VALIDATION OF A 3D UNDERKEEL CLEARANCE MODEL WITH FULL SCALE MEASUREMENTS

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ABSTRACT

The continuing growth of commercial vessel sizes is putting increasing pressure on the world's port authorities to adopt effective expansion strategies to ensure that their asset is able to meet growing capacity demands. Channel capacity expansion projects usually involve the consideration of extensive dredging which introduces considerable constraints with respect to cost and environmental impacts. Depth constrained ports require accurate under keel clearance (UKC) monitoring in order to safely and economically operate. Inaccurate determination of UKC can lead to excessive port design and dredging cost or even unsafe operations leading to vessel grounding.

This paper presents the full scale validation of an improved integrated approach for optimizing shipping channel capacity utilizing DHI's new state-of-the-art 3D under keel clearance (UKC) model Nonlinear Channel Optimization Simulator (NCOS). The aim of this validation exercise is to demonstrate the accuracy envelope of a 3D method for UKC prediction through various approaches for treatment of key input forcing parameters, wave frequency response, dynamic heel and squat. Measurements used for validation consisted of high resolution time series of UKC, roll, pitch and heave obtained during vessel inbound and outbound transits through the Port of Brisbane. Vessels included a mix of large bulk carriers and container vessels.

NCOS belongs to a new breed of UKC models that converge towards the same level of sophistication and realism as Full Bridge Simulators. The NCOS model uses the numerical 3D vessel frequency engine in the Full Bridge Simulator *SIMFLEX4* by FORCE TECHNOLOY for predicting wave-induced UKC allowance, which greatly improves the potential for using it in close integration with detailed maneuverability studies. The model uses a 2nd Order 3D panel method for evaluating vessel frequency response incorporating implicitly the effect of vessel forward speed and varying water depths. Adopting a Rayleigh distributed sea state; the probabilistic vessel execution is evaluated in each time step for various return periods. To ensure accurate predictions of UKC, NCOS relies on temporally and spatially varying environmental inputs such as wind, wave and hydrodynamic data to serve as forcing inputs to the model

Serving as the bases for this validation are full scale measurements taken during vessel transits through the Port of Brisbane. Differential Global Positioning Systems (DGPS) were located at the bow and on both the port and starboard bridge wings of the vessels to measure trajectory and the vertical position at each location. From these measurements roll, pitch, heave and total vertical excursion of the vessels throughout the transits were calculated.

With regards to calculating UKC wave allowance, the 3D vessel frequency response engine in NCOS supports wave forcing from a full directional wave spectrum, which provides the most accurate prediction. However due to the increased computational and storage overheads associated with the full integration in an operational framework, a simplified approach using synthetic JONSWAP spectra from integral wave parameters has also been investigated and benchmarked in this paper.

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In addition most ports have long term trust relationship with the use of empirical squat formulae presented in PIANC WG 121-2014 when estimating basic UKC, which raises a demand for assessing how these can be incorporated into a sophisticated 3D UKC framework. As a result we assess the performance impacts of incorporating an array of well-known squat formulations and we also investigate the effect of representing waves using either synthetic wave spectra from integral parameters to using full directional spectra as modelled by a spectral wave model.

The comparison includes timeseries of roll, pitch, heave, squat and total minimum vessel vertical excursion above the seabed (UKC). Comparisons to date show that NCOS has very accurately reproduced the measurements numerically which gives confidence that it can be used by ports to achieve target levels of channel operability, while potentially reducing required dredge volumes significantly compared to conventional estimates.

1 INTRODUCTION

The continuing growth of commercial vessel sizes is putting increasing pressure on the world's port authorities to adopt effective expansion strategies to ensure that their asset is able to meet growing capacity demands. Channel capacity expansion projects usually involve the consideration of extensive dredging which introduces considerable constraints with respect to cost and environmental impacts (Mortensen, 2017). Depth constrained ports require accurate under keel clearance (UKC) monitoring in order to safely and economically operate. Inaccurate determination of UKC can lead to excessive port design and dredging cost or even unsafe operations leading to vessel grounding.

This paper presents the full scale validation of an improved integrated approach for optimizing shipping channel capacity utilizing DHI's new state-of-the-art 3D under keel clearance (UKC) model Nonlinear Channel Optimization Simulator (NCOS). The aim of this validation exercise is to demonstrate the accuracy envelope of a 3D method for UKC prediction through various approaches for treatment of key input forcing parameters, wave frequency response, dynamic heel and squat. Measurements used for validation consisted of high resolution time series of UKC, roll, pitch and heave obtained during vessel inbound and outbound transits through the Port of Brisbane. Vessels included a mix of large bulk carriers and container vessels.

Serving as the bases for this validation are measurements taken during vessel transits through the Port of Brisbane. Measurements of the vessels roll, pitch, heave and total vertical excursion have been produced for 10 inbound and outbound transits. The vessels included in this paper are a mix of four large bulk carriers and container vessels. These measurements will enable the validation of the NCOS calculations including wave response, wind and turning heel and squat.

2 NOMENCLATURE

B: Vessel beam

C: Restoring Force

$C_{\emptyset}$: Rudder angle coefficient

d: Vessel motion point

∇: Ship volume displacement

$F^{(2)}$: Second order force/moments

F_k: Bilge keel factor

GM: Metacentric height

H_s: Significant wave height

RAO: Response amplitude operator

SWD: Still water depth

ι_R: Turning heel moment arm

$T^{(2)}$: Set down due to second order drift forces

T_{heel}: Set-down due to wind and turning heel

T: Vessel draft

T_p: Peak wave period

$T_{p,cor}$: Peak wave period correction factor

T_{squat}: Set-down due to squat

$H_{s,cor}$: Significant wave height correction factor

M_w: Wind heel moment

MWD: Mean wave direction

η: Timestep and vessel position

R_c: Turing radius

θ: Wave direction

$\emptyset$: Heel angle

U_c: Vessel speed relative to water

ω: Wave frequency

x: Ship motion

3 MEASUREMENT CAMPAIGN

Serving as the bases for this validation are measurements taken during vessel transits through the Port of Brisbane. Differential Global Positioning Systems (DGPS) were located at the bow (**Figure 1**) and on both the port and starboard bridge wings (**Figure 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.

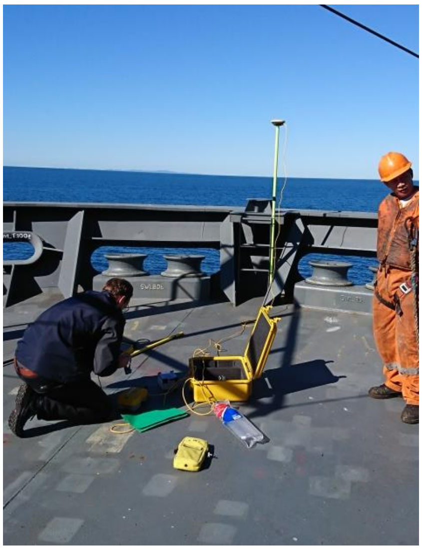

Figure 1: DGPS Setup on Bow

Figure 2: DGPS Setup on Starboard Bridge Wing

Table 1 describes the vessel transits included in the validation.

Vessel Name	Vessel Class	Draft (m)	LOA (m)	LPP (m)	Beam (m)	Transit Start Date and Time	Direction of Travel
B2	Bulk Carrier	13.50	253.50	249.20	43.00	15/06/2017 - 11:30	Outbound
B3	Bulk Carrier	13.53	253.50	249.20	43.00	30/07/2017 - 13:30	Outbound
C1	Container	12.10	294.10	282.20	32.20	11/07/2017 - 16:30	Inbound
C2	Container	12.68	255.00	244.00	37.30	24/07/2017 - 00:30	Inbound

Table 1: Description of Vessels included in the Measurement Campaign

4 NUMERICAL MODELLING METHODOLOGY

4.1 Vessel Wave Response

NCOS belongs to a new breed of UKC models that converge towards the same level of sophistication and realism as Full Bridge Simulators. The NCOS model uses the numerical 3D engine, SOMEGA, which is used in the Full Bridge Simulator *SIMFLEX4* by FORCE TECHNOLOY for calculating wave response, which greatly improves the potential for using it in close integration with detailed maneuverability studies. The model uses a 2^{nd} Order 3D panel method for evaluating vessel frequency response incorporating implicitly the effect of vessel forward speed and varying water depths. Adopting a Rayleigh distributed sea state; a probabilistic vessel approach is evaluated in each time step for various return periods.

