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Next Generation of Physics-based System for Port Planning and Efficient Operation

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ABSTRACT: The continuing surge in commercial vessel sizes is putting increasing pressures on the world's port authorities to adopt effective expansion strategies to ensure that their asset is able to meet growing capacity demands. Among the key challenges is to assure that correct strategic planning and operational measures are adopted to guarantee safe and efficient traffic not only through its shipping channel, but also at the port berthing facilities. DHI and FORCE TECHNOLOGY have collaborated to develop a novel physics-based vessel traffic management system named NCOS ONLINE. It is capable of taking into account of any relevant vessel constraints such as under-keel clearance (UKC), maneuverability and berth configuration that may constrict the movement of vessels through the channel or operability at berth, facilitating scenario planning and capacity assessment of proven unparalleled accuracy. The system incorporates the accuracy of high-end Full Mission Bridge Simulators with regards to vessel response under power and at berth. The underlying computational engines uses a powerful 3D panel method for vessel response calculations in combination with highly detailed environmental data such as wind, waves and hydrodynamics (water level and currents) simulated by use of MIKE Powered by DHI's recognized and scientific based computational models. The modular and integrated framework-based system has already been adopted by numerous port authorities, terminal operators and pilots worldwide for strategic port planning, design and 24/7 operational vessel traffic management. The paper focus on presenting the underlying equational framework and validation of the underlying physical response engines and provide a brief introduction to how they are integrated and operated through a series of user-friendly web dashboards.

1 INTRODUCTION

Low freight rates and high competition in the shipping and maritime industry has driven a strong demand towards optimizing the supply chain and establish better utilization of increasingly larger vessels entering the world fleet.

Both trends are currently increasing pressures on many ports and terminal operators to accommodate tighter transit schedules, reduce delays and accommodate larger and deeper drafted vessels. For more than a decade, full mission bridge 3D ship simulators such as SIMFLEX4 by FORCE TECHNOLOGY have been an essential tool in identifying and solving capacity constraints through the shipping channel, turning basin and during berthing. Capacity and operability assessment of moored vessels at berth are typically not carried out using simulators but often using a more simplistic static force balance approach. These tools used for strategic port capacity assessment are almost never used in day-to-day operational support systems. Instead strategic studies are usually limited to supporting operations through provision of static guidelines which does not utilize the full dynamic optimization potential of the port.

In this paper we will introduce a next generation type physics-based port traffic management system called NCOS ONLINE. The cloud-based system was originally presented in Mortensen et al 2016[5] and Mortensen et al 2018[6] and is capable of optimizing port capacity and reduce delays from channel to berth with the accuracy of 3D full bridge simulators and using the same numerical framework for both strategic planning and subsequent operational decision support. This paper focus on presenting the underlying equational framework and validation of the underlying physical response engines and provide a brief introduction to how they are integrated and operated through a series of user-friendly web dashboards.

2 NUMERICAL MODELLING FRAMEWORK

2.1 *Vessel Frequency Response*

For simulating wave vessel frequency response under power, NCOS ONLINE uses the 2nd order 3D panel method engine, S-OMEGA, which is used in the Full Bridge Simulator SIMFLEX4 by FORCE TECHNOLOY incorporating implicitly the effect of vessel forward speed and varying water depths. For simulating vessel wave frequency response at berth the numerical solution can be made more computationally efficient by neglecting forward speed. For this purpose, NCOS utilizes DHI's own 3D frequency radiation-diffraction solver FRC, which is DHI's boundary element code used to solve the linear boundary problem for the free surface flow around a body to calculate vessel first order wave forces and second order wave drift forces in the frequency-domain. Because of its computational efficiency FRC is capable of fast and accurately modelling a wide range of typical berth type multibody scenarios such as caused by reflective quays or tandem moored vessels.

2.2 *Vessel Motion Analysis*

NCOS is directly integrated with the phase-averaged 3rd generation wave model MIKE 21 Spectral Wave model (MIKE 21 SW) and phase resolving models like MIKE 21 Boussinesq Wave model (MIKE 21 BW) or the 3D model MIKE 3 Wave FM enabling the accurate prediction of spatially and temporally varying wave response through a channel and at berth.

For powered vessel response the frequency domain wave response is evaluated in the form of 1st order motion response amplitude operators (RAO's) and MIKE 21 SW model provides the wave conditions along with 2nd order vertical motions ($T^{(2)}$).

