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Coastal Engineering Assessment for Trial Oyster Shell Filled Bag Structures: Port River, Adelaide

WRL TR 2018/29 | October 2018

By I R Coghlan and G Lumiatti

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1 Introduction

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was engaged by the Estuary Care Foundation to prepare a desktop coastal engineering assessment for trial oyster shell filled bag structures in Port River, Adelaide.

The Estuary Care Foundation proposes to plant seagrass (relocated from elsewhere in the estuary) just north of Snowdens Beach on the left bank (looking downstream) of Port River (Figure 1.1). Oyster bags are proposed to be installed seaward of transplanted seagrass primarily to attenuate incident wave energy. A secondary objective is to encourage local shellfish to colonise the oyster bags.

A series of 5-10 separate oyster bag structures (alongshore extent 3-5 m) are proposed to be constructed along a 120 m length of shoreline (Figure 1.2). The oyster bags will have the same geometry as those deployed by OceanWatch Australia Ltd (hereafter "OceanWatch") at sites in NSW.

This desktop coastal engineering assessment was undertaken prior to deployment to assess the stability of the oyster bags for the expected water levels and wave climate (wind and boat waves) at the proposed site. This report summarises the methodologies and outcomes of the desktop assessment.

The assessment is limited to the coastal engineering aspects of the oyster bags, and does not assess other professional engineering aspects, planning and policy issues, liability issues, expected shellfish growth and environmental impacts. Since the present engineering knowledge of the behaviour of oyster bags is still in its infancy compared with traditional coastal structure materials (e.g. rock rubble, concrete monolith, floating breakwaters etc.), WRL has provided this advice in good faith, but the trial nature of the proposed oyster bag structures is emphasised.

Figure 1.1 Overview of Port River

Figure 1.2: Zoomed in views of proposed site for trial oyster bag structures

2 Background information

2.1 Laboratory physical modelling (oyster bag stability)

In 2015, WRL designed and completed preliminary two-dimensional physical modelling of generic oyster shell filled bags at full scale in a three metre wide wave flume to better understand their expected behaviour when exposed to wave attack. The modelling objectives were to assess the stability and wave attenuation of this type of coastal protection structure under a variety of water level and wave attack scenarios. The test program was conducted in two distinct phases:

1. The bags were not anchored to the bed or secured together; and
2. The bags were both anchored to the bed and tethered to each other.

The combination of variables tested in the physical model are summarised in Table 2.1. Three (3) water levels were tested corresponding to the top of each tier of oyster shell filled bags in a three tier high pyramid arrangement (Figure 2.1). Wave periods of 1, 2 and 3 s were considered to be representative of most wind and boat waves expected at potential sites. For each water level and wave period combination, the wave height was incrementally increased until depth limited or wave steepness limited conditions were achieved.

Test Condition	Condition Values
Depth of Water at Structure	0.16 m, 0.32 m, 0.40 m
Wave Period	1 s, 2 s, 3 s
Wave Height at Structure	0.05 m to 0.30 m

Table 2.1 Summary of wave and water level conditions tested in the physical model

Figure 2.1 Three tier oyster shell filled bag arrangement - secured (Phase 2 tests)

The oyster shells used to fill the bags were a mix of Sydney rock oyster (*Saccostrea glomerata*) and Pacific oyster (*Crassostrea gigas*) shells. The bag material used was coconut coir netting with 12 mm × 12 mm aperture with seams sewn with Manila rope. Two single bags, one double bag and one triple bag (Figure 2.2) were assembled. Each bag was measured and weighed (dry) prior to testing. Key measurements are summarised in Table 2.2.

