SQUAT MODELLING FOR OPERATIONAL UNDERKEEL CLEARANCE SYSTEMS

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1 INTRODUCTION

OMC International is the sole provider of Dynamic Underkeel Clearance (DUKC®) systems. OMC's systems predict and manage underkeel clearance for vessels travelling along depth restricted waterways. These systems have now advanced to a level where users, such as pilots and VTS officers, can monitor the vessel progress and underkeel clearance (UKC) in real-time and assess how changes in vessel speed can optimise vessel squat and trim.

This paper describes the how squat predictions are used in operational conditions and how real-time speed control is used to optimise vessel squat and trim for underkeel clearance purposes. Three case studies of operational systems are presented.

2 SQUAT MODELLING IN OPERATIONS

In OMC's experience, for the operational management of underkeel clearance, the prediction of squat requires a model, or collection of models, that are sufficiently fast, accurate, reliable, repeatable and conservative:

1. *Fast calculations.* In an operational scenario, computationally expensive and time consuming calculations are not feasible. Squat needs to be evaluated for an entire approach channel within seconds to minutes. This is particularly the case for real-time scenarios which need access to up-to-date squat predictions based on the latest information available.

2. *Accurate.* A squat estimate only needs to be as accurate as the situation demands. From a UKC management point of view, there is little point in 'perfecting' a particular squat prediction if errors or unknowns in other components of the UKC prediction are one or more orders of magnitude larger than the error in the squat prediction. For example, in swell conditions, wave-induced vessel motions can dominate and can reduce the UKC by an order of magnitude more than the reduction due to squat. In such conditions a less computationally expensive squat estimation may be adequate. Similarly, at locations where underkeel clearance does not control a proposed transit (in a naturally deep section of channel for instance), it may be sufficient to adopt a conservative, yet computationally inexpensive, squat estimate to speed up calculations without affecting sailing windows. However, at all times, knowledge of the magnitude of the error in the squat estimate is vital. For an operational squat model to provide benefits to users, the error distribution of the model or collection of models should be narrow and not be subject to extremes or outliers.

3. *Conservative*. The final UKC estimate produced by an operational UKC system needs to be sufficiently conservative. As part of the total UKC calculation, the squat estimate should be based on a deterministic prediction with an allowance for uncertainty based on the known error distribution and the conservatism level desired.

4. *Repeatable*. Squat predictions need to be auditable and traceable. If an investigation into a particular event is required, the model needs to be able to reproduce the exact same prediction if identical inputs are given.

5. *Reliable/stable*. The behaviour and outcome of a squat model to any combination of inputs needs to be known prior to going operational. Minor changes in inputs should not give wildly different squat values. It should also not be the case that a particular combination of inputs results in an unexpected underestimation of the actual vessel squat and in a potential breach of underkeel clearance and navigational safety.

6. *Flexible*. Existing squat formulae are generally simple but are known to be applicable under limited conditions and a limited range of inputs. A squat model or a collection models used in operational needs to be sufficiently flexible such that is covers the full range of possible conditions encountered in operations. This includes a large variety in vessel types, sizes, hull shapes, load states, engine commands, channel and met-ocean conditions are experienced.

A decision based squat model (See Figure **Error! No text of specified style in document.**-1), which incorporates many different sub-models and manages risk, is suitable for an operational UKC management system. Sub models can be as simple as a particular squat formula or can include more advanced computations depending on the scenario under consideration. Based on the inputs provided to it, the decision model selects which sub-model to adopt to produce a squat estimate. This decision is evaluated continuously and the selected sub-model may change over the course of the vessel's passage depending on the information available at time and the required accuracy and conservatism at each location. The concept behind the decision model is that not one squat model or formula is correct or applicable to all possible conditions but that the overall model provides an appropriate squat estimate for the conditions considered.

