Lake Michigan beach protection

2D physical modelling final report

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1. Introduction

1.1. Project overview

Lake Michigan recently experienced record breaking high water levels and the sandy shoreline of Illinois Beach State Park, Lake Michigan has eroded significantly, damaging and threatening rare wetlands. SmithGroup are designing a coastal protection scheme to stabilise the shoreline at the park. The scheme will include beach nourishment and beach control structures. These will be shore-connected and detached breakwaters armoured with heavy grades of natural rock. HR Wallingford was approached by SmithGroup to undertake 2 dimensional (2D) and 3 dimensional (3D) physical modelling to investigate the stability of the rock armour on the breakwaters, assess their wave transmission and the response of the nourished beaches.

The 2D and 3D models examined three distinct areas - Area 1: North Beach, Area 2: Camp Logan, and Area 3: Swimming Beach. The overall study location is shown in Figure 1.1. The 2D tests investigated the wave transmission of several structure cross-sections and the stability of the rock armour for two structures.

1.2. Objectives and scope of study

2D physical model tests were required to validate the detached breakwater designs by examining the following parameters:

- Wave transmission over and through the emergent and the low-crested detached breakwaters;
- The stability of the primary rock armour layers for an emergent structure.

The shore-connected breakwaters were not included in the 2D study. The vertical datum used in the study is International Great Lakes Datum 1985 (ft IGLD 85).

The 2D study was split into two distinct phases, each testing different types of structure.

- Phase 1 – Optimisation of various detached breakwater cross-sections based on their transmission coefficient;
- Phase 2 – Measurement of armour stability and wave transmission for emergent breakwater structures in preparation for 3D model studies.

Additional wave transmission and sand movement tests were conducted on some ecological structures and these are reported separately in Appendix B.

Unless stated otherwise all length values are in feet (ft). The rock grades used in this study substantially conform to the grades specified in the CIRIA Rock Manual (2007) and are presented in metric tonnes; a table of equivalent US lbs for the final tested rocks grades is given in Table 2.11. All values given in this report are in prototype dimensions unless stated otherwise.

1.3. Report outline

This report describes the main objectives of the 2D physical modelling and some basic information about the project in Section 1. Section 2 covers the model design, the facility used in the study and outlines the test methods and measurements. Section 3 describes the test conditions with the wave calibration results following in Section 4. The Test Programme is outlined in Section 5 with the results from the two test Phases presented in Section 6. Section 7 provides a short summary of the 2D physical modelling study.

Figure 1.1: Study location

Source: Google Earth

2. Test facilities and methods

2.1. Model scale

Froude scaling law is applied to physical models where gravity is the predominant factor in the fluid motion. Wave models, since wave motion is essentially a gravitational phenomenon, are therefore designed according to this law. Froude's law states that the Froude number, Fr, should be the same in model and prototype, where F_r is defined as:

$$Fr = \frac{u}{\sqrt{gL}} \qquad 2.1$$

where u is a characteristic velocity, g is the acceleration due to gravity and L is a characteristic length.

Wave models are not distorted, having the same horizontal and vertical scale. The linear scale of the model, to which the bathymetry and structures were constructed, is known as the geometric scale, λ. The Froudian scaling relationships for various different parameters are outlined below:

Length	λ	Time	$\lambda^{1/2}$
Velocity	$\lambda^{1/2}$	Force	λ^3
Volume	λ^3	Acceleration	1
Overtopping	$\lambda^{3/2}$		

In the design of a physical model of this type, the principal concern is to ensure that the main aspects of wave-structure interaction are reproduced faithfully at a scale that avoids significant scale effects. The test section must also be of a practical size to be handled in the facility selected and with the resources available. The depth of water at the paddle must be deep enough to produce the required offshore wave heights. The two phases of 2D testing were conducted at different scales to best meet the above criteria. The model scales were:

- Phase 1 – Transmission tests for detached breakwater structures – 1:30;
- Phase 2 – Confirmation tests for emergent breakwater sections – 1:35 (to match the scale of the concurrent 3D modelling studies).

2.2. Wave flume and bathymetry

The tests were carried out in HR Wallingford's Wave Flume 2, which is 40m long, 1.2m wide and has a maximum working depth of 1.7m (model dimensions). It is equipped with a piston-type wave paddle which is controlled by HR Wallingford's Merlin software. The paddle has an active wave-absorbing system to reduce the effect of waves reflected from the test section and can generate non-repeating random sea-states to any required spectral form, e.g., JONSWAP, Pierson Moskowitz, or user-defined forms - including bimodal spectra.

The flume bathymetric profile is shown in Figure 2.1 for Phase 1 tests (note the exaggerated vertical scale) and in Figure 2.2 for Phase 2. This profile was designed to reproduce the near-shore processes of shoaling and breaking, as required by the HYDRALAB III guidelines on the physical modelling of breakwaters (HYDRALAB III, 2007). The bathymetry represents a generalised case representing a mildly sloping seabed, and allowing all the different structures and model phases to be conducted on the same bathymetry.

The bathymetric profile used for all phases of the 2D study (Figure 2.1 and Figure 2.2) had a 1:24 transition slope from the flume floor followed by a 1:120 slope to an area of horizontal bed where the structures were placed.

Twin wire wave gauges were placed in various locations within the flume to measure the transmission coefficients and wave conditions. The locations and spacing were determined by SmithGroup's representatives onsite for the modelling study (email "flume set up for discussion", on July 22, 2020 and specifically drawing attachment *0179_001.pdf*). The Phase 1 spacings are presented in Table 2.1. The nominal wavelength used in the calculations (200 ft) assumes a 9-10s period wave in 15 ft water depth. The wave gauge locations for the Phase 2 stability tests are presented in Table 2.2.

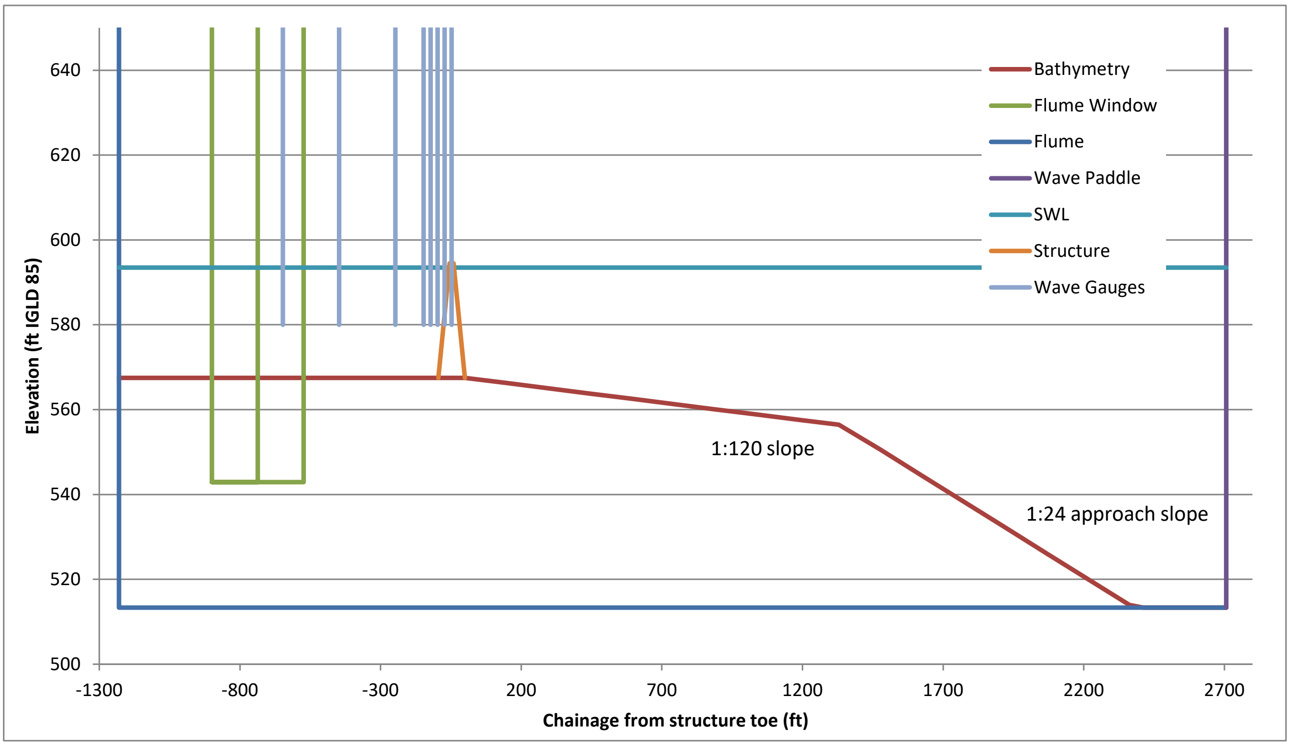

Figure 2.1: Flume configuration (Phase 1, Structure_01)

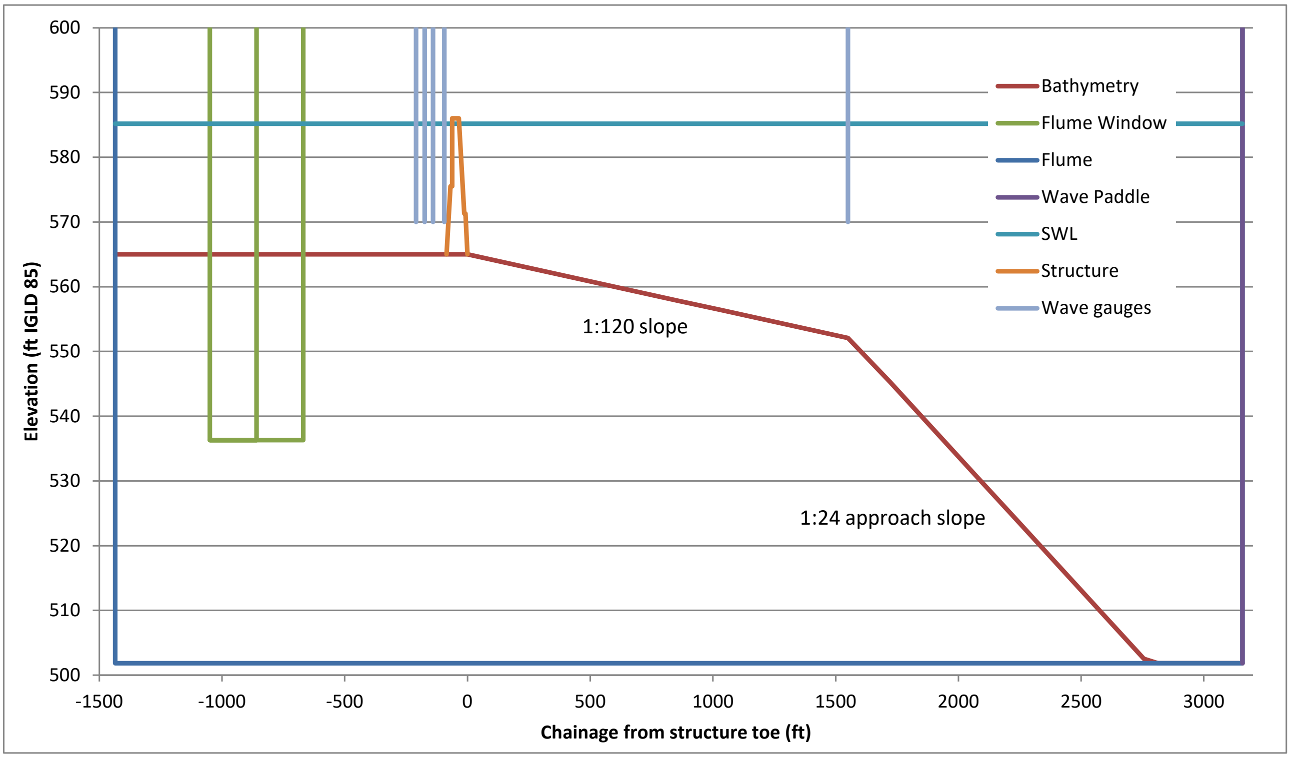

Figure 2.2: Flume configuration (Phase 2, 6-9t armour structure)

Table 2.1: Phase 1 wave gauge locations

Wave gauge	Distance from structure seaward edge of crest (ft)	Proportion of nominal wavelength
WG01	Various depending on structure	Centre of structure crest
WG02	25	L/8
WG03	50	L/4
WG04	75	3L/8
WG05	100	L/2
WG06	200	L
WG07	400	2L
WG08	600	3L

Table 2.2: Phase 2 wave gauge locations

Wave gauge	Distance from structure seaward toe (ft)	Description
WG01	-1,550	WG_offshore
WG02	95	Array_ref_01
WG03	140	Array_ref_02
WG04	175	Array_ref_03
WG05	209	Array_ref_04

2.3. Modelling materials

The breakwaters were reproduced in a combination of plywood and rock. Initially for the Phase 1 tests, all rock material was prepared so that the hydraulic performance (permeability) would be scaled correctly. Details of the permeability scaling method are given in Section 2.3.1 below, in which the material is scaled slightly larger than would be the case if purely geometric scaling was applied. In order to ensure that the correct grading is obtained, the materials are prepared in size subdivisions and then mixed in the correct proportions. An example image of a transmission test structure is shown in Figure 2.3.

For the Phase 2 stability tests, the armour layer was scaled to reproduce correctly its stability under wave attack, taking account of the differences between model and prototype armour densities, as well as model and prototype fluid densities. Details of the stability scaling method are given in Section 2.3.2 below. Details of the rock grades used for these structures are given in Section 2.6. All underlayer and core rock used in the stability tests was scaled to reproduce the permeability of the rock layer using the permeability scaling method described in Section 2.3.1 below.

Figure 2.3: Example transmission test structure with impermeable (plywood) crest

2.3.1. Rock scaling for permeability

In order to reproduce the permeability of the materials realistically, it was necessary to compensate for the scale effects which result from the use of Froude's scaling law. Work by Jensen and Klinting (1983) suggests a method of compensating for scale effects due to laminar flow by applying a correction factor to the ordinary geometric scale when determining rock sizes. The calculation of the correction factor uses a special Reynolds number, ξ_p, which is defined as the ratio of turbulent to laminar hydraulic gradients. The special Reynolds number is defined as:

$$\xi_p = \left(\frac{\beta_o}{\alpha_o}\right)\frac{1}{(n(1-n)^2)}U_p\frac{d}{v} \qquad 2.2$$

where α_o and $ß_o$ are constants derived from experiments; n is the porosity of the prototype rock mound; d is the size of the prototype rock; v 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:

$$K = \left(\frac{\xi_p}{2\sqrt{\lambda}}\right)\left[\left(\frac{1+4\lambda^{\frac{3}{2}}(1+\xi_p)}{{\xi_p}^2}\right)^{\frac{1}{2}} - 1\right] \qquad 2.3$$

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 been made. Experimental work by Engelund, (1953) suggested values for the empirical coefficients of α_o = 1500 and $ß_o$ = 3.6. The maximum prototype velocity in the mound was estimated at 0.5-1.0 m/s from simple calculations of wave velocities and comparisons with velocities calculated by a mathematical model of flow in rubble mounds. The porosity of the rock mound, *n*, used the standard value of 37% (The Rock Manual, CIRIA, 2007).

2.3.2. Rock scaling for stability

Differences between the density of the model and prototype armour rock, and between the model and prototype fluids, mean that, without compensation, the stability of the armour in the model would be different from that in the prototype. It was therefore necessary to correct the size of rock to be used in the model, so that it exhibits the same stability characteristics as the prototype.

A correction factor for density may be derived by reference to the Hudson equation (CERC, 1984) which states:

$$M\alpha \frac{\rho_s H_s^3}{\left(\frac{\rho_s}{\rho_f} - 1\right)^3 \cot\theta} \qquad 2.4$$

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:

$$M_m = M_p \frac{C_f}{\lambda^3} \qquad 2.5$$

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

$$C_f = \frac{\rho_{sm}}{\rho_{sp}} \left[\left(\frac{\rho_{sp}}{\rho_{fp}} - 1\right) / \left(\frac{\rho_{sm}}{\rho_{fm}} - 1\right) \right]^3 \qquad 2.6$$

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

2.4. Wave calibration

2.4.1. Phase 1– Transmission tests

All Phase 1 sea-states were defined by their monochromatic wave height, *H*, wave period, *T*, still water level, SWL and storm/test duration. Test conditions were calibrated in the flume after construction of the model bathymetry, but before construction of the test sections, to minimise corruption of the incident waves by reflections. The objective of the calibration process was to produce the wave conditions at the structure. The target calibration conditions are discussed in Section 3 of this report and the results of the wave calibrations are given in Section 4.

HR Wallingford's standard procedure for wave calibration is only applicable to a random series of waves that form a particular spectral shape. Typically, 1000 waves are generated, their spectral parameters analysed, and a reflection coefficient calculated. This reflection coefficient is then used to determine the incident and reflected components of the measured signal. The incident part of the measured spectrum is then compared with the target until the spectral wave height is within calibration tolerance.

For Phase 1, short (20 x model wave period duration) monochromatic wave packets were used. The wave heights and periods were determined by zero-crossing statistical analysis rather than spectral analysis. The measured wave height and period are compared directly to the target values, without any reflection coefficient applied. This is possible because the wave packet is so short that reflections do not influence the measured signal.

2.4.2. Phase 2 – Stability tests

All Phase 2 sea-states were defined by their spectral wave height, H_{m0}, peak period, T_p, still water level, SWL, peak enhancement factor, γ, and storm/test duration. Test conditions were calibrated in the flume after construction of the model bathymetry, but before construction of the test section, to minimise corruption of the incident waves by reflections. The objective of the calibration process was to produce the wave conditions at the toe of the structure. The target calibration conditions are discussed in Section 3.1.2 of this report and the results of the wave calibrations are given in Section 4.2.

The general procedure for wave calibration is an iterative process whereby the amplitude of the signal driving the wave generator is adjusted until the spectral significant wave height measured at the calibration point is within ±5% of the target significant prototype wave height. This involved the use of an in-line array of four wave gauges which was used to measure the incident waves. Time histories recorded at each wave gauge were then analysed spectrally by HR Wallingford's HR-Daq software to give the following parameters:

- Significant incident spectral wave height, H_{m0i};
- The mean spectral wave period, $T_{m0,2}$, defined using the zeroth and 2nd moments of the frequency spectrum;
- The spectral wave period, $T_{m-1,0}$, defined using the inverse and zeroth moments of the frequency spectrum.

For the present study, all the waves at the structure were defined at the toe of the structure, and in all cases the waves were breaking as they transferred from offshore to the structure. This was as expected as it was known that the waves would be affected by depth limited breaking. As waves break, there is a loss and transfer of energy within each frequency band, with the subsequent result that the recorded spectra no longer represents that generated offshore at the paddle or the target spectra. As an example, for wave condition WC_EXT_WL_02 (see Table 3.2) the wave spectrum recorded during wave calibration is shown in Figure 2.4. Under these circumstances, the spectral significant wave height (H_{m0}) calculated from the measured spectrum will be significantly different from the H_{m0} calculated form the target spectrum, it being defined by the integration under spectrum (m_0).

The criterion for the calibration of the wave conditions for the stability tests, was therefore to take the measured value of $H_{1/3}$, and compared with the H_s values supplied by SmithGroup (presented in Table 4.2). This calibration method was discussed and agreed with SmithGroup's onsite representative during the wave calibration process once the heavily broken nature of the wave conditions was understood.

