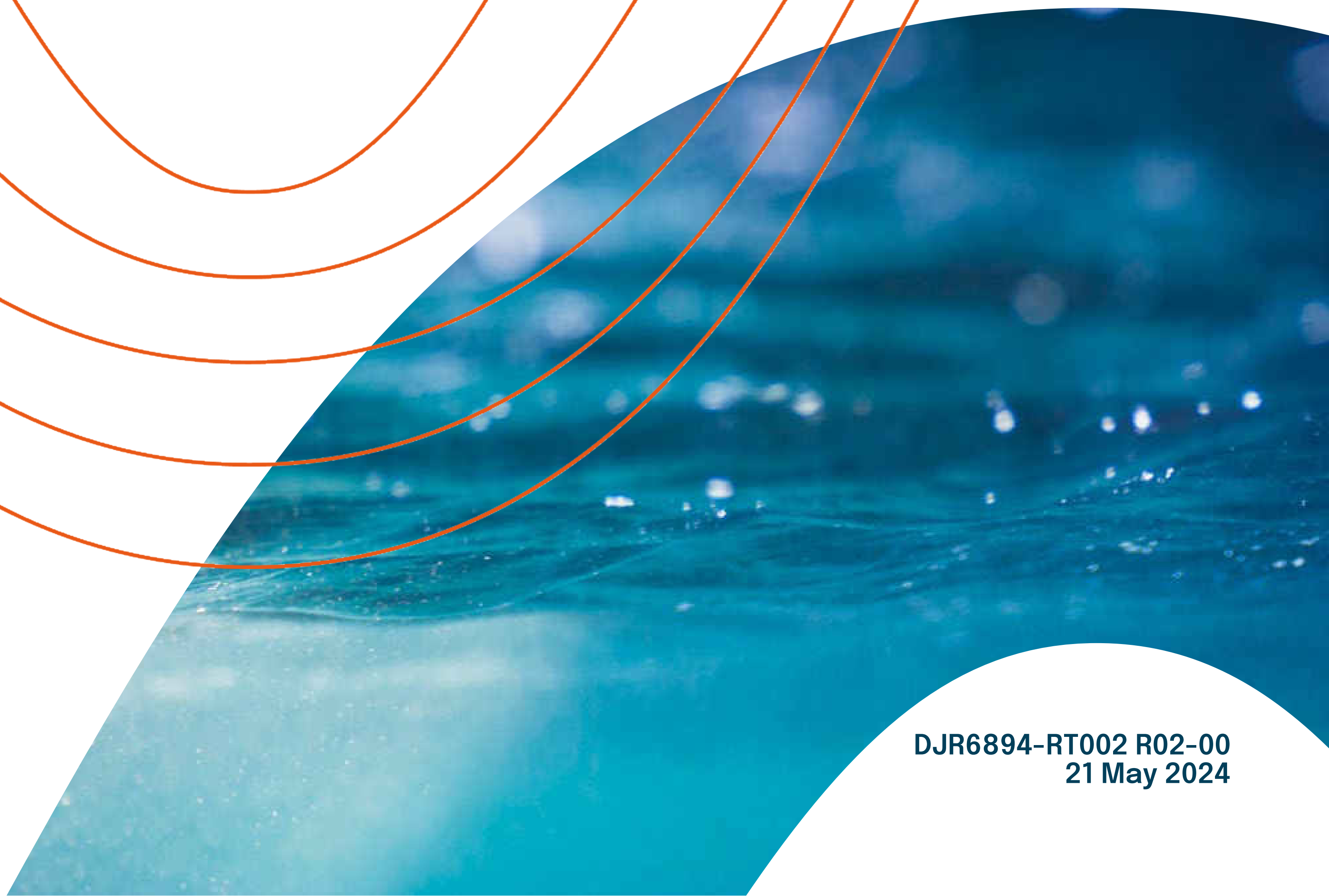
Ravenna Offshore LNG Terminal

Wave disturbance physical model study



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Summary

The Italian company Snam Rete e Gas (SRG) is developing an offshore LNG terminal in the Adriatic Sea, off the coast of Ravenna. The terminal is located approximately 8.5km offshore and will accommodate one FSRU (Floating Storage and Regasification Unit).

T.EN have contracted HR Wallingford to provide a 3D physical model study, which will be used to confirm feasibility study results.

This report focuses on the 3D physical model study of the wave disturbance and sheltering effects of the offshore breakwater.

The main objectives of the 3D physical model study were to provide information on the following aspects:

- Wave heights in and around the berth area behind the breakwater;
- The performance of the breakwater under design and survival wave conditions.

In order to meet the study aims and objectives the physical model covered the following series of tests:

- Test Series A – Calibration aspects of the study without breakwater or LNG terminal:
  - Waves for storm, design and survival conditions.
- Test Series B – Breakwater performance:
  - Wave disturbance.

The wave disturbance around the breakwater without the vessel was assessed, with particular attention paid to the wave conditions at the berth on Wave Probes 14, 15 and 16.

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1 Introduction

1.1 Background

The Italian company Snam Rete e Gas (SRG) is developing an offshore LNG terminal in the Adriatic Sea, off the coast of Ravenna. The terminal is located approximately 8.5km offshore and will accommodate one FSRU (Floating Storage and Regasification Unit).

The Ravenna LNG terminal is to be located approximately 8.5km offshore, see Figure 1.1. The pre-FEED design is progressing on the basis of using a location with existing infrastructure (an offshore jetty) and providing berthing with protection from the wave climate using a vertical caisson breakwater. The current design provides an approximately 1,030m long breakwater structure, with integrated anti-reflection caissons (see Figure 1.2) placed in a water depth of around 14m to 15m. New mooring dolphins and a jetty will be constructed at the site to accommodate the FSRU and associated LNGC vessels.

T.EN have contracted HR Wallingford to provide a 3D physical model study, which will be used to confirm feasibility study results.

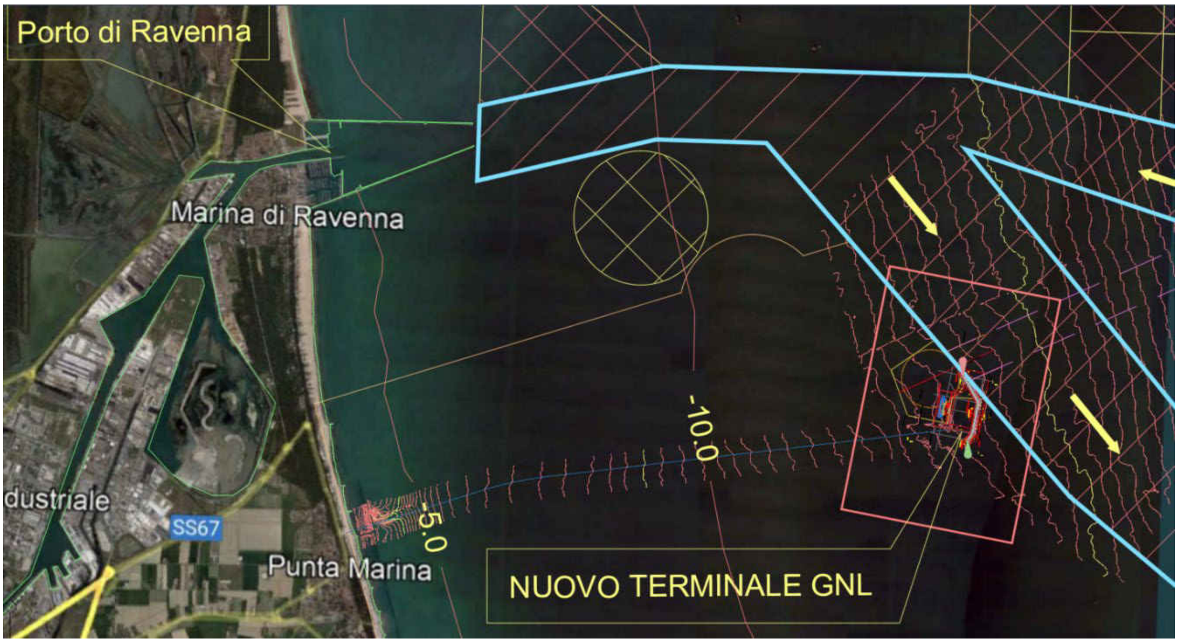


Figure 1.1: Proposed site

Source: GoogleEarth and DW-3320-003 - Layout Breakwater - Alternativa A2.1.dwg

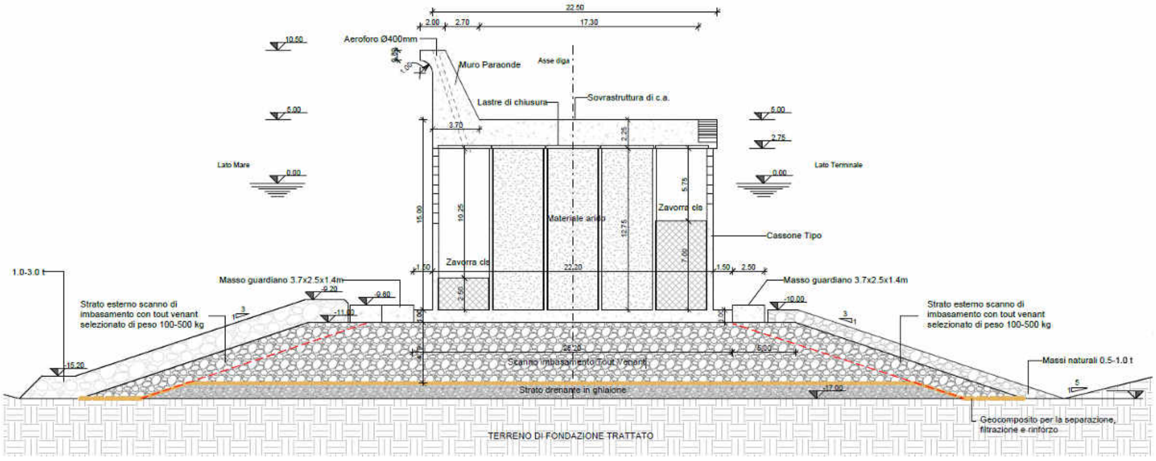


Figure 1.2: Caisson breakwater with anti-reflection chambers

Source: 000-ZB-B-17235-Sezioni tipologiche.pdf

In April 2023 the breakwater went through a design revision, bringing the vessel berths closer to the breakwater and moving the second berth north behind an extended caisson breakwater. The revised layout is given in Figure 1.3.

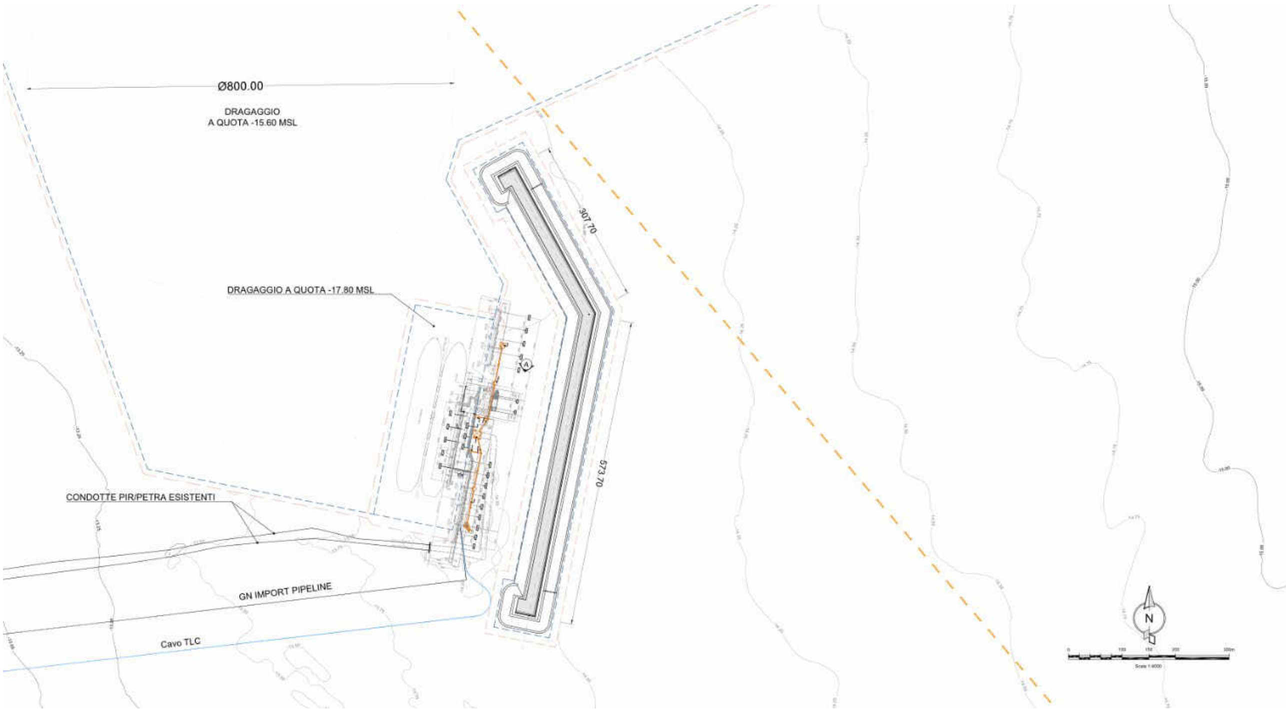


Figure 1.3: Revised terminal layout

Source: Planimetria 2 FSRU allineate rev.3-TAV 3 Ali di gabbiano.pdf

1.2 Study scope of work

The physical model study was completed in two stages:

- 2D physical model study investigating the performance of caisson breakwater;
- 3D model study investigating the wave disturbance and the sheltering effects of the breakwater.

This report focuses on the 3D physical model study of the offshore caisson breakwater.

The main objectives of the 3D physical model study are to provide information on the following aspects:

- Wave heights at and around the berth area behind the breakwater;
- The sheltering performance of the breakwater under design and survival wave conditions.

In order to meet the study aims and objectives the physical model covered the following series of tests:

- Test Series A – Calibration aspects of the study without breakwater or LNG terminal:
  - Waves for storm, design and survival conditions.
- Test Series B – Breakwater performance:
  - Wave disturbance.

1.3 Outline of this report

Following this introduction, Chapter 2 describes the modelling facilities, adopted scale, instrumentation and wave basin layout used to complete the study. The wave and water level conditions used for the study are given in Chapter 3, along with details of the model structure setup, the planning, post-processing methods. The test programme is Given in Chapter 4. Details of the wave calibrations are given in Chapter 5. Wave disturbance and measured conditions at the FSRU berth are given in Chapter 6. Finally, summary and conclusion are in given Chapter 7.

2 Physical model facilities

2.1 Scaling

For this study a scale of 1:58 was chosen to allow the wave periods of interest the to be generated and the whole breakwater structure to be included in the facility. With Froude scaling and a linear scale of 1:58, the time and velocity scales are $58^{½}$. This means events occurred about 7.6 times faster at model scale than at full (prototype) scale.

Froude's scaling law is applied to physical models where gravity and momentum are predominant factors in the fluid motion and where free surfaces occur, including all wave and current models, since wave motion is essentially a gravitational phenomenon. Froude's law states that the Froude number, Fr, should be the same in model and nature, where Fr is defined as:

$$Fr = \frac{u}{\sqrt{gD}}$$

Where:
- u is a characteristic velocity;
- g is acceleration due to gravity; and
- D is a characteristic length.

Such models should not be distorted. The linear scale of the model, to which the model was constructed, is known as the geometric scale, λ. The scaling relationships between measurements in the model and in nature can be derived from Froude's law and some important scaling relationships are:

Length	=	λ	
Time	=	$\lambda^{1/2}$	
Velocity	=	$\lambda^{1/2}$	
Discharge	=	$\lambda^{5/2}$	
Mass	=	$\lambda^3\rho$	(where ρ is the fluid density ratio; 1.025, assuming sea water to be normally 1025kg/m^3)
Force	=	$\lambda^3\gamma$	(where γ is the fluid specific weight ratio; 1.025)
Moments	=	$\lambda^4\gamma$	

In this report all values are quoted in prototype (full scale), unless stated differently. The specific gravity of water was assumed to be unity (1025kg/m^3).

2.2 Wave basin

HR Wallingford has a number of purpose-built physical modelling facilities, the largest of which is our Froude Modelling Hall.

The model study was completed in HR Wallingford's Wave and Current Basin E, see Figure 2.1. This Wave and Current Basin E has the following characteristics:

- Dimensions – 27m by 55.3m and 1.3m deep;
- Variable operating water depths – Maximum approximately 1.2m;
- Current flow working area – 21m by 36m.

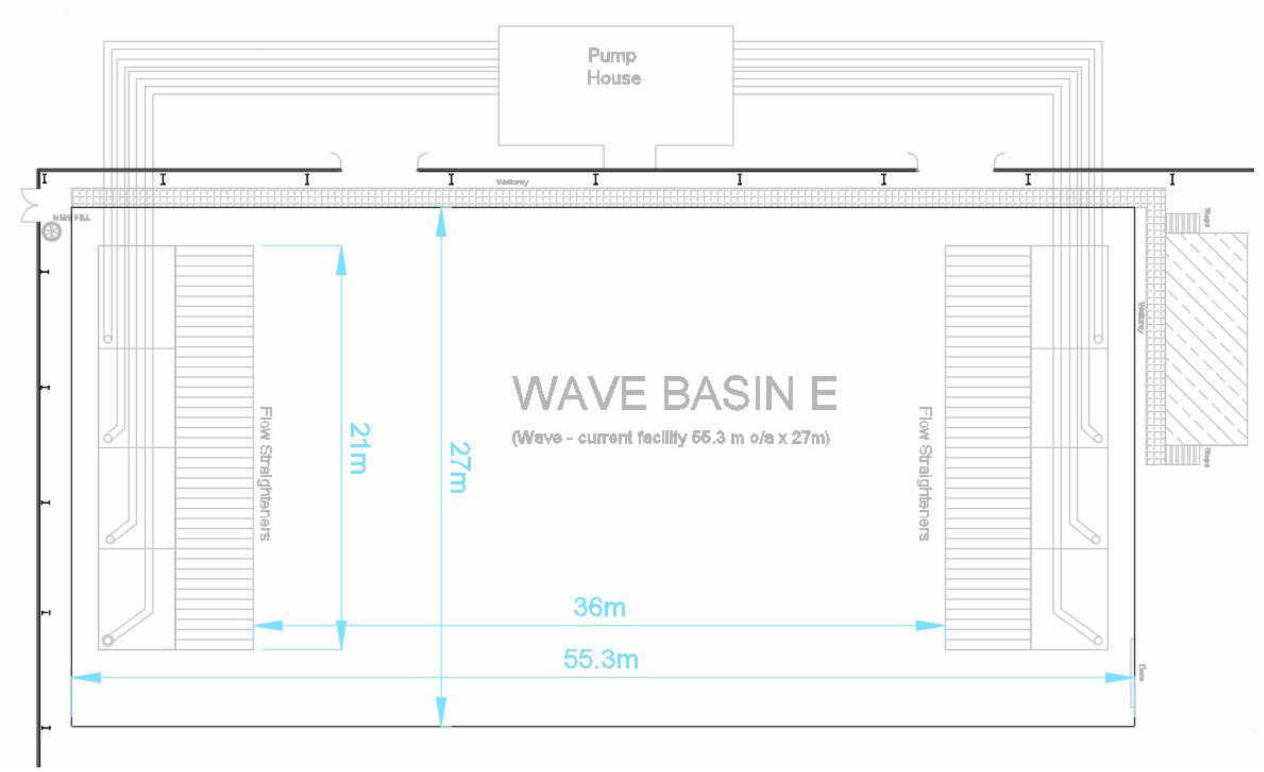


Figure 2.1: Basin E (wave and current facility)

An area of bathymetry which was proximately 1,800m by 1,200m was constructed in the test facility. This was used to investigate the sheltering performance of the breakwater, which was approximately 880m long. More details of the bathy layout are given in Section 2.4.

2.3 Wave generation

The Basin was equipped with HR Wallingford's wave generation system, which uses closed loop active/dynamic absorption to reduce unwanted wave energy. The level of re-reflected wave energy from the wavemaker can be significantly reduced by actively absorbing any waves that approach the wavemaker by modifying the motion of the wavemaker in real time. The wavemakers (Figure 2.2) which were used for this study are capable of generating wave heights of up to H_s = 0.25m model (14.5m at the scales used for this study) and can generate non-repeating random sea-states to any required spectral form, e.g. JONSWAP, Pierson-Moskowitz, TMA, or user-defined forms, the latter including bi-modal spectra and broadband top hat spectra. In addition they are capable of generating short-crested (multi-directional) waves with user-defined spreading functions, including Smax and $\cos^n\theta$ forms. All long-crested waves can be steered to produce oblique wave directions, see Figure 2.2.

Figure 2.2: Examples of steered waves

The wave generation system is able to generate, without significant spurious waves, wave frequencies up to around 2.5Hz to 3Hz (model). Above these frequencies the waves will not propagate correctly form the paddle. In order to ensure that the wave conditions for the study can be generated, the minimum wave period of interested is identified before setting the model scale.

