Dynamic Mooring Analysis of 6-Buoy Spread-Moored Ships at Cape Cuvier

Tim P. Gourlay[1], David W. Paynter[2] and Bradley J. Smith[3]
[1] Perth Hydro, Perth, Australia; tim@perthhydro.com
[2] Dampier Salt Ltd, Carnarvon, Australia.
[3] Hatch, Perth, Australia.

Abstract
An overview is given of dynamic moored ship motions and loads at the Port of Cape Cuvier, in Western Australia. The port is exposed to open-ocean long-period swell, with a year-round average significant swell height of 1.2 m. The port consists of a 6-buoy spread-mooring arrangement, with long natural surge, sway and yaw periods of moored ships.

A dynamic mooring numerical model has been developed, to calculate moored ship wave-induced motions and loads at the port. A nonlinear time-domain model is used, following PIANC guidelines. Detailed wave and mooring system effects are included. Validation is described for a test case with measured environmental and mooring load data, showing good agreement between calculated and measured results. Present and future use of the numerical model are discussed.

Keywords: moored ships, bulk loading, dynamic mooring analysis.

Nomenclature

CoG	Centre of gravity
D_P	Peak wave direction
DoF	Degrees of freedom
GNSS	Global navigation satellite system
H_S	Significant wave height
IRF	Impulse response function
KG	Centre of gravity height above keel
LBP	Length between perpendiculars
LAT	Lowest astronomical tide
LOA	Length overall
MB	Mooring buoy
MSL	Mean sea level
QTF	Quadratic transfer function
RAO	Response amplitude operator
T_P	Peak wave period
WST	Western standard time

Figure 1 Satellite view of Cape Cuvier, north of Shark Bay and Carnarvon on the west coast of Australia. Cape Cuvier is exposed to south-west swells from the Southern Ocean. Image Google Earth.

1. Introduction

Cape Cuvier is a salt and gypsum export terminal on the west coast of Australia. The area is subject to long-period swells from the Southern Ocean, which make this stretch of coast renowned for surf breaks such as Red Bluff and Gnaraloo. A satellite view of the Cape Cuvier coast is shown in Figure 1.

Cape Cuvier has a jetty with a fixed shiploader, and 6 mooring buoys numbered clockwise around the ship, as shown in Figure 2.

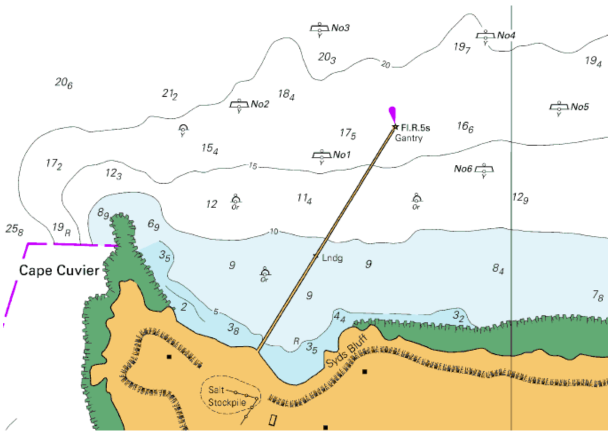

Figure 2 Port of Cape Cuvier, showing jetty and 6 mooring buoys. From chart AUS 73, Australian Hydrographic Office.

Because the shiploader is fixed, the ship must be warped forward and aft to load the different holds. Figure 3 shows No. 1 Hold being loaded for a 229 m Panamax ship.

Figure 3 Loading No. 1 Hold for the 229 m Panamax ship Alam Kekal

Figure 4 shows No. 5 Hold being loaded for the same ship. The ship has been warped forward, to have the shiploader in the right position for this hold.