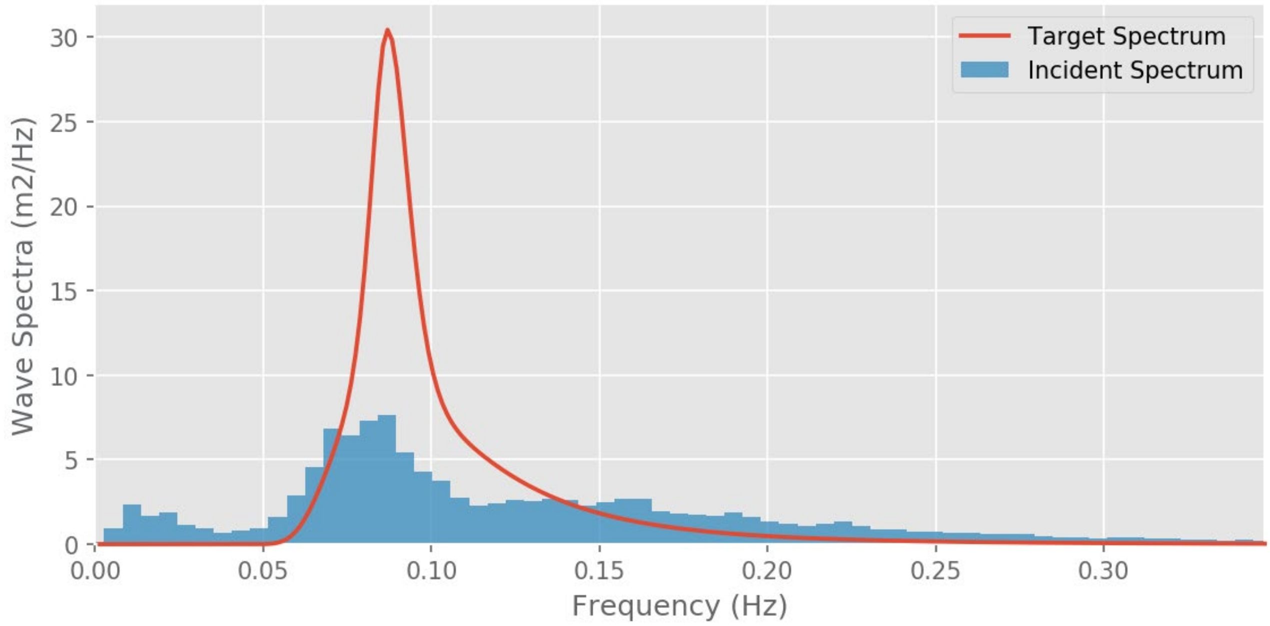

Figure 2.4: Wave condition WC_EXT_WL_02, showing significant transfer of Incident spectral wave energy due to wave breaking against the idealised Target spectrum

2.5. Measurements

2.5.1. Wave transmission

The wave transmission coefficient (C_t) was calculated from the incident wave height (taken from the wave calibration run without the structure present) and the transmitted wave height (taken from the relevant Test Part).

$$C_t = \frac{H_t}{\mathrm{H_i}} \quad 2.7$$

where C_t is the transmission coefficient (%), H_t is the transmitted wave height measured during a Test Part and H_i is the incident wave height measured during wave calibrations.

Transmission coefficients were calculated for the individual wave gauges positioned leeward of the structures (Table 2.1). Mean transmission coefficients were determined from all wave gauges, with the exception of those embedded within the structure, as representative for that particular structure and are the values presented in the results Section (6). A full set of transmission coefficients at each wave gauge location is provided separately in Appendix A. A summary of the wave gauges used to calculate the average coefficients is presented in Table 2.3 as selected by SmithGroup onsite representative.

Table 2.3: Wave gauges used to calculate structure average transmission coefficient

Structure type	Specific structure	Wave gauges used to determine the mean transmission coefficients
Emergent (Phase 1)	Structure_01	WG03 to WG08
Emergent (Phase 1)	Structure_02	WG04 to WG08
Emergent (Phase 1)	Structure_03	WG03 to WG08
Fish Street (Phase 1)	All	WG03 to WG08
Submerged (Phase 1)	All	WG03 to WG08
Habitat (Phase 1)	All	WG06 to WG08
Stability (Phase 2)	All	WG02 to WG05

2.5.2. Armour stability

Rocks displaced from the armour layer and toe were counted using an overlay photograph technique. Photographs were taken from a fixed camera position before and after each Test Part. The images were then superimposed and compared to identify instances of rock extraction. These images were also sent separately to SmithGroup for review.

Following assessment of the number of rocks displaced, the damage parameter, N_{od}, was calculated and then converted to a damage level parameter, S_d, for the armour layer. These calculated damage parameters are reported in Sections 6.2.1 and 6.2.2, respectively for the 6-9 tonne and 3-6 tonne rock armoured structures. The N_{od} number is determined using Equation 2.8 and is defined as the number of displaced stones in a strip one nominal rock diameter (D_{n50}) wide:

$$N_{od} = \frac{N_{displ}}{B/D_{n50}} \qquad 2.8$$

where N_{displ} is the number of displaced stones, B is the width of the test section; determined at the centreline of each section; and D_{n50} is the nominal stone diameter.

The damage parameter, S_d, can be estimated from N_{od} using Equation VI-5-61 from CEM (2002), reproduced here as Equation 2.9.

$$N_d = G(1 - n_v)S_d \qquad 2.9$$

where G is the gradation factor; usually between 1.2 and 1.6 for rock armour; and n_v is porosity with a value here of 0.37. The CEM (2002) and Via-Estrem *et al* (2013) suggest using the approximation shown in Equation 2.10, which for this study corresponds to a conservative approach to the gradation factor, G ≈ 1.2. Equation 2.10 has been used universally throughout the stability analysis of this study to convert N_{od} values to S_d.

$$S_d = 1.4N_{od} \qquad 2.10$$

2.5.3. Performance criteria

Stability or transmission performance criteria were not provided to HR Wallingford for this study. To allow assessment of the stability of the primary armour layers, HR Wallingford assumed the standard values given in Table 5.23 of the Rock Manual (CIRIA, 2007) to assess the performance in terms of S_d (see Table 2.4). For the toe armour, the recommended safe design limit of $N_{od} = 0.5$ was used. The S_d damage parameter was not measured directly within this study, but has been estimated from the N_{od} damage parameter as described in Section 2.5.2 above.

Table 2.4: Design values of the damage parameter, S_d, for armour stone in a double layer with a slope of 1:1.5 and 1:2

Damage level	S_d for 1:1.5 slope (-)	S_d for 1:2 slope (-)
Start of damage	2	2
Intermediate damage	3-5	4-6
Failure	8	8

Source: CIRIA, 2007

2.6. Test sections

2.6.1. Phase 1 – Transmission tests

The structures tested during Phase 1 fell into four categories: Emergent; Fish Street (Fish Fingers); Submerged; and Habitat. The structures evolved during testing based on the results of the preceding tests, so formal drawings were not always issued for each structure. The tables below (Table 2.6 to Table 2.9) provide the main parameters for each structure and a reference to any available drawings or selected photographs reproduced in this Section. The grades for the rock armour for the different Phase 1 structures are shown in Table 2.5. The ‘Habitat stone’ for the Habitat structures (Table 2.9) had a nominal size of 5mm model (email “12324 - IBSP Habitat Cross Section - 2D Flume” on August 20, 2020).

Table 2.5: Rock armour grades for Phase 1 structures

Structure type	Structure number	Armour grade	Source
Emergent	01 to 03	6-9 tonne	2020-0804 Flume Testing v0.xlsx
Fish Street	04 to 14	6-9 tonne	2020-0804 Flume Testing v0.xlsx
Submerged	15 to 18	1-2 tonne	2020-0804 Flume Testing v0.xlsx
Habitat	19 to 32	6-9 tonne	2020-0820 Flume Testing v5.xlsm

Table 2.6: Emergent structure parameters

Structure	Structure height (ft)	Crest width (ft)	Seaward slope	Notes	Drawing or photograph reference
Structure_01	27	13.5	1:1.5	Permeable rock crest	Figure 2.5 and Figure 2.6
Structure_02	27	27	1:1.5	Permeable rock crest	Figure 2.5
Structure_03	27	13.5	1:1.5	Impermeable plywood crest 7ft deep	Figure 2.5

Table 2.7: Fish Street (Fish Finger) structure parameters

Structure	Structure height (ft)	Crest width (ft)	Seaward slope	Fish Finger height (ft)	Fish Finger length (ft)	Notes	Drawing or photograph reference
Structure_04	27	13.5	1:1.5	17	60	Impermeable plywood crest	Figure 2.7, Figure 2.8 and Figure 2.9
Structure_05	26	13.5	1:1.5	17	60	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_06	25	13.5	1:1.5	17	60	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_07	25	13.5	1:1.5	17	40	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_08	24	13.5	1:1.5	17	40	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_09	23	13.5	1:1.5	17	40	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_10	25	13.5	1:1.5	17	20	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_11	24	13.5	1:1.5	17	20	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_12	23	13.5	1:1.5	17	20	Impermeable plywood crest	Figure 2.7 and Figure 2.8
Structure_13	25	13.5	1:1.5	17	20	Permeable rock crest	Figure 2.7 and Figure 2.8
Structure_14	25	13.5	1:1.5	17	40	Permeable rock crest	Figure 2.7 and Figure 2.8

Table 2.8: Submerged structure parameters

Structure	Structure height (ft)	Crest width (ft)	Seaward slope	Drawing or photograph reference
Structure_15	19	13.5	1:1.5	Figure 2.10 and Figure 2.11
Structure_16	19	13.5	1:4	Figure 2.10 and Figure 2.12
Structure_17	19	13.5	1:6	Figure 2.10 and Figure 2.13
Structure_18	19	13.5	1:8	Figure 2.10 and Figure 2.14

Table 2.9: Habitat structure parameters

Structure	Seaward structure height (ft)	Seaward Crest width (ft)	Distance between crests (ft)	Leeward Crest width (ft)	Seaward slope	Drawing or photograph reference
Structure_19	26	13.5	70	13.5	1:1.5	Figure 2.15 and Figure 2.16
Structure_20	25	13.5	70	13.5	1:1.5	Figure 2.15
Structure_21	24	13.5	70	13.5	1:1.5	Figure 2.15
Structure_22	23	13.5	70	13.5	1:1.5	Figure 2.15
Structure_23	22	13.5	70	13.5	1:1.5	Figure 2.15
Structure_24	21	13.5	70	13.5	1:1.5	Figure 2.15
Structure_25	20	13.5	70	13.5	1:1.5	Figure 2.15
Structure_26	26	13.5	95	13.5	1:1.5	Figure 2.15
Structure_27	25	13.5	95	13.5	1:1.5	Figure 2.15
Structure_28	24	13.5	95	13.5	1:1.5	Figure 2.15
Structure_29	23	13.5	95	13.5	1:1.5	Figure 2.15
Structure_30	22	13.5	95	13.5	1:1.5	Figure 2.15
Structure_31	21	13.5	95	13.5	1:1.5	Figure 2.15
Structure_32	20	13.5	95	13.5	1:1.5	Figure 2.15

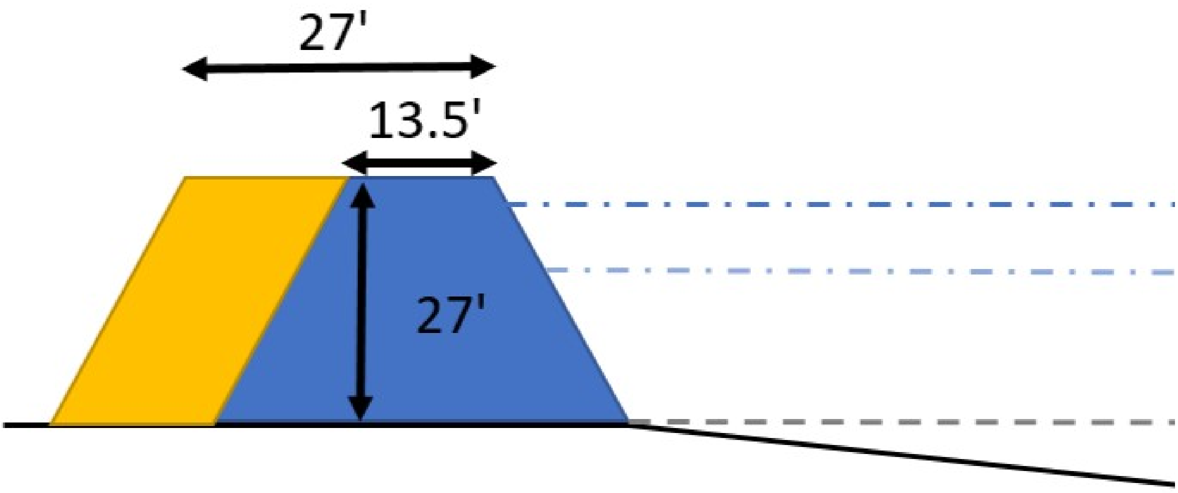

Figure 2.5: Sketch of Emergent structure cross-section (Structure_01 to 03)

Source: 2020-0804 Flume Testing v1.xlsx

Figure 2.6: Photograph of Structure_01 in flume prior to testing

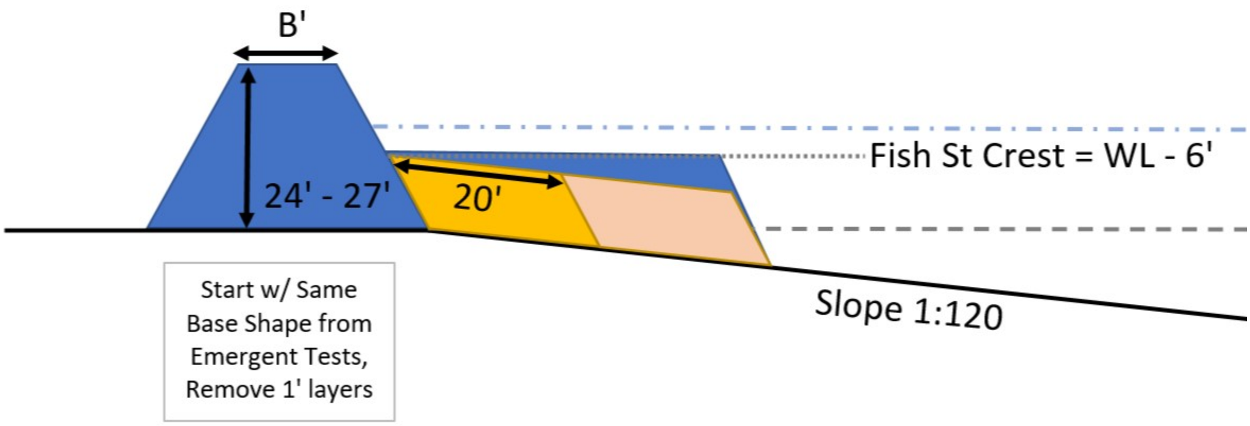

Figure 2.7: Sketch of Fish Street (Fish Finger) structure cross-section (Structure_04 to 14)

Source: 2020-0820 Flume Testing v5.xlsm

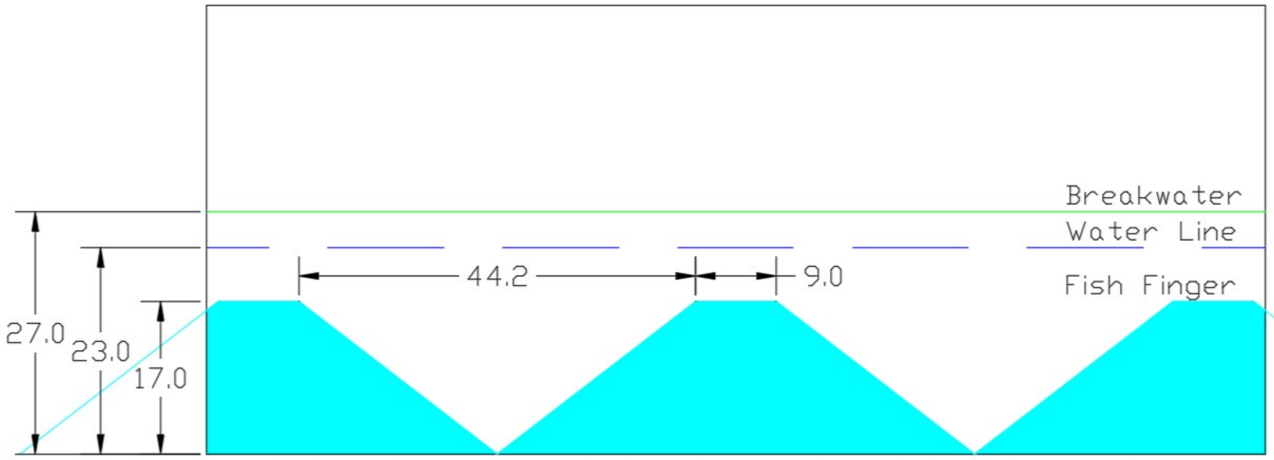

Figure 2.8: Front elevation drawing of Fish Street 'Fish Fingers' (Structures_04 to 14)

Source: 2020-0814 Fish Finger Dimensions.dwg

Figure 2.9: Photograph of Structure_04 in flume prior to testing

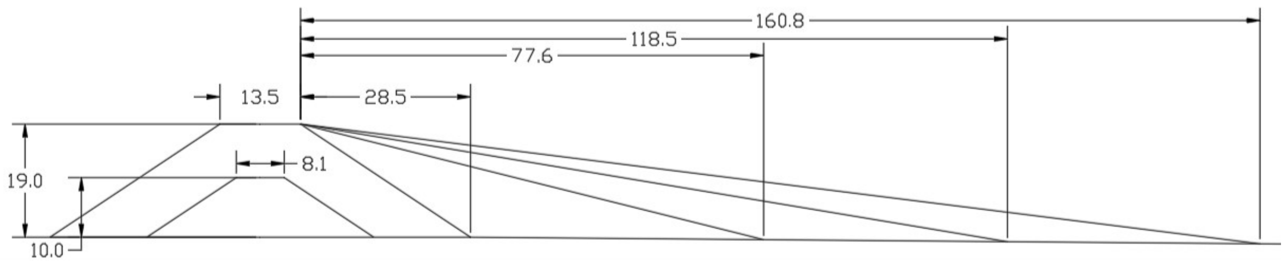

Figure 2.10: Cross-section drawing for Submerged structures showing all four slopes (Structure_15 to 18)

Source: 2020-0816 Submerged Breakwater Dimensions.dwg

Figure 2.11: Photograph of Structure_15 in flume prior to testing

Figure 2.12: Photograph of Structure_16 in flume prior to testing

Figure 2.13: Photograph of Structure_17 in flume prior to testing

Figure 2.14: Photograph of Structure_18 in flume prior to testing

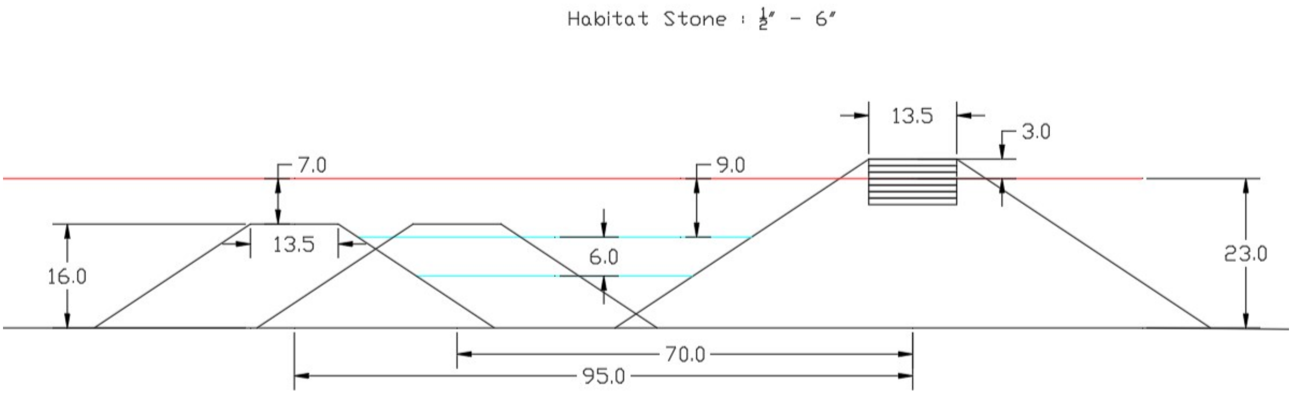

Figure 2.15: Cross-section drawing for Habitat structures showing both widths of habitat zone (Structure_19 to 32)

Source: 2020-0820 Habitat Breakwater Dimensions.dwg

Figure 2.16: Photograph of Structure_19 in flume prior to testing

2.6.2. Phase 2 – Stability tests

The cross-sections for the structures tested for stability are shown in Figure 2.17 and Figure 2.18. The structure dimensions for the physical model tests were confirmed to HR Wallingford in *2020-0902 Stability Cross Sections.dwg*. The rectangular block on the leeward side of the structure (right hand of Figure 2.17 and Figure 2.18) was an impermeable block modelled using engineering bricks in the 2D model (Figure 2.19). Two different rock armour grades were tested, 6-9 tonne and 3-6 tonne (metric tonnes). The target grading limits are given in Table 2.10 in prototype kg and Table 2.11 in prototype lbs. The grade curves of the prepared model armour rock classes are given Figure 2.20 and Figure 2.21 for the 6-9 tonne and 3-6 tonne armour rock, respectively. The 6-9 tonne structure had a slope of 1:1.5 and toe rock grade of 0.2-1.8 tonne. The 3-6 tonne structure had a slope of 1:2 and toe rock grade of 0.2-1 tonne. The prototype rock density was taken to be 2600 kg/m^3 for all rock grades.

