Results from Demonstration at Wave Tank

D10.4

Grant Agreement No.	774253
Start date of Project	1 November 2017
Duration of the Project	36 months
Deliverable Number	D10.4
Deliverable Leader	MARIN
Dissemination Level	PU
Status	V1.0
Submission Date	13-10-2020
Authors	William Otto (MARIN) W.Otto@marin.nl Clara Hüsken (MARIN) C.Husken@marin.nl

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774253.

Modification Control

Version #	Date	Author	Organisation
V0.1	04-08-2020 ff.	Clara Hüsken and William Otto	MARIN
V0.2	17-09-2020	Clara Hüsken	MARIN
V1.0	09-10-2020	Clara Hüsken	MARIN

Release Approval

Name	Role	Date
Julius Schay	WP Leader	10-09-2020
Wendy Murtinu	Project Office	23-09-2020
Maarten Flikkema	Project Coordinator	13-10-2020

Table of Contents Page

Review of Tables, Figures and Photos

Tables in the report:

Tables in the Table section:

Figures in the report:

Figures in the Figure section:

Executive Summary

In Task 10.5 of the Space@Sea project, an integrated Space@Sea island was tested and demonstrated in the Offshore Basin of the Maritime Research Institute Netherlands (MARIN) at a scale of 1:60. The exemplary island model was developed in Task 10.4 and described in [1]. Its layout and mooring were designed for deep waters in the Mediterranean Sea.

During the tank test campaign (Figure 1-1), the modules did not carry any superstructure. The reason was to reduce the amount of varying parameters (mass, COG, draught, etc.). By that, the effort and error rate in the physical and numerical setup of the already complex model could be limited. Moreover, it allowed a better understanding of the test results and the influence of the main parameters (position of module, environmental condition, etc.). In contrast, for the final demonstration of the Space@Sea island, all four Space@Sea use-cases (Energy@Sea, Living@Sea, Transport&Logistics@Sea and Farming@Sea) have been integrated and modelled, see Figure 1-2.

The aim of the model tests was to analyse the hydrodynamic response of the island on waves and current loads. Furthermore, the interaction of multiple subsystems (73 island-modules, 260 module-connectors, 46 mooring lines and container vessel, moored side-by-side to the island) was studied. Prior the tests, the weight distribution and several environmental conditions, including the 100-years sea state at the installation site, were calibrated. A static load test at the mooring lines and decay tests were carried out to check the model behaviour and use the results for tuning numerical simulations. During the seakeeping tests, the current speed, wave height, module's and vessel's six degree of freedom (6DoF) motion and the 6DoF connector- as well as mooring line loads were measured at dedicated locations.

The tank test campaign showed that the modular concept of the Space@Sea island is technically feasible. Furthermore, the hydrodynamic response of the island and its subcomponents matched the expectations from pre-studies and simulations. However, more developing work needs to be done in future, to make the islands more reliable in storm conditions and to meet the limiting criteria of the different applications, see [2]. For example, depending on the sea climate at the installation site, the wave ward modules need to be protect better against green water on deck. Together with the technical optimization, also the economical side needs to be addressed in future. Is it feasible and more efficient to develop fixed connectors or shall we standardly increase the side length of the modules to decrease the motions and enlarge the uninterrupted deck space? And most important to solve: How do we moor the island in shallower water depths – and to what depth is the floating island more advantageous than a heaped up one? With the tank test results, numerical models can be tuned and validated. Subsequently, the open questions, further island layouts, improved system parameters (p. e. amount, dimensions and stiffness of mooring and connectors) or different environmental conditions can be easily studied within the verified range.

For the demonstration of the island in October 2020, the modules were equipped with simplified models of superstructure (cranes, containers, PV, houses etc.) of the four different applications. With the demonstration, the technical development of the Space@Sea project was presented to the public and a visual impression given, how a modular floating island could look like.

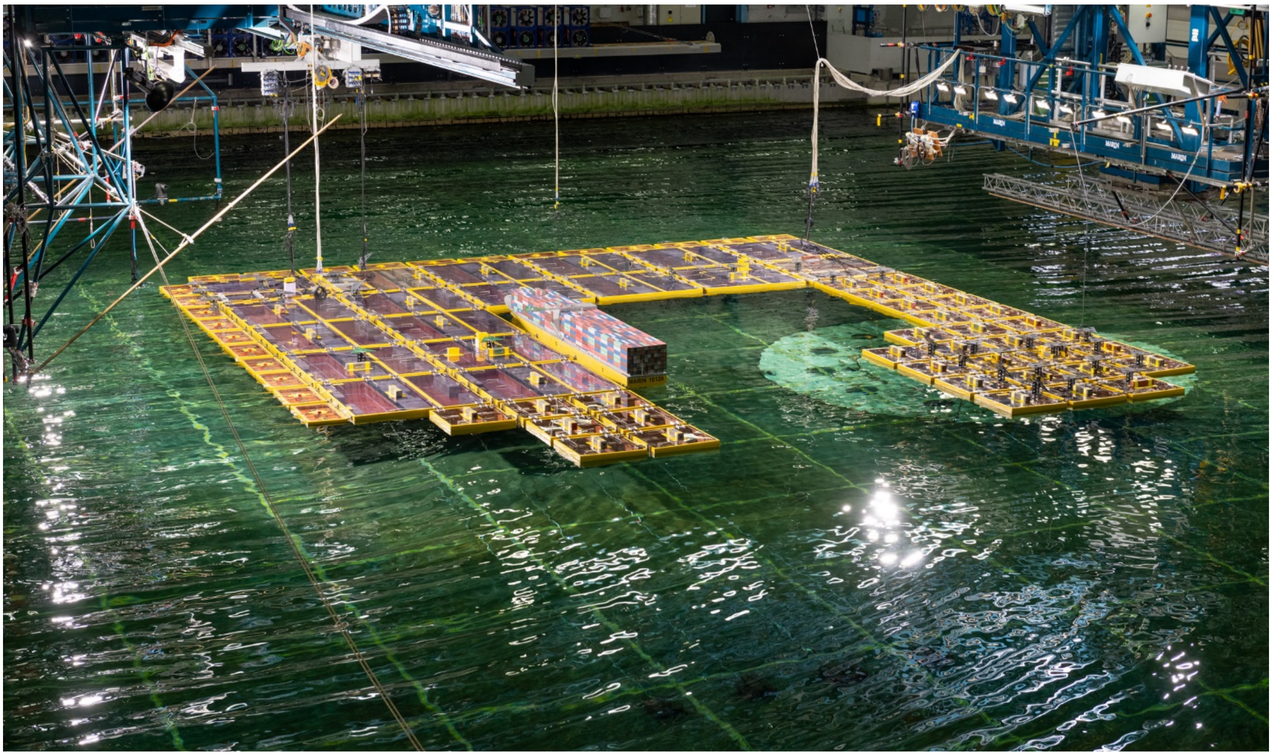

Figure 1-1: Hydrodynamics of Space@Sea island tested in MARIN's Offshore Basin

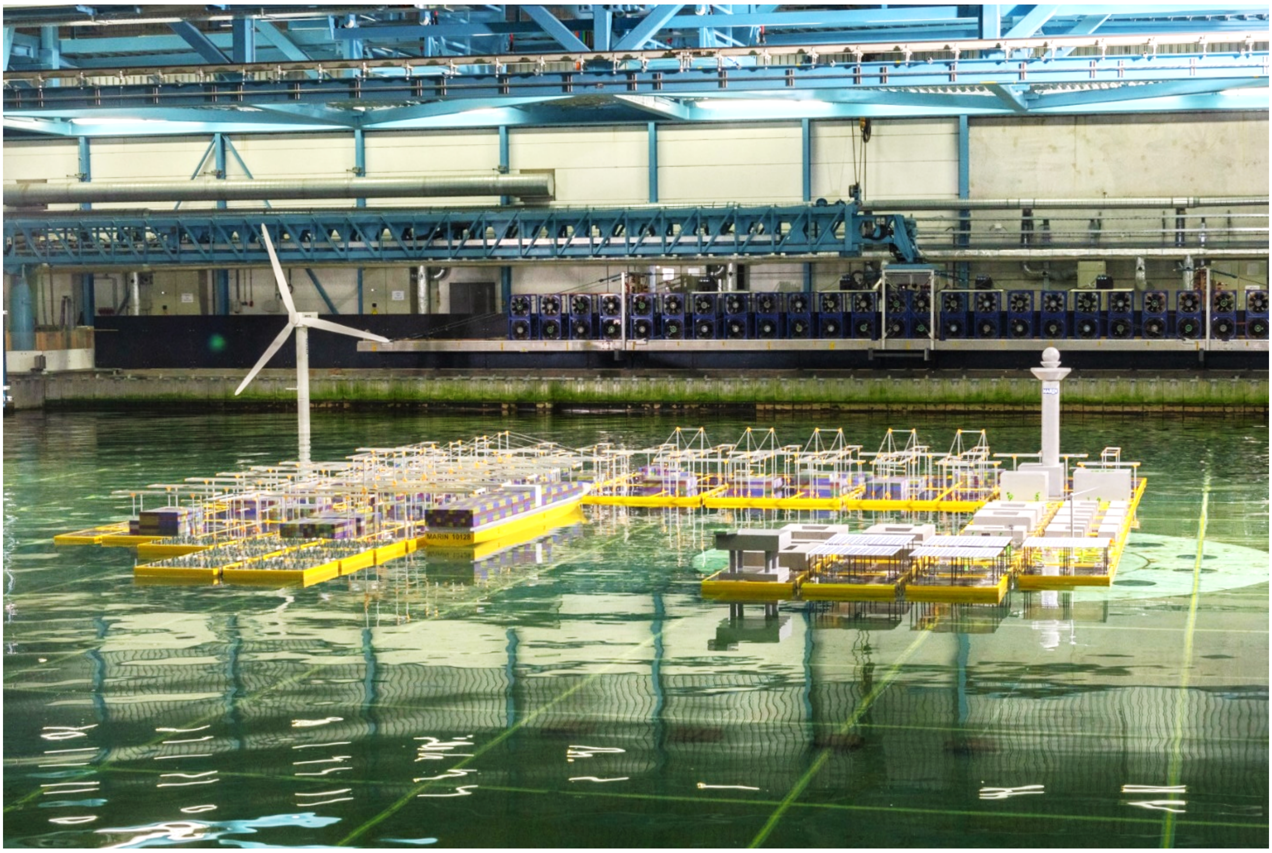

Figure 1-2: Visual demonstration of Space@Sea island in MARIN's Offshore Basin

1. Introduction

1.1 Background

The aim of the Space@Sea Project is to develop floating multipurpose space that is "sustainable and affordable […] by developing a standardized and cost efficient modular island with low ecological impact." Within the project, the four use-cases "Aquafarming, energy production and distribution, transport and logistics and living" are assessed [3]. In the preceding Task 10.4 of the work package (WP) 10, called "Integration and Demonstration", technical results from the Space@Sea project were collected, merged and modelled. In the here described final task of this WP, the integrated Space@Sea island model was tested and demonstrated in the wave basin at MARIN.