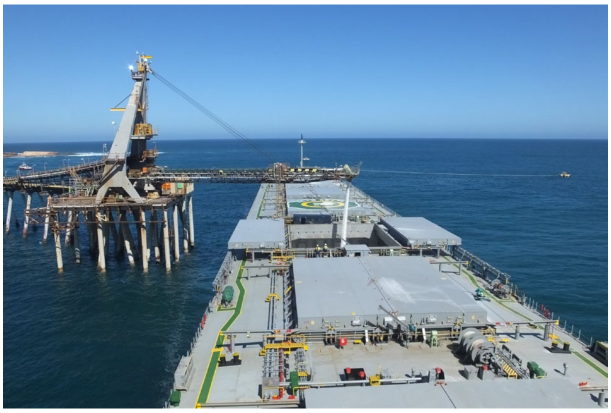

Figure 4 Loading No. 5 Hold for the 229 m Panamax ship Alam Kekal

The mooring buoys are positioned such that the moored ship points due west, with bow into the prevailing swell wrapping around the cape.

2. Dynamic mooring behaviour of ships at Cape Cuvier

Cape Cuvier is well instrumented for understanding the environment and ship mooring behaviour. Measured data sources include:

- Datawell DWR-G directional waverider buoy, 200 m west of Mooring Buoy 2 (see Figure 2), for measuring sea (< 8 s) and swell (8 – 30 s)
- RS Aqua WaveRadar REX² wave radar gauge, mounted on the jetty, primarily for measuring long period waves (> 30 s) and tide height
- Anemometer, mounted on the jetty, for measuring wind speed and direction, with second anemometer installed on the headland to provide comparative data
- Load cell on each mooring buoy, measuring dynamic mooring line loads.

Machine learning analysis on 6 years of measured data showed that swell height is the primary environmental factor for ship mooring loads at Cape Cuvier. The year-round average swell height, as measured at the waverider buoy, is 1.2 m. Recent dynamic mooring analysis has confirmed that long period waves (> 30 s) are also an important consideration. The importance of swell and long period waves at Cape Cuvier can be traced back to the pioneering work of O'Brien (1985).

Wind is of lesser importance for dynamic mooring loads. Even in a strong southerly sea breeze, the southern mooring buoys MB1 and MB6 tend to have moderate peak loads. Meanwhile, the bow and stern mooring buoys (MB2 and MB5) tend to have high peak loads, due to wave-induced surging of the ship.

The mooring lines at Cape Cuvier are very long (typically 50 – 250 m), so the mooring system is "soft" and the horizontal motion natural periods are long, as shown in Table 1.

Table 1 Typical natural motion periods for moored ships at Cape Cuvier

Natural motion periods		
	Handysize ships	*Panamax ships*
Surge	100 s	130 s
Sway	250 s	350 s
Heave	10 s	13 s
Roll	9 s	11 s
Pitch	9 s	12 s
Yaw	120 s	120 s

The soft mooring arrangement means that horizontal motion amplitudes tend to be large, but horizontal accelerations tend to be small. Loading is possible with surge and sway peak-to-peak motions of up to 10 metres. This is above the PIANC-recommended bulk carrier loading limits of 5 m peak-to-peak surge and 2.5 m zero-to-peak sway (PIANC 1995, Table 1.2). The slow horizontal motions mean that a skilled operator can observe the ship motions and move the shiploader discharge tip as required to efficiently load the hold.

The soft mooring arrangement at Cape Cuvier also has the advantage that the ship can be safely moored and loaded in large swell conditions, as compared to most shipping terminals. Loading of Handysize ships can be performed in up to 3.0 m swell, while loading of Panamax ships can be performed in up to 2.5 m swell, as measured at the waverider buoy near Mooring Buoy 2.

Despite the ship being bow-on to the prevailing swell, the directional spread of incoming swells means that wave-induced roll moments are exerted on the ship. For Panamax ships, the natural roll period can be close to the peak swell period, causing appreciable roll motions. Example measured roll motions for a Panamax ship are shown in Figure 5.

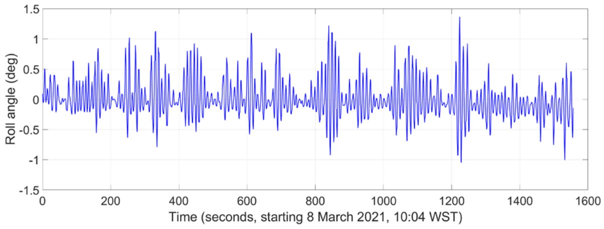

Figure 5 Roll motions for Panamax ship Alam Kekal, while loading No. 5 Hold as shown in Figure 4, with measured swell H_S = 1.5 m, T_P = 15.8 s and D_P = 270˚. Roll motions measured from the bridge with iPhone 12 and SensorLog software.