NCOS is directly integrated with SOMEGA and the MIKE 21 Spectral Wave model (MIKE21 SW) enabling the accurate prediction of spatially and temporally varying wave response through a channel. SOMEGA provides the frequency domain wave response in the form of motion response amplitude operators (RAOs) and MIKE21 SW provides the wave conditions. Based on the inputs from SOMEGA and MIKE21 SW, NCOS computes the full linear motion RAOs of responses to unit wave amplitude along with 2_{nd} order vertical motions ($T^{(2)}$).

The spectral form of the 1^{st} 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).

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

Where RAO_d is the RAO calculated by SOMEGA 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. The motion points are selected such that at any time one of the motion points will be the deepest point of the vessel.

In order to provide a robust solution NCOS allows for live wave data assimilation which enables manipulation of the wave spectra to more accurately match measured data when available. Separate wave height and wave period correction factors are used for the sea and swell wave components. This paper will investigate two alternative implementations for calculating the fully directional spectra S_η.

1. Implementation 1 involves extracting sea and swell integral wave components H_s, T_p and MWD from the MIKE21 SW model and synthetically generating fully directional spectra based on a JONSWAP spectrum in conjunction with user defined wave spreading and wave correction factors. In this implementation the wave correction factors for both sea and swell are applied as shown in (2) to (5).

$$H_s(Sea) = H_s(Sea) * H_{s,cor}(Sea) \tag{2}$$

$$H_s(Swell) = H_s(Swell) * H_{s,cor}(Swell) \tag{3}$$

$$T_p(Sea) = T_p(Sea) + T_{p,cor}(Sea) \tag{4}$$

$$T_p(Swell) = T_p(Swell) + T_{p,cor}(Swell) \tag{5}$$

2. Implementation 2 involves extracting the fully directional spectra directly from the MIKE21 SW

model. In this implementation the wave correction factors are applied as shown in (6) and (7). Where n is the number of discrete peaks in the measured wave spectrum.

$$S_\eta = \sum_{p=1}^{n} S_\eta\left(T_p(p)\right) * H_{s,cor}(p) \tag{6}$$

$$S_\eta = \sum_{p=1}^{n} S_\eta\left(T_p(p) + T_{p,cor}(p)\right) \tag{7}$$

Implementation 1 is expected to provide a more conservative calculation of the vessel motions since the wave energy will be more concentrated at the peak periods and mean wave directions. Implementation 2 is expected to be more accurate since it better describes the wave energy distribution. We compare both approaches herein, noting that despite being more conservative, implementation 1 allows for easier data assimilation of the SW results with measured wave conditions.

Once the motion spectra is determined NCOS then calculates the significant motions (9) and maximum motions (10) at each timestep.

$$\mathrm{m_n} = \int_0^\infty \omega^{\mathrm{n}} \mathrm{S_d}(\omega)\, \mathrm{d}\omega \tag{8}$$

$$\mathrm{x_{sig}} = 2 * \sqrt{\mathrm{m_0}} \tag{9}$$

$$\mathrm{x_{max}} = \sqrt{2 * \mathrm{m_0} * \ln\left(\frac{\mathrm{D}}{2 * \pi * \alpha}\sqrt{\frac{\mathrm{m_2}}{\mathrm{m_0}}}\right)} \tag{10}$$

Where D is the time duration where the spectra moments remain essentially constant and α is a small number which represents the likelihood that the maximum design motion will be exceeded. The results in this paper are based on an α value of 0.01 as recommended by (Lewandowski, 2014).

The 2nd order set down, $T^{(2)}$, is calculated from (11) to (13) where $F^{(2)}$ is the second order force/moments extracted from SOMEGA, θ is the wave direction and C is the restoring force.

$$S_{F^{(2)}}(\omega,\theta) = F^{(2)}(\omega,\theta).S_\eta(\omega,\theta) \tag{11}$$

$$x^{(2)}(\theta) = \frac{\int S_{F^{(2)}}(\omega,\theta)d\omega}{C} \tag{12}$$

$$T_d^{(2)}(\omega,\theta) = x_{heave}^{(2)}(\theta) + x_{roll}^{(2)}(\theta) * d_y + x_{pitch}^{(2)}(\theta) * d_x \tag{13}$$

This paper will compare the measured wave induced motions with the significant wave induced motions calculated by NCOS.

4.2 MIKE21 SW Model and Correction Factors

For this validation a MIKE21 SW model was produced for the Port of Brisbane. The MIKE21 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 2 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 3**.

For validation purposes the MIKE21 SW model outputs timeseries of sea and swell integral wave parameters at the location of multiple wave buoys (see locations in **Figure 4**) along the Port of Brisbane shipping channel.

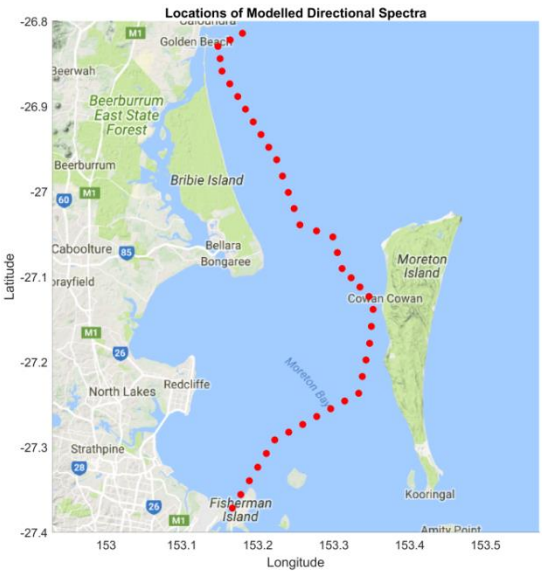

Figure 3: Port of Brisbane Directional Spectra Locations

Figure 4: Wave Buoys Locations

The MIKE 21 SW results have been compared to the measured data at wave buoys MC2, NW3, MN1 and NW4 in order to generate correction factors for each transit. Significant wave height correction factors were calculated by dividing the measured wave height by the modelled wave height at a distinct time step. Similarly, the peak wave period correction factors were calculated by subtracting the modelled period from the measured period. Correction factors were calculated separately for each wave buoy. The calculations were made at half hour intervals for two hours leading up to each transit and then these values were averaged giving an average correction factor for each wave buoy. The most conservative correction factor was then selected for use in the NCOS model. The correction factors are displayed in Table 2.

Vessel Name	**Correction Factors**			
	Significant Wave Height (Swell) [()]	Significant Wave Height (Sea) [()]	Peak Wave Period (Swell) [s]	Peak Wave Period (Sea) [s]
B2	0.902	0.973	0.231	3.687
B3	0.624	1.216	1.360	0.526

C1	0.892	1.106	3.297	0.877
C2	0.971	2.121	1.939	0.367

Table 2 Wave Correction Factors

4.3 Dynamic Heel

As well as wave induced motions NCOS includes dynamic heel. Heel is a ships non-wave induced roll motion and is caused by wind and turning. The wind and turning heel are calculated based on the guidelines provided in (PIANC, 2014) as detailed in (14) to (17).

$$\emptyset_w = \frac{M_w}{g\rho\nabla\mathrm{GM}} \tag{14}$$

$$\emptyset_R = C_\emptyset \frac{\iota_R U_c^2}{gR_c\mathrm{GM}} \tag{15}$$

$$\emptyset_{WR} = \emptyset_w + \emptyset_R \tag{16}$$

$$T_{heel} = F_k\left(\frac{B}{2}\sin\emptyset_{WR}\right) \tag{17}$$

The wind forcing in NCOS comes from The Bureau of Meteorology and rudder angles through the Port of Brisbane are based on observations made through the measurement campaign.

4.4 Squat

Squat is a steady downward displacement consisting of a translation (sinkage) and rotation (trim) due to the flow of water past the moving hull (PIANC, 2014). **Figure 5** visualizes this phenomenon.