The wavemakers are available in banks of 4m and for this project 5 x 4m sections were used, in order to generate waves over 1,160m length, see Figure 2.3. The mobile wavemakers permit complete flexibility in selecting the wave direction and if necessary generate waves from multiply directions simultaneously.

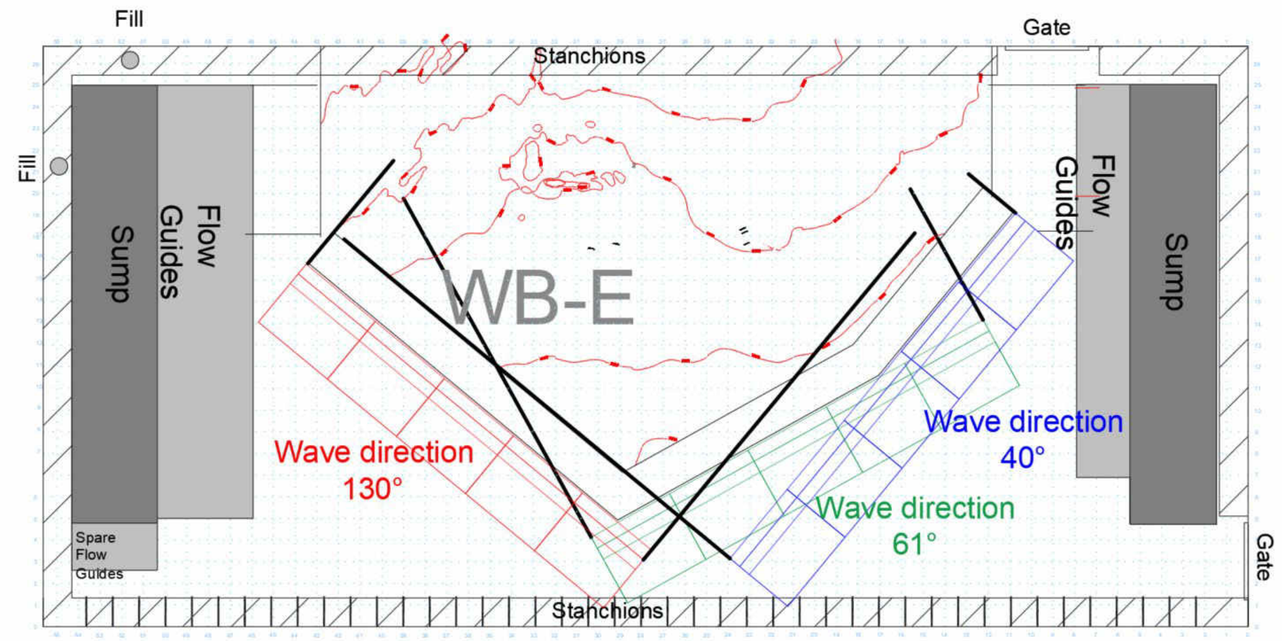


Figure 2.3: Wave generation position for waves from 40°N, 61°N and 125°N / 130°N

The LNG terminal is being positioned approximately 8.5km offshore and whilst the shoreline will provide a sources reflections it was not possible to fit the shoreline in the facility, as a Wave Basin over 140m would have been required at the chosen scale.

When completing a physical model studies of an offshore structures its important that the boundaries of the wave basin are well understood or managed. To minimise reflections the basin edges was managed using a shingle beach. The reflection characteristics of the beach was measured and confirmed during wave calibration.

2.4 Basin layout and bathymetry

The HYDRALAB III guidelines on the physical modelling of breakwaters (Reference 1) were consulted in setting the length of the model bathymetry. The layout was taken from data provided in AutoCAD drawing "F5_LAYOUT PROGETTO_05+nuovi dragaggi SNAM.dwg" with imbedding bathymetry contour information from "025m_2000_LMM_new.dwg".

Impermeable steel wave guides were used to prevented loss of wave energy from the modelled area. The wave basin boundaries were set with shingle beaches to help prevent the build-up of residual reflected waves within the facility. A fixed basin datum and study reference point was set at -19.5m MSL to ensure the water depth was adequate to allow waves to be generated correctly at the paddle. The bathymetry construction incorporated dredged areas, see Figure 2.4.

The bathymetry design incorporated 3 dredged areas:

- Dredged berthing pocket set to -17.8m MSL;

- Dredged navigation access channel set to -15.4m MSL;
- Dredged breakwater footprint set to -17m MSL.

The model bathymetry, see Figure 2.5 was constructed to extend over an area of at least 3 times the longest wave wavelength to ensure waves have the required space to transform correctly before reaching the test section.

This allows the bathymetry up to the -14.5m MSL to be included in the model. Rather than leaving a step between the representative bathy and the floor level at -19.5m LAT, an approach slope of 1 in 20 was used to transform the waves from the basin floor elevation to the start of the bathy. The 1 in 20 slope was kept constant and allowed the length of the slope to vary (note this is not shown Figure 2.5, but was included in bathy construction).

Figure 2.4: Bathy design incorporates 3 dredged area

The bathymetry of the terminal area was constructed within the wave basin using cement mortar over a compacted fill to an accuracy better than ±0.02m, horizontal and ±0.004m vertical model scale (equivalent to 1.16m and 0.23m, respectively, at full scale). The bathymetry extended approximately 1,800m x 1,200m (prototype).

The method of construction uses 3D bathymetry data to create cross-sections at 3m (model) intervals. These cross-sections were used to generate templates, which were installed and levelled in the basin.

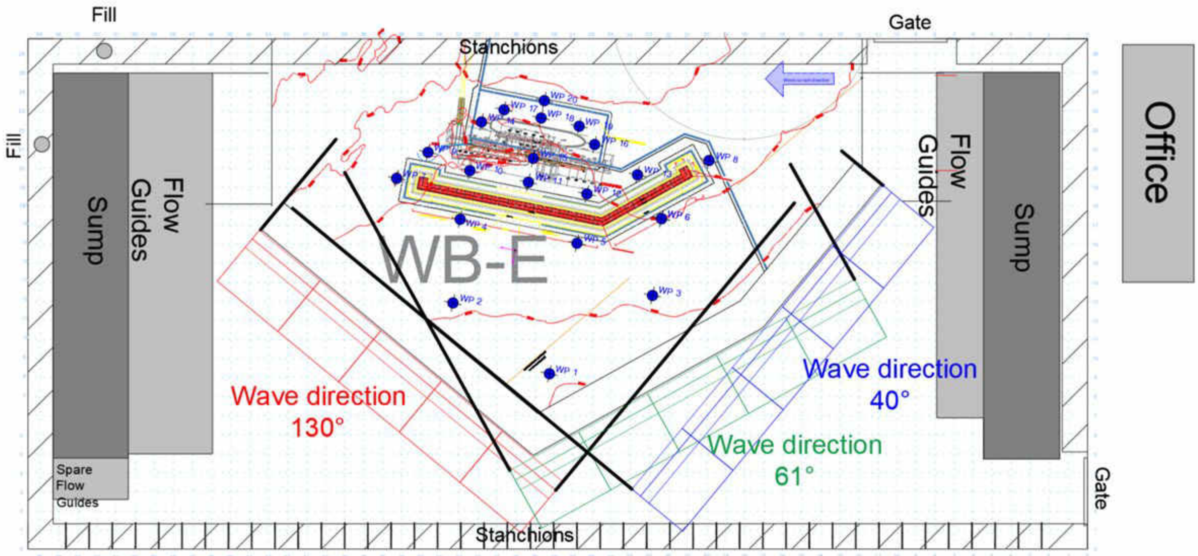


Figure 2.5: Basin E model Layout

Once installed, the wooden template bars were used to screed in cement mortar. This method gave an accuracy of finish within ±4mm (model) of the required level.

2.5 Model caissons

The breakwater is designed with caissons placed on the top of a rubble mound with a combination of concrete toe blocks and rock armour forming the scour protection. The model caissons were formed from groups of 2 or 3 units together and was designed using drawings provided by the client. It was constructed from marine plywood using a layout that provided a stiff structure under wave action, see Figure 2.6. Whilst the absorption chambers are not expected to provide much wave absorption during design conditions, they were included in the front and near face on the caisson to provide an insight into wave interaction behaviour with caisson and scour protection during extreme conditions.

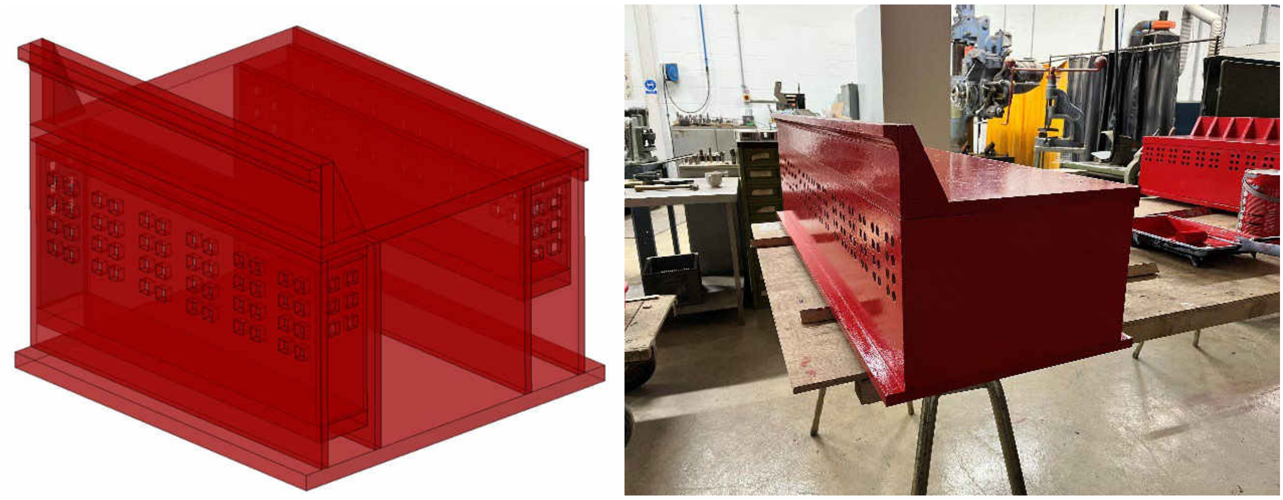


Figure 2.6: Model caisson design

The internal chambers and screens at the front and back of the caisson were included the model caisson design, see Figure 2.7.

Figure 2.7: Cassion elbow connection(left) and internal screens chambers (right)

2.6 Instrumentation

2.6.1 Wave probes

In order to measure waves/water surface elevations in the model, twin wire resistance Wave Probes (WP) were used in conjunction with HR Wallingford's wave probe measurement units. The location of the wave probes during the study where:

- Test Series A – wave calibration wave probe locations, see Figure 2.8;
- Test Series B – wave disturbance wave probe locations, see Figure 2.9.

Wave probes were calibrated to check their linear response on a daily basis to ensure accurate results. Water surface elevations were acquired at 13.1Hz prototype. The resolution of a wave probe is in the order of ±5.8mm (prototype) and after accounting for instrumentation and data acquisition noise provides an accuracy of ±115mm (prototype).

A summary of all the wave probe locations to prototype UTM coordinates (WGS84) are given in Table 2.1.

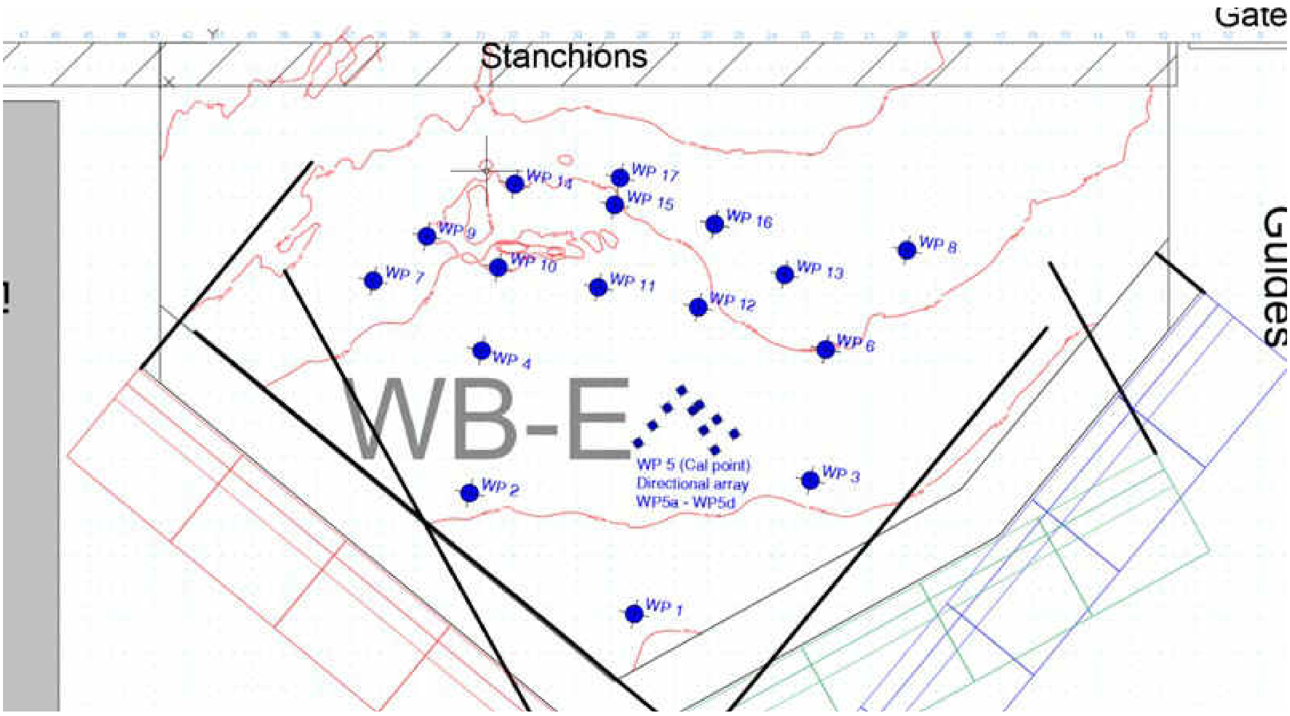


Figure 2.8: Wave probe locations during wave calibration – Test Series A

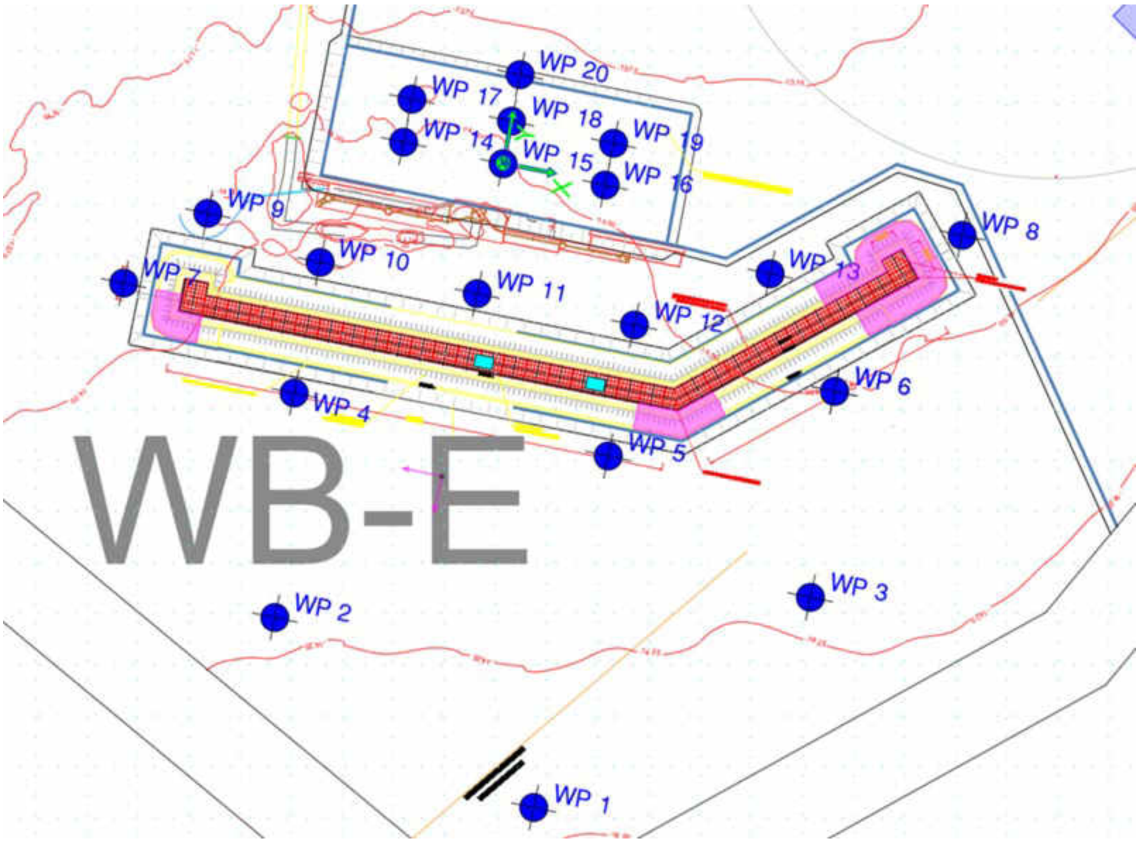


Figure 2.9: Wave probe locations during wave disturbance test – Test Series B

The position of the wave probes relative to the FSRU can be seen in Figure 2.10.

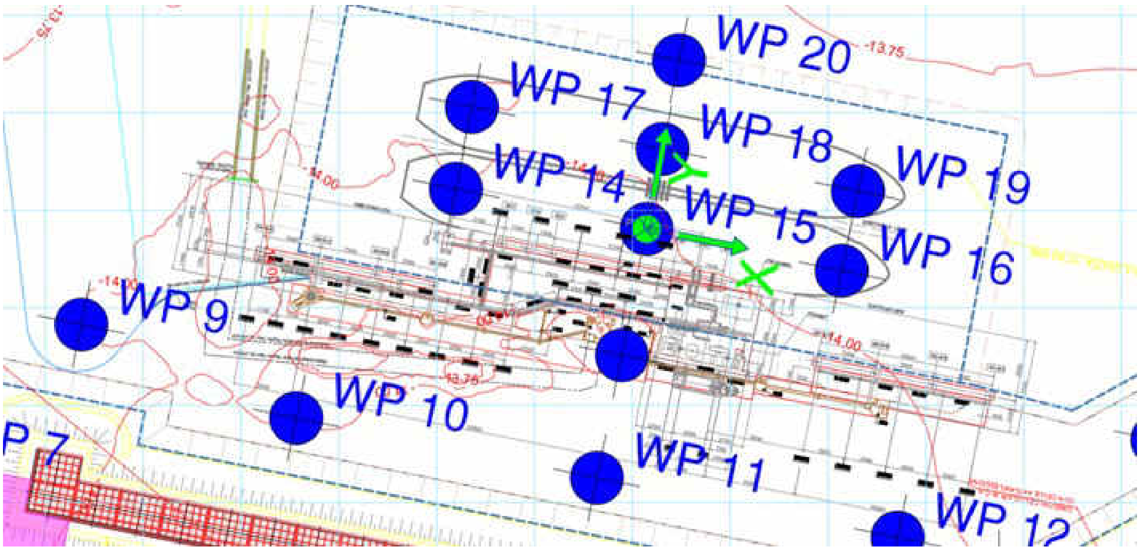


Figure 2.10: Wave probes positions around berth, without FSRU

Table 2.1: Wave probe locations to prototype UTM coordinates (WGS84)

Wave Probe	Test Series A		Test Series B	
	X easting (m)	Y northing (m)	X easting (m)	Y northing (m)
1	293031.7	4926702.7	293031.7	4926702.7
2	293488.7	4926477	293488.7	4926477
3	293465.9	4927084.8	293465.9	4927084.8
4	293234.1	4926499	293234.1	4926499
5	293305.5	4926855.4	293305.5	4926855.4
6	293232.2	4927112.2	293232.2	4927112.2
7	293109.3	4926305.5	293109.3	4926305.5
8	293055.2	4927257	293055.2	4927257
9	293030.1	4926401.1	293030.1	4926401.1
10	293085.8	4926528.5	293085.8	4926528.5
11	293121.3	4926706.7	293121.3	4926706.7
12	293156.9	4926885	293156.9	4926885
13	293098.7	4927039.1	293098.7	4927039.2
14	292949.4	4926623.2	292949.4	4926623.3
15	292973.2	4926736.2	292973.2	4926736.2
16	292998.1	4926851.9	292998.1	4926851.9
17	292925.7	4926745.6	292900.6	4926632.6
18	–	–	292925.7	4926745.6
19	–	–	292950.7	4926861.5
20	–	–	292872.8	4926755.4

2.6.2 Video

Video of the tests were recorded with a camera located with a view of the berth location. This video record has been provided digitally with this report.

3 Planning and design

3.1 Wave and water level conditions

The wave conditions were calibrated before building the offshore breakwater.