Table 2.10: Target rock grading characteristics in kg

Class	ELL (kg)	NLL (kg)	M_{50} (kg)	NUL (kg)	EUL (kg)
6-9 tonne	4200	6000	8038	9000	13500
3-6 tonne	2000	3000	4750	6000	9000
0.2-1.8 tonne	140	200	975	1800	2700
0.2-1 tonne	140	200	638	1000	1500

Table 2.11: Target rock grading characteristics in lbs

Class	ELL (lbs)	NLL (lbs)	M_{50} (lbs)	NUL (lbs)	EUL (lbs)
6-9 tonne	9259	13228	17721	19842	29762
3-6 tonne	4409	6614	10472	13228	19842
0.2-1.8 tonne	309	441	2150	3968	5952
0.2-1 tonne	309	441	1407	2205	3307

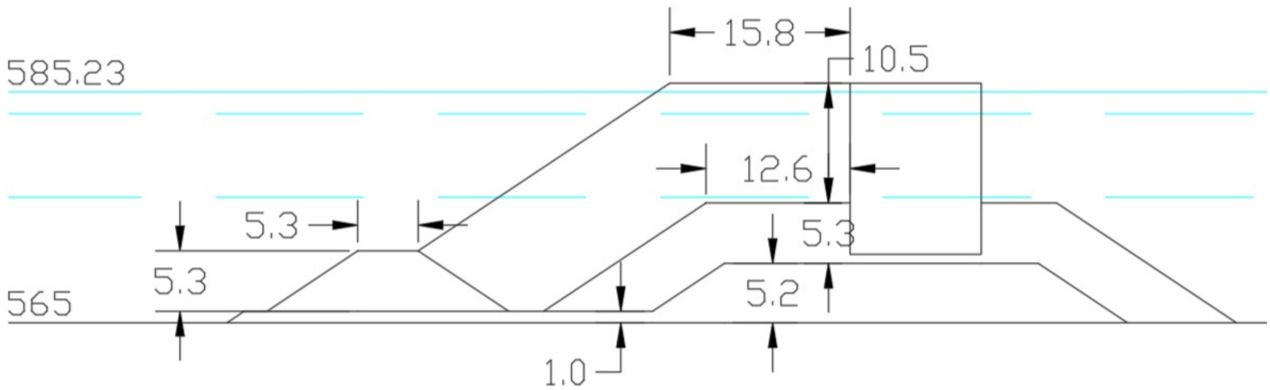

Figure 2.17: 6-9 tonne stability test structure cross-section

Source: 2020-0902 Stability Cross Sections.dwg

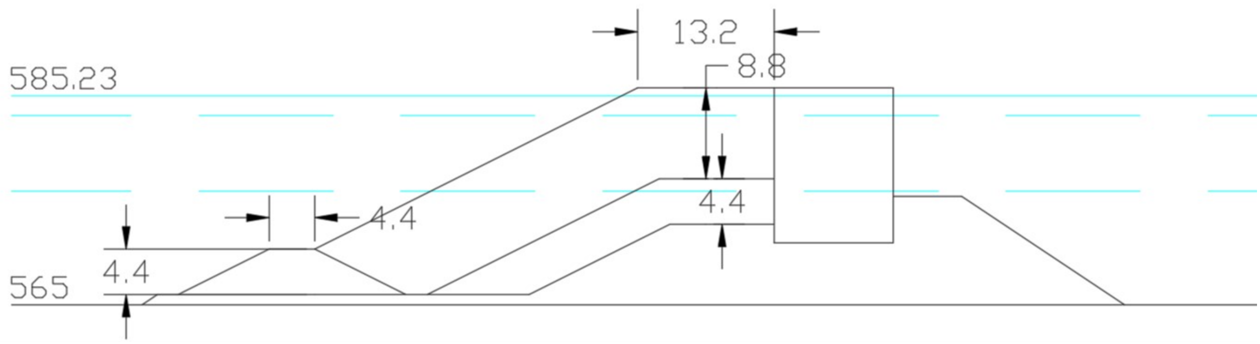

Figure 2.18: 3-6 tonne stability test structure cross-section

Source: 2020-0902 Stability Cross Sections.dwg

Figure 2.19: Representation of the 6-9 tonne rock armoured revetment in the 2D model

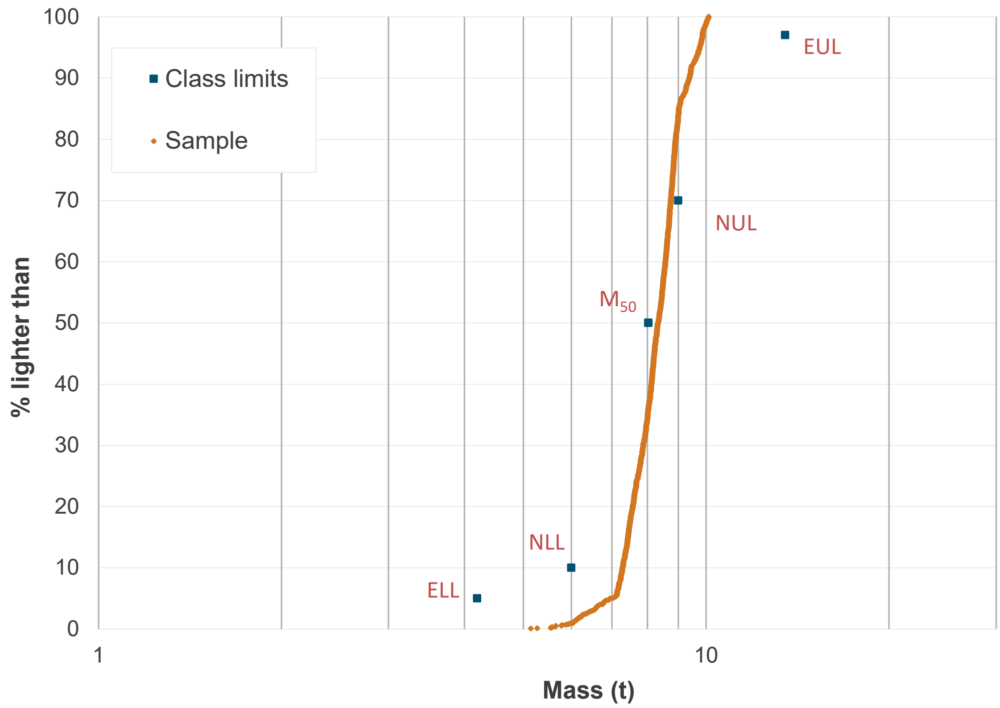

Figure 2.20: Model grading curve for 6-9 tonne armour

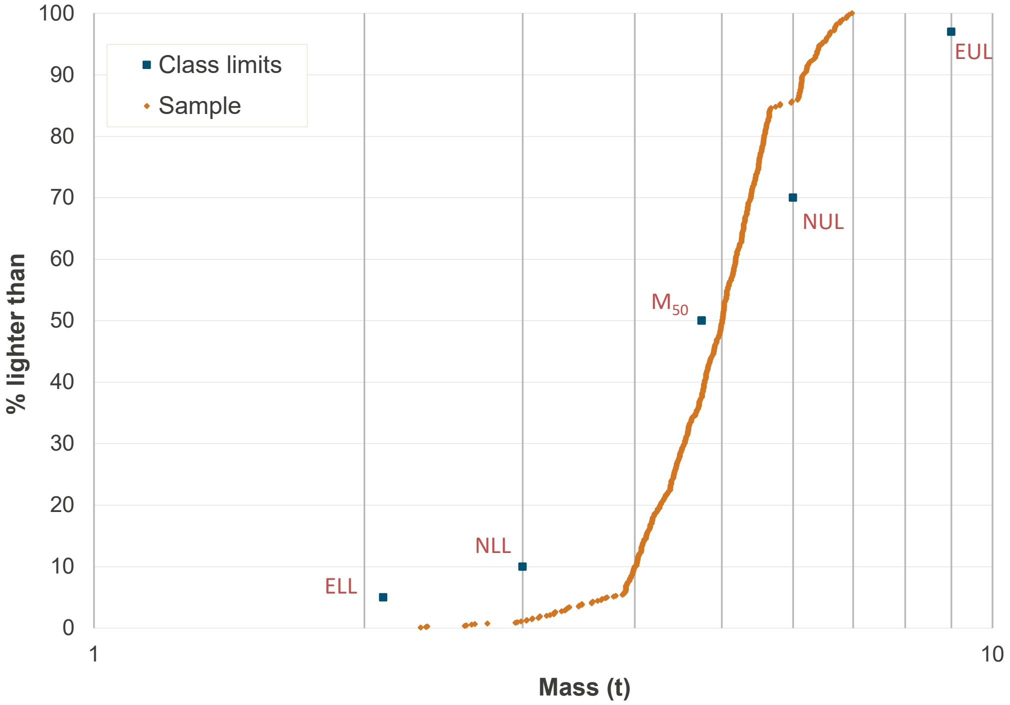

Figure 2.21: Model grading curve for 3-6 tonne armour

3. Test conditions

3.1. Wave conditions and water levels

The wave conditions and water levels for the different phases of 2D modelling are presented in the following sections. The wave conditions for the Phase 1 tests were provided initially in *2020-0804 Flume Testing v0.xlsx* (email "RE: urgent question related to flume tests" on August 04, 2020*)* and cover an envelope of conditions expected at the site. The Phase 2 wave conditions were provided in email "12324 - 2D Flume Stability Testing" on September 03, 2020 and cover extreme storm conditions.

3.1.1. Phase 1 – Transmission tests

The monochromatic wave conditions and water levels used for the transmission testing phase are shown in Table 3.1. Each condition was generated in 'packets' of 20 waves. The toe of the structures (horizontal area of the flume bathymetry) was at 567.5 ft IGLD 85, see Figure 2.1.

Table 3.1: Wave conditions for the Phase 1 transmission tests

Wave condition	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Target wave height, H (ft)	Target wave period, T (s)
Wcon_01_a	593.5	26	6.0	8.0
Wcon_01_b	593.5	26	7.0	8.0
Wcon_01_c	593.5	26	8.0	8.0
Wcon_01_d	593.5	26	10.0	8.0
Wcon_02_a	592.5	25	6.0	8.0
Wcon_02_b	592.5	25	7.0	8.0
Wcon_02_c	592.5	25	8.0	8.0
Wcon_02_d	592.5	25	10.0	8.0
Wcon_03_a	591.5	24	6.0	8.0
Wcon_03_b	591.5	24	7.0	8.0
Wcon_03_c	591.5	24	8.0	8.0
Wcon_03_d	591.5	24	10.0	8.0
Wcon_04_a	590.6	23	6.0	8.0
Wcon_04_b	590.6	23	7.0	8.0
Wcon_04_c	590.6	23	8.0	8.0
Wcon_04_d	590.6	23	10.0	8.0
Wcon_05_a	589.6	22	6.0	8.0
Wcon_05_b	589.6	22	7.0	8.0
Wcon_05_c	589.6	22	8.0	8.0
Wcon_05_d	589.6	22	10.0	8.0
Wcon_06_a	588.6	21	6.0	8.0

Wave condition	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Target wave height, H (ft)	Target wave period, T (s)
Wcon_06_b	588.6	21	7.0	8.0
Wcon_06_c	588.6	21	8.0	8.0
Wcon_06_d	588.6	21	10.0	8.0
Wcon_07_a	587.6	20	6.0	8.0
Wcon_07_b	587.6	20	7.0	8.0
Wcon_07_c	587.6	20	8.0	8.0
Wcon_07_d	587.6	20	10.0	8.0

Source: 2020-0804 Flume Testing v0.xlsx

3.1.2. Phase 2 – Stability tests

The Phase 3 stability tests used a non-repeating sequence of 3,000 random waves during testing with a JONSWAP spectral shape and a peak enhancement factor of $\gamma = 3.3$. The spectral wave parameters for the four conditions are given in Table 3.2. They cover high and low water conditions and a range of periods and wave heights. The toe of the structures (horizontal area of the flume bathymetry) was at 565 ft IGLD 85, see Figure 2.2.

Table 3.2: Wave conditions for the Phase 2 stability tests

Wave condition	Return period	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Target significant wave height, H_{m0} (ft)	Target peak wave period, T_p (s)
WC_LOW_WL	All other	576.0	11.0	7.0	11.5
WC_HIGH_WL	All other	583.3	18.0	11.0	11.5
WC_EXT_WL_01	1:10	585.2	20.0	11.0	10.0
WC_EXT_WL_02	All other	585.2	20.0	12.0	11.5

Source: Email: "12324 - 2D Flume Stability Testing", September 03, 2020

4. Wave calibration results

4.1. Phase 1 – Transmission tests

The results of the Phase 1 wave calibrations are summarised in Table 4.1, which presents the incident wave heights (*H*) and periods (*T*) at the eight wave gauges situated leeward of where the structures were built. The Phase 1 wave calibrations use the method outlined in Section 2.4.1, matching the average wave height from the eight wave gauges to the target.

During testing, Wcon_04_a to _d were run on some of the Fish Street structures instead of Wcon_05_a to _d, but with the Wcon_05 water level. Following testing the structure was removed and these conditions were re-run to get a calibration wave height to allow accurate transmission coefficients to be calculated from these tests. In Table 4.1 these conditions have '_22' appended to them, indicating the reduced water level they were run at.

Table 4.1: Calibrated wave conditions for Phase 1 transmission tests

Wave condition	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Calibration wave period, T (s)	Calibration wave height, H (ft)								
				WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08	Average (WG01 - 08)
Wcon_01_a	682.5	26	8.0	6.31	4.77	5.07	6.36	6.62	6.72	5.04	6.34	5.90
Wcon_01_b	682.5	26	8.0	7.29	5.57	6.15	7.57	7.77	7.91	5.78	7.50	6.94
Wcon_01_c	682.5	26	8.0	8.11	6.29	7.36	8.90	8.82	9.03	6.47	8.72	7.96
Wcon_01_d	682.5	26	8.0	9.75	7.83	9.93	11.69	10.46	11.28	7.76	11.35	10.01
Wcon_02_a	682.5	25	8.0	7.15	5.46	4.55	5.75	7.19	7.12	5.69	6.06	6.12
Wcon_02_b	682.5	25	8.0	8.20	6.09	5.51	7.03	8.40	8.40	6.36	7.30	7.16
Wcon_02_c	682.5	25	8.0	9.61	7.17	6.20	7.98	9.80	9.69	7.53	8.31	8.28
Wcon_02_d	682.5	25	8.0	11.56	8.46	8.61	10.91	12.06	12.31	8.66	10.90	10.43
Wcon_03_a	681.5	24	8.0	7.09	6.74	5.34	4.91	6.92	6.67	6.85	5.65	6.27
Wcon_03_b	681.5	24	8.0	7.68	7.76	7.02	6.49	7.54	7.26	7.82	6.71	7.28
Wcon_03_c	681.5	24	8.0	9.16	8.48	7.00	6.61	8.90	8.29	8.56	7.00	8.00
Wcon_03_d	681.5	24	8.0	12.59	10.84	8.59	9.68	12.12	11.90	10.71	10.27	10.84
Wcon_04_a	680.6	23	8.0	6.64	5.87	5.48	6.29	6.69	6.55	6.08	5.74	6.17
Wcon_04_b	680.6	23	8.0	7.09	8.41	6.92	5.16	6.86	6.77	8.27	5.98	6.93
Wcon_04_c	680.6	23	8.0	8.69	10.17	8.48	6.76	8.24	8.12	10.07	7.28	8.48
Wcon_04_d	680.6	23	8.0	12.15	13.02	10.08	9.15	11.24	10.59	12.42	9.56	11.03

Wave condition	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Calibration wave period, T (s)	Calibration wave height, H (ft)								
				WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08	Average (WG01 - 08)
Wcon_04_a_22	679.6	22	8.0	5.22	6.31	6.72	5.53	4.92	5.29	5.38	5.20	5.57
Wcon_04_b_22	679.6	22	8.0	5.77	8.01	7.46	4.96	5.71	5.91	6.23	6.16	6.27
Wcon_04_c_22	679.6	22	8.0	7.44	10.17	8.49	5.74	7.41	7.77	7.79	7.74	7.82
Wcon_04_d_22	679.6	22	8.0	10.53	13.39	10.30	7.88	9.81	9.54	10.20	10.13	10.22
Wcon_05_a	679.6	22	8.0	5.05	6.45	7.61	6.69	4.81	4.68	7.62	4.71	5.95
Wcon_05_b	679.6	22	8.0	6.56	8.98	8.29	6.42	6.42	6.23	9.14	6.07	7.26
Wcon_05_c	679.6	22	8.0	6.90	8.33	10.42	9.85	6.90	6.52	9.96	6.51	8.17
Wcon_05_d	679.6	22	8.0	11.37	13.43	10.90	8.98	10.50	9.77	13.37	9.57	10.99
Wcon_06_a	678.6	21	8.0	5.07	6.14	7.74	7.13	4.73	4.56	7.56	4.64	5.95
Wcon_06_b	678.6	21	8.0	5.74	7.33	9.18	8.13	5.09	5.19	8.86	5.39	6.86
Wcon_06_c	678.6	21	8.0	7.62	8.19	9.63	10.22	7.73	7.11	9.32	6.61	8.30
Wcon_06_d	678.6	21	8.0	9.94	12.56	13.28	10.28	9.50	8.41	14.09	9.09	10.89
Wcon_07_a	677.6	20	8.0	6.75	4.91	6.28	8.05	6.40	5.98	6.10	5.15	6.20
Wcon_07_b	677.6	20	8.0	7.63	5.96	7.49	9.49	7.53	6.82	7.08	6.04	7.25
Wcon_07_c	677.6	20	8.0	7.88	7.36	9.34	10.75	7.88	7.27	8.89	6.89	8.28
Wcon_07_d	677.6	20	8.0	9.08	10.55	12.54	13.20	9.57	9.02	11.65	8.41	10.50

4.2. Phase 2 – Stability tests

The results of the Phase 2 wave calibrations are summarised in Table 4.2, which presents the target wave heights (H_{m0}) and periods (T_p) at the structure, along with the measured $H_{1/3}$ as discussed in Section 2.4.2. The wave heights used as the incident condition for the transmission coefficient analysis of the stability structures are provided in Table 4.3.

Table 4.2: Results of wave calibration for Phase 2 stability tests

Wave condition	Target		Measured
	H_{m0} (ft)	T_p (s)	$H_{1/3}$ (ft)
WC_LOW_WL	7.0	11.5	6.00
WC_HIGH_WL	11.0	11.5	10.75
WC_EXT_WL_01	11.0	10.0	11.71
WC_EXT_WL_02	12.0	11.5	12.36

Table 4.3: Phase 2 incident wave heights for transmission coefficient analysis

Wave condition	Tp (s)	Incident wave height, $H_{1/3}$ (ft)					
		WG01	WG02	WG03	WG04	WG05	Average (WG02-05)
WC_LOW_WL	11.5	5.96	6.15	5.88	6.17	5.81	6.00
WC_HIGH_WL	11.5	11.38	11.06	10.89	10.72	10.35	10.75
WC_EXT_WL_01	10.0	12.47	11.95	11.70	11.75	11.45	11.71
WC_EXT_WL_02	11.5	13.86	12.66	12.40	12.35	12.04	12.36

5. Test Programme

The Test Programme consisted of two phases of testing covering various different structures. For Phase 1, the different structures fell into four categories, Emergent, Fish Street (Fish Fingers), Submerged and Habitat, details of which are provided in Section 2.6.1. Each structure was tested with a variety of wave conditions which are indicated in the results tables in Section 6.1.

During Phase 2 the stability of the structures was tested. Following calibration of the wave conditions described in Section 2.4.2, the 6-9 tonne armoured structure was constructed and tested with the sequence of wave conditions in Table 5.1. The structure was not repaired between Test Parts, resulting in cumulative damage throughout the Test Series. Following completion of these tests, the armour was removed, the front slope changed, and 3-6 tonne armour placed. The 3-6 tonne armoured structure was again tested cumulatively with the sequence given in Table 5.1.

Table 5.1: Phase 3 stability test sequence of wave conditions

Test Part	Wave condition	Return period	Depth at toe, h (ft)	Target significant wave height, H_{m0} (ft)	Target peak wave period, T_p (s)
01	WC_LOW_WL	All other	11	7.0	11.5
02	WC_HIGH_WL	All other	18	11.0	11.5
03	WC_EXT_WL_01	1:10	20	11.0	10.0
04	WC_EXT_WL_02	All other	20	12.0	11.5

6. Results

The results section is divided into the two Phases of testing, and, for Phase 1, further subdivided by the structure type.

6.1. Phase 1 – Transmission test results

The transmission coefficients presented in this section were calculated using the method described in Section 2.5.1. The different structures tested are described in Section 2.6.1.

6.1.1. Emergent structure test results

The results for each emergent structure (Structure_01 to Structure_03) are presented in Table 6.1 to Table 6.3, respectively. A summary of these results is shown in Figure 6.1 for Structures_01 and 02, from which it can be observed that there is a clear linear decrease in transmission as the freeboard increases. Additionally, the reduced transmission for a wider crest appears to be independent of the freeboard as demonstrated by the parallel offset of the two central trendlines. A similar trend is observed in Figure 6.2 with a reduced transmission coefficient when the crest is made impermeable.

