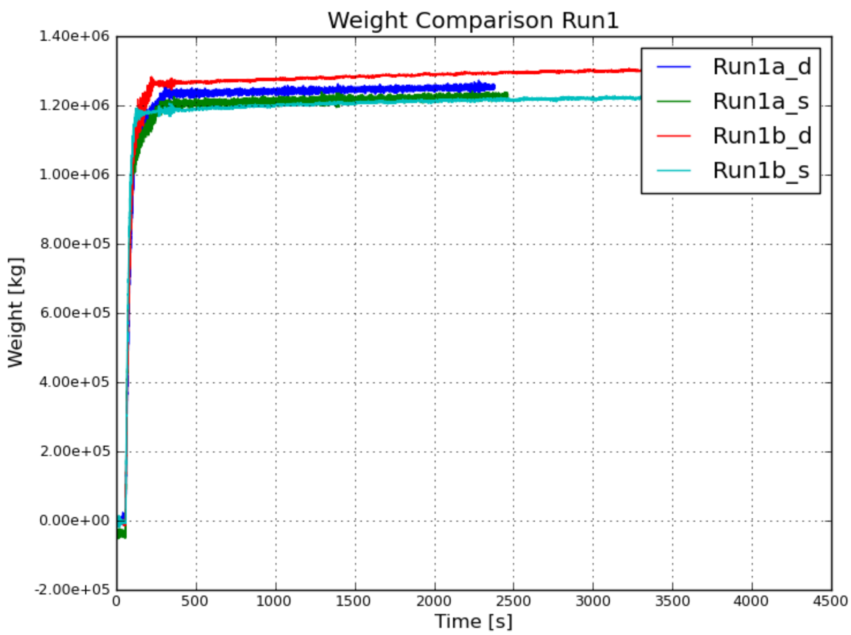


Figure 30 Weight Comparison Run1

A difference between the atmospheric and vacuum tests is found during the initial stages of the flooding. The atmospheric runs (Run1a) show a slightly more gradual increase in weight around the 300 seconds, see Figure 31. This is an indication that the air compressibility was higher for these runs: it acts as a stiffer spring and prevents the water from rushing in.

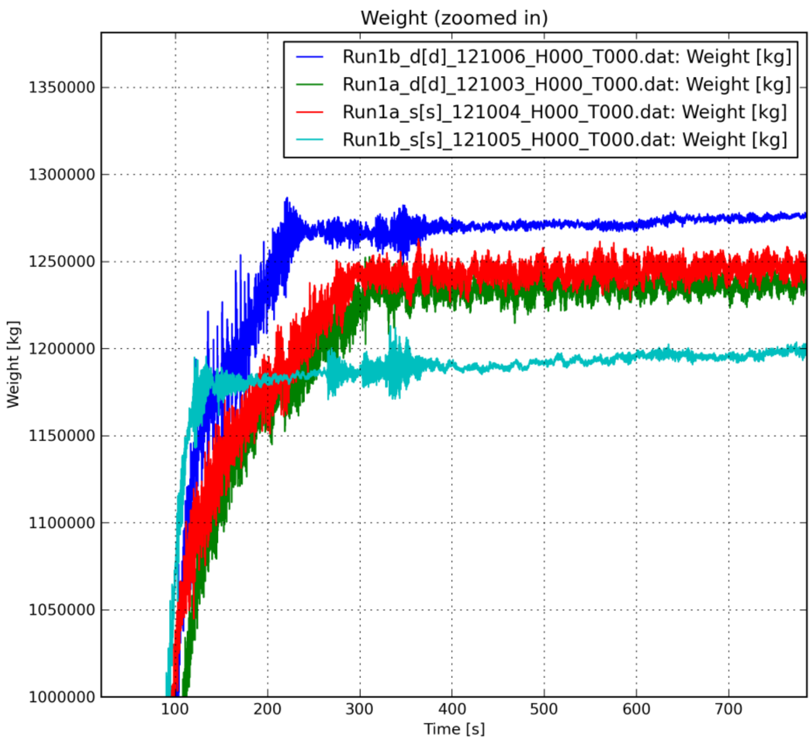


Figure 31 Weight comparison Run1 (zoomed in)

When inspecting the distance to the SWP for compartment S14, h14, see Figure 32, there appears to be a difference between the runs in how this compartments fills up. Especially the level of the detailed model in vacuum conditions asymptotically rises to just above zero, the simple model will probably also reach this level. The effect of the lower ambient air pressure (the 'b' runs) is visible in the shape of the curves. It is not possible to compare the '_s' and '_d' runs (the simple and detailed models) since the models have experienced a different amount of air leakage.

In phase I air leakage was discovered and prior to phase II and III the models were carefully inspected to try to find the leak while suspicious locations were sealed. From this data it appears that the source of the problems was not identified and repaired. The only conclusion can be that the leaks were very minor, nevertheless they have a relatively large influence on the level measurements.

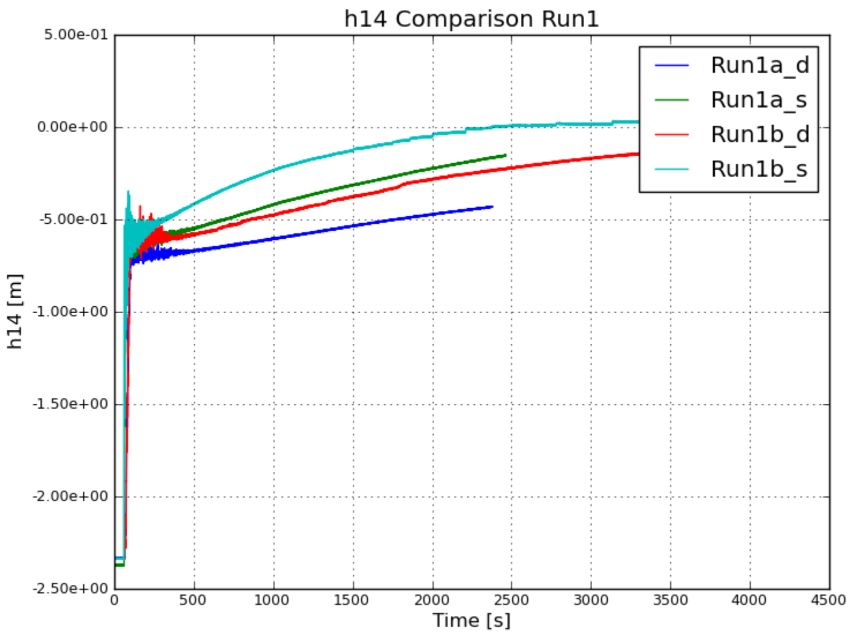


Figure 32 Compartment S14 distance to SWP - Run1

The differences in weight and centre of gravity are summarised in the tables below.

Weight [kg]	Atmospheric	Vacuum	
Simple	1.22E+06	1.22E+06	5.44E+02
Detailed	1.25E+06	1.30E+06	-5.34E+04
	-2.67E+04	-8.07E+04	

cog x [m]	Atmospheric	Vacuum	
Simple	0.052	0.106	-0.054
Detailed	0.067	0.071	-0.004
	-0.014	0.036	

cog y [m]	Atmospheric	Vacuum	
Simple	0.365	0.374	-0.010
Detailed	0.360	0.360	-0.001
	0.005	0.014	

The detailed model seems to be significantly heavier after flooding, both in atmospheric and vacuum conditions (see §4.4). The only significant shift in centre of gravity is in the x-direction during the vacuum run. It is difficult to compare the results between the atmospheric and the vacuum tests due to the differences in attitude and draft.

6.6 Run 2 Comparison (heel = 20.0 deg, trim = -3.0 deg)

Run 2 had the highest heel and trim values: 20.0 deg and -3.0 deg respectively. The measured levels cannot be directly compared since they are measured at different locations in the model. Air leakage did not play a role in all these runs: when inspecting the weight plot, the lines look very horizontal. This is confirmed by the calculated slope of the weight in the equilibrium phase:

Weight [kg/sec]	Atmospheric	Vacuum
Simple	5.11E-01	-2.03E+00
Detailed	3.21E-01	6.18E-01

When inspecting the measured levels, see Figure 33, it appears that compartment S12 (detailed) contained a significant amount of leak water prior to the start of the atmospheric test. The high heel and trim values exerted a significant pressure on the latex patch that bulged severely inward. It is likely that a small scratch caused the leakage into S12. Compartment S06 also had leakage prior to testing. It seems that the remote controlled valve had leaked. Both levels sensors (hm12.1 and hm6.1) were not corrected during the post-processing. For the same reason the z-forces were not zoeroed.

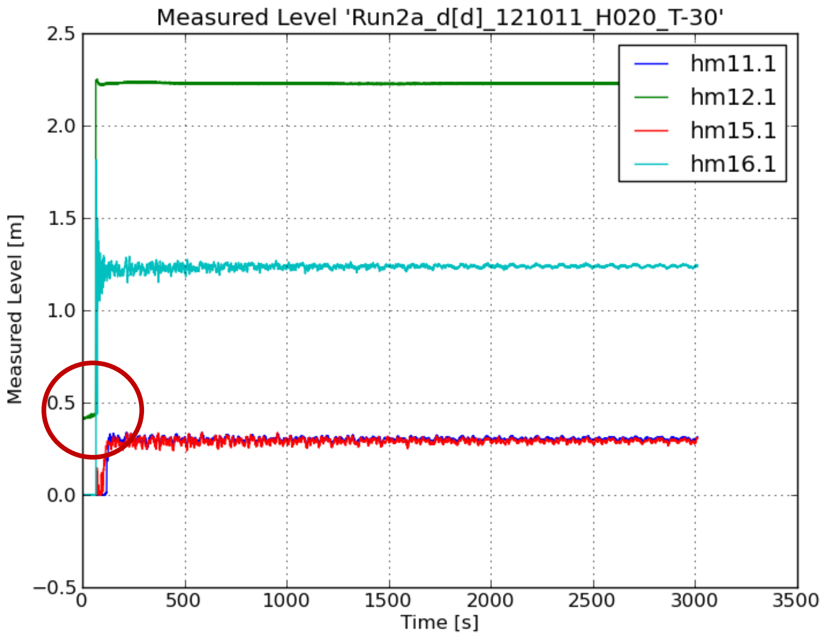


Figure 33 Comparison of measured levels Run2 (detailed, atmospheric)

Clearly visible is also the rise of the level prior to the damage (hm12.1).

At these extreme heel and trim angles S12 will not fill up completely: an air pocket is formed preventing the compartment to fill completely. In addition, the sensor is located in the aft part of the tank (which is fully submerged), thus the sensor measures its full range. This explains the very stable signal for S12 in Figure 33 while the other sensors appear to be subject to small waves in the basin. Therefore, the calculation between the level of S12 and the SWP can be done but its expected value is not equal to zero.

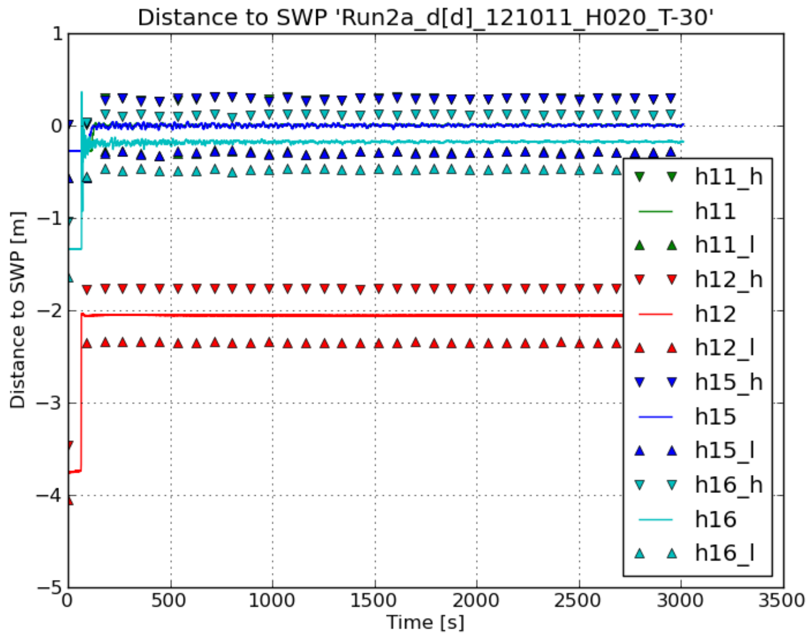


Figure 34 Distance to SWP Run 2 (detailed, atmospheric)

The levels of hm11.1 and hm15.1 are on top of each other, see Figure 34, which is to be expected since their location is on either side of the same bulkhead (albeit in different but connected compartments). There is a difference with hm16.1 but this is not significant (see the uncertainty determination in the previous paragraph: those numbers apply to this run as well).

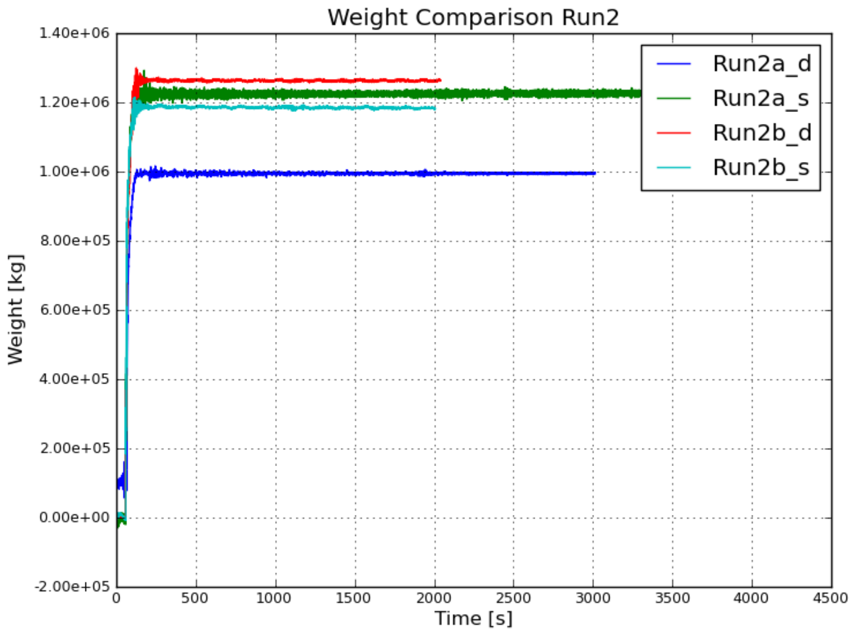


Figure 35 Weight comparison Run2

Weight [kg]	Atmospheric	Vacuum	
Simple	1.23E+06	1.18E+06	4.20E+04
Detailed	9.95E+05	1.26E+06	-2.68E+05
	2.31E+05	-7.86E+04	

cog x [m]	Atmospheric	Vacuum	
Simple	0.152	0.142	0.010
Detailed	0.180	0.153	0.027
	-0.028	-0.011	

cog y [m]	Atmospheric	Vacuum	
Simple	0.231	0.231	0.000
Detailed	0.215	0.226	-0.011
	0.015	0.005	

There is a difference in weight between the simple and detailed model that is higher than the uncertainty range of the weight sensors. The trend in atmospheric and vacuum is however different: while the simple model in atmospheric conditions is heavier than the detailed model it is the reverse in vacuum. The weight of the detailed model in atmospheric conditions looks rather low.