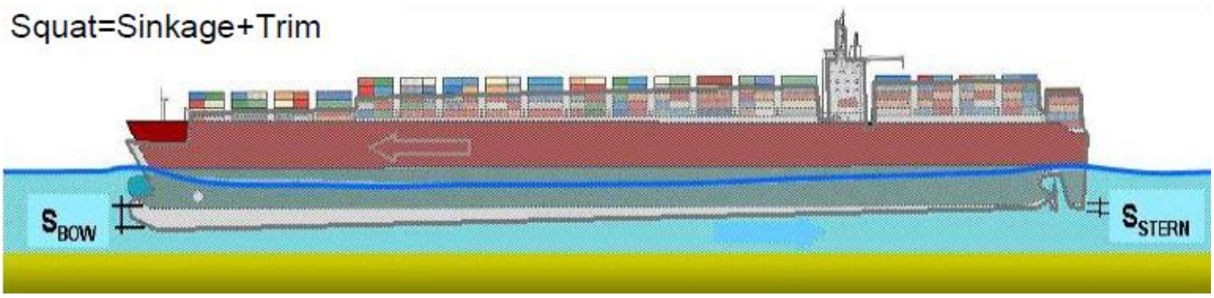

Figure 5: Ship Squat (PIANC, 2014)

NCOS is directly integrated with the MIKE 21 Hydrodynamic Model (MIKE21 HD) which provides the current speed and direction enabling the accurate calculation of the transiting vessels speed relative to water and consequently squat. NCOS utilizes well known empirical squat formulae including Millward (Millward, 1990), Yoshimura (Ohtsu K, 2006), Barrass (Barrass, 1979) and Huuska (Huuska, 1976).

The most important factors influencing ship squat are the speed through water, the block coefficient and the blockage factor. Ship squat is approximately proportional to the square of the ship speed, and generally squat is not significant for speeds less than 6 knots. The squat of a ship also depends on the block coefficients where ships with larger block coefficients have more squat compared to more slender vessels. Squat is generally directly proportional to the block coefficient. In shallow or restricted channels the non-dimensional blockage factor, the ratio of ship area to channel area, can lead to large increases in squat. Factors influencing the blockage factor include water depth, channel width, channel height and channel slope.

Channel parameters water depth, channel width, channel height and channel slope are generated by details bathymetry data through the Port of Brisbane.

This paper will evaluate the accuracy of each squat formula through comparisons with the measured results and ultimately develop a set of equations for utilizing a combination of each squat formula.

4.5 Governing Equations

Once the wave induced vessel motions (m_0 and $T^{(2)}$), squat (T_{squat}) and heel (T_{heel}) have been evaluated the grounding probability can be calculated. The residual depth Z, calculated in (18), defines the wave-induced depth threshold of the transit vessel.

$$Z = SWD + Tide - \left(T + T_{squat} + T_{heel} + T^{(2)}\right) - \Delta Z \tag{18}$$

Where $Tide$ is produced by a MIKE21 HD model and ΔZ is the minimum allowable water depth under the vessel after all other effects have been taken into account. $Q(Z)$, calculated in (19), is the grounding probability in each timestep.

$$Q(Z) = 1 - \left[1 - e^{\left(-1/2\frac{Z^2}{m_0}\right)}\right]^n \tag{19}$$

Where n is the number of waves passing the ship in the timestep.

Using (18) and (19) NCOS is capable of calculating the ships total vertical excursion based on a given exceedance probability and iteratively shifting a virtual sea floor by altering ΔZ. Keel levels calculated in this paper are based on an exceedance probability of 1% and a 20min wave ensemble.

P_{tot}, calculated in (20), is the integrated grounding probability for the whole transit based on the product of the grounding proability at each timestep $t1$ - tn.

$$P_{tot} = 1 - (1 - Q_{t1})(1 - Q_{t2})..(1 - Q_{tn}) \tag{20}$$

5 RESULTS

5.1 Wave Response Comparison and Validation

This section aims to directly investigate the validity of wave response implementation 1 and wave response implementation 2. In order to do this analysis, the measured vessel motion data has been high pass filtered to remove any motions with a period greater then 60s. This was done to attempt to remove roll motions induced by wind and turning and pitch and heave motions induced by squat so only motions that are purely wave induced are considered. Next, the significant motions were calculated. This was done by finding the mean of the highest one third of the vessel motions using a wave ensemble of 20 minutes at each timestep. This section of the paper will display comparative plots for the roll, pitch and heave motions for each transit. All motion plots in the following sections will include the measured motion after filtering, the significant measured motion and the significant motion calculated from the two NCOS models as well as time stamps of when each wave buoy (**Figure 4**) was passed.

One of the DGPS instruments located on the bridge of vessel B2 failed during its transit. As a result, the backup xsens device was used to measure the roll of the vessel in order to calculate the heave at the vessel center of gravity. The xsens device has a margin of error of 0.2 degrees. Since the beam of the ship is 43m, translating this error to the centre of the ship results in a vertical excursion error of up to 0.075m. This margin of error will be acceptable for calculating roll and pitch. However, heave will not be calculated with sufficient accuracy, so transit B2 will be left out of the heave calculations. For transits C1, C2 and B3 all three DGPS instruments performed successfully.

5.1.1 Roll

Figure 6 and **Figure 7** show that the calculated wave-induced significant roll of the bulk carriers was well represented by both wave response implementations with implementation 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.

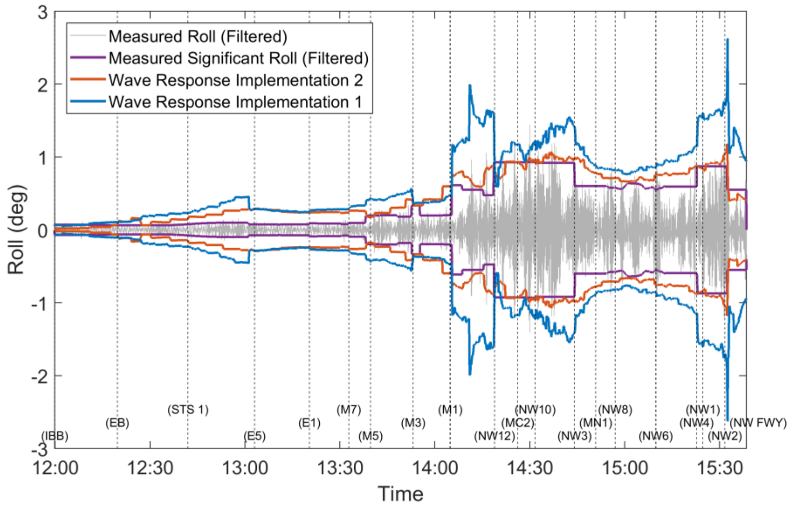

Figure 6: B2 Filtered Roll Validation (Bulk Carrier, Outbound)

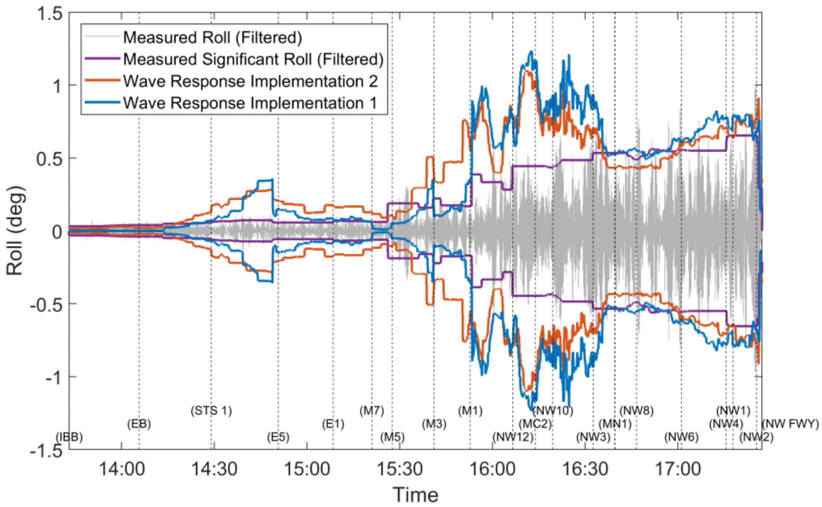

Figure 7: B3 Filtered Roll Validation (Bulk Carrier, Outbound)

For the container vessels the high pass filtering was not able to remove the noticeable roll generated by frequent rudder corrections through the transit and largely exceeded the wave induced roll motions. As a result the comparison for both the high pass filtered roll and total roll have been presented for these two ships. **Figure 9** and **Figure 11** present the total roll which shows that the character of the container roll response differs from that of the bulk carriers and is far more affected by wind and turning/rudder corrections. **Figure 8** and **Figure 10** show that the magnitude of the high pass filtered container measured roll is largely consistent along the length of the as opposed to being proportional to the large difference in wave conditions through the channel. **Figure 12** and **Figure 13** show that both the sea and swell significant wave height was largest offshore and reduced as ship C2 approached the port and that the peak wave periods remained constant. We thus expect the wave induced roll response will be decreasing along the transit, but this not being the case for measured roll confirms the expectation that the prominent roll motion is not wave induced for these two cases.