Figure 2.2 Example of triple oyster shell filled bag tested in the physical model

Bag #	Bag Type	Mass (kg)	Length (m)	Height (m)	Width (m)	Bulk Volume (m^3)	Dry Bulk Density (kg/m^3)	Porosity (%)
1	Single	12.84	0.92	0.17	0.32	0.039	327	0.82
2	Single	14.91	0.94	0.18	0.32	0.041	361	0.80
3	Double	30.25	0.91 0.91	0.20 0.19	0.27 0.24	0.070	430	0.76
4	Triple	34.48	0.92 0.92 0.90	0.17 0.13 0.18	0.25 0.21 0.22	0.078	444	0.75

Table 2.2 Summary of oyster shell filled bag dimensions tested in the physical model

The threshold wave heights for initiation of bag rocking were recorded for each water depth, wave period, and bag arrangement combination. Example photographs of the oyster shell filled bags under wave attack during testing Phase 2 are presented in Figure 2.3. For further details, refer to Coghlan et al. (2016).

Figure 2.3 Example photographs of wave attack on oyster shell filled bags during Phase 2
Note – Waves are travelling from right to left

2.2 Pilot field trials (oyster bag longevity)

The longevity and durability of the bag material is outside WRL's expertise. However, WRL understands that fields trials in NSW undertaken by OceanWatch found an average oyster shell filled bag life of 12-16 months prior to degradation of the bag material itself depending on the substrate (e.g. mud, sand, rock) and material composure (e.g. shellfish species, sharpness of shell edges, dry bulk density) inside the bags (Rowe, S., 2018, personal communication, 3 August).

As such, the nominal design life for the trial oyster bag structures is one (1) year.

3 Preliminary wave and water level design conditions

3.1 Long period ocean swell waves

Large ocean swells do not penetrate into the Port River upstream to the proposed site, therefore, they were not considered in this assessment.

3.2 Short period wind generated waves

3.2.1 Preamble

Wind wave heights were estimated using the principles of USACE Coastal Engineering Manual (2006), Part II Coastal Hydrodynamics as described below.

3.2.2 Design wind speed

Annual wind roses for Adelaide Airport (approximately 15 km south of the proposed site) from the Bureau of Meteorology are shown in Appendix A. While it is outside the scope of works, data from this site could be used to derive seasonal design wind speeds or regional wind velocities for average recurrence intervals (ARI) less than 1 year (e.g. 1 month or 6 month ARI).

Rather than using the data from Adelaide Airport, it was preferable to estimate the wind conditions which generate wind waves using the design wind velocities for Australia excluding tornadoes set out in *Australian Standard 1170.2* (2011). Design wind velocities (0.2 second gust, 10 m elevation) applicable to the present coastal engineering assessment (Port River falls within Region A1) are given for average recurrence intervals of 1 to 100 years in Table 3.1. Site wind speeds ($V_{sit,\beta}$), are calculated according to Equation 3.1 using multipliers for direction (M_d), terrain ($M_{z,cat}$), shielding (M_s) and topography (M_t).

$$V_{sit,\beta} = V_r M_d (M_{z,cat} M_s M_t) \tag{3.1}$$

Direction multipliers (M_d) for Terrain Category 1 (enclosed, limited-sized water surfaces at serviceability and ultimate wind speeds) are presented in Table 3.2. $M_{z,cat}$ is 1.12 at 10 m elevation (z). The shielding and topography multipliers were both 1.0.

Average Recurrence Interval (years)	Regional Wind Velocity (V_r) 0.2 s duration (m/s)
1	30
5	32
10	34
20	37
25	37
50	39
100	41

Table 3.1 Regional wind velocities (V_r not adjusted for direction)

Direction	Directional Multiplier for Wind Velocity (M_d)
N	0.90
NE	0.80
E	0.80
SE	0.80
S	0.85
SW	0.95
W	1.00
NW	0.95

Table 3.2 Directional wind velocity multipliers (M_d)

On this basis, WRL estimated 0.2 s duration wind gust speed for different directions and average recurrence intervals (Table 3.3).