1.2 Objectives

The main objective of the tank tests is to analyse the hydrodynamic response of the island in waves and currents. More detailed, following shall be investigated:

- Motions of multiple interacting bodies
- Loads in connectors between modules
- Loads in mooring lines
- Motions and connector forces of container vessel moored to the island
- Green water on deck or other observations.

Furthermore, the overall-model of the island, including superstructure on deck, shall be demonstrated.

1.3 Content of the report

In this report the following topics are addressed:

- Description of the sign conventions
- Description of the models used for the test campaign
- Description of the facility and environmental conditions
- Description of the measurements and data acquisition
- Description of the experimental procedures
- Discussion of the results
- Impressions of the island demonstration
- Conclusions and recommendations.

2. Facility, Model and Experimental Setup

The hydrodynamic tests were performed at MARIN's Offshore Basin at scale 1:60. Test facility, model and experimental setup are described in the following. More detailed information about the Space@Sea model can be found in Deliverable 10.3 [1].

2.1 Test facility

The Space@Sea tests were performed in the Offshore Basin (OB). A complete description of the Offshore Basin can be found in Appendix F01.

2.2 Sign convention

The applied sign convention and coordinate system are in accordance with the OCIMF [4] standard. An overview of this standard is given in Figure 2-1.

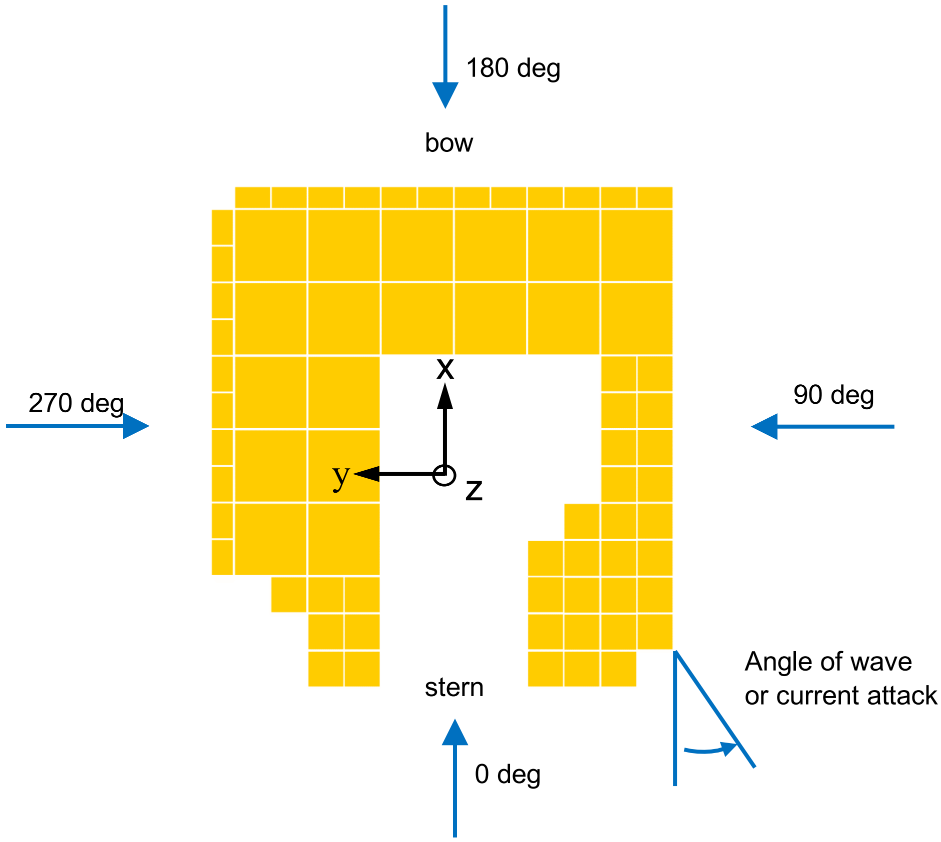

Figure 2-1: MARIN sign convention

The motions of the modules are positive in the following directions:

positive surge	(x)	:	towards the bow
positive sway	(y)	:	towards port side
positive heave	(z)	:	upwards
positive roll	(ϕ)	:	starboard side down
positive pitch	(θ)	:	bow down
positive yaw	(ψ)	:	bow towards port side

The forces and moments are positive in the following directions:

positive longitudinal force	(F_x)	:	towards the bow
positive lateral force	(F_y)	:	towards port side
positive vertical force	(F_z)	:	upwards
positive roll moment	(M_x)	:	starboard side down
positive pitch moment	(M_y)	:	bow down
positive yaw moment	(M_z)	:	bow towards port side

The relative environmental headings are defined as follows:

0 degree heading	:	stern on
90 degrees heading	:	starboard side on
180 degrees heading	:	bow on
270 degrees heading	:	port side on

2.3 Scale factor

All results of the model tests are presented as prototype values in the tables and figures in this report unless denoted otherwise. The model tests results are converted from the model scale values applying Froude's law of similitude. For scale λ of 1:60, this means that the conversion factors of Table 2-1 can be applied.

Table 2-1: Conversion factors for scale 1:60

Quantity	Model	Prototype	Ratio
Linear dimension	1 [m]	60.00 [m]	λ
Area	1 [m²]	3,600 [m²]	λ^2
Volume	1 [m³]	216,000 [m³]	λ^3
Time	1 [s]	7.746 [s]	$\sqrt{\lambda}$
Velocity	1 [m/s]	7.746 [m/s]	$\sqrt{\lambda}$
Acceleration	1 [m/s²]	1 [m/s²]	1
Angle	1 [deg]	1 [deg]	1
Angular velocity	1 [deg/s]	0.129 [deg/s]	$1/\sqrt{\lambda}$
Mass	1 [kg]	221.4 [tonne]	$\rho\lambda^3/1{,}000$
Force	1 [N]	221.4 [kN]	$\rho\lambda^3/1{,}000$
Moment	1 [Nm]	13,284.0 [kNm]	$\rho\lambda^4/1{,}000$

The ratio ρ_prototype/ρ_model = 1.025 between the specific weight of salt water and the fresh water in the basin indicates that all test results apply to seawater.

2.4 Model

The Space@Sea island was represented by the new built model M10183, manufactured at a geometrical scale ratio of 1:60, see Figure 2-2. It consisted of 73 modules, 46 catenary mooring lines and 260 flexible connectors. In addition, a model of a container vessel has been used to investigate the island-vessel interaction. The subcomponents are described in the following sections, respectively. The instrumentation is described later in section 4.3.

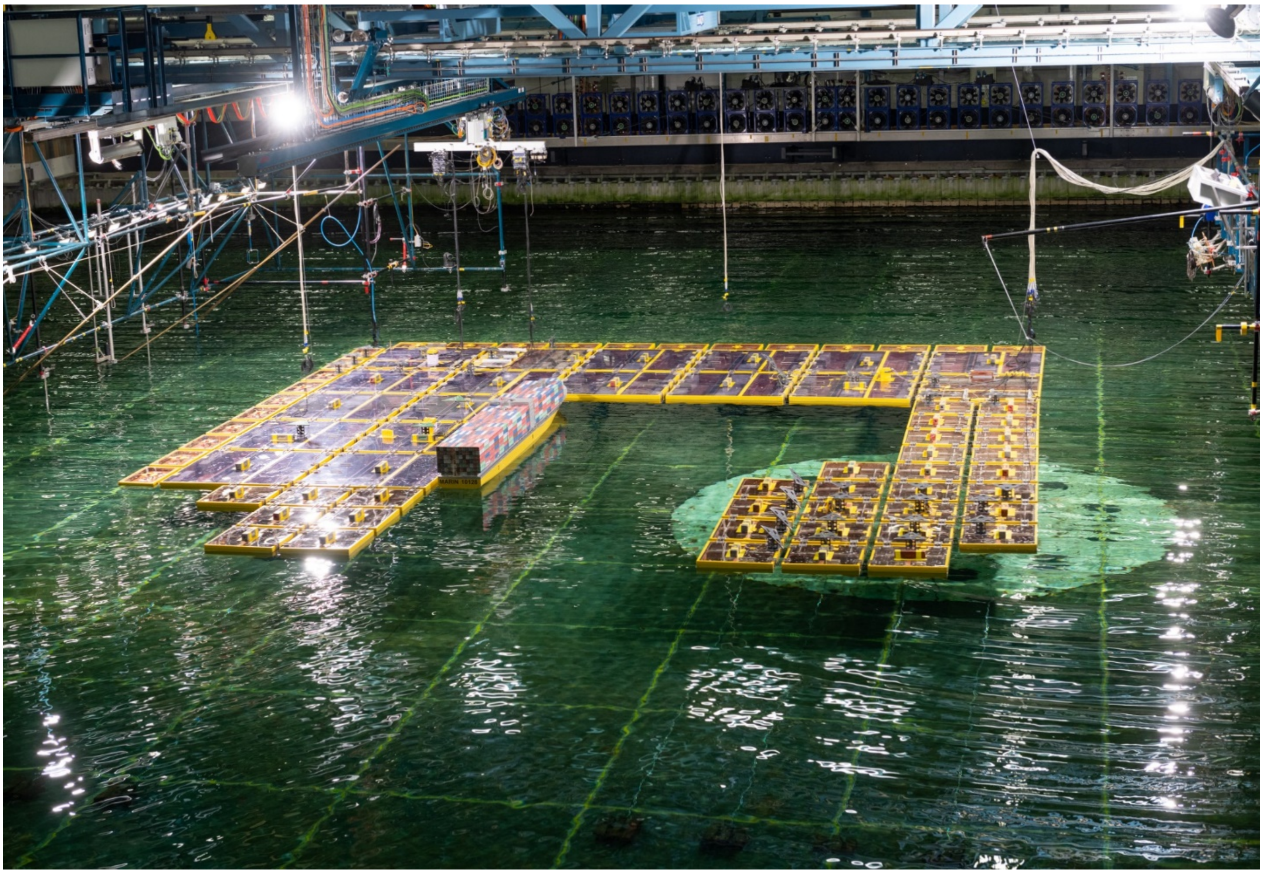

Figure 2-2: Modelsetup of Space@Sea island in MARIN's Offshore Basin

2.4.1 Layout and setup in basin

The exemplary island layout was developed in Task 10.4, described in Deliverable 10.3 [1]. Figure 2-3 shows the positions of the modules, connectors and mooring lines in the basin. The different coloring indicates the four use cases mentioned on page 10, where is:

- Pink: Energyhub@Sea (WP6)
- Green: Living@Sea (WP7)
- Blue: Farming@Sea (WP8)
- Orange: Transport&Logistics@Sea (WP9)

For the tank testing, however, the bare modules without superstructure and use-case-dependent weight distribution or similar varying parameters shall be tested.

