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The Development of a Vessel Under-Keel Clearance System for the Ports of South Africa

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Abstract: An Under-Keel Clearance (UKC) prediction system was developed for 6 of the major ports in South Africa. The objective of the system was to be cost-effective with minimal input requirements from the user and to integrate with the current port infrastructure to enhance decision-making. The UKC prediction system uses measured and modelled environmental data from the Integrated Ports Operation Support System (IPOSS), installed and operational at the ports. Since wave induced vertical vessel motions have a significant impact on the UKC of vessels at the South African ports, a detailed focus was placed on this environmental factor.

A numerical wave modelling study was undertaken to determine the wave climate in the navigation channels of the ports using a combination of nested spectral and Boussinesq wave models. The motion response of the sailing design vessels in waves was calculated with the 3D Panel model WAVESCAT, from which the wave induced vertical amplitude of the vessels was determined. The wave induced vertical amplitude, together with other factors as prescribed in international guidelines with respect to UKC was used to develop an algorithm to predict present and forecast UKC for ships entering and leaving each port. The wave induced vertical amplitude of selected ships were verified by full-scale and model scale measurement campaigns. The results were in good agreement.

Keywords: under-keel clearance, forecast system, ports, numerical models, measurements

Introduction

Ports are under continuous pressure to accommodate wider and deeper draught ships due to ship sizes steadily increasing. For ports to effectively deal with the changing shipping environment and to remain competitive and safe, accurate Under-Keel Clearance (UKC) predictions for ships entering and leaving ports are essential. South Africa's coastline is exposed to swell waves, and the effect of wave-induced vessel motions has a significant impact on the UKC of the vessels calling on its ports. Sufficient water depth must be available along the planned transit route to ensure a safe passage. To ensure this, accurate real-time and forecast environmental information along the route, as well as a validated method of predicting the ship's motion, are required.

Since the wave induced vertical vessel motions has a significant impact on the vessel UKC, the first step was to convert the offshore wave forecast and measured buoy wave data to locations along the critical transit route for each of the ports. A nested spectral wave model was set up for each offshore port area to compute the swell wave propagation to the nearshore port areas. The output of the spectral wave models served as input and boundary conditions for a Boussinesq wave model, which was subsequently used to compute the propagation along the entrance channel and into the port. The extent of the model domains for each port differs due to the layout and characteristics of each port. A framework of simulation runs was set up based on the offshore environmental data at the port site. These simulations were used to create an offshore wave input matrix with the corresponding output from the Boussinesq wave model. The motion response of various design vessels sailing in waves was then calculated with the 3D panel model Wavescat. The heave, roll and pitch motions were used to determine the Response Amplitude Operators (RAOs) of the vertical motions of each of the critical keel points on the vessel hull for the framework of wave conditions from the wave modelling study along various locations in the entrance channel. The keel point RAOs were used to determine the significant vertical movement of the keel points, from which the 1% exceedance vertical motion was deduced for sections along the channel. The wave-induced vertical amplitude, together with other ship-related, bottom-related and water-level factors were used to determine the minimum UKC of the vessel during transit. A large set of simulations were conducted for various vessel classes and draughts. Each offshore wave condition corresponds to a modelled vertical response of the vessel and the resulting UKC. By using an interpolation scheme, a UKC prediction was obtained for each offshore wave forecast and measured buoy wave condition.

Real-time metocean conditions in and around the eight national ports are monitored through a national port information system. This system monitors wind, waves and tides, which are displayed at each port. The environmental data from the information system are used as input to the UKC system. The UKC system displays the output of current and forecasted UKC information via the port information interface.

A range of full-scale measurement campaigns were also undertaken for the various ports for validation purposes. These measurements compared the wave-induced vertical measured ship motions to the modelled ship motions. The heave, roll and pitch motions were measured during vessel transits using three DGPS measurement units on the port, bow and starboard locations of the vessel. Physical model validations were also conducted in a hydraulics laboratory using 1:100 scale model tests. The sailing vessel motions in the physical scale model tests were measured using Inertial Measurement Units (IMU's) for a range of wave heights, directions, and periods and for different sailing speeds. Good comparisons were achieved between the validation measurements and modelled results.