Average Recurrence Interval (years)	Directional Site Wind Velocities ($V_{sit,\beta}$) 0.2 Second Duration (m/s)							
	N	NE	E	SE	S	SW	W	NW
1	30.2	26.9	26.9	26.9	28.6	31.9	33.6	31.9
5	32.3	28.7	28.7	28.7	30.5	34.0	35.8	34.0
10	34.3	30.5	30.5	30.5	32.4	36.2	38.1	36.2
20	37.3	33.2	33.2	33.2	35.2	39.4	41.4	39.4
25	37.3	33.2	33.2	33.2	35.2	39.4	41.4	39.4
50	39.3	34.9	34.9	34.9	37.1	41.5	43.7	41.5
100	41.3	36.7	36.7	36.7	39.0	43.6	45.9	43.6

Table 3.3 Regional wind velocities (V_r not adjusted for direction)

The longest wind fetches to the proposed site, which are expected to generate the largest wind waves, are from the North-northeast and South directions (approximate). The lengths, exact bearings and locations of these two fetches are shown in Table 3.4 and Figure 3.1.

Direction (approximate)	Fetch Bearing (degree TN)	Fetch Length (m)
NNE	26	951
S	174	808

Table 3.4 Wind wave fetch characteristics

Figure 3.1 Location of adopted wind wave fetches

Wind waves generated by winds blowing along the Port River are the result of sustained winds rather than extreme gusts. Therefore, the equivalent sustained 20 minute wind speeds were calculated using the approach set out in Figure II-2-1 of Part II of the USACE *Coastal Engineering Manual* (2006). A 20 minute duration was selected based on the approach set out in Figure II-2-3 of the same document (USACE, 2006), which describes duration as a function of fetch and wind speed. The selected duration relates to the almost 1 km fetch to the NNE and S of the proposed location of the trial oyster bag structures. The 1 to 100 year ARI sustained (20 minute) wind speeds from the NNE and S of are shown in Table 3.5.

Average Recurrence Interval (years)	Directional Site Wind Velocities 20 Minute Duration (m/s)	
	NNE	S
1	19.8	18.7
5	21.1	19.9
10	22.4	21.2
20	24.4	23.0
25	24.4	23.0
50	25.7	24.3
100	27.0	25.5

Table 3.5 Wind velocities for predominant wind fetches 20 minute duration

3.2.3 Design wind wave heights

Wind waves were calculated based on four equations from the *Coastal Engineering Manual* (Equation II-2-36: USACE, 2006) and reproduced in Appendix B. Significant wave heights (H_{m0}) and peak spectral wave period (T_p) - period being the time in seconds between successive wave crests - were estimated for the North-Northeast and South fetches and wind recurrence intervals from 1 to 100 years. The values obtained are summarised in Table 3.6.

Average Recurrence Interval (years)	Significant Wave Height (m)		Peak Spectral Wave Period (s)	
	NNE	S	NNE	S
1	30.2	26.9	26.9	26.9
5	32.3	28.7	28.7	28.7
10	34.3	30.5	30.5	30.5
20	37.3	33.2	33.2	33.2
25	37.3	33.2	33.2	33.2
50	39.3	34.9	34.9	34.9
100	41.3	36.7	36.7	36.7

Table 3.6 Design wind wave climate

For an expected working life of 12 months, there is a 63% chance of encountering a 1 year ARI wind wave event. Were this to eventuate, the trial oyster bag structures may be exposed to significant wave heights of approximately 0.35 m (1.5 s peak wave period) from either the NNE or S.

3.3 Boat waves

As a boat travels through the water, it generates a series of waves. The height and period of these waves vary depending on boat type and its speed. Table 3.7 summarises the primary parameters used to calculate the maximum height of waves generated by boats and large ships navigating through the Port River channel adjacent to the proposed location of the trial oyster bag structures. Boat/ship waves were calculated based on five main equations provided by Kriebel and Seelig (2005) and reproduced in Appendix C.