A total of 6 wave and water level conditions were used during the study. The conditions covered 50yr and 100yr return periods from 3 wave directions 40°N, 61°N and 130°N. A sensitivity test to 125°N was run using long crested waves.

A summary of the wave and water level conditions used during the study are given in Table 3.1.

Table 3.1: Wave conditions

Return period Tr (yrs)	Hs (m)	Tp (s)	JONSWAP γ factor	Wave direction (°N)	SWL (m MSL)	
50	3.4	8.0	3.3	40	HL	1.6
100	3.6	8.0	3.3		HL	1.7
50	5.2	9.4	3.3	61	HL	1.6
100	5.5	9.6	3.3		HL	1.7
50	3.6	8.9	3.3	125 / 130	HL	1.6
100	3.8	9.4	3.3		HL	1.7

3.2 Caisson mound

The caisson mound was constructed in stages using templates to guide position and depth of each rock layer. A cross section showing the mounds details along the trunk is given in Figure 3.1 and at the roundhead in Figure 3.2.

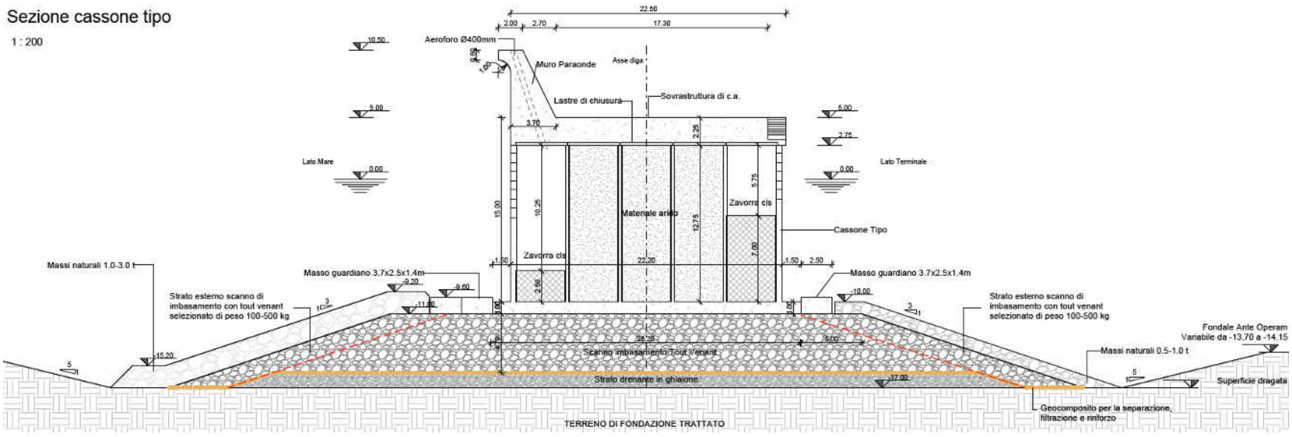


Figure 3.1: Trunk caisson mound cross section

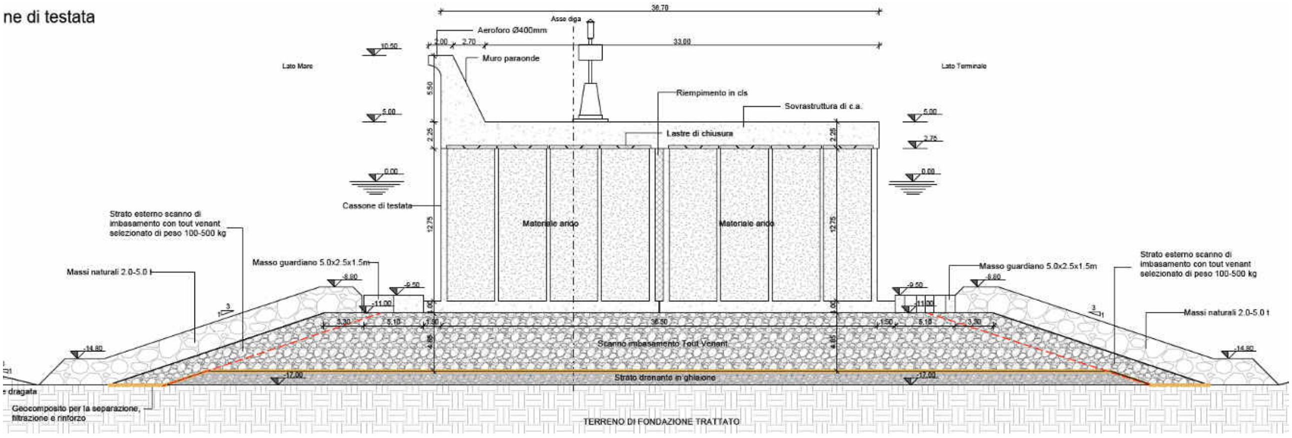


Figure 3.2: Roundhead caisson mound cross section

Following wave calibration an area of bathymetry was removed to represent the dredged pocket which holds the caisson breakwater, see Figure 3.3. Templates were then located in the dredged pocket and core material, made up of two sizes, placed. Following the core installation, the caissons and tow blocks were installed on the mound and underlayer and then rock armour was placed. The caissons were held in placed using threaded rod which was bolted into the basin floor.

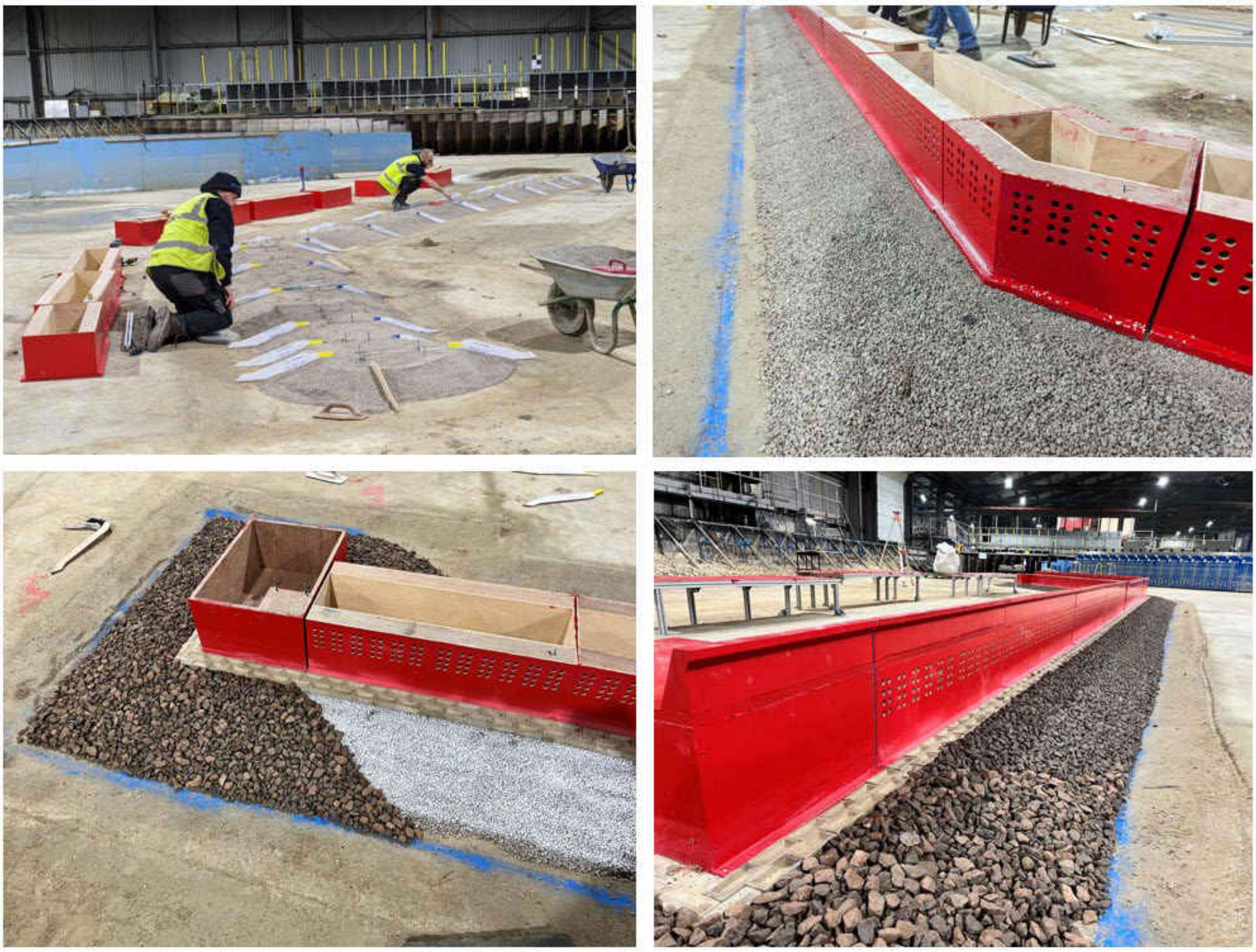


Figure 3.3: Breakwater mound construction sequence

3.2.1 Rock classes

The 2.0-5.0t, 1.0-3.0t and 0.5-1.0t rock armour classes were scaled using the Froude scaling laws to correctly reproduce its stability under wave attack, taking account of the differences between model and prototype rock densities, as well as model and prototype fluid densities. Details of the method are given in Appendix A.

The core mound/underlayer class (5-50kg and 100-500kg) were both scaled to reproduce the correct degree of permeability to water flow, thereby reducing scaling errors on armour stability. This scaling method involves making the materials slightly larger than they would be if only geometric scaling were to be applied. Details are given in Appendix B.

The following density values were provided and used in all scaling calculations:

- Armour rock density = 2,600kg/m^3;
- Core rock density = 2,600kg/m^3;
- Seawater density = 1,025kg/m^3.

The model rock was crushed limestone with a density of 2,650kg/m^3, and the model water density was assumed to be 1,000kg/m^3.

The model rock classes were prepared by sieving and mixing standard crusher grades. Grade curves of the resulting classes were obtained: by weighing individual rocks in the case of the of the armour classes. The results are plotted in Figure 3.4, Figure 3.5 and Figure 3.6, along with the upper and lower limits of the specifications.

Collectively, the grade curves show that all rocks were adequately scaled for physical modelling purposes. The grading curve for the 0.5t to 1.0t rock provides a good distribution, with a slightly heavy M_{50}.

The rocks were placed using methods that replicated the prototype construction techniques as closely as practicable. The core and filter layers were dumped from hand-held scoops, to profiles controlled by timber templates that had been levelled in position on the bathymetry with an optical level. The 0.5-1.0t, 1.0-3.0t and 2.0-5.0t armour rocks were placed in two distinct layers, to ensure that they were properly interlocked. The finished layers were spray painted in the stability test areas to help identify areas of damage.

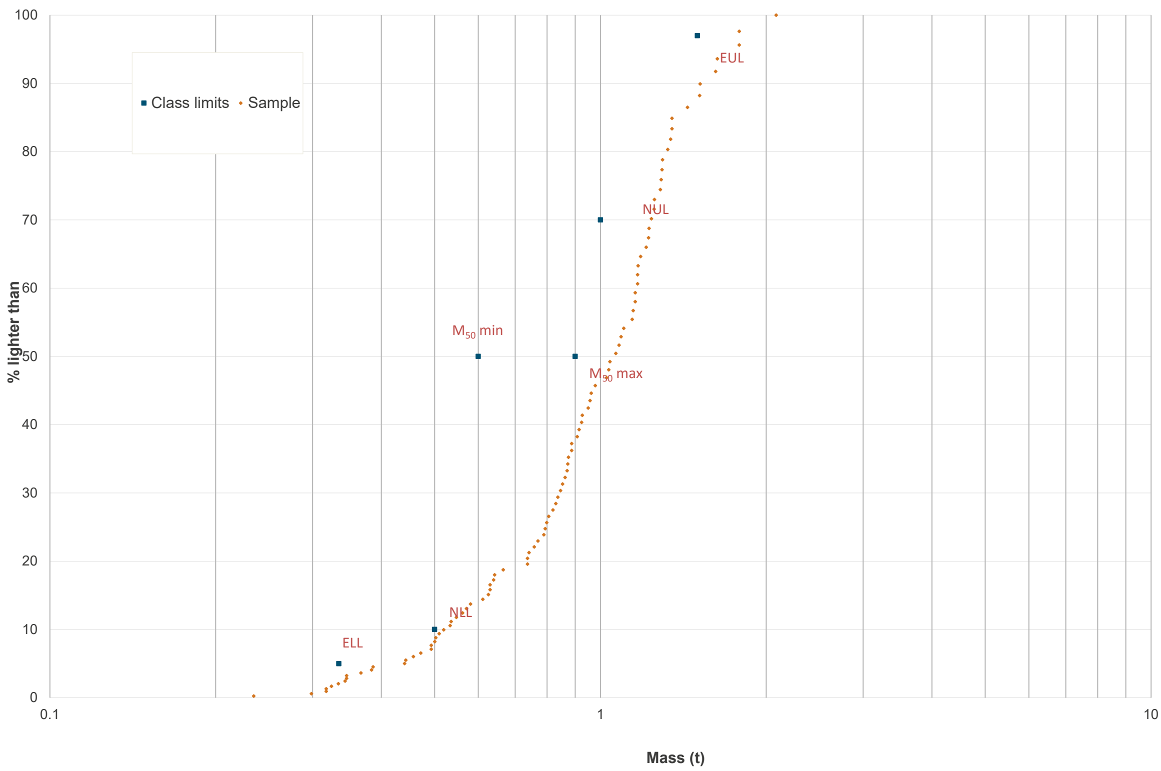


Figure 3.4: Rock grading curve for 0.5t to 1t rear armour

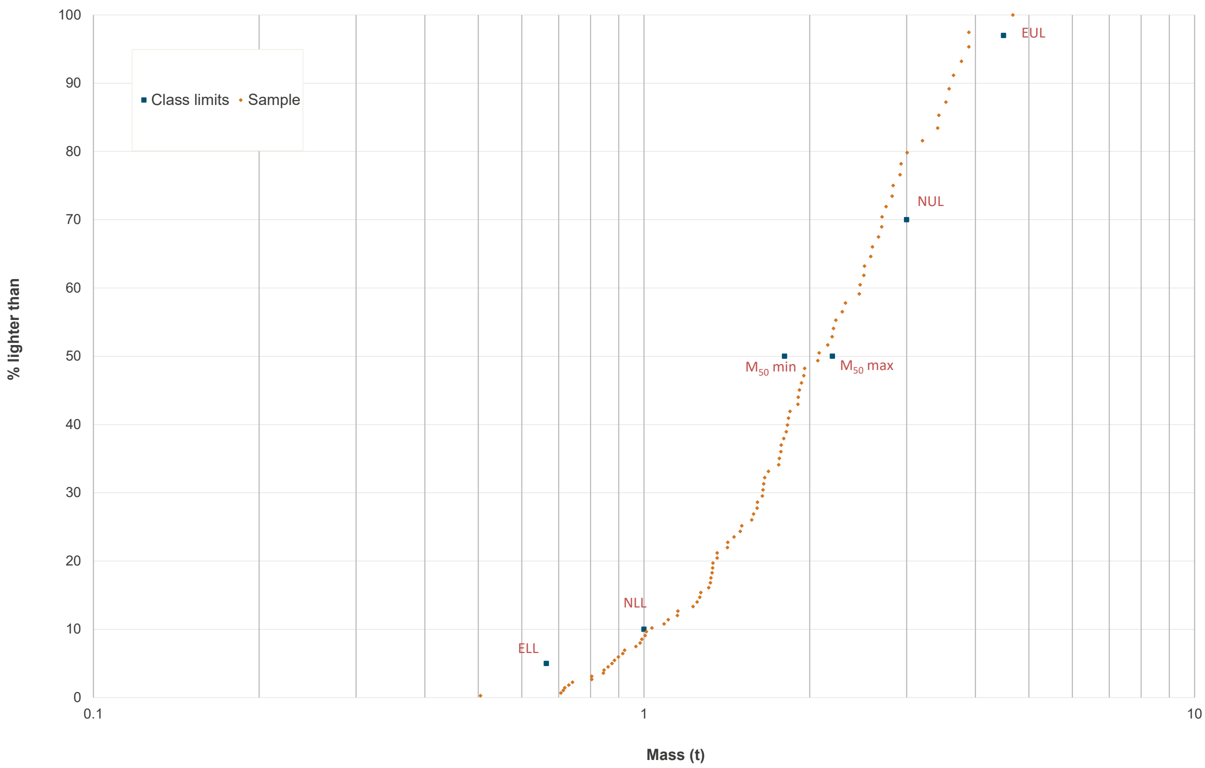


Figure 3.5: Rock grading curve for 1t to 3t seaward rock armour

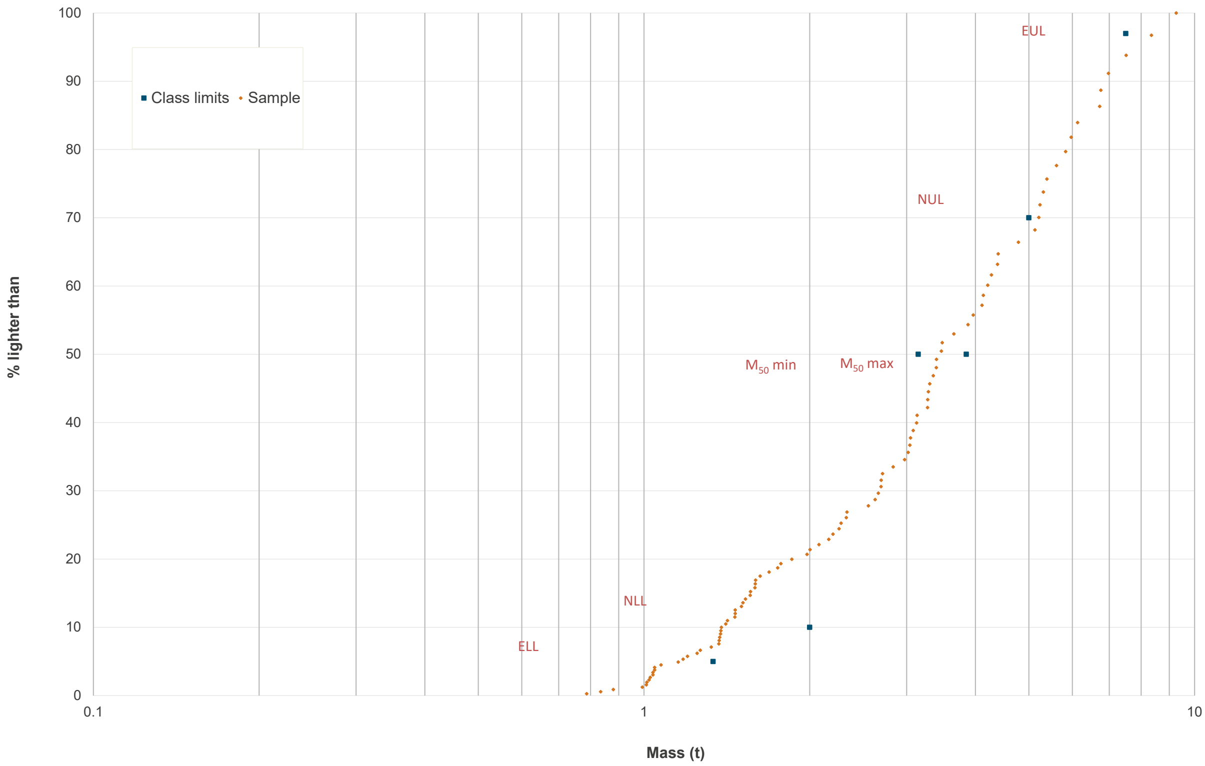


Figure 3.6: Rock grading curve for 2t to 5t seaward rock armour

Table 3.2: Armour rock class parameters

Class designation	y<5% (ELL)	y<10% (NLL)	y>70% (NUL)	y>97% (EUL)
0.5-1.0t	335kg	500kg	1,000kg	1,500kg
1.0-3.0t	665kg	1,000kg	3,000kg	1,429kg
2.0-5.0t	1,340kg	2,000kg	5,000kg	7,500kg

3.2.2 Concrete toe blocks

There were two sizes of toe blocks moulded from cement mortar with a barium additive that helped to control their density. They were scaled using the same Froude method as applied to the rock armour (described above). The following density value was provided for the scaling calculation:

- Concrete density = 2,300kg/m^3.

The sizes of the blocks are:

- Trunk section 26.6t units – 2.5m x 3.7m x 1.4m, with 2 holes 1m x 0.5m x 1.4m;
- Trunk section 39.7t units – 2.5m x 5.0m x 1.5m, with 2 holes 1m x 0.5m x 1.5m.

Allowing for water density correction, Froude scaling required a model block density of 2,244kg/m^3. All of the moulded blocks were sampled and found that the mass of the blocks fell within:

- Trunk blocks; +0.6% (0.17t) and -6.6% (1.77t) of the target value of 26.6t;
- Roundhead blocks; +6.4% (2.52t) and -3.2% (-1.28t) of the target value of 39.7t.