A flow diagram showing the outline of the development of the UKC management system is presented in Figure 1.

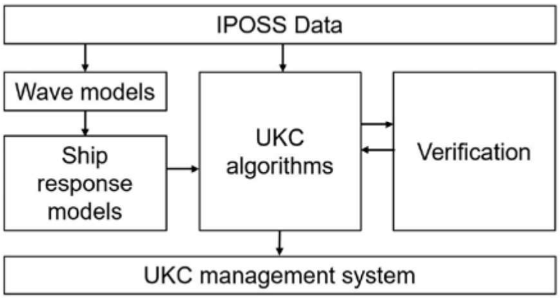

Figure 1 Flow diagram showing the outline of the development for the UKC management system.

Environmental information

Real-time metocean data is collected and recorded at eight locations around the South African Coastline, providing the ports with real-time wind, wave and ocean current data. Forecast Wavewatch III data from the National Oceanic Atmospheric Administration (NCEP) is also made available to the port operators. The data from various equipment installed at the ports is integrated into a network that displays the data in various forms at the port. All the major ports are equipped with the international standard Datawell Waverider® buoy measuring wave parameters needed for operational as well as modelling purposes.

Wave data is processed on-board the Datawell Waverider® buoy with a data output rate of 2.56Hz. Full data is availability every 30 minutes. The data is then transmitted via High Frequency (HF) to be received at a dedicated shore station where the data is recorded and disseminated using the CSIR developed Integrated Port Operational Support System (IPOSS). The IPOSS is available to the Vessel Traffic Services, Marine Pilots, Harbour Master and Port Engineers for operational decision-making purposes.

The measured wave buoy and forecast swell wave data from the IPOSS is used to feed into the detailed numerical wave models and UKC system.

Swell waves

A nested SWAN [1] model, consisting of 3 grids, was set up to compute the swell wave propagation from deep water to the nearshore area for each port. The extent of each of the grids differs depending on the characteristics of the offshore port areas. Each nested grid has a finer resolution and the ability to resolve the swell waves in more detail. The offshore SWAN grids extend to the offshore forecast wave output location, where the finest SWAN grid covers the area around the port and approach channel. The output of the SWAN model serves as input and boundary conditions for the Boussinesq Wave model.

A large framework set of SWAN model simulations was done to cover the offshore wave climate at each port. The model output of these simulations forms a framework for an interpolation scheme to transform offshore forecast wave data to the Waverider® buoy location and MIKE 21 Boussinesq Wave [2], [3] model boundaries.

The MIKE 21 Boussinesq Waves (BW) model was used for the numerical modelling of waves in further detail and wave penetration into each of the ports. An example of the Mike 21 BW output, showing water surface elevation at a particular time step, for the Port of Cape Town is presented in Figure 2.

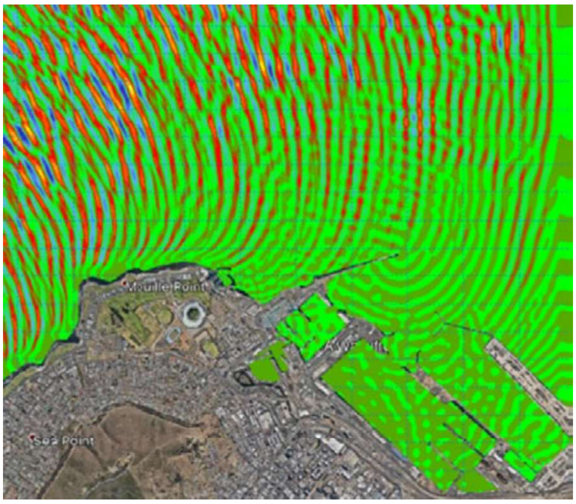

Figure 2 An example of the water level output from the Boussinesq Waves model simulation for the Port of Cape

Town showing the diffraction of waves around the main breakwater.

Mike 21 BW can simulate the combined effects of refraction, diffraction, reflection, shoaling, wave breaking, wave transmission and moving shorelines. In this study, the focus was on the first four processes. MIKE 21 BW solves the time domain formulation of the Boussinesq type equations using a flux-formulation with improved frequency dispersion characteristics.