In view of the errors in the vertical positioning of the models in vacuum the comparison of atmospheric and vacuum values is not of much value. The cog comparison does not reveal any significant differences.

6.7 Run 3 Comparison (heel = 0.0 deg, trim = -3.0 deg)

In all four measurement runs it appears that compartment S01 has leaked. The level sensor hm1.1 was therefore not zeroed in the post-processing. Air leakage also occurred, both in atmospheric and vacuum conditions.

The leakage is also visible from the slope calculation and from the weight plot, see Figure 36.

Weight [kg/sec]	Atmospheric	Vacuum
Simple	8.76E+00	4.47E+00
Detailed	8.05E+00	2.85E+00

There is a difference between the detailed and the simple model in the way that the level in compartment S11 rises. In the detailed model the level rise is similar when the atmospheric and the vacuum run are compared. The differences are between the runs with the simple model: the most probably cause is that the longitudinal gangway is ventilating the air from compartment S11. In the simple model the door to the compartment was located more to the fore end of the vessel.

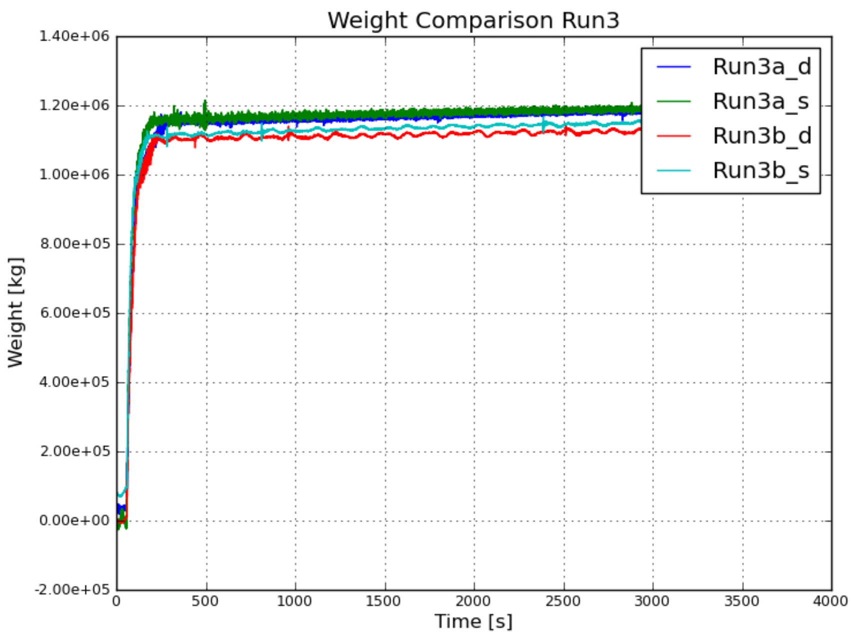


Figure 36 Weight comparison Run3

Weight [kg]	Atmospheric	Vacuum	
Simple	1.20E+06	1.16E+06	3.95E+04
Detailed	1.19E+06	1.13E+06	5.84E+04
	9.14E+03	2.80E+04	

cog x [m]	Atmospheric	Vacuum	
Simple	0.133	0.121	0.012
Detailed	0.144	0.127	0.017
	-0.010	-0.006	

cog y [m]	Atmospheric	Vacuum	
Simple	0.355	0.353	0.001
Detailed	0.349	0.347	0.002
	0.005	0.006	

The comparison of the weight after flooding shows a significant difference between the simple and detailed model in atmospheric conditions. The difference in vacuum is also significant but the reverse from the situation in atmospheric conditions. The cog shifts are minor and insignificant.

6.8 Run 4 Comparison (heel = 20.0 deg, trim = 0.0 deg)

In the vacuum runs the valve of compartment S06 has leaked. The levels sensors hm6.1 in both models was therefore not zeroed for these runs.

The levels in S11 and S15 are almost on top of each other for all the runs in this series, see Figure 37. The distance to the SWP is not zero but just within the uncertainty range of S11, S15 and S16.

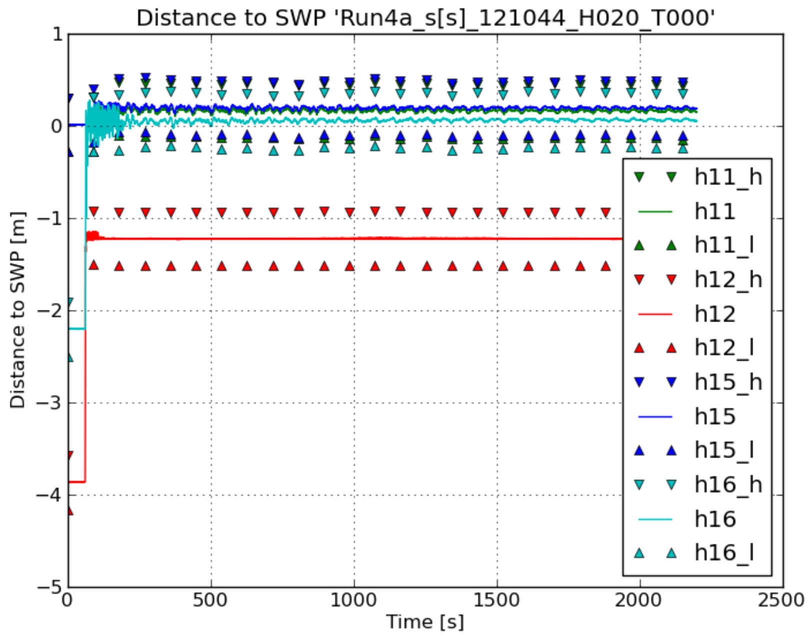


Figure 37 Distance to SWP Run 4 (simple, atmospheric)

S12 is pressurised and hence the level in S12 is not free to rise to the level of the SWP. The difference in level for S12 between al the atmospheric and vacuum runs is approximately 0.05 meter (full scale).

h12	Atmospheric	Vacuum	
Simple	-1.23E+00	-1.28E+00	4.83E-02
Detailed	-1.25E+00	-1.30E+00	5.36E-02
	2.22E-02	2.75E-02	

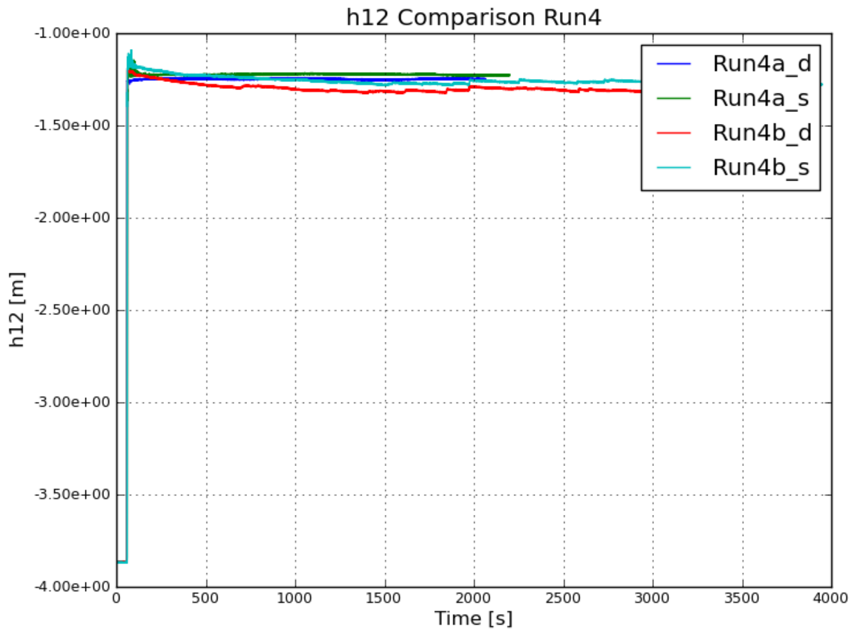


Figure 38 S12 Distance to SWP Run4

From the calculations on the draft measurements it can be concluded that the model's draft in vacuum was less than the model's draft in atmospheric conditions, approximately 0.66 m full scale. The level of S12, see Figure 38 and the table above, in vacuum is only 0.21 m lower than in the atmospheric test. Therefore, the level in S12 in vacuum is relatively higher than in atmospheric conditions.

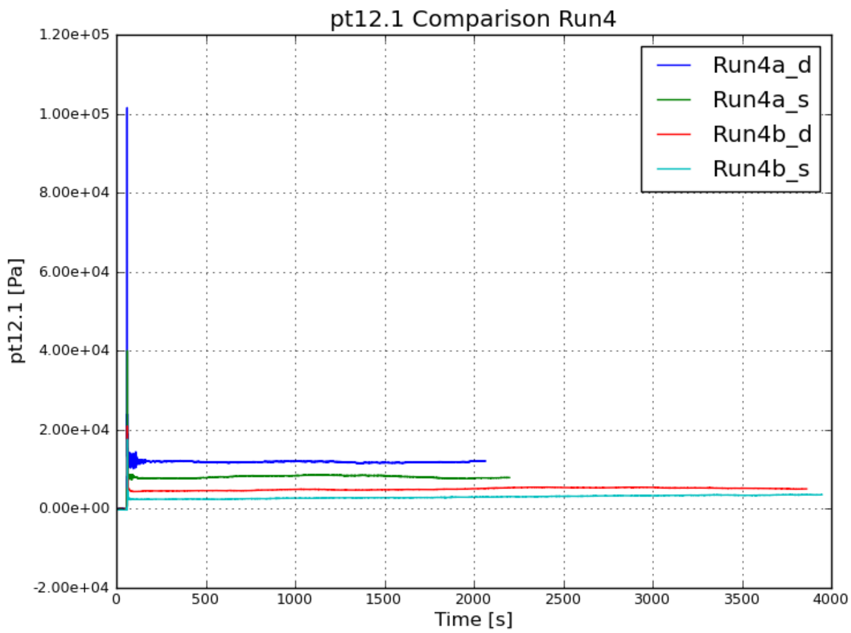


Figure 39 S12 Air pressure comparison Run4

The air pressure plot (see Figure 39) of S12 seems to indicate a larger level difference than the level measurements themselves. The highest over pressure was measured for the atmospheric runs: this was to be expected since more air molecules are closed in, hence stiffer air spring, hence larger water level difference, hence larger air pressure difference.

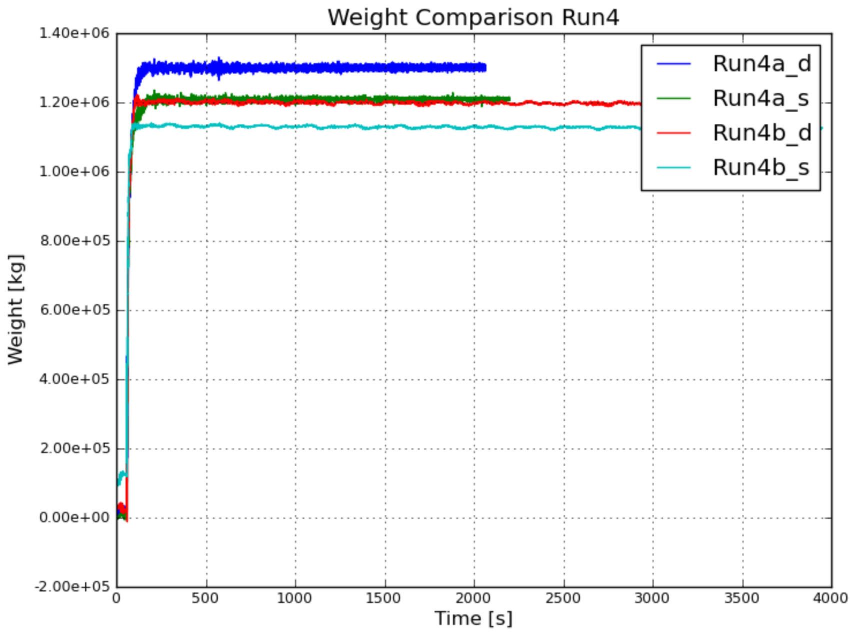


Figure 40 Weight comparison Run4

The somewhat sharper knuckle in the weight curve for the vacuum runs is again visible. The cause is the same as before: the scaled air pressure results in a less stiff spring.

Weight [kg]	Atmospheric	Vacuum	
Simple	1.21E+06	1.13E+06	8.25E+04
Detailed	1.30E+06	1.20E+06	1.04E+05
	-9.21E+04	-7.09E+04	

cog x [m]	Atmospheric	Vacuum	
Simple	0.074	0.078	-0.005
Detailed	0.109	0.143	-0.035
	-0.035	-0.065	

cog y [m]	Atmospheric	Vacuum	
Simple	0.218	0.208	0.010
Detailed	0.229	0.233	-0.004
	-0.011	-0.025	

There is a significant difference in the weight after flooding between the simple and the detailed model: the detailed model was heavier in both the atmospheric and the vacuum tests. The measurements also seem to indicate that both models were heavier in atmospheric conditions. This is contradicting the level measurement interpretation and the expectations. There is a slight tendency towards a cog difference in the x-direction. The cog difference in the y-direction is not significant.

6.9 Run 5 Comparison (heel = 10.0 deg, trim = -1.5 deg)

Inspection of the raw signals of atmospheric tests revealed that the remote controlled valve of S01 had leaked in both models: the compartment was nearly full in both cases at the start of the test. In addition, the latex covering the damage opening has leaked significantly for the detailed model in the atmospheric run. Also the valve of compartment S06 on the detailed model leaked: this compartment was nearly full as well. The level sensors hm1.1 (on both the detailed and the simple model) and the level sensors hm6.1 and hm12.1 (detailed model only) were therefore not zeroed just as the vertical force sensors for both models.

When looking at the distance to the SWP of the levels in S11, S12, S15 and S16 (see Figure 41) it can be concluded that there is a good correspondence between all the runs of the levels in S11, S15 and S16. The distance to the SWP is within the uncertainty limits. S12 has a lower level again due to compressed air pocket that formed above the water level and because the sensor is located in the aft part of the tank (which is fully submerged), thus the sensor measures its full range.

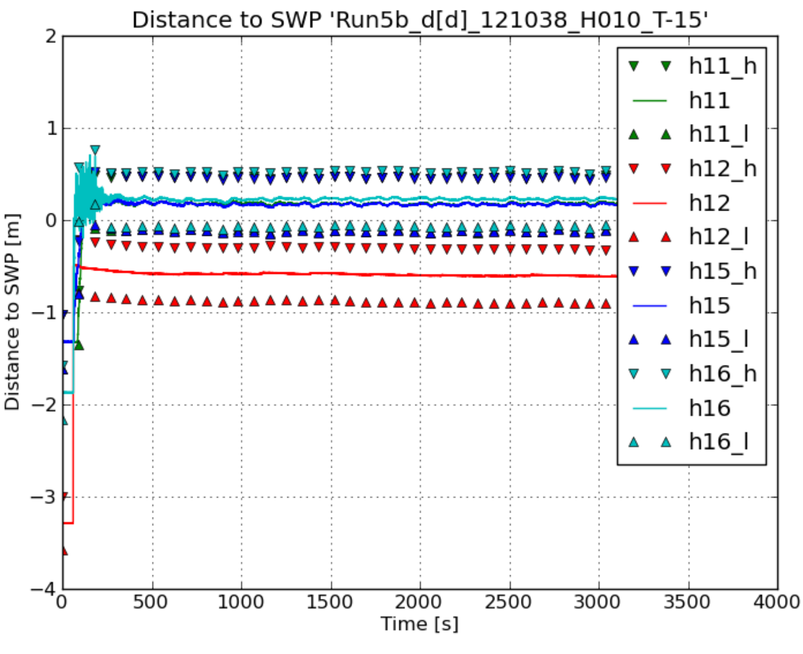


Figure 41

Figure 41 Distance to SWP Run5 (detailed, vacuum)

There is a difference in weight between the simple and the detailed model: the simple model was lighter in atmospheric and in the vacuum test. Both models seem to have been heavier in vacuum than in the atmospheric conditions. There is a possibility that there was a difference of the cog in x and y direction between the simple and detailed model in the atmospheric test. The other cog differences are not significant.