3. Dynamic mooring numerical modelling

Since 2021, Perth Hydro has been working with Dampier Salt Ltd and Wavelength Consulting (now part of Hatch) to model dynamic motions and loads of moored ships at Cape Cuvier.

Dynamic mooring analysis is done using nonlinear time-domain software, as required under PIANC (1995) guidelines. The nonlinear time-domain solver MoorMotions (www.moormotions.com) is used for the modelling.

MoorMotions utilises a fourth-order Runge-Kutta time-stepping method (Press et al. 1999, p.710) to solve the 6-DoF moored ship equation of motion. The equation of motion is essentially as given in Van Oortmerssen (1973, eq.4.23):

$$\sum_{j=1}^{6}[M_{ij}+A_{ij}(\infty)]\ddot{x}_j = X_i^{(1)} + X_i^{(2)} + F_i^{(\text{lines})} - \sum_{j=1}^{6} C_{ij}x_j - \int_0^\infty \sum_{j=1}^{6} L_{ij}(\tau)\ddot{x}_j(t-\tau)d\tau$$

The symbols are defined as follows:
x_j=motion in each degree of freedom, $j = 1, \ldots, 6$
M_{ij} =mass matrix
$A_{ij}(\infty)$ =added mass at infinite frequency
$X_i^{(1)}$ =first-order wave load
$X_i^{(2)}$ =second-order wave load
$F_i^{(\text{lines})}$ =net force produced by mooring line tension at each instant in time
C_{ij} =linear restoring coefficients
$L_{ij}(\tau)$ =hydrodynamic impulse response functions, see Gourlay (2021).

The coordinate system used is:
x_1= "surge" (fore-aft CoG motion, positive forward)
x_2 = "sway" (transverse CoG motion, positive port)
x_3 = "heave" (vertical CoG motion, positive up)
x_4 = "roll" (angle, positive to starboard)
x_5 = "pitch" (angle, positive bow-down)
x_6 = "yaw" (angle, positive bow-to-port).

Since natural surge, sway and yaw periods are typically longer than 1 minute for moored ships at Cape Cuvier (see Table 1), wave load modelling must include low-frequency wave loads. Low-frequency wave loads comprise two main effects: long-period wave loads; and second-order, slowly-varying wave loads.

Long-period wave loads are calculated using the long wave spectrum, combined with first-order wave load RAOs, to calculate 6-DoF wave load timeseries on the moored ship.

Second-order wave loads are calculated using the moored ship's quadratic transfer functions (QTFs). From the wave load QTFs, wave load timeseries on the moored ship are calculated using the method described in Newman (1974).

First-order wave load RAOs, second-order wave load QTFs, and hydrodynamic IRFs are calculated using WAMIT software (www.wamit.com). WAMIT has been extensively validated against other codes and model-test data, for wave-induced motions of cargo ships (Gourlay et al. 2015, 2019).

The combination of WAMIT and MoorMotions has been validated against Marin model test data for a moored tanker at an open berth (Gourlay 2019a). The method has also been validated against full-scale 6-DoF GNSS data for a moored bulk carrier in Geraldton (Gourlay 2019b).

Validation of WAMIT and MoorMotions, for a moored bulk carrier at Cape Cuvier, will be presented in this article.

4. Example Cape Cuvier dynamic mooring validation

For a test case, we consider a past visit of the Handysize bulk carrier "Crystal Island" during a long-period swell event. Principal dimensions of this ship are shown in Table 2.

Table 2 Principal dimensions of Handysize bulk carrier "Crystal Island"

Test case ship – Crystal Island	
LOA	169.5 m
LBP	160.4 m
Beam	27.20 m
Depth	13.60 m
Summer draft	9.80 m
Summer deadweight	28,000 tonnes

We consider the warping position before departure, from 14:33 – 15:10 WST on 29th April 2018, when the shiploader is at No. 3-4 Hold. At this time, the ship is fully loaded, with draft and displacement as shown in Table 3.

Table 3 Departure loading condition for "Crystal Island"

Test case – Loading condition	
Midship draft	9.82 m
Displacement	36,960 tonnes
KG	6.0 m

Measured environmental conditions at this time are shown in Table 4.