Table 6.1: Emergent Structure_01 average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_01	Wcon_03_a	3.0	6	8.0	42%
	Wcon_03_b	3.0	7	8.0	46%
	Wcon_03_c	3.0	8	8.0	52%
	Wcon_03_d	3.0	10	8.0	50%
	Wcon_04_a	4.0	6	8.0	31%
	Wcon_04_b	4.0	7	8.0	35%
	Wcon_04_c	4.0	8	8.0	43%
	Wcon_04_d	4.0	10	8.0	44%
	Wcon_05_a	5.0	6	8.0	22%
	Wcon_05_b	5.0	7	8.0	28%
	Wcon_05_c	5.0	8	8.0	34%
	Wcon_05_d	5.0	10	8.0	37%
	Wcon_06_a	6.0	6	8.0	20%
	Wcon_06_b	6.0	7	8.0	24%
	Wcon_06_c	6.0	8	8.0	26%
	Wcon_06_d	6.0	10	8.0	32%
	Wcon_07_a	7.0	6	8.0	17%
	Wcon_07_b	7.0	7	8.0	19%

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
	Wcon_07_c	7.0	8	8.0	23%
	Wcon_07_d	7.0	10	8.0	29%

Table 6.2: Emergent Structure_02 average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_02	Wcon_02_a	2.0	6	8.0	32%
	Wcon_02_b	2.0	7	8.0	36%
	Wcon_02_c	2.0	8	8.0	40%
	Wcon_02_d	2.0	10	8.0	44%
	Wcon_03_a	3.0	6	8.0	24%
	Wcon_03_b	3.0	7	8.0	29%
	Wcon_03_c	3.0	8	8.0	35%
	Wcon_03_d	3.0	10	8.0	38%
	Wcon_04_a	4.0	6	8.0	15%
	Wcon_04_b	4.0	7	8.0	18%
	Wcon_04_c	4.0	8	8.0	23%
	Wcon_04_d	4.0	10	8.0	35%
	Wcon_05_a	5.0	6	8.0	13%
	Wcon_05_b	5.0	7	8.0	14%
	Wcon_05_c	5.0	8	8.0	19%
	Wcon_05_d	5.0	10	8.0	23%
	Wcon_06_a	6.0	6	8.0	13%
	Wcon_06_b	6.0	7	8.0	13%
	Wcon_06_c	6.0	8	8.0	12%
	Wcon_06_d	6.0	10	8.0	20%

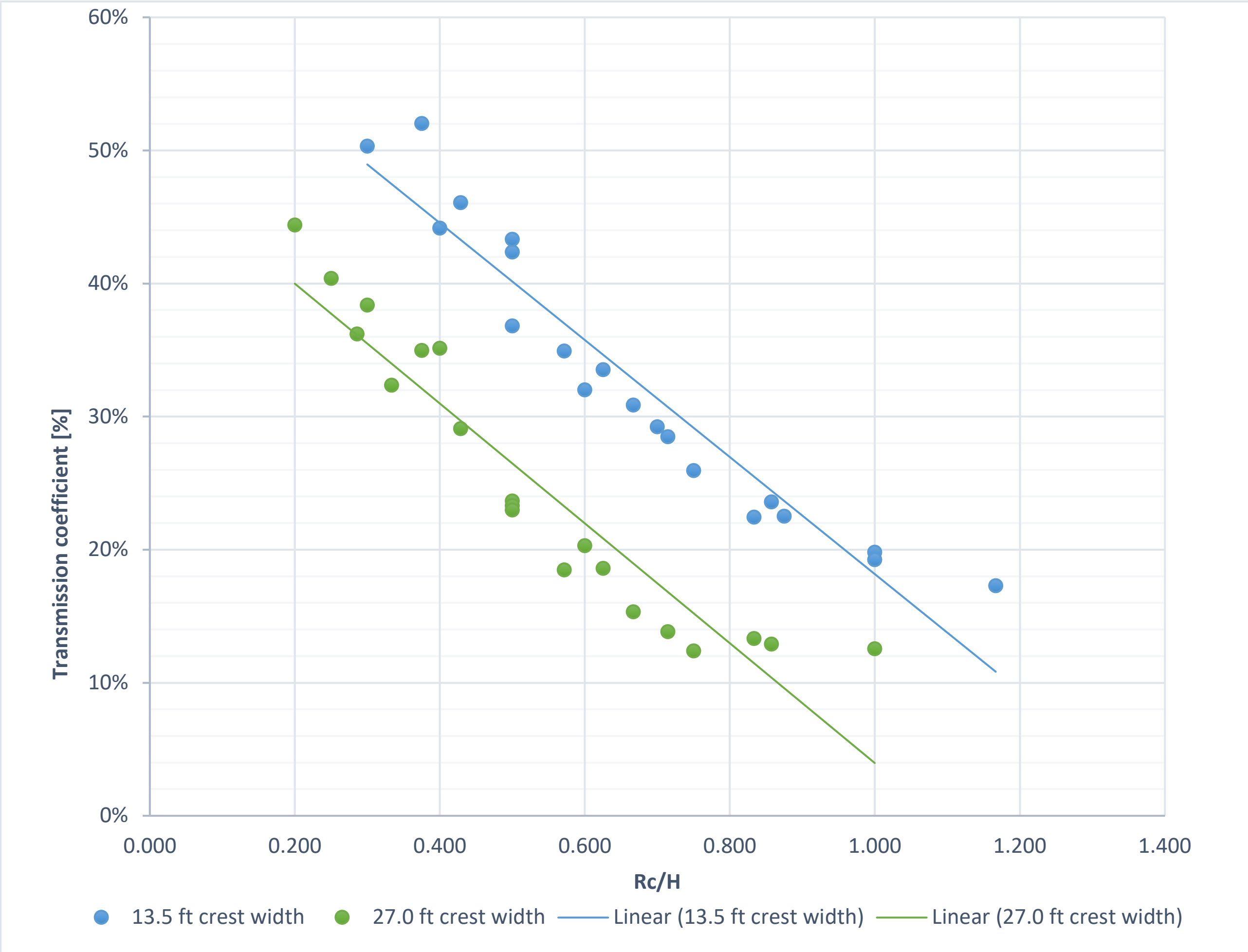

Figure 6.1: Emergent structure transmission – influence of crest width

Table 6.3: Emergent Structure_03 average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_03	Wcon_03_a	3.0	6	8.0	31%
	Wcon_03_b	3.0	7	8.0	37%
	Wcon_03_c	3.0	8	8.0	45%
	Wcon_03_d	3.0	10	8.0	47%
	Wcon_04_a	4.0	6	8.0	18%
	Wcon_04_b	4.0	7	8.0	25%
	Wcon_04_c	4.0	8	8.0	34%
	Wcon_04_d	4.0	10	8.0	40%
	Wcon_05_a	5.0	6	8.0	11%
	Wcon_05_b	5.0	7	8.0	18%
	Wcon_05_c	5.0	8	8.0	24%
	Wcon_05_d	5.0	10	8.0	34%
	Wcon_02_a	6.0	6	8.0	41%
	Wcon_02_b	6.0	7	8.0	44%
	Wcon_02_c	6.0	8	8.0	47%
	Wcon_02_d	6.0	10	8.0	49%
	Wcon_06_a	7.0	6	8.0	10%
	Wcon_06_b	7.0	7	8.0	18%
	Wcon_06_c	7.0	8	8.0	20%
	Wcon_06_d	7.0	10	8.0	27%

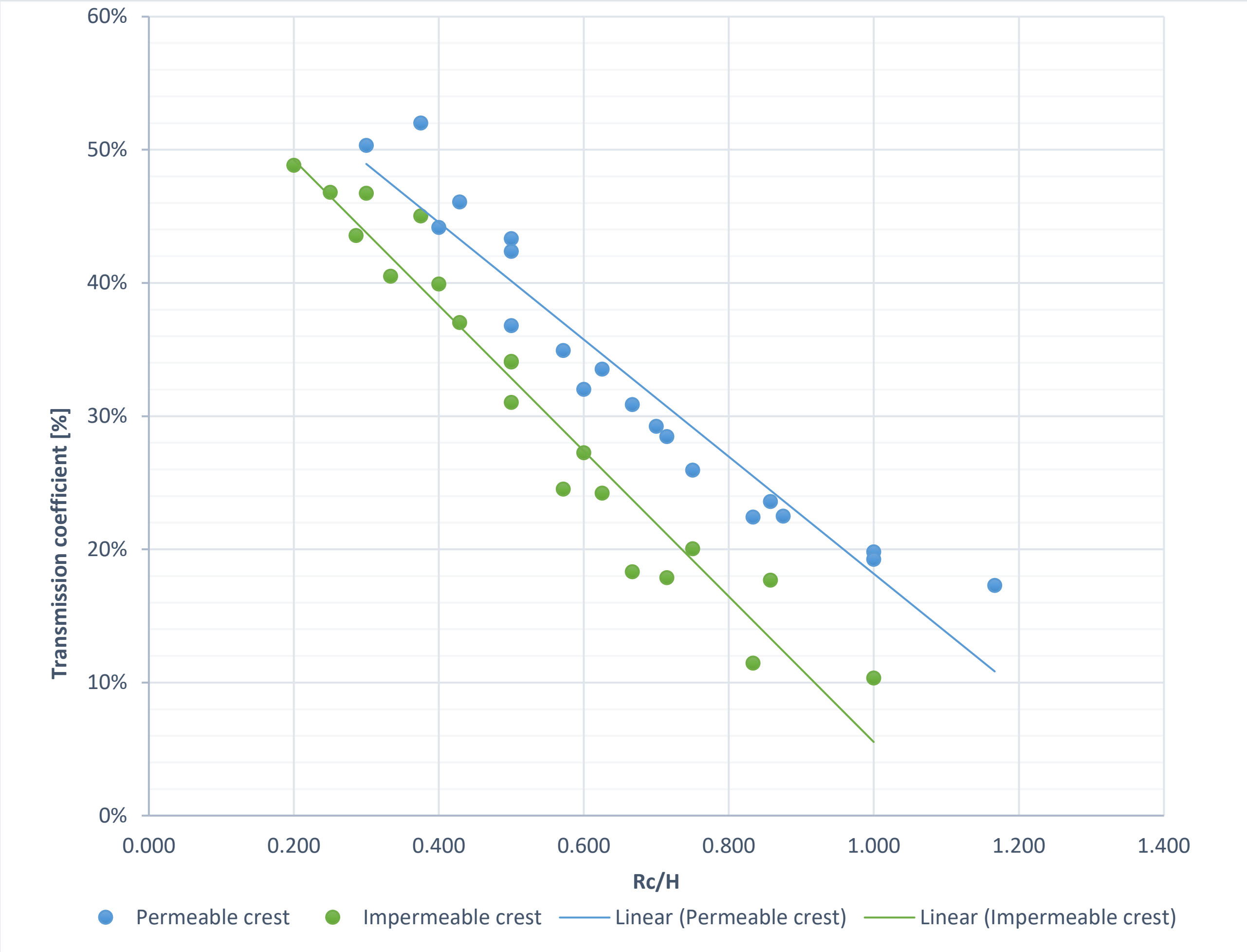

Figure 6.2: Emergent structure transmission – comparison of permeable and impermeable crest

6.1.2. Fish Street test results

The results for the Fish Street (Fish Finger) structures (Structure_04 to Structure_14) are presented in Table 6.4. A summary of these results is shown in Figure 6.3 and , and as expected, transmission reduces as freeboard increases. There is a reduction in transmission with increased Fish Finger length to 40 ft, but increasing further to 60 ft does not result in further reductions. As with the emergent structure results (Section 6.1.1), an impermeable crest results in lower transmission than a permeable one (Figure 6.4).

Table 6.4: Fish Street structures (Structure_04 to Structure_14) average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_04	Wcon_04_a	4.0	6	8.0	19%
	Wcon_04_b	4.0	7	8.0	22%
	Wcon_04_c	4.0	8	8.0	26%
	Wcon_04_d	4.0	10	8.0	26%
Structure_05	Wcon_04_a	3.0	6	8.0	23%
	Wcon_04_b	3.0	7	8.0	26%
	Wcon_04_c	3.0	8	8.0	32%
	Wcon_04_d	3.0	10	8.0	30%
	Wcon_04_a_22	4.0	6	8.0	15%
	Wcon_04_b_22	4.0	7	8.0	17%
	Wcon_04_c_22	4.0	8	8.0	22%
	Wcon_04_d_22	4.0	10	8.0	21%
Structure_06	Wcon_04_a_22	3.0	6	8.0	18%
	Wcon_04_b_22	3.0	7	8.0	19%
	Wcon_04_c_22	3.0	8	8.0	22%
	Wcon_04_d_22	3.0	10	8.0	23%
Structure_07	Wcon_04_a_22	3.0	6	8.0	16%
	Wcon_04_b_22	3.0	7	8.0	17%
	Wcon_04_c_22	3.0	8	8.0	22%
	Wcon_04_d_22	3.0	10	8.0	25%
Structure_08	Wcon_04_a_22	2.0	6	8.0	21%
	Wcon_04_b_22	2.0	7	8.0	24%
	Wcon_04_c_22	2.0	8	8.0	27%
	Wcon_04_d_22	2.0	10	8.0	30%
Structure_09	Wcon_04_a_22	1.0	6	8.0	28%
	Wcon_04_b_22	1.0	7	8.0	30%
	Wcon_04_c_22	1.0	8	8.0	32%

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
	Wcon_04_d_22	1.0	10	8.0	33%
Structure_10	Wcon_05_a	3.0	6	8.0	19%
	Wcon_05_b	3.0	7	8.0	22%
	Wcon_05_c	3.0	8	8.0	27%
	Wcon_05_d	3.0	10	8.0	29%
Structure_11	Wcon_05_a	2.0	6	8.0	25%
	Wcon_05_b	2.0	7	8.0	28%
	Wcon_05_c	2.0	8	8.0	31%
	Wcon_05_d	2.0	10	8.0	33%
Structure_12	Wcon_05_a	1.0	6	8.0	28%
	Wcon_05_b	1.0	7	8.0	33%
	Wcon_05_c	1.0	8	8.0	34%
	Wcon_05_d	1.0	10	8.0	35%
Structure_13	Wcon_05_a	3.0	6	8.0	26%
	Wcon_05_b	3.0	7	8.0	28%
	Wcon_05_c	3.0	8	8.0	30%
	Wcon_05_d	3.0	10	8.0	33%
Structure_14	Wcon_05_a	3.0	6	8.0	23%
	Wcon_05_b	3.0	7	8.0	25%
	Wcon_05_c	3.0	8	8.0	24%
	Wcon_05_d	3.0	10	8.0	28%

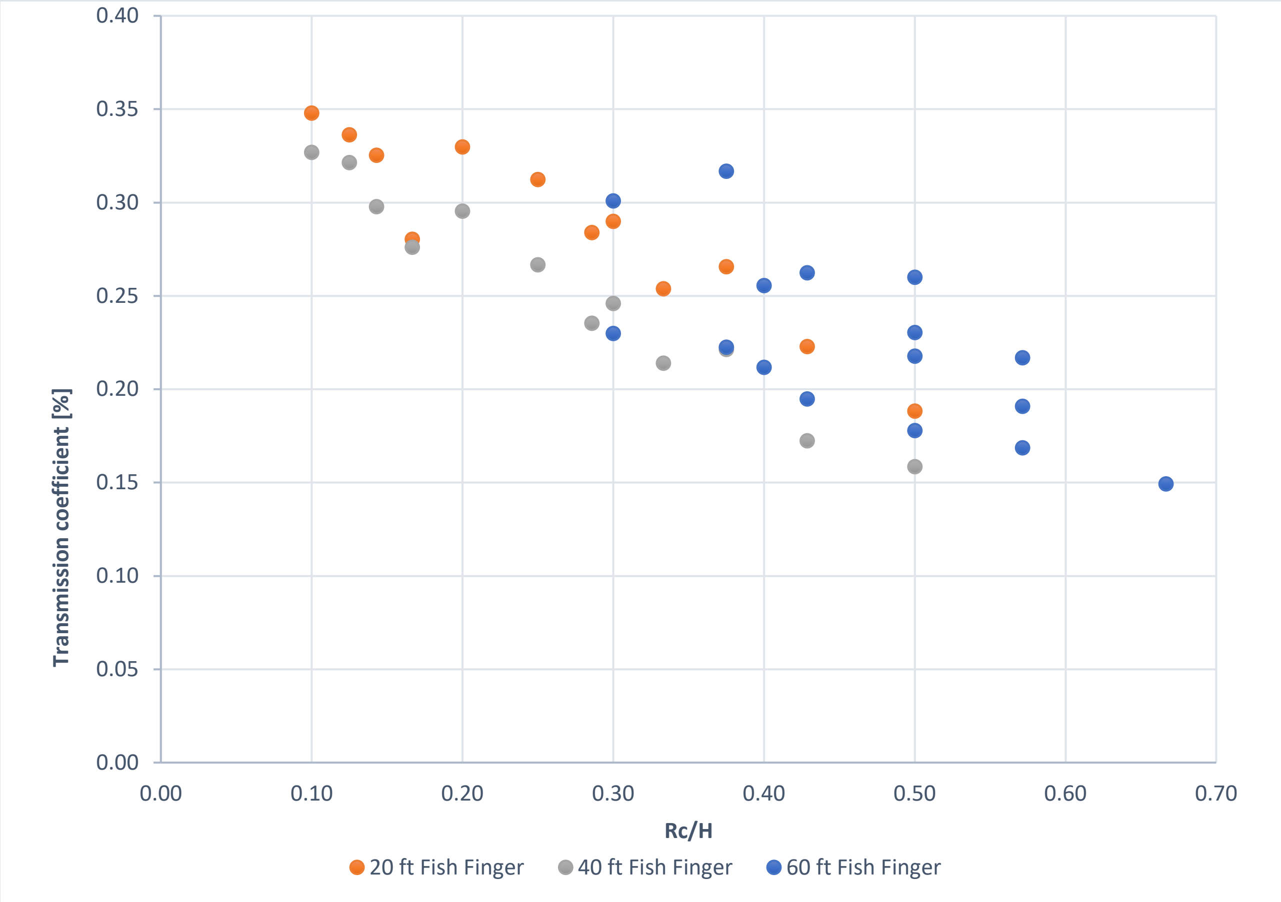

Figure 6.3: Fish finger structure transmission – influence of finger length

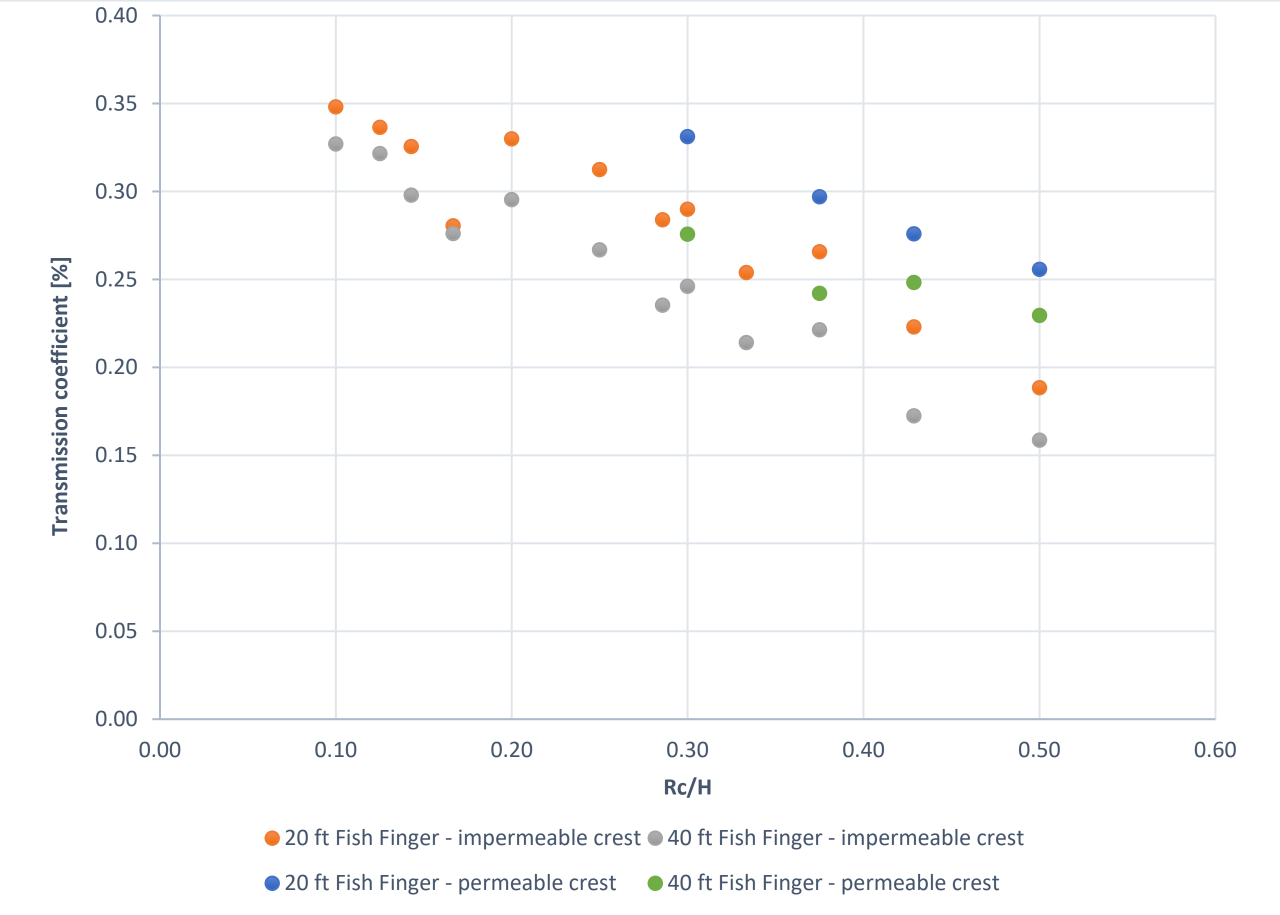

Figure 6.4: Fish finger structure transmission – comparison of permeable and impermeable crest

6.1.3. Submerged structure test results

The results for each submerged structure (Structure_15 to Structure_18) are presented in Table 6.5 to Table 6.8 respectively. A summary of these results is shown in Figure 6.5, which shows that the transmission decreases as the front slope is relaxed, as should be anticipated. As the slope reduces, there is a diminishing return on a reduction in transmission for slopes beyond 1:4.

