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AN IMPROVED INTEGRATED APPROACH FOR OPTIMISING SHIPPING CHANNEL CAPACITY FOR AUSTRALIAN PORTS

ABSTRACT

The continuing surge in commercial vessel sizes is putting increasing pressure on the world's port authorities to adopt effective expansion strategies to ensure that their assets are able to meet growing capacity demands. Among the key challenges is to assure that correct strategic and operational measures are adopted which guarantee safe and efficient traffic through shipping channels while also accommodating the demands of the commercial shipping industry. Channel capacity expansion projects usually involve the consideration of extensive dredging which introduces considerable constraints with respect to cost and environmental impacts.

This article presents an improved integrated approach for optimising shipping channel capacity utilising an Under-Keel Clearance (UKC) model Nonlinear Channel Optimisation Simulator (NCOS) in combination with the full-bridge ship simulator SIMFLEX4. The quantitative channel optimisation framework incorporates a full 3D vessel response in each time step made possible by recent advances in High Performance Computing.

The impact on channel capacity and UKC caused by long-term temporal and spatial variations in waves and water levels through the channel is handled deterministically using a high-resolution modelled dataset. Full-scale validation for large container vessels entering the Port of Brisbane during heavy wave conditions in early June 2016 demonstrated excellent agreement between measured and predicted UKC values.

The paper provides an overview of the modelling methodology and its successful application in recent channel optimisation studies for both Australian and overseas ports. It was demonstrated that using the more accurate integrated framework, it was possible to achieve target levels of channel operability, while reducing required dredge volumes significantly compared to conventional estimates.

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Above: While container ships take on gargantuan dimensions, the channels they pass through must be able to accommodate their deep draughts to reach their port destinations.

INTRODUCTION

The continuing surge in commercial vessels sizes is putting increasing pressure on the world's port authorities to adopt effective expansion strategies to ensure that their assets are able to meet growing capacity demands. Among the key challenges is to assure that correct strategic and operational measures are adopted to guarantee safe and efficient traffic through shipping channels while also accommodating the demands of the commercial shipping industry. Channel capacity expansion projects usually involve the consideration of extensive dredging which introduces considerable constraints with respect to cost and environmental impacts.

This article presents an improved integrated approach for optimising shipping channel capacity utilising a state-of-the-art Under-Keel Clearance (UKC) model NCOS in combination with the full-bridge ship simulator SIMFLEX4.

The paper presents the technical methodology behind the approach followed by two Australian ports, demonstrating its successful application and validation.

METHODOLOGY FOR SIMULATION

In channel design, advanced full-bridge simulators have been used for many years to

assess vessel manoeuvrability, while often more pragmatic methods have been applied for assessing associated vessel UKC requirements. The study presents a new numerical framework for channel design optimisation using the advanced UKC model NCOS in combination with the top tier full-bridge simulator SIMFLEX4.

NCOS belongs to a new breed of UKC models that converges towards the same level of sophistication and realism as full-bridge simulators. The NCOS model uses identical numerical engines as SIMFLEX4 for predicting squat and wave-induced UKC allowance, which greatly improves the potential for using it in close integration with detailed manoeuvrability studies.

The impact on manoeuvrability and UKC caused by long-term temporal and spatial variations in waves and water levels through the channel is handled deterministically using a high-resolution 2D dataset model generated by MIKE 21, which are subsequently used to drive both models NCOS can incorporate the entire long-term Metocean dataset to provide a highly detailed quantitative assessment of channel capacity with regards to UKC and identify a suitable scenario matrix for full-bridge simulations in SIMFLEX4.

Unlike NCOS, it is not possible to test every single weather combination in a full-mission bridge simulator. As NCOS includes most of the same detailed response physics it becomes a highly suitable tool for identifying those environmental conditions that proves most challenging to manoeuvrability. Both models use a full 3D vessel panel method for evaluation of the frequency response due to waves, while also implicitly including the forward speed and water depth in the source terms. In particular for large bulky vessels this provides an important increase in accuracy compared to older 2D strip theory methods, which are required to invoke a slender body assumption.