Residual turning and rudder correction response can be seen in the high pass filtered container measured roll signal after corners as the ship stabilizes. This gives an indication that the container vessels respond with the same roll period to wind and turning agitation as they do to wave forcing and the high pass filtering cannot remove the wind and turning induced roll. Importantly for roll motion, containers have a high centre of gravity and large windage area when compared to bulk carriers. As a result, their response to turning and wind is much greater and this response has not been fully removed by the high pass filter.

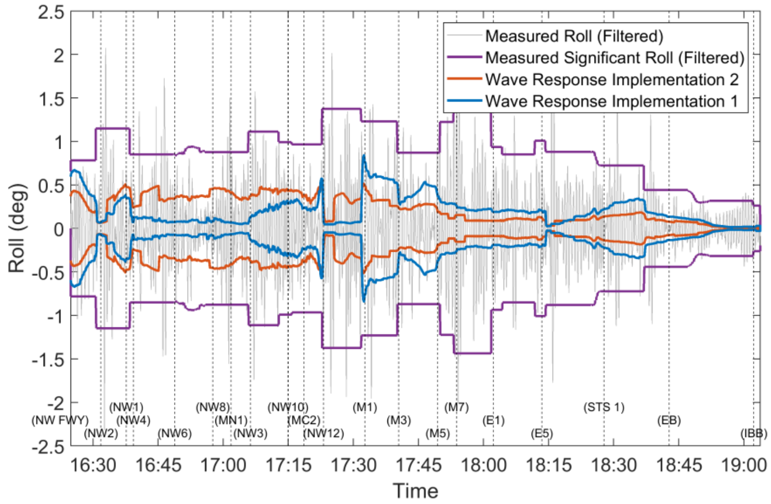

Figure 8: C1 Filtered Roll Validation (Container Vessel, Inbound)

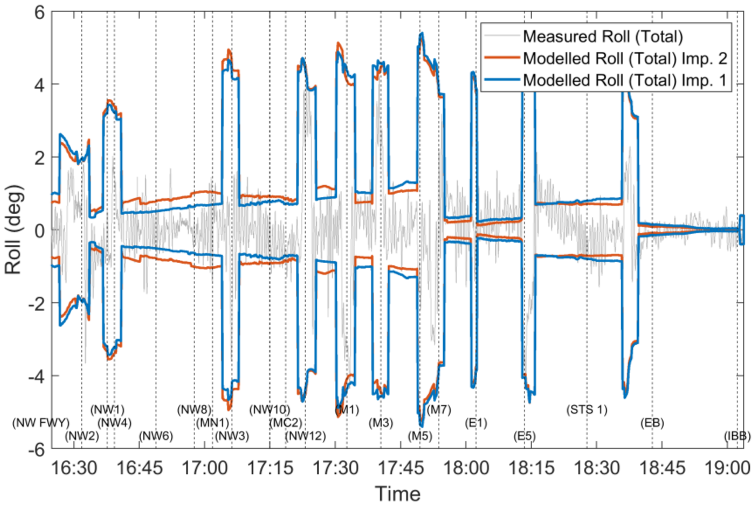

Figure 9: C1 Non-filtered Roll Validation incl. effects of wind and turning (Container Vessel,

Inbound)

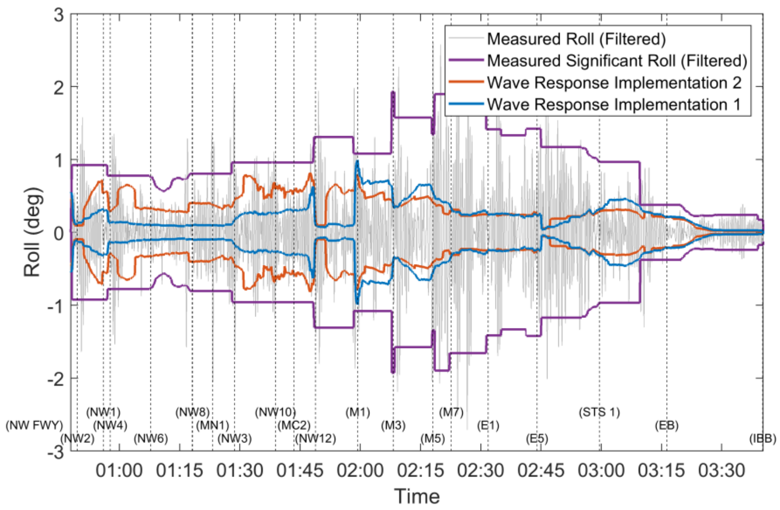

Figure 10: C2 Filtered Roll Validation (Container Vessel Inbound)

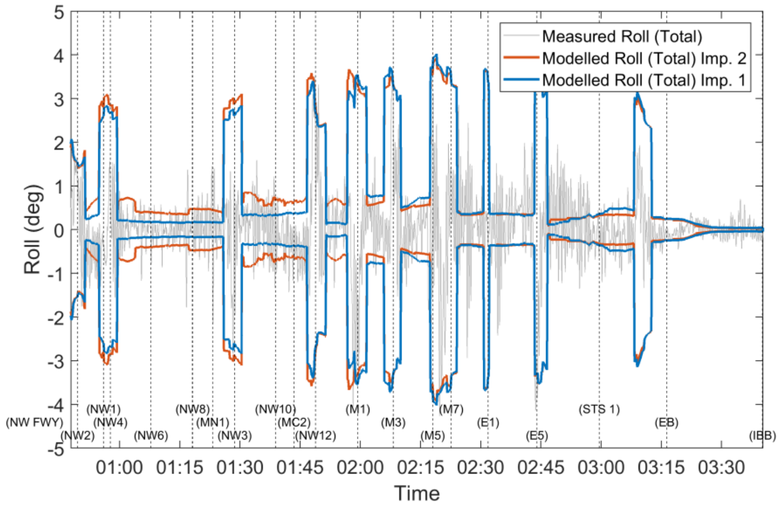

Figure 11: C2 Non-filtered Roll Validation incl. effects of wind and turning (Container Vessel Inbound)

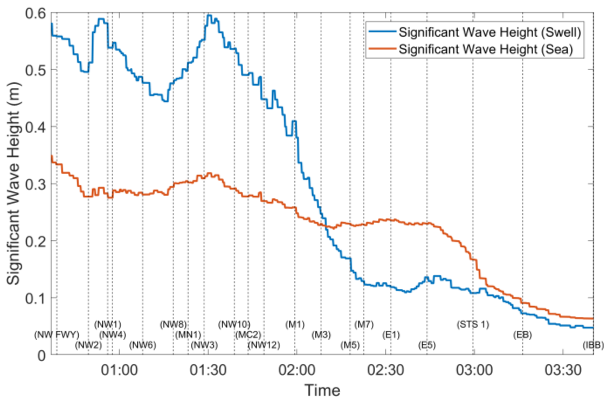

Figure 12: C2 Sea and Swell Significant Wave Height

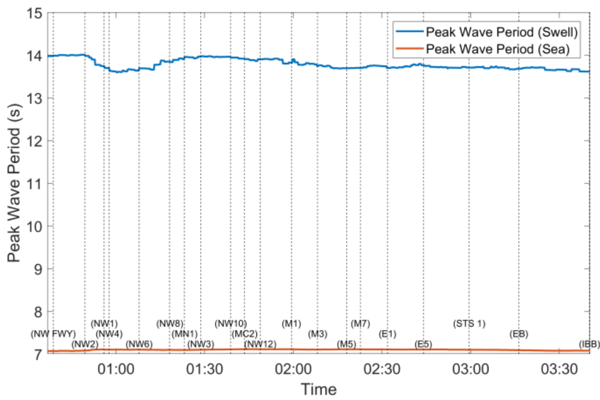

Figure 13: C2 Sea and Swell Peak Wave Period

The root-mean-square (RMS) error, average absolute error and maximum absolute error have been calculated for the roll of the above transits over their entire domain and are displayed below in **Table 3**. Because the wave induced roll motion cannot be extracted from the measured roll data for the container vessels, and this investigation involves comparing purely wave induced motions, the two containers were not included in these error calculations.