Table 6.5: Submerged Structure_15 average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_15	Wcon_03_a	-5.0	6	8.0	94%
	Wcon_03_b	-5.0	7	8.0	88%
	Wcon_03_c	-5.0	8	8.0	90%
	Wcon_03_d	-5.0	10	8.0	78%
	Wcon_04_a	-4.0	6	8.0	83%
	Wcon_04_b	-4.0	7	8.0	83%
	Wcon_04_c	-4.0	8	8.0	82%
	Wcon_04_d	-4.0	10	8.0	73%
	Wcon_05_a	-3.0	6	8.0	79%
	Wcon_05_b	-3.0	7	8.0	75%
	Wcon_05_c	-3.0	8	8.0	71%
	Wcon_05_d	-3.0	10	8.0	63%
	Wcon_06_a	-2.0	6	8.0	71%
	Wcon_06_b	-2.0	7	8.0	67%
	Wcon_06_c	-2.0	8	8.0	59%
	Wcon_06_d	-2.0	10	8.0	58%
	Wcon_07_a	-1.0	6	8.0	64%
	Wcon_07_b	-1.0	7	8.0	58%
	Wcon_07_c	-1.0	8	8.0	57%
	Wcon_07_d	-1.0	10	8.0	55%

Table 6.6: Submerged Structure_16 average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_16	Wcon_03_a	-5.0	6	8.0	93%
	Wcon_03_b	-5.0	7	8.0	86%
	Wcon_03_c	-5.0	8	8.0	84%
	Wcon_03_d	-5.0	10	8.0	71%
	Wcon_04_a	-4.0	6	8.0	75%
	Wcon_04_b	-4.0	7	8.0	75%
	Wcon_04_c	-4.0	8	8.0	71%
	Wcon_04_d	-4.0	10	8.0	65%
	Wcon_05_a	-3.0	6	8.0	70%
	Wcon_05_b	-3.0	7	8.0	67%
	Wcon_05_c	-3.0	8	8.0	63%
	Wcon_05_d	-3.0	10	8.0	57%
	Wcon_06_a	-2.0	6	8.0	63%
	Wcon_06_b	-2.0	7	8.0	61%
	Wcon_06_c	-2.0	8	8.0	54%
	Wcon_06_d	-2.0	10	8.0	51%
	Wcon_07_a	-1.0	6	8.0	49%
	Wcon_07_b	-1.0	7	8.0	50%
	Wcon_07_c	-1.0	8	8.0	48%
	Wcon_07_d	-1.0	10	8.0	47%

Table 6.7: Submerged Structure_17 average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_17	Wcon_03_a	-5.0	6	8.0	89%
	Wcon_03_b	-5.0	7	8.0	84%
	Wcon_03_c	-5.0	8	8.0	84%
	Wcon_03_d	-5.0	10	8.0	64%
	Wcon_04_a	-4.0	6	8.0	75%
	Wcon_04_b	-4.0	7	8.0	73%
	Wcon_04_c	-4.0	8	8.0	66%
	Wcon_04_d	-4.0	10	8.0	56%
	Wcon_05_a	-3.0	6	8.0	68%
	Wcon_05_b	-3.0	7	8.0	60%
	Wcon_05_c	-3.0	8	8.0	55%
	Wcon_05_d	-3.0	10	8.0	50%
	Wcon_06_a	-2.0	6	8.0	59%
	Wcon_06_b	-2.0	7	8.0	55%
	Wcon_06_c	-2.0	8	8.0	47%
	Wcon_06_d	-2.0	10	8.0	44%
	Wcon_07_a	-1.0	6	8.0	46%
	Wcon_07_b	-1.0	7	8.0	44%
	Wcon_07_c	-1.0	8	8.0	42%
	Wcon_07_d	-1.0	10	8.0	40%

Table 6.8: Submerged Structure_18 average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_18	Wcon_03_a	-5.0	6	8.0	92%
	Wcon_03_b	-5.0	7	8.0	89%
	Wcon_03_c	-5.0	8	8.0	86%
	Wcon_03_d	-5.0	10	8.0	65%
	Wcon_04_a	-4.0	6	8.0	82%
	Wcon_04_b	-4.0	7	8.0	80%
	Wcon_04_c	-4.0	8	8.0	72%
	Wcon_04_d	-4.0	10	8.0	57%
	Wcon_05_a	-3.0	6	8.0	72%
	Wcon_05_b	-3.0	7	8.0	63%
	Wcon_05_c	-3.0	8	8.0	58%
	Wcon_05_d	-3.0	10	8.0	49%
	Wcon_06_a	-2.0	6	8.0	63%
	Wcon_06_b	-2.0	7	8.0	58%
	Wcon_06_c	-2.0	8	8.0	47%
	Wcon_06_d	-2.0	10	8.0	43%
	Wcon_07_a	-1.0	6	8.0	47%
	Wcon_07_b	-1.0	7	8.0	44%
	Wcon_07_c	-1.0	8	8.0	41%
	Wcon_07_d	-1.0	10	8.0	38%

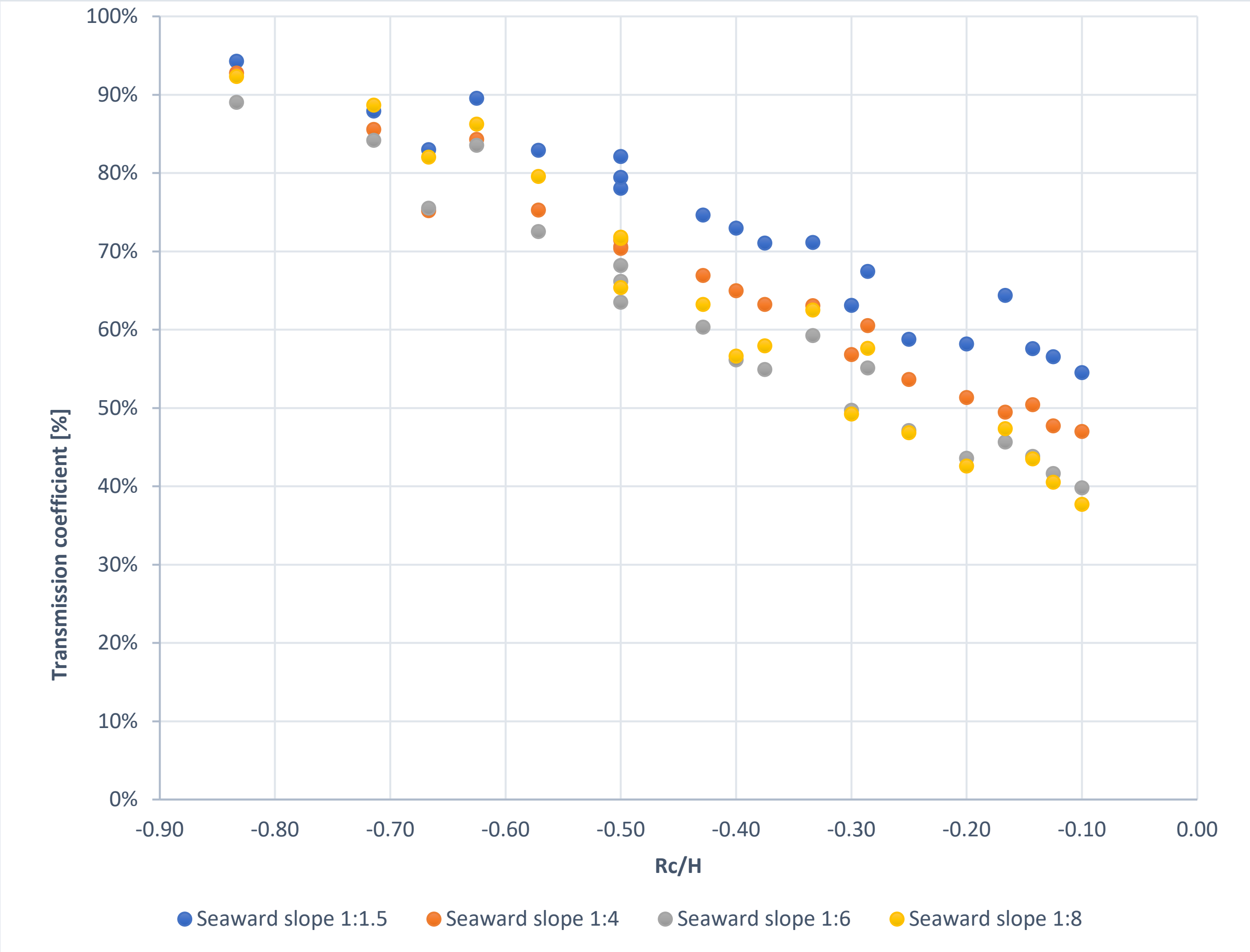

Figure 6.5: Submerged structure transmission

6.1.4. Habitat structure test results

The results for the habitat structures (Structure_19 to Structure_32) are presented in Table 6.9. A summary of these results is shown in Figure 6.6, from which it can be observed that an increase in distance between the crest results in a reduction in wave transmission.

Table 6.9: Habitat structures (Structure_19 to Structure_32) average transmission coefficients

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
Structure_19	Wcon_04_a	3.0	6	8.0	19%
	Wcon_04_b	3.0	7	8.0	22%
	Wcon_04_c	3.0	8	8.0	26%
	Wcon_04_d	3.0	10	8.0	34%
Structure_20	Wcon_04_a	2.0	6	8.0	22%
	Wcon_04_b	2.0	7	8.0	27%
	Wcon_04_c	2.0	8	8.0	31%
	Wcon_04_d	2.0	10	8.0	35%
Structure_21	Wcon_04_a	1.0	6	8.0	29%
	Wcon_04_b	1.0	7	8.0	30%
	Wcon_04_c	1.0	8	8.0	33%
	Wcon_04_d	1.0	10	8.0	38%
Structure_22	Wcon_04_a	0.0	6	8.0	33%
	Wcon_04_b	0.0	7	8.0	34%
	Wcon_04_c	0.0	8	8.0	37%
	Wcon_04_d	0.0	10	8.0	42%
	Wcon_07_a	0.0	6	8.0	17%
	Wcon_07_b	0.0	7	8.0	20%
	Wcon_07_c	0.0	8	8.0	23%
	Wcon_07_d	0.0	10	8.0	29%
Structure_23	Wcon_07_a	1.0	6	8.0	19%
	Wcon_07_b	1.0	7	8.0	23%
	Wcon_07_c	1.0	8	8.0	28%
	Wcon_07_d	1.0	10	8.0	33%
Structure_24	Wcon_07_a	2.0	6	8.0	22%
	Wcon_07_b	2.0	7	8.0	30%
	Wcon_07_c	2.0	8	8.0	30%
	Wcon_07_d	2.0	10	8.0	34%
Structure_25	Wcon_07_a	3.0	6	8.0	26%
	Wcon_07_b	3.0	7	8.0	50%
	Wcon_07_c	3.0	8	8.0	35%
	Wcon_07_d	3.0	10	8.0	23%
Structure_26	Wcon_04_a	3.0	6	8.0	11%

Structure	Wave condition	Crest freeboard R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T
	Wcon_04_b	3.0	7	8.0	13%
	Wcon_04_c	3.0	8	8.0	19%
	Wcon_04_d	3.0	10	8.0	26%
Structure_27	Wcon_04_a	2.0	6	8.0	15%
	Wcon_04_b	2.0	7	8.0	17%
	Wcon_04_c	2.0	8	8.0	22%
	Wcon_04_d	2.0	10	8.0	29%
Structure_28	Wcon_04_a	1.0	6	8.0	22%
	Wcon_04_b	1.0	7	8.0	23%
	Wcon_04_c	1.0	8	8.0	26%
	Wcon_04_d	1.0	10	8.0	33%
Structure_29	Wcon_04_a	0.0	6	8.0	25%
	Wcon_04_b	0.0	7	8.0	27%
	Wcon_04_c	0.0	8	8.0	31%
	Wcon_04_d	0.0	10	8.0	35%
	Wcon_07_a	3.0	6	8.0	8%
	Wcon_07_b	3.0	7	8.0	11%
	Wcon_07_c	3.0	8	8.0	15%
	Wcon_07_d	3.0	10	8.0	21%
Structure_30	Wcon_07_a	2.0	6	8.0	18%
	Wcon_07_b	2.0	7	8.0	22%
	Wcon_07_c	2.0	8	8.0	25%
	Wcon_07_d	2.0	10	8.0	35%
Structure_31	Wcon_07_a	1.0	6	8.0	21%
	Wcon_07_b	1.0	7	8.0	26%
	Wcon_07_c	1.0	8	8.0	30%
	Wcon_07_d	1.0	10	8.0	35%
Structure_32	Wcon_07_a	0.0	6	8.0	28%
	Wcon_07_b	0.0	7	8.0	29%
	Wcon_07_c	0.0	8	8.0	30%
	Wcon_07_d	0.0	10	8.0	40%

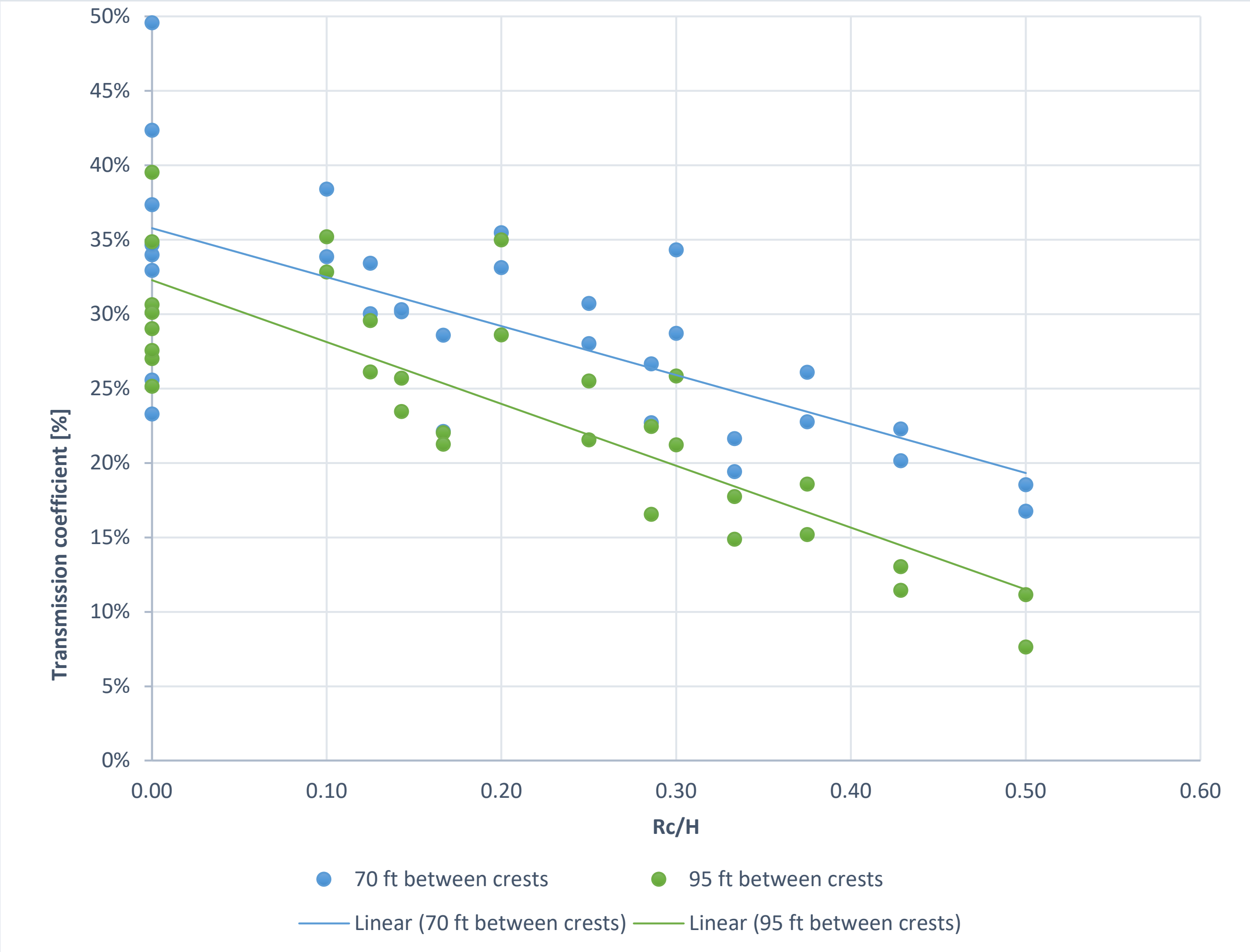

Figure 6.6: Habitat structure transmission

6.2. Phase 2 – Stability test results

The pre and post test photographs for both the different armour grade structures are presented below along with the calculated damage parameters for the armour layer and toe mound. Transmission coefficients were also recorded during the stability tests and are also presented below.

6.2.1. 6-9 tonne rock armour

The pre-test photograph of the 1:1.5 sloped 6-9 tonne rock armour structure is shown in Figure 6.7. Subsequent post-test photographs (Figure 6.8 to Figure 6.11) show the cumulative damage to the structure after each Test Part. Cumulative numbers of extracted rocks and the corresponding damage parameters (S_d for armour layer and N_{od} for toe) are presented in Table 6.10 and Table 6.11. The transmission coefficients recorded during the 6-9 tonne rock armour tests are given in Table 6.12. There was no damage recorded for the 6-9 tonne structure armour and minimal damage to the toe with movement below the N_{od} = 0.5 limit (Section 2.5.3).

