Variable Channel Design for Ports and Harbours in Macro Tidal Environments

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Abstract
The width and depth of a navigational channel are critical to ensure navigational safety. These channel design parameters are commonly determined based on ship parameters, surrounding environmental conditions and tested through ship simulation processes as outlined in design guidelines such as PIANC and ROM.

A common approach in channel design starts with use of the minimum water level and acceptable operable environmental conditions such as wind, current and wave to develop a conceptual channel design and to test and optimize the design dimensions through ship simulation processes.

In macro tidal environments, the rapidly changing water level leads to rapid changes in the current velocity and often direction, which can affect a ship's handling and the channel design dimensions. This paper presents a variable channel design approach, whereby the channel dimensions are assessed at several locations along the channel length/transit and at several intervals in a tidal cycle. This approach allows for the channel dimensions to be optimized, reducing the dredging volume, cost and environmental impact.

The evaluation of the channel design for large cruise ships entering into the Port of Broome has been selected as a case study. The Port has a maximum spring tide of 9 metres, which generates currents of up to 4.5 knots in the channel. The variable channel design approach was used for the design of the approach channel into Broome. This approach may be applicable to other ports and harbours in macro tidal environments.

Keywords: Channel Design, Macro Tidal Environment, Dredging, Ship Simulation, Cruise Ship

1. Introduction

The design of navigational channel is critical in ensuring safety to navigation. The process of designing a navigation channel is well described in design guidelines such as by PIANC (Permanent International Association of Navigation Congresses) [6] and Puertos del Estado as part of the ROM programme (Recommendations for Maritime Works) [7].

In a macro tidal environments, the channel design process faces the added challenge of dealing with the rapidly changing water level, which leads to changes in the tidal current velocity and direction. These rapid changes in current velocity and direction directly affect the handling of ship and hence the channel design.

This paper focuses on the horizontal channel dimension (channel width) and aims to outline the unique challenges of channel design in macro tidal environments and how a variable channel approach can be used to address the design problems.

2. Design Guidelines

2.1 PIANC Guideline – Horizontal Channel Dimension

The PIANC channel design guideline was recently updated in 2014 [6]. The new guideline has also been prepared in close corporation with IAPH ((International Association of Ports & Harbours), IMPA (International Maritime Pilots Associations) and IALA ((International Association of Marine Aids to Navigation and Lighthouse Authorities) and hence continue to have the benefits of technical input and acceptance by those organisations, which play important role in ensuring navigational safety. The new guideline [6] continues to be well accepted by the industry and is considered as "best practice" for the conceptual design of navigational channel.

The conceptual design method under the PIANC guideline for a straight channel (as illustrated Figure 1) is based on the following equations, which are expressed in terms of the design ship's beam.

For one-way channel.

$$W = W_{BM} + \sum W_i + W_{BR} + W_{BG} \qquad (1)$$

For two-way channel.

$$W = 2W_{BM} + 2\sum W_i + W_{BR} + W_{BG} + \sum W_p \qquad (2)$$

Where W_{BM} is for width for basic manoeuvring lane as a multiple of the design ship's beam; $\sum W_i$ is for additional width to allow for the effects of wind, current and wave as a multiple of the design ship's beam; $\sum W_p$ is for passing distance; W_{BR}, W_{BG} are for bank clearance

Details of the width allowances under various conditions can be found in [7] and have not been repeated in this paper.

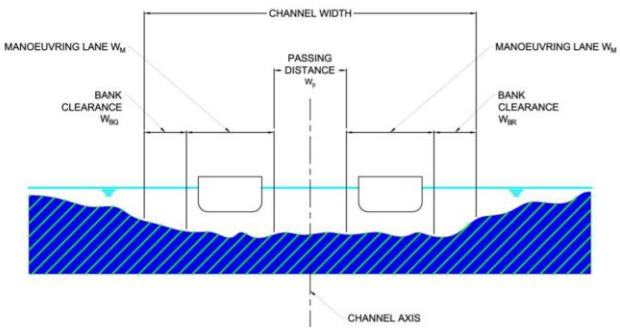

Figure 1: PIANC's Channel Width Elements

As expressed by Mocke, R, et al. [4], the use of the PIANC guidelines may involve some level of subjectivity and it is possible to either under- or over-estimate the required channel design width, which can adversely affect a project depending on how the factors are applied. The challenge is in the ability to use the guideline with confidence based on the best information available, in order to take forward a realistic design into the ship simulation and detailed design optimisation stages.

2.2 ROM Guideline – Horizontal Channel Dimension

The ROM guideline (ROM, 3.1-99) [7] is often referred to as the Spanish design standard, which is part of a larger ROM Programme (Recommendations for Maritime Works) developed by Puertos del Estado in Spain.