Primary Input Parameters	Abbreviations	Units
Boat Length	L	m
Boat Draft	D	m
Boat Speed	V	m/s
Water Depth	d	m
Sailing Line Distance	y	m
Beam (width of the hull)	B	m
Displacement	Δ	kg
Distance from the bow to the widest part of the hull	L_e	m

Table 3.7 Boat parameters for estimating boat generated waves

Based on information provided by Flinders Ports (Port of Adelaide operator), it is understood that the maximum allowable boat speed in the proposed section of the river is 7 knots (3.6 m/s). The water depth in the channel is 10.6 m at mid-tide (bed level is -9.3 m to Lowest Astronomical Tide (LAT); Mean Sea Level (MSL) is +1.3 m LAT; see Table 3.10). The distance between the centre of the channel and proposed location of the trial oyster bag structures is approximately 120 m. Since ships may sail as much as 30 m off this sailing line, a minimum distance of 90 m was considered reasonable. These values for boat speed, water depth and distance between the sailing line and the proposed trial oyster bag structures were adopted for all boat wave calculations.

The Estuary Care Foundation and Flinders Ports indicated that the following boats/ships pass the proposed location of the trial oyster bag structures:

- MV Accolade II (regular operator in Port River);
- Stadacona (occasional operator in Port River);
- California Highway (occasional operator in Port River);
- Commercial tugs (4 tugs owned by Svitzer regularly operating in Port River); and
- Pleasure craft (various public vessels regularly operating in Port River).

Information on the geometry and displacement of each boat/ship was gathered from a range of sources including the Estuary Care Foundation, Flinders Ports, direct communication with vessel owners and reference websites. The values for the boat parameters used to calculate the height of boat generated waves, including boat speed, water depth and distance between the sailing line and the proposed trial oyster bag structures, are summarised in Table 3.8 (see footnotes for information sources).

Primary Input Parameters	Units	Vessels Operating at the Proposed Site				
		MV Accolade II (regular operator)	**Stadacona** (occasional operator)	**California Highway** (occasional operator)	**Commercial Tugs** (regular operator)	**Pleasure Craft** (regular operator)
L	m	108.69[3]	182.90[1]	199.97[9]	31.5[7]	5.35[9]
D	m	6.017[3]	10.88[1]	8.4[5]	4.60[7]	0.40[9]
V	knot	7.00	7.00	7.00	7.00	7.00
d	m	10.60	10.60	10.60	10.60	10.60
y	m	90	90	90	90	90
B	m	23.00[3]	27.6[1]	32.26[9]	11.00[7]	2.30[9]
Δ	kg	11,188[4]	41,626[2]	21,000[6]	895[8]	1.00[10]
L_e	m	27.00[11]	40.00[2]	75.00[12]	6.13[8]	3.00[9]

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11. Estimated by WRL based on Nearmap aerial photograph of MV Accolade II dated 26 July 2013.

12. "K" Line (2018b), RE: Request for California Highway Displacement Value. [E-mail] Message from A Pereira (albinop@kline.com.au) to I R Coghlan (i.coghlan@wrl.unsw.edu.au). Sent 24/9/2018 4:26 PM.

Table 3.8 Values for boat parameters for estimating boat generated waves

The wave heights estimated to be generated by each vessel at 7 knots according to the methodology of Kriebel and Seelig (2005) are shown in Table 3.9. The highest wave height (0.31 m) was generated by the commercial tugs which regularly use this stretch of the Port River.

Vessels Operating at the Proposed Site	Wave Height (m)
MV Accolade II (regular operator)	0.02
Stadacona (occasional operator)	0.03
California Highway (occasional operator)	0.01*
Commercial Tugs (regular operator)	0.31
Pleasure Craft (regular operator)	0.10

* Note C_b for the California Highway was obtained directly (“K Line”, 2018b) rather being calculated using Equation C.1.