Vessel	RMS Error (deg)		Mean Absolute Error (deg)		Max Absolute Error (deg)	
	Imp. 1	Imp. 2	Imp. 1	Imp. 2	Imp. 1	Imp. 2
B2	0.3814	0.1493	0.2919	0.121	2.0724	0.631
B3	0.2204	0.1932	0.1372	0.1366	0.7905	0.6522
Average	0.3009	0.17125	0.21455	0.1288	1.43145	0.6416

Table 3: RMS and Mean/Max Absolute Error of Wave Induced Roll

From the figures, it can be seen that wave response implementation 2 provides a more accurate fit to the measured roll data than wave response implementation 1. The quantifiable data displayed in **Table 3** supports this observation with the wave response implementation 2 demonstrating close to an average decrease of 50 percent in all errors from the wave response implementation 1. This indicates that forcing NCOS with the fully directional wave spectra is recommended to most accurately represent the wave induced roll motions.

5.1.2 Pitch

Figure 14 to **Figure 17** show that the squat motion experienced during each transit has successfully been filtered from the measurements leaving just the wave induced pitch motion. These figures and **Table 4** all show that both wave response implementation 1 and 2 have accurately reproduced the measured wave induced pitch response. As with roll, wave response implementation 2 has provided a more accurate result then wave response implementation 1.

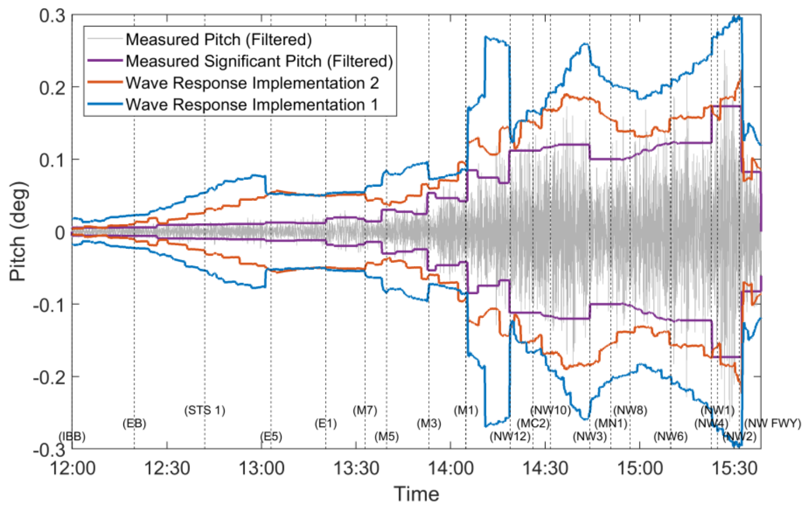

Figure 14: B2 Pitch Validation

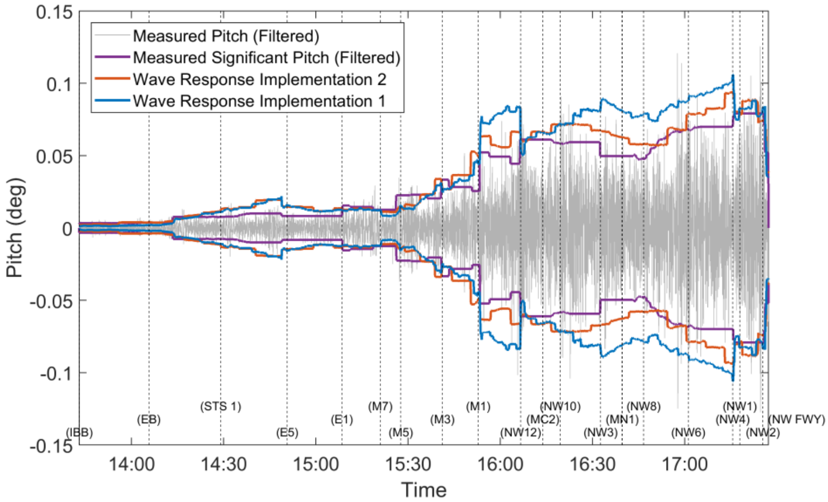

Figure 15: B3 Pitch Validation

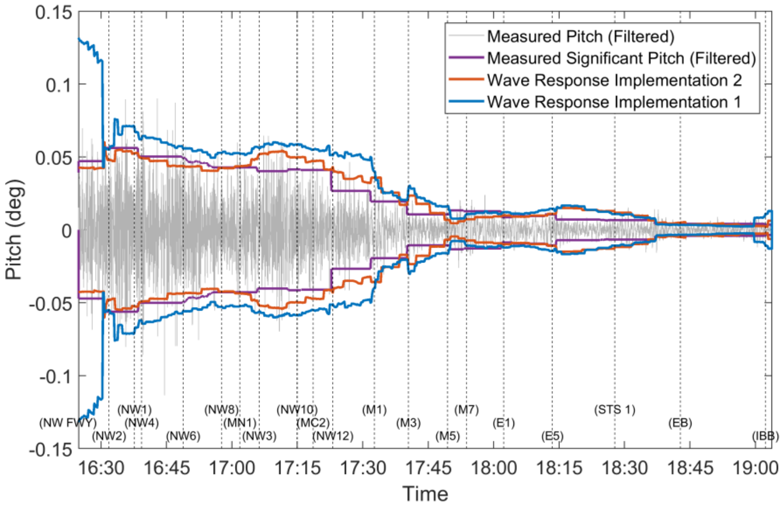

Figure 16: C1 Pitch Validation

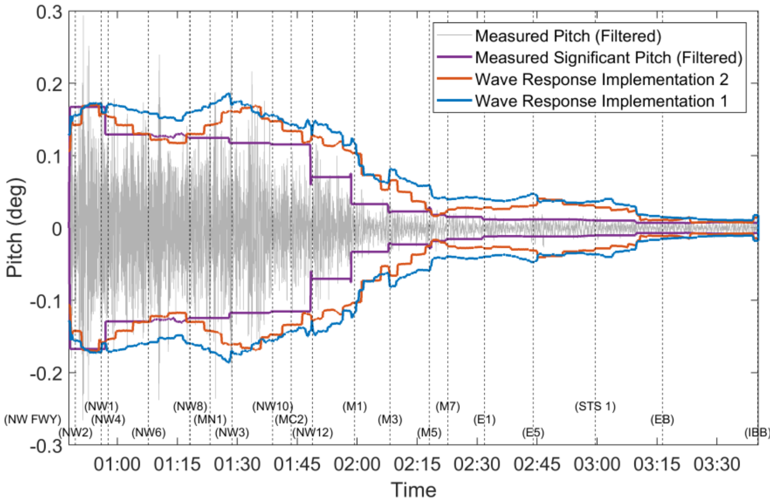

Figure 17: C2 Pitch Validation

Vessel	RMS Error (deg)		Mean Absolute Error (deg)		Max Absolute Error (deg)	
	Imp. 1	Imp. 2	Imp. 1	Imp. 2	Imp. 1	Imp. 2
B2	0.0756	0.0345	0.0632	0.0288	0.2138	0.1414
B3	0.0152	0.0085	0.0108	0.0064	0.0397	0.0274
C1	0.0179	0.006	0.0106	0.0045	0.0851	0.0165
C2	0.0342	0.0244	0.0293	0.0185	0.0917	0.0734
Average	0.0357	0.0184	0.0285	0.0146	0.1076	0.0647

Table 4: RMS and Mean/Max Absolute Error of Wave Induced Pitch

Table 4 shows that wave response implementation 2 demonstrates close to an average decrease of 50 percent in all errors from the wave response implementation 1. This indicates that forcing NCOS with the fully directional wave spectra is recommended to most accurately represent the wave induced pitch motions.

5.1.3 Heave

Figure 18 to **Figure 20** again show that the squat motion experienced during each transit has successfully been filtered from the measurements leaving just the wave induced heave motion. These figures and **Table 5** show that both wave response implementation 1 and 2 have accurately reproduced the measured wave induced heave response for transits B3, C1 and C2. Again, wave response implementation 2 has provided a more accurate result then wave response implementation 1.