DETERMINING A VESSEL'S MOTIONS
For each unique 3D vessel hull, the UKC model computes the full linear motion response amplitude operators (RAOs) of responses to unit wave amplitude along with 2nd order vertical motions. The spectral form

of the motions of a user-specified number of points on the vessel in a specific sea state is calculated from the motion RAO for the specified point and the sea spectrum in the following way:

$$S_d(\omega) = RAO^2(\omega) \bullet S_\eta(\omega) \qquad (I)$$

Where $Sd(\omega)$ are the wave spectra obtained from MIKE 21 at each time step and vessel position and $S\eta(\omega)$ is the resulting response spectra. The rms value used in the probability distribution of the motion is:

$$rms = \sqrt{m_0} \qquad (II)$$

m_0 is the 0th moment of the power spectrum of the motion. The spectral moments m_n are calculated from the spectral distribution as:

$$m_n = \int_0^\infty \omega^n S_d(\omega)\, d\omega \qquad (III)$$

The residual depth Z defines the wave-induced depth threshold of the passing vessel, which is defined as:

$$Z = SWD + \eta_{Tide} - (T + T_{squat} + T^{(2)}) - \Delta Z \qquad (IV)$$

where **SWD** is the still water depth and η_{Tide} is the tide elevation obtained from MIKE 21 at each time step and vessel position. **T** is the vessel draft, T_{squat} is the set-down due to squat and $T^{(2)}$ is the vertical motion calculated from the second order drift forces. ΔZ is a safety buffer and defined as the minimum allowable water depth under the vessel after all other effects have been taking into account.

Wave-induced UKC allowance is generated by a combination of coupled vessel heave, pitch and roll motions. In a natural irregular sea-state, the effect on maximum vessel vertical motions will – over a prolonged duration – converge towards a singular value representing the statistical worst-case scenario.

SIMFLEX4 uses the above framework to calculate a full Six degrees of freedom (6DOF) vessel response in the time domain. This approach provides a powerful insight into the dynamic interactions between weather-induced vessel motions and manoeuvrability. However, in order to provide an UKC assessment on its own, it requires an extensive matrix of Monte Carlo simulations to assure the response envelope in each sea-state is correctly captured.

To eliminate the need for a time-consuming Monte Carlo approach and avoid unwarranted large levels of conservatism, NCOS adopts the following probabilistic approach for integrating the residence time of the vessel in each sea-state:

$$Q(Z) = 1 - \left[1 - e^{\left(-\frac{1}{2}\frac{z^2}{m_0(z)}\right)} \right]^N \qquad (V)$$

Where the function $Q(Z)$ expresses the probability of grounding in a given time step dt. During each time step during the passage, N wave encounters and corresponding motion amplitudes are experienced. It is observed that $Q(Z)$ assumes the extreme motion amplitude distribution follows a Rayleigh distribution. Resultantly, the total probability Pexc of the vessel comprising the minimum threshold for vessel manoeuvrability can be expressed by:

$$P_{exc} = 1 - (1 - Q_{t1})(1 - Q_{t2}) \ldots (- Q_{tN}) \qquad (VI)$$

where the length of the navigational channel and the vessel speed profile will govern the number of time steps tN required to complete vessel transit.

A more comprehensive description of the technical framework behind NCOS can be found in the case study investigation of Australia's Port of Brisbane (see References).

CASE STUDY: PORT OF BRISBANE
Responsible for 95 per cent of Queensland's container trade, the Port of Brisbane (PoB) is one of Australia's busiest container ports. The total annual trade value is estimated at approximately 50 billion AUD making it a key economic contributor to the State economy.

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is DHI's Global Executive for Ports and Navigation with more than 10 years of experience in management, model development and technical supervision of complex numerical modelling projects involving 2D and 3D hydrodynamics, wave mechanics, moored vessel interaction and sediment transport. His key areas of expertise include numerical modelling, non-linear wave mechanics, sediment transport, moored ship hydrodynamics, drifting vessel dynamics and computational fluid dynamics.

The PoB shipping channel is 90-km-long and extends from the northern tip of Bribie Island, across Moreton Bay and into the Brisbane River (see Figure 1).