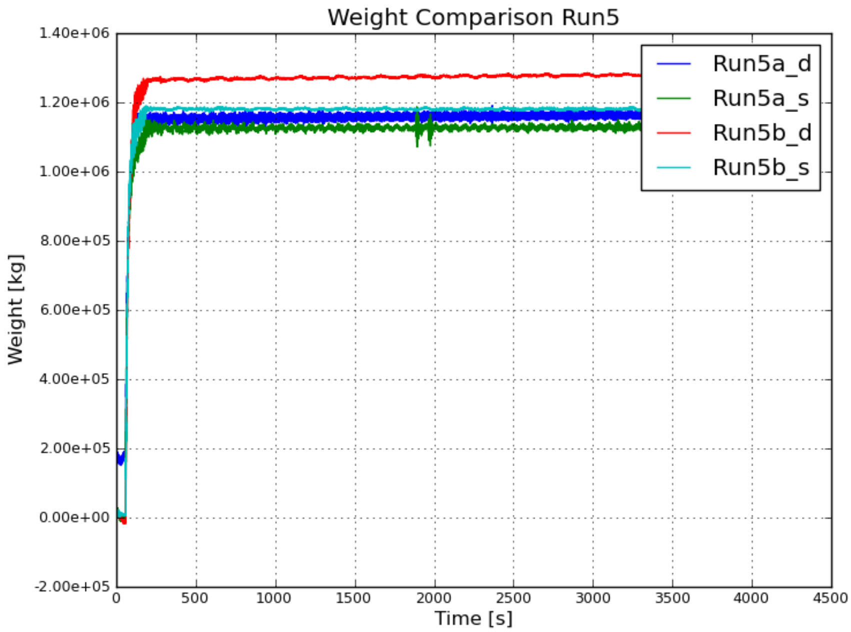


Figure 42 Weight comparison Run5

Weight [kg]	Atmospheric	Vacuum	
Simple	1.13E+06	1.18E+06	-5.21E+04
Detailed	1.16E+06	1.28E+06	-1.16E+05
	-3.62E+04	-9.97E+04	

cog x [m]	Atmospheric	Vacuum	
Simple	0.068	0.096	-0.029
Detailed	0.112	0.120	-0.009
	-0.044	-0.024	

cog y [m]	Atmospheric	Vacuum	
Simple	0.298	0.298	0.000
Detailed	0.308	0.303	0.005
	-0.010	-0.004	

6.10 Run 6 Comparison (heel = 10.0 deg, trim = -3.0 deg)

When the levels of S11, S12, S15 and S16 are compared, it is evident that the level in compartment S12 is again significantly lower than the SWP level: the air compression effect prevented the level in S12 to rise. The other level measurements compare very well to each other, see Figure 43. The distance to the SWP is within their uncertainty limits.

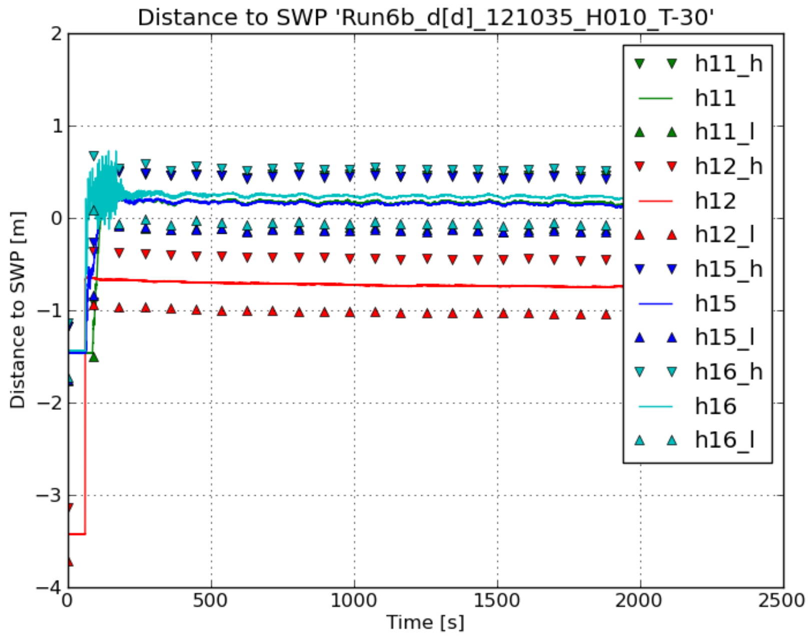


Figure 43 Distance to SWP Run6 (detailed, vacuum)

The fluctuations in the level of S11, S15 and S16 are probably caused by small waves in the basin. It is striking that they are almost exactly in phase. The sensor in S12 is fully submerged and thus gives a very stable signal.

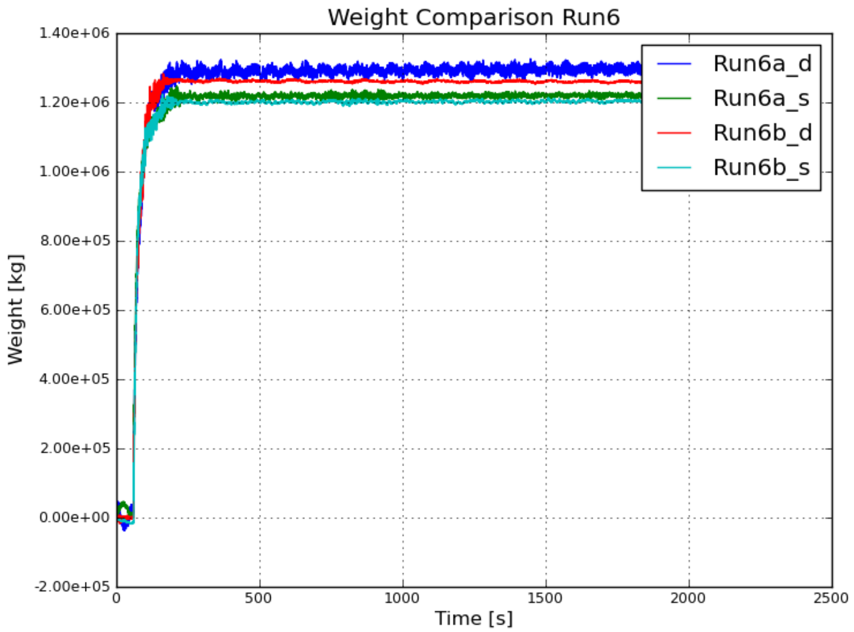


Figure 44 Weight comparison Run6

Weight [kg]	Atmospheric	Vacuum	
Simple	1.22E+06	1.20E+06	1.80E+04
Detailed	1.30E+06	1.26E+06	3.80E+04
	-7.67E+04	-5.67E+04	

cog x [m]	Atmospheric	Vacuum	
Simple	0.149	0.154	-0.005

Detailed	0.163	0.164	-0.001
	-0.014	-0.010	

cog y [m]	Atmospheric	Vacuum	
Simple	0.299	0.296	0.003
Detailed	0.297	0.295	0.002
	0.002	0.000	

There is a significant difference in weight between the simple and the detailed model: the detailed model was heavier in both the atmospheric and the vacuum tests. Both models seem to have been heavier in atmospheric conditions. The cog differences in both directions are not significant.

6.11 Run 7 Comparison (heel = 5.0 deg, trim = -1.5 deg)

The data for compartments S11, S12, S15 and S16 are reasonably close to each other for each run, see Figure 45. S12 is measuring its full range. Also the distance to SWP is within uncertainty limits for these measurements.

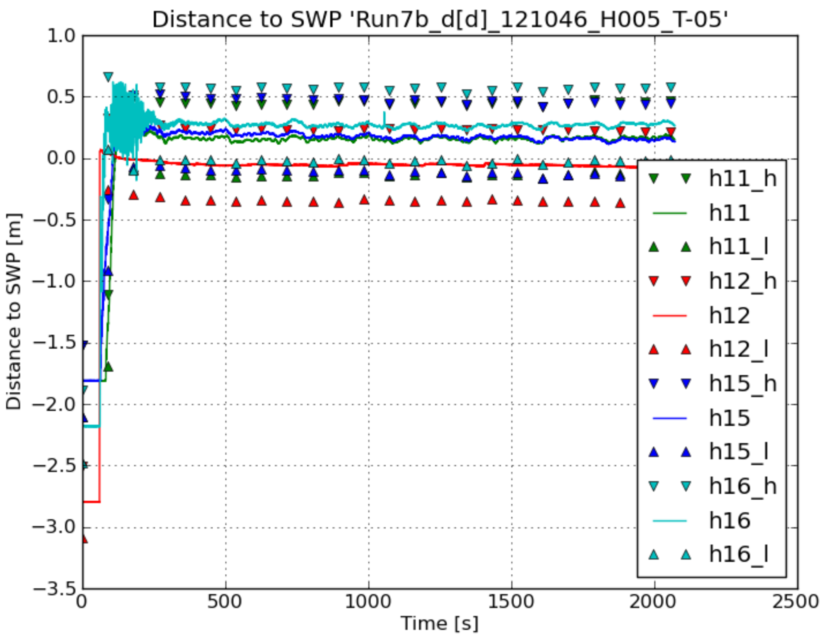


Figure 45 Distance to SWP Run7 (detailed, vacuum)

The measurement of h12 suggests that the level is close to the SWP. When the measured pressure for that same run is inspected - ‘Run7b_d’ - a slight overpressure is measured. On all air pressure plots of S12 there is a high peak visible at the start of the flooding test, this is caused by the large volume of water that suddenly rushes into this compartment when the latex membrane is failing.

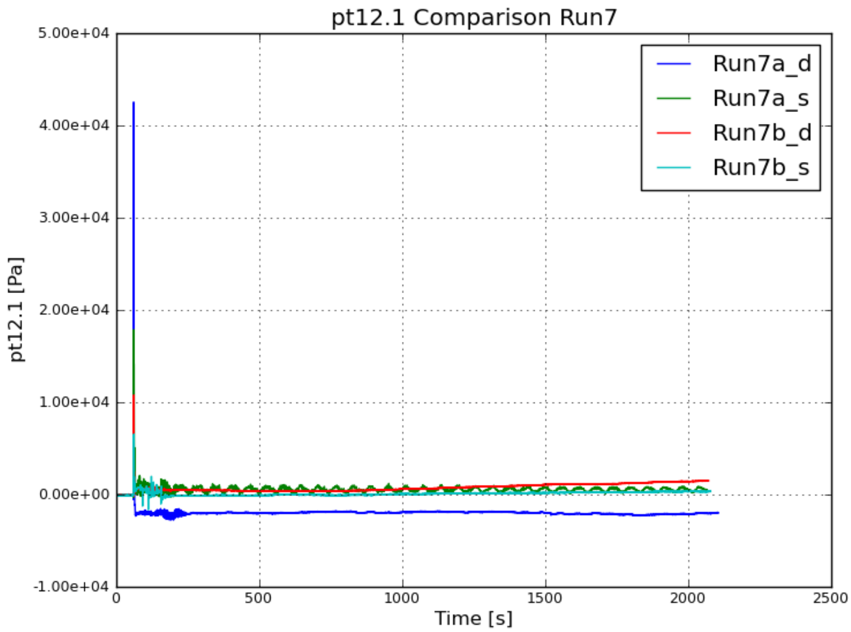


Figure 46 Air pressure comparison Run7

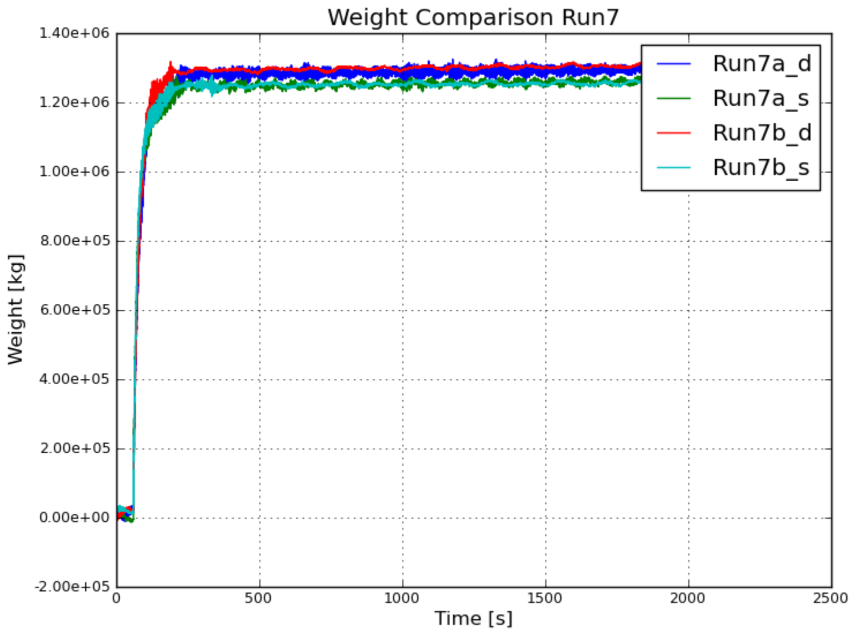


Figure 47 Weight comparison Run7

Weight [kg]	Atmospheric	Vacuum	
Simple	1.26E+06	1.25E+06	5.75E+03
Detailed	1.30E+06	1.31E+06	-1.06E+04
	-3.45E+04	-5.09E+04	

cog x [m]	Atmospheric	Vacuum	
Simple	0.079	0.079	-0.001
Detailed	0.077	0.079	-0.002

	0.002	0.000	

cog y [m]	Atmospheric	Vacuum	
Simple	0.336	0.334	0.002
Detailed	0.335	0.334	0.001
	0.001	0.000	

There is a significant difference in weight between the simple and the detailed model: the detailed model being heavier in both the atmospheric and the vacuum tests. The differences between the vacuum and atmospheric tests are insignificant for both models. The cog differences in both directions are not significant.

6.12 Overview

When all the measured weights are plotted, per model and per ambient test condition, no conclusive statement can be formulated about weight differences, either between the simple and detailed model, or between the atmospheric and vacuum tests. The uncertainty in draft control of both models might have played a large role in the spread and, to a certain level, the inconsistency of the results.