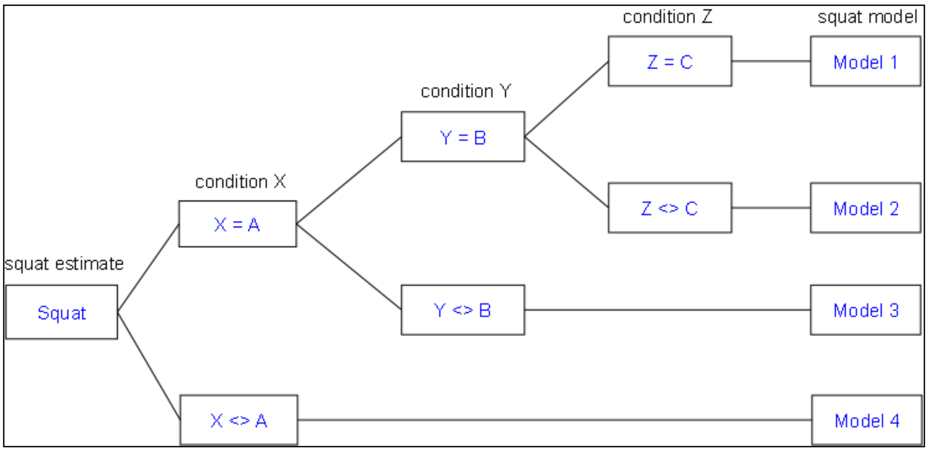

Figure Error! No text of specified style in document.**-1: Schematic overview of a decision based squat model**

To estimate vessel squat most models include vessel speed through water and a measure of channel blockage or water depth. For an operational system to work successfully, access to water levels, tidal streams and bathymetric data, both in real-time and forecasts is required. This is shown schematically in Figure **Error! No text of specified style in document.**-2.

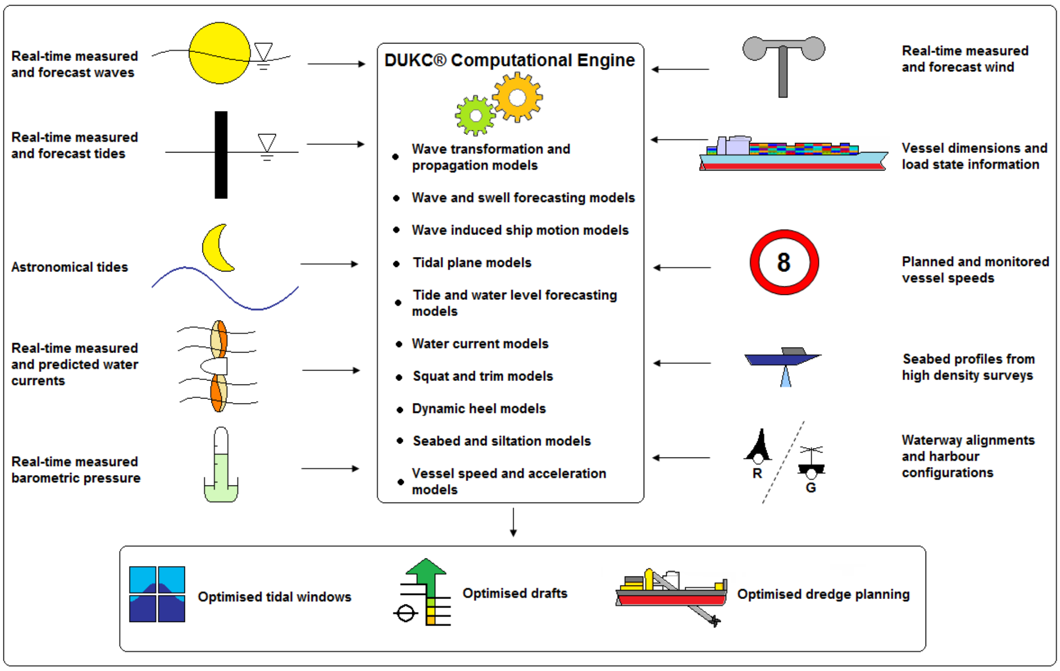

Figure Error! No text of specified style in document.**-2: Schematic overview of data inputs to dynamic underkeel clearance and squat modelling**

The ability to forecast water levels, water density and tidal streams up to 1 or more days ahead with reasonable accuracy is at least as important for the usability of the UKC predictions in operations as having a reliable and accurate squat model (or models). This is particularly the case for the planning vessel movements and/or planning the amount of cargo that can be loaded onto a vessel one or more days ahead. However, the accuracy and required conservatism of the squat estimate become more important as the uncertainty in water level and tidal streams forecasts reduces. Generally this occurs as the forecast horizon reduces and sailing time approaches. Ultimately the remaining control the pilot has in real-time to changing circumstances, such as delays and worsening met-ocean conditions, is control of his speed, and therefore squat, to ensure safe UKC throughout the transit.