The ROM channel design guideline provides a different method for developing a conceptual channel design, it includes steps for assessing the drift angles on ship and its influence on the channel width design. The ROM's approach (as illustrated in Figure 2) is based on the following equations and is determined based on the design ship's beam and length.

$$B_t = B_n + B_r \qquad (3)$$

Where B_t is the fairway/channel overall width; B_n is the fairway/channel nominal width or clear space, which must permanently available for vessel navigation, including safety margins. B_r is an additional reserve width into account for boundary related factors.

For one-way channel, the $B_n$channel width is based on the following equation.

$$B_n = B + b_d + b_{dv} + 2(b_e + b_r + b_b) + (rh_{sm} + rh_{sd})_i + (rh_{sm} + rh_{sd})_d \qquad (4)$$

For two-way channel, the $B_n$channel width is based on the following equation.

$$B_n = 2\,[B + b_d + b_{dv} + 2(b_e + b_r + b_b)] + (rh_{sm} + rh_{sd})_i + (rh_{sm} + rh_{sd})_d \qquad (5)$$

Where B is the max beam of design ship; b_e is for additional width to account for positioning errors; b_r is the additional response width; b_b is the additional width for covering an error which might derive from the navigation marking systems; $(rh_{sm})_{i\ and\ d}$ is the additional safety clearance, which should be considered on each side of the channel to enable the navigate without being affected by bank suction and rejection effects; $(rh_{sd})_{i\ and\ d}$ is the safety margin or unhindered horizontal clearance, which must always be available between the vessel and channel's banks, slopes or boundaries. b_d is additional width of the vessel's swept path produced by navigation with a certain angle (drift angle) caused by wind, wave, current and is expressed by the following equation.

$$b_d = L_{pp}.Sin\,\beta \qquad (6)$$

Where L_{pp} is the length between perpendicular of design ship, β is the drift angle.

b_{dv} is the additional width of the vessel path caused by the varying environmental conditions, expressed as follow (and illustrated in Figure 11).

$$b_{dv} = V_{rr}.t_c.Sin(\beta_0 - \beta_l) \qquad (7)$$

Where V_{rr} is the vessel speed relative to the current speed in the same direction; t_c is the time necessary to correct the vessel's maneuver; β_0 is the max drift angle in the environmental condition varying area; β_l is the drift angle on the navigation stretch before and after the environmental condition variation.

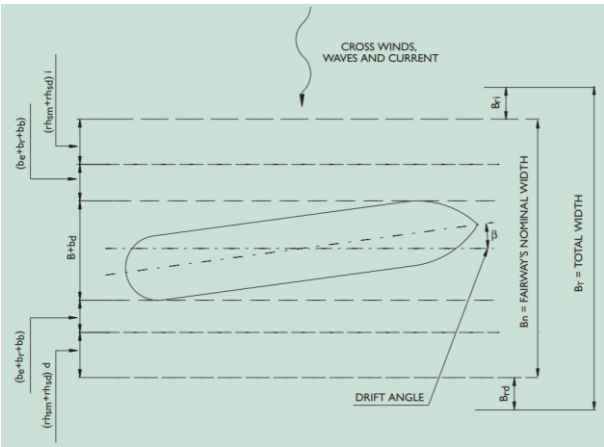

Figure 2: ROM's Channel Width Elements

Details of the width allowances and coefficient factors contributing to the drift angle calculations under various conditions can be found in the ROM [7] and have not been repeated in this paper.

3. Variable Channel Design Approach

In macro tidal environments, the port facilities are often exposed to rapidly changing current velocity and direction, which can affect ship's handling.

In addition to dividing the channel into separate sections that exhibit differing characteristics based on the prevailing wind speed, wind direction, wave height and wave direction [4], the variable channel design approach extends the design process to assess the width requirement at different times in the tidal cycle.

Figure 3 shows an example of a time-series plot of water level, current velocity and current direction. The time-steps (t_1, t_2, t_3) indicate the water level, current velocity and current direction at the nominated time interval in a tidal cycle.