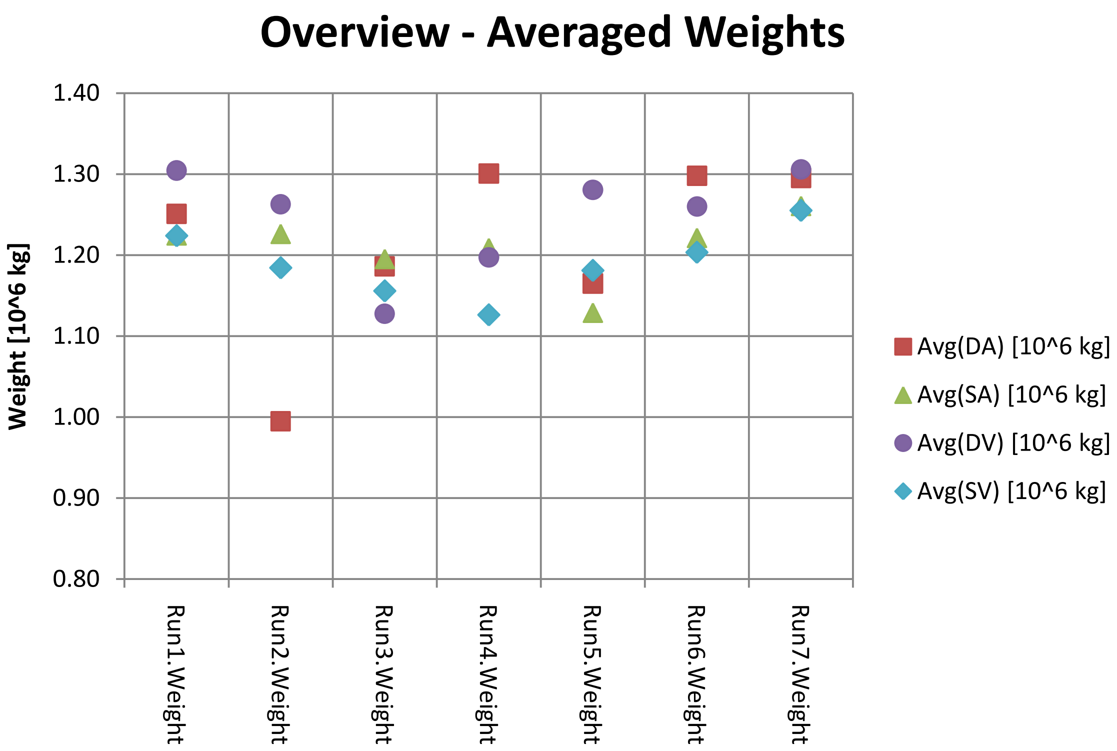


Figure 48 Equilibrium Weight (full scale)

Another factor that contributes to the uncertainty in weight is the leakage of both drain valves used to close compartment S01 and S06 during some runs and of course the leakage of the damage opening (particularly in Run2a_d, Run5a_s and Run5a_d).

The zero levels of the weight sensors were determined (and corrected) in the manner as described in §5.4 and this has eliminated the effect of accumulated leakage water between the runs. No correction has been applied for the amount of leakage water that has accumulated prior to starting the first run in either vacuum or atmospheric conditions. The applied corrections for the weight (as percentage of the equilibrium value) are given below:

	Zero Corrections			
	Avg(DA)	Avg(SA)	Avg(DV)	Avg(SV)

	[%]	[%]	[%]	[%]
Run1.Weight	0.7%	0.5%	-2.9%	4.0%
Run2.Weight	4.0%	0.8%	1.1%	2.4%
Run3.Weight	0.4%	0.7%	0.3%	1.0%
Run4.Weight	0.2%	0.3%	0.4%	-0.7%
Run5.Weight	3.2%	1.8%	0.0%	0.6%
Run6.Weight	0.3%	0.5%	1.3%	1.0%
Run7.Weight	0.1%	0.3%	-0.5%	-0.3%

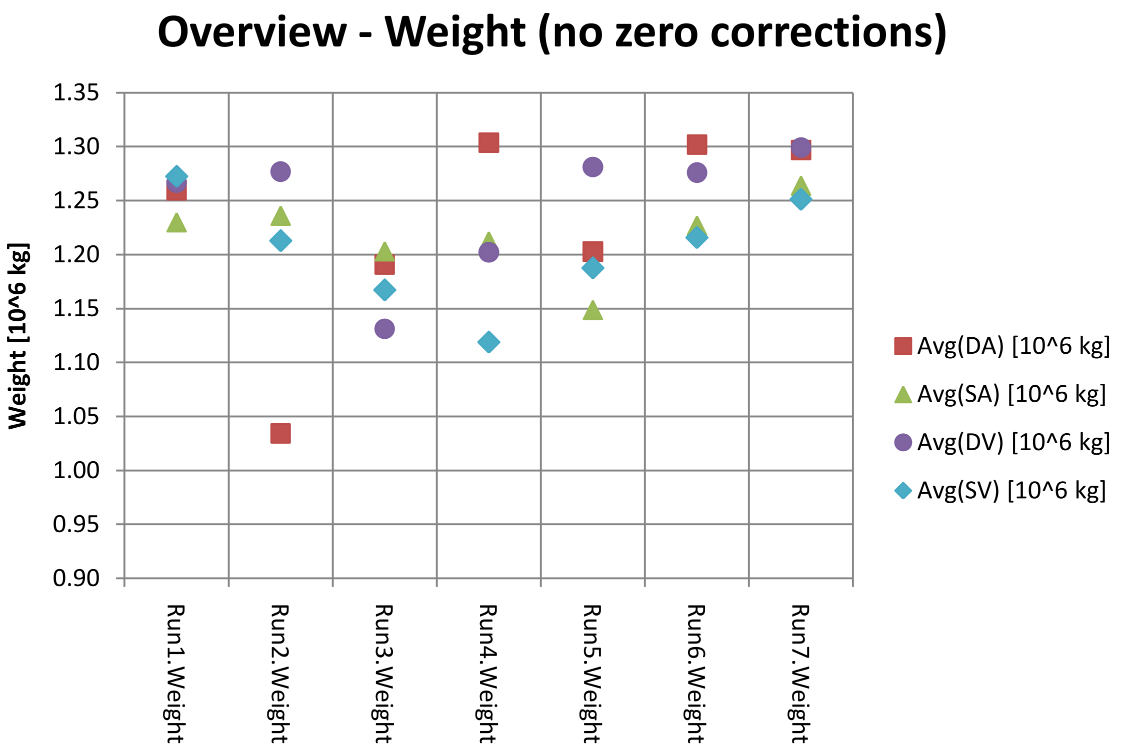


Figure 49 Equilibrium Weights (not corrected, full scale)

When Figure 48and Figure 49 are compared than it appears that applying the corrections does not significantly change the overall differences.

	Weight - Uncorrected values			
	Avg(DA)	Avg(SA)	Avg(DV)	Avg(SV)
	[10^6 kg]	[10^6 kg]	[10^6 kg]	[10^6 kg]
Run1.Weight	1.2596	1.2300	1.2667	1.2724
Run2.Weight	1.0344	1.2362	1.2768	1.2128
Run3.Weight	1.1908	1.2031	1.1313	1.1672
Run4.Weight	1.3037	1.2123	1.2022	1.1188
Run5.Weight	1.2027	1.1486	1.2811	1.1875
Run6.Weight	1.3019	1.2270	1.2760	1.2157
Run7.Weight	1.2969	1.2640	1.2992	1.2511

7 SUMMARY & CONCLUSIONS

7.1 Overall

For the joint industry project FLOODSTAND model tests have been performed in the Depressurised Towing Tank of MARIN to assess the influence of the ambient air pressure and detail of modelling on the flooding of damaged ship structures. The tests focussed on the flooding itself and the dynamic properties of the ship were excluded. Two ship models were created (scale 1:20), each with a different level of detail. These models were flooded in atmospheric and low pressure conditions for a number of fixed heel and trim combinations and a constant draft.

These types of flooding tests have never before been done on such a large model scale and under both atmospheric and low pressure conditions. The type, the amount and the required accuracy of the measurements in combination with the low pressure conditions, the model complexity and the required positioning accuracy of the model made this a very challenging project.

7.2 Preparation phase

In view of the explorative character of these model tests a considerable effort was spent on the preparations for this project. Potential risks were identified and contingency measures or design changes were made to eliminate or minimize them. Nevertheless, a number of problems surfaced in the first attempt which made it necessary to repeat the tests because the required accuracy could not be achieved.

A relatively large part of the project budget and time was spend on the preparation, the calibration and the calibration checks. Additionally, the complexity of the models, the number of sensors, the sensitivity for air and water leakage that surfaced during the tests would have required a test planning with quite some slack to redo runs that were identified as suspicious. In hindsight, to get a better grip on uncertainty and achievable repeatability, the test program should have included many more repetitive runs for each heel/trim configuration. Both these issues would have either severely limited the number of configurations to be tested or would have increased the required test time.

7.3 Model tests

The problems that surfaced during the tests mainly had to do with the repeatable accuracy of the positioning of the models in the facility. To be able to compare modeltest runs in atmospheric and vacuum conditions both the attitude and the draft of the models should be controlled very precise. Despite modifications to the facility equipment and other measures the required accuracy was not achieved.

In addition to this, there were problems with the level measurement accuracy. Most likely those were related to the difference in water properties between the vacuum part and the atmospheric part of the facility and to the time period between the test phases (approximately three months) which deteriorated the level sensor quality. Further research will be required to unravel all the details of these problems and hopefully find solutions for future projects.

7.4 Post processing and analysis

The model tests resulted in a huge amount of data. Considering all the issues encountered during the tests there are many ways to post process, and possibly correct the data. Also, redundancy in the collected data can be exploited to a much greater detail. However, it was decided not to apply corrections unless it was absolutely certain that they could be explained and were not caused by some other measurement artefact. For example, corrections of the draft of the model derived from draft measurements will result in other predictions for the distance to the SWP for each compartment. These distances are also influenced by the measured level inside each compartment which might be affected by the same problem as the draft measurement. Therefore, as always, it is dangerous to ignorantly apply corrections.

Furthermore, not all the data that could be used for the corrections was a complete set. The data collected during the calibration check was merely used as a quality check and was not used to calculate and apply corrections. The same can be said about the PERSPEX tube measurements. Besides, the calibration problems might also have been caused by an inhomogeneous mix of basin water in which case it is impossible to do any correction: it would have required different calibration factors for each and every level sensor inside the model (and the draught sensors): this is an impossible task.

The two major problems (the unexpected high uncertainty in level measurement and the problematic draft control), made it impossible to use the redundancy in the data and correct for the – assumed – errors. That is, using the level measurements and attitude data to calculate the distance to the still water plane can give an indication that the draft and attitude control was in-accurate, or vice versa, using the measured draft and attitude can give an indication that the measured level in certain compartments is in-accurate. But what to do when both cannot really be trusted? Because of these reasons the modeltests do not provide the definitive answer to the question whether air pressure has an influence on the flooding process. The same applies to the difference in level of detail chosen for the models in these modeltests. This lack of clear conclusions is very unfortunate, not only for the FLOODSTAND project but also for MARIN.

On the other hand, the measurements done with the PERSPEX tube show a large difference in inner and outer level when the measurements in atmospheric and vacuum are compared. This is at least an indication that air pressure can have a significant influence. The size of this influence on the overall flooding process might however be dependent on the geometry and the conditions. To add to this, the slow rise of the level which as observed during some of the tests is caused by a very slow leakage of air from the compartments. This is also an indication that the presence of air and its compressibility influences the flooding process: this behaviour would not have been seen when the compartments had been fully ventilated.

However, the data might still be used as validation material for simulation tools. In the post processing the errors in the attitude (heel, trim and draft) are assessed and these could be fed as input to the simulation tools. In addition, the post processing gives information about the most likely attitude and draft of the models. These can be used as input for a simulation model in order to try to reproduce the data. A next step, outside this project, could be to use the data of a part of the runs in a simulation model to investigate the issues and when that is successful, use the data of the rest of the runs for validation.

7.5 Lessons Learned

In addition to the findings described in §7.2 through §7.4 of this chapter an important number of lessons with respect to the preparation and execution of this type of tests has been learned:

- Model construction
  Constructing models that are both air and watertight, with quite a high level of detail proved to be a challenging issue. In addition, taking care that the model can be properly drained and ventilated both in atmospheric and low pressure is also not an easy task. Much was learned about the importance of various details during the preparation of the tests.

- Selection of the right measurement principle
  The unforeseen time period between the measurements (approximately three months) had a negative influence on the quality of the level sensors. The second problem has been the sensitivity for the conductivity of the medium (water in this case): variations in conductivity probably caused a significant part of the calibration problems that were experienced during the tests. If this had been known a different type of measurement principle would have been chosen that is less sensitive to ageing (corrosion, peeling off). However, at the time of testing level sensors based on a different measurement principle were only available in the prototype stage and not suited for use under low pressure conditions.

- Damage opening mechanism design
  Initiating the damage in a quick, reproducible and reliable manner was essential for the success of these tests. The comparatively large damage opening (in absolute size) added to the complexity. The engineering and testing spent at this issue has proven very valuable.

- Exploiting measurement redundancy
  As an example of data redundancy, ventilated compartments having a free flooding connection to other ventilated compartments should have the same level ("law of communicating vessels"). This type of redundancy in the measurement data can give insight in the obtained accuracy of the tests. Preferably, these checks should be done during the testing. That will make it possible to identify low

quality runs and redo them. In this test campaign a number of runs would have been a candidate to be redone. In view of the tight schedule it would inevitably have resulted in the cancellation of an equal number of planned configurations.

- Propagation of uncertainty
  To be fully exploited the previous point requires a good insight in all the measurement uncertainties involved and how these uncertainties propagate through the calculations. A method was implemented to do these calculations including full propagation of uncertainty. This can be valuable when a comparison with simulation data has to be made.

- Attitude & draft control
  The importance of an accurate and repeatable attitude and draft control were demonstrated clearly, but unfortunately with negative consequences. To improve the accuracy and repeatability of the attitude and draught control of the current facility equipment will probably require a substantial budget. Nevertheless, it is an essential improvement if this type of projects has to be done again.