The spectral form of the 1st order motions of a user-specified number of motion points (*d*) on the vessel in a specific sea state is calculated from the motion RAO for the specified point and the sea spectrum as shown in (1).

$$S_d\left(\omega\right) = RAO_d^2\left(\omega\right).S_\eta\left(\omega\right) \tag{1}$$

where RAO_d is the RAO calculated by S-OMEGA translated to each motion point on the vessel d, S_η is the wave spectra at each timestep and vessel position η and S_d is the resulting motion response spectra at each motion point d. Equational framework for calculating dynamic heel and squat is presented in Harkin A. et al 2018 [1].

The 2nd order set down, $T^{(2)}$, is calculated from (2) to (4) where $F^{(2)}$ is the second order force/moments extracted from S-OMEGA, θ is the wave direction and C is the restoring force.

$$S_{F^{(2)}}\left(\omega,\theta\right) = F^{(2)}\left(\omega,\theta\right)\cdot S_\eta\left(\omega,\theta\right) \tag{2}$$

$$x^{(2)}\left(\theta\right) = \frac{\int S_{F^{(2)}}\left(\omega,\theta\right)d\omega}{C} \tag{3}$$

$$T_d^{(2)}\left(\omega,\theta\right) = x_{heave}^{(2)}\left(\theta\right) + x_{roll}^{(2)}\left(\theta\right)*d_y + x_{pitch}^{(2)}\left(\theta\right)*d_x \tag{4}$$

For moored vessel response NCOS uses its non-linear dynamic vessel mooring analysis model MIKE 21 MA to calculate vessel motions in the time-domain. The incident wave potential φ_I and first order dynamic pressure P_I is evaluated across the 3D vessel hull from a 2D/3D wave input from MIKE 21 BW/MIKE 3 Wave FM or a surface evaluation time series synthesized from MIKE 21 SW. The first order radiation velocity potential φ_j is computed by FRC. The wave exciting force $F_{jD}(t)$ is then calculated from the Haskind relations:

$$\begin{gathered}F_{jD}\left(t\right) = \iint\limits_{S_b} P_I\left(\vec{x},t\right).n_j\left(\vec{x}\right)d\vec{x} + \\ \rho\int_{-\infty}^{\infty}\left(\iint\limits_{S_b}\varphi_j\left(\vec{x},t-\tau\right)\dot{\varphi}_{In}\left(\vec{x},\tau\right)d\vec{x}\right)d\tau\end{gathered} \tag{5}$$

Subsequently the equation of motion for the moored vessel is evaluated in the time domain using Equation 2.

$$\begin{gathered}\sum_k^N\left[\left(M_{jk}+\alpha_{jk}\right)\ddot{x}_k\left(t\right)+\int_0^t K_{jk}\left(t-\tau\right)\dot{x}_k\left(\tau\right)d\tau + C_{jk}x_k\left(t\right)\right] = \\ F_{jD}\left(t\right)+F_{jnl}\left(t\right) \qquad j = 1,2,\ldots,N\end{gathered} \tag{6}$$

Second order wave drift forces are calculated using the far field approximation method presented in Newman J. N. (1974) [2]. Wind and current forcing are accounted for as either spatially uniform (0D) or spatially varying (2D) data files using vessel specific drag coefficients. Mooring line and fender forces are calculated based on actual load-displacement curves. Viscous damping is included as a combination of constant friction damping plus linear, quadratic and cubic damping.

2.3 *Numerical Model Validation Examples*

2.3.1 *Vessel motion and underkeel clearance in Navigational Channel*

Serving as the bases for this validation are measurements taken during vessel transits through the Port of Brisbane, Australia. Differential Global Positioning Systems (DGPS) were located at the bow (Figure 2-1) and on both the port and starboard bridge wings (Figure 2-2) of the vessels to measure trajectory and the vertical position at each location. An XSens Inertial Measurement Unit (IMU) was also used to measure the vessel roll and pitch as contingency in the event that any of the DGPS units did not work correctly. From these measurements roll, pitch, heave and total vertical excursion of the vessels throughout the transits were calculated.

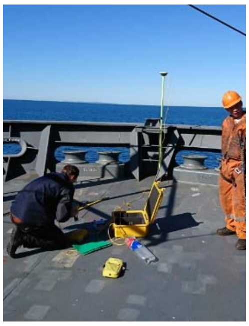


Figure 2-1. DGPS Setup on Bow

Figure 2-2. DGPS Setup on Starboard Bridge Wing

Table 1 describes the vessel transits included in the validation.