The MIKE 21 BW outputs wave parameters at all locations along the approach channel of each port. A large framework set of Mike 21 BW simulations were done which correspond to different swell wave conditions at the Waverider® buoy. These framework runs are made up of various wave heights, peak periods, and wave directions to cover the wave climate around the port.

The framework of the SWAN and MIKE 21 BW model output is thus essentially used to transform offshore forecast swell waves and measured swell waves at the Waverider® buoy position to modelled swell waves at all locations along the approach channel. For the wave events not modelled, an interpolation scheme was applied to the framework to obtain corresponding values for each possible wave condition.

The bathymetry used for these models was based on digitised data from the South African Navy (SAN) hydrographic charts, as produced by the South African Navy Hydrographic Office, and the latest surveys.

Wave induced vertical response

The ship-related factors are the most important in vertical channel design. A more detailed analysis was carried out than provided by the PIANC concept design guidelines to obtain a more realistic and accurate wave-induced vertical vessel response.

3D panel models of the hulls were prepared for each of the design vessels for each port. The motion response of the sailing design vessels for a framework of wave conditions along the approach channel for each port was calculated with the 3D Panel model WAVESCAT. The heave, roll and pitch motions were used to determine the Response Amplitude Operators (RAOs) of the vertical motions of each of the critical keel points at various sailing speeds and channel depths. Six critical keel points on the hulls of the vessels were defined for the analyses. The critical keel points are graphically shown in Figure 3 as red dots.

Figure 3 Panel model example of a design vessel and corresponding critical keel point locations in red dots.

The keel point RAOs were used to determine the significant vertical movement of the keel points. The keel point RAOs of a 95 000 DWT Tanker sailing in a −18 m CD channel at 4 knots, are shown in Figure 4 as an example. The colour filled contours indicate the vertical response amplitude (in meters) a keel point will experience, subject to a 1 m wave with a specific encounter frequency and direction relative to the heading of the vessel.

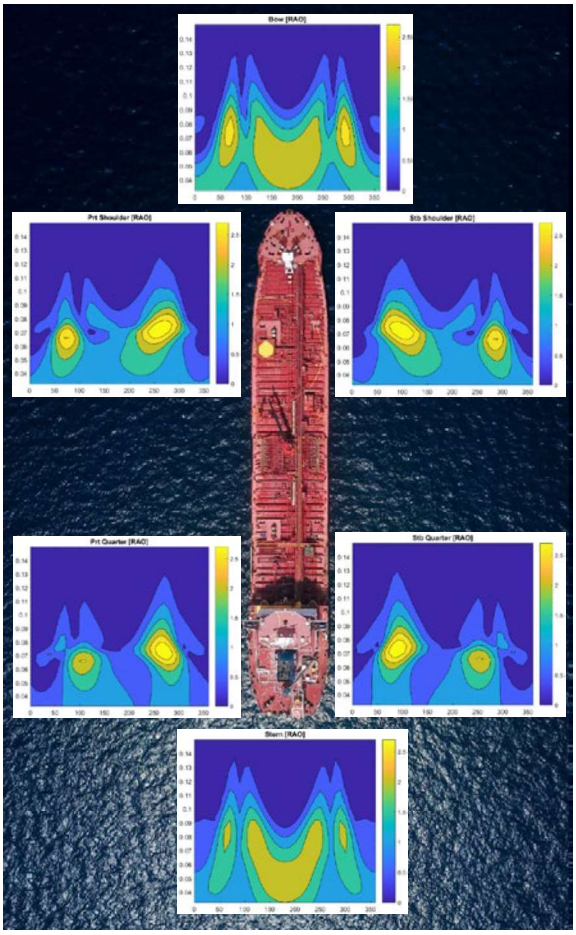

Figure 4 The keel point RAOs of a 95 000 DWT Tanker sailing in a −18 m CD channel at 4 knots.

The squat of each of the keel points was also calculated by the Wavescat 3D Panel model.

Channel depth factors

The PIANC Harbour Approach Channels Design Guidelines [4] recommend the following factors to be taken into account for determining the depth of a navigation channel. In this assessment, the channel depth refers to the "channel dredge level". Three factors must be taken into account, namely, water level factors, ship-related factors and bottom-related factors.