REFERENCES

[1]	FLOODSTAND Project definition Version 27-05-2008	HTT	R. Jalonen
[2]	The ESTONIA model tests MARIN Project 20374	MARIN	E. van Daalen N. Carette

Wageningen, August 2010
MARITIME RESEARCH INSTITUTE NETHERLANDS

APPENDIX A – TESTPROGRAM

		Test number (MMS)					Scaled pressure
		Detailed	**Simple**	**Heel [deg]**	**Trim [deg]**	**Harbour (atmospheric)**	**DTT (50 mBar)**
1	Calibration			0.0	0.0	x	
2	Check calibration	121001.txt .. 121002.txt		0.0	0.0	x	x
3	Run 1a (485)	121003.txt ben 1	121004.txt ben 2	0.0	0.0	x 1023	
4	Run 1b (485)	121006.txt ben 2	121005.txt ben 3	0.0	0.0		x
5	Run 2a (485)	121011.txt ben 6	121013.txt ben 7	20.0	-3.0	x 1028	
6	Run 2b (478)	121015.txt ben 9	121014.txt ben 8	20.0	-3.0		x
7	Run 3a (485)	121018.txt ben 11	121017.txt ben 10	0.0	-3.0	x 1028	
8	Run 3b (478)	121019.txt ben 12	121020.txt ben 13	0.0	-3.0		x
9	Check Calibration	121021.txt .. 121033.txt		0.0	0.0	x	
10	Calibration (Optional, only when 9 not successful)			0.0	0.0		
11	Run 4a (485)	121045.txt ben 34	121044.txt ben 33	20.0	0.0	x 1018	
12	Run 4b (478)	121042.txt	121043.txt	20.0	0.0		x

		ben 31	ben 32				
13	Run 5a (488)	121041.txt ben 21	121040.txt ben 20	10.0	-1.5	x 1024	
14	Run 5b (478)	121038.txt ben 18	121039.txt ben 19	10.0	-1.5		x
15	Run 6a (485)	121035.txt ben 15	121034.txt ben 14	10.0	-3.0	x 1025	
16	Run 6b (478)	121036.txt ben 16	121037.txt ben 17	10.0	-3.0		x
17	Run 7a	121049.txt ben 38	121048.txt ben 19	5.0	-0.5	x 1013	
18	Run 7b	121046.txt ben 35	121047.txt ben 36	5.0	-0.5		x
19	Check Calibration	121050.txt .. 121075.txt		0.0	0.0	x	
20	Check Calibration	121076.txt .. 121100.txt		0.0	0.0		x

APPENDIX B – CALIBRATION CHECK RESULTS

Not corrected with tube-calibration data

	First check		Interm.	Final check		Sensor Average		Total
Sensor	Atm. [-]	Vac. [-]	Atm. [-]	Atm. [-]	Vac. [-]	Atm. [-]	Vac. [-]	[-]
GH01	0.9433	0.8682	0.8243	1.0220	0.8462	0.9299	0.8572	0.9008
GH06	0.8516	0.8889	0.8302	0.9448	0.9021	0.8755	0.8955	0.8835
GH10	0.8776	0.7838	0.8038	1.0212	0.7711	0.9009	0.7774	0.8515
GH11	0.9168	0.8246	0.9997	1.0160	0.9030	0.9775	0.8638	0.9320
GH12	0.7093	0.6415	0.8824	1.0672	0.8623	0.8863	0.7519	0.8325
GH13	0.8392	0.7558	0.7601	1.0175	0.8919	0.8723	0.8239	0.8529
GH14	0.8675	0.8027	0.8839	0.9404	0.7805	0.8973	0.7916	0.8550
GH15	0.9135	0.8308	0.8404	0.9923	0.8463	0.9154	0.8386	0.8846
GH16	0.5826	0.5545	0.8563	1.0320	0.8317	0.8236	0.6931	0.7714
GH17-1	0.9311	0.7788	0.9876	1.0085	0.9393	0.9757	0.8591	0.9291
GH17-2	0.9409	0.7883	0.9571	0.8280	0.9250	0.9086	0.8567	0.8879
GH18	0.9388	0.7992	0.9853	0.9922	0.9395	0.9721	0.8693	0.9310
GH24	1.0049	0.9102	0.9773	0.8569	0.9243	0.9464	0.9173	0.9347
Average	0.8705	0.7867	0.8914	0.9799	0.8741	0.9140	0.8304	0.8805
Std	0.1122	0.0967	0.0810	0.0699	0.0566	0.0995	0.1823	0.1035

W01	0.9099	0.8213	0.7957	1.0170	0.8405	0.9076	0.8309	0.8769
W06	0.8621	0.7878	0.8455	0.9619	0.9077	0.8898	0.8477	0.8730
W10	0.7903	0.7188	0.9963	0.9648	0.8996	0.9171	0.8092	0.8740
W11	0.9182	0.8404	0.8362	0.9938	0.9292	0.9161	0.8848	0.9036
W12	0.9071	0.8155	1.0041	1.0042	0.9183	0.9718	0.8669	0.9298
W13	0.9116	0.7986	0.8106	0.9704	0.8353	0.8975	0.8169	0.8653
W14	0.8806	0.7880	0.7935	0.9556	0.7760	0.8766	0.7820	0.8387
W15	0.9509	0.8553	0.8483	1.0068	0.9423	0.9353	0.8988	0.9207
W16	0.9406	0.8556	0.8545	1.0355	0.9635	0.9436	0.9095	0.9299
W17-1	0.9892	0.8729	0.9386	0.8447	0.9790	0.9242	0.9259	0.9249
W17-2	0.9924	0.8769	0.9518	0.8520	0.9777	0.9321	0.9273	0.9302
W18	0.9924	0.8880	0.9603	0.8590	1.0110	0.9372	0.9495	0.9421
W24	0.9946	0.8895	0.9732	0.8949	1.0357	0.9543	0.9626	0.9576
Average	0.9261	0.8314	0.8930	0.9508	0.9243	0.9233	0.8779	0.9051
Std	0.0604	0.0496	0.0789	0.0663	0.0739	0.0713	0.1853	0.0767

Corrected with tube-calibration data:

	First check		Interm.	Final check		Sensor Average		Total
Sensor	Atm. [-]	Vac. [-]	Atm. [-]	Atm. [-]	Vac. [-]	Atm. [-]	Vac. [-]	[-]
GH01	Do Data Available		0.9585	1.0730	1.0937	1.0157	1.0937	1.0417
GH06			1.0402	1.0632	1.0561	1.0517	1.0561	1.0532
GH10			1.0291	1.0589	1.0131	1.0440	1.0131	1.0337
GH11			1.0306	1.0533	1.0312	1.0420	1.0312	1.0384
GH12			1.0410	1.0428	1.0235	1.0419	1.0235	1.0358
GH13			1.0313	1.0550	1.0175	1.0432	1.0175	1.0346
GH14			1.0543	1.0666	1.0112	1.0605	1.0112	1.0440
GH15			1.0218	1.0274	1.0419	1.0246	1.0419	1.0303
GH16			1.0270	1.0343	1.0133	1.0306	1.0133	1.0248
GH17-1			1.0125	1.0412	1.0673	1.0269	1.0673	1.0403
GH17-2			0.9811	1.0113	1.0510	0.9962	1.0510	1.0145
GH18			1.0100	1.0243	1.0033	1.0171	1.0033	1.0125
GH24			1.0017	1.0154	0.8982	1.0085	0.8982	0.9717
Average			1.0184	1.0436	1.0247	1.0310	1.0247	1.0289
Std			0.0261	0.0200	0.0461	0.0261	0.2774	0.0336

W01	Do Data Available		0.9565	1.0665	1.0664	1.0115	1.0664	1.0298
W06			1.0431	1.0520	1.0616	1.0476	1.0616	1.0522
W10			1.0276	1.0001	1.0261	1.0139	1.0261	1.0179
W11			1.0244	1.0297	1.0600	1.0271	1.0600	1.0381
W12			1.0336	1.0396	1.0455	1.0366	1.0455	1.0396
W13			1.0352	1.0057	1.0659	1.0205	1.0659	1.0356
W14			1.0317	1.0515	1.0679	1.0416	1.0679	1.0504
W15			1.0313	1.0431	1.0608	1.0372	1.0608	1.0451
W16			1.0318	1.0434	1.0717	1.0376	1.0717	1.0490
W17-1			0.9620	1.0129	1.0126	0.9875	1.0126	0.9959
W17-2			0.9756	1.0187	1.0198	0.9971	1.0198	1.0047
W18			0.9843	1.0202	1.0632	1.0023	1.0632	1.0226
W24			0.9973	1.0073	0.9836	1.0023	0.9836	0.9961
Average			1.0104	1.0301	1.0465	1.0202	1.0465	1.0290
Std			0.0308	0.0209	0.0274	0.0277	0.2809	0.0300

APPENDIX C - SENSOR NAMES & LOCATIONS

Table 8 Level sensors

New Name	'Raw' Name		X	Y	Vertical Extend Z (from~to)
	Simple	Detailed	[m]	[m]	[m]
hm1.1	GH01	W01	22.95	-0.68	2.19~4.05
hm6.1	GH06	W06	45.00	-0.68	0.43~4.05
hm10.1	GH10	W10	22.95	2.65	4.216~6.87
hm11.1	GH11	W11	22.95	6.48	4.216~6.87
hm12.1	GH12	W12	23.05	-4.86	4.216~6.87
hm13.1	GH13	W13	29.45	2.65	4.216~6.87
hm14.1	GH14	W14	35.95	2.65	4.216~6.87
hm15.1	GH15	W15	23.05	6.48	4.216~6.87
hm16.1	GH16	W16	45.00	0.00	4.216~6.87
hm17.1	GH17_1	W17_1	12.00	-7.29	7.096~9.80
hm17.2	GH17_2	W17_2	12.45	-3.18	7.096~9.80
hm18.1	GH18	W18	12.45	-3.08	7.096~9.80
hm24.1	GH24	W24	38.50	-8.80	7.096~9.80

Table 9 Air pressure sensors

New Name	'Raw' Name		X	Y	Z
	Simple	Detailed	[m]	[m]	[m]
pt1.1	PressA_S01	PressA_D01	23.0	-0.68	3.69
pt6.1	PressA_S06	PressA_D06	45.0	-0.77	3.69
pt12.1	PressA_S12	PressA_D12	29.79	-3.42	6.75
pt18.1	PressA_S18	PressA_D18	12.24	-3.04	9.75

APPENDIX D – SUB-FRAME LAYOUT

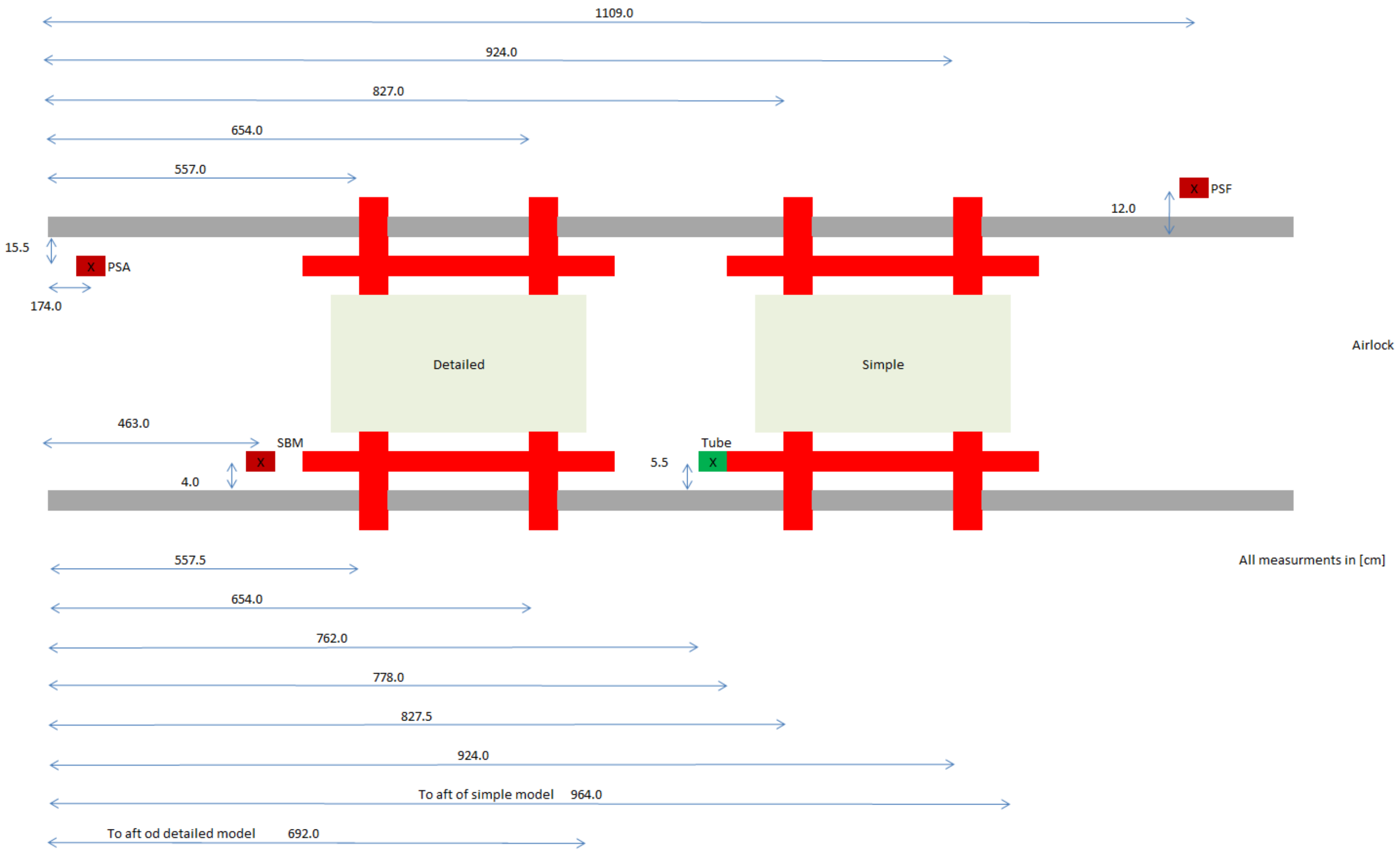
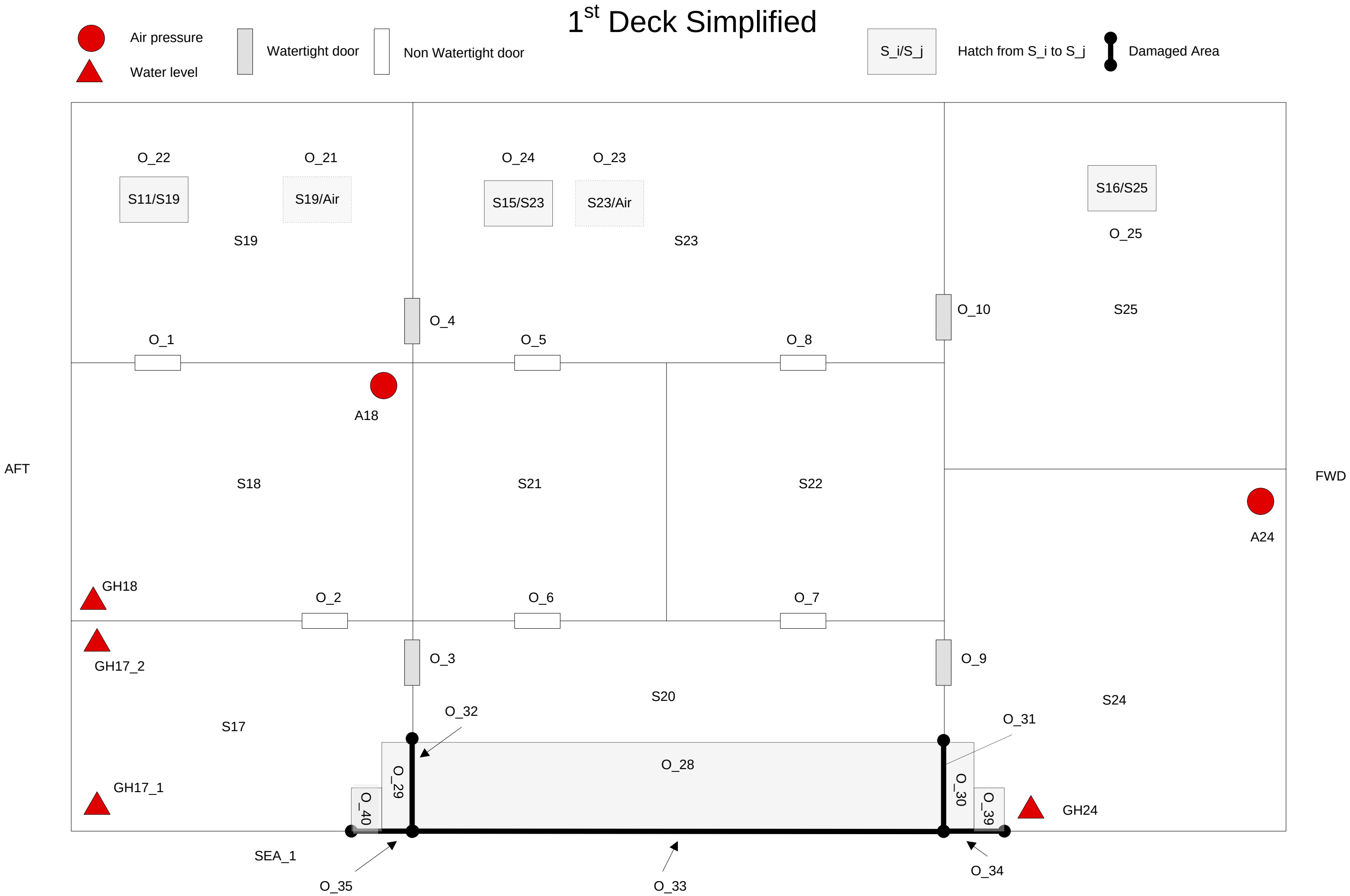
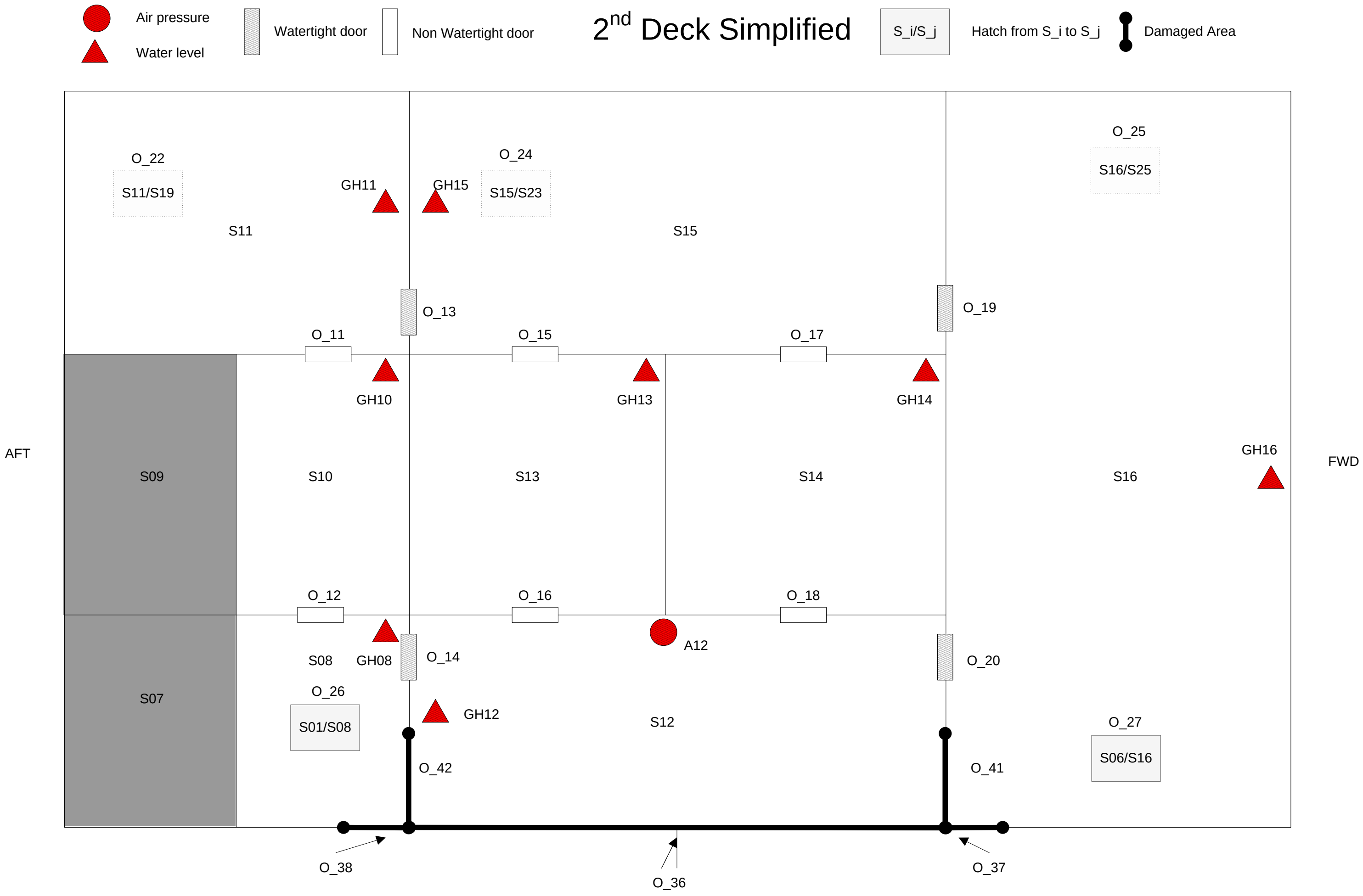