Table 3.9 Estimated boat generated wave heights for vessels travelling at 7 knots at proposed site

While wave periods for these vessels have not been calculated, the large ships (MV Accolade II, Stadacona and California Highway) are expected to have wave periods less than 3.0 s in the channel based on similar sized container and cruise ships operating at low speeds (Sorensen, 1967). Similarly, the commercial tugs and various pleasure craft are expected to have wave periods less than 2.0 s (MSB NSW, 1987; Glamore and Hudson, 2005).

3.4 Preliminary water level conditions

Elevated water levels consist of (predictable) tides, which are forced by the sun, moon and planets (astronomical tides), a tidal anomaly and other local processes. Astronomical tidal planes for Port Adelaide are shown in Table 3.10, based on values from AusTides (2017). While the Mean High Water Springs (MHWS) mark is approximately 1.0 m above MSL (-0.152 m Australian Height Datum AHD), some tides will reach up to approximately 1.5 m above mean sea level without any additional tidal anomaly. Chart datum, which is used in bathymetric charts and tidal predictions, is approximately 1.452 m below AHD (BoM, 2010).

Description	Water Level (m relative to datum)	
	LAT	AHD
Highest Astronomical Tide (HAT)	2.8	1.348
Mean High Water Springs (MHWS)	2.3	0.848
Mean High Water Neaps (MHWN)	1.3	-0.152
Mean Sea Level (MSL)	1.3	-0.152
Mean Low Water Neaps (MLWN)	1.3	-0.152
Mean Low Water Springs (MLWS)	0.3	-1.152
Lowest Astronomical Tide (LAT)	0.0	-1.452

Table 3.10 Astronomical tidal water levels for Adelaide (Source: AusTides, 2017; BoM, 2010)

Tidal anomalies primarily result from factors such as regional wind setup (or setdown) and barometric effects, which are often combined as “storm surge”. Additional anomalies occur due to “trapped” long waves propagating along the coast. Design storm surge levels (astronomical tide + anomaly) are recommended in the *Port Adelaide Seawater Stormwater Flooding Study* (City of Port Adelaide Enfield, 2005) based on data from the Outer Harbor and Inner Harbour tide gauges in Port River and reproduced in Table 3.11. These values exclude wave setup and runup effects which can be significant where waves break on shorelines. Note that the 100 year ARI water level at the Inner Harbour (nearest the proposed site of the trial oyster bag structures) is higher than at the Outer Harbor due to tidal amplification.

Average Recurrence Interval (years)	Water Level Excl. Wave Setup and Runup (m AHD)	
	Outer Harbor	Inner Harbour
1.111	1.602	
2	1.787	
5	1.948	
10	2.047	
20	2.138	
50	2.248	
100	2.325	2.50

Table 3.11 Design water levels Tide + Storm Surge (Source: City of Port Adelaide Enfield, 2005)

Water levels at any specific shoreline location are also subject to local wind setup, wave setup and wave runup. Local wind setup and wave setup are considered negligible due to the relative small wave heights and short wave periods. Local freshwater flooding of the Port River is also negligible (runoff in Adelaide is largely directed to the River Torrens to the south); “storm surge” is the major source of flooding.

While land subsidence is prevalent in Adelaide (City of Port Adelaide Enfield, 2005), it is considered appropriate to exclude land subsidence and sea level rise from the preliminary water level assessment due to the modest desired working life of the trial oyster shell bag structures.

3.5 Processes not considered

Consideration of the influence of the following processes on the stability of the oysters bags was outside the scope of works:

- Tidal currents;
- Flood velocities;
- Vessel thruster currents;
- Direct boat/ship collisions and/or propeller strikes;
- Expected beach scour level at the toe and vertical settlement of the bags; and
- Strength of anchoring stakes into the riverbed.