Table 6.10: 6-9 tonne structure cumulative rock amour damage

Test Part	Wave condition	Return period	Cumulative no. rocks displaced	S_d (-)
01	WC_LOW_WL	All other	0	0.0
02	WC_HIGH_WL	All other	0	0.0
03	WC_EXT_WL_01	1:10	0	0.0
04	WC_EXT_WL_02	All other	0	0.0

Table 6.11: 6-9 tonne structure cumulative rock toe damage (0.2-1.8 t rock)

Test Part	Wave condition	Return period	Cumulative no. rocks displaced	N_{od} (-)
01	WC_LOW_WL	All other	0	0.00
02	WC_HIGH_WL	All other	1	0.02
03	WC_EXT_WL_01	1:10	2	0.03
04	WC_EXT_WL_02	All other	2	0.03

Table 6.12: 6-9 tonne structure full transmission coefficients

Wave condition	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T					
			Average (WG02 to WG05)	WG01	WG02	WG03	WG04	WG05
WC_LOW_WL	6.6	11.5	10%	98%	9%	9%	11%	9%
WC_HIGH_WL	11.2	11.5	44%	101%	46%	46%	43%	43%
WC_EXT_WL_01	11.2	10.0	51%	100%	44%	56%	53%	50%
WC_EXT_WL_02	12.1	11.5	39%	83%	40%	41%	37%	37%

Figure 6.7: 6-9 tonne rock armour structure – pre-test photograph

Figure 6.8: 6-9 tonne rock armour structure – post Test Part 01 photograph (WC_LOW_WL)

Figure 6.9: 6-9 tonne rock armour structure – post Test Part 02 photograph (WC_HIGH_WL)

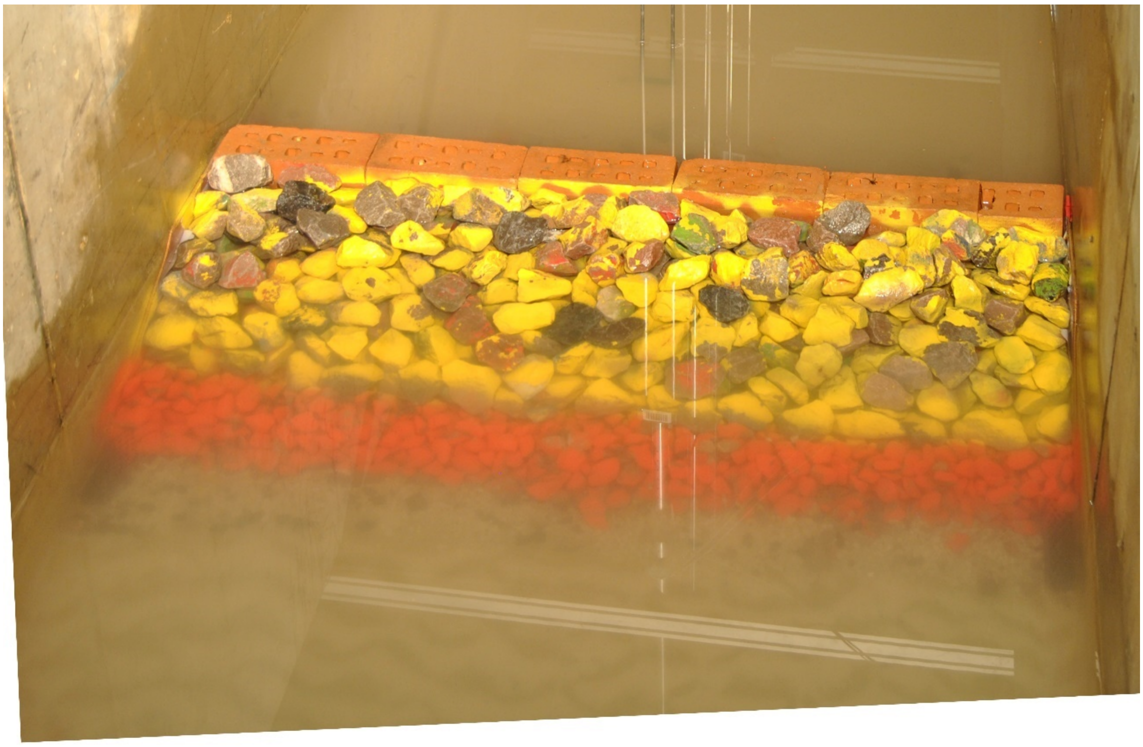

Figure 6.10: 6-9 tonne rock armour structure – post Test Part 03 photograph (WC_EXT_WL_01)

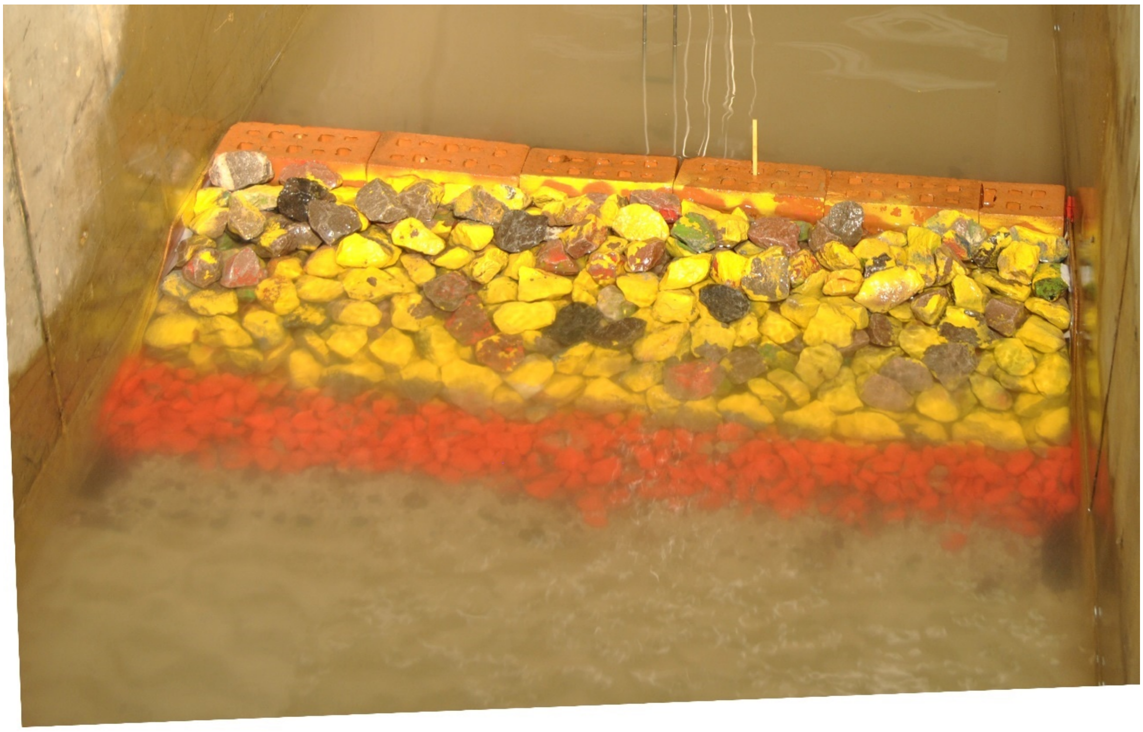

Figure 6.11: 6-9 tonne rock armour structure – post Test Part 04 photograph (WC_EXT_WL_02)

6.2.2. 3-6 t rock armour

The pre-test photograph of the 1:2 sloped 3-6 tonne rock armour structure is shown in Figure 6.12. The subsequent post-test photographs (Figure 6.13 to Figure 6.16) show the cumulative damage to the structure after each Test Part. Cumulative numbers of extracted rocks and the corresponding damage parameters (S_d for armour layer and N_{od} for toe) are presented in Table 6.13 and Table 6.14. The transmission coefficients recorded during the 3-6 tonne rock armour tests are given in Table 6.15. There was minimal damage recorded for the 3-6 tonne structure armour and toe, all below the S_d and N_{od} limits (Section 2.5.3).

Table 6.13: 3-6 t structure cumulative rock amour damage

Test Part	Wave condition	Return period	Cumulative no. rocks displaced	S_d (-)
01	WC_LOW_WL	All other	0	0.0
02	WC_HIGH_WL	All other	4	0.2
03	WC_EXT_WL_01	1:10	6	0.2
04	WC_EXT_WL_02	All other	8	0.3

Table 6.14: 3-6 t structure cumulative rock toe damage (0.2-1.0 t rock)

Test Part	Wave condition	Return period	Cumulative no. rocks displaced	N_{od} (-)
01	WC_LOW_WL	All other	2	0.03
02	WC_HIGH_WL	All other	10	0.14
03	WC_EXT_WL_01	1:10	11	0.16
04	WC_EXT_WL_02	All other	16	0.23

Table 6.15: 3-6 t structure full transmission coefficients

Wave condition	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T					
			Average (WG02 to WG05)	WG01	WG02	WG03	WG04	WG05
WC_LOW_WL	6.6	11.5	4%	92%	4%	4%	4%	4%
WC_HIGH_WL	11.2	11.5	45%	111%	51%	51%	44%	32%
WC_EXT_WL_01	11.2	10.0	31%	97%	31%	32%	30%	30%
WC_EXT_WL_02	12.1	11.5	33%	102%	35%	33%	29%	33%

Figure 6.12: 3-6 tonne rock armour structure – pre-test photograph

Figure 6.13: 3-6 tonne rock armour structure – post Test Part 01 photograph (WC_LOW_WL)

Figure 6.14: 3-6 tonne rock armour structure – post Test Part 02 photograph (WC_HIGH_WL)

Figure 6.15: 3-6 tonne rock armour structure – post Test Part 03 photograph (WC_EXT_WL_01)

Figure 6.16: 3-6 tonne rock armour structure – post Test Part 04 photograph (WC_EXT_WL_02)

7. Summary

Two phases of tests have been conducted in this 2D physical modelling study. Phase 1 investigated the transmission coefficients of various structures which fall into four main types (Emergent, Fish Street (Fish Fingers), Submerged and Habitat). The effect of crest width, freeboard and permeability on transmission coefficients was investigated, as was the effect of seaward structure slope angle and several different habitat enhancement features such as Fish Fingers. Transmission coefficients were reduced with wider or impermeable crests and structure slopes of 1:4 (for submerged structures). The Fish Fingers and other habitat enhancement features generally reduced the transmission coefficients if present.

Phase 2 investigated the stability of two different armour grades on an emergent breakwater in preparation for the 3D physical modelling studies being undertaken concurrently as part of the wider Lake Michigan project. Damage levels were low or very low for both main armour grades, well below the standard limits for design given in the Rock Manual (CIRIA, 2007).

8. References

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Appendices

A. Full transmission coefficient results

A.1. Emergent structure tests

Table A.1: Emergent Structure_01 full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Average transmission coefficient, C_T	Transmission coefficient, C_T							
						WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_01	Wcon_03_a	3.0	6.0	8.0	42%	58%	48%	50%	49%	43%	42%	35%	35%
	Wcon_03_b	3.0	7.0	8.0	46%	65%	50%	46%	54%	46%	49%	41%	40%
	Wcon_03_c	3.0	8.0	8.0	52%	63%	52%	51%	60%	53%	56%	46%	46%
	Wcon_03_d	3.0	10.0	8.0	50%	57%	50%	49%	53%	52%	58%	47%	44%
	Wcon_04_a	4.0	6.0	8.0	31%	53%	39%	36%	32%	31%	32%	29%	26%
	Wcon_04_b	4.0	7.0	8.0	35%	58%	36%	37%	43%	35%	40%	26%	28%
	Wcon_04_c	4.0	8.0	8.0	43%	57%	38%	39%	49%	44%	54%	37%	37%
	Wcon_04_d	4.0	10.0	8.0	44%	52%	37%	43%	50%	49%	53%	31%	38%
	Wcon_05_a	5.0	6.0	8.0	22%	64%	25%	20%	22%	28%	28%	15%	22%
	Wcon_05_b	5.0	7.0	8.0	28%	59%	24%	27%	36%	31%	37%	20%	20%
	Wcon_05_c	5.0	8.0	8.0	34%	69%	34%	27%	33%	38%	49%	25%	29%
	Wcon_05_d	5.0	10.0	8.0	37%	52%	31%	34%	47%	40%	48%	23%	29%
	Wcon_06_a	6.0	6.0	8.0	20%	56%	23%	15%	20%	28%	26%	13%	17%
	Wcon_06_b	6.0	7.0	8.0	24%	58%	24%	17%	25%	36%	32%	16%	17%
	Wcon_06_c	6.0	8.0	8.0	26%	56%	31%	25%	27%	32%	36%	20%	17%
	Wcon_06_d	6.0	10.0	8.0	32%	56%	27%	23%	39%	41%	47%	18%	24%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Average transmission coefficient, C_T	Transmission coefficient, C_T							
						WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
	Wcon_07_a	7.0	6.0	8.0	17%	50%	31%	16%	15%	22%	21%	16%	14%
	Wcon_07_b	7.0	7.0	8.0	19%	54%	33%	17%	14%	26%	25%	18%	15%
	Wcon_07_c	7.0	8.0	8.0	23%	65%	33%	19%	19%	33%	29%	18%	17%
	Wcon_07_d	7.0	10.0	8.0	29%	84%	29%	24%	26%	39%	42%	20%	24%

Table A.2: Emergent Structure_02 full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Average transmission coefficient, C_T	Transmission coefficient, C_T							
						WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_02	Wcon_02_a	2.0	6.0	8.0	32%	104%	53%	41%	38%	28%	28%	35%	34%
	Wcon_02_b	2.0	7.0	8.0	36%	103%	53%	46%	42%	33%	31%	42%	33%
	Wcon_02_c	2.0	8.0	8.0	40%	99%	50%	48%	47%	42%	33%	47%	34%
	Wcon_02_d	2.0	10.0	8.0	44%	95%	38%	43%	44%	42%	39%	55%	42%
	Wcon_03_a	3.0	6.0	8.0	24%	95%	36%	26%	25%	21%	22%	23%	28%
	Wcon_03_b	3.0	7.0	8.0	29%	101%	36%	27%	30%	29%	29%	27%	31%
	Wcon_03_c	3.0	8.0	8.0	35%	98%	35%	39%	41%	33%	36%	29%	36%
	Wcon_03_d	3.0	10.0	8.0	38%	84%	30%	41%	47%	40%	34%	32%	40%
	Wcon_04_a	4.0	6.0	8.0	15%	95%	29%	25%	15%	14%	14%	18%	16%
	Wcon_04_b	4.0	7.0	8.0	18%	99%	24%	22%	22%	17%	17%	17%	20%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Average transmission coefficient, C_T	Transmission coefficient, C_T							
						WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
	Wcon_04_c	4.0	8.0	8.0	23%	98%	24%	27%	28%	24%	24%	16%	25%
	Wcon_04_d	4.0	10.0	8.0	35%	82%	26%	34%	46%	38%	37%	25%	30%
	Wcon_05_a	5.0	6.0	8.0	13%	118%	20%	15%	13%	15%	15%	10%	14%
	Wcon_05_b	5.0	7.0	8.0	14%	109%	16%	16%	18%	14%	15%	10%	13%
	Wcon_05_c	5.0	8.0	8.0	19%	120%	24%	17%	17%	24%	22%	12%	19%
	Wcon_05_d	5.0	10.0	8.0	23%	85%	17%	23%	31%	25%	27%	15%	18%
	Wcon_06_a	6.0	6.0	8.0	13%	86%	22%	11%	12%	16%	17%	8%	10%
	Wcon_06_b	6.0	7.0	8.0	13%	98%	21%	10%	12%	18%	17%	8%	10%
	Wcon_06_c	6.0	8.0	8.0	12%	94%	21%	12%	13%	15%	16%	9%	9%
	Wcon_06_d	6.0	10.0	8.0	20%	87%	18%	15%	24%	25%	28%	11%	13%

Table A.3: Emergent Structure_03 full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Average transmission coefficient, C_T	Transmission coefficient, C_T							
						WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_03	Wcon_03_a	3.0	6.0	8.0	31%	87%	33%	33%	39%	33%	30%	25%	27%
	Wcon_03_b	3.0	7.0	8.0	37%	87%	39%	40%	41%	39%	36%	37%	29%
	Wcon_03_c	3.0	8.0	8.0	45%	83%	46%	51%	54%	44%	45%	41%	35%
	Wcon_03_d	3.0	10.0	8.0	47%	70%	42%	46%	48%	46%	56%	45%	40%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Average transmission coefficient, C_T	Transmission coefficient, C_T							
						WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
	Wcon_04_a	4.0	6.0	8.0	18%	90%	21%	22%	16%	19%	19%	16%	18%
	Wcon_04_b	4.0	7.0	8.0	25%	92%	19%	25%	31%	25%	27%	18%	22%
	Wcon_04_c	4.0	8.0	8.0	34%	84%	32%	35%	39%	35%	37%	30%	30%
	Wcon_04_d	4.0	10.0	8.0	40%	75%	26%	40%	43%	43%	48%	31%	34%
	Wcon_05_a	5.0	6.0	8.0	11%	108%	10%	11%	14%	14%	13%	7%	10%
	Wcon_05_b	5.0	7.0	8.0	18%	97%	11%	16%	21%	21%	19%	13%	17%
	Wcon_05_c	5.0	8.0	8.0	24%	103%	21%	21%	21%	31%	30%	20%	23%
	Wcon_05_d	5.0	10.0	8.0	34%	73%	22%	35%	42%	36%	41%	21%	29%
	Wcon_02_a	2.0	6.0	8.0	41%	86%	43%	51%	44%	38%	38%	41%	31%
	Wcon_02_b	2.0	7.0	8.0	44%	86%	62%	57%	44%	38%	41%	51%	31%
	Wcon_02_c	2.0	8.0	8.0	47%	81%	59%	53%	48%	44%	43%	53%	39%
	Wcon_02_d	2.0	10.0	8.0	49%	81%	59%	45%	46%	49%	47%	63%	43%
	Wcon_06_a	6.0	6.0	8.0	10%	101%	12%	10%	12%	13%	13%	6%	8%
	Wcon_06_b	6.0	7.0	8.0	18%	107%	14%	12%	18%	24%	26%	12%	15%
	Wcon_06_c	6.0	8.0	8.0	20%	89%	17%	17%	18%	23%	26%	17%	18%
	Wcon_06_d	6.0	10.0	8.0	27%	78%	15%	24%	33%	29%	36%	19%	22%

A.2. Fish Street structure tests

Table A.4: Fish Street structures (Structure_04 to Structure_14) full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_04	Wcon_04_a	4.0	7.0	8.0	19%	73%	22%	26%	25%	19%	15%	16%	14%
	Wcon_04_b	4.0	7.0	8.0	22%	75%	17%	26%	29%	22%	22%	14%	18%
	Wcon_04_c	4.0	8.0	8.0	26%	69%	26%	32%	32%	25%	26%	17%	24%
	Wcon_04_d	4.0	10.0	8.0	26%	56%	17%	28%	34%	24%	22%	18%	28%
Structure_05	Wcon_04_a	3.0	6.0	8.0	23%	76%	26%	31%	23%	25%	20%	22%	18%
	Wcon_04_b	3.0	7.0	8.0	26%	78%	23%	32%	34%	28%	27%	17%	20%
	Wcon_04_c	3.0	8.0	8.0	32%	72%	29%	37%	37%	35%	30%	20%	31%
	Wcon_04_d	3.0	10.0	8.0	30%	56%	25%	32%	35%	29%	31%	21%	33%
	Wcon_04_a_22	4.0	6.0	8.0	15%	92%	20%	16%	21%	19%	12%	11%	10%
	Wcon_04_b_22	4.0	7.0	8.0	17%	95%	15%	17%	25%	21%	16%	12%	11%
	Wcon_04_c_22	4.0	8.0	8.0	22%	81%	20%	24%	35%	23%	19%	13%	17%
	Wcon_04_d_22	4.0	10.0	8.0	21%	66%	14%	21%	30%	19%	19%	17%	21%
Structure_06	Wcon_04_a_22	3.0	6.0	8.0	18%	97%	17%	17%	23%	23%	19%	13%	13%
	Wcon_04_b_22	3.0	7.0	8.0	19%	95%	15%	16%	31%	18%	22%	13%	17%
	Wcon_04_c_22	3.0	8.0	8.0	22%	79%	23%	21%	36%	23%	21%	15%	19%
	Wcon_04_d_22	3.0	10.0	8.0	23%	64%	15%	25%	32%	19%	20%	19%	22%
Structure_07	Wcon_04_a_22	3.0	6.0	8.0	16%	97%	15%	16%	21%	19%	15%	12%	12%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_08	Wcon_04_b_22	3.0	7.0	8.0	17%	94%	14%	14%	25%	17%	19%	13%	15%
	Wcon_04_c_22	3.0	8.0	8.0	22%	84%	14%	22%	34%	19%	23%	16%	20%
	Wcon_04_d_22	3.0	10.0	8.0	25%	64%	16%	24%	31%	24%	24%	20%	25%
	Wcon_04_a_22	2.0	6.0	8.0	21%	101%	22%	22%	27%	23%	24%	17%	17%
	Wcon_04_b_22	2.0	7.0	8.0	24%	96%	20%	23%	33%	21%	23%	19%	23%
	Wcon_04_c_22	2.0	8.0	8.0	27%	79%	18%	28%	37%	22%	22%	24%	27%
	Wcon_04_d_22	2.0	10.0	8.0	30%	63%	17%	27%	38%	24%	37%	24%	26%
Structure_09	Wcon_04_a_22	1.0	6.0	8.0	28%	87%	28%	26%	30%	28%	32%	22%	27%
	Wcon_04_b_22	1.0	7.0	8.0	30%	89%	22%	26%	42%	29%	34%	22%	25%
	Wcon_04_c_22	1.0	8.0	8.0	32%	66%	23%	28%	37%	31%	39%	30%	28%
	Wcon_04_d_22	1.0	10.0	8.0	33%	56%	25%	30%	41%	33%	38%	25%	29%
Structure_10	Wcon_05_a	3.0	6.0	8.0	19%	110%	19%	18%	22%	24%	21%	10%	19%
	Wcon_05_b	3.0	7.0	8.0	22%	98%	16%	22%	26%	28%	23%	11%	22%
	Wcon_05_c	3.0	8.0	8.0	27%	98%	28%	24%	23%	34%	33%	17%	29%
	Wcon_05_d	3.0	10.0	8.0	29%	67%	26%	34%	35%	31%	28%	19%	27%
Structure_11	Wcon_05_a	2.0	6.0	8.0	25%	111%	25%	24%	28%	34%	32%	13%	21%
	Wcon_05_b	2.0	7.0	8.0	28%	92%	24%	30%	35%	32%	32%	15%	27%
	Wcon_05_c	2.0	8.0	8.0	31%	91%	31%	29%	27%	39%	39%	20%	33%
	Wcon_05_d	2.0	10.0	8.0	33%	61%	25%	34%	40%	36%	33%	24%	32%
Structure_12	Wcon_05_a	1.0	6.0	8.0	28%	100%	34%	28%	26%	37%	33%	16%	29%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_13	Wcon_05_b	1.0	7.0	8.0	33%	83%	26%	32%	40%	36%	33%	22%	32%
	Wcon_05_c	1.0	8.0	8.0	34%	79%	33%	30%	28%	41%	41%	27%	34%
	Wcon_05_d	1.0	10.0	8.0	35%	55%	30%	33%	40%	37%	40%	24%	35%
	Wcon_05_a	3.0	6.0	8.0	26%	72%	26%	24%	26%	26%	35%	16%	27%
	Wcon_05_b	3.0	7.0	8.0	28%	65%	25%	29%	35%	25%	34%	17%	26%
	Wcon_05_c	3.0	8.0	8.0	30%	66%	31%	28%	29%	32%	39%	20%	29%
	Wcon_05_d	3.0	10.0	8.0	33%	47%	26%	35%	42%	33%	31%	21%	37%
Structure_14	Wcon_05_a	3.0	6.0	8.0	23%	69%	24%	22%	24%	24%	30%	11%	27%
	Wcon_05_b	3.0	7.0	8.0	25%	60%	23%	25%	32%	24%	29%	12%	27%
	Wcon_05_c	3.0	8.0	8.0	24%	65%	23%	23%	25%	26%	28%	16%	28%
	Wcon_05_d	3.0	10.0	8.0	28%	45%	17%	32%	37%	27%	26%	16%	28%