Figure 50 Schematic drawing (not on scale)

		Sensor Location		
New sensor name	**'Raw' sensor name**	**x**	**y**	**z**
		[m]	**[m]**	**[m]**
Draft_PSf	GH_PSF	0.00	0.00	0.00
Draft_PSa	GH_PSA	9.35	0.28	0.00
Draft_SBm	GH_SBM	6.46	1.10	0.00
Tube bottom (Tube_In/Tube_Out)	GHB_in/GHB_out	3.47	1.08	-0.46
Detailed Model				
Origin	-	2.33	0.63	0.00
Fx_PS (S6)	WFXps	2.33	1.11	0.67
Fx_SB (S5)	WFXsb	2.33	0.15	0.67
Fy (S4)	WFY	2.33	0.00	0.67
Fz_f (S1)	WFZF	2.77	0.63	0.67
Fz_PSa (S3)	WFZpsA	2.11	1.01	0.67
Fz_SBa (S2)	WFZsbA	2.11	0.25	0.67
Simple Model				
Origin	-	5.03	0.63	0.00
Fx_PS (S6)	WFXps	5.03	1.11	0.67
Fx_SB (S5)	WFXsb	5.03	0.15	0.67
Fy (S4)	WFY	5.03	0.00	0.67
Fz_f (S1)	WFZF	5.47	0.63	0.67
Fz_PSa (S3)	WFZpsA	4.81	1.01	0.67
Fz_SBa (S2)	WFZsbA	4.81	0.25	0.67

APPENDIX E – SCHEMATIC MODEL LAYOUT




Air pressure
Water level
Watertight door
Non Watertight door
2nd Deck Simplified
S_i/S_j
Hatch from S_i to S_j
Damaged Area
O_22
S11/S19
GH11
GH15
O_24
S15/S23
O_25
S16/S25
S11
S15
O_13
O_19
O_11
O_15
O_17
GH10
GH13
GH14
AFT
S09
S10
S13
S14
S16
GH16
FWD
O_12
O_16
O_18
S08
GH08
O_14
A12
O_20
S07
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GH12
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S06/S16
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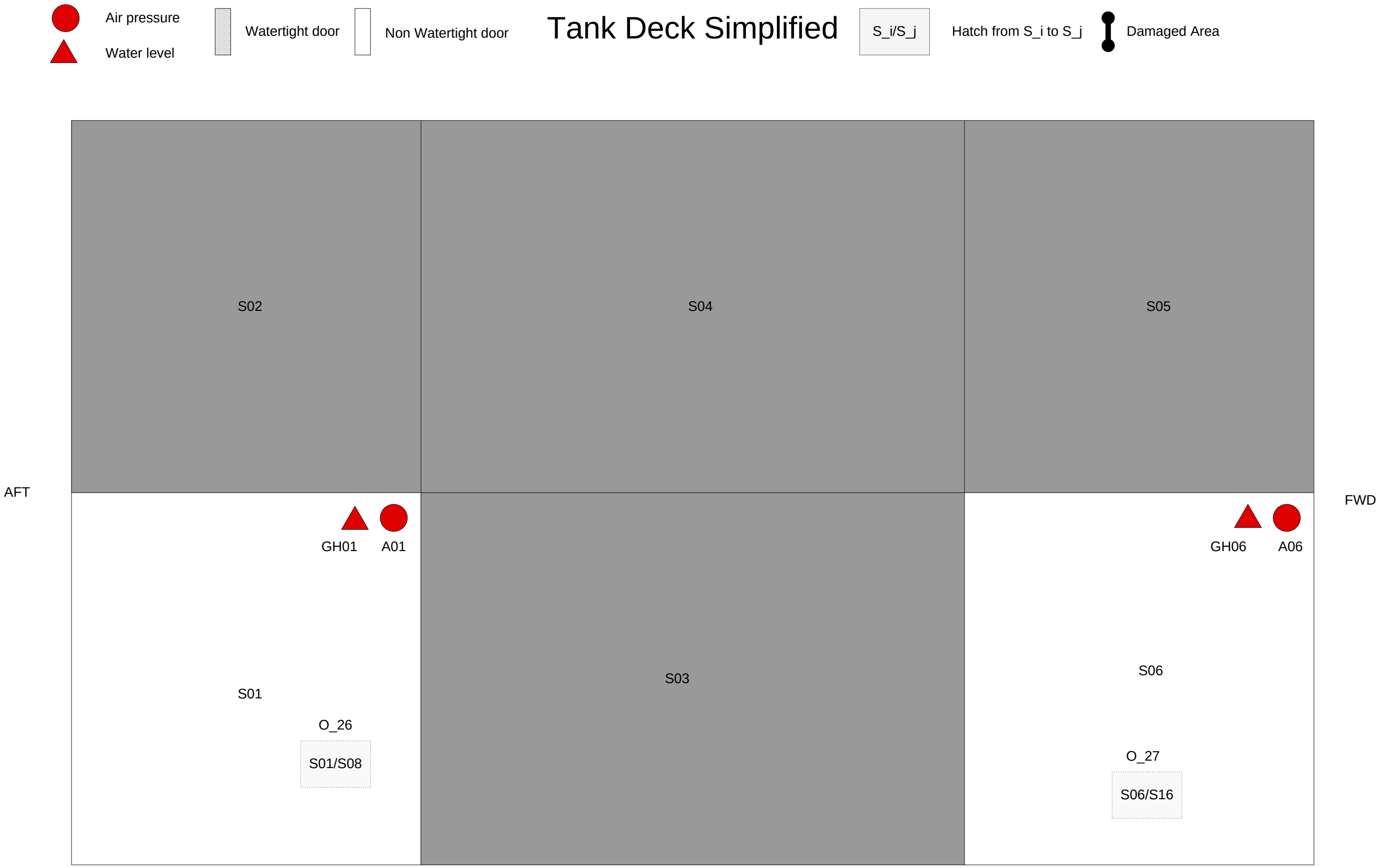
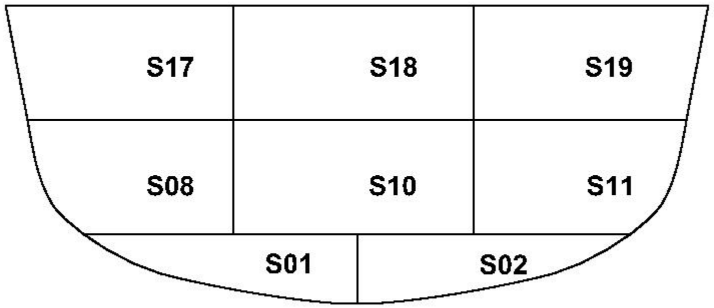
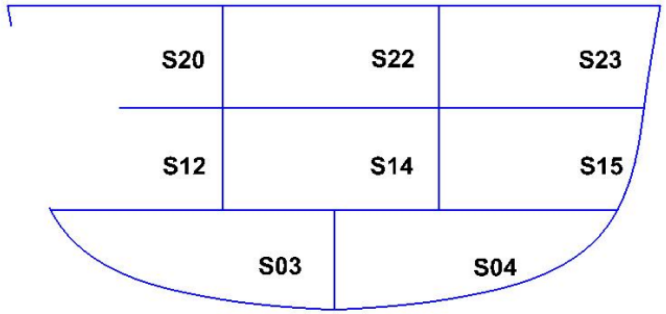
O_41
O_38
O_36
O_37


Air pressure
Water level
Watertight door
Non Watertight door
Tank Deck Simplified
S_i/S_j
Hatch from S_i to S_j
Damaged Area
AFT
FWD
S02
S04
S05
GH01
A01
S01
O_26
S01/S08
S03
GH06
A06
S06
O_27
S06/S16