The declared depth in the channel is 14 metres below Lowest Astronomical Tide (LAT) downstream of Lytton Rocks and increases to 15 metres beyond the East Channel. Local tidal conditions are semidiurnal with tidal amplitudes at the river mouth approximately 30 per cent larger than at the outer fairway. Mean high water levels are approximately 2 metres above LAT. The Northwest Channel is frequently exposed to energetic swell action from the Coral Sea, while the Spitfire channel and river entrance is subject to significant tidal currents during ebb and flood tides. Prevailing winds originate from the southeast with speeds frequently exceeding 20 knots.

Accommodating Larger Classes of Vessels

The PoB currently services container vessels up to 5,600 Twenty-Foot Equivalent Units (TEU) but identified the need to explore the feasibility of accommodating 8,500 TEU in the near future. Container vessels are more susceptible to wave-induced motion compared to most other vessel classes such as tankers and bulk carriers. When compared to their smaller counterparts, 8,500 TEU container class vessels are noticeably longer, wider and with deeper draughts.

Figure 1. Port of Brisbane (PoB) is one of Australia's busiest container ports. The PoB shipping channel is 90-km-long and extends from the northern tip of Bribie Island, across Moreton Bay and into the Brisbane River. Photo Peter Budd Photography, courtesy of Port of Brisbane
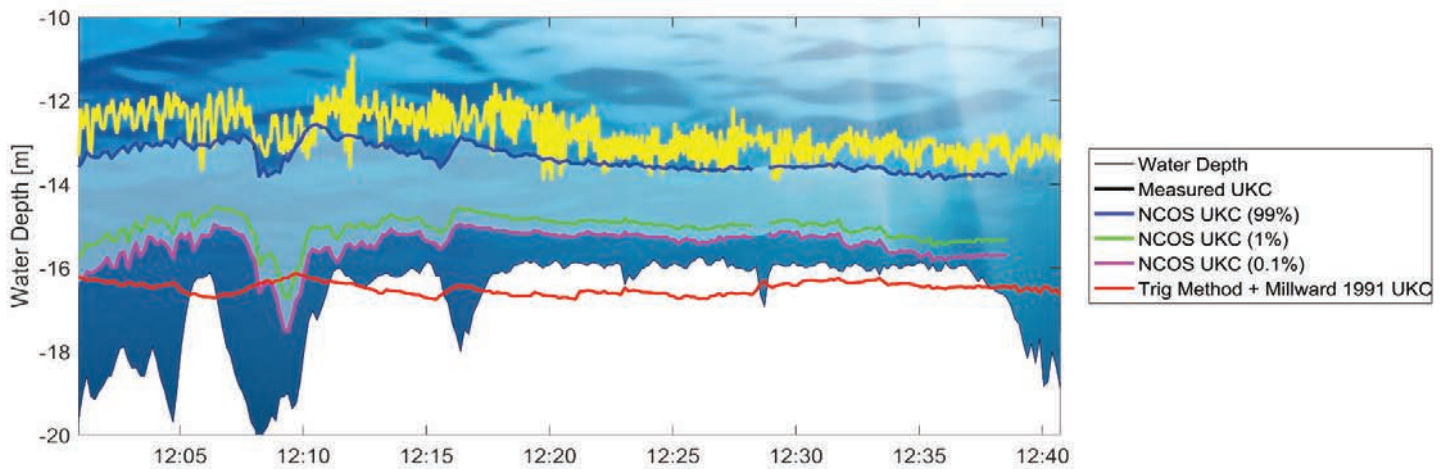
Figure 2. Comparison of measured UKC for Safmarine Makutu as predicted by NCOS and the Trigonometric Method. In this context, UKC is defined as the lowest point of the vessel at each time step.

To avoid unnecessarily conservative channel expansion while still assuring a safe and navigable passage, it was decided to utilise the software package Nonlinear Channel Optimisation Simulator (NCOS) in combination with SIMFLEX4.