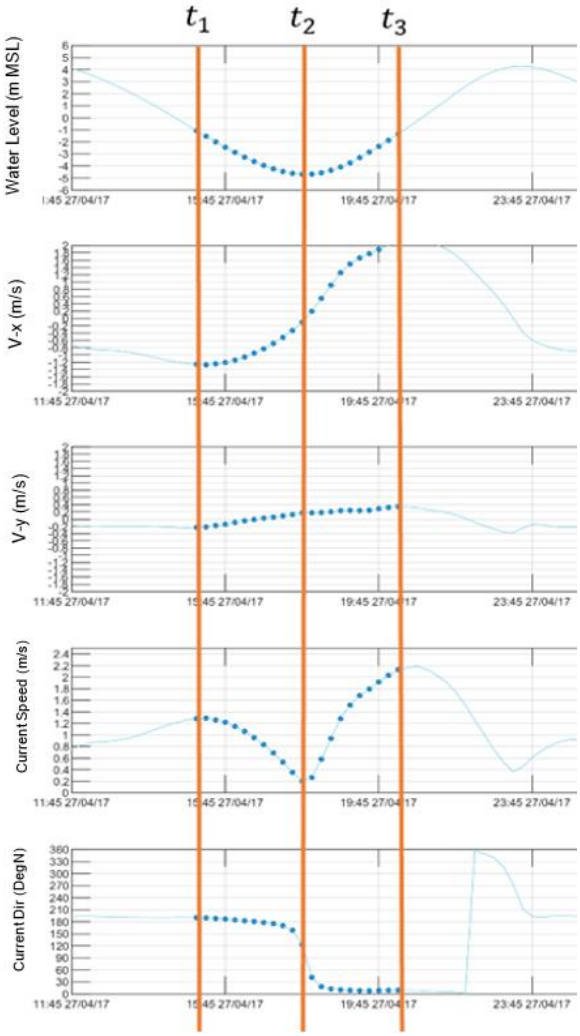

Figure 3: Timeseries plot of water levels and current conditions.

To respond to the unique challenges of working in this macro tidal environments, the authors enhanced the PIANC channel design equations *(1)* and *(2)* and ROM channel design equations *(4)* and *(5)* to include a time element to consider the water level and current conditions at the specified time-step. The extended equations are as shown below.

For one-way channel under PIANC

$$W_t = W_{BM} + \sum W_{i,t} + W_{BR} + W_{BG} \qquad (8)$$

For two-way channel under PIANC

$$W_t = 2W_{BM} + 2\sum W_{i,t} + W_{BR} + W_{BG} + \sum W_p \qquad (9)$$

For one-way channel under ROM

$$B_{n,t} = B + b_{d,t} + b_{dv,t} + 2(b_e + b_r + b_b) + (rh_{sm} + rh_{sd})_i + (rh_{sm} + rh_{sd})_d \qquad (10)$$

For two-way channel under ROM

$$B_{n,t} = 2\left[B + b_{d,t} + b_{dv,t} + 2(b_e + b_r + b_b)\right] + (rh_{sm} + rh_{sd})_i + (rh_{sm} + rh_{sd})_d \qquad (11)$$

Where t is the critical timestep(s), which are used in the channel design.

4. Case Study - Broome Channel

Broome is a regional centre and tourist town in the Kimberley region of Western Australia and located in a macro-tidal environment with a tidal range of up to 9 metres in spring tide period. The Port of Broome is the largest deep-water access port servicing the Kimberley region and is key infrastructure supporting cruise tourism in the region.

Deep water access into the Port can be made via a naturally deep channel with depth up to -40m LAT. However, this channel is narrow and constrained by shoals. Accessibility for large cruise ships is tidally constrained without access to this natural feature and. they have to wait for a favourable tidal condition to enter the Port which often may not be the optimal time for cruise operators.

The variable channel design approach was used as part of a channel improvement project to provide all tide access for large cruise ships and to allow for this particularly during the optimal sailing windows of 03:00 – 06:00 for arrival and 18:00 – 20:00 for departure.

The metocean conditions at the Port are unique and characterised by differing conditions in the following sections of the channel (as shown in Figure 4)

- Outer channel area (CH1)
- Outer channel, approach to The Cut (CH2)
- Inner channel area, north of The Cut (CH3)
- Inner channel/approach to turning basin (CH4)

Ships are exposed to different current velocities at different locations along the channel and at different time in the tidal cycle, including current velocity of up to 4.5 knots.

The current velocity is directly related to water level/tide and affects the drift angle of the ship in the following ways:

- Low current velocity, which occurs during slack tide period has a lesser impact on the ship's drift angle, channel size and basin excursions (illustrated in Figure 5)
- High current velocity, which occurs outside of slack tide period, leads to high ship drift angle, channel size and basin excursions (illustrated in Figure 6).