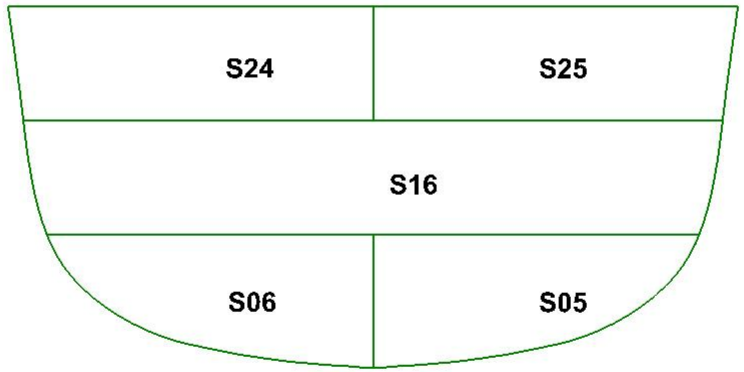
A-A Cross Section

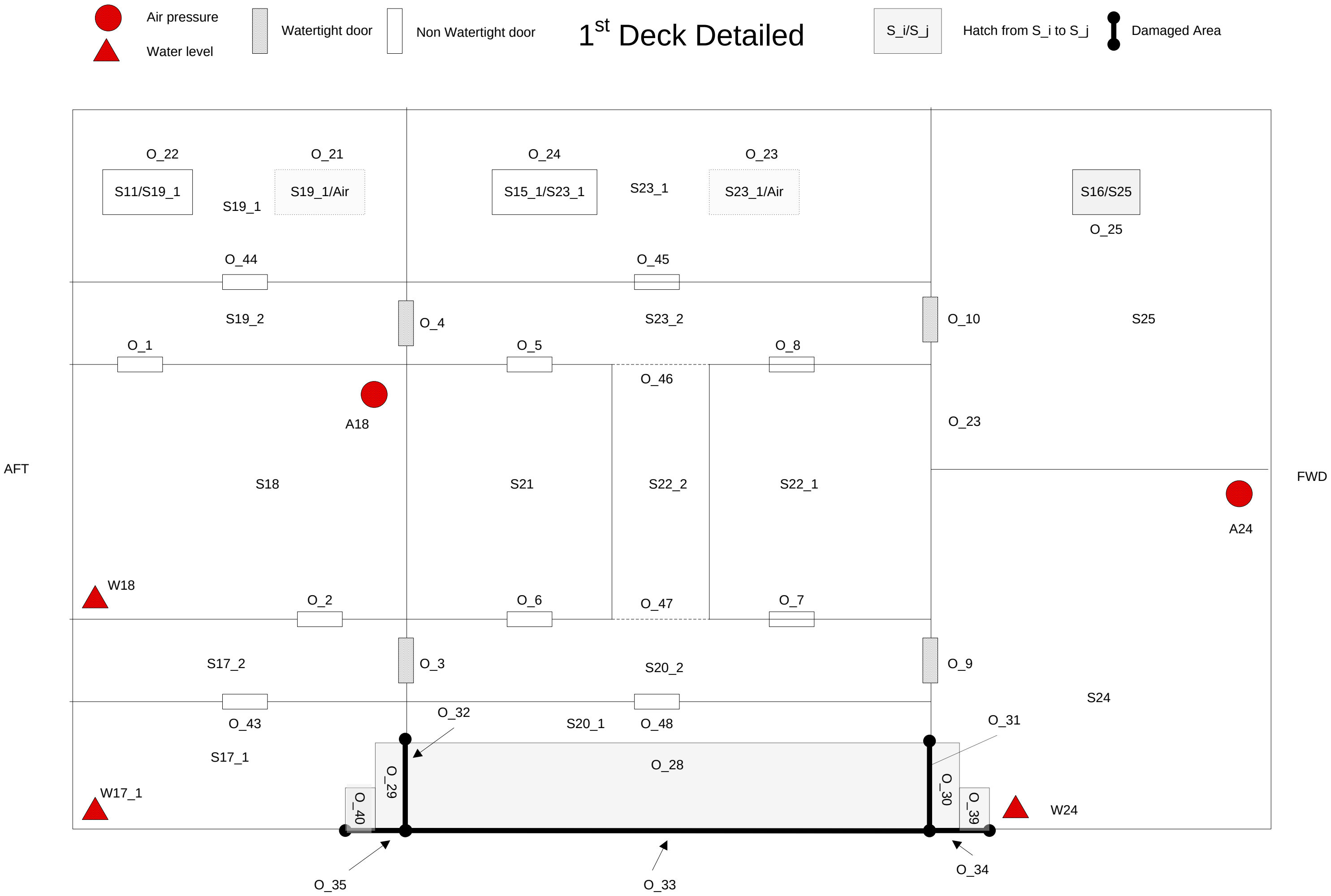


B-B Cross Section



C-C Cross Section




Air pressure
Water level
Watertight door
Non Watertight door
1st Deck Detailed
S_i/S_j
Hatch from S_i to S_j
Damaged Area
AFT
FWD
O_22
O_21
S11/S19_1
S19_1
S19_1/Air
O_24
O_23
S15_1/S23_1
S23_1
S23_1/Air
S16/S25
O_25
O_44
O_45
S19_2
O_4
S23_2
O_10
S25
O_1
O_5
O_8
O_46
A18
O_23
S18
S21
S22_2
S22_1
A24
W18
O_2
O_6
O_47
O_7
S17_2
O_3
S20_2
O_9
S24
O_43
O_32
S20_1
O_48
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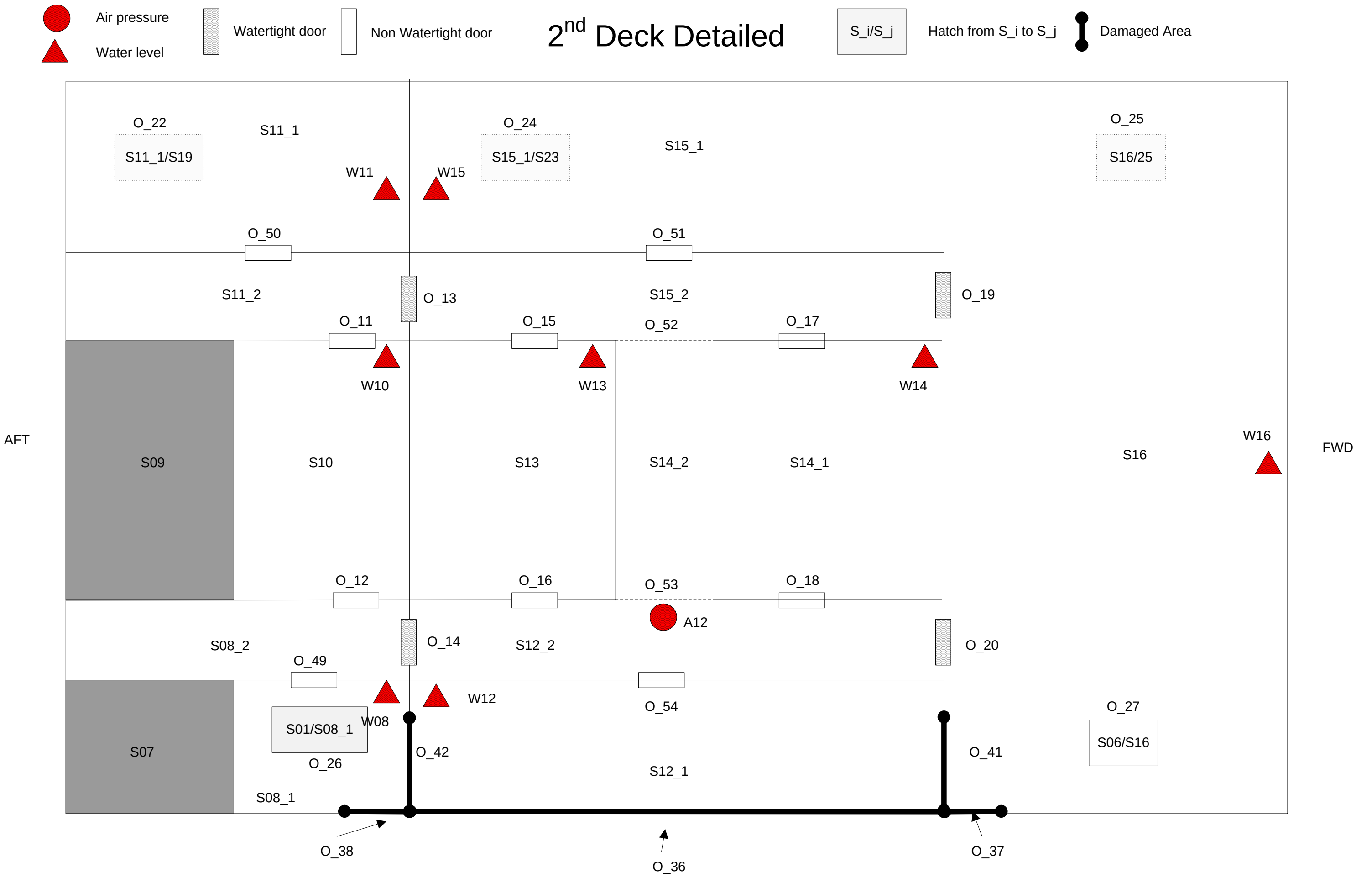
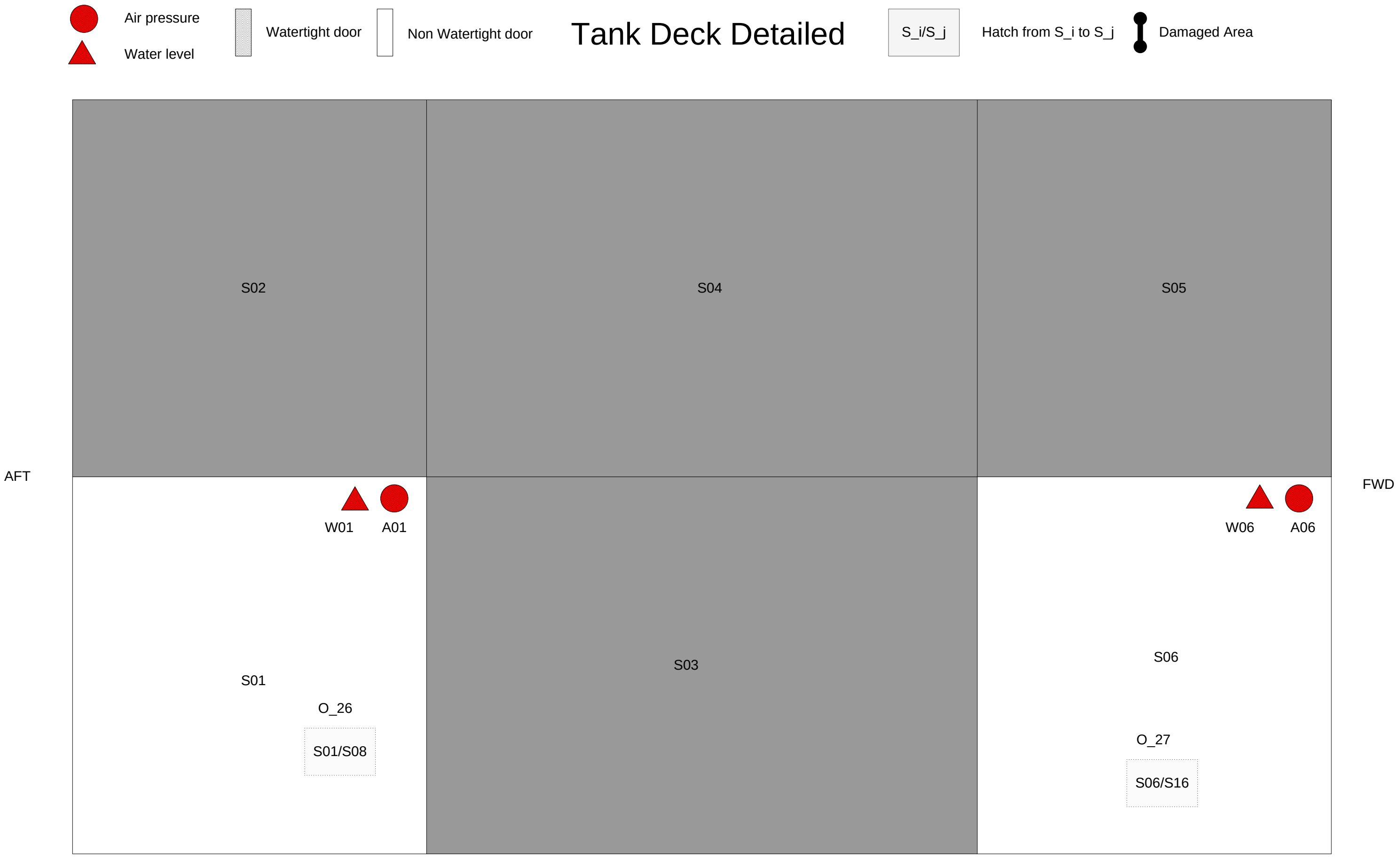
W24
O_35
O_33
O_34


Air pressure
Water level
Watertight door
Non Watertight door
2nd Deck Detailed
S_i/S_j
Hatch from S_i to S_j
Damaged Area
O_22
S11_1/S19
S11_1
W11
W15
O_24
S15_1/S23
S15_1
O_25
S16/25
O_50
O_51
S11_2
O_13
S15_2
O_19
O_11
O_15
O_52
O_17
W10
W13
W14
AFT
S09
S10
S13
S14_2
S14_1
S16
W16
FWD
O_12
O_16
O_53
O_18
A12
S08_2
O_49
O_14
S12_2
O_20
W12
O_54
O_27
S01/S08_1
W08
S07
O_42
O_41
S06/S16
O_26
S12_1
S08_1
O_38
O_36
O_37


Air pressure
Water level
Watertight door
Non Watertight door
Tank Deck Detailed
S_i/S_j
Hatch from S_i to S_j
Damaged Area
AFT
FWD
S02
S04
S05
W01
A01
W06
A06
S01
O_26
S01/S08
S03
S06
O_27
S06/S16

APPENDIX F – OPENING DEFINITIONS

Simple Model

Nr.	Comp.		Type	Corner No.	X from AP (m)	Y from CL (m)	Z from base (m)	Area
1	S19	S18		1	13.40	2.95	8.57	1.19
				2	14.10	2.95	8.57	
				3	14.10	2.95	6.87	
				4	13.40	2.95	6.87	
2	S18	S17		1	21.60	-3.13	8.57	1.19
				2	20.90	-3.13	8.57	
				3	20.90	-3.13	6.87	
				4	21.60	-3.13	6.87	
3	S17	S20	WD	1	23.00	-4.10	7.17	1.19
				2	23.00	-4.10	8.87	
				3	23.00	-3.40	8.87	
				4	23.00	-3.40	7.17	
4	S19	S23	WD	1	23.00	4.10	7.17	1.19
				2	23.00	4.10	8.87	
				3	23.00	3.40	8.87	
				4	23.00	3.40	7.17	
5	S23	S21		1	26.60	2.95	8.57	1.19
				2	26.60	2.95	6.87	
				3	25.90	2.95	6.87	
				4	25.90	2.95	8.57	
6	S21	S20		1	26.60	-3.13	8.57	1.19
				2	26.60	-3.13	6.87	
				3	25.90	-3.13	6.87	
				4	25.90	-3.13	8.57	
7	S20	S22		1	32.40	-3.13	8.57	1.19
				2	32.40	-3.13	6.87	
				3	33.10	-3.13	6.87	
				4	33.10	-3.13	8.57	
8	S22	S23		1	32.40	2.95	8.57	1.19
				2	32.40	2.95	6.87	
				3	33.10	2.95	6.87	
				4	33.10	2.95	8.57	

9	S20	S24	WD	1	36.00	-4.10	7.17	1.19
				2	36.00	-4.10	8.87	
				3	36.00	-3.40	8.87	
				4	36.00	-3.40	7.17	
10	S23	S25	WD	1	36.00	4.10	7.17	1.19
				2	36.00	4.10	8.87	
				3	36.00	3.40	8.87	
				4	36.00	3.40	7.17	
11	S11	S10		1	21.60	2.95	5.75	1.19
				2	20.90	2.95	5.75	
				3	20.90	2.95	4.05	
				4	21.60	2.95	4.05	
12	S10	S08		1	21.60	-3.13	5.75	1.19
				2	20.90	-3.13	5.75	
				3	20.90	-3.13	4.05	
				4	21.60	-3.13	4.05	
13	S11	S15	WD	1	23.00	4.10	4.35	1.19
				2	23.00	4.10	6.05	
				3	23.00	3.40	6.05	
				4	23.00	3.40	4.35	
14	S08	S12	WD	1	23.00	-4.10	4.35	1.19
				2	23.00	-4.10	6.05	
				3	23.00	-3.40	6.05	
				4	23.00	-3.40	4.35	
15	S15	S13		1	26.60	2.95	5.75	1.19
				2	26.60	2.95	4.05	
				3	25.90	2.95	4.05	
				4	25.90	2.95	5.75	
16	S13	S12		1	26.60	-3.13	5.75	1.19
				2	26.60	-3.13	4.05	
				3	25.90	-3.13	4.05	
				4	25.90	-3.13	5.75	
17	S15	S14		1	32.40	2.95	5.75	1.19
				2	32.40	2.95	4.05	