Table 1. Description of Vessels included in the Measurement Campaign

Vessel Name	Vessel Class	Draft (m)	LOA (m)	LPP (m)
B2	Bulk Carrier	13.50	253.50	249.20
B3	Bulk Carrier	13.53	253.50	249.20
C1	Container	12.10	294.10	282.20
C2	Container	12.68	255.00	244.00

For this validation a MIKE 21 SW model was produced for the Port of Brisbane. The MIKE 21 SW model has been setup to generate a 2D unstructured data file containing sea and swell integral wave parameters to be used with wave response implementation 1. For wave response implementation No 0 the MIKE21 SW model was setup to produce 40 fully direction spectra timeseries along the Port of Brisbane shipping channel. The locations of these 40 directional spectra are displayed in Figure 2-3.

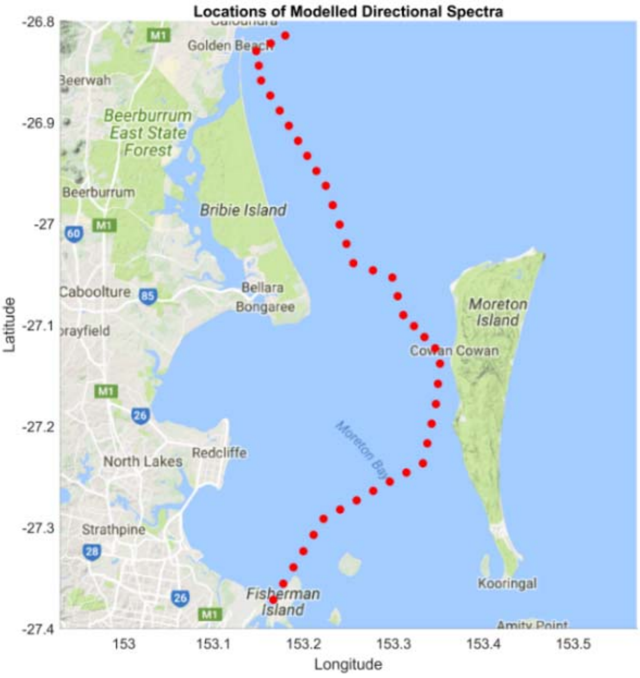


Figure 2-3. Port of Brisbane Directional Spectra Locations

Figure 2-4 and Figure 2-5 show that the calculated wave-induced significant roll of the bulk carriers was well represented by both wave response implementations with implementation No 2 being the most accurate. This included the relatively calm inner components of the transit, moving to the more exposed regions in the latter half of the outbound transits.

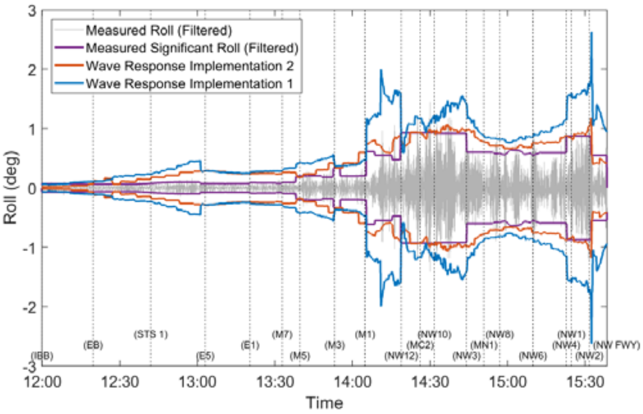


Figure 2-4. B2 Filtered Roll Validation (Bulk Carrier, Outbound)