Table 4 Measured environmental conditions

Test case – Environmental conditions		
Parameter	*Value*	*Source*
H_S Swell	1.55 m	Waverider buoy
T_P Swell	17.4 s	
D_P Swell	271˚	
H_S Long waves	0.20 m	Jetty laser gauge
Wind	13-15 kn SW	Jetty anemometer

Additional environmental parameters, as modelled, are shown in Table 5.

Table 5 Modelled environmental parameters

Modelled environmental parameters	
Wave spectrum	Bretschneider standard spectrum
Wave spreading	Cosine-squared wave spreading, max. spread ±45˚
Long wave spectrum	Constant spectral energy density from 0.0209 rad/s (300 s period) to 0.209 rad/s (30 s period)

5. WAMIT calculations

Basic wave load RAOs and QTFs, and hydrodynamic IRFs, are firstly calculated using WAMIT for Crystal Island in departure condition. The hull shape is modelled using the Japan Bulk Carrier standard hull (NMRI 2015), stretched to the correct dimensions. A surface mesh for the hull is developed using DELFTship and OCTOPUS software, as shown in Figure 6.

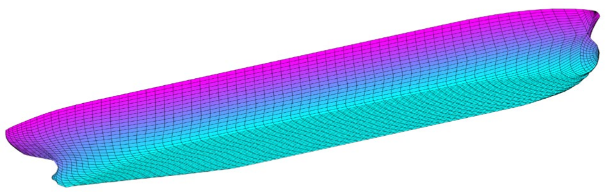

Figure 6 4256-panel surface mesh for Crystal Island, as used for WAMIT calculations

WAMIT calculations are then performed, using the settings shown in Table 6.

Table 6 WAMIT settings for Crystal Island test case

WAMIT settings	
WAMIT solver	Direct solver, standard velocity potential
Representative water depth	17 m, including tide
Degrees of freedom	Coupled 6-DoF
1st - order wave loads	Diffraction potential
2nd - order wave loads	Momentum balance
Roll gyradius	35% beam
Pitch gyradius	25% LOA
Yaw gyradius	25% LOA
Wave headings relative to ship, for wave loads	0˚ : 15˚ : 360˚
Wave frequencies, for wave loads	0.01 : 0.01 : 1.50 rad/s
Wave frequencies, for IRFs	0.00 : 0.01 : 4.00 rad/s, plus infinite frequency
IRF method	WAMIT f2t utility, time step 0.1 s, length 65 s

6. Mooring system modelling

The six mooring buoys at Cape Cuvier are each moored by 84 mm steel chain to a 10-tonne clump weight and multiple anchors. The depth and chain length for each mooring buoy are shown in Table 7.

Table 7 Mooring buoy chain lengths

Mooring buoy chain lengths		
	Depth at MSL (LAT +1.0m)	*Chain length, MB to clump weight*
MB1 (port fwd breast lines)	16.7 m	60.8 m
MB2 (head lines)	22.7 m	70.8 m
MB3 (stbd fwd breast lines)	23.6 m	67.4 m
MB4 (stbd aft breast lines)	23.7 m	60.2 m
MB5 (stern lines)	21.0 m	64.3 m
MB6 (port aft breast lines)	16.9 m	63.2 m

The mooring buoys move toward or away from the ship when the ship mooring lines are under high or low tension. An example is shown in Figure 7 for MB2.

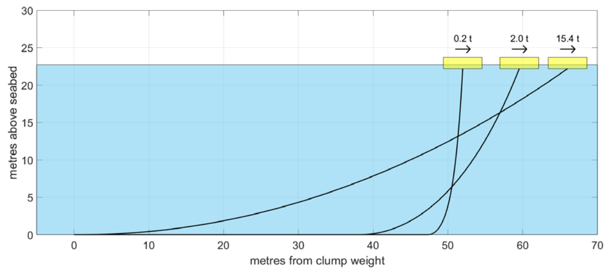

Figure 7 Mooring buoy position, as a function of horizontal load, for MB2. 15.4 tonnes corresponds to the chain lift-off tension in this case.