A.3. Submerged structure tests

Table A.5: Submerged Structure_15 full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_15	Wcon_03_a	-5.0	6.0	8.0	94%	104%	91%	100%	112%	92%	86%	93%	83%
	Wcon_03_b	-5.0	7.0	8.0	88%	113%	83%	79%	97%	91%	86%	90%	84%
	Wcon_03_c	-5.0	8.0	8.0	90%	111%	74%	84%	112%	83%	84%	90%	84%
	Wcon_03_d	-5.0	10.0	8.0	78%	94%	63%	83%	92%	73%	69%	83%	68%
	Wcon_04_a	-4.0	6.0	8.0	83%	106%	104%	99%	75%	77%	81%	88%	77%
	Wcon_04_b	-4.0	7.0	8.0	83%	111%	76%	78%	101%	83%	78%	77%	80%
	Wcon_04_c	-4.0	8.0	8.0	82%	115%	64%	63%	101%	91%	83%	76%	79%
	Wcon_04_d	-4.0	10.0	8.0	73%	96%	54%	60%	86%	80%	75%	68%	69%
	Wcon_05_a	-3.0	6.0	8.0	79%	133%	84%	70%	68%	95%	95%	65%	83%
	Wcon_05_b	-3.0	7.0	8.0	75%	113%	68%	64%	76%	86%	81%	67%	75%
	Wcon_05_c	-3.0	8.0	8.0	71%	127%	75%	52%	57%	100%	93%	44%	81%
	Wcon_05_d	-3.0	10.0	8.0	63%	87%	53%	61%	70%	70%	69%	37%	71%
	Wcon_06_a	-2.0	6.0	8.0	71%	132%	68%	71%	63%	82%	90%	46%	74%
	Wcon_06_b	-2.0	7.0	8.0	67%	115%	68%	61%	61%	95%	79%	36%	72%
	Wcon_06_c	-2.0	8.0	8.0	59%	96%	62%	61%	50%	64%	73%	38%	67%
	Wcon_06_d	-2.0	10.0	8.0	58%	88%	53%	50%	58%	69%	76%	36%	60%
	Wcon_07_a	-1.0	6.0	8.0	64%	93%	69%	71%	54%	62%	71%	63%	66%
	Wcon_07_b	-1.0	7.0	8.0	58%	77%	68%	65%	49%	57%	67%	48%	60%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
	Wcon_07_c	-1.0	8.0	8.0	57%	88%	54%	60%	51%	61%	69%	36%	63%
	Wcon_07_d	-1.0	10.0	8.0	55%	87%	51%	49%	44%	64%	69%	40%	61%

Table A.6: Submerged Structure_16 full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_16	Wcon_03_a	-5.0	6.0	8.0	93%	111%	87%	86%	110%	89%	89%	95%	88%
	Wcon_03_b	-5.0	7.0	8.0	86%	116%	82%	69%	90%	94%	90%	91%	80%
	Wcon_03_c	-5.0	8.0	8.0	84%	111%	76%	64%	101%	84%	85%	90%	82%
	Wcon_03_d	-5.0	10.0	8.0	71%	94%	59%	66%	75%	75%	67%	77%	64%
	Wcon_04_a	-4.0	6.0	8.0	75%	106%	94%	84%	62%	76%	74%	75%	80%
	Wcon_04_b	-4.0	7.0	8.0	75%	109%	67%	66%	87%	80%	71%	65%	82%
	Wcon_04_c	-4.0	8.0	8.0	71%	101%	56%	58%	82%	83%	75%	56%	73%
	Wcon_04_d	-4.0	10.0	8.0	65%	92%	48%	49%	78%	78%	68%	56%	61%
	Wcon_05_a	-3.0	6.0	8.0	70%	117%	71%	58%	56%	95%	83%	54%	77%
	Wcon_05_b	-3.0	7.0	8.0	67%	104%	58%	50%	68%	82%	69%	58%	75%
	Wcon_05_c	-3.0	8.0	8.0	63%	114%	71%	45%	47%	90%	78%	46%	72%
	Wcon_05_d	-3.0	10.0	8.0	57%	83%	47%	44%	62%	70%	67%	41%	57%
	Wcon_06_a	-2.0	6.0	8.0	63%	118%	56%	56%	61%	77%	79%	41%	65%
	Wcon_06_b	-2.0	7.0	8.0	61%	110%	55%	50%	52%	82%	68%	43%	69%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
	Wcon_06_c	-2.0	8.0	8.0	54%	89%	56%	49%	42%	64%	57%	42%	67%
	Wcon_06_d	-2.0	10.0	8.0	51%	82%	45%	31%	48%	69%	65%	37%	58%
	Wcon_07_a	-1.0	6.0	8.0	49%	66%	60%	60%	40%	44%	55%	44%	53%
	Wcon_07_b	-1.0	7.0	8.0	50%	73%	49%	54%	45%	50%	57%	42%	55%
	Wcon_07_c	-1.0	8.0	8.0	48%	60%	50%	49%	39%	49%	52%	43%	54%
	Wcon_07_d	-1.0	10.0	8.0	47%	73%	43%	42%	41%	55%	54%	35%	56%

Table A.7: Submerged Structure_17 full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_17	Wcon_03_a	-5.0	6.0	8.0	89%	96%	88%	100%	95%	84%	86%	80%	90%
	Wcon_03_b	-5.0	7.0	8.0	84%	108%	68%	73%	87%	89%	90%	79%	88%
	Wcon_03_c	-5.0	8.0	8.0	84%	104%	65%	72%	98%	83%	84%	79%	85%
	Wcon_03_d	-5.0	10.0	8.0	64%	79%	53%	57%	67%	65%	63%	68%	62%
	Wcon_04_a	-4.0	6.0	8.0	75%	89%	91%	90%	65%	71%	72%	69%	85%
	Wcon_04_b	-4.0	7.0	8.0	73%	90%	61%	75%	85%	68%	72%	54%	81%
	Wcon_04_c	-4.0	8.0	8.0	66%	87%	58%	62%	68%	67%	68%	61%	70%
	Wcon_04_d	-4.0	10.0	8.0	56%	69%	47%	46%	62%	63%	65%	45%	56%
	Wcon_05_a	-3.0	6.0	8.0	68%	95%	56%	59%	55%	71%	88%	49%	87%
	Wcon_05_b	-3.0	7.0	8.0	60%	79%	45%	57%	61%	63%	70%	41%	69%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
	Wcon_05_c	-3.0	8.0	8.0	55%	83%	59%	53%	45%	59%	68%	46%	57%
	Wcon_05_d	-3.0	10.0	8.0	50%	61%	43%	43%	51%	59%	60%	32%	54%
	Wcon_06_a	-2.0	6.0	8.0	59%	85%	43%	50%	51%	62%	83%	42%	67%
	Wcon_06_b	-2.0	7.0	8.0	55%	58%	47%	46%	44%	64%	74%	46%	56%
	Wcon_06_c	-2.0	8.0	8.0	47%	56%	46%	47%	42%	50%	56%	35%	52%
	Wcon_06_d	-2.0	10.0	8.0	44%	45%	38%	37%	45%	49%	53%	27%	51%
	Wcon_07_a	-1.0	6.0	8.0	46%	57%	49%	42%	37%	42%	53%	44%	57%
	Wcon_07_b	-1.0	7.0	8.0	44%	49%	42%	44%	36%	43%	49%	37%	53%
	Wcon_07_c	-1.0	8.0	8.0	42%	51%	34%	37%	37%	44%	47%	33%	51%
	Wcon_07_d	-1.0	10.0	8.0	40%	43%	33%	36%	35%	46%	46%	29%	48%

Table A.8: Submerged Structure_18 full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_18	Wcon_03_a	-5.0	6.0	8.0	92%	104%	86%	99%	109%	85%	87%	89%	85%
	Wcon_03_b	-5.0	7.0	8.0	89%	109%	81%	83%	91%	95%	88%	88%	88%
	Wcon_03_c	-5.0	8.0	8.0	86%	104%	73%	83%	97%	86%	81%	88%	84%
	Wcon_03_d	-5.0	10.0	8.0	65%	80%	53%	58%	75%	68%	63%	71%	58%
	Wcon_04_a	-4.0	6.0	8.0	82%	89%	94%	95%	73%	79%	82%	84%	80%
	Wcon_04_b	-4.0	7.0	8.0	80%	92%	63%	80%	92%	83%	77%	66%	80%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
	Wcon_04_c	-4.0	8.0	8.0	72%	92%	52%	61%	84%	80%	74%	64%	67%
	Wcon_04_d	-4.0	10.0	8.0	57%	66%	42%	45%	59%	60%	60%	57%	59%
	Wcon_05_a	-3.0	6.0	8.0	72%	109%	65%	64%	68%	81%	91%	56%	72%
	Wcon_05_b	-3.0	7.0	8.0	63%	91%	49%	58%	74%	70%	67%	45%	66%
	Wcon_05_c	-3.0	8.0	8.0	58%	89%	58%	49%	51%	73%	67%	45%	63%
	Wcon_05_d	-3.0	10.0	8.0	49%	48%	40%	45%	52%	53%	54%	39%	53%
	Wcon_06_a	-2.0	6.0	8.0	63%	98%	46%	53%	56%	72%	84%	46%	64%
	Wcon_06_b	-2.0	7.0	8.0	58%	91%	42%	45%	54%	74%	72%	39%	61%
	Wcon_06_c	-2.0	8.0	8.0	47%	64%	35%	44%	40%	52%	56%	37%	52%
	Wcon_06_d	-2.0	10.0	8.0	43%	47%	31%	34%	43%	50%	54%	26%	48%
	Wcon_07_a	-1.0	6.0	8.0	47%	53%	50%	42%	39%	48%	58%	49%	47%
	Wcon_07_b	-1.0	7.0	8.0	44%	48%	42%	41%	37%	44%	51%	40%	49%
	Wcon_07_c	-1.0	8.0	8.0	41%	46%	33%	38%	34%	44%	52%	33%	42%
	Wcon_07_d	-1.0	10.0	8.0	38%	59%	33%	31%	34%	40%	45%	27%	50%

A.4. Habitat structure tests

Table A.9: Habitat structures (Structure_19 to Structure_32) full transmission coefficients

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_19	Wcon_04_a	3.0	6.0	8.0	19%	30%	24%	26%	18%	16%	21%	19%	15%
	Wcon_04_b	3.0	7.0	8.0	22%	34%	22%	27%	31%	23%	27%	19%	21%
	Wcon_04_c	3.0	8.0	8.0	26%	39%	26%	37%	36%	32%	32%	20%	27%
	Wcon_04_d	3.0	10.0	8.0	34%	36%	31%	45%	41%	38%	44%	24%	35%
Structure_20	Wcon_04_a	2.0	6.0	8.0	22%	44%	34%	42%	21%	21%	24%	20%	20%
	Wcon_04_b	2.0	7.0	8.0	27%	43%	31%	39%	34%	25%	34%	19%	27%
	Wcon_04_c	2.0	8.0	8.0	31%	39%	33%	42%	37%	36%	36%	21%	35%
	Wcon_04_d	2.0	10.0	8.0	35%	36%	35%	48%	40%	39%	43%	27%	36%
Structure_21	Wcon_04_a	1.0	6.0	8.0	29%	43%	45%	41%	28%	33%	33%	23%	30%
	Wcon_04_b	1.0	7.0	8.0	30%	46%	34%	43%	39%	35%	36%	21%	34%
	Wcon_04_c	1.0	8.0	8.0	33%	45%	39%	46%	42%	34%	37%	24%	39%
	Wcon_04_d	1.0	10.0	8.0	38%	37%	41%	48%	41%	41%	45%	27%	43%
Structure_22	Wcon_04_a	0.0	6.0	8.0	33%	-	36%	56%	36%	30%	32%	26%	41%
	Wcon_04_b	0.0	7.0	8.0	34%	-	29%	49%	48%	34%	36%	23%	43%
	Wcon_04_c	0.0	8.0	8.0	37%	-	32%	44%	48%	43%	42%	26%	45%
	Wcon_04_d	0.0	10.0	8.0	42%	-	37%	45%	50%	45%	52%	28%	47%
	Wcon_07_a	3.0	6.0	8.0	17%	-	25%	21%	17%	19%	21%	14%	15%
	Wcon_07_b	3.0	7.0	8.0	20%	-	20%	22%	18%	22%	24%	17%	19%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_23	Wcon_07_c	3.0	8.0	8.0	23%	-	23%	23%	22%	29%	27%	18%	23%
	Wcon_07_d	3.0	10.0	8.0	29%	-	34%	25%	29%	37%	34%	19%	32%
	Wcon_07_a	2.0	6.0	8.0	19%	-	26%	24%	15%	21%	21%	19%	18%
	Wcon_07_b	2.0	7.0	8.0	23%	-	24%	27%	19%	25%	28%	18%	22%
	Wcon_07_c	2.0	8.0	8.0	28%	-	27%	28%	27%	34%	35%	19%	31%
	Wcon_07_d	2.0	10.0	8.0	33%	-	35%	30%	31%	39%	41%	22%	36%
Structure_24	Wcon_07_a	1.0	6.0	8.0	22%	35%	34%	29%	20%	28%	27%	18%	21%
	Wcon_07_b	1.0	7.0	8.0	30%	34%	30%	29%	27%	32%	39%	21%	30%
	Wcon_07_c	1.0	8.0	8.0	30%	34%	27%	29%	29%	37%	37%	19%	34%
	Wcon_07_d	1.0	10.0	8.0	34%	41%	28%	29%	31%	39%	47%	22%	33%
Structure_25	Wcon_07_a	0.0	6.0	8.0	26%	-	40%	33%	24%	30%	31%	23%	23%
	Wcon_07_b	0.0	7.0	8.0	50%	-	46%	54%	41%	44%	60%	41%	48%
	Wcon_07_c	0.0	8.0	8.0	35%	-	36%	34%	27%	37%	43%	26%	35%
	Wcon_07_d	0.0	10.0	8.0	23%	-	22%	20%	22%	28%	31%	16%	24%
Structure_26	Wcon_04_a	3.0	6.0	8.0	11%	42%	19%	21%	17%	12%	10%	12%	11%
	Wcon_04_b	3.0	7.0	8.0	13%	41%	15%	21%	27%	15%	12%	13%	14%
	Wcon_04_c	3.0	8.0	8.0	19%	41%	20%	27%	33%	19%	19%	15%	22%
	Wcon_04_d	3.0	10.0	8.0	26%	32%	29%	36%	35%	28%	29%	19%	30%
Structure_27	Wcon_04_a	2.0	6.0	8.0	15%	-	24%	26%	22%	15%	12%	17%	15%
	Wcon_04_b	2.0	7.0	8.0	17%	-	21%	27%	32%	17%	14%	16%	19%
	Wcon_04_c	2.0	8.0	8.0	22%	-	21%	32%	35%	23%	21%	17%	26%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_28	Wcon_04_d	2.0	10.0	8.0	29%	-	28%	37%	39%	33%	34%	22%	30%
	Wcon_04_a	1.0	6.0	8.0	22%	-	35%	40%	32%	27%	23%	20%	23%
	Wcon_04_b	1.0	7.0	8.0	23%	-	29%	38%	46%	32%	26%	17%	27%
	Wcon_04_c	1.0	8.0	8.0	26%	-	26%	38%	45%	33%	29%	19%	30%
	Wcon_04_d	1.0	10.0	8.0	33%	-	30%	38%	43%	35%	34%	28%	37%
Structure_29	Wcon_04_a	0.0	6.0	8.0	25%	38%	34%	44%	35%	32%	25%	22%	28%
	Wcon_04_b	0.0	7.0	8.0	27%	37%	28%	37%	43%	31%	29%	18%	34%
	Wcon_04_c	0.0	8.0	8.0	31%	37%	30%	39%	43%	36%	34%	19%	39%
	Wcon_04_d	0.0	10.0	8.0	35%	33%	24%	35%	42%	39%	39%	27%	38%
	Wcon_07_a	3.0	6.0	8.0	8%	32%	20%	10%	9%	11%	9%	7%	7%
	Wcon_07_b	3.0	7.0	8.0	11%	34%	24%	13%	11%	16%	15%	9%	10%
	Wcon_07_c	3.0	8.0	8.0	15%	35%	25%	16%	10%	22%	21%	11%	14%
	Wcon_07_d	3.0	10.0	8.0	21%	39%	23%	20%	19%	26%	31%	13%	20%
Structure_30	Wcon_07_a	2.0	6.0	8.0	18%	37%	41%	21%	15%	25%	23%	15%	15%
	Wcon_07_b	2.0	7.0	8.0	22%	43%	40%	26%	21%	27%	29%	19%	19%
	Wcon_07_c	2.0	8.0	8.0	25%	44%	38%	24%	27%	32%	34%	19%	24%
	Wcon_07_d	2.0	10.0	8.0	35%	52%	35%	28%	33%	38%	43%	23%	39%
Structure_31	Wcon_07_a	1.0	6.0	8.0	21%	-	47%	25%	20%	29%	26%	17%	21%
	Wcon_07_b	1.0	7.0	8.0	26%	-	42%	25%	23%	31%	31%	20%	27%
	Wcon_07_c	1.0	8.0	8.0	30%	-	44%	27%	27%	37%	38%	18%	33%
	Wcon_07_d	1.0	10.0	8.0	35%	-	28%	28%	33%	43%	38%	25%	43%

Structure	Wave condition	Crest freeboard, R_c (ft)	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T								
					Average	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
Structure_32	Wcon_07_a	0.0	6.0	8.0	28%	31%	54%	28%	30%	30%	35%	20%	28%
	Wcon_07_b	0.0	7.0	8.0	29%	30%	46%	27%	31%	34%	39%	21%	27%
	Wcon_07_c	0.0	8.0	8.0	30%	35%	45%	25%	33%	39%	41%	18%	32%
	Wcon_07_d	0.0	10.0	8.0	40%	46%	31%	27%	35%	41%	45%	27%	46%

Note: For some tests data from WG_01 was not available. SmithGroup on-site representatives confirmed during testing that this gauge was not needed for the analysis and a repeat tests was not required.

B. Healthy Port Futures structure tests

B.1. Introduction

In addition to the two phases of testing described in the main report, additional transmission tests were conducted on the Healthy Port Futures structures. Following the transmission tests sand was added between the structures to determine if it would migrate within the cells.

B.2. Test facility and methods

The test facility and methods were identical to those described in the main report (Section 2). The following section provides specific information relating to the Healthy Port Futures tests such as scale, probe layout *et cetera*.

B.2.1. Model scale and facility

The scale for the Healthy Port Futures tests was 1:10. This was based on matching the model wave conditions already calibrated for Phase 1 with the conditions required for the Healthy Port Futures tests. The wave conditions for the Healthy Port Futures tests were smaller prototype conditions than Phase 1, hence the larger model scale when using the Phase 1 model waves.

The flume configuration for the Healthy Port Futures tests is shown in Figure B.1 (note the exaggerated vertical scale). The bathymetry represents a generalised case representing a mildly sloping seabed, and allowing all the different structures and model phases to be conducted on the same bathymetry. The bathymetric profile used had a 1:24 transition slope from the flume floor followed by a 1:120 slope to an area of horizontal bed where the structures were placed (the same bathymetry used for Phases 1 and 2).

Twin wire wave gauges were placed in various locations within the flume to measure the transmission coefficients and wave conditions. The locations are shown graphically in Figure B.1 and are tabulated in Table B.2.