While tidal currents have not been considered in this assessment, it is noted that peak tidal velocities on ebb tides of 0.85 m/s (opposite the Australian Submarine Corporation on 8 October 2006; 2.437 m LAT high tide falling to 0.050 m LAT low tide) and 0.66 m/s (Outer Harbor swing basin 23 July 2013; 2.513 m LAT high tide falling to 0.107 m LAT low tide) have previously been recorded by Flinders Ports (2018). However, it is understood that these measurements did not coincide with a “storm surge” event when higher velocities may occur.

Since local freshwater flooding is negligible, freshwater flood velocities are also considered negligible.

Consideration of the influence of the trial oyster bag structures on existing siltation processes around the public boat ramp, immediately downstream of the proposed site, was also outside the scope of works.

4 Stability of trial oyster bag structures at the proposed site

In terms of cross-shore position of the oyster shell bags on the inter-tidal profile, toe elevations to replicate conditions tested in the wave flume are set out in Table 4.1 for 1, 2 and 3 tier oyster bag structure arrangements. With this cross-shore position, depth limited waves exceeding that tested in the flume could only occur for water levels exceeding the Mean High Water Springs level (2.3 m LAT; 0.85 m AHD) coincident with wind or boat waves exceeding 0.3 m in height.

Oyster Bag Structure Type	Minimum Toe Elevation (m relative to datum)	
	LAT	AHD
1 Tier	2.14	0.69
2 Tiers	1.98	0.53
3 Tiers	1.90	0.45

Table 4.1 Toe elevations to replicate conditions tested in WRL's wave flume

However, it is acknowledged that this is likely above the optimal zone for promoting new shellfish growth on the oyster shell filled bags. While WRL is unaware of the optimal zone to maximise promotion of new shellfish growth in the Port River, in NSW, the optimal zone for growth of Sydney Rock and Pacific oysters is 0.7 m below to 0.2 m above MSL (Bishop et al., 2010).

As noted in Section 2, the maximum wave height tested on oyster bags in the laboratory physical model was 0.3 m. This is approximately equivalent to the wave height estimated to be produced by the regularly operating commercial tugs (0.31 m) and the 1 year ARI wind waves (0.29 m (S) to 0.34 m (NNE). On the basis that the oyster bag structures have a nominal working life of 12 months and are considered an experiment, WRL considers that the trial oyster bag structures could be deployed in deeper water depths than those set out in Table 4.1, because the incident waves are not depth limited. The additional submergence is expected to reduce the wave forces on the trial oyster bag structures (similar to a traditional submerged breakwater). WRL recommends that the Estuary Care Foundation seek advice from a marine ecologist with local expertise to establish the optimal zone for promoting new shellfish growth and install the trial oyster shell bags structures within this zone. That is, for boats regularly operating in this section of the Port River and wind waves up to 1 year ARI, the trial oyster bags are expected to be stable regardless of the toe elevation of the structures.

It is noted that the stability of the trial oysters bags is not assured for wind wave events greater than 1 year ARI if the structures are deployed in deeper water depths than those set out in Table 4.1. It is also noted that the maximum wave heights (0.3 m) tested in the physical model were monochromatic, but that 1 year ARI wind wave heights are for irregular waves. That is, approximately 13.5% of individual waves would exceed the characteristic significant wave height (0.29 m (S) to 0.34 m (NNE) calculated.

WRL recommends that the Estuary Care Foundation seek advice from OceanWatch as to their recommendations for filling, installing and securing oyster bags. This practical experience is outside of WRL's area of expertise. However, the geometry of the bags should be consistent with the properties tested in the laboratory physical model (Table 2.2). Care in quality control should be undertaken to ensure that the mass/density of the filled oyster bags remains consistent throughout filling (e.g. measuring and weighing each bag). WRL recommends that the oyster bags be anchored to the bed on both the landward and seaward side according to OceanWatch's recommendations and, for 2 and 3 tier structures, that the oyster bags be fastened together.