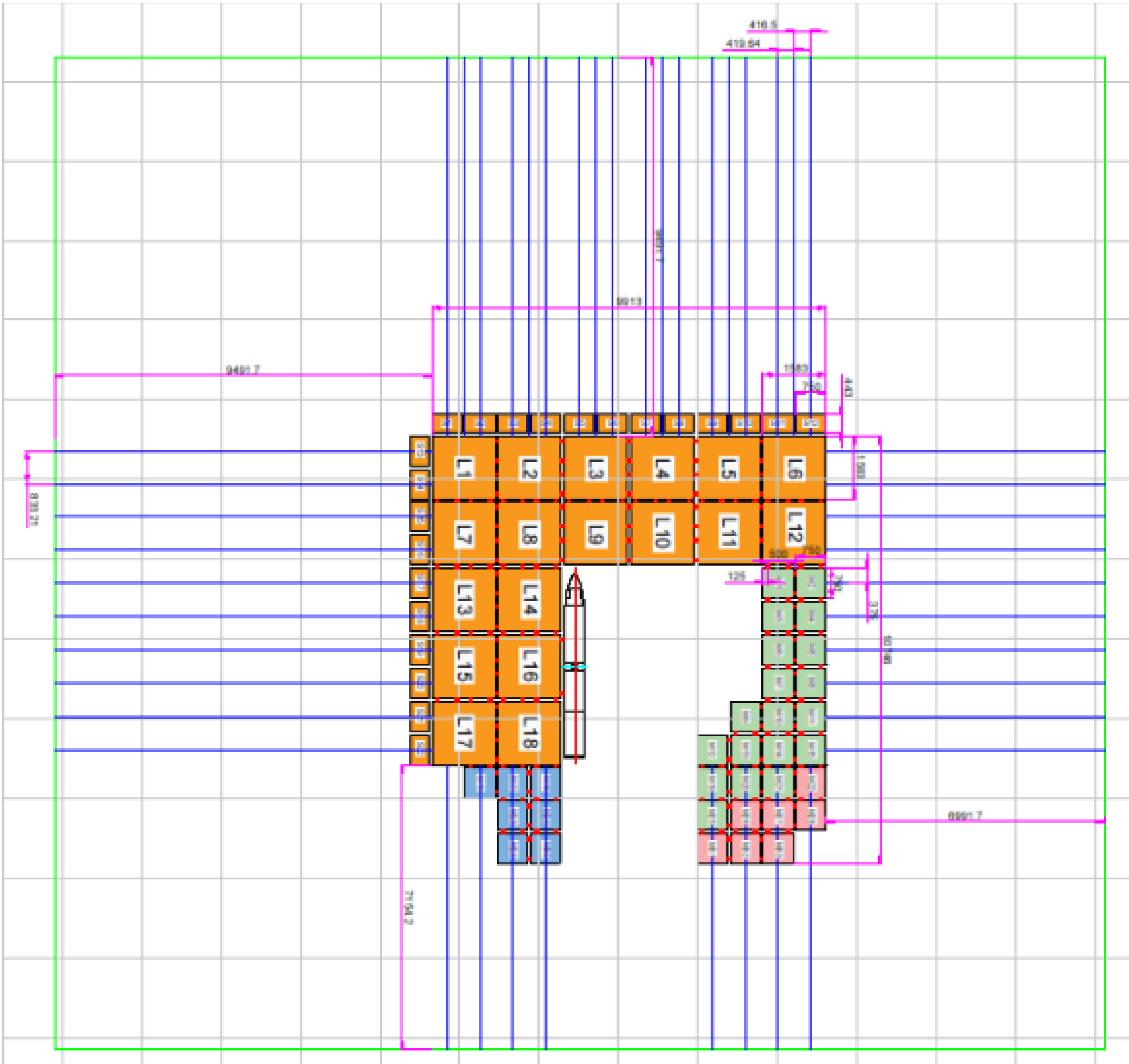

Figure 2-3: Overview over island setup in the OB with cargo vessel, connectors, numbered modules and projected mooring lines

2.4.2 Modules

Three types of modules are used for the island: Squared standard modules with two different side lengths and a rectangular module for the wave energy converters (WECs). The modules were build according to the dimensions proposed in the Basic- and Detailed Design Report [5] and [6] by WP4 and the information about the WEC from [7] of WP6. The main particulars are listed in following Table 2-2.

Table 2-2: Main particulars of Space@Sea modules

Module	Length [m]	Breadth [m]	Height [m]	Draught [m]	Freeboard [m]
45m x 45m	45	45	11	8	33
95m x 95m	95	95	11	8	3
WEC	26.58	45	4	2	2

The bottom, and sides of the modules were constructed of wood and painted yellow for good visibility on photographs and video recordings. Draft marks were added at the water line of 8.0m for the standard modules and 3m for the WEC-modules. The lids are made of transparent Plexiglas in order to be able to visually detect leakage during the test campaign. To avoid leakage, impregnated, pre-compressed foam sealing tape was put under the lid which was then screwed on. As shown on the following figures, wooden stiffeners have been included against deforming of the modules. A torsion test of a large module showed an average deformation of only 0.157 mm/kg on the corners.

For the model test programme, the modules were ballasted even keel at the desired draught. Prior to the model tests the weight distribution was calibrated and verified for sample-modules, see Table 2-3. The procedure to calibrate the weight distribution is described in the Appendix M01. Exemplary constructed und ballasted modules are visible on Figure 2-4.

Table 2-3: Model mass properties of Space@Sea modules

Module	Mass of empty Module [t]	Mass of Ballast [t]	Overall mass [t]	Radii of Inertia [m]		
				k_xx	k_yy	k_zz
45m x 45m	3520.80	12420.00	15940.80	13.38	13.38	18.36
95m x 95m	15012.00	56548.80	71560.80	27.60	27.60	38.76
WEC	1425.60	972.00	2397.60	13.02	7.74	15.06

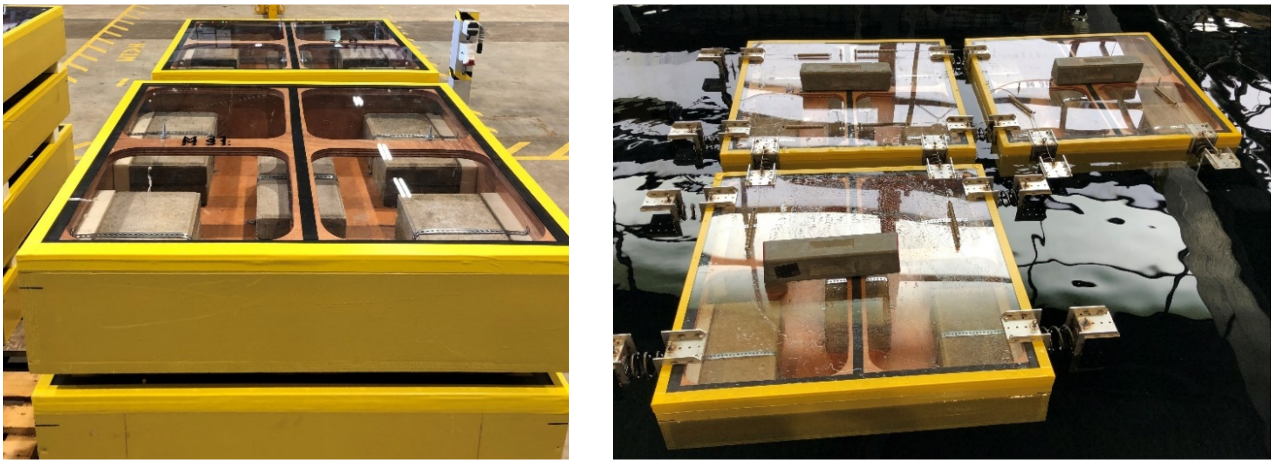

Figure 2-4: Photo of exemplary modules with fix ballasts inside the hull (left) and additional ones on deck for trimming (right)

2.4.3 Connectors

Within the Space@Sea project, different connectors have been analyzed. For the tank tests, the flexible 'Graz-connector' has been chosen. Its properties are described in [6]. In full scale, it consists of fenders, being pre-compressed by pretensioned cables. For the model tests, fenders and cables have been modelled by using springs with suitable properties. To significantly reduce costs and effort for the manufacturing of the model, the connectors have been bundled, providing similar characteristics like the original engineering design. Bundling factor and main characteristics of the fender- and cable springs are gathered in following table.

Table 2-4: Main properties of fender- and cable-springs for model of Graz-Connector

Component	Bundling factor	Diameter Spring [m]	Diameter Wire [m]	Initial Length [m]	Axial Stiffness [MN/m]	Traverse Stiffness [MN/m]	Bending Stiffness [MNm/rad]
Fenderspring	2/12	3	0.3	5.1	52.38	42.08	132.78
Cablespring	2/3	0.6	0.12	7.32	9.54	neglected	neglected

The horizontal positions of the fender- and cable springs can be seen on Figure 2-3. The fenders are mounted with a distance of 7.5m from the outer edges. On the 45m-modules, the springs therefore have a distance of 30m to each other. On the 95m-modules the distance varies between 7.5m and 30m. The vertical height of the central axis of the fender springs is 1.8m below deck level of the modules. The cables are placed above the fendersprings, approximately 0.35m above deck level of the modules.