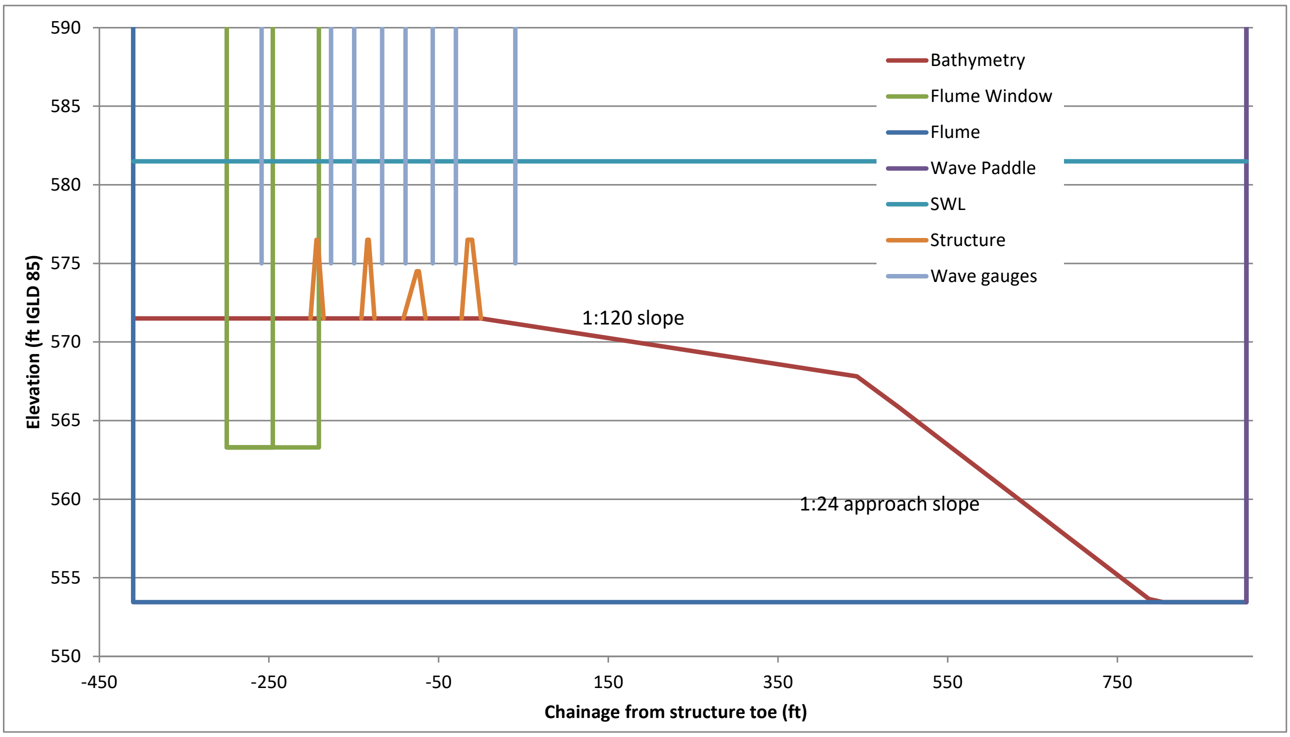

Figure B.1: Flume configuration

Table B.1: Wave gauge locations

Wave gauge	Distance from structure seaward edge of crest (ft)	Description
WG01	-40*	Seaward of Structure 01
WG02	30	Leeward of Structure 01
WG03	57	Seaward of Structure 02
WG04	89	Leeward of Structure 02
WG05	117	Seaward of Structure 03
WG06	150	Leeward of Structure 03
WG07	177	Seaward of Structure 04
WG08	259	Leeward of Structure 04

*Note: * WG01 initially closer to Structure 01 and moved further seaward due to reflections and in consultation with SmithGroup on-site representatives*

B.2.2. Calibrations and measurement techniques

The wave calibrations for the Healthy Port Futures tests used the method described in Section 2.4.1. The transmission coefficients for each wave gauge location were calculated using the method described in Section 2.5.1 with the wave height measured by WG01 during calibrations taken as the incident wave for each Test Part. A transmission coefficient for each structure was also calculated using the seaward gauge as the incident wave and the leeward gauge as the transmitted wave in addition to an overall coefficient using WG01 (calibration run) and WG08.

For the tests with sand between the structures, photographs were taken pre and post-test. The tests were observed by SmithGroup's representatives on-site at HR Wallingford who made observations during testing in addition to the photographic record.

B.2.3. Test sections

The structure for the Healthy Port Future tests is shown in Figure B.2 and consist of four shore parallel rubble mound structures. The structure dimensions for the physical model tests were confirmed to HR Wallingford in *2020-0821 Healthy Port Futures.dwg*. The structures were reproduced in the flume using permeability scaled D_{50} = *18"* rock (*2020-0824 Flume Testing v6.xlsm*). Following initial transmission measurements, sand was added between the rubble mound structures.

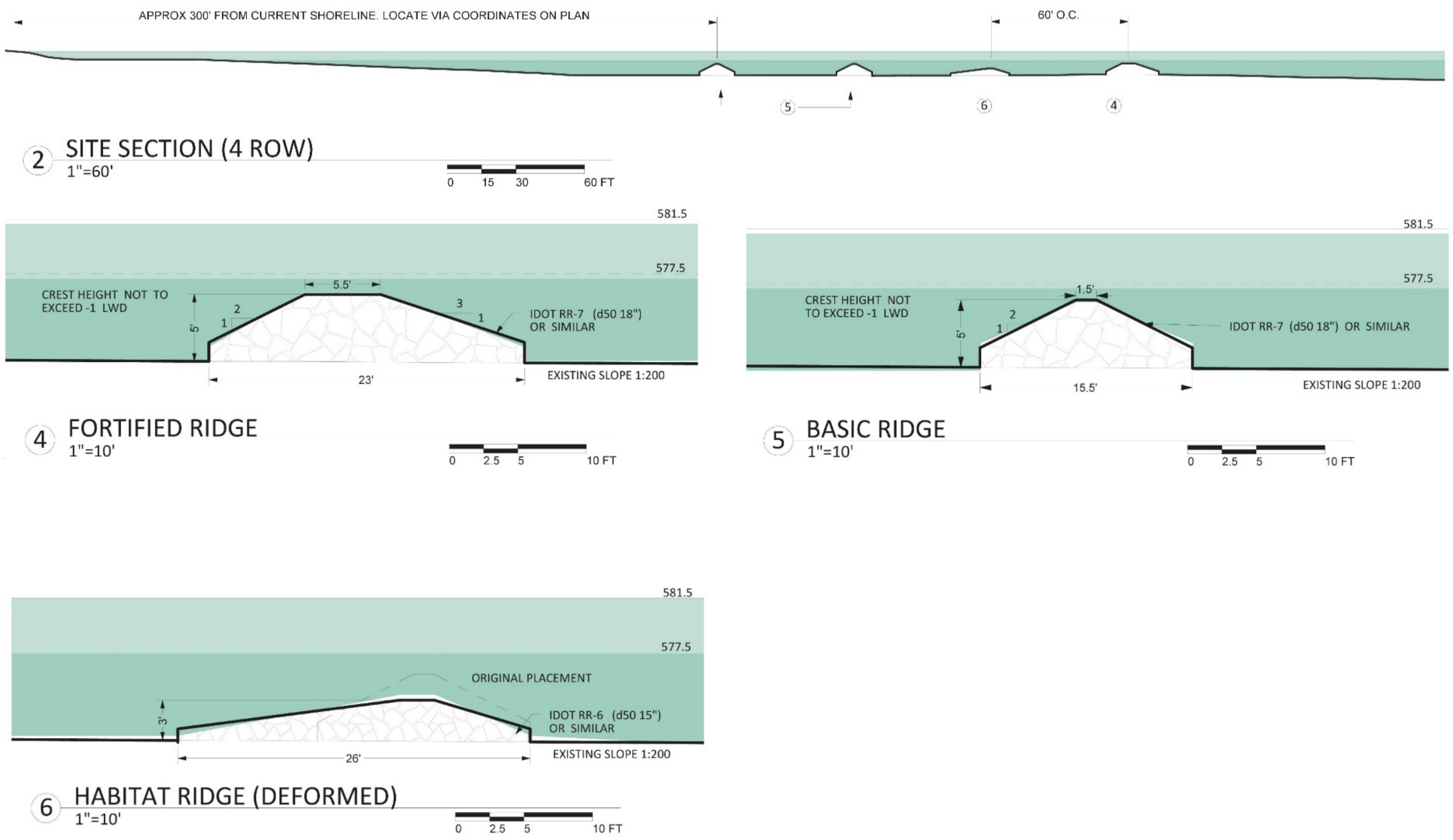

Figure B.2: Healthy Port Future structures Source: 200403_IBSP_HPF_Plans+Sections.pdf

B.3. Test conditions and performance criteria

The Healthy Port Futures test wave conditions, were provided in *2020-0804 Flume Testing v6.xlsm* (email "RE: 12324 - Rock Sizing for Last Test" on August 24, 2020).

The monochromatic wave conditions and water levels used for the Healthy Port Futures testing phase are shown in Table B.2. Each condition was generated in 'packets' of 20 waves. The toe of the structures (horizontal area of the flume bathymetry) was at 571.5 ft IGLD 85.

Table B.2: Wave conditions for the Phase 2 Healthy Port Future tests

Wave condition	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Target wave height, H (ft)	Target wave period, T (s)
SS09_TP_05_a	580.5	9	1.5	5.0
SS09_TP_05_b	580.5	9	2.0	5.0
SS09_TP_05_c	580.5	9	2.5	5.0
SS09_TP_05_d	580.5	9	3.0	5.0
SS09_TP_05_e	580.5	9	3.5	5.0
SS09_TP_05_f	580.5	9	4.0	5.0
SS09_TP_08_c	580.5	9	2.5	8.0
SS09_TP_08_d	580.5	9	3.0	8.0
SS09_TP_08_e	580.5	9	3.5	8.0
SS09_TP_08_f	580.5	9	4.0	8.0
SS09_TP_08_g	580.5	9	4.5	8.0
SS09_TP_08_h	580.5	9	5.0	8.0
SS06_TP_05_a	577.5	6	1.5	5.0
SS06_TP_05_b	577.5	6	2.0	5.0
SS06_TP_05_c	577.5	6	2.5	5.0
SS06_TP_05_d	577.5	6	3.0	5.0
SS06_TP_05_e	577.5	6	3.5	5.0
SS06_TP_05_f	577.5	6	4.0	5.0
SS06_TP_08_c	577.5	6	2.5	8.0
SS06_TP_08_d	577.5	6	3.0	8.0
SS06_TP_08_e	577.5	6	3.5	8.0
SS06_TP_08_f	577.5	6	4.0	8.0
SS06_TP_08_g	577.5	6	4.5	8.0
SS06_TP_08_h	577.5	6	5.0	8.0

Source: 2020-0804 Flume Testing v6.xlsm

B.4. Wave calibration results

The results of the Healthy Port Futures test wave calibrations are summarised in Table B.3, which presents the incident wave heights (*H*) and periods (*T*) at all eight wave gauges situated leeward of where the structures were once built. The calibrations used the method outlined in Section 2.4.1.

Table B.3: Calibrated wave conditions for Phase 2 Healthy Port Futures tests

Wave condition	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Calibration wave period, T (s)	Calibration wave height, H (ft)								
				WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08	Average (WG01-08)
SS09_TP_05_a	580.5	9	5.0	1.84	1.79	1.34	1.43	1.83	1.90	1.23	1.23	1.57
SS09_TP_05_b	580.5	9	5.0	2.54	2.42	1.80	1.97	2.51	2.55	1.65	1.68	2.14
SS09_TP_05_c	580.5	9	5.0	3.06	3.09	2.42	2.36	3.07	3.28	2.21	2.25	2.72
SS09_TP_05_d	580.5	9	5.0	3.61	3.74	2.96	2.78	3.67	3.96	2.77	2.69	3.27
SS09_TP_05_e	580.5	9	5.0	4.44	4.31	3.80	3.38	4.51	4.77	3.26	3.42	3.99
SS09_TP_05_f	580.5	9	5.0	4.68	5.12	4.68	3.95	4.75	5.67	4.19	4.08	4.64
SS09_TP_08_c	580.5	9	8.0	3.40	2.69	2.17	4.08	1.98	4.24	1.86	2.24	2.83
SS09_TP_08_d	580.5	9	8.0	3.45	3.20	2.77	4.32	3.10	4.35	3.25	2.27	3.34
SS09_TP_08_e	580.5	9	8.0	6.07	4.72	5.11	6.23	5.10	6.94	5.03	3.55	5.34
SS09_TP_08_f	580.5	9	8.0	7.44	5.89	6.20	6.50	5.15	6.50	4.58	3.98	5.78
SS09_TP_08_g	580.5	9	8.0	7.73	5.58	5.56	4.84	4.27	5.36	3.99	3.80	5.14
SS09_TP_08_h	580.5	9	8.0	7.02	4.42	4.85	4.86	3.83	5.25	4.26	3.78	4.78
SS06_TP_05_a	577.5	6	5.0	1.42	1.35	1.50	1.75	2.22	2.43	1.94	1.60	1.78
SS06_TP_05_b	577.5	6	5.0	2.23	2.23	2.55	2.99	3.10	3.40	2.53	2.43	2.68
SS06_TP_05_c	577.5	6	5.0	3.32	3.51	2.41	1.84	3.14	3.47	3.80	2.52	3.00

Wave condition	Still water level, SWL (ft IGLD 85)	Depth at toe, h (ft)	Calibration wave period, T (s)	Calibration wave height, H (ft)								
				WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08	Average (WG01-08)
SS06_TP_05_d	577.5	6	5.0	2.67	2.41	2.26	2.07	1.85	1.78	1.55	0.96	1.94
SS06_TP_05_e	577.5	6	5.0	3.82	3.28	2.94	2.36	2.54	2.76	2.59	2.08	2.79
SS06_TP_05_f	577.5	6	5.0	3.06	2.99	2.88	2.59	2.95	3.24	2.89	2.32	2.87
SS06_TP_08_c	577.5	6	8.0	4.93	2.25	2.86	1.68	3.06	1.58	3.08	1.83	2.66
SS06_TP_08_d	577.5	6	8.0	4.81	2.76	4.36	1.96	3.17	1.62	3.84	1.63	3.02
SS06_TP_08_e	577.5	6	8.0	3.32	1.81	3.53	2.02	3.60	1.99	3.15	1.96	2.67
SS06_TP_08_f	577.5	6	8.0	3.20	2.29	3.11	1.99	3.08	2.11	2.96	1.94	2.59
SS06_TP_08_g	577.5	6	8.0	3.25	3.31	3.51	2.54	3.23	1.95	3.29	2.08	2.89
SS06_TP_08_h	577.5	6	8.0	3.29	3.11	2.71	2.77	2.87	2.51	3.56	2.09	2.86

B.5. Test programme

The Healthy Port Future structures (Figure B.2) were installed after wave calibrations. The transmission coefficients were then measured for all the conditions given in Table B.2. Following the transmission tests, sand was added between the structures. These Test Parts were conducted using the conditions in Table B.4.

Table B.4: Phase 2 Healthy Port Futures sand test conditions

Test Part	Wave condition	Depth at toe, h (ft)	Target wave height, H (ft)	Target wave period, T (s)
01	SS09_TP_05_c	9	2.5	5.0
02	SS09_TP_05_d	9	3.0	5.0
03	SS09_TP_05_e	9	3.5	5.0
04	SS09_TP_05_f	9	4.0	5.0
05	SS06_TP_08_c	6	2.5	8.0
06	SS06_TP_08_d	6	3.0	8.0
07	SS06_TP_08_e	6	3.5	8.0
08	SS06_TP_08_f	6	4.0	8.0

B.6. Results

B.6.1. Wave transmission

The transmission coefficients presented in Table B.5 were calculated using the method described in Section B.2.2 and are presented for each structure, each wave gauge location (cumulative effect up to that gauge) and an overall coefficient.

B.6.2. Sand movement test

Pre and post test photographs are presented for the Healthy Port Futures structure sand tests. A pre-test photograph is presented in Figure B.3 and a photograph looking seaward following all Test Parts is shown in Figure B.4 and in Figure B.5 looking leeward from the last structure. The dunes and ripples formed in the retained sand are visible in Figure B.4 compared to the flat starting bed profile in Figure B.3. Figure B.5 shows ripples forming in the sand in the lee of the structure, but no clear evidence of sand migration was observed. All tests were observed by the SmithGroup onsite representatives, who undertook analysis and drew conclusions on the outcome of these sand tests.

Figure B.3: Healthy Port Futures sand retention pre-test photograph (looking seaward)

Figure B.4: Healthy Port Futures sand retention post-test photograph (looking seaward)

Figure B.5: Healthy Port Futures sand retention post-test photograph (Leeward of final structure)

Table B.5: Healthy Port Futures structure transmission coefficients

Wave condition	Target wave height, H (ft)	Target wave period, T (s)	Transmission coefficient, C_T												
			Overall	Struct 1	Struct 2	Struct 3	Struct 4	WG01	WG02	WG03	WG04	WG05	WG06	WG07	WG08
SS09_TP_05_a	2.0	5.0	47%	73%	102%	107%	96%	59%	73%	70%	72%	71%	76%	49%	47%
SS09_TP_05_b	2.0	5.0	43%	75%	95%	107%	87%	59%	75%	75%	72%	67%	72%	49%	43%
SS09_TP_05_c	2.0	5.0	45%	80%	111%	111%	96%	61%	80%	64%	71%	72%	80%	46%	45%
SS09_TP_05_d	3.0	5.0	45%	84%	128%	103%	79%	64%	84%	58%	74%	82%	84%	57%	45%
SS09_TP_05_e	4.0	5.0	41%	82%	97%	112%	89%	65%	82%	74%	72%	70%	78%	47%	41%
SS09_TP_05_f	4.0	5.0	44%	75%	110%	96%	88%	71%	75%	68%	75%	78%	75%	49%	44%
SS09_TP_08_c	2.0	8.0	41%	91%	125%	120%	47%	96%	91%	64%	81%	72%	86%	88%	41%
SS09_TP_08_d	3.0	8.0	44%	94%	78%	122%	79%	100%	94%	107%	83%	78%	95%	56%	44%
SS09_TP_08_e	4.0	8.0	31%	66%	76%	120%	93%	70%	66%	78%	59%	56%	67%	33%	31%
SS09_TP_08_f	4.0	8.0	24%	60%	77%	106%	67%	64%	60%	42%	32%	45%	47%	35%	24%
SS09_TP_08_g	4.0	8.0	24%	46%	84%	107%	71%	77%	46%	45%	38%	42%	45%	34%	24%
SS09_TP_08_h	5.0	8.0	28%	41%	82%	109%	96%	94%	41%	52%	43%	46%	51%	30%	28%
SS06_TP_05_a	2.0	5.0	37%	98%	97%	94%	135%	130%	98%	48%	46%	41%	38%	28%	37%
SS06_TP_05_b	2.0	5.0	22%	69%	121%	118%	121%	115%	69%	41%	50%	27%	32%	18%	22%
SS06_TP_05_c	2.0	5.0	13%	54%	158%	102%	89%	88%	54%	30%	47%	25%	25%	15%	13%
SS06_TP_05_d	3.0	5.0	19%	63%	122%	204%	90%	127%	63%	50%	61%	30%	62%	21%	19%
SS06_TP_05_e	4.0	5.0	18%	48%	104%	151%	82%	111%	48%	46%	48%	26%	39%	22%	18%
SS06_TP_05_f	4.0	5.0	21%	61%	113%	138%	101%	116%	61%	46%	52%	28%	39%	21%	21%

SS06_TP_08_c	2.0	8.0	15%	38%	68%	84%	49%	76%	38%	50%	34%	32%	27%	30%	15%
SS06_TP_08_d	3.0	8.0	19%	42%	82%	90%	62%	81%	42%	51%	42%	34%	30%	30%	19%
SS06_TP_08_e	4.0	8.0	28%	40%	93%	73%	69%	142%	40%	67%	62%	50%	37%	41%	28%
SS06_TP_08_f	4.0	8.0	26%	55%	66%	58%	61%	154%	55%	80%	53%	56%	32%	42%	26%
SS06_TP_08_g	4.0	8.0	25%	79%	88%	63%	57%	132%	79%	64%	56%	51%	32%	44%	25%
SS06_TP_08_h	5.0	8.0	30%	88%	55%	66%	71%	150%	88%	94%	52%	52%	34%	43%	30%

B.7. Summary

The Healthy Port Futures tests looked at the transmission coefficient of the Healthy Port Future structures and also the sand movement within the cells created by the structures. The average overall transmission coefficient was 30%. There was no significant movement of sand within the cells between structures, with observations showing the formation of typical ripple and dune patterns.

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