				3	33.10	2.95	4.05	
				4	33.10	2.95	5.75	
18	S12	S14		1	32.40	-3.13	5.75	1.19
				2	32.40	-3.13	4.05	
				3	33.10	-3.13	4.05	
				4	33.10	-3.13	5.75	
19	S15	S16	WD	1	36.00	4.10	4.35	1.19
				2	36.00	4.10	6.05	
				3	36.00	3.40	6.05	
				4	36.00	3.40	4.35	
20	S12	S16		1	36.00	-4.10	4.35	1.19
				2	36.00	-4.10	6.05	
				3	36.00	-3.40	6.05	
				4	36.00	-3.40	4.35	
21	S19	SEA	HATCH	1	13.40	6.65	9.80	0.64
				2	13.40	5.85	9.80	
				3	14.20	5.85	9.80	
				4	14.20	6.65	9.80	
22	S11	S19	HATCH	1	13.40	6.65	6.87	0.64
				2	13.40	5.85	6.87	
				3	14.20	5.85	6.87	
				4	14.20	6.65	6.87	
23	S23	SEA	HATCH	1	24.40	6.65	9.80	0.64
				2	24.40	5.85	9.80	
				3	25.20	5.85	9.80	
				4	25.20	6.65	9.80	
24	S15	S23	HATCH	1	24.40	6.65	6.87	0.64
				2	24.40	5.85	6.87	
				3	25.20	5.85	6.87	
				4	25.20	6.65	6.87	
25	S16	S25	HATCH	1	40.10	4.90	6.87	0.64
				2	40.10	4.10	6.87	
				3	40.90	4.10	6.87	
				4	40.90	4.90	6.87	

26	S01	S08	HATCH	1	20.80	-5.00	4.05	0.64
				2	20.80	-5.80	4.05	
				3	20.00	-5.80	4.05	
				4	20.00	-5.00	4.05	
27	S06	S16	HATCH	1	40.10	-7.00	4.05	0.64
				2	40.10	-6.20	4.05	
				3	40.90	-6.20	4.05	
				4	40.90	-7.00	4.05	
28	S12	S20	HATCH	1	23.00	-5.45	6.87	39.00
				2	23.00	-8.45	6.87	
				3	36.00	-8.79	6.87	
				4	36.00	-5.79	6.87	
29	S08	S17	HATCH	1	23.00	-8.45	6.87	1.50
				2	23.00	-5.45	6.87	
				3	22.50	-5.45	6.87	
				4	22.50	-8.45	6.87	
30	S16	S24	HATCH	1	36.00	-8.79	6.87	1.50
				2	36.50	-8.79	6.87	
				3	36.50	-5.79	6.87	
				4	36.00	-5.79	6.87	
31	S24	S20		1	36.00	-8.79	6.87	9.32
				2	36.00	-9.15	9.80	
				3	36.00	-5.79	9.80	
				4	36.00	-5.79	6.87	
32	S17	S20		1	23.00	-8.45	6.87	9.67
				2	23.00	-9.05	9.80	
				3	23.00	-5.45	9.80	
				4	23.00	-5.45	6.87	
33	S20	SEA		1	23.00	-8.85	9.00	28.18
				2	23.00	-8.45	6.87	
				3	36.00	-8.79	6.87	
				4	36.00	-9.19	9.00	
34	S24	SEA		1	36.00	-9.19	9.00	2.16
				2	36.00	-8.79	6.87	
				3	37.00	-8.79	6.87	

				4	37.00	-9.00	9.00	
35	S17	SEA		1	23.00	-8.45	6.87	2.17
				2	23.00	-8.85	9.00	
				3	22.00	-8.83	9.00	
				4	22.00	-8.43	6.87	
36	S12	SEA		1	23.00	-8.45	6.87	37.63
				2	23.00	-7.80	4.05	
				3	36.00	-8.14	4.05	
				4	36.00	-8.79	6.87	
37	S16	SEA		1	36.00	-8.79	6.87	2.89
				2	36.00	-8.14	4.05	
				3	37.00	-8.14	4.05	
				4	37.00	-8.79	6.87	
38	S08	SEA		1	22.00	-8.43	6.87	2.89
				2	22.00	-7.78	4.05	
				3	23.00	-7.80	4.05	
				4	23.00	-8.45	6.87	
39	S16	S24	HATCH	1	36.50	-7.79	6.87	0.50
				2	36.50	-8.79	6.87	
				3	37.00	-8.79	6.87	
				4	37.00	-7.79	6.87	
40	S08	S17	HATCH	1	22.50	-7.43	6.87	0.50
				2	22.00	-7.43	6.87	
				3	22.00	-8.44	6.87	
				4	22.50	-8.44	6.87	
41	S12	S16		1	36.00	-8.79	6.87	7.54
				2	36.00	-8.14	4.05	
				3	36.00	-5.79	4.05	
				4	36.00	-5.79	6.87	
42	S08	S12		1	23.00	-8.45	6.87	7.54
				2	23.00	-7.80	4.05	
				3	23.00	-5.45	4.05	
				4	23.00	-5.45	6.87	

Detailed Model

Nr.	Compartments		Type	Corner No.	X from AP (m)	Y from CL (m)	Z from base (m)	Area
1	S19_2	S18		1	13.40	2.95	8.57	1.19
				2	14.10	2.95	8.57	
				3	14.10	2.95	6.87	
				4	13.40	2.95	6.87	
2	S18	S17_2		1	21.60	-3.13	8.57	1.19
				2	20.90	-3.13	8.57	
				3	20.90	-3.13	6.87	
				4	21.60	-3.13	6.87	
3	S17_2	S20_2	WD	1	23.00	-4.10	7.17	1.19
				2	23.00	-4.10	8.87	
				3	23.00	-3.40	8.87	
				4	23.00	-3.40	7.17	
4	S19_2	S23_2	WD	1	23.00	4.10	7.17	1.19
				2	23.00	4.10	8.87	
				3	23.00	3.40	8.87	
				4	23.00	3.40	7.17	
5	S23_2	S21		1	26.60	2.95	8.57	1.19
				2	26.60	2.95	6.87	
				3	25.90	2.95	6.87	
				4	25.90	2.95	8.57	
6	S21	S20_2		1	26.60	-3.13	8.57	1.19
				2	26.60	-3.13	6.87	
				3	25.90	-3.13	6.87	
				4	25.90	-3.13	8.57	
7	S20_2	S22_1		1	32.40	-3.13	8.57	1.19
				2	32.40	-3.13	6.87	
				3	33.10	-3.13	6.87	
				4	33.10	-3.13	8.57	
8	S22_1	S23_2		1	32.40	2.95	8.57	1.19
				2	32.40	2.95	6.87	
				3	33.10	2.95	6.87	
				4	33.10	2.95	8.57	
9	S20_2	S24	WD	1	36.00	-4.10	7.17	1.19
				2	36.00	-4.10	8.87	

				3	36.00	-3.40	8.87	
				4	36.00	-3.40	7.17	
10	S23_2	S25	WD	1	36.00	4.10	7.17	1.19
				2	36.00	4.10	8.87	
				3	36.00	3.40	8.87	
				4	36.00	3.40	7.17	
11	S11_2	S10		1	21.60	2.95	5.75	1.19
				2	20.90	2.95	5.75	
				3	20.90	2.95	4.05	
				4	21.60	2.95	4.05	
12	S10	S08_2		1	21.60	-3.13	5.75	1.19
				2	20.90	-3.13	5.75	
				3	20.90	-3.13	4.05	
				4	21.60	-3.13	4.05	
13	S11_2	S15_2	WD	1	23.00	4.10	4.35	1.19
				2	23.00	4.10	6.05	
				3	23.00	3.40	6.05	
				4	23.00	3.40	4.35	
14	S08_2	S12_2	WD	1	23.00	-4.10	4.35	1.19
				2	23.00	-4.10	6.05	
				3	23.00	-3.40	6.05	
				4	23.00	-3.40	4.35	
15	S15_2	S13		1	26.60	2.95	5.75	1.19
				2	26.60	2.95	4.05	
				3	25.90	2.95	4.05	
				4	25.90	2.95	5.75	
16	S13	S12_2		1	26.60	-3.13	5.75	1.19
				2	26.60	-3.13	4.05	
				3	25.90	-3.13	4.05	
				4	25.90	-3.13	5.75	
17	S15_2	S14_1		1	32.40	2.95	5.75	1.19
				2	32.40	2.95	4.05	
				3	33.10	2.95	4.05	
				4	33.10	2.95	5.75	
18	S12_2	S14_1		1	32.40	-3.13	5.75	1.19

				2	32.40	-3.13	4.05	
				3	33.10	-3.13	4.05	
				4	33.10	-3.13	5.75	
19	S15_2	S16	WD	1	36.00	4.10	4.35	1.19
				2	36.00	4.10	6.05	
				3	36.00	3.40	6.05	
				4	36.00	3.40	4.35	
20	S12_2	S16		1	36.00	-4.10	4.35	1.19
				2	36.00	-4.10	6.05	
				3	36.00	-3.40	6.05	
				4	36.00	-3.40	4.35	
21	S19_1	SEA	HATCH	1	13.40	6.65	9.80	0.64
				2	13.40	5.85	9.80	
				3	14.20	5.85	9.80	
				4	14.20	6.65	9.80	
22	S11	S19_1	HATCH	1	13.40	6.65	6.87	0.64
				2	13.40	5.85	6.87	
				3	14.20	5.85	6.87	
				4	14.20	6.65	6.87	
23	S23_1	SEA	HATCH	1	24.40	6.65	9.80	0.64
				2	24.40	5.85	9.80	
				3	25.20	5.85	9.80	
				4	25.20	6.65	9.80	
24	S15_1	S23_1	HATCH	1	24.40	6.65	6.87	0.64
				2	24.40	5.85	6.87	
				3	25.20	5.85	6.87	
				4	25.20	6.65	6.87	
25	S16	S25	HATCH	1	40.10	4.90	6.87	0.64
				2	40.10	4.10	6.87	
				3	40.90	4.10	6.87	
				4	40.90	4.90	6.87	
26	S01	S08_1	HATCH	1	20.80	-5.00	4.05	0.64
				2	20.80	-5.80	4.05	
				3	20.00	-5.80	4.05	
				4	20.00	-5.00	4.05	

27	S06	S16	HATCH	1	40.10	-7.00	4.05	0.64
				2	40.10	-6.20	4.05	
				3	40.90	-6.20	4.05	
				4	40.90	-7.00	4.05	
28	S12_1	S20_1	HATCH	1	23.00	-5.45	6.87	39.00
				2	23.00	-8.45	6.87	
				3	36.00	-8.79	6.87	
				4	36.00	-5.79	6.87	
29	S08_1	S17_1	HATCH	1	23.00	-8.45	6.87	1.50
				2	23.00	-5.45	6.87	
				3	22.50	-5.45	6.87	
				4	22.50	-8.45	6.87	
30	S16	S24	HATCH	1	36.00	-8.79	6.87	1.50
				2	36.50	-8.79	6.87	
				3	36.50	-5.79	6.87	
				4	36.00	-5.79	6.87	
31	S24	S20_1		1	36.00	-8.79	6.87	9.32
				2	36.00	-9.15	9.80	
				3	36.00	-5.79	9.80	
				4	36.00	-5.79	6.87	
32	S17_1	S20_1		1	23.00	-8.45	6.87	9.67
				2	23.00	-9.05	9.80	
				3	23.00	-5.45	9.80	
				4	23.00	-5.45	6.87	
33	S20_1	SEA		1	23.00	-8.85	9.00	28.18
				2	23.00	-8.45	6.87	
				3	36.00	-8.79	6.87	
				4	36.00	-9.19	9.00	
34	S24	SEA		1	36.00	-9.19	9.00	2.16
				2	36.00	-8.79	6.87	
				3	37.00	-8.79	6.87	
				4	37.00	-9.00	9.00	
35	S17_1	SEA		1	23.00	-8.45	6.87	2.17
				2	23.00	-8.85	9.00	
				3	22.00	-8.83	9.00	
				4	22.00	-8.43	6.87	

36	S12_1	SEA		1	23.00	-8.45	6.87	37.63
				2	23.00	-7.80	4.05	
				3	36.00	-8.14	4.05	
				4	36.00	-8.79	6.87	
37	S16	SEA		1	36.00	-8.79	6.87	2.89
				2	36.00	-8.14	4.05	
				3	37.00	-8.14	4.05	
				4	37.00	-8.79	6.87	
38	S08_1	SEA		1	22.00	-8.43	6.87	2.89
				2	22.00	-7.78	4.05	
				3	23.00	-7.80	4.05	
				4	23.00	-8.45	6.87	
39	S16	S24	HATCH	1	36.50	-7.79	6.87	0.50
				2	36.50	-8.79	6.87	
				3	37.00	-8.79	6.87	
				4	37.00	-7.79	6.87	
40	S08_1	S17_1	HATCH	1	22.50	-7.43	6.87	0.50
				2	22.00	-7.43	6.87	
				3	22.00	-8.44	6.87	
				4	22.50	-8.44	6.87	
41	S12_1	S16	HATCH	1	36.00	-8.79	6.87	7.54
				2	36.00	-8.14	4.05	
				3	36.00	-5.79	4.05	
				4	36.00	-5.79	6.87	
42	S08_1	S12_1	HATCH	1	23.00	-8.45	6.87	7.54
				2	23.00	-7.80	4.05	
				3	23.00	-5.45	4.05	
				4	23.00	-5.45	6.87	
43	S17_1	S17_2		1	17.04	-4.50	8.57	1.19
				2	17.04	-4.50	6.87	
				3	17.74	-4.50	6.87	
				4	17.74	-4.50	8.57	
44	S19_1	S19_2		1	17.04	4.50	8.57	1.19
				2	17.04	4.50	6.87	
				3	17.74	4.50	6.87	

				4	17.74	4.50	8.57	
45	S23_1	S23_2		1	29.14	4.50	8.57	1.19
				2	29.14	4.50	6.87	
				3	29.84	4.50	6.87	
				4	29.84	4.50	8.57	
46	S23_1	S22_2		1	29.05	2.95	9.80	2.64
				2	29.05	2.95	6.87	
				3	29.95	2.95	6.87	
				4	29.95	2.95	9.80	
47	S22_2	S20_2		1	29.05	-3.13	9.80	2.64
				2	29.05	-3.13	6.87	
				3	29.95	-3.13	6.87	
				4	29.95	-3.13	9.80	
48	S20_2	S20_1		1	29.40	-4.50	8.57	1.20
				2	29.40	-4.50	6.87	
				3	30.10	-4.50	6.87	
				4	30.10	-4.50	8.57	
49	S08_1	S08_2		1	19.80	-4.50	5.75	1.20
				2	20.50	-4.50	5.75	
				3	20.50	-4.50	4.05	
				4	19.80	-4.50	4.05	
50	S11_1	S11_2		1	17.04	4.50	5.75	1.20
				2	17.74	4.50	5.75	
				3	17.74	4.50	4.05	
				4	17.04	4.50	4.05	
51	S15_1	S15_2		1	29.14	4.50	5.75	1.20
				2	29.84	4.50	5.75	
				3	29.84	4.50	4.05	
				4	29.14	4.50	4.05	
52	S15_2	S14_2		1	29.05	2.95	6.87	2.54
				2	29.95	2.95	6.87	
				3	29.95	2.95	4.05	
				4	29.05	2.95	4.05	

53	S14_2	S12_2		1	29.05	-3.13	6.87	2.54
				2	29.95	-3.13	6.87	
				3	29.95	-3.13	4.05	
				4	29.05	-3.13	4.05	
54	S12_2	S12_1		1	29.40	-4.50	5.75	1.20
				2	30.10	-4.50	5.75	
				3	30.10	-4.50	4.05	
				4	29.40	-4.50	4.05	

APPENDIX G – SECTIONS IN DAMAGED AREA