Because of the mooring buoy movement, a chain catenary analysis is included in the dynamic modelling, to allow each mooring buoy to move under the applied horizontal load. Because of the slow ship movement and comparatively light weight of the mooring buoys, the horizontal loads due to mooring line tension and chain tension are assumed to be in equilibrium at each instant in time.

The positioning of the ship and mooring buoys for the Crystal Island test case is shown in Figure 8. The mooring buoy positions are shown at chain lift-off tension.

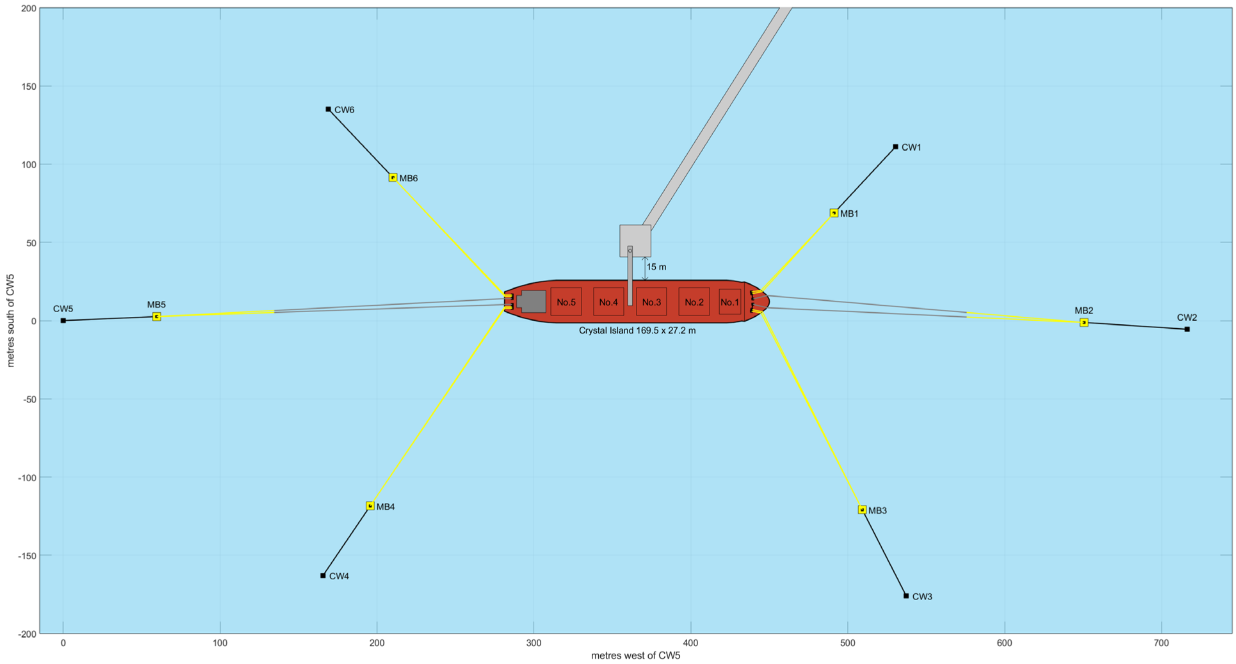

Figure 8 Mooring arrangement for Crystal Island test case, total 12 mooring lines. Yellow lines are polypropylene; grey lines are steel wire; black lines are anchor chain.

The mooring line lengths, from buoy to fairlead, are as shown in Table 8.

Table 8 Mooring line lengths (buoy to fairlead) for Crystal Island test case

Mooring line lengths	
MB1 (port fwd breast lines)	67.9 m
MB2 (head lines)	202.5 m
MB3 (stbd fwd breast lines)	141.5 m
MB4 (stbd aft breast lines)	153.0 m
MB5 (stern lines)	221.9 m
MB6 (port aft breast lines)	103.8 m

The port-supplied mooring line types used at the time of the test case are shown in Table 9. These mooring lines are used on every ship, by winding them onto each ship's winches at anchor before tying up to the mooring buoys.

Table 9 Mooring line details

Mooring line types during test case		
	Danstrong Polypropylene	*Steel wire*
Diameter	70 mm	36 mm
MBL	80.3 t	92.2 t
Elongation at breaking	15-18%	2%
Use	Breast lines; 75 m tail on head and stern lines	Head and stern lines

A photo of the steel wires and Danstrong breast lines is shown in Figure 9.