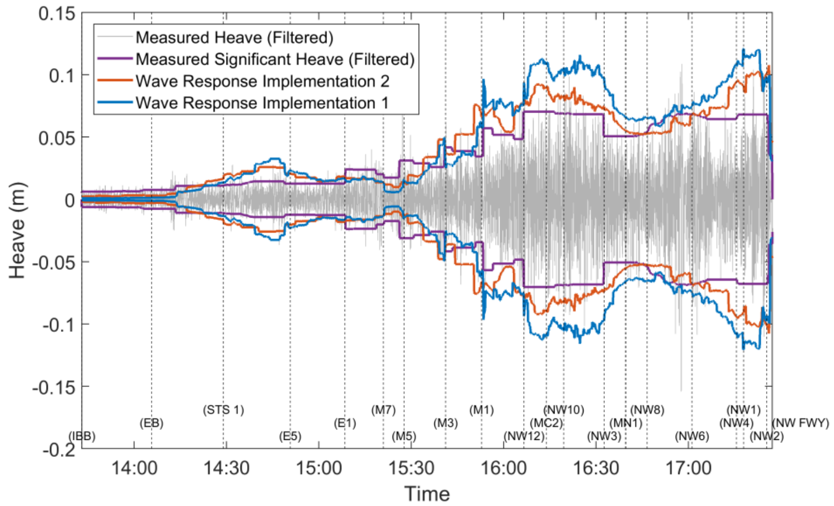

Figure 18: B3 Heave Validation

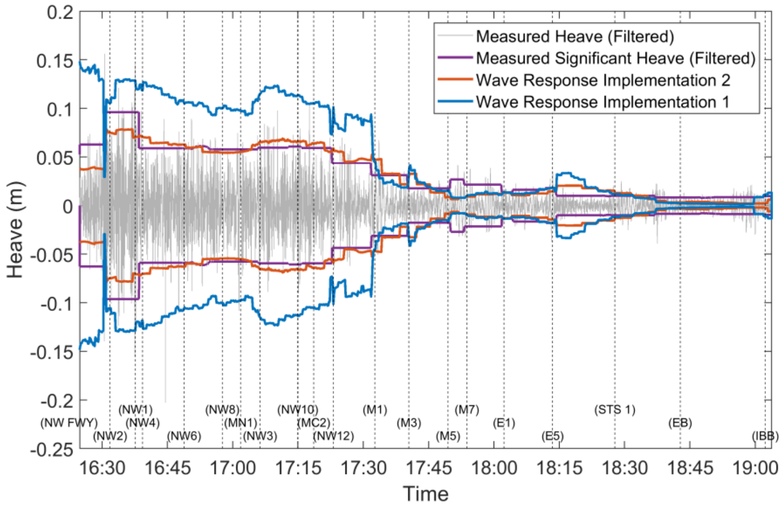

Figure 19: C1 Heave Validation

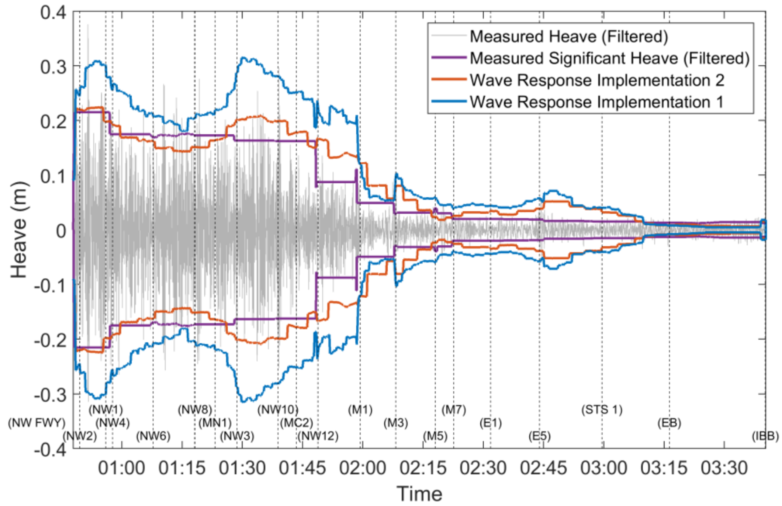

Figure 20: C2 Heave Validation

Vessel	RMS Error (m)		Mean Absolute Error (m)		Max Absolute Error (m)	
	Imp. 1	Imp. 2	Imp. 1	Imp. 2	Imp. 1	Imp. 2
B3	0.0197	0.0127	0.0148	0.0096	0.0638	0.072
C1	0.0333	0.0098	0.0244	0.0074	0.0871	0.0594
C2	0.0602	0.0262	0.0449	0.0198	0.1607	0.115
Average	0.0377	0.0162	0.0280	0.0123	0.1039	0.0821

Table 5: RMS and Mean/Max Absolute Error of Wave Induced Heave

Table 5 shows that wave response implementation 2 demonstrates close to an average decrease of 50 percent in the RMS and mean absolute errors with similar maximum absolute errors from the wave response implementation 1. This indicates that forcing NCOS with the fully directional wave spectra is recommended to most accurately represent the wave induced heave motions.

Overall, both wave response implementation 1 and 2 are capable of accurately reproducing the measured results with wave response implementation 2 providing the most accuracy.

5.2 Squat Comparison and Validation

NCOS utilizes well known empirical squat formulae Millward (Millward, 1990), Yoshimura (Ohtsu K, 2006), Barrass (Barrass, 1979) and Huuska (Huuska, 1976). Each formula is most suitable under different vessel and channel specific parameters. As a result, NCOS utilizes a combination of these squat formulae simply choosing which formula to use based on the corresponding vessel and channel specific parameters in order to provide the most accurate result while still being conservative.

The development of the combined squat implementation resulted in selection criteria for choosing between squat formulae. The best squat formula is considered to be the one which gives a value closest to the measured squat while still being conservative. Once the best squat formula for each timestep of each measured transit was found, ranges of block coefficient, vessel speed (relative to water) and water depth were assigning to each squat formula. Equations representing these ranges are displayed in **Table 6** and **Table 7**.

Selection Criteria		
Speed Interval	**Depth Interval**	**Combined Squat**
≥ 20 knts		Barras
18 knts - 20 knts	> 25m	Huuska
18 knts - 20 knts	≤ 25m	Barras
14 knts - 18 knts	≥ 17.5m	Yoshimura
14 knts - 18 knts	< 17.5m	Barras
4 knts - 14 knts		Barras
< 4 knts		Yoshimura

Table 6: Best Fitting Squat Formula Ranges for Ships with Block Coefficient < 0.75

Selection Criteria		
Speed Interval	**Depth Interval**	**Combined Squat**
≥ 12 knts		Huuska
< 12 knts	< 18 m	Huuska
11 knts - 12 knts	≥ 20 m	Huuska
< 12 knts	18 m - 20 m	Barrass
< 11 knts	20 m - 27 m	Barrass
< 11 knts	≥ 27 m	Huuska

Table 7: Best Fitting Squat Formula Ranges for Ships with Block Coefficient ≥ 0.75