All water level factors are taken into consideration since measured water levels at the port area are used in the UKC system. This may include tidal offsets, storm surges, and other unfavourable conditions such as a water level depression due to the impact of local meteorological conditions (e.g. effect of high-pressure systems).

The ship-related factors, which are factors relating to the motion of the vessel have been considered. This includes dynamic factors such as the vertical response of the vessel due to wave action and squat, i.e. localised reduction of water level around the hull (squat) with increasing sailing speed, thereby reducing under-keel clearance. These factors were addressed in the preceding section. Dynamic heel due to a turning vessel and wind effects were considered by applying the equations in Section 2.4.2.2 of PIANC Harbour Approach Channels Design Guidelines using general design vessel dimensions, turn speed and 5% exceedance windspeeds as measured at each port. The dynamic heel factors will not be described in detail in this study.

A single bottom-related factor was used to account for all the bottom-related factors, based on the PIANC concept design guidelines.

Design criteria

The criteria for an entrance channel depth depend on the risk acceptable to the port, where the risk is defined as the probability of a grounding incident multiplied by the financial and environmental impact and consequence. The general criteria often used are PIANC Harbour Approach Channels Design Guidelines:

- During 25 years, the probability of a ship touching the channel bottom with possible consequent minor damage must not be more than 10%.
- The probability that a vessel touches the channel bottom during a single channel transit must always be less than 1% for all weather conditions.

The first criterion requires a more detailed analysis since it is dependent on projected traffic in the port over 25 years. For the UKC assessment, only the second criterion is considered, which is also the general approach applied in evaluating the required under-keel clearance in channel design studies.

The wave conditions from the numerical wave modelling study to determine the wave climate in the navigation channel were used to determine the probability of bottom touch of the design vessels inside the channel. Representative wave parameters were determined for the various points along the channel. The channel was divided into three sections for this assessment.

The probability of bottom touch of a single transit was calculated according to the probabilistic detailed design guidelines [4] for various channel depths. This was done for both arriving and departing design vessels.

If the wave heights follow a Rayleigh distribution and the vessel motions are small enough to accept a linear relationship between wave height and vertical ship motions, then the vertical motion of the keel points on the vessel will also be Rayleigh distributed and can be computed for low probabilities of exceedance. Due to the linear relationship, the Raleigh factor RF is given by [5], [6]

$$RF = \sqrt{\frac{lnN_0}{2}} \tag{1}$$

where N_0 is the (sufficiently large) number of waves encountered during the vessel transit or wave oscillations experienced by the ship. It then follows that the expected maximum amplitude of vertical motions A_{s-max} is given by:

$$A_{s-max} = A_s \times RF \tag{2}$$

where A_s is the largest significant vertical motion amplitude from all the critical keel points. The above computation procedure illustrates the wave response allowance for a vessel during a single transit in a channel. A probability *p* of bottom touch can further be specified for each transit. It is generally accepted that a 1 % probability of bottom touch per transit event is acceptable. In this case, the Rayleigh factor RF can be computed for a 1:100 transit event, thus a probability that is based on $100 \times N_0$. The Rayleigh factor RF will then be calculated as:

$$RF_p = \sqrt{\frac{ln\left(\frac{N_0}{p}\right)}{2}} \tag{3}$$

where $p = 0.01$. The expected maximum amplitude of vertical motions is calculated as described below.

The encounter wave periods T_e is calculated by [4]:

$$T_e = \frac{1}{f_e} = \frac{2\pi}{\omega_e} = \frac{T_z}{(1-S_{eff})} \tag{4}$$

where f_e is the encounter frequency (Hz), ω_e is the encounter circular frequency (rad/s), T_z the wave period (s) and S_{eff} the effective speed ratio calculated by:

$$S_{eff} = \frac{v_s \cos \mu}{c} \tag{5}$$

Where v_s the sailing speed (m/s), μ the wave encounter angle (degrees) relative to the ship's heading and c the wave celerity (m/s). The duration of the vessel in the channel is then determined:

$$t_s = \frac{L}{v_s} \tag{6}$$

The number of wave oscillations, N_0 , experienced by the ship is then:

$$N_0 = \frac{t_s}{T_s} \tag{7}$$

The Rayleigh factor RF can then be computed:

$$RF = \sqrt{\frac{\ln N_0}{2}} \tag{8}$$

The Rayleigh factor RF can also be computed using equation 8 for a 1 % probability exceedance:

$$RF_{1\%} = \sqrt{\frac{\ln\left(\frac{N_0}{p}\right)}{2}} \tag{9}$$

The expected maximum vertical ship amplitude $A_{s-exceed}$ is then:

$$A_{s-max} = A_s \times RF \tag{10}$$

and

$$A_{s-max-1\%} = A_s \times RF_{1\%} \tag{11}$$

The maximum vertical ship amplitude for the transit under consideration, according to the 1% exceedance criteria will be $A_{s-max-1\%}$.

Verifications

A Differential Global Positioning System (DGPS) was used in the full-scale measurement campaigns to validate the numerical models [7]. A ground-based DGPS reference station was set up in the port area and mobile DGPS receivers were positioned on the vessel.

Field engineers gained access to incoming and outgoing vessels by accompanying the port pilots when boarding a vessel. One mobile DGPS unit was then placed at deck level on the bow of the vessel while two other units were placed on the port and starboard side of the bridge wings. The DGPS measurements at each location were computed in real time by receiving Real-Time Kinematic (RTK) position corrections from the land-based DGPS reference station. The RTK corrections that were sent to the receivers resulted in measurement accuracies of between one to three cm. The sampling rate at each location on the vessel was set to 1Hz (One sample per second). Each of the data points sampled contained its own spatial coordinates (X, Y, and Z position values) as longitude, latitude, and elevation.

While on board, the vessel particulars, present loading conditions and layout drawings of the vessel were obtained. The location of each mobile DGPS receiver for a known point on the layout drawings was then measured. The loading conditions together with the mobile receiver positions were used to transform and rotate the longitude, latitude, and elevation data to be to the vessel coordinate system around the vessel's centre of gravity for each time step. The heave, roll and pitch motions of the vessel were calculated by post-processing the data in the vessel coordinate system. These motions could then be translated to vertical critical keel point motions, and directly compared to the Wavescat modelled results.

The validation exercise was done by dividing the measured vessel motions into different sections of the approach channel, where water depth, vessel speed, vessel direction and wave conditions are similar. Each of these sections could then be replicated in the Wavescat model, using the modelled wave conditions that was present during measurements. The modelled and measured significant vertical amplitude of each critical keel point is presented in Table 1 for 3 different bulk carriers measured at a defined approach channel section at the Port of Saldanha Bay.

Table 1 The modelled and measured significant vertical amplitude of each critical keel point for 3 different bulk carrier vessels at the Port of Saldanha Bay.

Significant vertical amplitude of critical keel points		
Vessel name	Indian Partnership	
Keel point	Modelled [m]	Measured [m]
Centre Fore	0.45	0.57
Starboard Shoulder	0.32	0.45
Port Shoulder	0.32	0.47
Starboard Quarter	0.44	0.37
Port Quarter	0.44	0.41
Centre Aft	0.58	0.49
Vessel name	IVS Naruo	
Keel point	Modelled [m]	Measured [m]
Centre Fore	0.51	0.59
Starboard Shoulder	0.37	0.45
Port Shoulder	0.37	0.42
Starboard Quarter	0.42	0.50
Port Quarter	0.42	0.52
Centre Aft	0.57	0.68
Vessel name	Golden Beijing	

Keel point	Modelled [m]	Measured [m]
Centre Fore	0.16	0.16
Starboard Shoulder	0.14	0.14
Port Shoulder	0.14	0.14
Starboard Quarter	0.17	0.11
Port Quarter	0.17	0.14
Centre Aft	0.19	0.14

A 1:100 scale 150 000 DWT model bulk carrier vessel with a partially laden draught of 15 m was used in this study. The ship was calibrated with weights to replicate general bulk carrier characteristics such as the Longitudinal Centre of Gravity (LCG), Vertical Centre of Gravity (VCG) and radius of gyrations. The vessel was equipped with a radio-controlled motor and rudder. The vessel motor speed can additionally be controlled by an onboard microcontroller that can be pre-programmed and adjusted by the user while the vessel heading is controlled by a radio control transmitter.