3 FULL-SCALE MEASUREMENTS AND VALIDATION

Prior to deploying an operational DUKC® system, it is imperative to undertake full-scale measurements to validate the underlying models and assumptions and confirm their applicability to the port and its users. This process involves:

1. Configuring the DUKC® system to meet port and user requirements. This includes setting up the underlying engineering models for bathymetry, tidal plane and tidal streams and integrating with real-time data.
2. Recording vessel motions using survey grade GPS equipment. Three roving units are placed onboard, one on each bridge wing and one forward. An additional roving unit

may be placed mid-ships if deemed necessary. The roving units are complemented by one or more base stations positioned onshore at survey points to provide the correction signal.

3. Extracting all relevant UKC factors and vessel motions for all points of the transit from the GPS observations. This includes vessel squat, wave-induced vessel motions, vessel heel, and keel elevation.
4. Simulating the recorded passage within the DUKC® system and comparing computed motions and UKC values against measured values.
5. If necessary, calibrating the underlying models and algorithms. If required, a second validation and comparison process takes place.

This process is undertaken prior to deployment and is repeated periodically during system reviews at regular intervals to ensure that modelling remains accurate and applicable within the operational DUKC® system. The process may also be repeated if operational conditions change significantly from those encountered during measurements and model assumptions are no longer valid. For example, this can occur if waterways and depths have changed dramatically or if new vessel types need to be modelled.

SQUAT MONITORING & SPEED CONTROL

In the last few years, OMC's DUKC® software has developed from a desktop program which produces pre-transit UKC predictions to a service based system that enables on-the-fly (real-time) UKC calculations onboard vessels or within a VTS environment. Vessel positions, speed and course are obtained from a combination of GPS, AIS or radar and are integrated within the UKC calculations.

The combination of real-time data and on-the-fly DUKC® calculations provides system users with the capability of assessing the impact of changes in vessel speed on UKC in real time. Changes in vessel speed impact on underkeel clearance primarily through:

1. Changes in vessel speed changes the waypoint arrival times and consequently the tidal heights and streams encountered at these waypoints. For longer transits where large distances are covered, small changes in speed can significantly change the time at which waypoints are reached.
2. Changes in engine speed directly impact on the vessel's speed through water and vessel squat.
3. Changes in speed through water affect the wave encounter frequency and consequently on the wave induced vessel motions.
4. Changes in speed over ground affect the amount of inertial vessel heel.

It is possible to not only assess the impact of voluntary changes in speed but also involuntary or forced changes in speed, such as those caused by adverse weather, currents, vessel breakdown or other traffic. Real-time UKC information combined with speed control allow ports operators to monitor UKC continuously and actively manage UKC when necessary.

OMC has deployed several real-time systems to various ports around the world. The sections below provide three case studies of how real-time speed control has been used in operational scenarios in three ports.

5 CASE STUDIES

5.1 LOWER & OUTER WESER (GERMANY)

In 2008 OMC were contracted by the Wasser- und Schifffahrtsamt (WSA) to develop a tidal scheduling system for the Lower and Outer Weser and includes the ports of Bremen, Brake, Nordenham and Bremerhaven (Figure **Error! No text of specified style in document.**-3). OMC deployed a DUKC® system customised to meet WSA's requirements. The system is accessible by users in the Marine Departments and VTS Centres of both Bremerhaven and Bremen, as well as by users in the Upper Weser and Lower Weser Pilot organisations. The system provides safe sailing windows and maximum drafts for deep draft vessel and includes real-time UKC monitoring and speed control as described in the previous section.

Integrated within the system are real-time tide, wave and AIS data from various sensors along the river. Real-time sensor outputs are combined with water level forecasts produced by the Bundesamt für Seeschifffahrt und Hydrographie (BSH). Models to predict salinity and tidal streams along the river are also included.