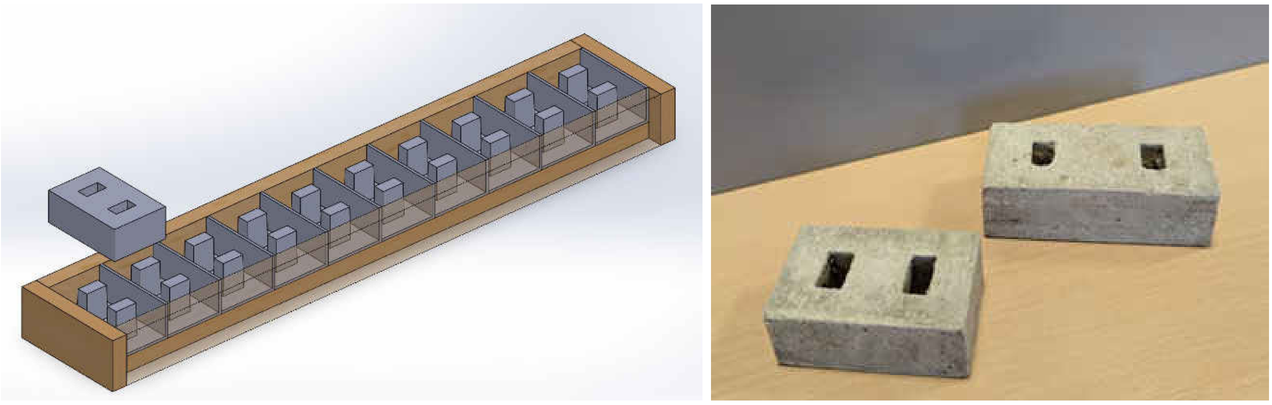


Figure 3.7: Toe block mounds

4 Test programme

An overview of all the test series is given in Table 4.1. The study was completed in a number of stages:

- Stage 1 (Construction): Following the design and layout of the physical model, the representative existing bathymetry was constructed and wave probs placed in the model. The wave generation system was setup ready for wave calibration.
- Stage 2 (Test Series A): Calibration of the wave paddles to achieve the required wave conditions at the specified calibration point (WP5 at the toe of the breakwater), with the wave paddles being moved between directions.

  Following calibration of the waves, the dredged pockets at the berth and breakwater were excavated, along with navigation access channel. The breakwater was then constructed.
- Stage 3 (Test Series B): undertook wave disturbance tests for various wave conditions. Test Series B1 measured combinations of waves for 3 wave directions. The primary purpose of the tests was to measure the wave conditions at the mid-ship location for validation of numerical modelling. Test Series B2 measured the response for short-crested waves.

The tests were completed using a range of different water levels. The water level was set in the basin via electronic point gauge and the point gauge value was monitored on a test by test basis. The target water level was maintained within ±60mm (prototype) of the target water level.

A test by test detailed matrix is given in Table 4.2 and Table 4.3. The tests were not necessary completed in this order, but were completed in a sequence designed to minimise the number of times the wave generation system required moving for the different wave directions.

Table 4.1: Overview test programme

Test Series	Description	Purpose of test series	Number of tests
A1	Wave calibration (without breakwater or LNG terminal)	Calibration of design wave conditions. Match target wave conditions within ±5% at a specific location without corruption from structures or vessel.	6 test parts
B1	Wave disturbance (without vessels)	wave disturbance tests for 50yr and 100yr. This provided a data set of conditions around the breakwater for validation of numerical modelling.	9 test parts
B2	Short-Crested wave disturbance (without vessels)	Wave disturbance for 50yr and 100yr short-crested wave conditions.	6 test parts

Table 4.2: Test Series A1 – Wave calibration

Test Series	Test	Wave condition						
		Return period Tr (yrs)	Hs (m)	Tp (s)	Wave spectra	Wave direction (°N)	SWL (m MSL)	
A1 - Design wave calibration (without breakwater)	1	50	3.4	8.0	Jonswap	40	HL	1.6
	2	100	3.6	8.0	Jonswap		HL	1.7
	3	50	5.2	9.4	Jonswap	61	HL	1.6
	4	100	5.5	9.6	Jonswap		HL	1.7
	5	50	3.6	8.9	Jonswap	130	HL	1.6
	6	100	3.8	9.4	Jonswap		HL	1.7

Table 4.3: Test Series B1 and B2 – Wave disturbance

Test Series	Test	Wave condition						
		Return period Tr (yrs)	Hs (m)	Tp (s)	Wave type	Wave direction (°N)	SWL (m MSL)	
B1 - Wave disturbance	1	100	3.6	8.0	Long-crested	40	HL	1.7
	2	100	5.5	9.6		61	HL	1.7
	3	100	3.8	9.4		125	HL	1.7
B2- Short-crested wave disturbance Smax = 16	1	50	3.4	8.0	short-crested	40	HL	1.6
	2	100	3.6	8.0			HL	1.7
	3	50	5.2	9.4		61	HL	1.6
	4	100	5.5	9.6			HL	1.7
	5	50	3.6	8.9		130	HL	1.6
	6	100	3.8	9.4			HL	1.7

5 Test Series A – wave calibration

5.1 Wave calibration method

The wave conditions were calibrated in the wave basin before installing the dredged pockets, access channel and breakwater. The objective of the calibration tests was to produce the specified wave conditions at the calibration point, in this case, the location of the seaward face of caisson at WP5. During wave calibration a shingle spending beach was installed at the boundary walls, to reduce reflections and minimise uncertainty and ensure the incident wave height was correctly measured.

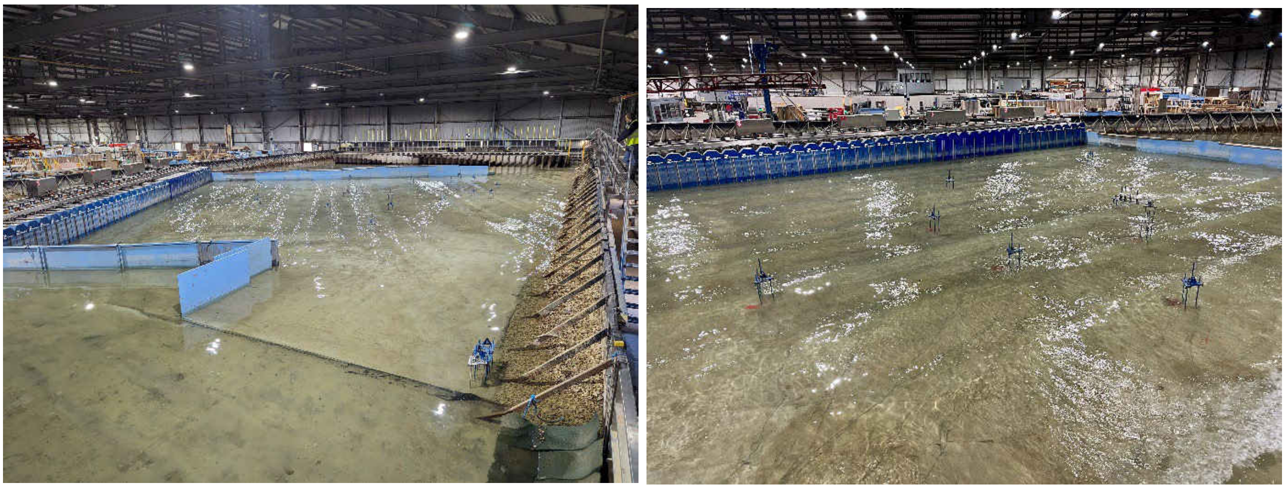


Figure 5.1: Wave calibration

Calibration was an iterative process, with the amplitude of the signal driving the wave generator being adjusted until the spectral significant wave height measured at the calibration point was within a tolerance of ±5% of the target significant wave height. An absorption beach was used to limit reflected waves and reduce multi-directional reflections at the calibration point.

For each wave condition, an in-line array of four wave probes were used to measure the incident wave. Time histories recorded by each gauge in the array were analysed spectrally by HR Wallingford's HR DAQ software to provide the following parameters:

- Significant incident spectral wave height, H_{m0};
- Peak spectral wave period, T_p of the incident wave spectrum;
- The mean spectral wave period, $T_{m0,2}$, defined using the 0th and 2nd moments of the incident spectrum;
- The spectral energy wave period, $T_{m-1,0}$, defined using the -1st and 0th moments of the incident spectrum.

Data recorded by the array was analysed to determine the reflection coefficient and adjust the measured total significant wave height to the incident spectral parameters defined above. For each condition, the wave generation produced non-repeating wave sequences, with durations of at least 1,000 times the mean wave period, $T_{m0,2}$, of the target spectrum in order to gain a good description of the wave spectra. This gave a statistically significant sample for the wave calibration analysis.

The reflection analysis was based on measuring the wave height at the four wave-probe array (at differing and known gauge spacings in constant water depth). The method calculates the incident and reflected wave spectral energy and the reflection coefficient using the method of

Isaacson (1991) at frequencies spread over the relevant frequency range. The reflection coefficient (C_r) was calculated using the following equation:

$$C_r = \sqrt{\frac{m_{0r}}{m_{0i}}} \quad (1)$$

Where m_{0i} and m_{0r} are the incident and reflected wave spectral energy respectively.

The total wave height (H_{Tot}) is therefore expressed as:

$$H_{Tot} = \sqrt{H_{m0i}^2 + H_{m0r}^2} \quad (2)$$

This can be expressed in terms of the incident wave height (H_{m0i}) as:

$$H_{Tot} = \sqrt{H_{m0i}^2 + (C_r H_{m0i})^2} \quad (3)$$

or:

$$H_{m0i} = \frac{H_{Tot}}{\sqrt{1 + C_r^2}} \quad (4)$$

5.2 Wave calibration results

A summary of the wave conditions calibrated during Test Series A1 is presented in Table 5.1. Further measured wave parameters and plotted wave spectra are given in Appendix C.

Table 5.1: Summary of calibrated wave conditions

Test Series	Wave condition	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave spectra	Wave direction (°N)	SWL (m MSL)		Measured incident wave height (m)	Error (%)
A1 - Design wave calibration	WC1	50	3.4	8	Jonswap gamma = 3.3	40	HL	1.6	3.33	2.0%
	WC2	100	3.6	8			HL	1.7	3.49	3.0%
	WC3	50	5.2	9.4		61	HL	1.6	5.02	3.5%
	WC4	100	5.5	9.6			HL	1.7	5.47	0.5%
	WC5	50	3.6	8.9		130	HL	1.6	3.57	0.9%
	WC6	100	3.8	9.4			HL	1.7	3.85	-1.4%

The wave calibrations were completed to the required ±5% of the target value. Reflections were kept to a minimum to provide confident in the incident condition being generated from the wave paddles and spectral shape and peaks where found to match well that of the theoretical target conditions (see Appendix C).

The measured refection coefficient from absorption beach placed at the edge of the was found to fall between 9% and 10%.

5.3 Additional wave conditions

During testing additional wave conditions were requested to investigate wave response under short-crested design and overload sea conditions. The additional wave conditions are shown in Table 5.2.

Table 5.2: Short-crested wave conditions

Return period (yrs)	Significant wave height Hs (m)	Peak wave period Tp (s)	Wave spectra	Spreading Smax	Wave direction (°N)
50	3.4	8.0	Short-crested Jonswap shape factor γ = 3.3	16	40
100	3.6	8.0			
50	5.2	9.4			61
100	5.5	9.6			
50	3.6	8.9			130
100	3.8	9.4			

The wave generation system uses the same transfer functions for long-crested waves or when steering waves for oblique or multi-directional waves, it can therefore be assumed that the generation settings acquired during wave calibration are still valid for these additional tests.

A couple of checks were made to support this assumption:

- Wave probe 8, at the end of the breakwater is likely to be least effected by the presence of the breakwater for waves from 61°N. The short-crested conditions at WP8 were therefore compared with that measured during wave calibration;
- The measured conditions around the breakwater for long-crested and short-crested waves can be compared.

The measured significant waves height at WP8 for the wave calibration and wave disturbance tests with long-crested and short-crested waves is given in Table 5.3. The results show a slight increase in wave height for the presence of the breakwater and again a similar increase when introducing short-crested waves.

A good comparing of the energy content in the waves spectra can be seen in Figure 5.2.

Table 5.3: Measured Hs at WP8 - 100yr wave condition from 61°N

Test	A1-4	B1-2	B2-4
Hs (m)	5.5	5.5	5.5
Tp (s)	9.6	9.6	9.6
Wave type	long-crested	long-crested	short-crested
SWL (m MSL)	1.7	1.7	1.7
Measured Hs (m)	5.50	5.70	5.67

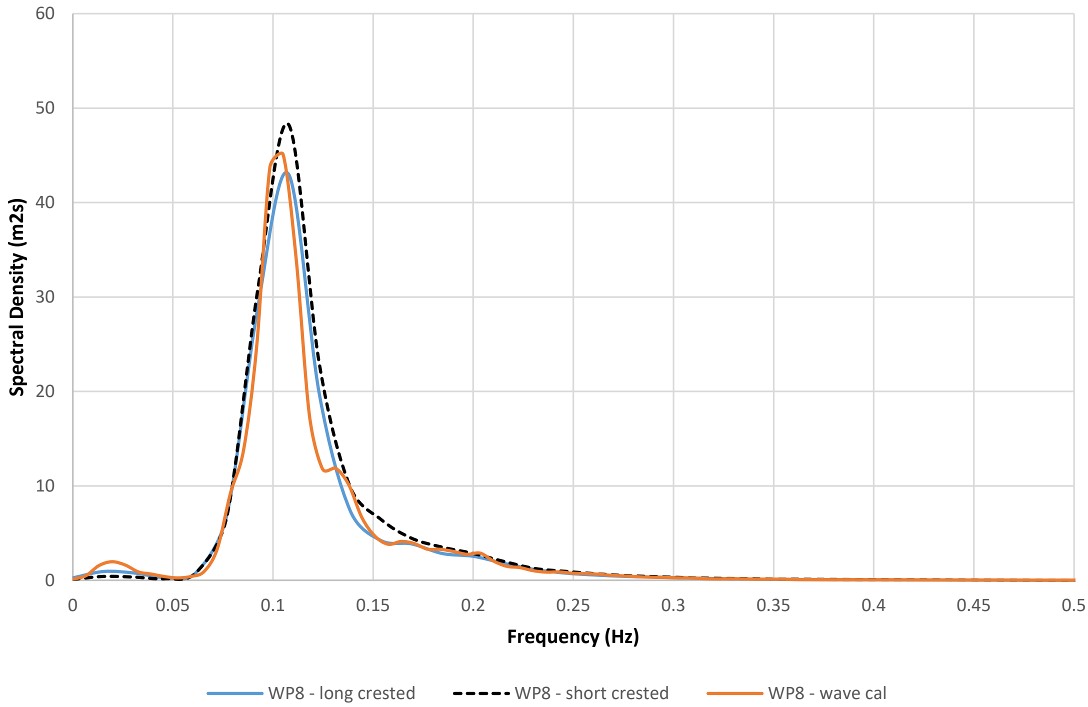


Figure 5.2: WP8 measured spectra

The individual maximum measured wave height is plotted for long-crest and short-crested tests and whilst some variation is shown, similar values are seen. At WP18, WP19 and WP20, the short-crested waves are seen to be slight higher. This is due to the waves coming from more oblique directions under directional spreading. This in turn reduces the sheltering effect of the breakwater.

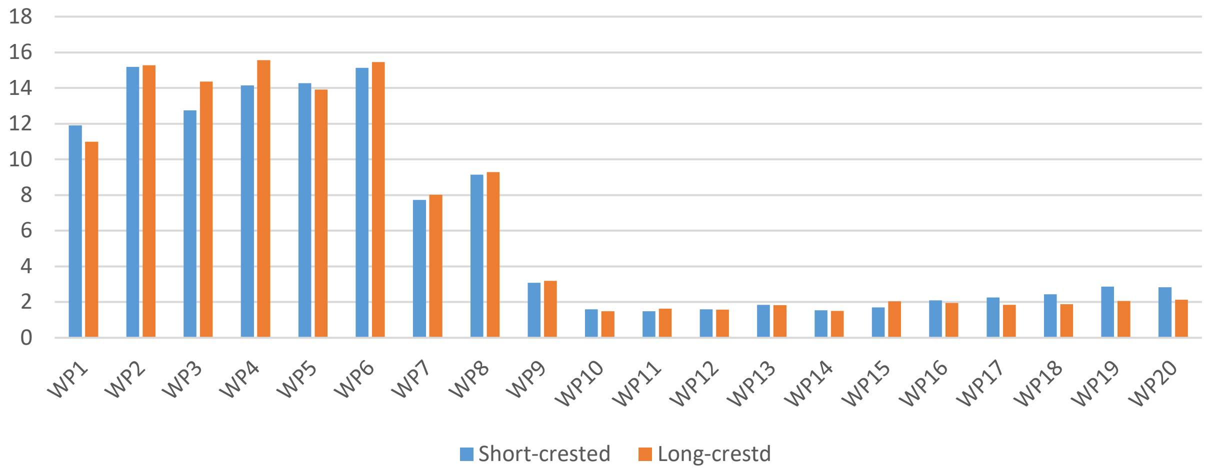


Figure 5.3: Measured maximum wave height - 100yr wave condition from 61°N

6 Test Series B – Wave disturbance tests

Test Series B was completed to measure wave disturbance around the breakwater, with particular focus at providing the wave conditions are the mid-ship location of the FSRU. Wave probes (WP) 14, 15 and 16 where placed along the centre line of the vessel, with WP15 at the midships of the FSRU. The wave probe positions during Test Series D are given in Figure 6.1.

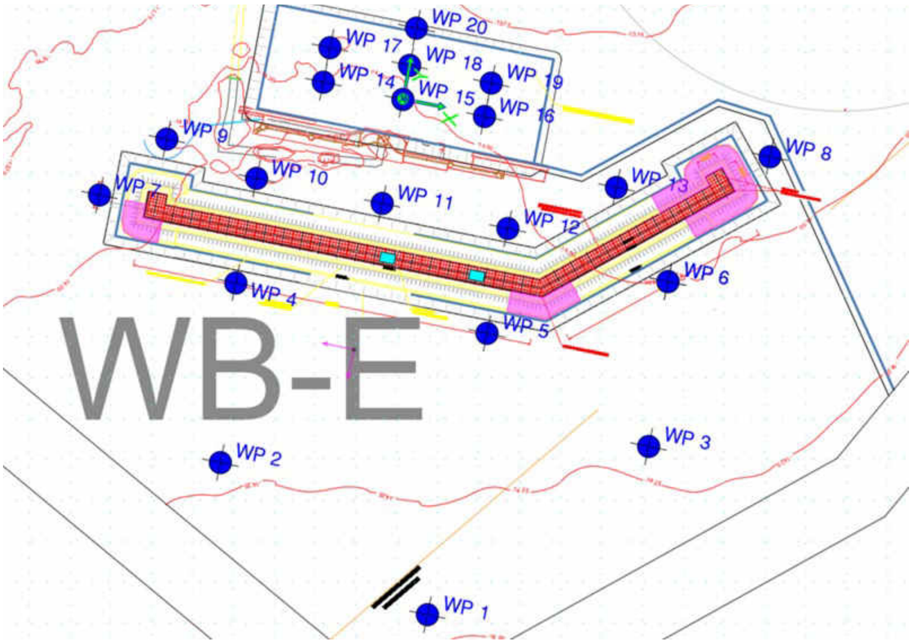


Figure 6.1: Wave probe locations during wave disturbance test

At the client's request information on the measured wave spectra at WP15 was provided for use in a seakeeping physical model study being completed separately at another facility. Information on what was provided can be found in Section 6.1.2.

6.1 Test Series B1 – wave disturbance tests

Test Series B1 investigated the wave disturbance for 3 waves directions. The wave disturbance measurements have been provided digitally with this report. The files provided (example of Test B1-1) cover the following:

- B1-1_A.spc.csv — Wave probe spectral results;
- B1-1_A.sta.csv — Wave probe statistical results;
- B1-1_A.tms.csv — Wave probe time series;
- B1-1_A.wves.csv — Wave probe zero crossing results;
- B1-1_A.ext.csv — Wave probe 6 & 12hr Weibull extremes;
- B1-1_analogue_spc_WP#.pdf — Wave probe spectral plot;
- B1-1_analogue_tms_WP#.pdf — Wave probe time series plot;
- B1-1_Weibull_A_#.pdf — Wave probe 6 & 12hr Weibull extremes plots.

For the purpose of discussion and to provide a high level evaluation of the results the significant wave height (H_s) and maximum wave height (H_{max}) have been tabled for the report. The tabled results of wave conditions are as follows:

- Measured significant wave height (H_s) is given in Table 6.1;
- Measured maximum wave height (H_{max}) is given in Table 6.2.