NCOS enables a comprehensive assessment of channel deepening requirements based on hundreds of thousands of time domain simulations spanning several years of vessel traffic subject to historical temporally and spatially varying tide, wind and wave conditions. SIMFLEX4 was used for assessing manoeuvrability constraints utilising matrices of critical environmental conditions as identified by NCOS.

Charting Safmarine Makutu
In order to document the accuracy of NCOS for the navigation channel, a full-scale UKC monitoring campaign was carried out for the piloting of an inbound container vessel, Safmarine Makutu, on 6 June 2016. The 277-metre LPP (length between perpendiculars) vessel is one of the largest container vessels currently frequenting the Port of Brisbane and has a draught of 11.3 metres. The transit occurred in the wake of a very large swell event that hit Australia's eastern seaboard during June 2016.

During the monitored voyage, predicted offshore wave heights exceeded 3 metres with spectral peak periods of 12.8 seconds from the East-Southeast. Significant wave

heights in the Northwest Channel exceeded 2 metres in some places with local wave directions varying spatially along the channel from East to Northeast.
The measured and modelled UKC for the 40-minute-long transit of the Safmarine Makutu through the North West Channel were compared (see Figure 2). Measured UKC was calculated as the instantaneously lowest point on the vessel hull at each time step due to squat, heel, pitch, roll and heave relative to the dashed line. The UKC prediction of NCOS is illustrated by a blue, yellow and green line. The blue line represents calculated squat, while the yellow and green lines present total predicted UKC including squat and wave allowance with a 75 per cent and 1 per cent exceedance probability, respectively. The operational motivation for having two lines is to provide both information of the likely UKC profile as well as the extreme value, which would typically govern the safety criteria in the channel.

It is observed how the 75 per cent probability exceedance prediction fits well with actual measurements, while the 1 per cent provides a consistently conservative buffer compared to measured values. The red line illustrates the comparative UKC prediction if using one of the more simplistic methods as defined in 'Harbour Approach Channels Design Guidelines' (see References).

Using Equation V, the compounded touch-bottom risk for the entire 40-minute-long

transit was estimated to 0.6 per cent with NCOS. The validation study confirms the NCOS capability to provide a robust stochastic framework for an accurate estimate of vessel UKC response for large container vessels, while at the same time giving the Port operator a transparent framework for understanding the levels of conservatism applied to assure safe operability within its shipping channel.

Studying the Channel's Capacity
For the subsequent channel capacity study, temporal and spatial variations in waves and water levels through the channel was modelled deterministically over 36 months using MIKE 21. The channel bathymetry was incorporated as a high-resolution computational mesh with grid cell resolution down to 40 metres, each of which represent the highest point from the underlying survey dataset.

For UKC assessment purposes, inbound and outbound vessel transits were set to commence every 30 minutes for each assessed vessel configuration and speed profile. Each voyage represented a unique historical timeline of waves and water level variations experienced by each vessel during the transit. The entire shipping channel was included in the model domain (see Figure 3). Seven vessels were used to represent the envelope of shapes, loading conditions and draughts covered within the 8,500 TEU class. The UKC assessment is based on tracking six

Figure 4. A detailed 3D panel grid is used to represent the full geometry of each vessel. Six points shown as red squares are placed strategically along the vessel hull to track minimum UKC requirements.

Figure 3. Illustration of the PoB Shipping channel setup in NCOS.

points placed strategically along the vessel hull (see Figure 4).

SIMULATING VESSEL OPERABILITY FOR EVERY TRANSIT SCENARIO

The total amount of transits simulated exceeded 2.2 million and covered more than 100,000 unique combinations of environmental conditions, three passing speed profiles and two directions. Model outputs were configured to include the integrated probability of an extremity of the vessel momentarily extending less than the specified safety margin of 0.5 metres above the seabed.

For this study, a safety probability threshold of 1:100 risk exceedance per vessel voyage was adopted for the shipping channel. A probabilistic operability breakdown for the existing channel is presented in relation to the time of the tide at the Brisbane Bar where the vessel transit begins (see Figure 5). Vessel 1 represents a typical 8,500 TEU class with a draught of 13.0 metres, while Vessel 2 represents larger and wider type of 8,500 TEU with a draught of 13.6 metres. Two speed profiles are also considered.