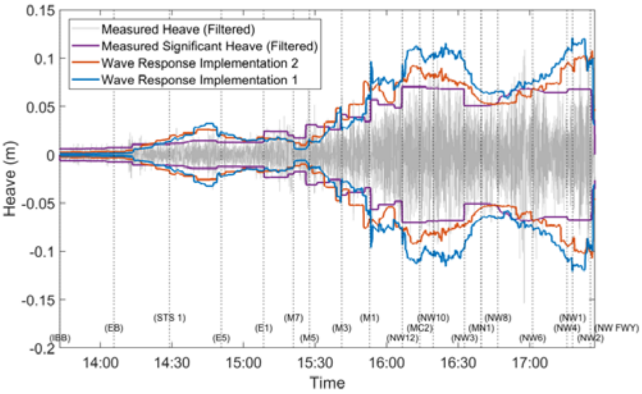


Figure 2-5. B3 Heave Validation

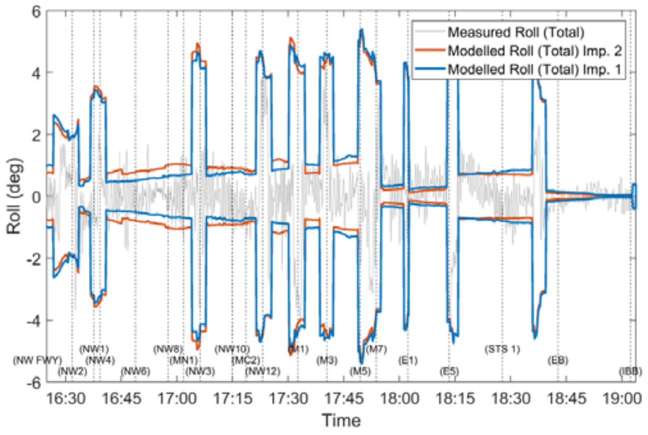


Figure 2-6. C1 Non-filtered Roll Validation incl. effects of wind and turning (Container Vessel, Inbound)

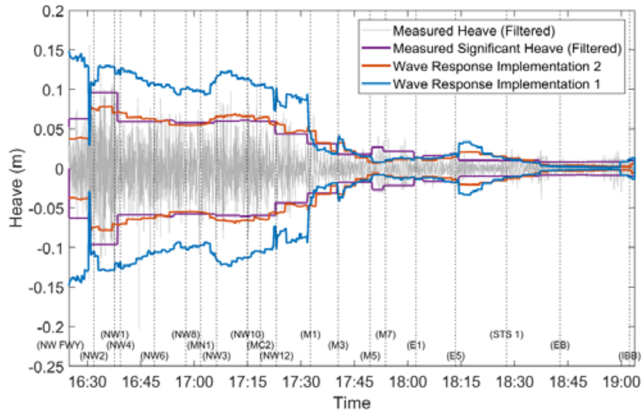


Figure 2-7. C1 Heave Validation

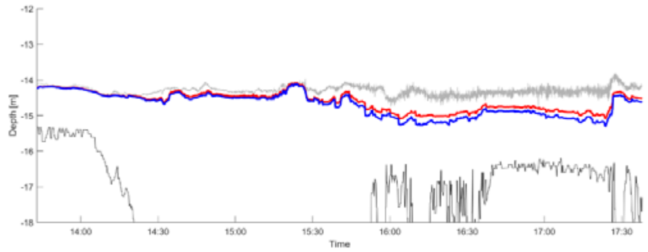


Figure 2-8. B3 UKC Validation

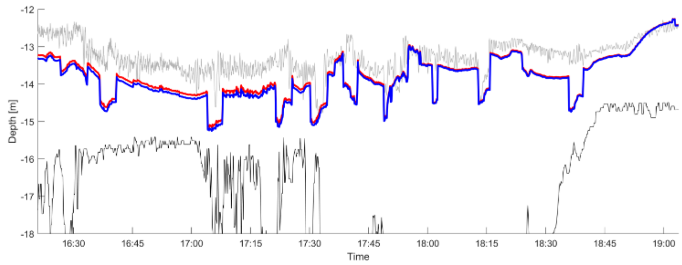


Figure 2-9. C1 UKC Validation

Direct comparison between measured and modelled UKC was excellent and demonstrated a high level of accuracy in capturing various drivers conservatively without being overly conservative. Additional validation is presented in Harkin A. et al 2018 [1].

2.3.2 *Moored vessel motion at sheltered LNG Berth*

Offshore structures, such as gravity-based structures (GBS), are used in the petroleum industry as drilling, extraction and storage units for crude oil or natural gas. The interaction between moored vessels and such structures involves complex wave diffraction/sheltering and radiation effects. In order to accurately perform mooring analyses of these scenarios, a coupling of mooring analysis and complex wave modelling is required.

An LNG tanker was moored at a water depth of 15m using 14 synthetic rope lines with 11m tails and 4 SCN2000 E1.5 fenders. The vessel characteristics are given in Table 2 and mooring system is illustrated in Figure 2-10.

Table 2. Vessel characteristics.

Characteristic	Value
LOA [m]	318.2
Beam [m]	50.6
Draft [m]	12
Displacement [m^3]	133824

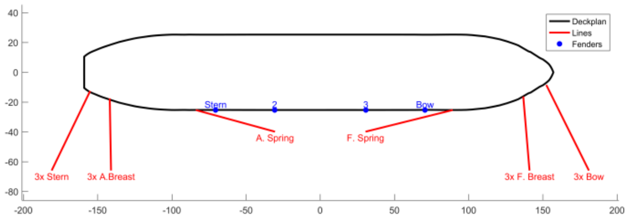


Figure 2-10. Mooring system definitions.

The physical model is displayed in Figure 2-11.