Figure 21: Squat Comparison and Validation Legend

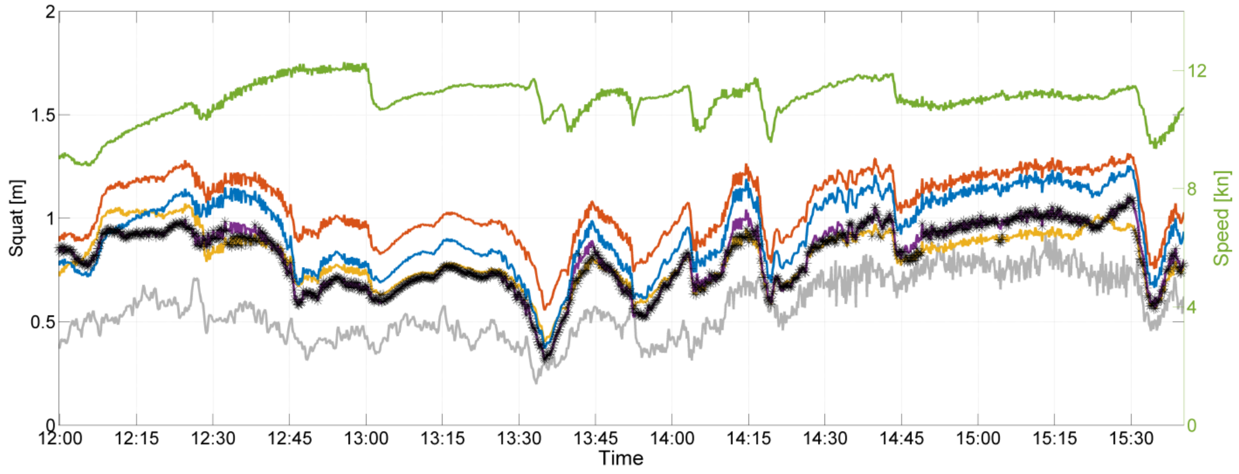

Figure 22: B2 Squat Comparison

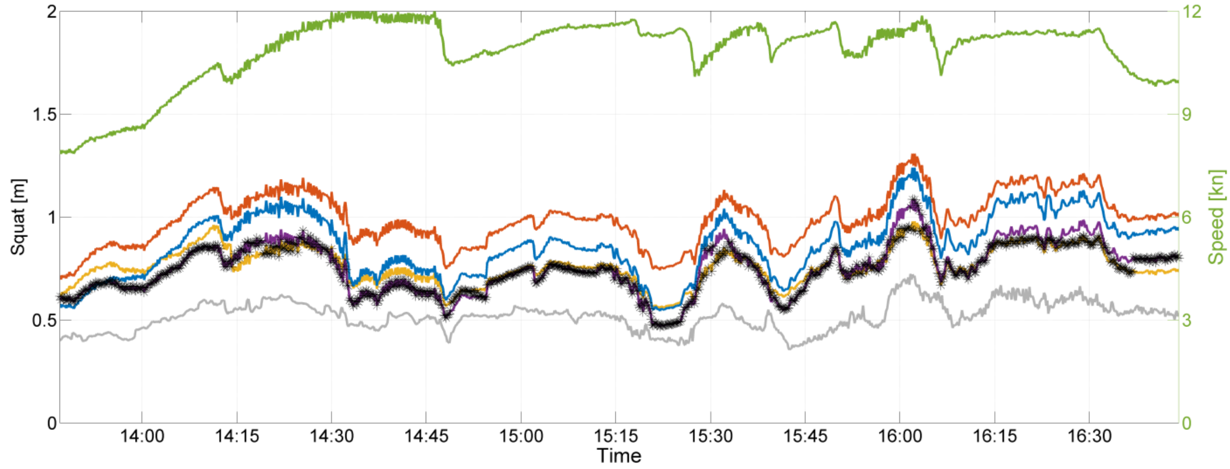

Figure 23: B3 Squat Comparison

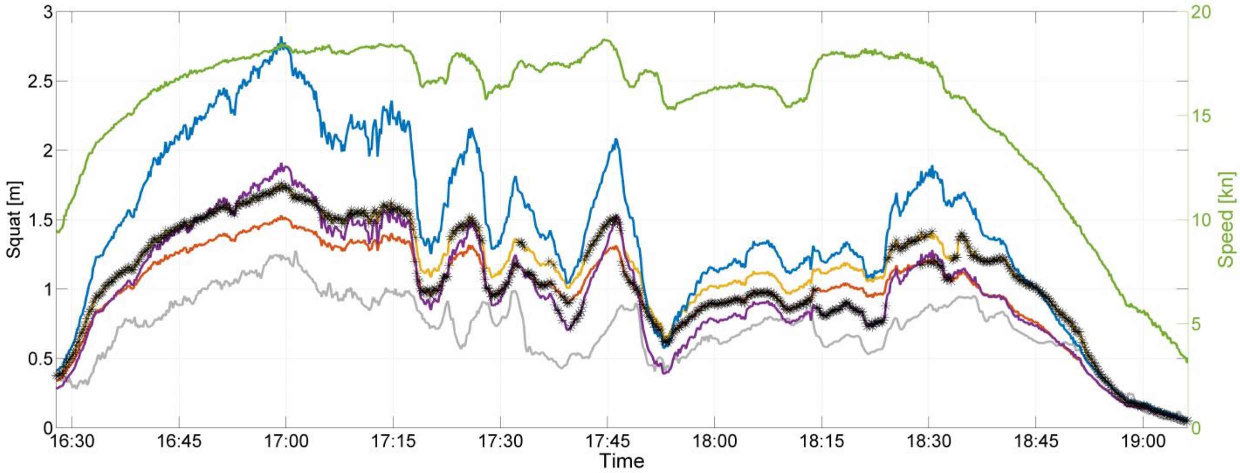

Figure 24: C1 Squat Comparison

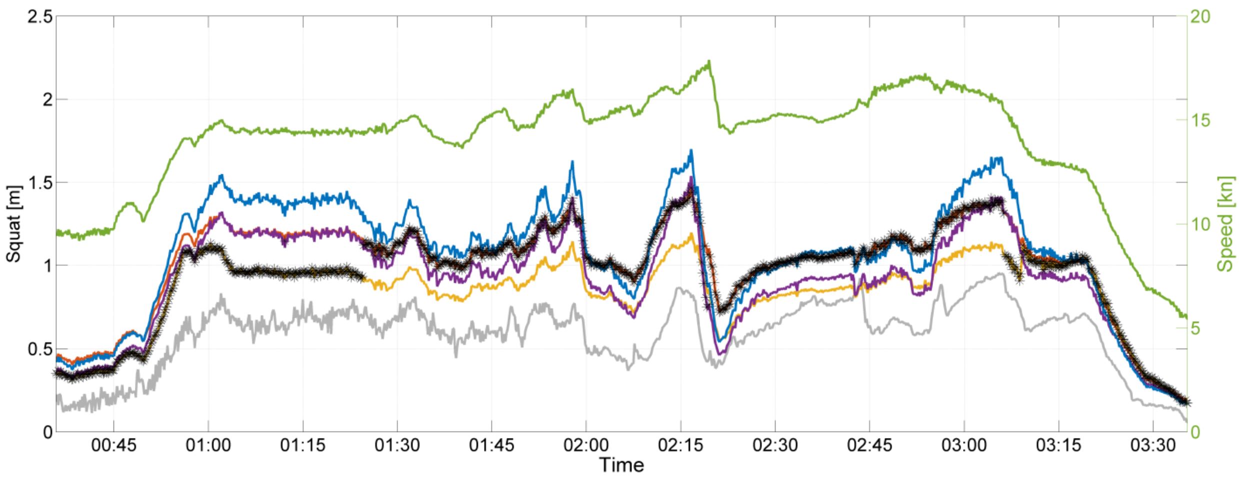

Figure 25: C2 Squat Comparison

Figure 22 to **Figure 25** show that the squat formulae behave differently for bulk carrier and container ships. Container ships are more slender and typically have block coefficient values in the range from 0.54 to 0.71, where bulk carriers typically have block coefficient values greater than 0.8 to 0.85. In general, a bulkier ships will have comparatively more squat than a more slender container ship for the same speed (PIANC, 2014). Through the Port of Brisbane container ships travel much faster than bulk carriers. As a result the various squat formulae will relate to these two vessel types differently.

Figure 22 and **Figure 23** show that the Barrass and Huuska squat formulae provide adequate results for the bulk carrier squat, while Yoshimura and Millward are more conservative. **Figure 24** and **Figure 25** show that Barrass, Huuska and Yoshimura provide adequate results for the container squat, while Millward is again more conservative.

5.3 UKC Validation

The total vertical exclusion was calculated for each transit and compared to the measurements. Wave response implementation 2 and the combined squat implementation have been applied for calculating the wave induced vessel motions and squat. In order to provide both likely and conservative results, the total vertical excursion is calculated based on two depth exceedance probabilities 1% and 75%.