5 Future research opportunities

If the Estuary Care Foundation intends to increase the present level of understanding of coastal engineering aspects of oyster shell filled bags, two opportunities for future research have been identified by WRL. Cross-sectional monitoring surveys could be undertaken seaward and landward of the trial oyster shell filled bag structures and at another control location nearby with similar wave exposure and sediment composition. The deployment of a wave gauge and/or an imaging system, which is able to accurately measure waves with relatively small heights and periods just offshore of the oyster shell filled bags, would also assist in performance monitoring and verification of the desktop wind wave and boat generated wave climate estimates.

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Appendix A BoM wind rose plots for Adelaide Airport

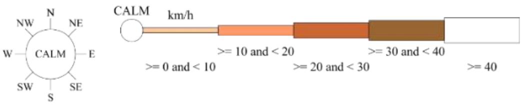
Rose of Wind direction versus Wind speed in km/h (16 Feb 1955 to 05 Apr 2016)

Custom times selected, refer to attached note for details

ADELAIDE AIRPORT

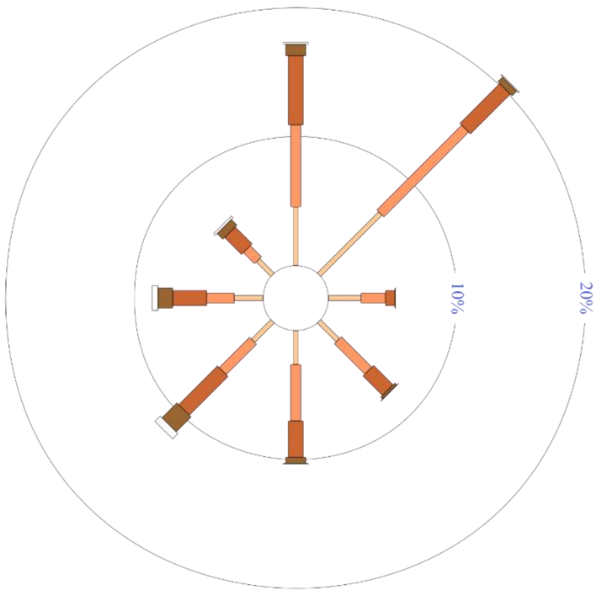
Site No: 023034 • Opened Feb 1955 • Still Open • Latitude: -34.9524° • Longitude: 138.5204° • Elevation 2m

An asterisk (*) indicates that calm is less than 0.5%.
Other important info about this analysis is available in the accompanying notes.



9 am
22458 Total Observations

Calm 13%



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Rose of Wind direction versus Wind speed in km/h (16 Feb 1955 to 05 Apr 2016)