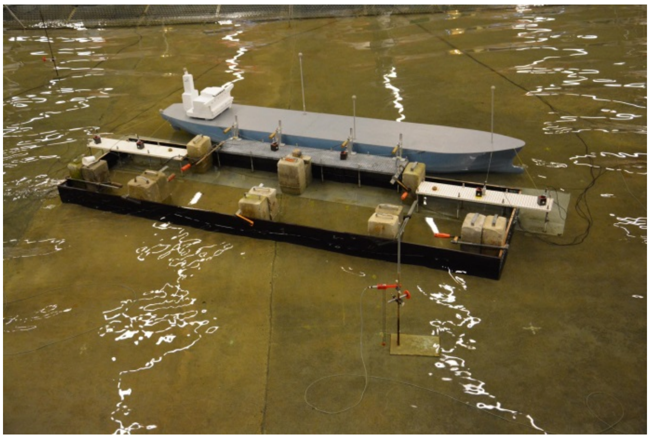


Figure 2-11. Sheltered berth physical model setup.

The wave conditions considered for this validation are a significant wave height of 3m and a peak period of 12s. The wave direction is perpendicular to the GBS to maximise its sheltering effects. A MIKE 21 BW model was again used to replicate these wave conditions numerically to serve as the wave forcing input for MIKE 21 MA.

When moored vessels are in close proximity to fixed structures, such as a GBS, viscous damping effects become complex and significant (especially in shallow water) MIKE 21 MA can account for viscous damping and its effect on moored vessel motions but requires damping coefficients to be established a priory. Based on physical modelling results a linear roll induced damping coefficient of 4.3E+06kNms/rad was established, which was applied to the numerical model setup. Viscous damping in other modes were considered too small to have practical significance.

Test results obtained with the numerical model have been compared to the physical model results. Comparison of motion spectra and peak-to-peak motions are presented in Figure 2-12 and Figure 2-13 and comparisons of maximum line and fender forces are presented in Figure 2-14 and Figure 2-15.

The result comparisons show that MIKE 21 MA has very accurately reproduced the physical model results. Again, a long period response of the moored ship has been observed and is mostly due to the effect of the natural resonance frequency of the mooring system. Additional validation is presented in Harkin A. et al 2017 [3].

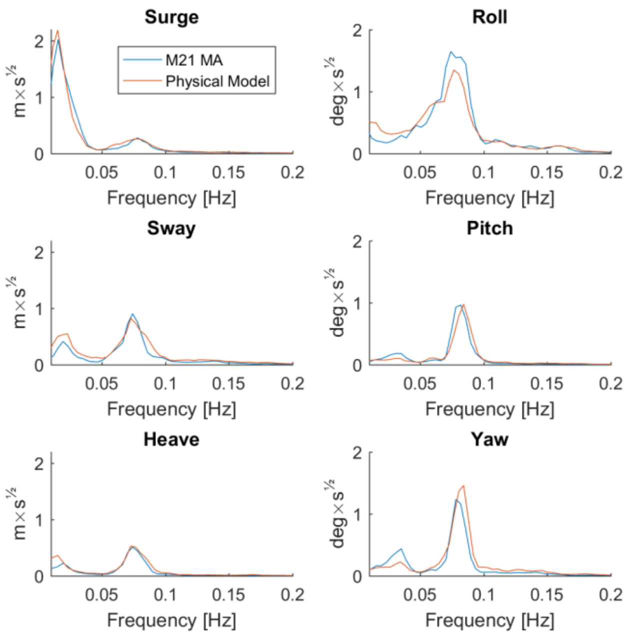


Figure 2-12. Motion spectra validation.

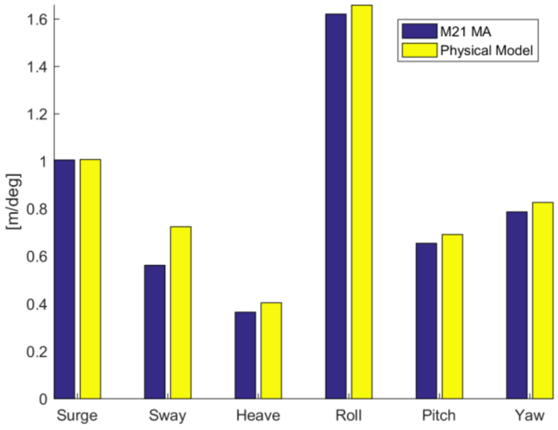


Figure 2-13. Peak to peak motion validation.