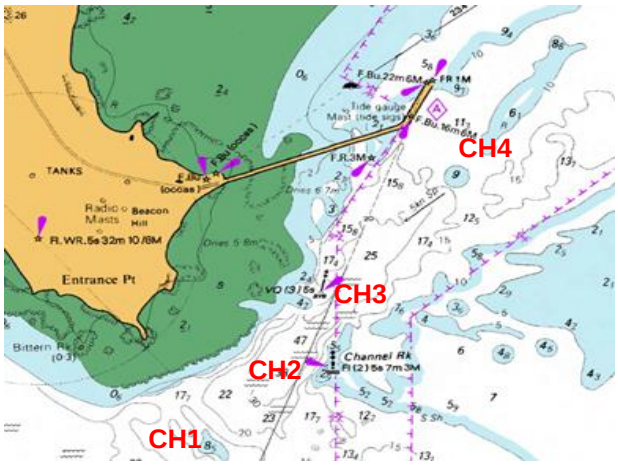

Figure 4: Chart showing the approach into the Port of Broome (CH1) Outer Channel (CH2) Outer Channel, Approach to The Cut (CH3) Inner Channel, North of the Cut (CH4) Inner Channel, Approach to Turning Basin

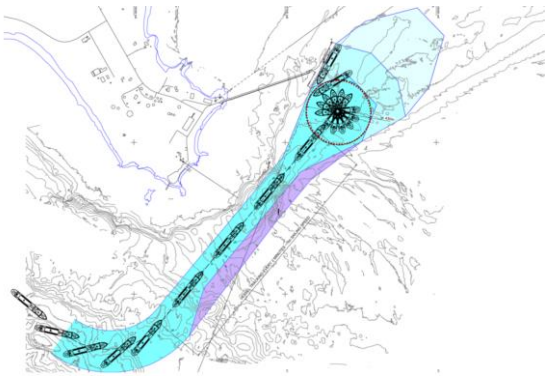

Figure 5: Ship arrival during low tide and low current velocity condition

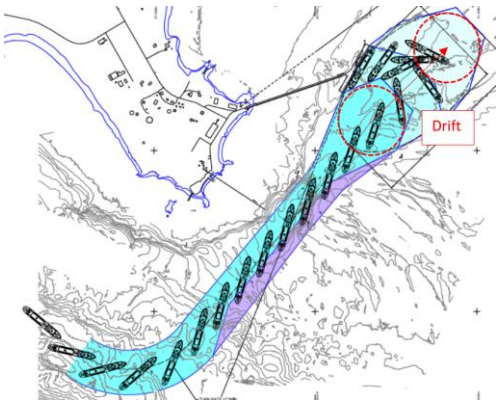

Figure 6: Ship arrival during high current velocity condition adversely affecting the ship's heading direction

4.1 Site Conditions

4.1.1 Tide

Broome's tidal planes is provided in Table 1 [2].

Table 1: Tidal Plane

Tidal Description	Levels (m LAT 2009)
HAT	10.605
MHWS	9.325
MHWN	6.365
MSL	5.460
AHD	5.322
MLWN	4.555
MLWS	1.596
LAT	0.114
Datum, "Broome, LAT 2009"	0.000

4.1.2 Wave Conditions

Hydrodynamic and wave modelling were carried out using TUFLOW and SWAN software. The models were calibrated against 3 months of in-field measured data. The calibrated model was then used to hindcast the nearshore wave conditions over a period of 5 years [1].

Figure 7: The wave model output points for assessing the ship navigation in the channel

Based on the modelling results and an assessment of probability of exceedance, the following wave conditions were selected for the detailed engineering design and ship simulation studies.

- Sea wave height of 2m - 3m in the outer channel area
- Sea wave height of 1m - 1.5m in the inner channel area
- Wave period of 5 seconds
- Wave direction of 135° and 315°
- Swell wave height of 0.1m
- Swell wave period of 20 seconds
- Swell wave direction of 270°.

4.1.3 Wind Conditions

The predominant winds are from E-SE (135 °) and W-NW (315 °) as shown in Figure 8. Wind speed of 20 knots was selected as the basis of design.

Higher wind speed condition of 30 knots was used in the desktop simulation stage to test the limit of the channel design. Furthermore, extreme wind speeds of 40 knots and above were tested during the

desktop simulation stage as part a set of emergency departure cases.

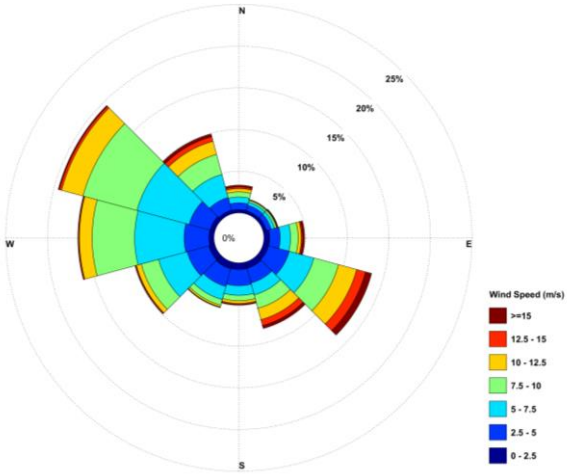

Figure 8: Wind Rose at The Port

4.1.4 Hydrodynamic Conditions

Tidal current conditions were extracted at 4 sections along the channel as shown in Figure 9. The information was extracted at 9 time-steps in one low spring tide cycle as listed in Table 2.