2.4.4 Mooring

The model of the catenary mooring (Figure 2-5) has been derived from the engineering design, developed in WP3 for a module-arrangement similar to the tested one and for 100m water depth [8]. Components have been chosen that lead to a good representation of the restoring force characteristics, mooring line shape and pretention. Similar to the connectors, mooring lines have been bundled in order to reduce manufacturing time and costs. An overview over the distribution and projected lengths of the mooring lines can be found on Figure 2-3. The underwater mass per mooring line, including the selected stainless steel chain C4 ø4 x 32mm, shackle and load sensor or a dummy of it as well as the line lengths are gathered in following Table 2-5. For anchoring in the tank, 50kg gravity anchors have been used.

Table 2-5: Main properties of mooring

Longer lines No. 1-28 at bow and port side		
Component	**Underwater mass [kg/m]**	**Length [m]**
Carabiner	553.5	5.5
Chain	797.7	436.6
Forcesensor/dummy	195.7	7.9
Average/Sum	768.3	10.0

Shorter lines No. 29-46 at starboard and stern		
Component	**Underwater mass [kg/m]**	**Length [m]**
Carabiner	553.5	5.5
Chain	797.7	436.6
Forcesensor/dummy	195.7	7.9
Average/Sum	765.0	7.5

During manufacturing, each line was cut to the aimed length, weighed in water and in some cases equipped with additional mass, equally distributed over the length. In advance of the tank testing, a static load test with adjusting the anchor positions as well as a check of the free floating zero position of the island model have been done to further compensate for possible small deviations in line length or similar. The results of the static load test are described later in 6.1 on page 31.

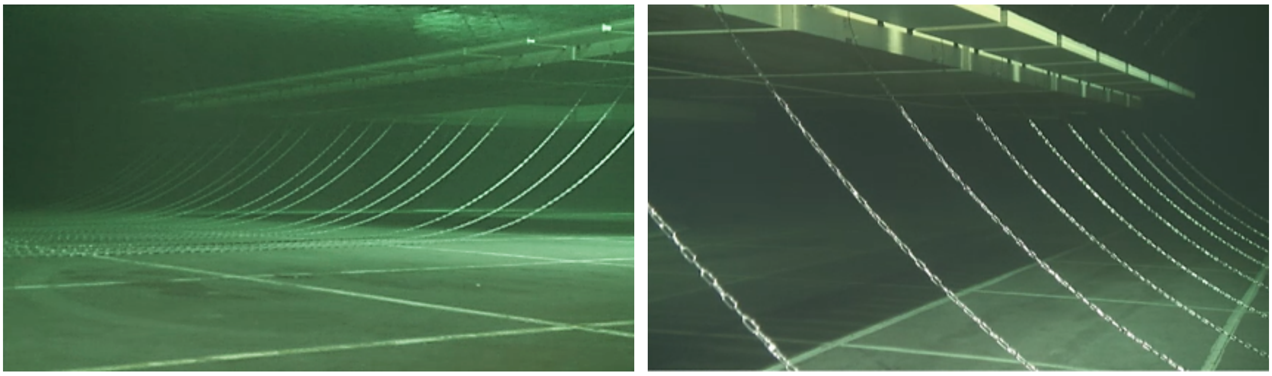

Figure 2-5: Mooringlines

2.4.5 Side by side vessel

For the investigation of vessel-island interaction, the already existing MARIN model M10128 has been moored at the Space@Sea island, see Figure 2-6. For the side-by-side mooring, two Graz-connectors (section 2.4.3) have been used that are also placed in between the modules. The connectors are placed on module number L16, 125mm from the outer edges, see Figure 2-3.

Figure 2-6: Containervessel moored to Space@Sea island in sheltered harbour basin

Figure 2-7: Side by Side mooring of containervessel and harbour quay

The main particulars and lineplan of the model can be found below.

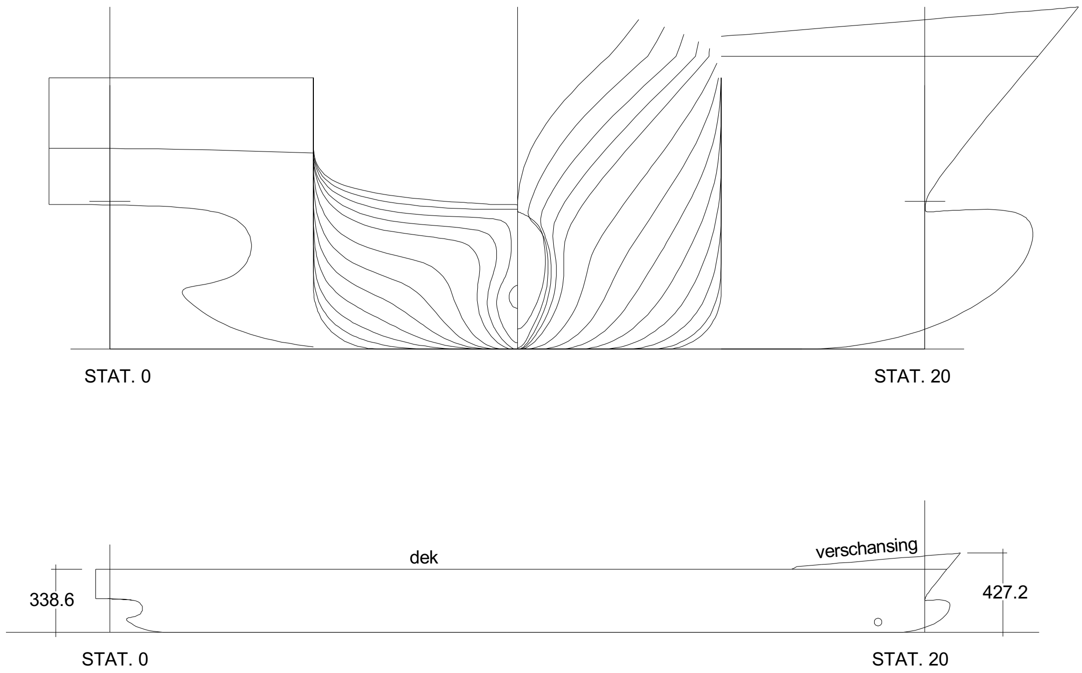

Figure 2-8: Lineplan of the container vessel model used for the investigation of island-vessel-interaction

Table 2-6: Main particulars of container vessel

Designation	Symbol	Unit	Magnitude
Length between perpendiculars	L_{pp}	[m]	269.92
Breadth	B	[m]	30.57
Depth	D	[m]	20.32
Draught	T	[m]	12.2
Displacement	Δ	[tonnes]	58,644.0
Longitudinal CoG	LCG	[m]	-6.0
Transverse CoG	TCG	[m]	0.0
Vertical CoG	KG	[m]	12.7
Roll radius of gyration	k_{xx}	[m]	13.0
Pitch radius of gyration	k_{yy}	[m]	64.2
Yaw radius of gyration	k_{zz}	[m]	64.8

3. Simulation of Environmental Conditions

3.1 General

The environmental conditions generated in the Offshore Basin are presented in this chapter. Furthermore, the procedures to calibrate the environmental conditions are described. A general description of the wave and current generation capabilities of the Offshore Basin can be found in Appendix F01 and E01.

Prior to the model tests, the current and waves were calibrated by measurements at the design position of the model (without the vessel present in the basin). During the calibration and model tests, the current and waves were monitored at the reference positions.

3.2 Current

The current profile was calibrated prior to the wave adjustment by an 1-hour stationary measurement at 12.0 m below the water surface. The procedure to calibrate the current profile is described in Appendix E02. A review of the calibrated stationary measurements is given in TABLE 1.

3.2.1 Waves

The irregular seas were adjusted such that the spectral density distribution corresponds with the required theoretical energy distribution at the design position of the model in the basin. The wave spectra used throughout the tests were JONSWAP wave spectra. A detailed description of different types of wave spectra formulations is given in Appendix E03. The JONSWAP spectra are formulated as follows:

$$S_{\varsigma}(\omega) = \frac{C \cdot H_S^2 \cdot \omega_p^4}{\omega^5} \cdot \exp\left(-1.25 \cdot \frac{\omega_p^4}{\omega^4}\right) \cdot \gamma^{\exp\left(-\left(\frac{\omega-\omega_p}{\omega_p \cdot \sigma \cdot \sqrt{2}}\right)^2\right)}$$

with

$$C \cong \frac{0.597 + 0.3125 \cdot \gamma}{1.27 + 1.47 \cdot \gamma + 0.168 \cdot \gamma^2}$$

in which

$S_{\varsigma}(\omega)$	=	spectral density at wave frequency ω, [m^2/s]
ω	=	circular wave frequency, [rad/s]
ω_p	=	peak frequency = $2\pi/T_P$, [rad/s]
T_P	=	peak period, [s]
H_s	=	significant wave height, [m]
γ	=	peak enhancement factor 3.3

and $\sigma = \begin{bmatrix} \sigma_a \text{ for } \omega \le \omega_p \\ \sigma_b \text{ for } \omega > \omega_p \end{bmatrix}$ or $\sigma = \begin{bmatrix} \sigma_a \text{ for } T \ge T_P \\ \sigma_b \text{ for } T < T_P \end{bmatrix}$

The dimensionless shape parameters σa and σb were taken is:

σ_a = 0.07

σ_b = 0.09

The significant wave height is defined as: $H_S = 4 \cdot \sqrt{\int_0^{\infty} S_{\varsigma}(\omega) d\omega} = 4 \cdot \sqrt{m_{\varsigma 0}}$

where $\sqrt{m_{\zeta 0}}$ is the area beneath the wave spectrum.

3.2.2 Wave calibration procedure

The wave calibration procedure is described in Appendix E04. Note that only the first order wave spectrum can be calibrated. The second order group wave spectrum and the maximum crest amplitudes cannot be calibrated and are a result of the applied wave seed.

