Under-Keel Clearance at the Columbia River Bar

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Abstract
The Columbia River Bar (USA) is one of the most dangerous and challenging navigated stretches of water in the world. However, successful passage grants access to several inland ports and waterways through which transportation between the US Pacific Northwest and the world averages 40 million tons of cargo valued at $20 billion each year.

During 2011 and 2012 OMC International performed under-keel clearance (UKC) modelling and detailed validation studies for the Columbia River Bar Pilots including measurement and analysis of the motion of 24 vessels crossing the Columbia River Bar in moderate to high seas. Measurements and detailed UKC modelling reveal that UKC needs to be carefully managed on the Columbia River Bar. Conditions under which touch bottom events might occur vary greatly with vessel class and transit direction and that no clear "rules of thumb" can be established to ensure risky transits are avoided. A web-based demonstration DUKC® system has been used by the Columbia River Bar Pilots to analyse the UKC of more than 130 deep-draft transits.

Keywords: Columbia River Bar, under-keel clearance, risk assessment, ship motion measurement, ship motion modelling.

1. Introduction

The Columbia River Bar, where the outflow of North America's 3rd largest river meets the high-energy ocean swells of the North East Pacific has long been regarded as a dangerous, but vital, waterway. Since discovery and exploration by Europeans in the early 19th century the 100 mile (160 km) stretch of river to the city of Portland has been developed into a maintained shipping channel along which more than $18 billion in goods now flow each year.

Upstream of Portland a further 360 miles (580 km) of maintained navigation channel (14 feet (4.3m) deep) provides navigation by barge all the way to Lewiston Idaho through a series of 8 dams and locks which provide an elevation gain of more than 700 feet (220m) (Figure 1). This waterway is the third largest grain export gateway in the world and the US West Coast's second largest automobile import gateway. All import and export goods shipped along this important waterway must cross the Columbia River Bar to reach the Pacific Ocean.

Between 2006 and 2010 the 105 mile navigation channel between Astoria and Portland was dredged to increase the maximum allowable draft of vessels calling at the Lower Columbia River ports from 40 to 43 feet (12.2 to 13.1 metres). The depth of the Columbia River Bar remained unchanged and is maintained at a depth of 55 feet (16.8 metres). At times of high swells the vertical motion of large commercial vessels crossing the Columbia River Bar can be significant and under-keel clearance on the Bar may become critical.

Vessel motions and under-keel clearance on the Columbia River Bar has been previously investigated. From 1978 to 1980 a major measurement campaign was performed by Tetra Tech [1] in an effort to establish vessel wave response. This study was a remarkable effort considering the cumbersome equipment (200 kg) available at that time to measure and record each ship's motion. 53 ships were measured crossing the Bar over a 2 year period. Downward wave response ranged up to 22 feet (6.7m) in swells up to 15-20 feet (4.5-6m) in height. However, results of this study are not directly relevant to present-day shipping as the vessel fleet crossing the Bar has changed significantly in the last 30 years.

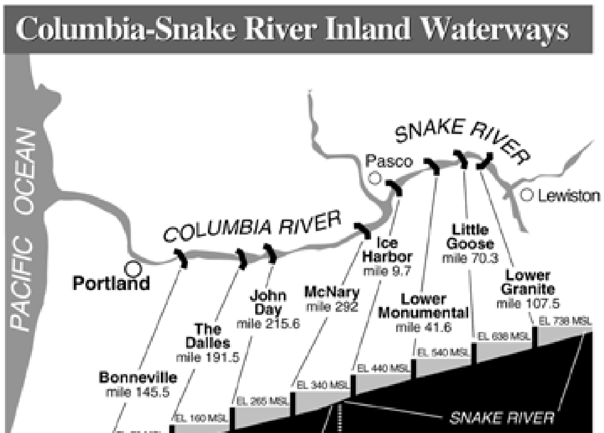

Figure 1 The extensive Columbia-Snake River Inland Waterways showing major dams and lake elevations (Source: Pacific Northwest Waterways Association).

More recently, as part of the engineering associated with the river deepening project, the depth of the Columbia River Bar was assessed. Although several puzzling inconsistencies were found in previous studies the Bar depth was left unchanged at 55 feet.
In 2011 the Columbia River Bar Pilots (CRBP) obtained funding from the Oregon Department of Transportation Connect Oregon III grant programme for the purposes of enhancing navigational safety over the Columbia River Bar. The CRBP's grant included 80% of the funding required to deploy 2 new wave buoys, perform a study to analyse under-keel clearance (UKC) of a modern vessel fleet over the Bar and provide a demonstration computer-based Dynamic Under-keel Clearance (DUKC®) system for evaluation by the CRBP.