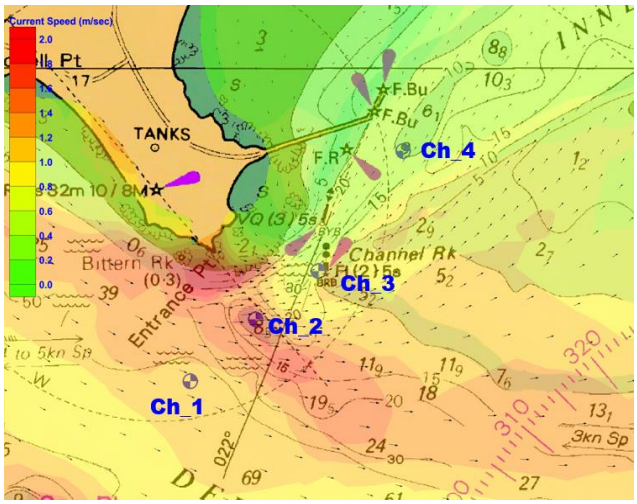

Figure 9: Hydrodynamic model output points

Table 2: Current Velocities at Various Water Levels

Time	Water Level (m MSL)	Current velocity (m/s)				Note
		CH1	CH2	CH3	CH4	
1	-0.26	1.1	1.3	0.4	1.4	Ebb
2	-1.76	1.2	1.4	0.4	1.3	Ebb
3	-3.26	1.0	1.2	0.3	1.2	Ebb
4	-4.56	0.7	0.7	0.1	0.8	Ebb
5	-5.46	0.1	0.2	0.1	0.1	Slack
6	-4.56	0.7	1.2	0.2	0.6	Flood
7	-3.26	0.9	1.9	0.3	0.7	Flood
8	-1.76	1.1	2.3	0.3	0.7	Flood
9	-0.26	1.2	2.3	0.4	0.6	Flood

4.2 Design Ship

The design ship is based on a cruise ship with the following dimensions, which were selected based on an assessment of cruise ship fleet visiting Fremantle.

Table 3: Design Ship Dimensions

Ship Particulars	Ship Dimensions
Length Overall (m)	300
Beam (m)	40
Draft (m)	8.5

4.3 Vertical Channel Dimension – Underkeel Clearance Study

An UnderKeel Clearance (UKC) Study was undertaken by Perth Hydro [5], which included ship squat assessment, wind heel assessment and wave induced motion assessment. The vertical motion allowance was calculated using the Response Amplitude Operators (RAOs). Furthermore, transit simulations were carried out based on the 5 year hindcast data (wind speed and direction, tide level and directional wave spectra). An example of the wave induced motion results is provided in Figure 10.

Based on the study, a UKC depth allowance of 1.71m was used in the vertical channel design.

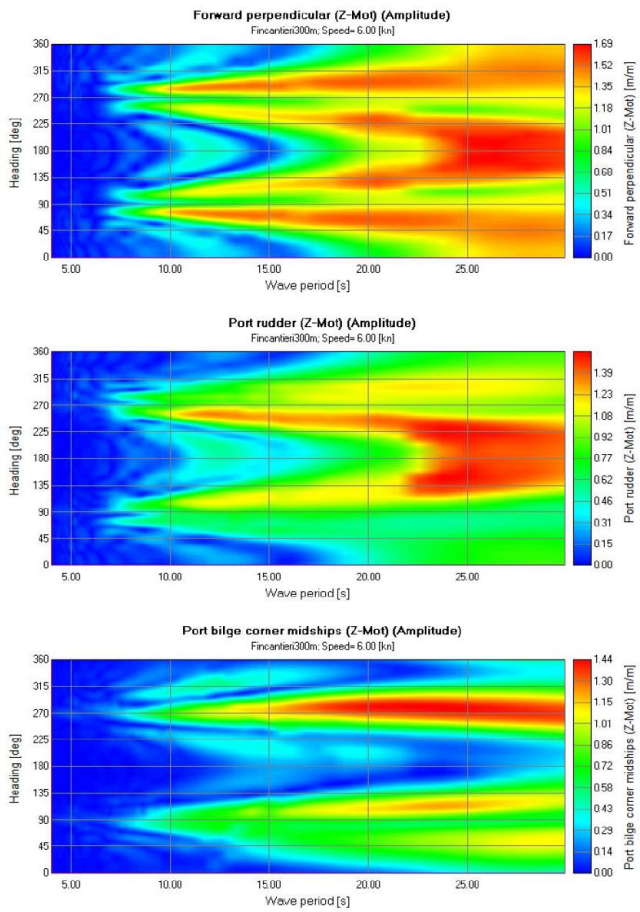

Figure 10: Wave induced motions results at forward perpendicular, port rudder and port bilge corner

4.4 Water Level

Based on an assessment of the probability of exceedance for predicted water level over 19-year period, a low water level of 0.21m was selected. This corresponded to a 99.99% probability of exceedance.