Table 6.1: Measured significant wave height H_s

Test	Wave return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP1 (m)	WP2 (m)	WP3 (m)	WP4 (m)	WP5 (m)	WP6 (m)	WP7 (m)	WP8 (m)	WP9 (m)	WP10 (m)	WP11 (m)	WP12 (m)	WP13 (m)	WP14 (m)	WP15 (m)	WP16 (m)	WP17 (m)	WP18 (m)	WP19 (m)	WP20 (m)
B1-1	100	3.60	8.0	40	HL_100	1.7	3.78	3.30	4.92	4.99	4.40	3.99	3.04	3.52	1.24	0.68	0.62	0.56	0.69	0.80	0.77	0.79	0.75	0.89	0.99	0.93
B1-2	100	5.50	9.6	61	HL_100	1.7	6.45	7.07	6.73	9.14	7.87	8.09	4.72	5.70	1.73	0.93	0.89	0.87	1.08	0.99	0.96	1.08	1.12	1.09	1.26	1.12
B1-3	100	3.8	9.4	125	HL_100	1.7	5.25	4.77	3.67	5.91	5.22	4.12	4.68	2.92	2.90	0.84	0.71	0.57	0.61	1.10	0.74	0.62	1.33	0.80	0.68	0.85

Table 6.2: Measured maximum wave height H_{max}

Test	Wave return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP1 (m)	WP2 (m)	WP3 (m)	WP4 (m)	WP5 (m)	WP6 (m)	WP7 (m)	WP8 (m)	WP9 (m)	WP10 (m)	WP11 (m)	WP12 (m)	WP13 (m)	WP14 (m)	WP15 (m)	WP16 (m)	WP17 (m)	WP18 (m)	WP19 (m)	WP20 (m)
B1-1	100	3.60	8.0	40	HL_100	1.7	6.83	6.00	9.76	8.51	7.85	7.39	6.07	6.47	2.04	1.21	1.02	0.98	1.22	1.36	1.30	1.38	1.31	1.69	1.98	1.57
B1-2	100	5.50	9.6	61	HL_100	1.7	10.92	13.17	17.19	15.29	16.64	16.19	7.61	9.39	3.09	1.67	1.55	1.36	1.63	1.76	1.61	1.69	2.51	1.80	2.04	1.89
B1-3	100	3.8	9.4	125	HL_100	1.7	9.08	9.15	7.21	11.63	10.87	6.73	8.22	5.02	5.68	1.29	1.10	1.03	0.90	2.54	1.52	1.05	2.97	1.59	1.10	1.62

6.1.1 Wave disturbance at berth

The measured wave conditions below provide the conditions measured at WP14, WP15 and WP16. The measured significant wave height is given in Table 6.3 and the measured Maximum wave height in Table 6.4.

Table 6.3: Significant wave height at berth

Test	Wave conditions						Measured H_s			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B1-1	100	3.60	8.0	40	HL_100	1.7	0.80	0.77	0.79	0.79
B1-2	100	5.50	9.6	61	HL_100	1.7	0.99	0.96	1.08	1.01
B1-3	100	3.8	9.4	125	HL_100	1.7	1.10	0.74	0.62	0.82

Table 6.4: Maximum wave height at berth

Test	Wave conditions						Measured H_{max}			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B1-1	100	3.60	8.0	40	HL_100	1.7	1.36	1.30	1.38	1.35
B1-2	100	5.50	9.6	61	HL_100	1.7	1.76	1.61	1.69	1.69
B1-3	100	3.8	9.4	125	HL_100	1.7	2.54	1.52	1.05	1.70

6.1.2 Supply of measured wave spectra to MARIN

HR Wallingford was requested to provide measured wave spectra behind the breakwater along the centre line of the FSRU. With the intension that this data would be used by an other laboratory as part of a physical model study being completed for seakeeping assessment.

The non-directional spectral density data has been provide, so that it can be implemented as a "user defined" spectra in the laboratories wave generation system. The wave data which has been provide is at the mid-ship point of the FSRU (Wave Probe 15). The location of Wave Probe 15 is shown in Figure 2.10 and the measured results for the 100yr storm from 40°N, 61°N and 125°N is given in Table 6.5.

Table 6.5: Measured significant wave height at WP15

Test	Total spectra Hs (m)	Total spectra Tp (s)
B1-1	0.77	8
B1-2	0.96	9.6
B1-3	0.74	9.4

The unidirectional wave spectra for each of the 100yr wave conditions is plotted below for convenience, see Figure 6.2, Figure 6.3 and Figure 6.4. To give the measured value context and understand of differences, the data is plotted again the theoretical JONSWAP spectra, based on the measured significant wave height at WP15.

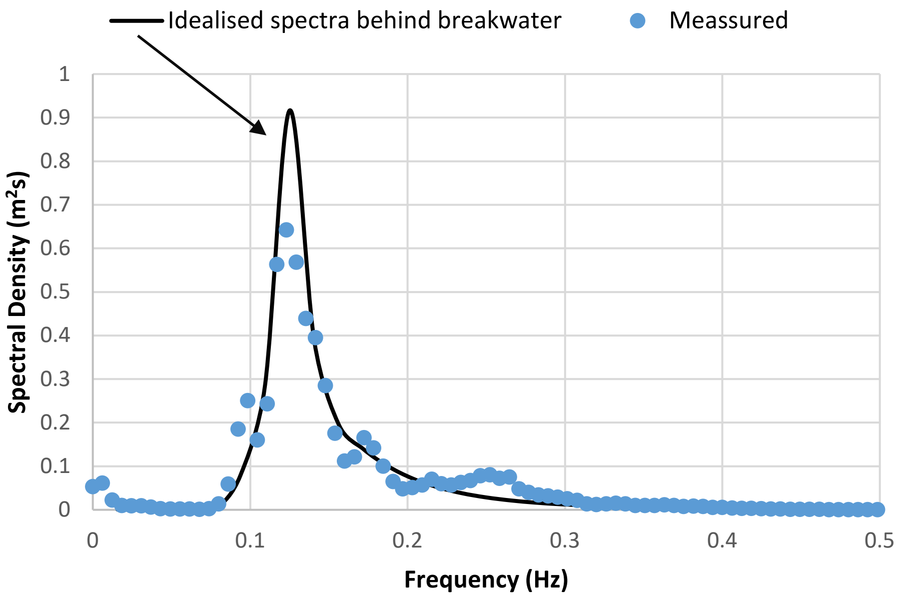


Figure 6.2: Measured Spectra Test B1-1, 100yr 40˚N

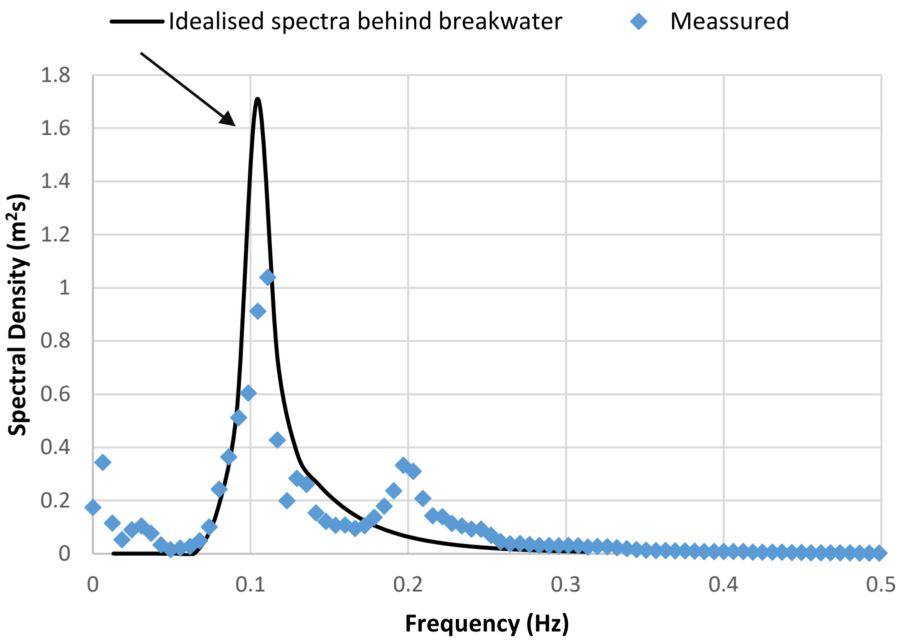


Figure 6.3: Measured Spectra Test B1-2, 100yr 61˚N

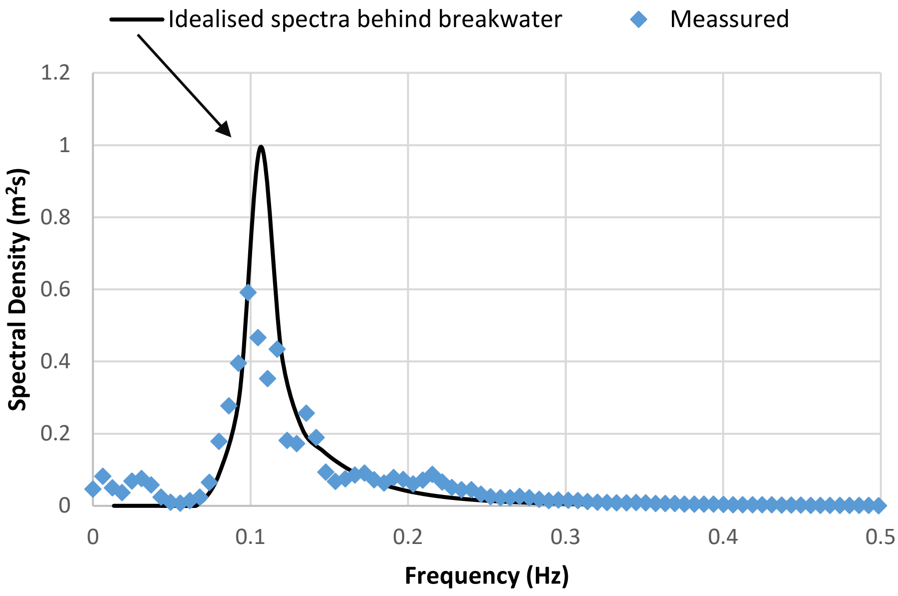


Figure 6.4: Measured Spectra Test B1-3, 100yr 125˚N

As well as providing the data described at the start of this Chapter, the following file was provided and contains the measured data. This is replicated below in Table 6.6:

- DJR6894-User_defined-spectra_R01-00.xlsx.

Table 6.6: Measured wave spectra

Test	B1-1	B1-2	B1-3
Frequency (Hz)	Spectral Density (m^2s) at WP15	Spectral Density (m^2s) at WP15	Spectral Density (m^2s) at WP15
0	0.053758	0.173734	0.046057
0.006155	0.06151	0.343645	0.081251
0.01231	0.022762	0.115711	0.049355
0.018465	0.009991	0.052929	0.03652
0.02462	0.009156	0.08968	0.068118
0.030775	0.009294	0.104671	0.07555
0.03693	0.00652	0.07654	0.057529
0.043085	0.002873	0.033512	0.023839
0.04924	0.002173	0.015462	0.009553
0.055395	0.002074	0.021383	0.006551
0.06155	0.001844	0.027483	0.013898
0.067705	0.001322	0.049661	0.023676
0.07386	0.002848	0.100489	0.064912
0.080015	0.013642	0.242237	0.178507
0.08617	0.059298	0.364472	0.277228
0.092325	0.185551	0.511803	0.3953
0.09848	0.250806	0.604395	0.591627
0.104635	0.160582	0.912325	0.465713
0.11079	0.243855	1.039308	0.352082
0.116945	0.563726	0.427522	0.43396

Test	B1-1	B1-2	B1-3
0.1231	0.642822	0.19928	0.18105
0.129255	0.568949	0.283638	0.17173
0.13541	0.43966	0.260059	0.256456
0.141565	0.39567	0.154283	0.188738
0.14772	0.285456	0.121421	0.093314
0.153875	0.176081	0.106759	0.067783
0.16003	0.112046	0.107579	0.074878
0.166185	0.121698	0.095094	0.085301
0.17234	0.165568	0.105522	0.090568
0.178495	0.142216	0.136894	0.071469
0.18465	0.10041	0.178633	0.063196
0.190805	0.06493	0.237052	0.078229
0.19696	0.047967	0.33287	0.073052
0.203115	0.05123	0.309351	0.05993
0.20927	0.057269	0.208308	0.070518
0.215425	0.070283	0.143382	0.086504
0.22158	0.060055	0.1393	0.065467
0.227735	0.057255	0.114407	0.05013
0.23389	0.062703	0.104236	0.043942
0.240045	0.067427	0.091829	0.044395
0.2462	0.078454	0.091846	0.031894
0.252355	0.080355	0.069454	0.02504
0.25851	0.072707	0.045943	0.022018
0.264665	0.075446	0.037636	0.022156
0.27082	0.048586	0.038174	0.025885
0.276975	0.040076	0.034794	0.022225
0.283129	0.034676	0.030645	0.017872
0.289284	0.031862	0.03062	0.013876
0.295439	0.029135	0.029963	0.015805
0.301594	0.025226	0.031729	0.015102
0.307749	0.022199	0.02975	0.013749
0.313904	0.014201	0.025225	0.011167
0.320059	0.012662	0.027062	0.009236
0.326214	0.014071	0.026478	0.008797
0.332369	0.014989	0.022536	0.008117
0.338524	0.013831	0.018821	0.007603
0.344679	0.010227	0.015957	0.008636
0.350834	0.009988	0.01349	0.007888
0.356989	0.010475	0.012207	0.006076
0.363144	0.011517	0.011992	0.006464
0.369299	0.010503	0.010803	0.006361
0.375454	0.008293	0.010518	0.004372
0.381609	0.009007	0.00943	0.004246
0.387764	0.00783	0.007731	0.004368
0.393919	0.005773	0.008362	0.003888

Test	B1-1	B1-2	B1-3
0.400074	0.005709	0.007851	0.003334
0.406229	0.004317	0.008313	0.002771
0.412384	0.003521	0.007775	0.002331
0.418539	0.00336	0.005929	0.002603
0.424694	0.00273	0.005572	0.002718
0.430849	0.002435	0.005994	0.002233
0.437004	0.00246	0.005599	0.001485
0.443159	0.001722	0.004832	0.001342
0.449314	0.001125	0.004303	0.001308
0.455469	0.001043	0.004026	0.001104
0.461624	0.000996	0.003556	0.000862
0.467779	0.000922	0.003714	0.000794
0.473934	0.000744	0.003412	0.000658
0.480089	0.000605	0.003072	0.000449
0.486244	0.000633	0.002899	0.00033
0.492399	0.000543	0.002371	0.000359
0.498554	0.000392	0.001955	0.000294

6.2 Test Series B2 – Short-crest wave disturbance sensitivity tests

Test Series B2 measured wave disturbance for the short-crested waves, which were used for sensitivity testing. It should be noted that the short-crested wave generation system does not allow wave steering at the same time as generating multiply directional waves. For this reason the short-crested waves were run from a 130°N and not 125°N.

The measured wave conditions below provide the conditions measured at WP14, WP15 and WP16 for short-crested waves. The measured significant wave height is given in Table 6.3 and the measured Maximum wave height in Table 6.4.

The measured wave conditions for all the other wave probes are given in Table 6.9 for significant wave height an the maximum wave height in Table 6.10.

Table 6.7: Significant wave height at berth

Test	Wave conditions						Measured H_s			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B2-1	50	3.4	8.0	40	HL	1.6	0.99	1.09	1.15	1.08
B2-2	100	3.6	8.0		HL	1.7	1.08	1.14	1.24	1.15
B2-3	50	5.2	9.4	60	HL	1.6	0.96	0.94	1.00	0.96
B2-4	100	5.5	9.6		HL	1.7	1.09	1.05	1.16	1.10
B2-5	50	3.6	8.9	130	HL	1.6	1.50	0.95	0.73	1.06
B2-6	100	3.8	9.4		HL	1.7	1.75	1.10	0.89	1.25

Table 6.8: Maximum wave height at berth

Test	Wave conditions						Measured H_{max}			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B2-1	50	3.4	8.0	40	HL	1.6	1.94	1.94	2.36	2.08
B2-2	100	3.6	8.0		HL	1.7	1.92	2.10	2.18	2.07
B2-3	50	5.2	9.4	60	HL	1.6	1.70	1.62	1.77	1.70
B2-4	100	5.5	9.6		HL	1.7	1.93	1.94	2.18	2.01
B2-5	50	3.6	8.9	130	HL	1.6	2.42	1.60	1.43	1.82
B2-6	100	3.8	9.4		HL	1.7	2.69	1.92	1.63	2.08

Table 6.9: Measured significant wave height H_s

Test	Wave return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP1 (m)	WP2 (m)	WP3 (m)	WP4 (m)	WP5 (m)	WP6 (m)	WP7 (m)	WP8 (m)	WP9 (m)	WP10 (m)	WP11 (m)	WP12 (m)	WP13 (m)	WP14 (m)	WP15 (m)	WP16 (m)	WP17 (m)	WP18 (m)	WP19 (m)	WP20 (m)
B2-1	50	3.4	8.0	40	HL	1.6	3.45	3.34	3.78	3.91	3.73	3.83	2.55	3.24	1.24	0.79	0.64	0.53	0.99	0.99	1.09	1.15	1.06	1.25	1.46	1.40
B2-2	100	3.6	8.0		HL	1.7	3.71	3.64	4.12	4.18	4.01	4.17	2.89	3.44	1.39	0.85	0.70	0.58	1.06	1.08	1.14	1.24	1.15	1.33	1.57	1.48
B2-3	50	5.2	9.4	61	HL	1.6	6.01	6.35	6.00	7.22	6.50	6.40	4.39	4.95	1.73	0.78	0.71	0.70	1.11	0.96	0.94	1.00	1.04	1.06	1.30	1.20
B2-4	100	5.5	9.6		HL	1.7	6.72	7.25	6.80	7.94	7.56	7.65	4.91	5.67	1.91	0.91	0.83	0.83	1.33	1.09	1.05	1.16	1.16	1.20	1.43	1.31
B2-5	50	3.6	8.9	130	HL	1.6	4.34	3.88	3.46	4.50	4.32	3.63	4.10	2.33	3.00	0.84	0.58	0.44	0.62	1.50	0.95	0.73	1.79	1.09	0.80	1.18
B2-6	100	3.8	9.4		HL	1.7	5.10	4.68	4.11	5.76	5.52	4.15	4.81	2.77	3.54	1.02	0.73	0.58	0.75	1.75	1.10	0.89	2.07	1.29	0.99	1.40

Table 6.10: Measured maximum wave height H_{max}

Test	Wave return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP1 (m)	WP2 (m)	WP3 (m)	WP4 (m)	WP5 (m)	WP6 (m)	WP7 (m)	WP8 (m)	WP9 (m)	WP10 (m)	WP11 (m)	WP12 (m)	WP13 (m)	WP14 (m)	WP15 (m)	WP16 (m)	WP17 (m)	WP18 (m)	WP19 (m)	WP20 (m)
B2-1	50	3.4	8.0	40	HL	1.6	6.06	6.19	6.88	7.15	7.75	7.30	4.81	5.85	2.56	1.41	1.01	0.89	1.60	1.94	1.94	2.36	1.88	2.38	2.60	3.03
B2-2	100	3.6	8.0		HL	1.7	6.37	6.39	9.09	7.37	8.48	7.30	5.68	6.58	2.71	1.50	1.22	1.02	1.84	1.92	2.10	2.18	2.21	2.28	3.01	2.89
B2-3	50	5.2	9.4	61	HL	1.6	10.91	11.98	11.22	13.77	12.52	13.15	7.21	9.13	2.82	1.37	1.12	1.16	1.80	1.70	1.62	1.77	1.92	1.72	2.33	2.12
B2-4	100	5.5	9.6		HL	1.7	11.08	15.81	13.16	13.70	14.54	15.11	8.18	9.75	3.11	1.42	1.36	1.28	2.22	1.93	1.94	2.18	1.95	1.97	2.47	2.92
B2-5	50	3.6	8.9	130	HL	1.6	7.56	7.76	5.83	8.38	8.16	6.71	7.67	4.29	5.29	1.77	0.95	0.75	1.06	2.42	1.60	1.43	3.50	1.91	1.38	2.03
B2-6	100	3.8	9.4		HL	1.7	12.50	8.60	6.79	10.46	9.95	7.66	8.68	5.51	5.94	1.91	1.26	0.95	1.28	2.69	1.92	1.63	3.82	2.22	1.72	2.41

7 Summary and conclusions

The following section provides a summary of the study findings.

7.1 Wave calibration

Wave conditions have been calibrated over the existing bathymetry without the breakwater or dredging in place.

Table 7.1: Summary of calibrated wave conditions

Test Series	Wave condi-tion	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave spectra	Wave direction (°N)	SWL (m MSL)		Measured incident wave height (m)	Error (%)
A1 - Design wave calibration	WC1	50	3.4	8	Jonswap gamma = 3.3	40	HL	1.6	3.33	2.0%
	WC2	100	3.6	8			HL	1.7	3.49	3.0%
	WC3	50	5.2	9.4		61	HL	1.6	5.02	3.5%
	WC4	100	5.5	9.6			HL	1.7	5.47	0.5%
	WC5	50	3.6	8.9		130	HL	1.6	3.57	0.9%
	WC6	100	3.8	9.4			HL	1.7	3.85	-1.4%

The wave calibrations were completed to the required ±5% of the target value. Reflections were kept to a minimum to provide confident in the incident condition being generated and to minimise reflections from basin boundaries. The measured refection coefficient from absorption beach placed at the edge of the was found to fall between 9% and 10%.