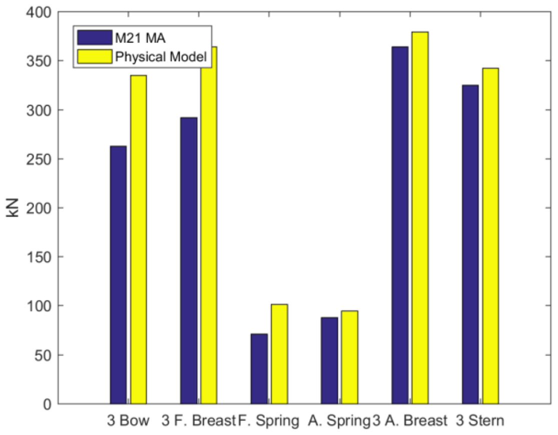


Figure 2-14. Maximum line forces.

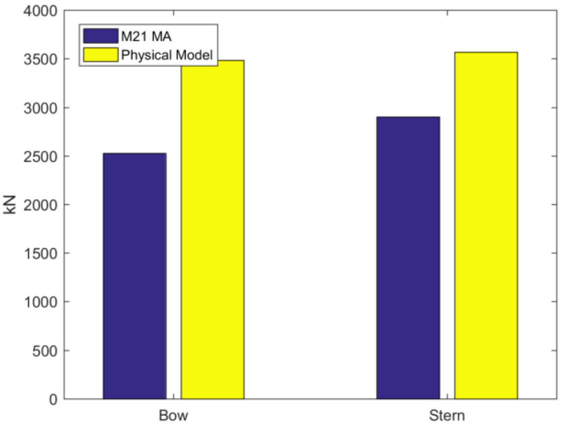


Figure 2-15. Maximum fender forces.

3 NCOS ONLINE INTEGRATION

NCOS ONLINE incorporates the powerful vessel response engine S-OMEGA and MIKE 21 MA in combination with the hydrodynamic and wave modelling capabilities of MIKE computational engine models to provide a powerful cloud-based physics-based port traffic management system supporting both strategic planning and 24/7 operational decision support.

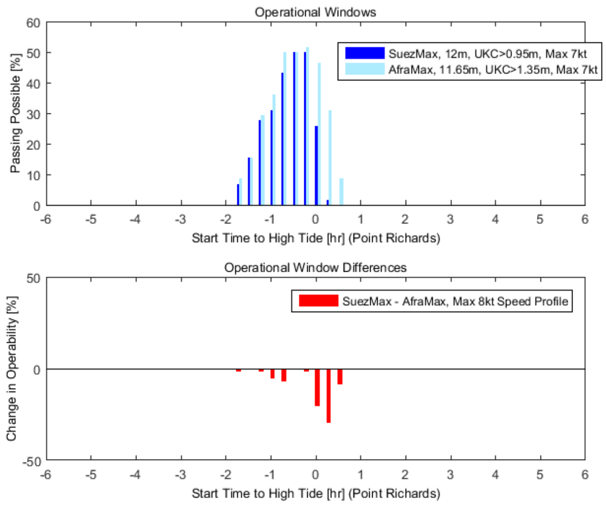


Figure 3-1. Cannel capacity windows for deep draft Suezmax and Aframax tankers for port of Geelong

Through its sophisticated framework the system is capable of implicitly taking into account a wide variety of relevant vessel constraint such as UKC, maneuverability and moored vessel motions that may constrict the movement of vessels through the channel or operability at berth.

As an example of strategic planning application is its capability to provide a detailed assessment of navigational channel capacity through detailed simulation of future vessel traffic scenarios based on typically 1 to 20 years of deterministically modelled variations in water level, winds currents and waves through the entire domain. Figure 3-1 show the tidal dependent operability constraints of the navigational channel into Port of Geelong (Australia) based on approximately 2,700 simulations of inbound transits with the larger Suezmax tanker with a draft of 12.0 m and an Aframax tankers at 11.65 m as presented in Mortensen et al 2017[4]. As observed operability for these large vessels for this port are significantly constrained to suitable tide and weather windows.