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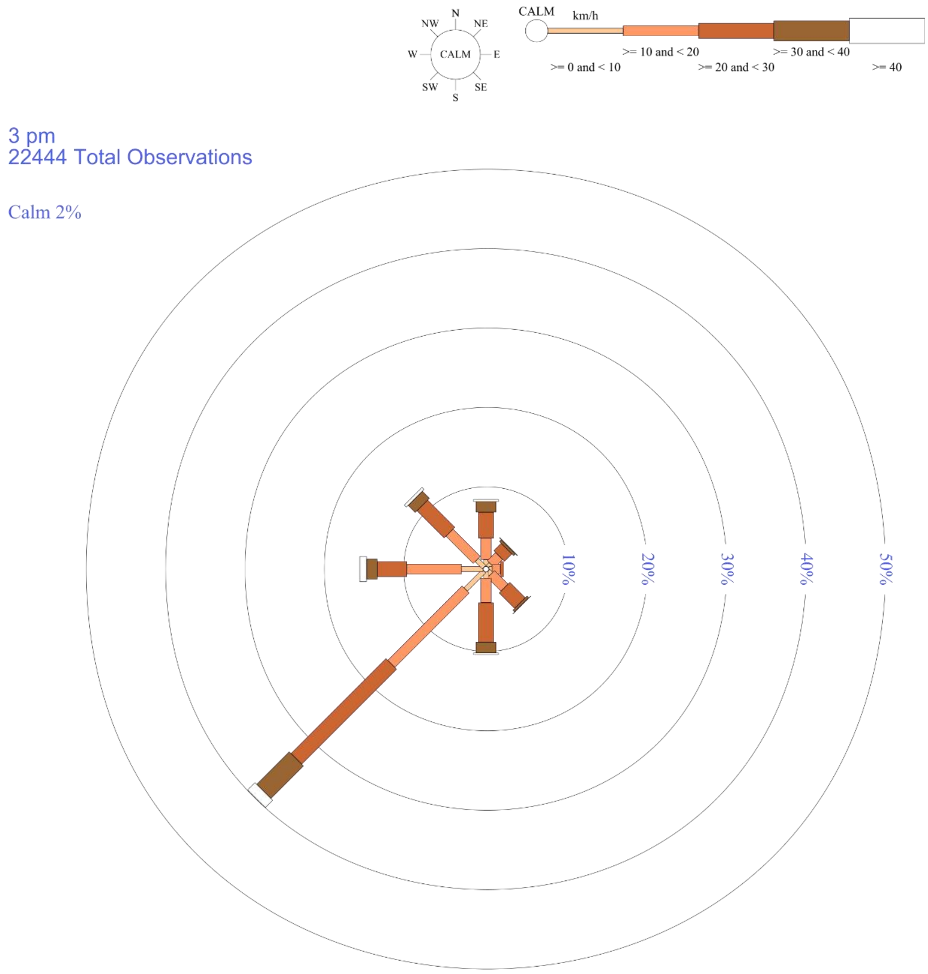

Appendix B Equations for estimating wind wave heights

Wind waves were calculated based on four equations from the *Coastal Engineering Manual* (Equation II-2-36: USACE, 2006) and reproduced as Equations B.1 to B.4.

$$\frac{gH_{m0}}{u_*^2} = 4.13 * 10^{-2} * \left(\frac{gX}{u_*^2}\right)^{1/2} \quad \text{(B.1)}$$

$$\frac{gT_p}{u_*} = 0.751 \left(\frac{gX}{u_*^2}\right)^{1/3} \quad \text{(B.2)}$$

$$C_D = \frac{u_*^2}{U_{10}^2} \quad \text{(B.3}$$

$$C_D = 0.001(1.1 + 0.035U_{10}) \quad \text{(B.4)}$$

Where:

- X = straight line fetch distance over which the wind blows (units of m)
- H_{m0} = energy-based significant wave height (m)
- C_D = drag coefficient
- U_{10} = wind speed at 10 m elevation (m/s)
- u_* = friction velocity (m/s)

Appendix C Equations for estimating boat wave heights

Boat/ship waves were calculated based on five main equations provided by Kriebel and Seelig (2005) and reproduced as Equations C.1 to C.5.

$$C_b = \frac{\nabla}{\mathrm{LBD}} \tag{C.1}$$

$$\alpha = 2.35(1 - C_b) \tag{C.2}$$

$$F^* = F_L \exp\left(\alpha \, \frac{\mathrm{D}}{\mathrm{d}}\right) = \frac{\mathrm{V}}{\sqrt{gL}} \exp\left(\alpha \frac{\mathrm{D}}{\mathrm{d}}\right) \tag{C.3}$$

$$\beta = 1 + 8 * tanh^3(0.45\left(\frac{L}{L_e}\right) - 2)) \tag{C.4}$$

$$\frac{gH}{V^2} = \beta(F^* - 0.1)^2 \, \left(\frac{y}{L}\right)^{-1/3} \tag{C.5}$$

Where:

- C_b = Block coefficient
- *A* = Empirical coefficient that depends on the ship hull form
- F^* = Modified Froude Number
- β = Empirical coefficient that depends on the shape of the bow
- *H* = Wave Height