Additional wave conditions using short-crested waves with a Smax =16 were required during the wave disturbance test, these used the same calibration settings acquired for the long crested waves.

7.2 Wave disturbance

Wave disturbance tests have provided measurements around the breakwater. Short-crested waves were investigated to provide validation against more realistic sea states with a spreading value of Smax =16.

The main focus of the study was to provide wave conditions at the berth. The measured wave conditions at Wave Probe 14, 15 and 16 (along the centre-line of the FSRU) provided the significant wave heights shown in Table 7.2 and the maximum wave heights shown in Table 7.3. These are for long-crested waves.

The measured conditions at the berth when generating short-crested waves are given in Table 7.4 for the significant wave height and in Table 7.5 for the maximum wave height during the 3hr storm duration.

Table 7.2: Significant wave height at berth – long-crested waves

Test	Wave conditions						Measured H_s			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B1-1	100	3.60	8.0	40	HL_100	1.7	0.80	0.77	0.79	0.79
B1-2	100	5.50	9.6	61	HL_100	1.7	0.99	0.96	1.08	1.01
B1-3	100	3.8	9.4	125	HL_100	1.7	1.10	0.74	0.62	0.82

Table 7.3: Maximum wave height at berth– long-crested waves

Test	Wave conditions						Measured H_{max}			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B1-1	100	3.60	8.0	40	HL_100	1.7	1.36	1.30	1.38	1.35
B1-2	100	5.50	9.6	61	HL_100	1.7	1.76	1.61	1.69	1.69
B1-3	100	3.8	9.4	125	HL_100	1.7	2.54	1.52	1.05	1.70

Table 7.4: Significant wave height at berth – short-crested waves

Test	Wave conditions						Measured H_s			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B2-1	50	3.4	8.0	40	HL	1.6	0.99	1.09	1.15	1.08
B2-2	100	3.6	8.0		HL	1.7	1.08	1.14	1.24	1.15
B2-3	50	5.2	9.4	60	HL	1.6	0.96	0.94	1.00	0.96
B2-4	100	5.5	9.6		HL	1.7	1.09	1.05	1.16	1.10
B2-5	50	3.6	8.9	130	HL	1.6	1.50	0.95	0.73	1.06
B2-6	100	3.8	9.4		HL	1.7	1.75	1.10	0.89	1.25

Table 7.5: Maximum wave height at berth – short-crested waves

Test	Wave conditions						Measured H_{max}			
	Return period Tr (yrs)	Hs (m)	Tp (s)	Wave direction (°N)	SWL (m MSL)		WP14 (m)	WP15 (m)	WP16 (m)	Avg. (m)
B2-1	50	3.4	8.0	40	HL	1.6	1.94	1.94	2.36	2.08
B2-2	100	3.6	8.0		HL	1.7	1.92	2.10	2.18	2.07
B2-3	50	5.2	9.4	60	HL	1.6	1.70	1.62	1.77	1.70
B2-4	100	5.5	9.6		HL	1.7	1.93	1.94	2.18	2.01
B2-5	50	3.6	8.9	130	HL	1.6	2.42	1.60	1.43	1.82
B2-6	100	3.8	9.4		HL	1.7	2.69	1.92	1.63	2.08

8 References

1. HYDRALAB III Deliverable NA3.1, Version 1.3, August 2007.
2. Isaacson, M. (1991). Measurement of regular wave reflection. J. Waterway, Port, Coastal and Ocean Engineering. 117(6), 553-569.

Appendices

A Scaling of primary armour

As described in Section 3.2, there were slight variations between the model and prototype armour densities, as well as between model and prototype fluid densities. If not compensated for these variations would mean that stability of the armour in the model would be different from that in the prototype. It was therefore necessary to correct the size of the units used in the model, so that they exhibited the same stability characteristics as the prototype.

A correction factor for density may be derived by reference to the Hudson equation (Ref. A.1) which states:

$$M \propto \frac{\rho_s H_s^3}{\left(\rho_s/\rho_f - 1\right)^3 \cot\theta}$$

Where: M is the mass of the armour unit.

H_s is the significant wave height.

θ is the structure slope angle to the horizontal.

ρ_s is the density of the armour.

and ρ_f is the density of the displacing fluid.

The correction factor (C_f) for the armour mass may thus be calculated from the following equation:

$$M_m = M_p \frac{C_f}{\lambda^3}$$

Where λ is the model scale. This leads to the following expression for the correction factor:

$$C_f = \frac{\rho_{sm}}{\rho_{sp}}\left[\left(\frac{\rho_{sp}}{\rho_{fp}} - 1\right)\Big/\left(\frac{\rho_{sm}}{\rho_{fm}} - 1\right)\right]^3$$

Where the subscripts p and m respectively refer to parameters in the prototype and model.

Reference

A.1 Coastal Engineering Research Centre. (1984) "Shore Protection Manual." CERC, US Government Printing Office, Washington, Vols 1 & 2.

B Scaling of filter layer and core

At the scale selected for this model study there will be conditions where the flow through the model core is not fully turbulent. Scale effects will thus affect the flow of water through the core. Therefore, in order to reproduce realistically the permeability of the core, it is necessary to compensate for the scale effects which result from the use of Froude's scaling law. Work by Jensen and Klinting (Ref. B.1) suggests a method of compensating for scale effects due to laminar flow by applying a correction factor to the ordinary geometric scale when determining core sizes. The calculation of the correction factor uses a special Reynolds number, ξ_p, which is defined as the ratio of turbulent to laminar hydraulics gradients. The special Reynolds number is defined as:

$$\xi_p = (\beta_0/\alpha_0)1/(n(1-n)^2)U_p\, d/\nu$$

Where: α_0 and β_0 are constants derived from experiments.

n is the porosity of the prototype rock mound.

d is the size of the prototype rock.

ν is the kinematic viscosity of water.

U_p is the maximum velocity in the prototype mound.

The ratio of rock size in prototype to model, K, is then given by:

$$K = (\xi_p/2\sqrt{\lambda})[(1+4\lambda^{3/2}\,(1+\xi_p)/\xi_p 2)^{1/2} - 1]$$

Where λ is the geometric scale.

Throughout this analysis it is assumed that the porosity of model and prototype rock is identical.

To enable the above equations to be used in calculating a correction factor certain assumptions have to be made. Experimental work by Engelund (Ref. B.2) suggested values for the empirical coefficients of α_0 = 1500 and β_0 = 3.6. The maximum prototype velocity in the mound was estimated at 0.5-1.0m/s from some simple calculations of wave velocities and comparisons with velocities calculated by a simple mathematical model of flow in rubble. The porosity of the rock mound, n, was also estimated at 35-37%.

References

B.1 Jensen, O.J. and Klinting, P. 'Evaluation of Scale Effects in Hydraulic Models by Analysis of Laminar and Turbulent Flows', Coastal Engineering, pp 319-329, 1983.

B.2 Engelund, F. 'The Laminar and Turbulent Flows of Ground Water through Homogeneous Sand', Trans. Danish Acad Tech Sci, 3(4), 1953.

C Wave calibration

C.1.1 Wave condition A1-1

Table C.1: Wave calibration results for WC1

Wave Probe	Statistical parameters				Spectral parameters			Incident wave height		
	H_{max} (m)	$H_{1/10}$ (m)	$H_{1/3}$ (m)	T_m (s)	H_{m0} (m)	T_p (s)	$T_{m0,2}$ (s)	H_s avg (m)	Cr	H_{si} (m)
WP1	6.88	4.02	3.20	6.75	3.24	7.62	6.46			
WP2	4.54	3.35	2.61	6.50	2.66	8.02	6.29			
WP3	5.84	4.31	3.37	6.48	3.43	8.02	6.27			
WP4	6.11	4.73	3.67	7.02	3.68	8.02	6.67			
WP5	5.58	4.01	3.22	6.83	3.31	8.02	6.36	3.35	0.10	3.33
WP6	6.41	4.14	3.29	6.70	3.38	8.02	6.55			
WP7	6.32	4.34	3.39	6.97	3.45	8.02	6.72			
WP8	6.10	4.25	3.41	6.66	3.53	8.02	6.52			
WP9	6.48	4.80	3.71	6.90	3.76	8.02	6.57			
WP10	6.40	4.49	3.47	6.73	3.51	7.62	6.44			
WP11	5.64	4.26	3.33	6.86	3.38	7.62	6.49			
WP12	6.55	4.25	3.37	6.97	3.45	8.02	6.59			
WP13	6.26	3.88	3.06	6.58	3.19	8.02	6.39			
WP14	5.55	4.10	3.25	6.86	3.34	7.62	6.58			
WP15	5.92	3.93	3.05	6.82	3.09	8.02	6.63			
WP16	5.57	3.92	3.10	6.83	3.16	8.02	6.49			
WP17	5.80	3.91	3.01	6.82	3.05	8.02	6.59			
WP5b	5.46	4.02	3.23	6.70	3.34	8.02	6.32			
WP5c	6.15	4.17	3.34	6.79	3.40	8.02	6.46			
WP5d	6.52	4.12	3.29	6.88	3.34	8.02	6.49			

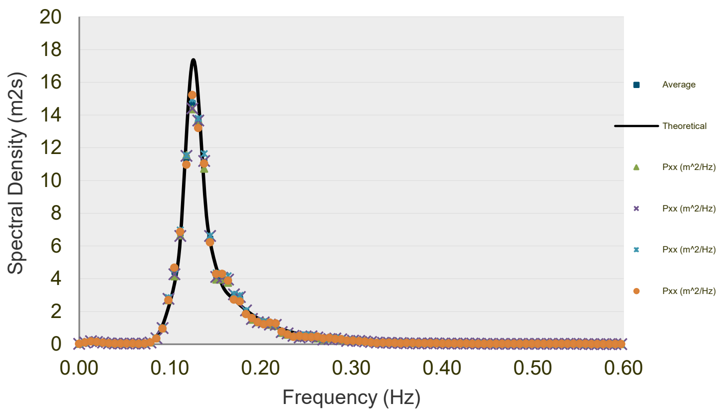


Figure C.1: Measured wave spectra

C.1.2 Wave condition A1-2

Table C.2: Wave calibration results for WC2

Wave Probe	Statistical parameters				Spectral parameters			Incident wave height		
	H_{max} (m)	$H_{1/10}$ (m)	$H_{1/3}$ (m)	T_m (s)	H_{m0} (m)	T_p (s)	$T_{m0,2}$ (s)	H_s avg (m)	Cr	H_{si} (m)
WP1	5.82	4.26	3.38	6.75	3.45	8.02	6.51			
WP2	4.92	3.46	2.72	6.53	2.78	8.02	6.41			
WP3	5.90	4.57	3.56	6.65	3.61	8.02	6.46			
WP4	6.36	5.01	3.94	7.14	4.00	8.02	6.79			
WP5	5.84	4.18	3.40	6.90	3.47	8.02	6.46	3.51	0.09	3.49
WP6	6.24	4.43	3.53	6.72	3.63	8.02	6.54			
WP7	6.12	4.55	3.62	7.16	3.62	8.02	6.76			
WP8	6.92	4.45	3.57	6.79	3.64	8.02	6.50			
WP9	7.03	4.93	3.94	7.03	3.95	8.02	6.70			
WP10	6.80	4.84	3.78	6.94	3.75	8.02	6.50			
WP11	6.56	4.39	3.44	7.00	3.49	8.02	6.60			
WP12	5.83	4.41	3.49	6.94	3.56	8.02	6.60			
WP13	6.30	4.26	3.37	6.64	3.44	8.02	6.39			
WP14	5.81	4.34	3.36	6.85	3.40	8.02	6.61			
WP15	6.15	4.39	3.44	6.78	3.50	8.02	6.58			
WP16	6.51	4.38	3.46	6.91	3.49	8.02	6.42			
WP17	6.01	4.49	3.54	6.89	3.58	8.02	6.53			
WP5b	6.40	4.26	3.44	6.88	3.50	8.02	6.42			
WP5c	6.78	4.35	3.50	6.80	3.56	8.02	6.55			
WP5d	6.62	4.28	3.42	6.88	3.49	8.02	6.59			

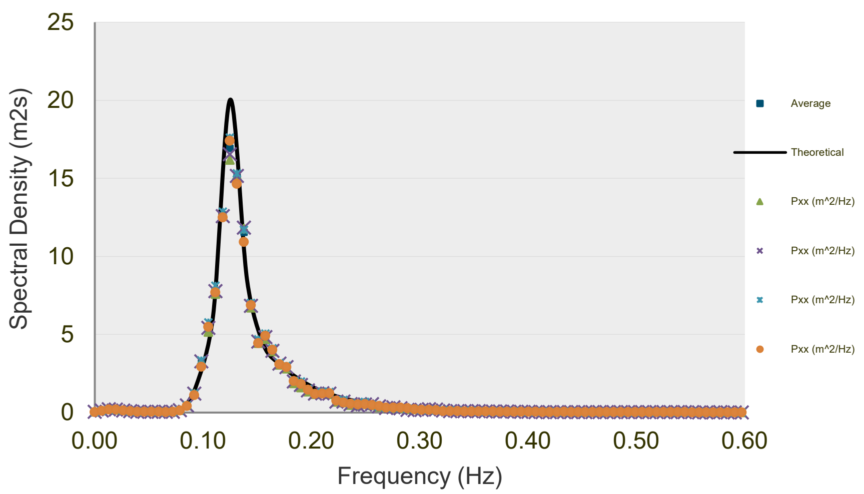


Figure C.2: Measured wave spectra

C.1.3 Wave condition A1-3

Table C.3: Wave calibration results for WC3

Wave Probe	Statistical parameters				Spectral parameters			Incident wave height		
	H_{max} (m)	$H_{1/10}$ (m)	$H_{1/3}$ (m)	T_m (s)	H_{m0} (m)	T_p (s)	$T_{m0,2}$ (s)	H_s avg (m)	Cr	H_{si} (m)
WP1	8.68	6.86	5.51	7.91	5.38	9.52	7.13			
WP2	7.22	4.81	3.75	7.48	3.88	9.52	7.25			
WP3	8.70	6.46	5.13	7.89	5.07	9.52	7.28			
WP4	9.21	6.54	5.54	8.61	5.62	9.52	7.83			
WP5	8.55	6.02	4.91	8.13	4.99	9.52	7.48	5.04	0.10	5.02
WP6	8.48	6.08	5.01	8.18	5.02	9.52	7.47			
WP7	7.22	4.87	3.81	7.55	3.97	9.52	7.33			
WP8	8.07	6.08	4.95	8.17	5.01	9.52	7.53			
WP9	8.25	5.99	5.03	8.44	5.22	9.52	7.83			
WP10	8.79	6.98	5.70	8.65	5.73	9.52	7.73			
WP11	8.60	6.13	4.97	8.26	5.06	9.52	7.58			
WP12	8.20	6.04	4.89	8.13	4.95	9.52	7.54			
WP13	8.26	6.15	5.02	8.22	5.11	9.52	7.50			
WP14	8.68	6.53	5.39	8.30	5.45	9.52	7.60			
WP15	8.50	5.94	4.84	8.17	4.96	9.52	7.61			
WP16	8.43	6.14	4.99	8.20	5.07	9.52	7.53			
WP17	8.76	6.06	4.96	8.18	5.05	9.52	7.61			
WP5b	7.90	6.04	4.95	8.08	5.02	9.52	7.48			
WP5c	7.81	6.19	5.09	8.21	5.14	9.52	7.53			
WP5d	7.73	5.98	4.93	8.11	5.03	9.52	7.61			

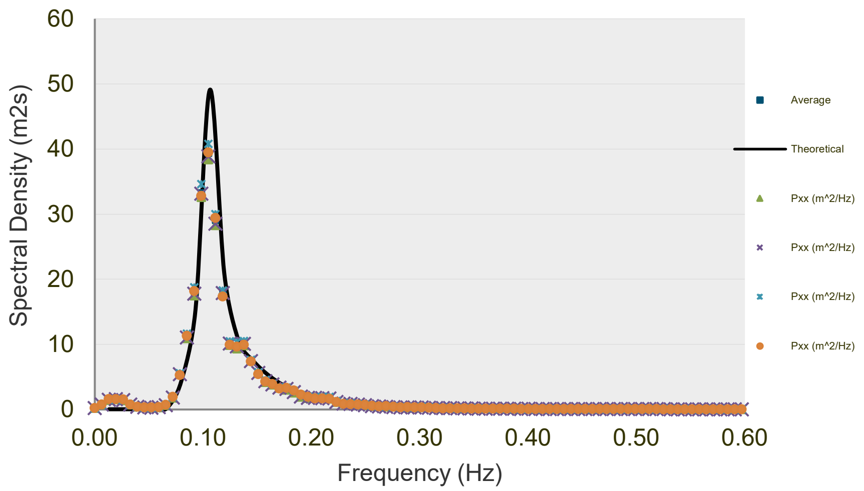


Figure C.3: Measured wave spectra

C.1.4 Wave condition A1-4

Table C.4: Wave calibration results for WC4

Wave Probe	Statistical parameters				Spectral parameters			Incident wave height		
	H_{max} (m)	$H_{1/10}$ (m)	$H_{1/3}$ (m)	T_m (s)	H_{m0} (m)	T_p (s)	$T_{m0,2}$ (s)	H_s avg (m)	Cr	H_{si} (m)
WP1	9.44	7.40	6.06	8.34	5.91	9.52	7.23			
WP2	8.09	5.51	4.38	7.89	4.45	9.52	7.50			
WP3	8.79	7.05	5.74	8.17	5.66	9.52	7.42			
WP4	9.27	7.06	5.97	8.97	6.20	9.52	8.04			
WP5	8.08	6.49	5.41	8.55	5.45	9.52	7.67	5.50	0.10	5.47
WP6	8.27	6.53	5.44	8.55	5.46	9.52	7.74			
WP7	8.33	5.34	4.29	8.19	4.46	10.15	7.69			
WP8	8.27	6.63	5.50	8.50	5.50	9.52	7.69			
WP9	8.38	6.47	5.44	8.67	5.60	9.52	7.95			
WP10	9.70	7.56	6.35	9.00	6.35	10.15	7.83			
WP11	9.18	6.66	5.50	8.69	5.66	9.52	7.87			
WP12	8.62	6.69	5.48	8.44	5.61	10.15	7.78			
WP13	8.52	6.51	5.45	8.47	5.62	9.52	7.83			
WP14	9.58	7.02	5.79	8.68	5.85	10.15	7.85			
WP15	8.62	6.78	5.62	8.61	5.69	10.15	7.76			
WP16	8.51	6.58	5.48	8.70	5.68	10.15	7.86			
WP17	9.73	6.75	5.62	8.58	5.71	10.15	7.80			
WP5b	7.75	6.55	5.43	8.53	5.46	9.52	7.64			
WP5c	8.27	6.71	5.57	8.58	5.59	9.52	7.67			
WP5d	8.56	6.61	5.44	8.61	5.51	9.52	7.80			

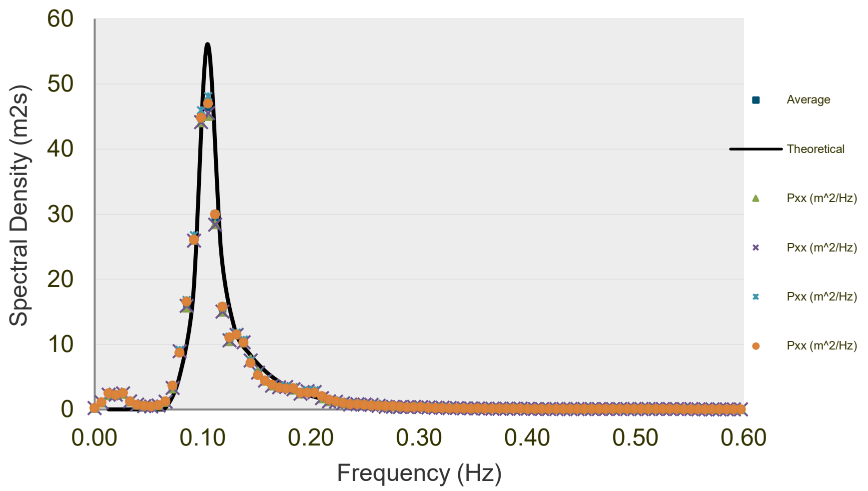


Figure C.4: Measured wave spectra

C.1.5 Wave condition A1-5

Table C.5: Wave calibration results for WC5

Wave Probe	Statistical parameters				Spectral parameters			Incident wave height		
	H_{max} (m)	$H_{1/10}$ (m)	$H_{1/3}$ (m)	T_m (s)	H_{m0} (m)	T_p (s)	$T_{m0,2}$ (s)	H_s avg (m)	Cr	H_{si} (m)
WP1	6.57	4.48	3.54	6.68	3.60	8.96	6.44			
WP2	6.50	4.56	3.60	6.98	3.62	8.46	6.60			
WP3	6.25	3.64	2.91	6.94	3.00	8.96	6.71			
WP4	6.43	4.57	3.62	7.14	3.71	8.96	6.97			
WP5	6.51	4.30	3.43	7.21	3.53	8.96	6.70	3.59	0.09	3.57
WP6	7.21	5.09	4.10	7.72	4.19	8.46	7.28			
WP7	7.16	5.04	3.93	7.29	3.95	8.96	6.81			
WP8	6.70	4.73	3.90	7.77	3.93	8.46	7.28			
WP9	6.61	4.86	3.84	7.34	3.88	8.96	6.92			
WP10	6.10	4.26	3.44	7.24	3.50	8.96	6.97			
WP11	6.90	4.52	3.58	7.39	3.70	8.96	6.97			
WP12	7.35	4.60	3.67	7.39	3.79	8.96	6.96			
WP13	7.17	4.45	3.46	7.47	3.52	8.96	7.03			
WP14	6.35	4.69	3.74	7.30	3.81	8.96	6.83			
WP15	7.05	4.39	3.47	7.32	3.60	8.96	7.04			
WP16	7.30	4.47	3.55	7.48	3.61	8.46	7.03			
WP17	6.91	4.37	3.42	7.40	3.49	8.96	6.95			
WP5b	6.53	4.31	3.45	7.25	3.55	8.96	6.66			
WP5c	6.74	4.45	3.58	7.21	3.71	8.96	6.86			
WP5d	6.49	4.28	3.43	7.23	3.55	8.96	6.92			