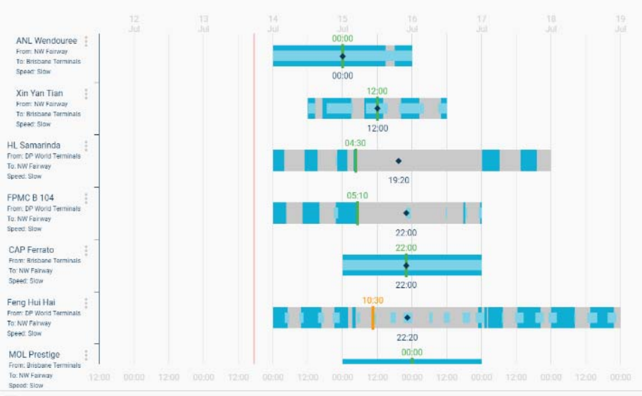


Figure 3-2. Operational Planning Interface

NCOS ONLINE provides the option to plan such transits through its operational planning interface illustrated in Figure 3-2. Using an intuitive dashboard, the port traffic controller types in each unique vessel calling the port and the system returns its safe transit windows based on forecasted weather and water levels for the next 7 days. The system provides differentiated support to multiple user groups each with their own unique access levels and tailored dashboards such as for Shipping Operators, Port Owners, Port Traffic Control, Terminal Operators and Pilots.

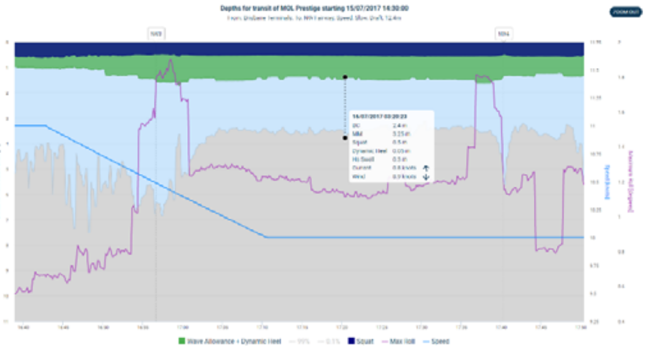


Figure 3-3. As soon as a vessel transit is designated, the Pilot has access to a range of detailed decision support information.

As soon as a transit is locked by traffic control, the scheduled transit becomes accessible to the vessel Pilot, who gets notified of the roster update and is then able to inspect the specifics of his transit such as the UKC profile, his speed profile, vessel response and weather conditions as illustrated in Figure 3-3. Harbour Masters oversee the entire process through their own dashboards and have exclusive access rights to increase the conservatism of various safety parameters in the system if unusual circumstances dictate this type of action.

The berth planning itself is also operated through similar dashboards that is used to plan the appropriate mooring line configuration and berth marker that fits the forecasted weather conditions and scheduled berth utilization. The system provides a graphical GIS overview of proposed mooring system layouts and provides the user the option for planning is mooring arrangement based either on forecasted values or pre-defined environmental forces as illustrated in Figure 3-4.

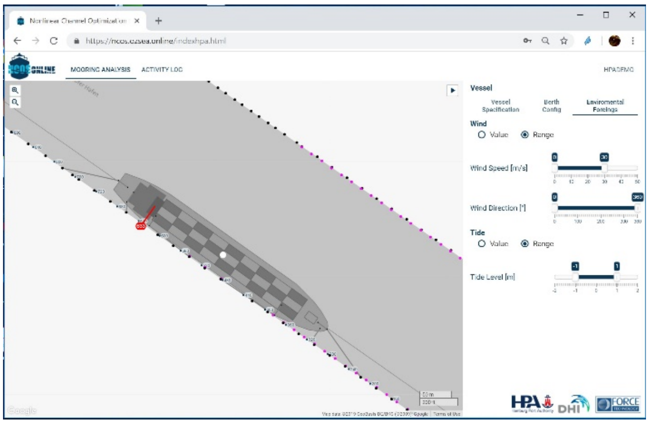


Figure 3-4. Effective GIS based mooring arrangement planning through NCOS ONLINE.

Once a mooring plan has been locked in the system The system provides a running forecast of motions and mooring system forces while the vessel is at berth and provide automatic alerts and notifications if attention is required for mitigating potentially hazardous conditions for the moored vessel as illustrated in Figure 3-5.