Figure 9 Port-supplied steel wire stern lines and Danstrong aft breast lines, as used for Crystal Island test case. Shown here on Alam Kekal, March 2021.

The steel wire head and stern lines are long and heavy enough to have a significant sag (up to 10 m) when in operation. Therefore, we include a dynamic catenary analysis for the head and stern lines.

Because mooring lines are not perfectly elastic, allowance is made for mooring line energy dissipation through each load cycle. Mooring line energy dissipation was set at 35% through each load cycle, for polypropylene mooring lines or tails, as measured for similar lines in Van Zwijnsvoorde (2022, Table 3.5).

The exact line pre-tensions at the time of the test case are not known. The load monitoring system, at the time, only recorded peak loads through each motion cycle. We have assumed that the line pre-tensions are at the recommended level for Handysize ships at Cape Cuvier, as shown in Table 10.

Table 10 Standard mooring line pre-tensions for Handysize ships at Cape Cuvier

Mooring line pre-tension	
Head and stern lines	10 tonnes on each line
Breast lines	7.5 tonnes on one line in each pair (on winch). Other line on bitts at low pre-tension.

7. Validation results and outlook

Measured peak mooring buoy loads for the Crystal Island test case are shown in Table 11, together with calculated values from dynamic mooring analysis.

Table 11 Mooring buoy peak loads for Crystal Island test case

Mooring buoy peak loads		
	Calculated	*Measured*
MB1	25 tonnes	29 tonnes
MB2	51 tonnes	58 tonnes
MB3	11 tonnes	9 tonnes
MB4	13 tonnes	14 tonnes
MB5	47 tonnes	32 tonnes
MB6	20 tonnes	25 tonnes

The calculated peak loads are generally close to the measured values, given the uncertainty present in the pre-tension modelling. MB2 & MB5 (for head and stern lines respectively) take the highest load, as is usually observed at the port. The measured difference between MB2 and MB5 loads is larger than calculated, indicating that second-order drift loads may have been under-estimated. MB1 (for port forward breast lines) also takes high loads, because of its comparatively short lines.

Some important changes have happened at Cape Cuvier, since the Crystal Island test measurements were taken:

- Head and stern lines have been replaced with low-stretch HMPE lines and high-stretch anti-snapback tails.
- Tail lengths have been increased from 75 m to 90 m, to further reduce peak loads on MB2 and MB5.
- A new load monitoring system has been installed on all mooring buoys.
- Mooring buoy load data and environmental data are now displayed and logged in the one system.

The replacement of steel wire with HMPE, for head and stern lines, is primarily to improve safety in the event of line breakage, following OCIMF's (2018) MEG4 guidelines. A further measure is the introduction of anti-snapback (ASB) soft tails on the head and stern lines. These contain a loose inner core, which stays intact and prevents snapback, in the event of the tail breaking.

The new mooring buoy load monitoring system will measure loads continuously at 2 Hz, as compared to ~0.2 Hz for the previous system. The higher-frequency load monitoring will allow average loads, as well as peak loads, to be more reliably measured.

Mooring buoy load data is now overlaid with wind and swell data to provide real time observations remotely. Citec is currently being used as the platform for this. Figure 10 shows an example of measured mooring buoy loads and swell data from the visit of MV Enishi. Additional inputs can be added from any of the mooring buoy load cells or environmental instruments.

Figure 10 Real-time data monitoring for visit of MV Enishi (1-3 January 2023). (Top) Measured load on MB3; (Middle) Measured swell H_S; (Bottom) Measured swell T_P.

The dynamic mooring numerical model is now being used to assess alternative mooring arrangements and hardware for the terminal, to optimize moored ship motions and loads. Failure modes are also being studied, to assess the impact of a failed mooring line or mooring buoy on the ship movement, and the resulting requirement for stand-by tugs.

With the new load monitoring system, it is the intention to conduct additional validation of the dynamic mooring numerical model, using new measured motion and load data. The model may then be used in dynamic ship motion and load forecasting, or to refine the existing swell and long wave limits.

8. References

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