3.2.3 Irregular waves

An overview of target and realized irregular waves is listed in TABLE 2.

4. Measured Values, Data Acquisition and Post Processing

4.1 General

An overview of the measured signals as well as their definitions and sign conventions is given in this chapter. Furthermore, the applied instrumentation is listed and some key information of the measurement system is given. Finally, an overview of the signals that were derived from the measured signals is given. The location of the model instrumentation is presented in TABLE 3 to TABLE 6, the labelling of the modules and mooring lines is shown on FIGURE 1 in the appendix.

4.2 Data acquisition

Part of the signals were measured using an analogue system and part of the applied measurement systems had a direct digital output. For the data acquisition of the analogue signals the MARIN Measurement System (MMS2) was used. Before sampling an on-line anti-aliasing filter was applied. All the signals were sampled and stored at a sampling rate of 200 Hz. The sampling rate of 200 Hz results in a time interval of respectively 0.0387 seconds (prototype values) between each two subsequent samples. The digital signals were measured with the MSES system. For the digital signals no on-line filtering and sampling is required. The digital signals included the measured displacements from the optical measurement systems and the logging of system feedback signals. The applied sampling rate for the digital signals was 100 Hz.

The irregular wave tests each had a duration of ½ + 3 hours (prototype values). This means that at a sample rate of 100 Hz 162665 data points are available for the statistical analysis of each measured channel. The first half hour of the measurement is considered as start up time to let possible transient phenomena vanish. In total 139427 data points are used for the data analysis. This is assumed to be sufficient to allow a reliable statistical analysis on low frequency as well as wave frequency phenomena.

4.3 Instrumentation / measured quantities

This section summarizes the instrumentation that was installed in the basin and on the model during the test campaign. The following signals were measured and recorded at a sampling frequency of 100 Hz or 200 Hz:

- *Reference wave heights*
  Resistance type wave probe, see Figure 4-1.
- *Current velocity at reference position*
  Acoustic current velocity meter (NOBSKA), see Figure 4-1.
- *Translations (X, Y, Z) and rotations (ϕ, θ, ψ) of different modules*
  NDI contact-less optical position measurement system (above water). The system determines the module's motions based on the recorded positions of three infrared LEDs on a position target placed on the model, see Figure 4-2 and Figure 4-3. Based on the measured motions of the three LEDs the NDI system calculates the 6 degrees of freedom (3 translations and 3 rotations). All motions are defined in the basin-fixed (BF) system of axes, except roll and pitch which are defined in the ship-fixed (SFT0) system of axes.
- *Fender loads*
  6 component frame force transducers (3 directions; FX, FY, FZ) at different fenders.
- *Side-by-side line tensions*
  Ring-shaped strain gauge force transducers placed in the each line at fairlead position.

- *Mooring line tensions*
  Ring-shaped strain gauge force transducers placed in the fairlead of each mooring line at the bow- and port-side.