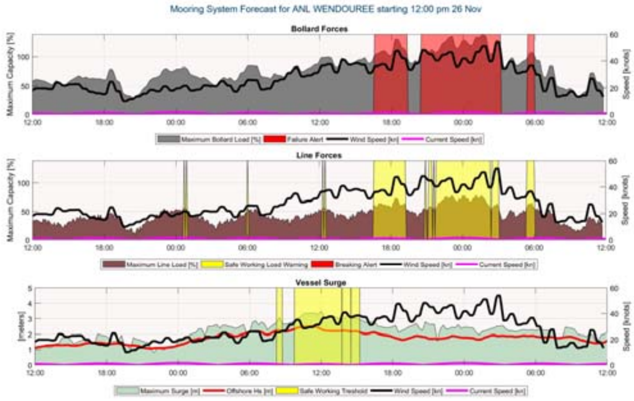
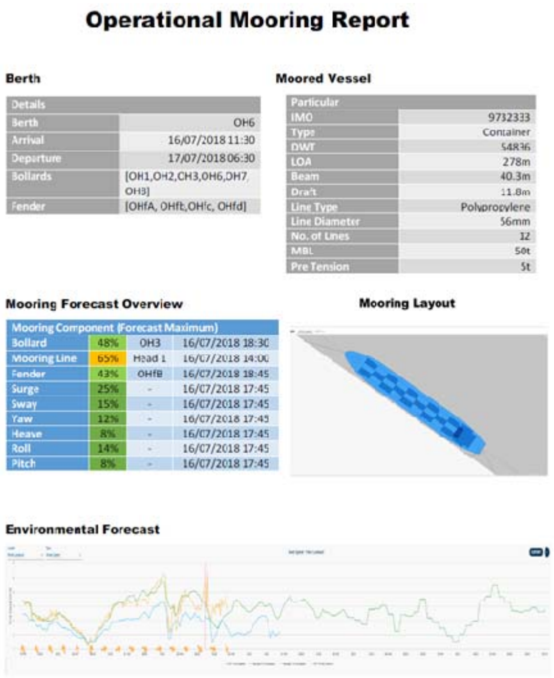


Figure 3-5. Example of operational berth forecast

The system also provides a number of automated operational mooring reports, which allows communication to be easily shared with the vessel

Master, terminal operators and stevedores see Figure 3-6.

Figure 3-7 shows an example of calculated wave fields (short and long waves) within a port used as input for dynamic mooring analysis of a LNG carrier at berth.



Operational Mooring Report

Berth

Details	
Berth	OH6
Arrival	16/07/2018 11:30
Departure	17/07/2018 06:30
Bollards	[OH1,OH2,CH3,OH6,DH7, OH3]
Fender	[OHfA, OHfb,OHfc, OHfd]

Moored Vessel

Particular	
IMO	9732333
Type	Container
DWT	54836
LOA	278m
Beam	40.3m
Draft	11.8m
Line Type	Polypropylene
Line Diameter	56mm
No. of Lines	12
MBL	50t
Pre Tension	5t

Mooring Forecast Overview

Mooring Component (Forecast Maximum)			
Bollard	48%	OH3	16/07/2018 18:30
Mooring Line	65%	Head 1	16/07/2018 14:00
Fender	43%	OHfB	16/07/2018 18:45
Surge	25%	-	16/07/2018 17:45
Sway	15%	-	16/07/2018 17:45
Yaw	12%	-	16/07/2018 17:45
Heave	8%	-	16/07/2018 17:45
Roll	14%	-	16/07/2018 17:45
Pitch	8%	-	16/07/2018 17:45

Mooring Layout

Environmental Forecast

Figure 3-6. Example of Mooring System Forecast showing max bollard forces, line forces and vessel surge. Should also have the option to include max Fender force, sway, heave, roll, pitch, yaw.

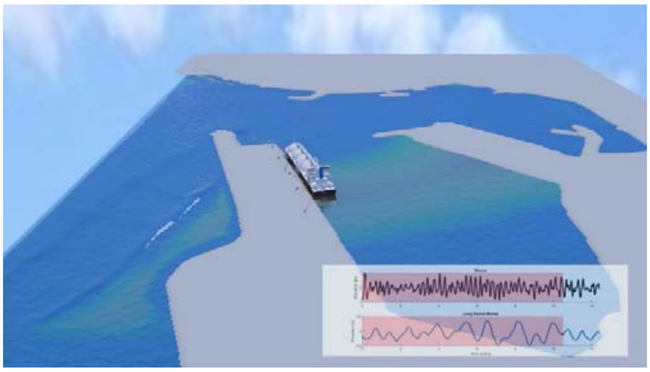


Figure 3-7. Example of vessel (LNG carrier) motion calculation using MIKE 21 MA at berth caused by offshore waves (short waves, the white foam indicates wave breaking at the coast) and infragravity waves (long waves, colored).

4 CONCLUSIONS

This paper presents the equational frame work, numerical accuracy and practical application of utilizing an online physics-based traffic management system can significantly increase port capacity to accommodate larger and deeper drafted vessels from channel to berth. The system demonstrates a capacity to incorporate the operational user group requirements of multiple port operators and provides a flexible platform for a more effective and user-friendly management tool for optimizing constrained port traffic flow both now and in the future.

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