4.5 Horizontal Channel Dimension – PIANC v ROMS

4.5.1 PIANC Method

The channel width at 4 sections along the channel (location CH1, CH2 and CH3) are provided below. Table 4 and Table 5 provide the width factor and recommended channel width based on [6].

Table 4: Beam Multiplier for Channel Width

Design Depth (m LAT 2009)	CH1	CH2	CH3	CH4
-10.0	2.8B	2.8B	3.6B	3.6B
-9.1	3.8B	3.8B	3.9B	3.6B
-7.8	3.8B	4.4B	4.4B	3.6B
-6.3	3.8B	4.4B	4.4B	3.6B
-4.8	3.8B	4.4B	4.4B	3.6B

Table 5: Recommended Channel Width (m)

Design Depth (m LAT 2009)	CH1	CH2	CH3	CH4
-10.0	112	112	144	144
-9.1	152	152	156	144
-7.8	152	176	176	144
-6.3	152	176	176	144
-4.8	152	176	176	144

4.5.2 ROM Method

As noted previously, the ROM approach provide a method to assess the ship's drift angles due to current, wind and wave. Using this approach, the channel width requirement was also assessed at the key locations along the channel and at different stages of the tide.

The conditions at the Port of Broome can be described as a navigation channel with varying environmental conditions over the sailing route/track as described in [7] and illustrated in Figure 11.

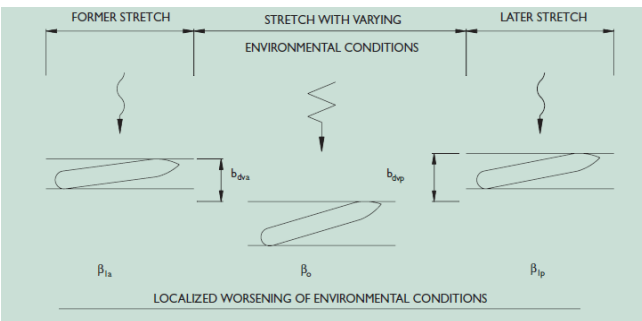

Figure 11: Navigational Channel with Varying Conditions

Vessels transiting into the Port of Broome experiences varying environmental conditions as they approach The Cut area. Consequently, the vessel experiences drift, which requires additional width (b_{dv}) for the vessel to adjust to the varying conditions and counteracting forces.

The three environmental forces, which affect the channel design are wind, wave and current. Each of these factors are further elaborated below.

Wind

The drift angle due to wind is influenced by windage area of the vessel, wind direction and wind speed relative to the vessel speed.

Wave

The drift angle due to wave is affected by significant wave height, angle between wave propagation and the vessel's direction, vessel's speed and draft.

Current

The drift angle due to current is affected by current velocity, absolute vessel speed relative to the seabed and the angle between the absolute current direction and the vessel's heading.

The current induced drift angles were calculated at 4 locations along the vessel's transit and at 5 critical water levels during the flood tide condition.

Based on the ship simulation process (Section 4.6), it was reported that the ship arrival cases were more challenging than the ship departure cases. Under the ship arrival cases, the handling of the ship was more difficult in flood tide condition (where the tidal current is pushing on the stern of the vessel) then ebb tide condition (where the tidal current is pushing on the bow of the vessel).

The combined drift angles based on ROM are as shown in Table 6.

Table 6: Combined Wind, Wave and Current Drift Angles

Design Depth (m LAT 2009)	CH1	CH2	CH3	CH4
-10.0	19°	22°	18°	17°
-9.1	29°	45°	20°	17°
-7.8	33°	65°	22°	17°
-6.3	36°	76°	23°	17°
-4.8	37°	76°	24°	17°

Additional width of the vessel swept path (B_{dv})

The additional width necessary for the ship's manoeuver under varying environmental conditions is approximated by assuming that drift caused by the unbalanced cross forces, which increases the ship's swept path followed by the time in which the ship moves from one balance status to another. It is important to note that, this is an approximation

only. The ship's swept path can only be accurately determined by other methods, such as ship simulation study, complex mathematical model (e.g. computational fluid dynamic) or physical models [7].