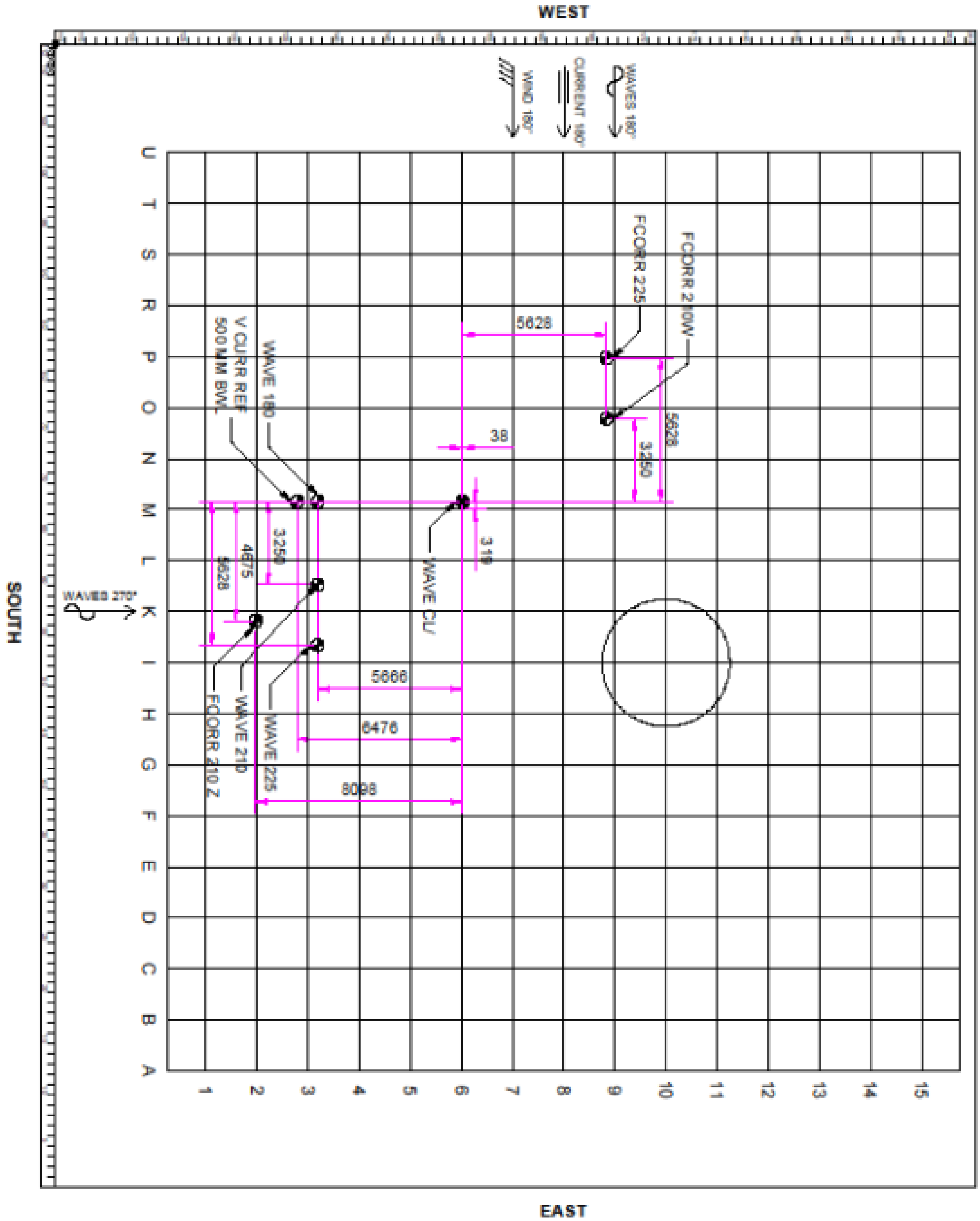

Figure 4-1: Position of wave and current sensors in basin

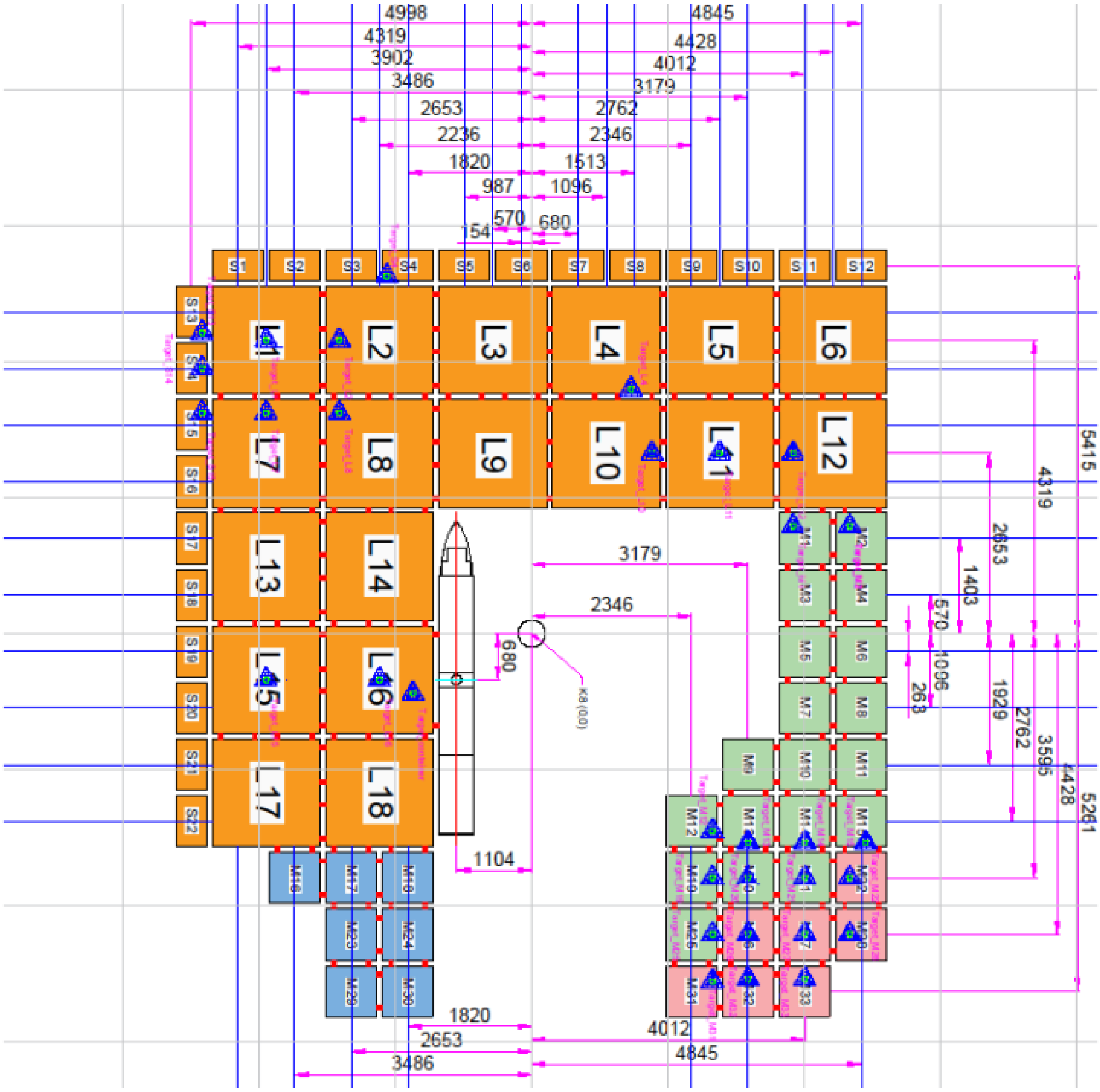

Figure 4-2: Position of reflectors for contact-less measurement

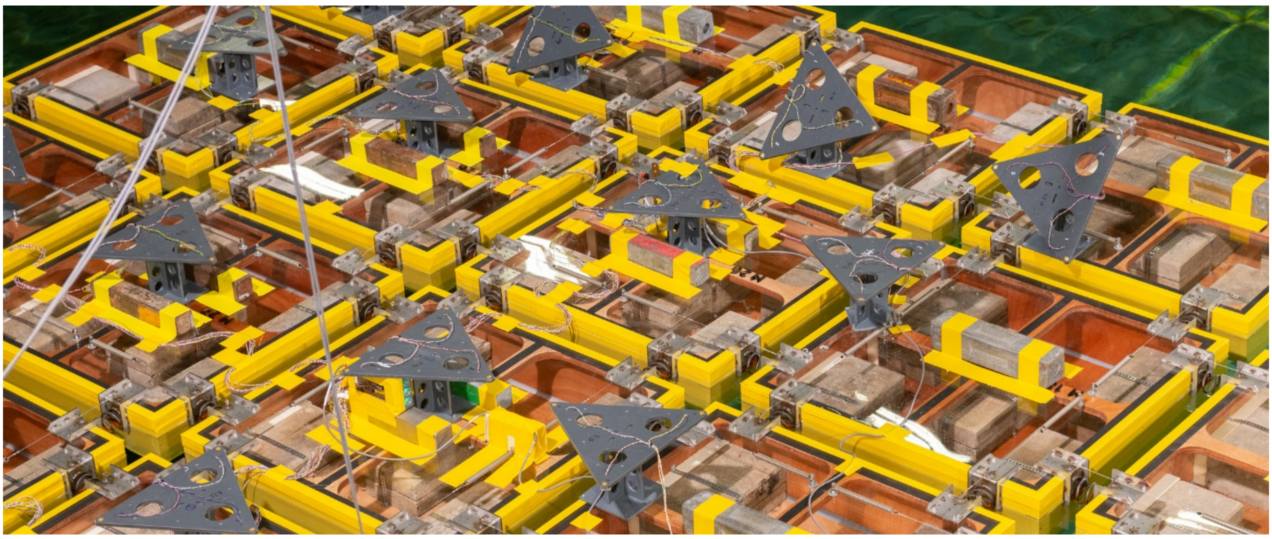
Figure 4-3: Triangular position targets on selected modules for contact-less optical position measurement system

TABLE 8 to TABLE 16 in the appendix represent a list of the measured quantities including their designation, sign conventions and measuring devices.

4.4 Derived quantities

In TABLE 17 through TABLE 22, a review of the signals derived from the measured signals is presented. The signals that were derived from the measured signals are as follows:

- Motions of different islands at CoG (6DOF).
- Total forces and moments around different fenders.

The formulas used to calculate the derived signals are described in Appendix D12. The derived signals include the motions at CoG for different islands and the total loads in different fenders.

4.5 Examples of signals in irregular wave tests

The records of the signals during the tests were of one of the following types:

- The type I record consists of a fast oscillating value, of which the frequency corresponds to the frequency of the wave (WF).

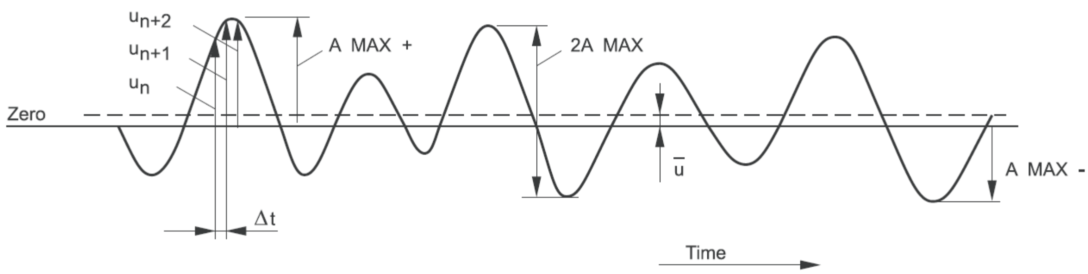

Figure 4-4: Type I signal with WF oscillations

- The type II record consists of a fast oscillating value, which is superimposed on a slowly varying value (LF).

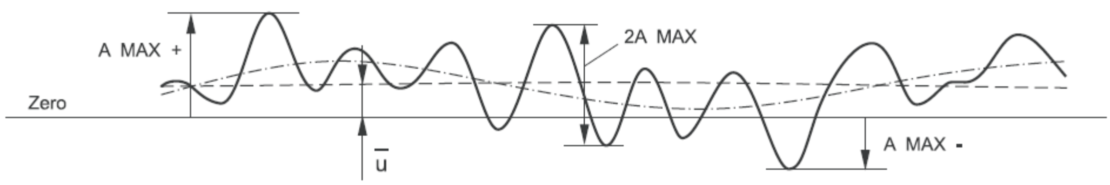

Figure 4-5: Type II signal with combined WF and LF oscillations

- The type III record consists also of an oscillating signal of which the frequency corresponds to the wave frequency, superimposed on a slowly varying signal. But in this case the fast oscillating part is small compared to the slowly varying signal.

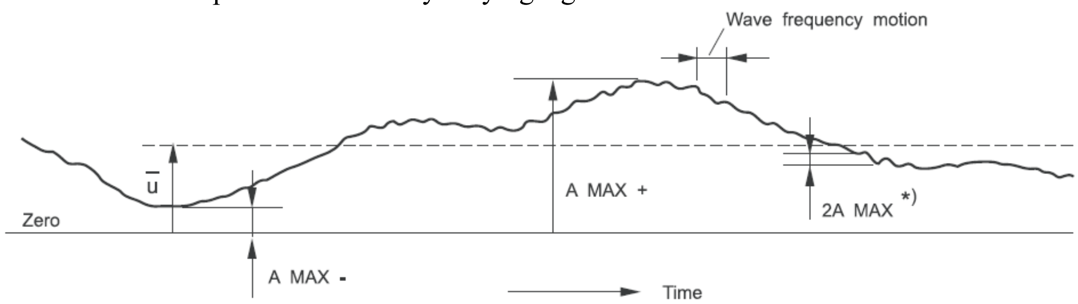

Figure 4-6: Type III signal with LF oscillations

- The type IV record is typical for slamming loads as well as green water on deck.

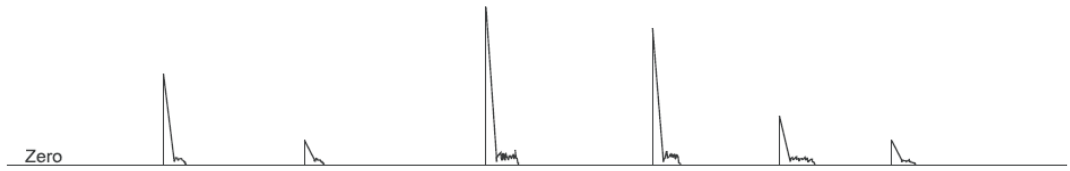

Figure 4-7: Type IV signal for impact loads

4.6 Types of data reduction

Each paragraph of this chapter discusses types of analyses that have been applied to present the model test results.

4.6.1 Statistical analysis

The two types of statistical analysis that can be done on the measured data are described in the Appendix D03 at the end of this report. They are referred to as Statistical and Extrema Statistical analysis later on in this report.

4.6.2 Signal filtering

For all signals a Low Frequency (LF) and Wave Frequency (WF) filtering, including a statistical analysis was carried out. The boundary of all filter settings are documented in Table 4-1. The Nyquist frequency ω_{NY} is about 81.12 rad/s.

Table 4-1: Filter settings in [rad/s]

Tests	UF	LF	WF
Tests in Waves	$0.0 - \omega_{NY}$	0.0 – 0.2	0.2 – 2.0

4.6.3 Decay Analysis

The decay tests are analysed in order to determine the natural periods and damping coefficients. The method used to analyse the damping coefficients based on a decay test are described in Appendix D01.

4.6.4 Weibull fits

For the extreme values of a number of signals (e.g. roll motion) a 3-parameter Weibull fit was made through 10, 25 and 50% of the highest peak or through values. This fitted line was used to determine the most probable maximum (MPM) values of the signals. A description of this methodology is given in Appendix D05.

4.6.5 Response Spectra

The motion response spectrum was determined for all irregular wave tests. It was analysed at the target position. A mathematical description of irregular phenomena is given in Appendix D02.

4.6.6 Response Amplitude Operator (RAO)

The motion RAO was determined for all wave tests. It was analysed at the target position. The lead signal is the calibrated wave. The theoretical background of the RAO is described in Appendix D06.

4.6.7 Fast Fourier transform (FFT)

Several analysis needs an FFT, like the response spectra or the filtered extrema statistical analysis. The FFT is always applied on resampled data to avoid issues due to non-equidistant data.