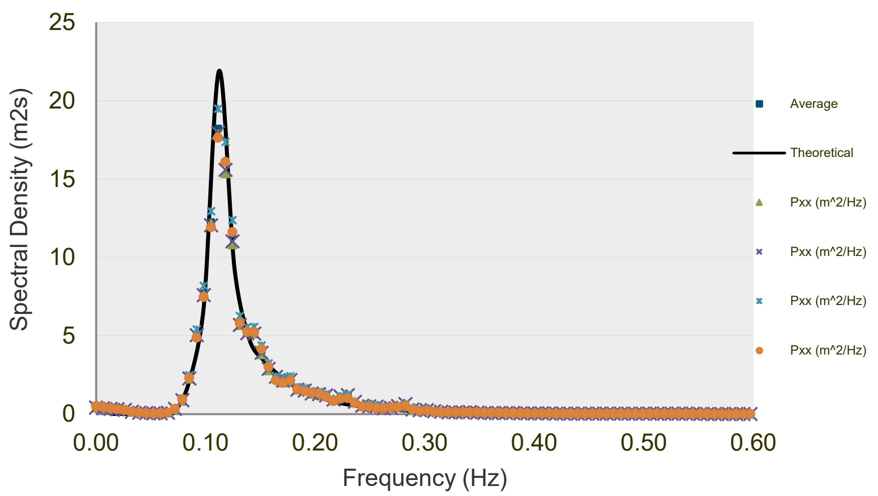


Figure C.5: Measured wave spectra

C.1.6 Wave condition A1-6

Table C.6: Wave calibration results for WC6

Wave Probe	Statistical parameters				Spectral parameters			Incident wave height		
	H_{max} (m)	$H_{1/10}$ (m)	$H_{1/3}$ (m)	T_m (s)	H_{m0} (m)	T_p (s)	$T_{m0,2}$ (s)	H_s avg (m)	Cr	H_{si} (m)
WP1	7.64	5.15	4.02	7.38	4.09	9.52	7.01			
WP2	7.52	5.29	4.14	7.52	4.10	9.52	6.90			
WP3	6.22	4.27	3.39	7.44	3.43	8.96	7.10			
WP4	7.14	5.13	4.13	7.80	4.17	9.52	7.37			
WP5	6.77	4.70	3.78	7.52	3.81	9.52	7.09	3.87	0.10	3.85
WP6	7.53	5.74	4.70	8.30	4.78	9.52	7.65			
WP7	7.51	5.82	4.66	7.91	4.65	9.52	7.34			
WP8	6.85	5.46	4.53	8.40	4.59	9.52	7.72			
WP9	7.85	5.79	4.58	7.95	4.56	9.52	7.33			
WP10	6.96	4.90	3.92	7.91	3.94	9.52	7.38			
WP11	7.69	4.95	4.00	7.80	4.06	9.52	7.44			
WP12	7.44	5.02	4.01	8.02	4.05	9.52	7.43			
WP13	7.38	4.85	3.88	7.85	3.95	9.52	7.49			
WP14	7.33	5.31	4.32	7.95	4.37	9.52	7.34			
WP15	7.31	4.80	3.84	7.86	3.93	9.52	7.40			
WP16	6.49	4.96	3.99	7.99	4.03	9.52	7.46			
WP17	7.26	5.06	4.00	7.98	4.04	9.52	7.52			
WP5b	6.93	4.73	3.79	7.58	3.81	9.52	7.09			
WP5c	6.80	4.97	3.97	7.68	4.01	9.52	7.24			
WP5d	7.05	4.82	3.83	7.81	3.86	9.52	7.30			

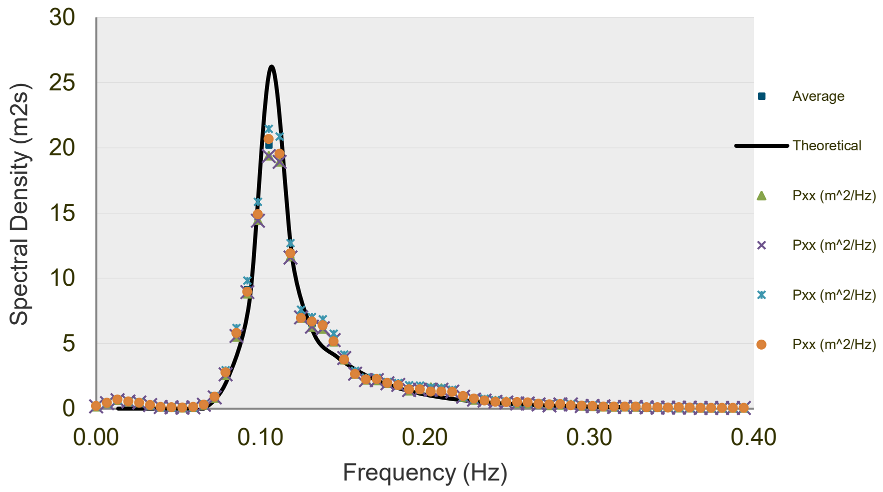
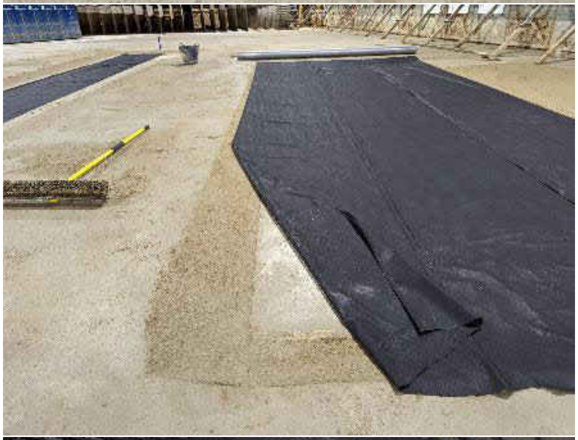


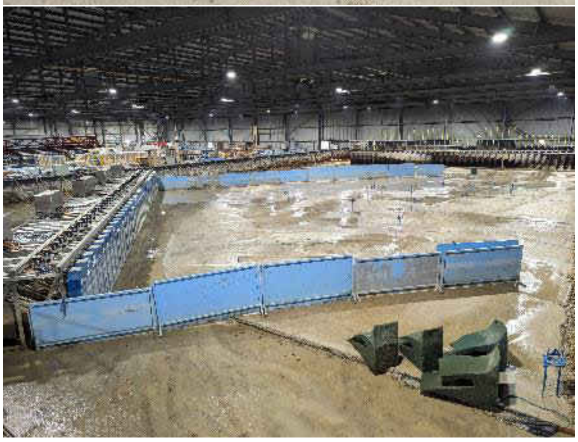
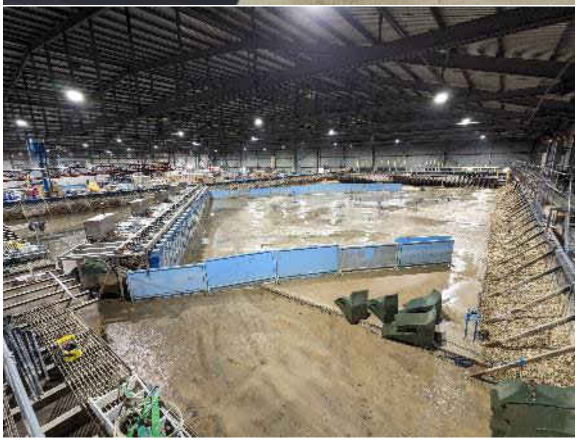
Figure C.6: Measured wave spectra

D Photographs

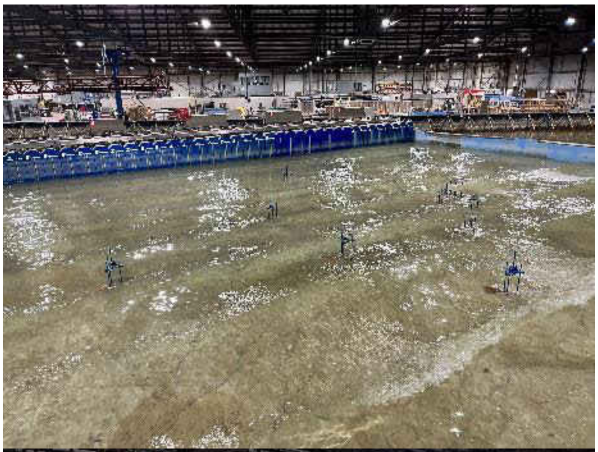
D.1 Bathymetry

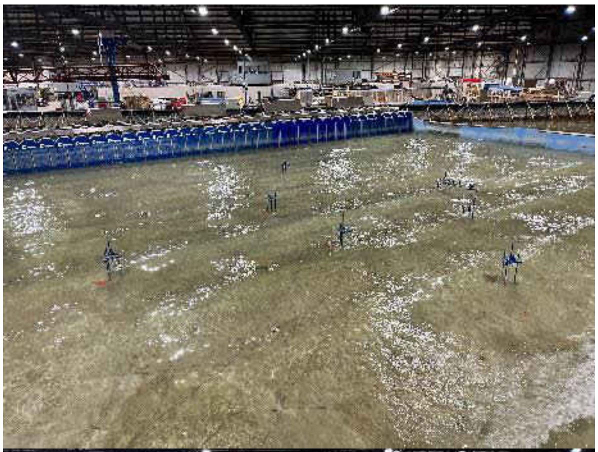


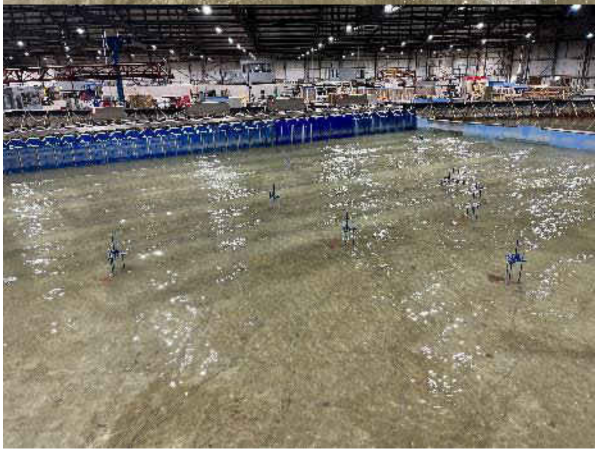


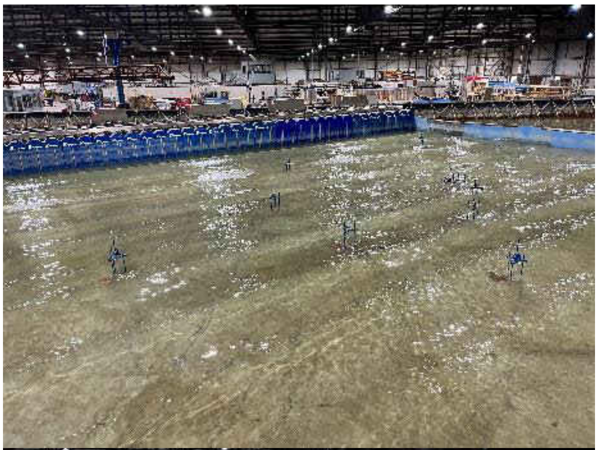
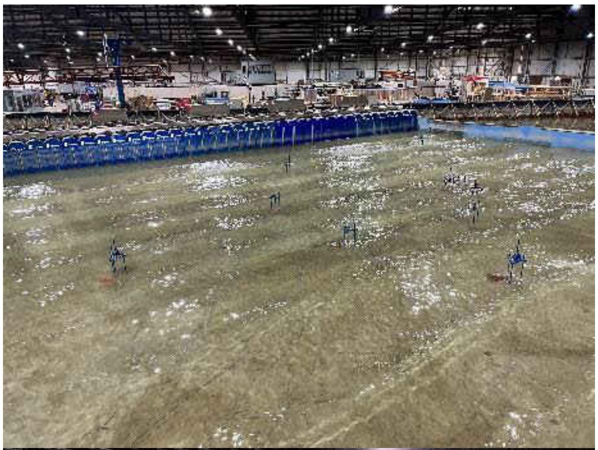



D.2 Wave calibration

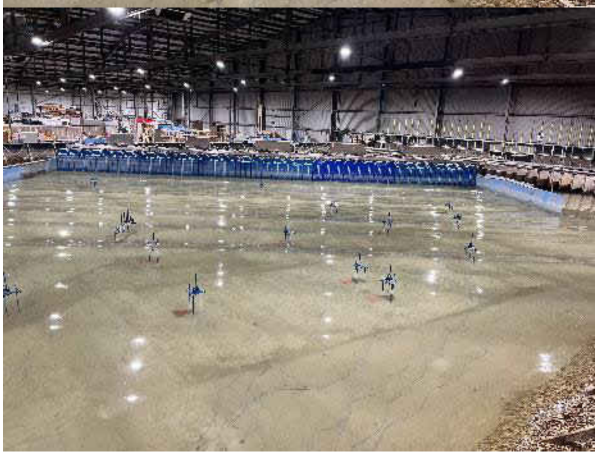
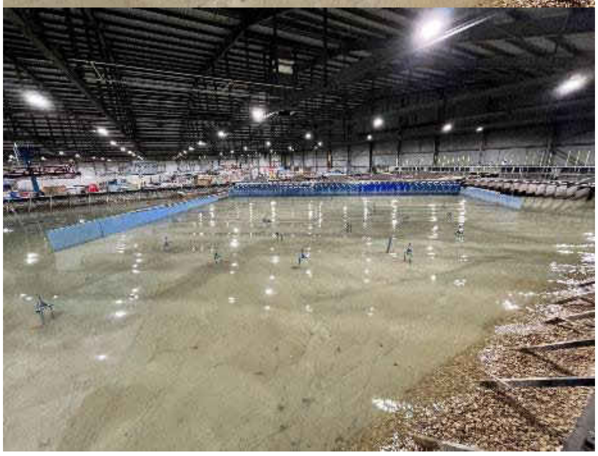


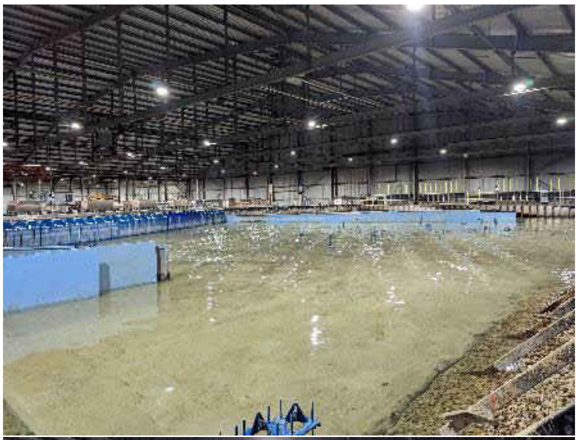
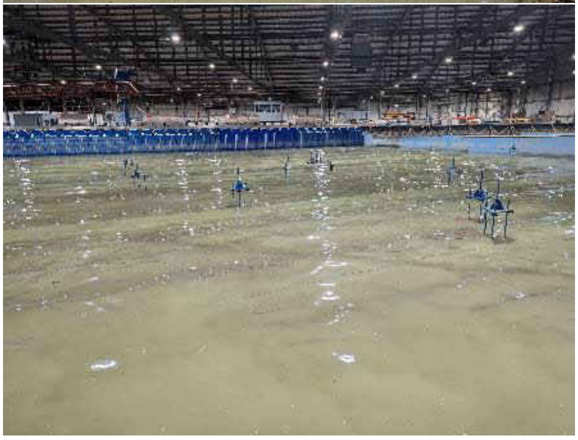
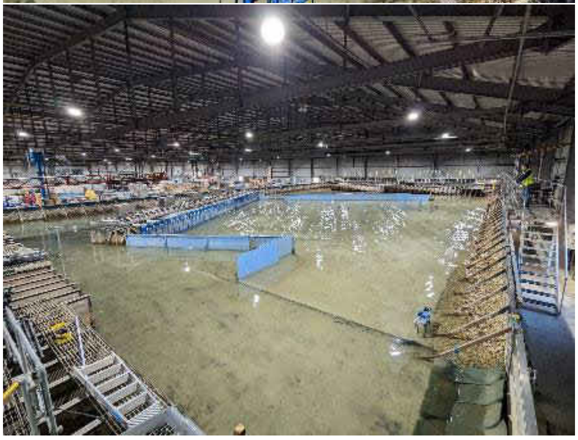