A measurement instrument was developed consisting of 3 Arduino microcontrollers, each paired with a stackable SD card shield for logging data received from a connected MPU6050 Inertial Measurement Unit (IMU). Each IMU consists of a 3-Axis accelerometer and a 3-Axis gyroscope. Analyses software was developed to process data from the measurement instrument to translate it to vertical motions.

A model scale measurement campaign was conducted for various swell wave conditions and two vessel speeds. These measurements were then analysed and compared with computational results using the 3D panel model Wavescat. Waves were generated using multi-element wave generators. The wave generators comprise a rack and pinion paddle system and waves are generated by synchronised pulsating movements of the individual paddles. The wavemaker setup for this study comprised a wave bank of 24 m. Vessel motion measurements were conducted over a 24 m distance. This included waves encountering the sailing vessel at an angle of 45° (shouldering waves), 90° (beam on waves) and 225° (quartering waves) and a steady speed of 5 knots and 10 knots for various irregular wave conditions.

The measured and modelled maximum vertical amplitude for the model scale vessel travelling at 10 knots for various irregular wave conditions from a shouldering direction are presented in Figure 6.

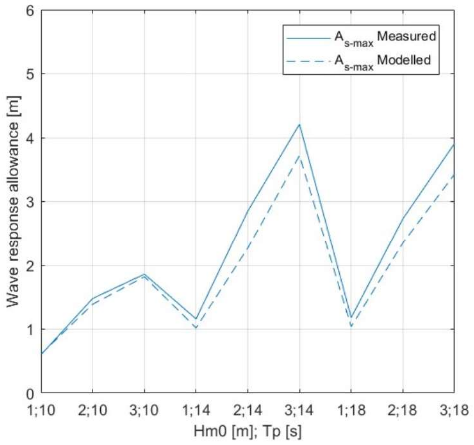

Figure 5 The measured and modelled maximum vertical amplitude for the model scale vessel travelling at 10 knots for various irregular wave conditions encountering the vessel from a shouldering direction.

Results

The predicted minimum UKC for each section for the design vessel under consideration is then calculated by:

$$UKC_{1\%} = Channel_{dredge} + WL - squat - A_{s-max-1\%} - DH - BF \qquad (12)$$

where $Channel_{dredge}$ is the dredged channel depth, WL is the measured water level, DH is the dynamic heel and BF is the bottom related factor. The maximum vertical keel point amplitude for each section was determined using the largest occurring vertical amplitude for the wave conditions along the defined section. The number of encountered waves was based on the total length of all sections to comply with the 1% probability transit criteria, this approach is however considered conservative. The critical approach channel sections for the Port of Richards Bay are presented in Figure 6.

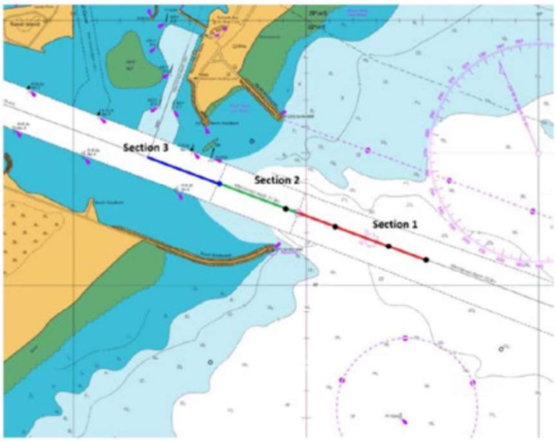

Figure 6 The critical approach channel sections for the Port of Richards Bay.

The predicted minimum UKC for each critical section in red, green, and blue is presented in Figure 7, where the solid line prediction is based on measured wave and water levels, and the dotted line forecast wave and water levels.