4.7 Data analysis and deliverables for each type of test

4.7.1 Current calibration

Channels:

- Current velocity at the centreline of the basin

Deliverables:

- Stationary measurements:
    - Statistics including mean, std, max, min and Turbulence
    - Time traces – plotted and in HDF5 format

4.7.2 Irregular wave calibration

Channels:

- Wave probe at the centreline of the basin (position of the model)

Deliverables

- (Extrema) statistics of measured wave elevation
- Comparison measured vs. specified wave spectrum
- Comparison of measured vs. specified significant wave height H_s
- Comparison of measured vs. specified peak period T_p
- Comparison of wave crest probability distribution to the Rayleigh and Forristall distributions (plot)
- Comparison of measured vs. theoretical wave group spectrum
- Time traces – H5 format

Channels:

- Other wave probes

Deliverables

- Time traces – HDF5 format

4.7.3 Decay Tests

Channels:

- 6DOF motions at CoG

Deliverables:

- PQ analysis

- Time trace plot of measured quantity (for example, roll for a roll decay) combined with a fit based on the derived PQ values
- Time traces – plotted and in HDF5 format

4.7.4 Model Tests in Irregular Waves

Channels:
- Reference basin wave elevations
- Current velocity at the reference position of the basin
- 6DOF motions at CoG of the instrumented islands
- Loads and moments around instrumented fenders
- Stroke of two wave flaps (one per side)
- Mooring loads
- Side by side loads

Deliverables:
- Time trace plots of the unfiltered measured quantities
- Time traces of the unfiltered measured quantities – HDF5 format
- Time traces of the filtered measured quantities (LF+WF) – HDF5 format
- (Extrema) Statistical mean crossing statistical analysis of unfiltered signals (UF)
- (Extrema) Statistical mean crossing statistical analysis of filtered signals (LF+WF)
- Spectrum response plots and tables for the motions of the islands
- Spectrum response plots and tables for the loads and moments around instrumented fenders
- Spectrum response plots and tables for the mooring and side by side loads
- RAO plots and tables for the motions of the islands
- RAO plots and tables for the loads and moments around instrumented fenders
- Weibull Analysis for relevant signals

4.7.5 Static Loads of the mooring system

Channels:
- Carriage offset
- Loads applied on the total island configuration by the mooring arrangement
- Line tensions

Deliverables:
- Plot offset curves
- Statistical analysis
- HDF5 files

4.8 Visualization

During the model tests and the preparations still photographs were taken. Furthermore, video recordings were made.

Still photographs

Still photographs were taken of the models in the workshop, the test set-up in the basin and during a selected number of model tests. A selection of the photographs is shown on the photo pages at the end of this report in addition to the ones placed in the text.

Video recordings

Video recordings were made to obtain a good overall impression of the behaviour of the floaters. Two above water video cameras and two underwater video cameras were used for the wave tests.

5. Test Review and Experimental Procedures

5.1 Test review

In this section, a brief overview of the model tests performed is given. A more complete overview is shown in at the end of this report.

- Static offset tests [see TABLE 23]
- Decay tests
- Tests in irregular waves [see TABLE 24 through TABLE 26]

5.2 Experimental procedures

The test procedures applied in the different types of model tests performed in this project phase are described in this section.

5.2.1 Weight distribution procedure

Prior to the tests in the basin, the weight distribution of the models was prepared and calibrated for one sample of each module-type. The experimental procedure followed to prepare the weight distribution of the model is described in Appendix M05.

5.2.2 Zero adjustment

All results presented in this report are given with respect to the 'zero values' taken after each setup change and at the beginning of every new day. In its zero-position, the floater is at the specified draft and at even keel. The zero values in each test represent the actual values of the respective quantities for the model in this starting position.

5.2.3 Current calibration

Stationary current was calibrated in the basin prior to the start of the model tests. The experimental procedure followed to calibrate the current is described in Appendix E02.

5.2.4 Wave calibration

Irregular waves were calibrated in the basin prior to the start of the model tests. The experimental procedure followed to calibrate waves is described in Appendix E04.

5.2.5 Static load tests

Prior to the actual wave model tests, the stiffness of the horizontal mooring arrangement was verified by means of pull-out tests, also referred to as static load tests. The experimental procedure followed to carry out the static load tests is described in Appendix P02.

5.2.6 Decay tests

Motion decay tests are carried out by pulling or pushing the model from its equilibrium position, after which it is released. In this project, decay tests were carried out for surge, sway and yaw. The resulting decaying motions are recorded for later analysis. The experimental test procedure followed to carry out the decay tests is described in Appendix P03.

5.2.7 Tests in waves

The procedure followed to execute the tests in waves is described in Appendix P04 at the end of this report. The basin setup and mooring arrangement are described in chapter 2.

6. Results and Discussion

6.1 Static load mooring system

The static load results are summarized in TABLE 23. The static load was executed per side of the island, i.e., in total four static load test were performed for the North, East, South and West side. A force frame was connected to the basin carriage. Underneath the force frame, a truss beam was bolted representing the side of the island. The truss is considered to be rigid. The mooring lines are connected to the fairleads on the beam. The fairleads on the beam are located such that they correspond to the fairleads of the free floating islands. The static load is performed over the offset range expected to be found in the stationkeeping tests, which is +10m to -20m.

There is a good agreement between the static load tests and the theoretical offset curve. As it is a non-segmented line consisting of catenary chain only, this was also expected. The static load tests confirmed a proper installation of the mooring system in the test-up.

6.2 Natural periods and damping values

Decay tests with the moored island were performed to identify the natural periods and damping of the global response. It should be noted that with 73 interconnected modules, there are theoretically 438 orthogonal modes which all have their own natural period and damping. In three consecutive decay tests it is aimed to only excite the global surge, sway and yaw motion. It is however physically unavoidable that other modes will get excited as well, which makes the analysis of the decay tests less straight forward. An example is shown in Figure 6-1. A beating pattern, typical for multiple modes interacting, can be seen. This leads to an amplification of the signal after 2000s.

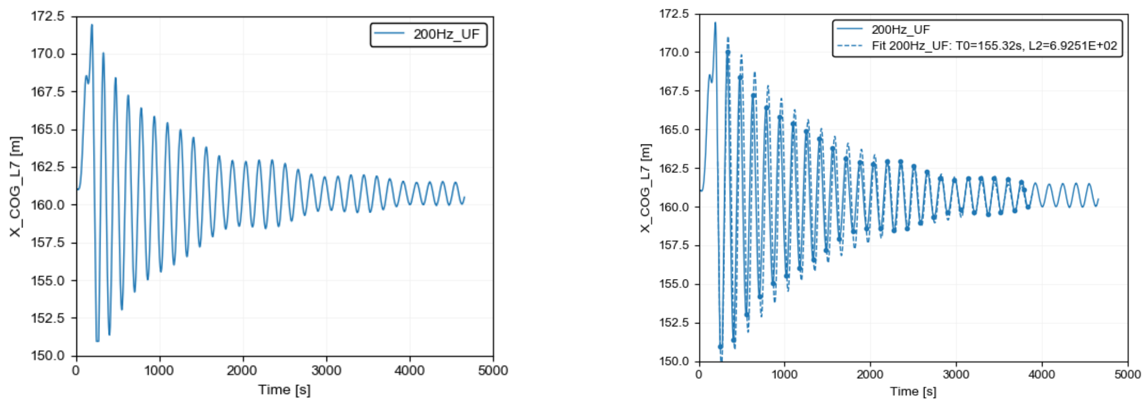

Figure 6-1: Surge module L7, decay test no. 30381_02OB_04_001_001_01. Raw data (left) and fit (right)

To get an estimate of the natural period and damping of the global surge response, a theoretical decay timetrace of a single mode is fitted on the raw data. This gives a reliable estimate of the natural period and damping. It should be noted that due to the interaction between mode shapes it is not feasible to exactly determine these values. The estimated values are presented in Table 6-1.

Table 6-1: Natural period global moored response

Mode	Natural period	% of critical damping
Surge	155 s	1.9 %
Sway	232 s	*Could not be determined*
Yaw	180 s	*Could not be determined*

6.3 Current only test

In calm water with currents only, the island has shown a stable behaviour. The maximum overall displacement variations in a 1.0 hour test were 0.3m in surge-, 0.2m in sway- and 0.02m in heave-direction. The mean offset due to the current is limited to only 0.045m. From the theoretical static offset curve of the mooring system, this corresponds to a global current load of only 170kN. The current-velocity had a mean value of 0.945 m/s and a standard deviation of 0.05 m/s.

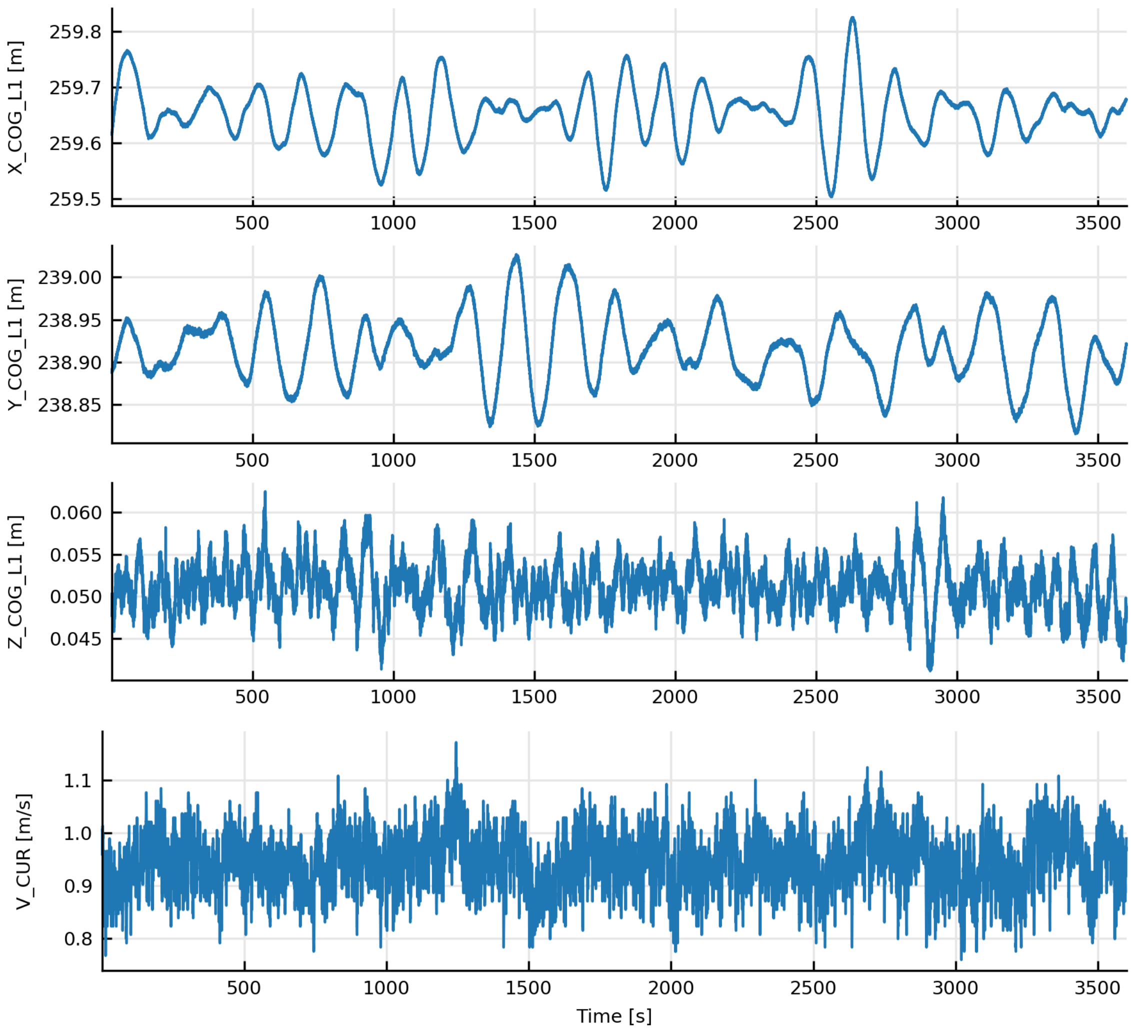

Figure 6-2: Surge X_COG_L1, sway Y_COG_L1 and heave Z_COG_L1 of module L1 for current V_CUR

The load in all mooring lines at the bow of the island had a mean value of 1774.53kN with a standard deviation of 7.09kN. On the port side, the average load in the lines 19-22 was 1674.47kN with a larger standard deviation of 12.24kN.