The wave buoys were deployed and are now maintained by Scripps Institute of Oceanography. One buoy (NDBC station 46248 – Astoria Canyon) is located 25 miles offshore in approximately 200 m water depth. The other (NDBC station 46243 – Clatsop Spit) is located 2.5 miles from the tip of the southern breakwater in approximately 25 m water depth. The Clatsop Spit buoy was located as close to the Columbia River Bar as possible within the constraints of keeping the buoy clear of the shipping to avoid having it run down and sheltered from the main ebb current jet to avoid having the buoy submerged by currents which routinely exceed 4 knots.

The UKC study, performed by Melbourne-based OMC International and reported in this paper, aimed to determine the risk profile of a representative modern fleet of vessels, thoroughly validate the numerical models used in the study, and establish the same, validated, numerical models in a real-time web based system for use by the CRBP to predict and manage the grounding risk experienced by vessels crossing the Columbia River Bar.

2. Approach

The Columbia River Bar UKC Study was performed in 5 distinct stages, as follows:

2.1 Configuration of under-keel clearance modelling

In order to perform under-keel clearance modelling, environmental models of waves, tidal levels, tidal currents, water density and ship motion models are required.

For the UKC Desk Study two full years of environmental conditions were obtained by utilising an existing, calibrated, combined Delft3D/SWAN numerical model of the Columbia River Estuary [2]. This model was run using forcing/boundary conditions measured at the NOAA Columbia River Bar Buoy (46029) and USGS river discharge data recorded at the Beaver Army Terminal near Quincy, OR (14246900). A series of output points were placed in the wave and hydrodynamic models in order to obtain the required output data along the channel centreline (Figure 2). Model outputs were validated against available data.
Wave-current interaction is a critical process as currents stronger than 2 knots can significantly alter the amplitude, direction, and wavelength of ocean swells and therefore critically affect the impact of these swells on vessel motion. Unfortunately, wave-current interaction at the mouth of the Columbia River is still imperfectly understood [2],[3]. The Delft3D model was selected because of its ability to link the wave and current models in an attempt to model these effects however the model is known to suffer limitations when waves meet strong opposing (ebb) currents [2].

For the live DUKC® system, where predictive calculations of UKC are required the tidal hydrodynamic predictions are obtained from the Port of Portland "Loadmax" river level forecast system [4] and the NOAA Columbia River Estuary Operational Forecast System (CREOFS) [5]. Operational wave forecasts are not available for the Columbia River Bar. For the demonstration DUKC® system the waves used in the ship motion predictions were derived by using the latest wave spectrum measured at the Clatsop Spit wave buoy transformed by algorithms derived from the Delft3D/SWAN modelling to account for spatial variations in the waves along the shipping channel expected at the appropriate stage of the tidal cycle.

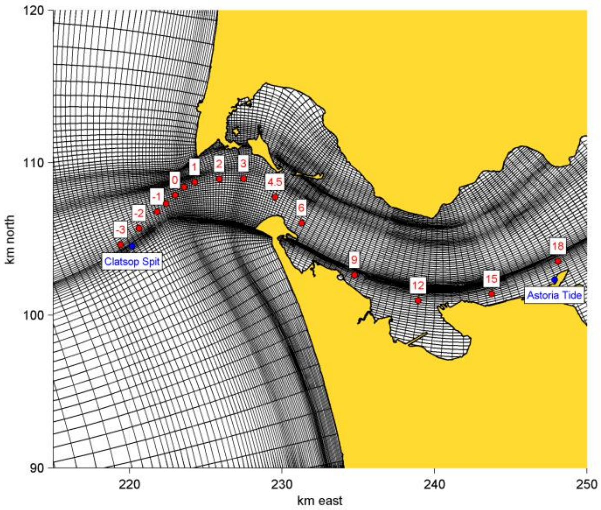

Figure 2 A portion of the Delft3D model grid showing output station locations (red) and wave and tide instrument locations (blue).

Ship motions are modelled using OMC International's DUKC® system [6] which was configured to compute under-keel clearance components such as squat, wave response, heel, and draft adjustment due to water density changes every ¼ mile (400 m) along the shipping channel from 3 miles offshore of the Columbia River Bar to approximately 20 miles up the river near the town of Astoria (Figure 3) where the Columbia River Bar Pilots hand over pilotage of vessels to the Columbia River Pilots.