Safe operability for the presented 8,500 TEU vessels is linked to being able to commence transit during the right time of the tide, especially for the deeper draughted Vessel 2 (see Figure 5). For the 13 metres draughted vessel, the only constraining channel bottleneck is the NW Channel during energetic wave conditions, which favours

passing this section during peak flood.

The 13.6 metres vessel suffers the same bottleneck but to a much lesser degree of depth constrictions at berth during large ebb tides. It is also observed how the operability for outbound transits are less than for inbound due to the typical relative wave direction in the NW channel during outbound transit more frequently coming from the quarter-stern, which causes increased vessel motions and increasing UKC requirements.

Capacity Study Results in Clarity to Take Action

Operability for the 13 metres draughted vessel was more than 98 per cent even when limiting speed in the NW channel to 10 knots (average speed profile). For the 13.6 metres draughted vessel the operability is reduced to a maximum of 96 per cent for inbound and 93 per cent for outbound vessels when limiting speed in the NW channel to 9 knots (slow speed profile).

Based on the extensive scenario matrix, NCOS was utilised to identify critical vessel scenarios which were to be tested in SIMFLEX4 in order to investigate manoeuvrability safety aspects

and optimise channel bends and swing basin. All simulations were carried out as full-bridge simulations in the SmartShip simulator in Brisbane. All vessels were under command by Brisbane Marine Pilots and supervised by navigational experts from FORCE Technology. During the assessment, it was discovered the NW2 bend of the channel had to be widened towards the north to accommodate 8,500 TEU vessels. It was also established that vessel passing could not occur in the NW channel with an acceptable safety margin. Turning in the existing swing basin was considered safe but tight without much margin for error. A proposed new swing basin was found to provide ample space for 8,500 TEU vessel and could be subject to further optimising if required.

Overall, the channel capacity project for Port of Brisbane provided the necessary assurance for the port that it was indeed possible to safely accommodate 8,500 TEU vessels up to a limit of 13.6 metres draught within their existing channel subject to weather. Very little requirements for dredging would be needed thereby providing potentially large cost savings compared to older conventional methods used for the assessment. Following
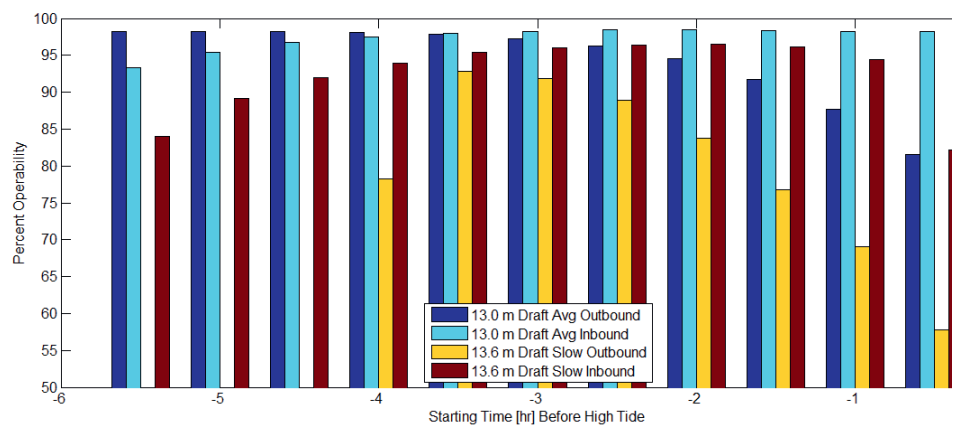

Figure 5. Channel capacity as a percentage operability in relation to draught and tide. 'Avg' represents an average speed profile and 'Slow' represents a slow speed profile through the channel. Only two of the seven representative vessels are presented due to space restrictions.

Figure 6. Overall, the channel capacity project for Port of Brisbane provided the necessary assurance for the port that it was indeed possible to safely accommodate 8,500 TEU vessels up to a limit of 13.6 metres draught within their existing channel subject to weather. Very little requirements for dredging would be needed thereby providing potentially large cost savings compared to older conventional methods used for the assessment. Following the completion of the study, the first 8,500 TEU vessel entered the port in December 2016. Photo 2015 Aerial Advantage, courtesy of Port of Brisbane

the completion of the study, the first 8,500 TEU vessel entered the port in December 2016 (see Figure 6).