Based on the above-mentioned design factors, the recommended channel width based on ROM is provided in Table 7

Table 7: Recommended Channel Width based on ROM

Design Depth (m)	CH1	CH2	CH3	CH4
-10.0	223	232	219	207
-9.1	293	349	249	207
-7.8	327	418	249	207
-6.3	337	435	241	207
-4.8	338	429	245	208

4.6 Ship Simulation Process

4.6.1 Fast Simulation

Desktop fast simulation was carried out at Broome Maritime Simulation Centre to evaluate the suitability of the channel under multiple combinations of environmental parameters, including extreme cases such as emergency departure cases under extreme wind conditions of up to 40 knots and 50 knots and arrival cases under extreme swell conditions with swell wave height of up to 2m in the outer channel.

The desktop fast simulation process provides a mean to test multiple combinations of environmental conditions in a relatively short amount of time. A total of 132 cases were tested.

An example of the simulation run outputs is shown in Figure 12.

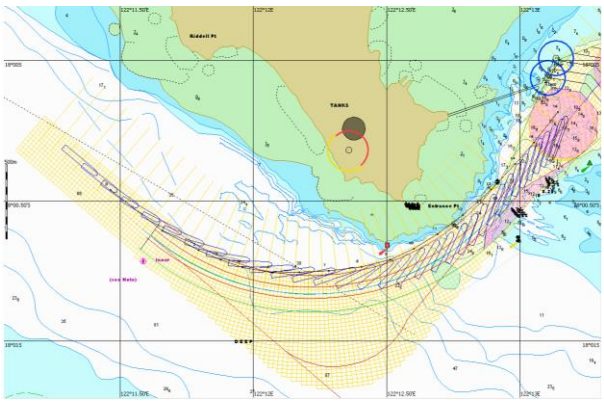

Figure 12: Desktop fast simulation run output

4.6.2 Bridge Ship Simulation

Two rounds of bridge ship simulation were conducted at Broome Maritime Simulation Centre and attended by the Harbour Master, marine pilots and engineer.

In the first round of ship simulation, a total of 41 simulation cases were completed. Based on the outcome of the first ship simulation, the design channel was modified to incorporate observations and learnings from the first bridge simulation.

In the second round of ship simulation, a total 23 simulation cases were completed. An example of simulation run outputs is provided in Figure 13.

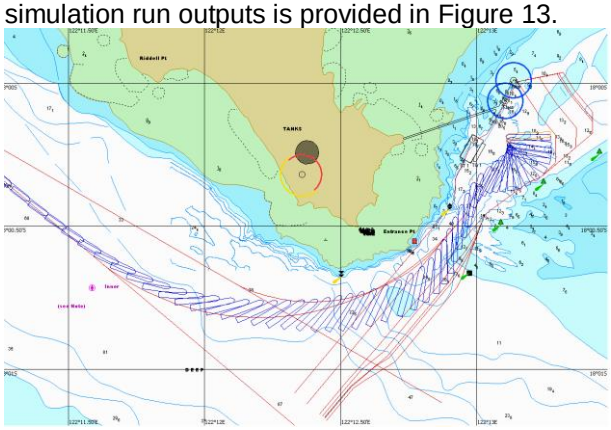

Figure 13: Ship simulation run output (Wind: 20 kts NW, Max Flood tide, 2 x FP (60,700 kW), B/th: 3 x 2,200 kW, S,th: 3 x 2,200kW)

4.7 Discussion

PIANC's and ROM's channel design guidelines provide two different design approaches and channel dimensions. A comparison between the two design methods at the location CH2, CH3 and CH4 are shown in Figure 14, Figure 15 and Figure 16 respectively.

Based on the results of the bridge simulation study, the ROM guideline provides more conservative channel dimensions, which were more in line with the final design dimensions developed following the completion of the bridge simulation. Similar observations have been reported by [3].

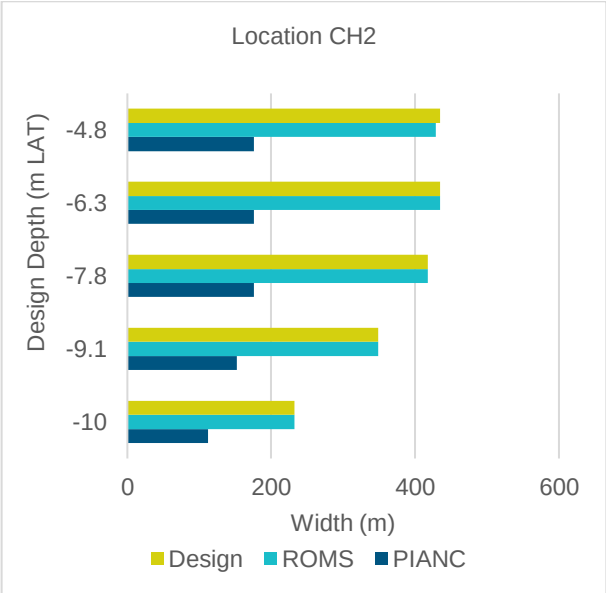

Figure 14: Design width (Post Bridge Sim), ROM and PIANC comparisons at location CH2