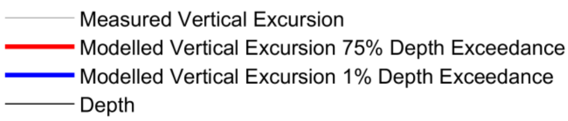

Figure 26: UKC Validation Legend

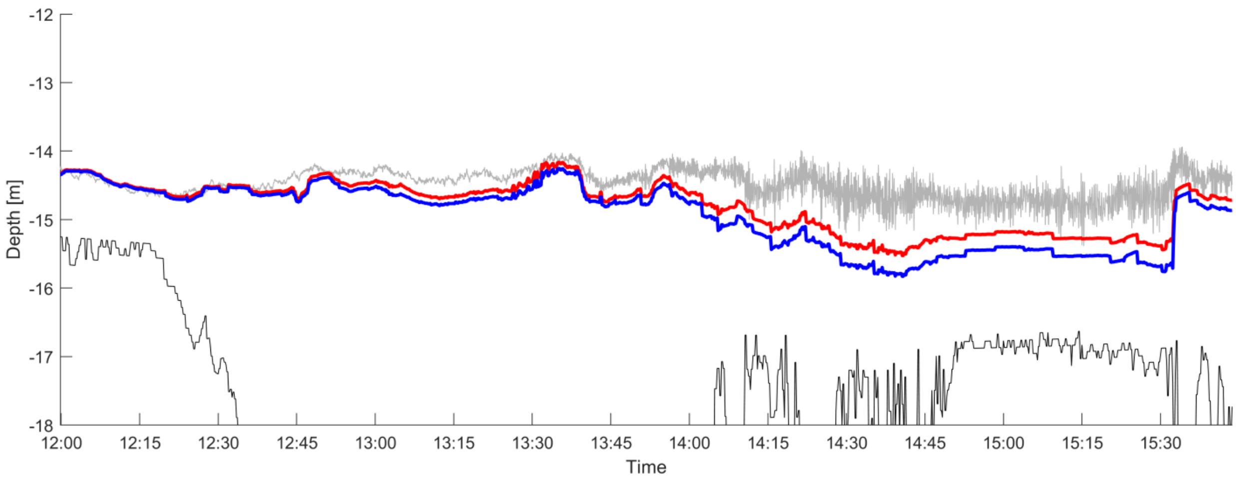

Figure 27: B2 UKC Validation

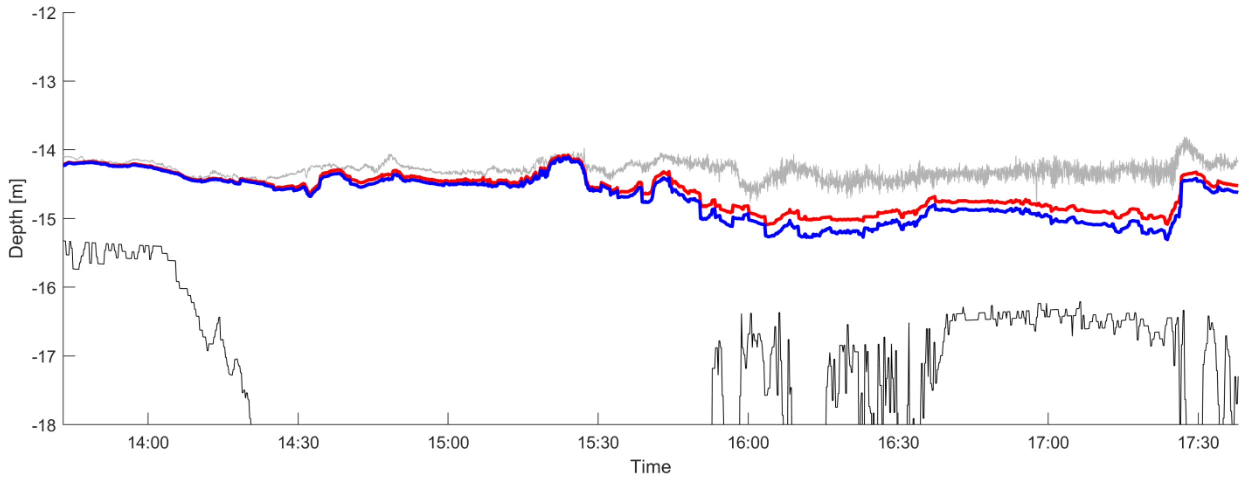

Figure 28: B3 UKC Validation

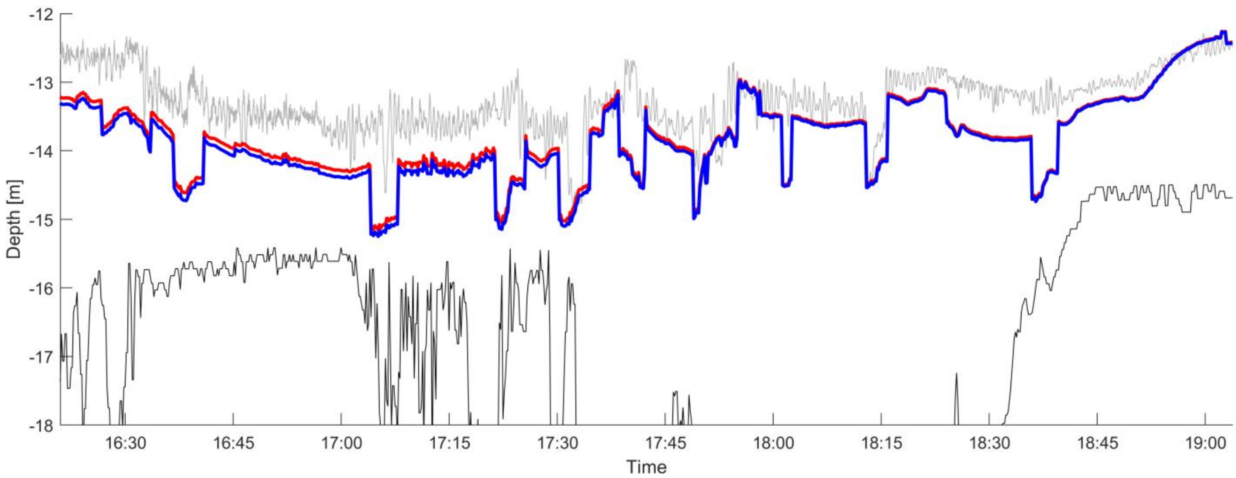

Figure 29: C1 UKC Validation

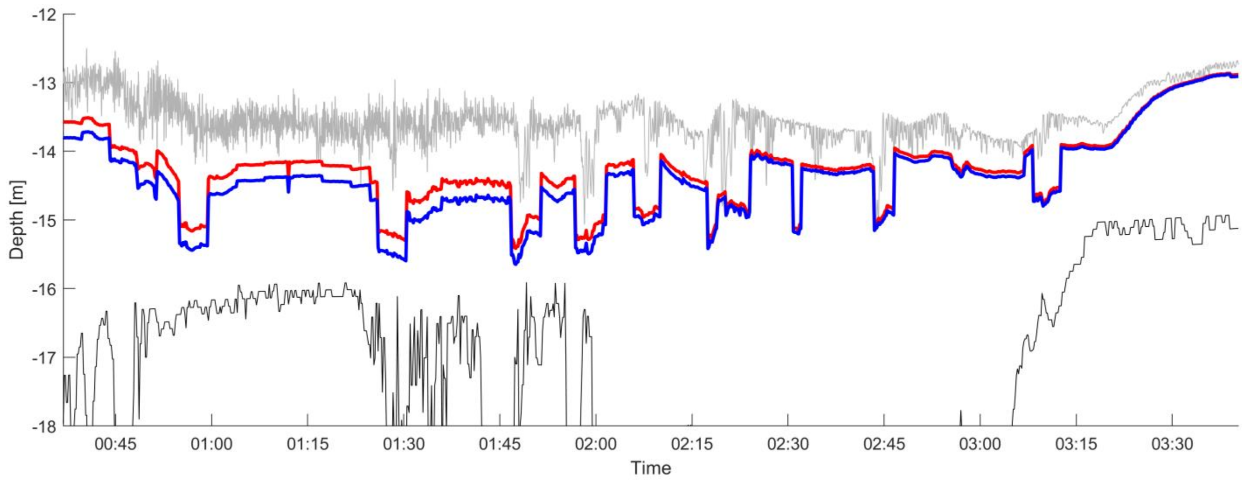

Figure 30: C2 UKC Validation

Figure 27 to **Figure 30** show that NCOS has been able to accurately reproduce the measured total vertical excursion.

6 SUMMARY

In order to validate DHI's new UKC model NCOS, model results have been compared to the measurements taken during four transits through the Port of Brisbane. The comparison includes timeseries of roll, pitch, heave, squat and total vertical excursion. Two wave response implementations have been tested which resulted in the finding that it is recommended to force NCOS with a fully directional wave spectra then with separated sea and swell integral wave components. Four empirical squat formulae have been compared. This comparison demonstrated that all squat formulas performed well with varies levels of conservatism and each formula being suitable under different vessel and channel specific parameters which resulted in the generation of a combined squat implementation which provides very accurate squat predictions while still being conservative. 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.

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