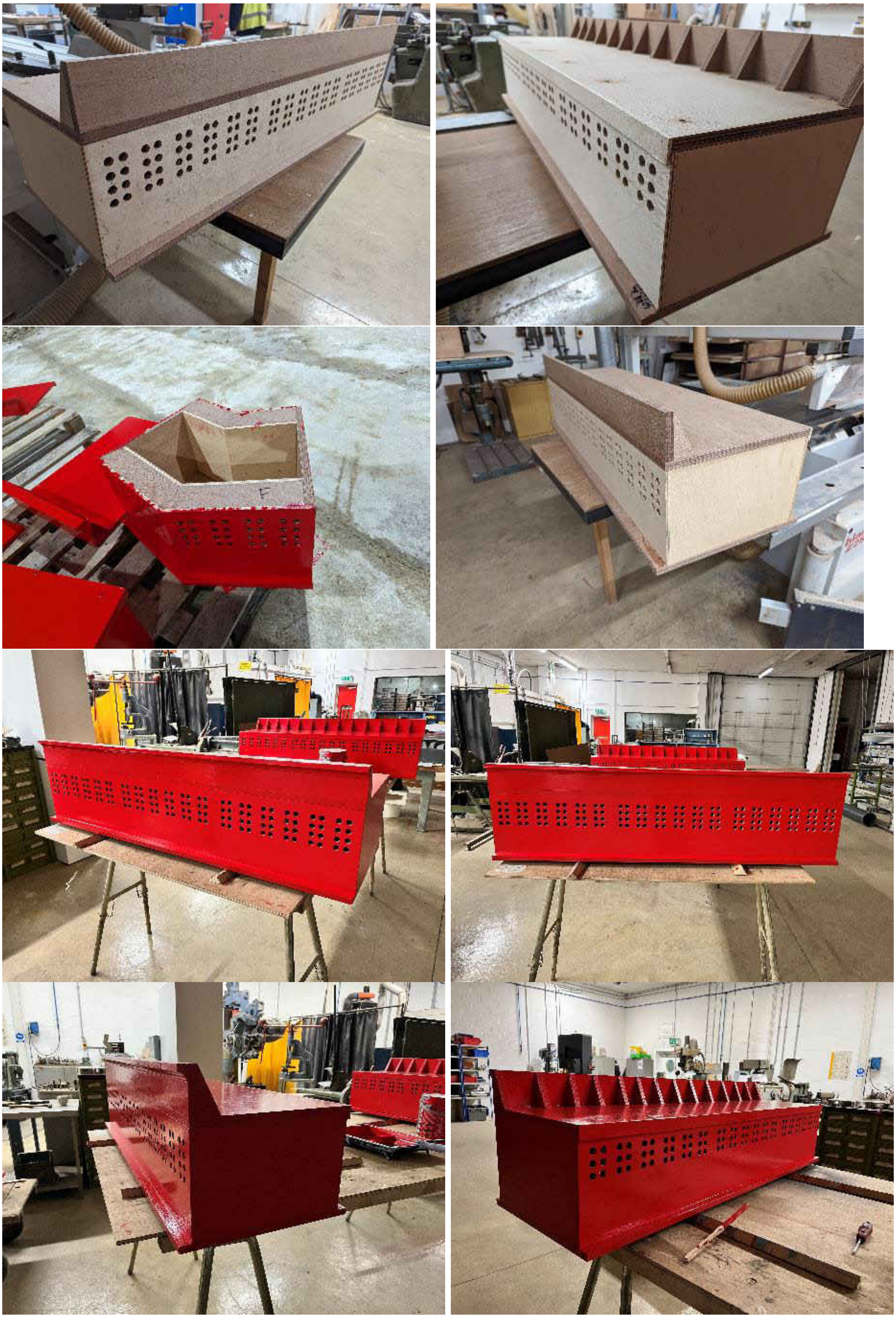





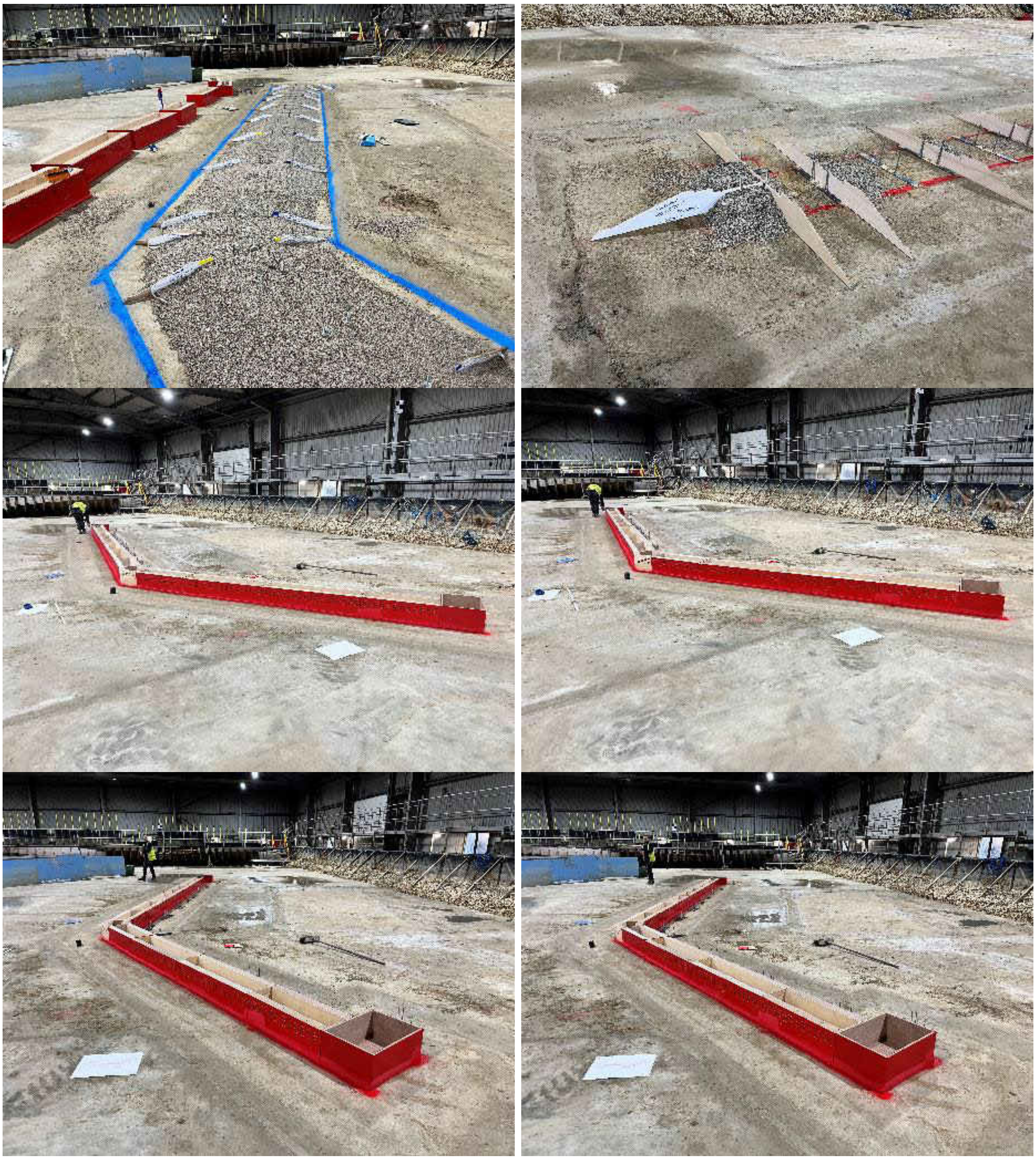
D.3 Model caissons

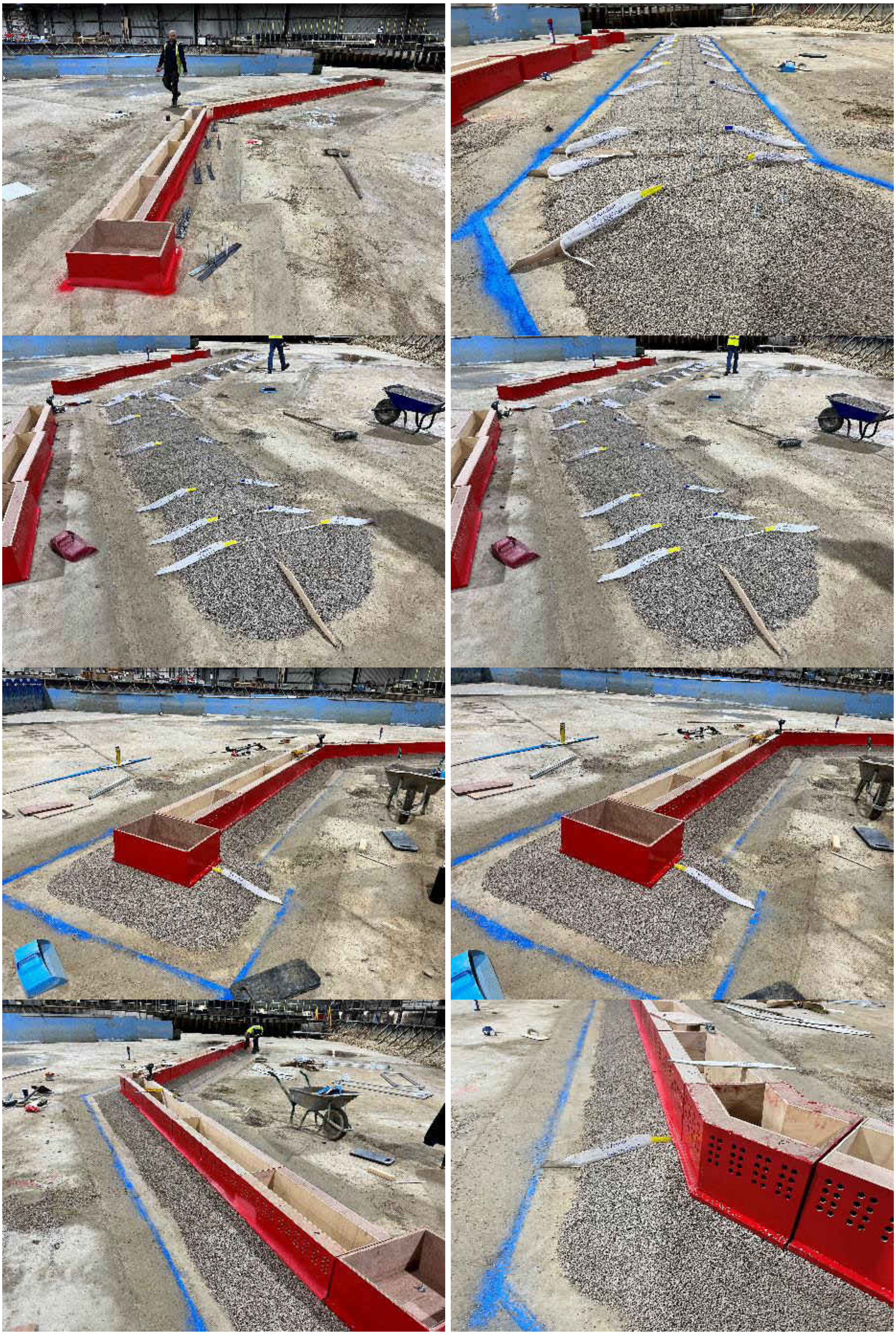


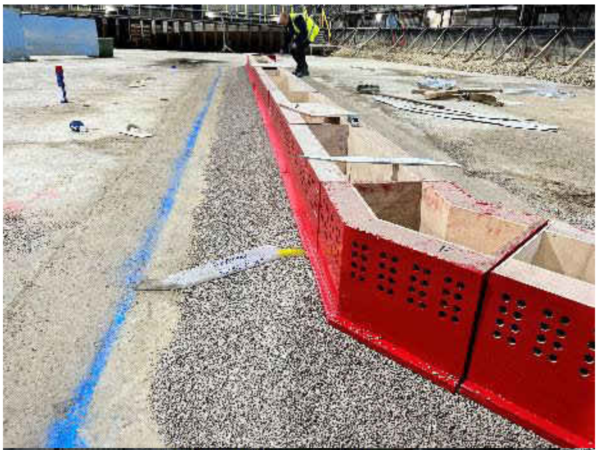





D.4 Breakwater construction







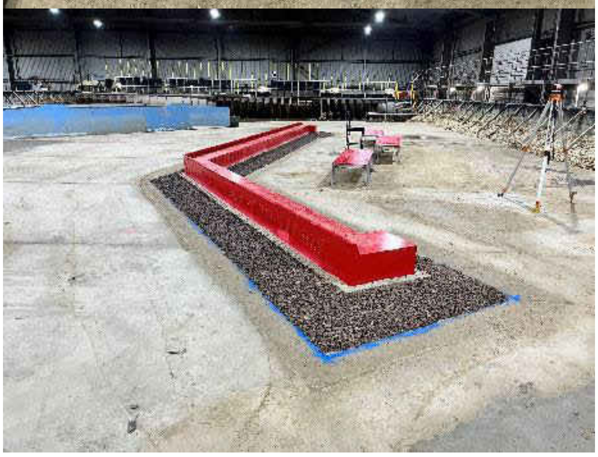




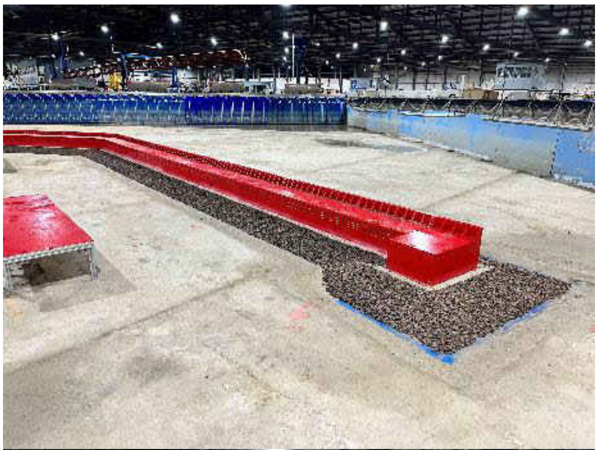


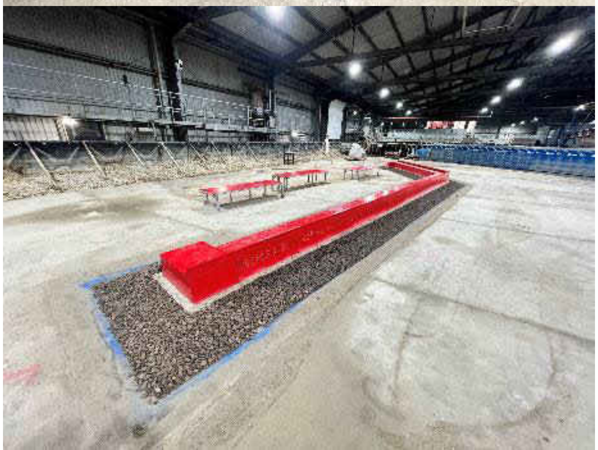
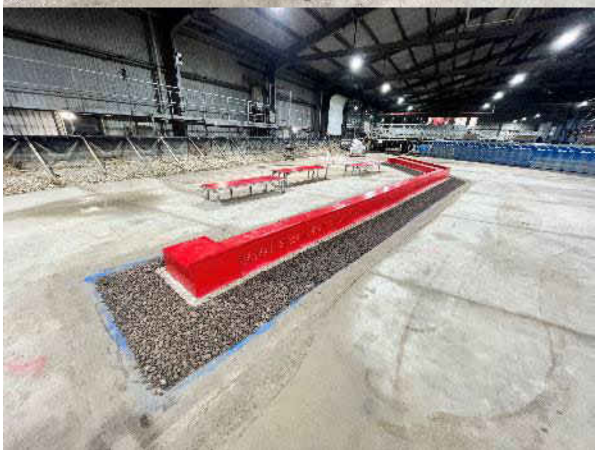
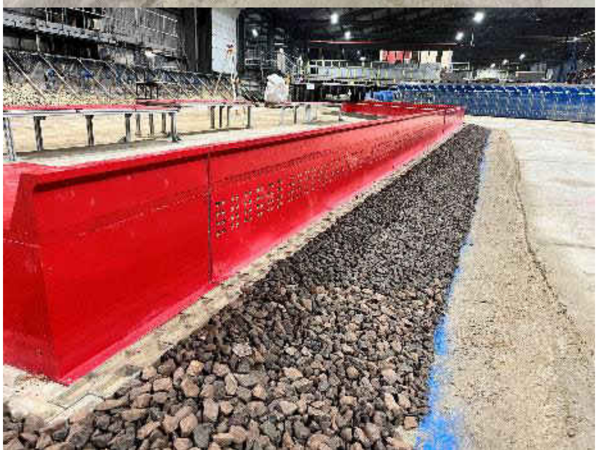




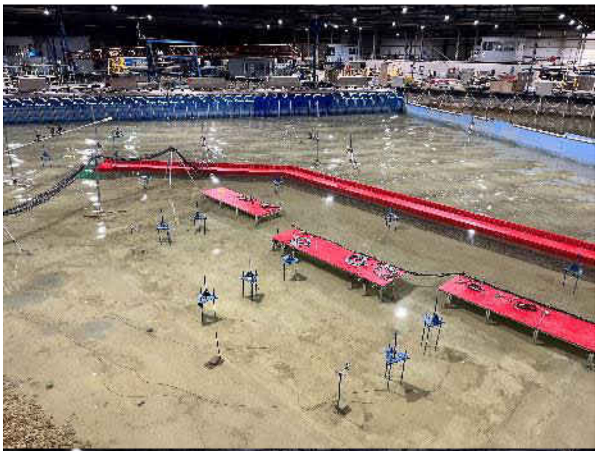
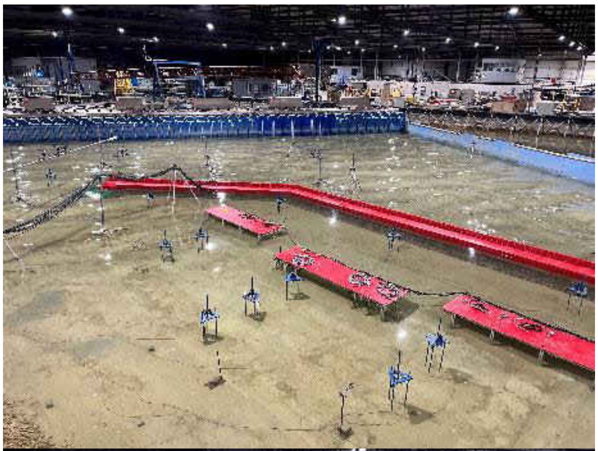
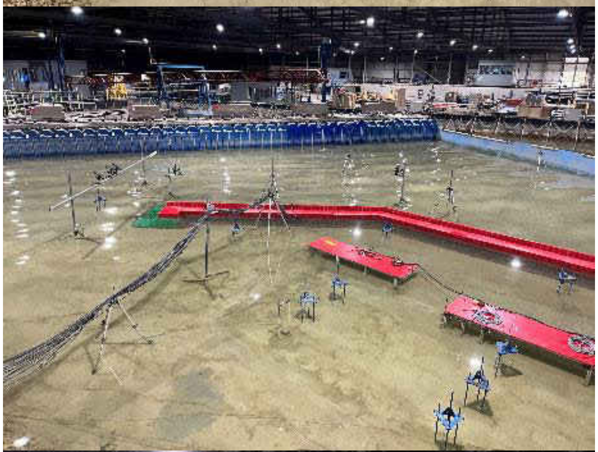
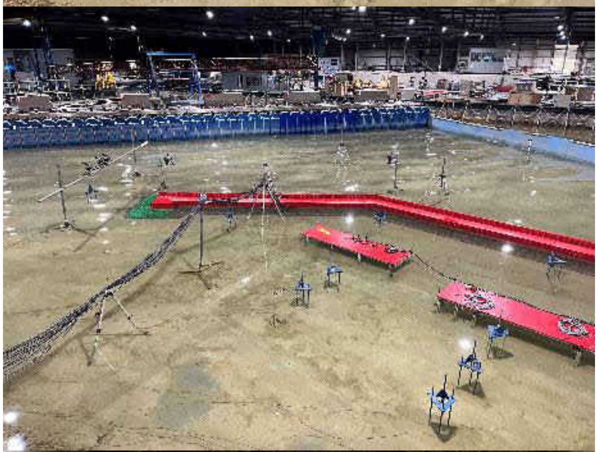
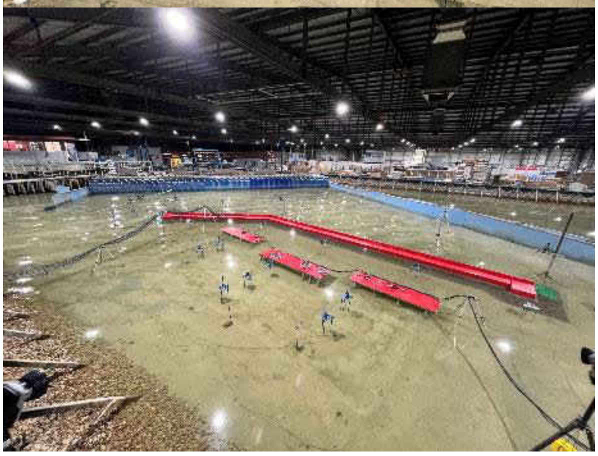
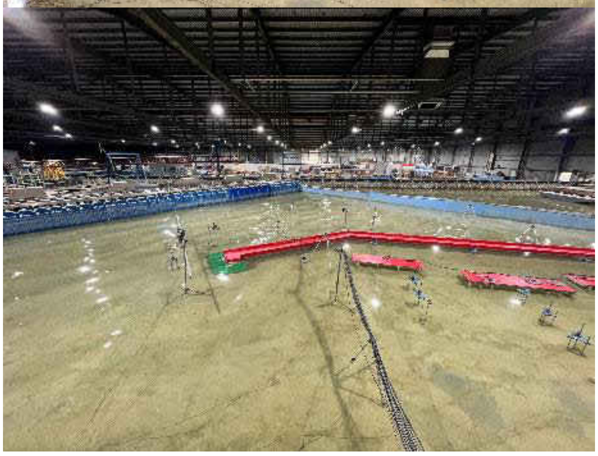



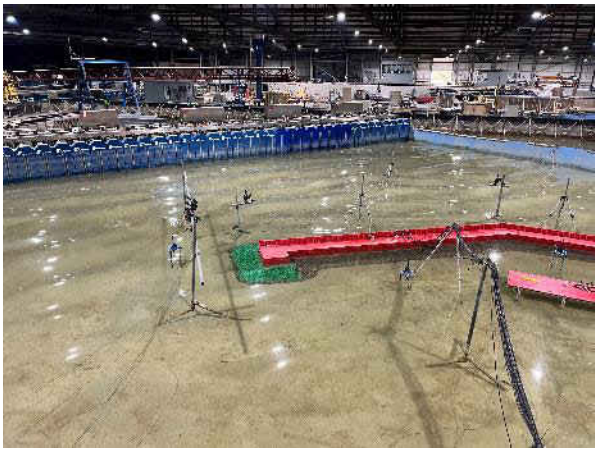
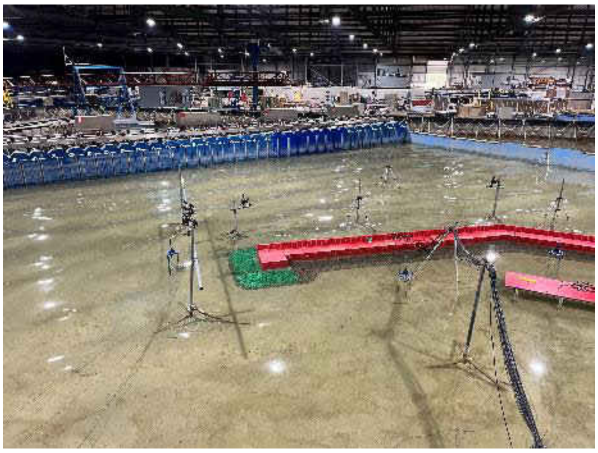




D.5 Test Series B

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