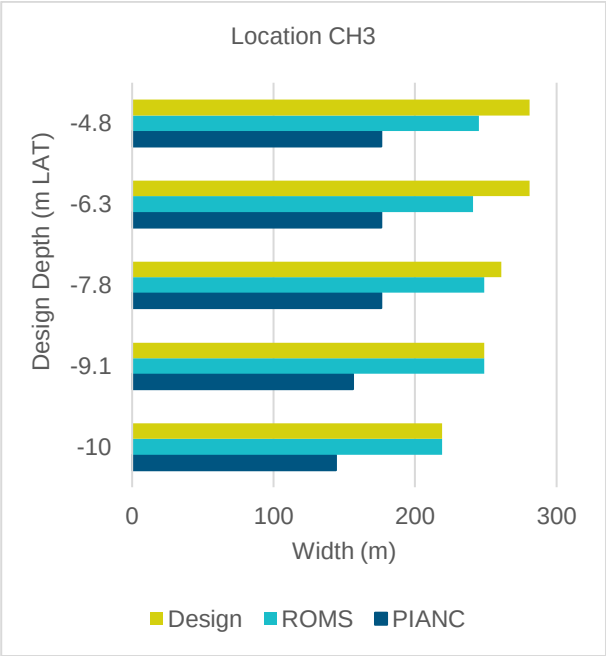

Figure 15: Design width (Post Bridge Sim), ROM and PIANC comparisons at location CH3

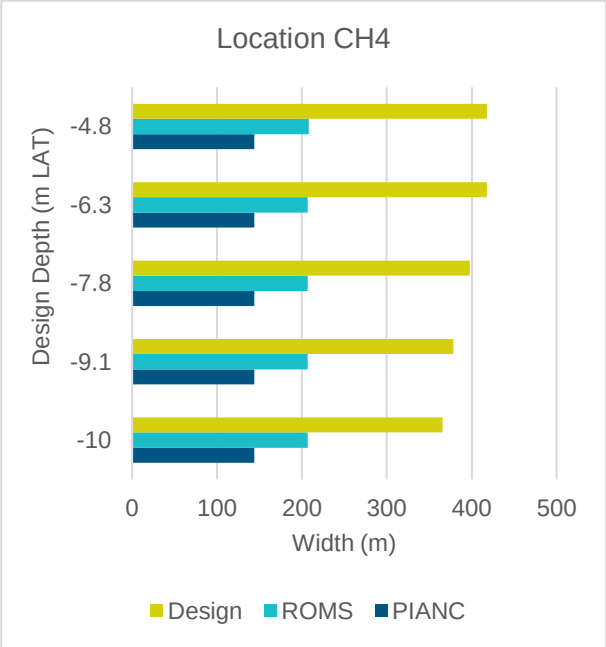

Figure 16: Design width (Post Bridge Sim), ROM and PIANC comparisons at location CH4. The design width is based on the naturally deep and width channel at this location.

A 3D visualisation of the channel design is provided in Figure 17. The variable channel geometry specifies the required horizontal dimensions at the various tide levels. This variable channel and basin envelope were overlayed on the existing naturally deep bathymetry allowing dredging to be confined to seabed features that extrude into the design envelope space.

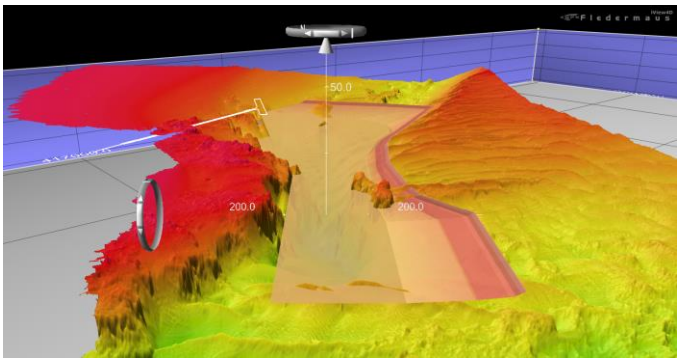

Figure 17: 3D Visualisation showing the final channel design. Dredging is confined to seabed features that extrude into the design envelope.

5. Conclusion and Recommendation

By using the variable channel design approach, dredging volume can be minimised, which minimises cost and environmental impact, while ensuring that large cruise vessels are able to navigate the channel during optimal sailing windows at all tide conditions with appropriate case by case passage planning.

The authors hope that this design approach can be beneficial to other ports and harbours, which are located in macro tidal environments.

6. Acknowledgements

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- Scott Baker, Kimberley Ports Authority Engineering Mamager

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