6.4 Current and Wave response

6.4.1 Motion response

Surge, Sway and Yaw

The measured motions in surge, sway and yaw are characterized by the low frequent content. Almost no wave frequent or high frequent horizontal motions were measured. This is illustrated in Figure 6-3, where the standard deviation of the unfiltered signal is compared to the standard deviation of the low frequent signal (see Section 4.6.2 for filter settings). As the two are almost identical for all tests, the wave frequent horizontal motions are marginal.

In Figure 6-4, the effect of current is shown on the horizontal motions of the platform. It can be seen that depending on the seastate, the current can either have a dampening or amplifying effect. The differences are in the order of 10%.

It should be noted that the maximum excursion in a 3 hour seastate is not a converged statistic due to the long natural period of the mooring system. Typically only 66 oscillation occur per test.

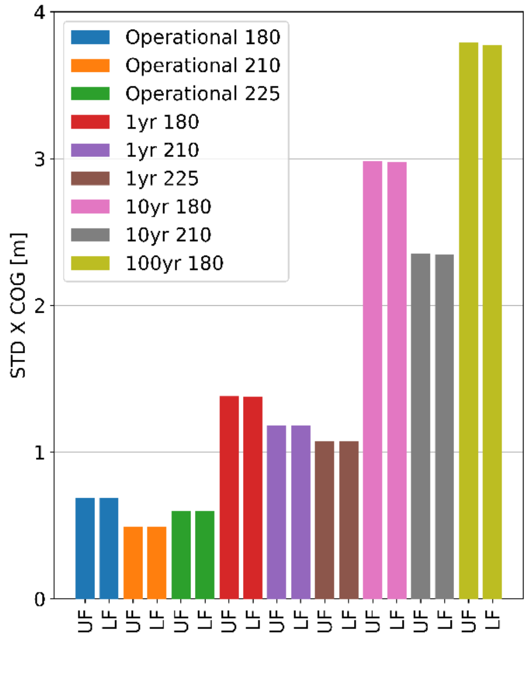

Figure 6-3: Surge standard deviation unfiltered (UF) and Low frequent (LF), tests without current

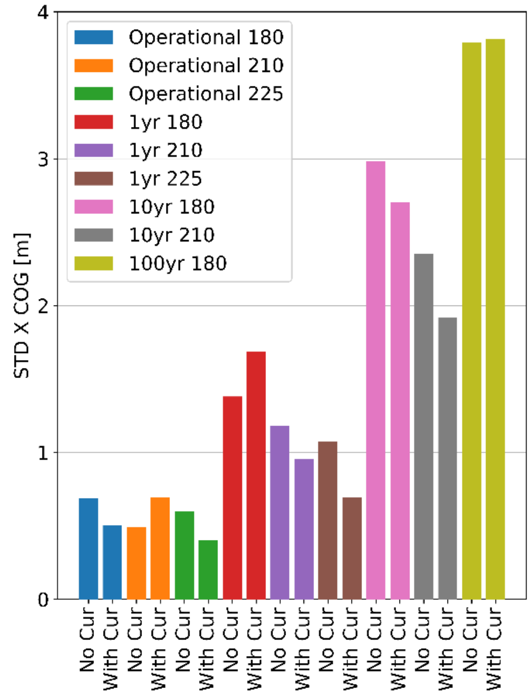

Figure 6-4: Surge standard deviation unfiltered, tests with and without current (Cur)

Pitch motions

The Most Probable Maximum (MPM) pitch angle of each test has been derived for all modules with a measuring target. At the waveward side of the island, the wave-energy converters, developed in Task 6.2 [7], are absorbing and reflecting part of the incoming wave energy which leads to reduced pitch of the modules behind. The pitch motion of the first and second row of modules is shown in Figure 6-5 in Figure 6-7. It can be seen that the first module on the waveward side (L1) is pitching more than the module on the second row (L7). From simulations it was found that the first row diffracts the incoming wave at the keel plate, sheltering the modules on the second row and further. The MPM pitch angle is under 0.5 degrees for all operational and

1 year conditions. For the 10 years and 100 years tests, the MPM pitch goes up to respectively 3 and 7 degrees. The rapid increase is mainly due to the wave-length/module-length ratio. It is expected that larger modules than 90m x 90m will maintain the low pitch response in these seastates as well.

The MPM pitch of the small modules on the last (M33) and second last row (M27) is shown in Figure 6-6 and Figure 6-8. Interesting is that the response of the module on the last row is higher than the module on the second last row. Despite being sheltered by the wave-ward modules, the pitch response is similar or even larger. Most likely this is due to their small dimensions (45m x 45m) and the fact that the small modules are not moored.

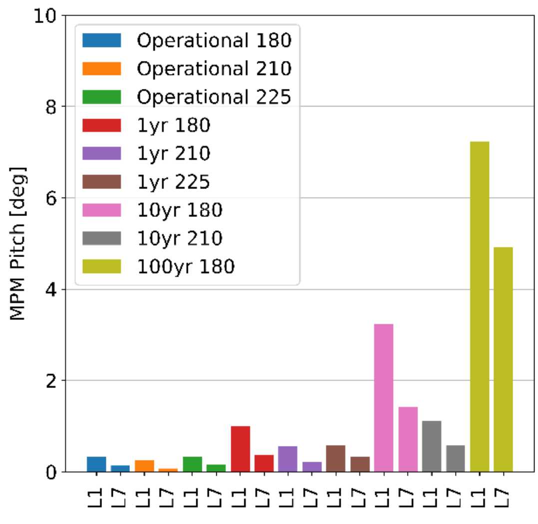

Figure 6-5: Pitch motion module L1 (front row) and L7 (second row). Tests without current

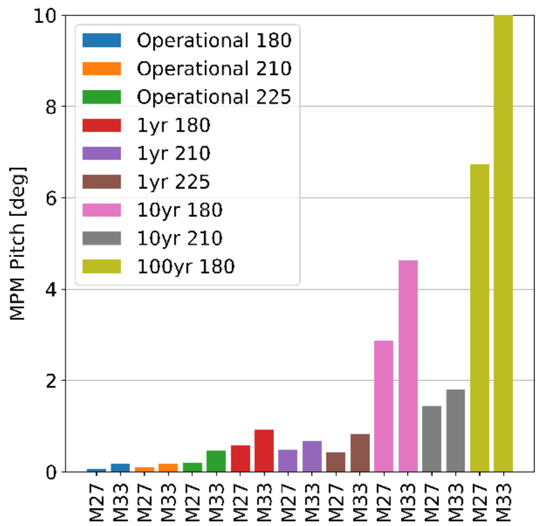

Figure 6-6: Pitch motion module M27 (second last row) and M33 (last row). Tests without current

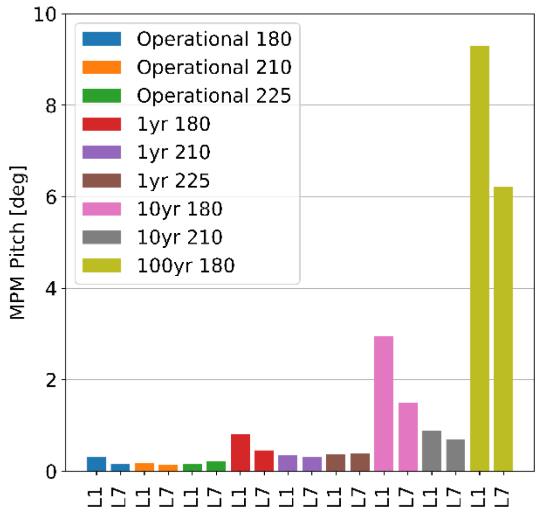

Figure 6-7: Pitch motion module L1 (front row) and L7 (second row). Tests with current

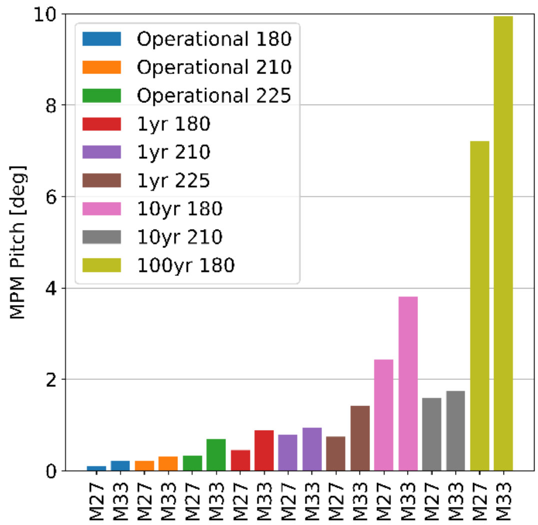

Figure 6-8: Pitch motion module M27 (second last row) and M33 (last row). Tests with current

The WECs show large pitch amplitudes for all tested sea states. The reason is, that, apart from friction, the pitch motion has not been damped. The reason was that modelling the power take off (PTO) system is a big challenge due to scaling effects and was not supposed to be part of the tank tests.