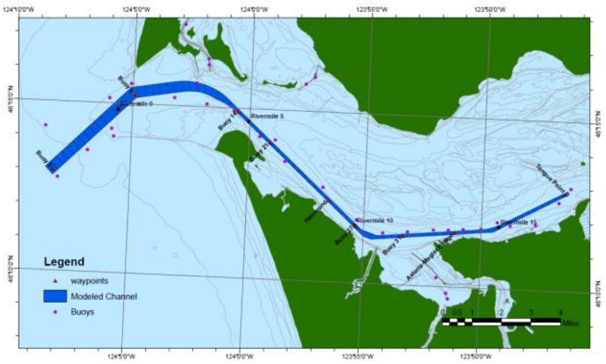

Figure 3 Arrangement of the DUKC® calculation locations for the Columbia River Bar. Calculation locations are arranged every ¼ mile (400 m) along the deep-draft shipping channel. This layout provides sufficient resolution to capture spatial variation in ship keel elevation while keeping computational effort to a manageable level.

Analysis of the resulting under-keel clearance results was separated into two distinct regions: the Bar (River Mile (RM) -3 to RM 3) where vessel wave response may play a significant role in under-keel clearance and the River (RM 3 to RM 17.5) where under-keel clearance is predominantly determined by tidal water levels and vessel squat.

2.2 UKC Desk Study

The UKC Desk Study was performed by selecting a representative fleet of 10 vessels and transit directions and simulating that each of these vessels sailed over the Columbia River Bar each hour for the 2 year period 1 April 2009 to 31 March 2011. Times during this period where the Bar had been declared closed to shipping (approximately 3% of the time) were excluded from the analysis. This resulted in a simulation database of approximately 170,000 hypothetical vessel transits across the Bar.

Each transit was then evaluated against the CRBP's "Three foot rule" which is intended to ensure that all vessels maintain a 3 foot (0.9m) gross UKC clearance in the River section (RM 3 to 17.5) of the transit. Transits that did not satisfy the three foot rule were excluded from further consideration.

The remaining transits were classified as either "fair", "risky", or "hazardous" depending on the assessed probability of the transit experiencing a bottom-touch event over the Bar. Results were then aggregated and patterns were analysed by ship type for factors such as tidal stage at time of sailing, offshore wave conditions that contributed to risky or hazardous transits. A limited sensitivity analysis was also performed.

2.3 Summer validation measurements

During July to August 2011 OMC performed full-scale measurement and analysis on 6 vessels transiting over the Columbia River Bar. Measurements were performed using high-precision Trimble GNSS (GPS) receivers located on the bow and both bridge wings of each target vessel. The pilot launch was also equipped with high-precision GPS and acted as a "chase boat" which escorted each vessel over the Bar. This allowed accurate measurement of the water surface elevation along the time/space trajectory followed by the vessel. GPS data recorded were post-processed against data from an on-shore base station. This method of GPS data processing results in absolute processed positions with sub-decimetre accuracy. A limited number of conductivity, temperature and depth (CTD) measurements were also performed from the pilot chase boat around the time of each transit.

Processed GPS data and knowledge of the on-board location of the GPS units relative to the ship's hull were then analysed to extract detailed series of ship motion and under-keel clearance. These data could then be used to validate the DUKC® model predictions for tide level, squat, heel, wave response, and draft adjustment due to density change.

2.4 Winter validation measurements

Due to the strong seasonality of conditions at the Columbia River Bar, wave response recorded during the summer validation measurements was expected to be minimal. However, during winter when wave response was expected to be more significant, the prevailing conditions meant that performing ship motion measurements using traditional GPS instruments was not feasible or safe.

Figure 4 A bulk carrier outbound over the Columbia River Bar. Deployment and retrieval of GPS equipment on deck is not practical under such conditions. To capture such conditions an alternative ship motion measurement approach is required. Photo courtesy of Columbia River Bar Pilots.

In order to circumvent this problem OMC developed and tested the new "iHeave" device which is more thoroughly described in a companion paper at this conference [7]. The iHeave is a simple, compact, but highly accurate motion sensor which can be set up and activated by a marine pilot on the bridge of a ship within a minute or two. The iHeave device was used by the CRBP between November 2011 and March 2012) to accurately measure short period vessel motions (primarily wave response) on board 24 vessels transiting the Columbia River Bar. Data recorded by the iHeave were sent back to OMC for detailed processing and analysis. The processed iHeave ship motion data were compared with corresponding DUKC® simulation results prepared for each measured transit.