CASE STUDY: PORT OF GEELONG

The Victorian Regional Channels Authority (VRCA) required an investigation of the feasibility of the Geelong channels to provide safe transit for Suezmax tankers to access the Vitol Refinery Pier at the Victoria province's Port of Geelong. An increase in tanker size from the current Aframax to larger Suezmax was desired to improve the economics of the refineries operations. However, additional dredging to either widen or deepen the channels to cater to the larger Suezmax tankers was not considered feasible at present.

The Geelong channels are approximately 27 kilometres of dredged channel through the sheltered but shallow waters of Corio Bay (see Figure 7). The channels have a width of typically 120 metres and declared depth of 12.3 metres. A small semidiurnal tide with a range of approximately 0.9 metres currently enables a small tidally assisted window for

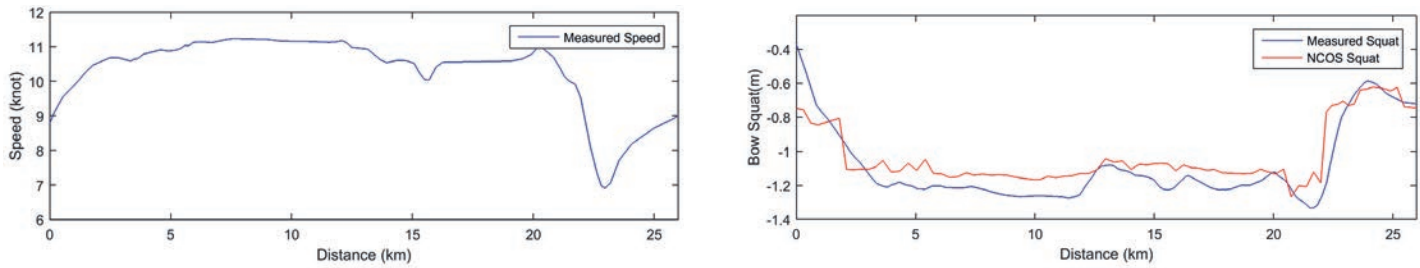Figure 7. Two Geelong Channels in Corio Bay and the location of 'The Cut'.

Figure 8. Comparison between measured squat for the Dubai Attraction as predicted by NCOS.

transits of the channels by Aframax tankers of 115,000 DWT (dead-weight tonnage) and with draughts of up to 11.65 metres. The Geelong channels include a section referred to as 'The Cut', where the channel is incised through very shallow water and is flanked by 10-m-high banks. Through this reach in particular, the significant blockage effect of the vessel in the channel distorts the flow fields around the vessel hull that both increases squat as well as generates a suction effect towards the channel banks. As well, a bow-out drift angle is typically required to overcome the channel bank directed sway forces and keep the vessel in the channel's centre, potentially posing a significant challenge for pilots to navigate.

Feasibility for Suezmax and Aframax Vessels to Access the Geelong Channel

Due to the complexity of the under-keel clearance constraints and interactions on the navigability of 'The Cut', the VRCA required an integrated and highly accurate channel optimisation framework to determine the feasibility of bringing in larger Suezmax tankers to the Vitol Refinery Pier without channel widening and dredging works.

A NCOS UKC model of the Geelong Channel was developed to enable the under-keel clearance constraints and associated tidal-assisted transit windows for larger Suezmax tankers of 150,000 DWT and draughts of 12.0 metres to be determined for the existing channels. The tidal dynamics in the NCOS model were derived from detailed two dimensional hydrodynamic modelling results made with MIKE 21.

The NCOS model also included a detailed spatially varying description of the restricted

channel geometry parameters to enable the channel blockage factor to be dynamically estimated and its subsequent influence on the vessel squat to be simulated. Due to the sheltered environment of Corio Bay, wave-induced vertical motions could be neglected from the NCOS analysis and UKC modelled as a function of draught, squat, tide and bathymetry/channel geometry.