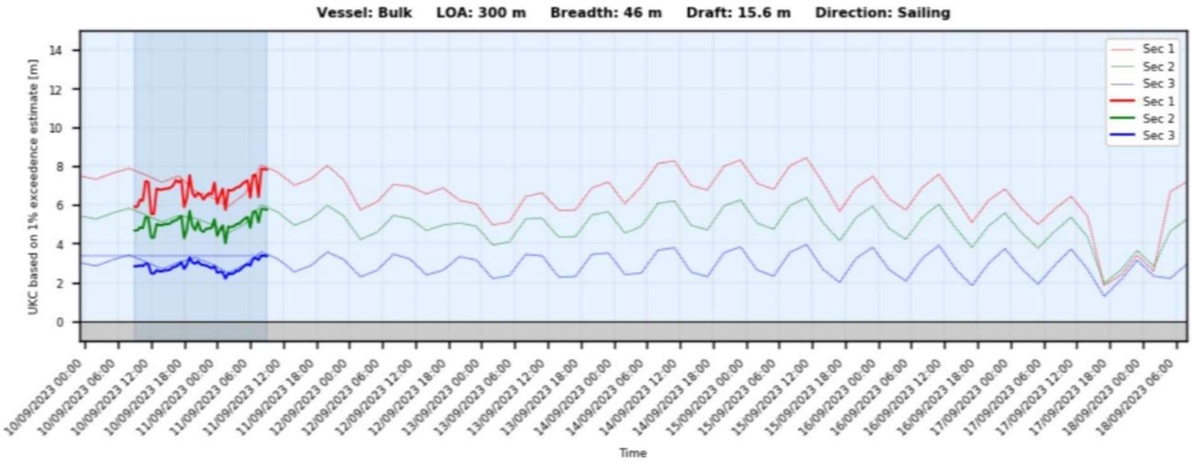

Figure 7 The predicted minimum UKC for each critical section in red, green, and blue.

The minimum UKC for the present time is also presented by a visual ship, as shown in Figure 8. This is based on the present measured wave and water level measurements. If any of the real-time measurement instruments are offline, this prediction is based on forecast data. The visual representations in Figure 6, Figure 7 and Figure 8 are displayed to the port via the IPOSS. The port operators have the option to change the design vessel size, type and draught, and the minimum UKC predictions will change accordingly.

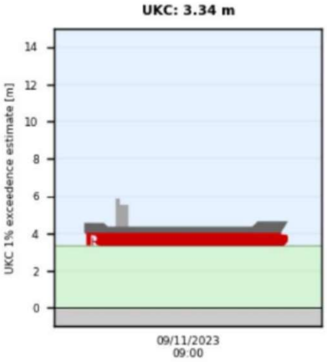

Figure 8 Visual representation of the predicted minimum UKC for the present conditions based on the 1% exceedance criteria.

Discussion and Conclusion

An Under-Keel Clearance (UKC) prediction system was successfully developed and implemented at 6 of the major ports of South Africa. The system was able to integrate with the existing port infrastructure, utilising the available measured metocean and forecast data without the need for major port infrastructure or system updates. The proposed system required a delicate balance between cost, accuracy, and operational ease, which require minimal input from the user. Due to these reasons, various simplifications were implemented and are discussed below.

Only a limited number of design vessels for each port was modelled, where focus was placed on the deep draught design vessels expected at each of the ports. The vessel library for each port can however be expanded should the need arise. Vessel speeds were based on analyses of measured ship data for each of the critical channel sections and can't be varied. The UKC predictions are thus based on normal operational ship speeds. Provision for the effect of dynamic heel due to turning and wind is based on a calculated constant factor for each design vessel based on the port layout, ship characteristics and wind speeds at the port. The UKC prediction is also based on the nominal dredge level and does not consider any changes in channel depth due to siltation.

The expected maximum amplitude of vertical motions of the vessel were calculated for numerous wave conditions along the approach channel. The wave conditions in each channel section, resulting in the largest vertical response amplitude were used to represent the wave condition in that section. The duration of the vessel in each section is then determined using equation 6, where the length of the entire approach channel is used, and not only the length of each section. The maximum vertical ship amplitude for the transit under consideration for each section is then calculated by equation 11. This approach was followed to not exceed the 1% probability criteria for the entire channel. Due to this, the predicted minimum UKC for each section is slightly conservative. To improve on this, a probability of bottom touch can be predicted per position in the channel where the probability of bottom touch can then be calculated by summing all probabilities of each position along the entire approach channel. This approach will result in a probability of bottom touch prediction, where the approach currently applied results in an expected minimum UKC prediction. It has however been found that the differences between these two approaches are small, over the short lengths of the critical approach channels where the UKC system has been implemented.

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