2.5 Live demonstration DUKC® system

Following the successful completion of the winter validation measurements a web-based demonstration DUKC® system was established (Figure 5). To provide reliable and high-quality service to the Columbia River Bar Pilots the demonstration DUKC® system was hosted on the Microsoft Azure Cloud. Access to the DUKC® system is limited to registered Columbia River Bar Pilots who can use the system to plan upcoming transits and monitor the calculated UKC of transits currently underway.

Figure 5 Example output of the demonstration DUKC® system showing a profile of UKC-related information for a particular transit of a specific ship. Black indicates sea bed, light grey is ship's draft and dark grey is dynamic motions allowance. Pale blue indicates predicted UKC.

Data inputs to the system consist of ship principal particulars, loading and stability parameters, live ship speed and position data from AIS, river level forecasts issued daily by the Port of Portland Loadmax system, and Bar water level, current, and density forecasts issued twice daily by the NOAA CREOFS model. Live environmental data are also used and made available on the website from local tide gauges and wave buoys. Default ship stability parameters representative of each vessel class were able to be selected by the user in case actual stability parameters were not available for a particular transit.

3. Results

3.1 UKC Study

Key results of the UKC Study include:

1. Confirmation of a significant level of risk to be managed (2.0% risky transits and 0.5% hazardous transits over all transits analysed) in the absence of pilot judgement.
2. Clarification that transit risk varies significantly between the different vessel classes with deeper (larger) ships not necessarily presenting the greatest risk as shorter (and slightly shallower) ships tend to resonate more with the prevailing swells experienced at the Columbia River Bar.
3. Confirmation that wave response of vessels crossing the CRB is the greatest contributor to risky and hazardous transits,with heave and pitch motions dominating the large-amplitude wave response.
4. Hazardous transits were identified with a minimum offshore wave height of 8 feet (2.4m), but more typically occur when the offshore wave height is above 13 feet (4.0m). However there is not a simple relationship between offshore wave height and transit risk
5. Hazardous transits tend to be associated with to the following conditions:
   - Downward wave response greater than 18 feet (5.5 m)
   - Offshore swell periods between 12 to 20 seconds
   - Swells coming from the SW through to the NW
   - Low water and peak ebb tide over the CRB.
6. The critical region for UKC is the shallow region of the channel, over the Bar, between RM -2 and RM 2 with the majority of transits controlled at RM 0

3.2 Summer validation measurements

DUKC tide plane predictions compared very well with chase boat measurements, with a maximum error of approximately 1 foot (0.3 m) over the Columbia River Bar.

The DUKC® density predictions are within the range of density measurements taken before and after each transit.

Measured squat is generally well represented by the DUKC® squat model, which is typically conservative by less than 1 foot (0.3 m). An exception to this is that squat of container vessels over the CRB is over-predicted by approximately 1.5 feet (0.5 m).

Measured heel of bulk carriers is negligible (less than 0.4 feet, (0.1 m)) and the pattern is only vaguely represented by the DUKC® inertial heel model. Measured heel of container vessels is small, up to 1.5 feet (0.5 m). The DUKC® inertial heel model makes a reasonable first approximation to the pattern and amplitude of the observed heel.

During the summer campaign measured wave response never exceeded 4.5 feet (1.4 m), which is very low in comparison to what is expected in the winter campaign. The large amplitude wave response expected from the winter campaign will produce more relevant data to validate the DUKC® wave response model.

3.3 Winter validation measurements

The winter iHeave ship motion measurement results indicate the following:

1. Maximum downwards wave response ranged from 4.8 feet (1.5 meters) to 17.1 feet (5.2 meters), with values in the range of 10-15 feet (3.0-4.5 meters) being fairly typical.
2. Roll was not a critical wave response component for determining minimum UKC over the CRB for the 24 deep draft transits measured.
3. Inbound vessels have significantly longer period heave and pitch motions than outbound vessels due to the effect of following waves.
4. Roll period is unaffected by transit direction but is dependent on vessel class and load condition.
5. Of the 24 vessels measured during the winter campaign, 4 are assessed as having a significant level of risk (with "measured" minimum keel elevation within 3 feet of the design 55 foot channel depth
6. UKC was not a concern for any of the 4 inbound vessels measured. This is primarily because inbound vessels are timed to cross the CRB near high water.
7. The majority of "risky" transits occurred near low water at the CRB. All "risky" transits occurred at times when the modelled water level at the CRB was predicted to be 2 to 3 feet lower than the level measured at the Astoria tide gage at the time. This gradient in the tide plane should be confirmed by further water level measurements on the Columbia River Bar.
8. Two of the four "risky" transits were container vessels travelling at high speed over the CRB. Reducing speed could increase the UKC of these vessels by reducing squat however the consequent impact on wave response would also need to be considered investigated.
9. Waves and therefore wave response at the CRB are extremely complex to predict. The DUKC® wave response calculations are state-of-the-art, but are far from perfect. Many of the measured transits are very well predicted, but a few contain significant errors.
10. Adjusting the vessel heading to account for possible crabbing (set) effects has a significant effect on the predicted vessel wave response for many vessels. This implies that uncertainty in vessel heading and wave angle are likely to be significant contributors to the uncertainty in predicted UKC.
11. In this complex environment an uncertainty allowance of 6 feet on top of the DUKC® prediction of best estimate wave response is required to ensure DUKC® results during significant events are conservative.

3.4 Live demonstration DUKC® system

The Columbia River Bar Pilots have used the demonstration DUKC® system over the winter of 2012-2013 to plan more than 130 transits and successfully monitored the computed UKC of 70 of those transits across the CRB. Transit planning allows a pilot to predetermine, up to 24 hours in advance, a suitable sailing time and speed to pass both the Bar and River sections of the transit with sufficient UKC. Transit monitoring takes the actual time and speed data from the ship transit and computes what UKC would have existed, according to the validated DUKC® models and actual measured wave and tide data.

An example transit planning screen is shown in Figure 6.

Figure 6 Example planning output of the demonstration DUKC® system for the Columbia River Bar showing 24 hour scans of predicted UKC over both the Bar and River sections of the transit for a particular ship. Red, orange and green indicate times of high, medium and low risk of grounding respectively.

The large, 6 foot (1.8 m), uncertainty in the wave response predictions means that an undesirably high proportion of the transits cannot be classified as either safe or hazardous with a high level of confidence. This requires pilots to continue to exercise judgement in the many uncertain cases.

Pilots report that the DUKC® tidal window predictions in the River section of the transit approximately correspond to traditional pilot calculations.

The DUKC® website provides a visual tool which the Columbia River Bar Pilots have used to analyse safer sailing times and determine hazardous time windows when vessels should not sail. Use of the DUKC® website has also improved pilots understanding of both tidal slope and wave response in regards to UKC.

4. Discussion and Conclusions

The Columbia River Bar presents an extreme test of our ability to model and predict coastal processes such as waves and currents. However several skilled local organisations are working on operational environmental models and these efforts should be encouraged.

The UKC Study reported here confirms the results of earlier studies and reveals the complexity of ship/wave/tide/current interaction at the Columba River Bar. The UKC Study predicts that significant UKC risk exists for certain vessel classes and requires careful management

Summer validation measurements confirm the accuracy of the DUKC® tide, current and squat models established during this study.

Winter validation measurements indicate that in 4 of the 24 transits measured the keel of the ship went within 3 feet (0.9 m) of the design channel depth. This confirms the importance of UKC management over the Bar.

Winter validation measurements also emphasise the complexity of modelling vessel wave response in such a dynamic environment – especially when the waves themselves are poorly modelled at the Bar.

Despite the undesirable uncertainty in wave response predictions, the demonstration DUKC® system was found to be a useful tool by the Columbia River Bar pilots in operation over 2012/13 winter. The pilots used the system to analyse the UKC of more than 130 deep-draft transits and improved their understanding of the associated UKC issues.

Results highlight the need to consider the CRB as one of several controlling “gates” for a successful transit up or down the river.

The following further work is indicated:

a) Further measurements to confirm the tidal slopes and vertical survey datum at the Bar, identified as critical in this study.
b) Improved wave modelling and forecasting at the Columbia River Bar.
c) Improved vessel wave response modelling under the complex wave/current conditions experienced at the Bar.
d) Detailed and integrated consideration of departure strategies for deep draft vessels departing ports on the Columbia River in order to ensure that UKC criteria are met at ALL gate locations on the lower Columbia River and Bar.

5. Acknowledgements

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