To validate the NCOS model and the schematisation of the restricted channel geometry and its influence on vessel squat in particular, the NCOS model of the Geelong channels was compared to measured squat from instrumented transits of Aframax tankers commissioned by the VRCA.

For an example of the bow squat time series

for an inbound transit of the Geelong channels by the Aframax tanker, the Dubai Attraction (IMO 9422536), compared to the NCOS squat predictions (see Figure 8).

A very good correlation to the measure squat is considered to have been achieved by the NCOS model. It is important to note the influence of 'The Cut' on the tankers squat at the approximate 22 kilometre mark. The significant channel blockage through this reach forces the vessel to slow down however the squat remains elevated and in fact slightly increases through this reach, despite the slower vessel speed over ground.

Following validation of the NCOS model, approximately 2,700 simulations of inbound transits with the larger Suezmax tanker with a
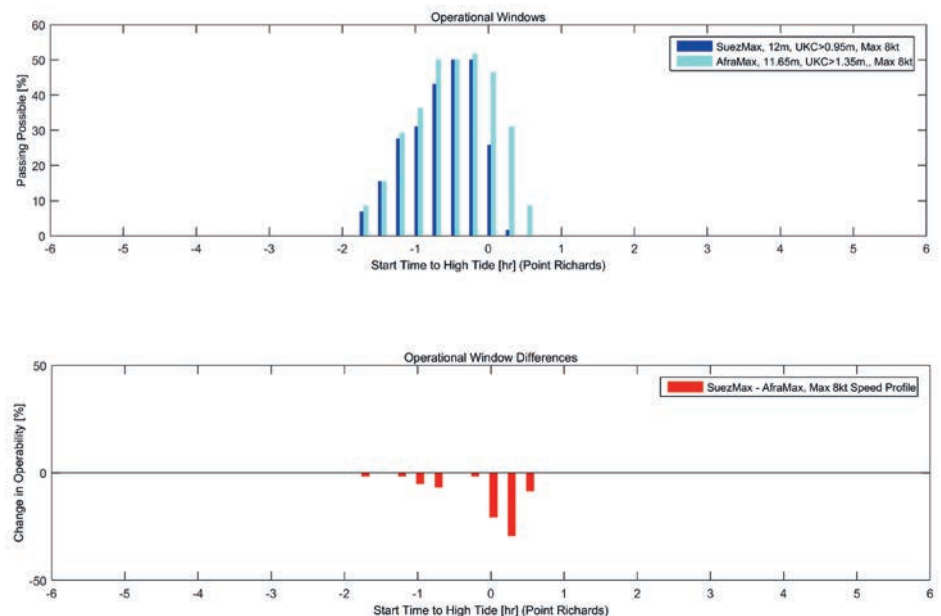

Figure 9. Channel capacity as a percentage operability in relation to the local tide for Aframax and Suezmax tankers.

draught of 12.0 metres were simulated to identify the tidal assisted sailing windows from a UKC perspective.

The predicted UKC operability as the tidal cycle dependent percentage for the Suezmax tankers and the Aframax tankers are dually presented for comparison purposes in Figure 9. It can be seen that the channel operability is severely constrained for both tankers, with maximum operability at approximately 50 per cent just one hour before high tide. Due to the semidiurnal tides, this effectively equates to a single, one-hour-long safe UKC transit window per day for these tankers in the Geelong channels.

Safe Sailing Windows through The Cut

To achieve a similar level of operability for the Suezmax as the existing Aframax tankers however, a lower manoeuvrability margin of 0.95 metres Net UKC was required. The reduced manoeuvrability margin was required to offset both the increase draught as well as the additional squat predicted through 'The Cut' due to the increased channel blockage created by the Suezmax. Reducing the Net UKC margin can reduce the vessel's response to the rudder and the ability of the pilots to counter the bank suction effects through 'The Cut'.

To assess the navigability of 'The Cut' during the identified safe sailing windows predicted by NCOS with the larger Suezmax vessel and reduced manoeuvrability margin, a series of full-bridge ship simulations in SIMFLEX4 were undertaken. The SIMFLEX4 simulation model was driven with exactly the same high-resolution channel bathymetry/geometry model, two dimensional tidal water level and current modelling outputs, and squat

formulation as NCOS. This ensured the squat and channel blockage characteristics of the Suezmax vessel in the SIMFLEX4 simulations produced the same UKC and hence manoeuvrability margin as predicted by NCOS. A matrix of full-mission bridge navigation simulations, incorporating varying wind, visibility speed profiles and tidal current conditions were undertaken for the 12.0 metres draught Suezmax to identify the constraints to navigability during the safe UKC transit windows identified by NCOS. Significant drift angles were initially observed sailing the 12.0 metres Suezmax with similar speed profiles as are currently used for the Aframax and with a strong, 25 knot N wind (beam on) scenario. At 'The Cut', the addition of the bank forces posed challenges to navigation and significant rudder and engine force were required to keep the vessel in the channel and appropriate additional engine power or steering capacity contingency were not left available (see Figure 10).

Subsequent simulations through 'The Cut' with the reduced wind speed scenarios and sailing speeds of approximately 6.5 knots provided much more capacity for manoeuvring. It was ultimately deemed feasible to bring in Suezmax tankers up to 12.0 metres into the existing channels. The ability to bring in Suezmax tankers is however subject to the tighter UKC sailing windows identified by NCOS and the vessel speed and wind condition scenario constraints identified by the SIMFLEX4 simulations to manage the bank suction effects through 'The Cut'. The integrated channel capacity modelling undertaken on behalf of the VRCA is considered to have provided the highly accurate and robust analysis demanded to provide the confidence required to bring in

large Suezmax tankers without extensive channel widening and dredging. It has saved significant capital works dredging costs for the Port client while assisting to improve its economics.

CONCLUSIONS

This article provides a presentation of a novel method for optimising channel capacity for two prominent Australian ports to accommodate larger vessels.

Full-scale validation campaigns were included to confirm model accuracy and compare predictions to alternative methods before proceeding with channel design.

The case studies highlighted the importance of a seamless integration of UKC and manoeuvrability assessments, which helped to identify and manage several significant complex aspects affecting vessel response hydrodynamics for each port and allowed for a robust and transparent platform for optimising channel design.

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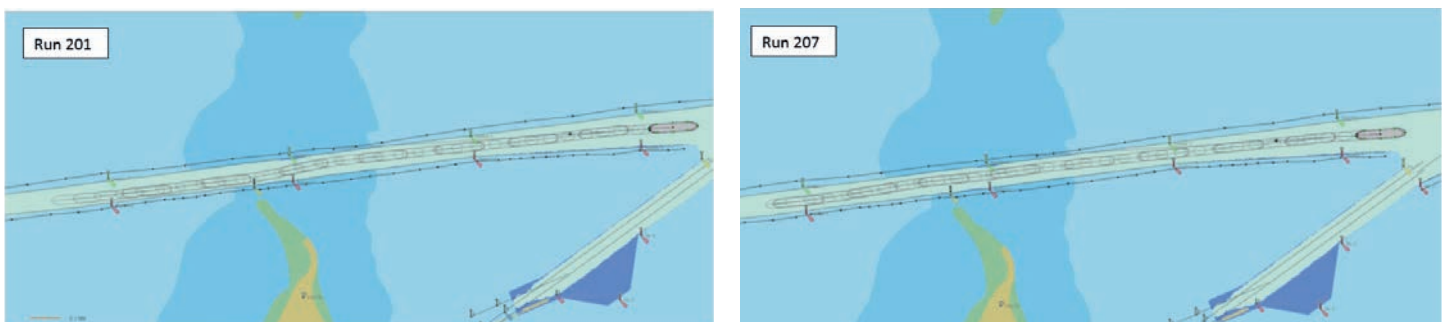PIANC Report No. 121 - 2014, Harbour Approach Channels - Design Guidelines. (2014). PIANC Secrétariat Général.

Figure 10. SIMFLEX4 Vessel Track models transit of 'The Cut' for high and moderate wind scenarios for the 12.0 metres Suezmax.