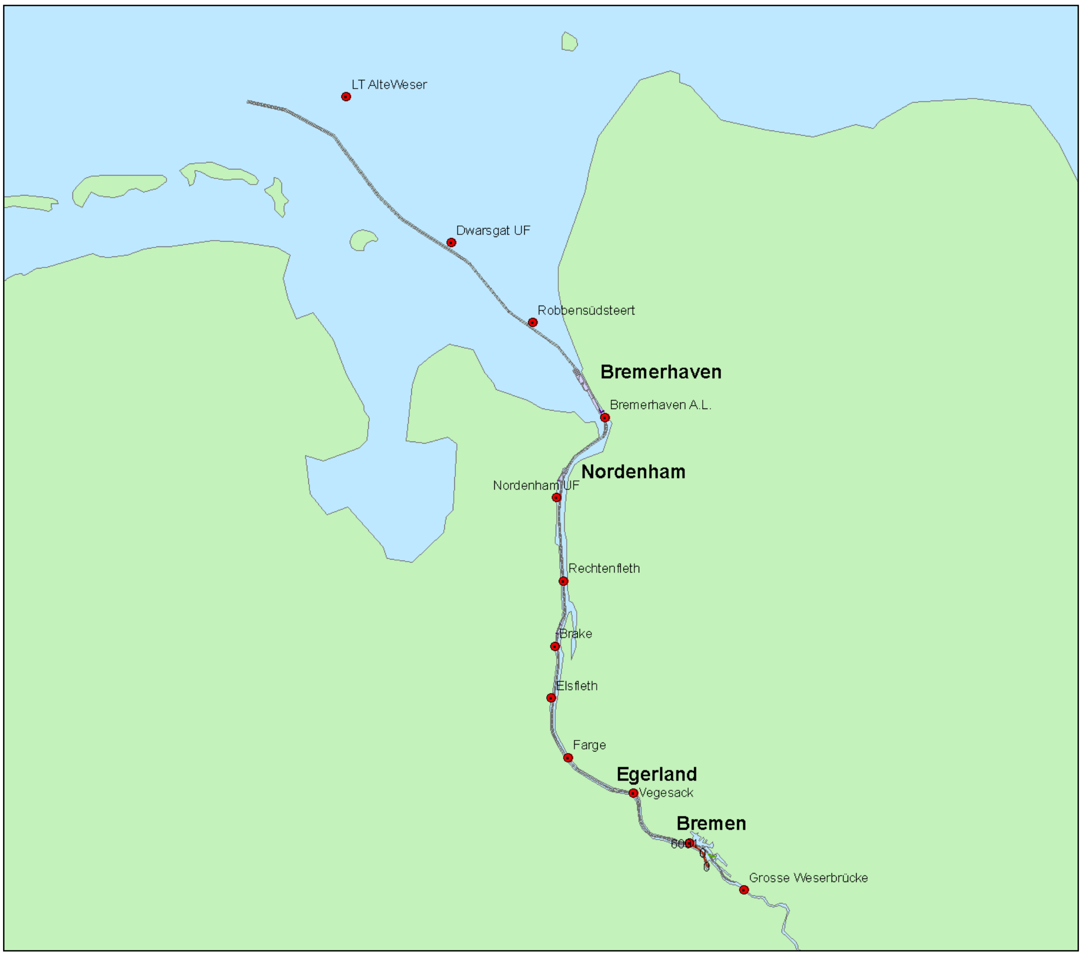

Figure Error! No text of specified style in document.**-3: Map of the DUKC® Weser extent including key ports and monitoring locations**

Full-scale vessel motions measurements were undertaken in conjunction with Fachhochschule Oldenburg (FHO) and WSA. Post-panamax container vessels were targeted in particular as squat modelling undertaken for these types of vessels was limited and additional comparisons between squat model outputs and measurements was required. In total 8 measurements were collected.

Additional to the 8 measurements, data from 19 historical measurements were provided to OMC by FHO for further model validation. For 12 of these recorded passages, the SHore Independent Precise Squat (SHIPS[i]) method of observation was used by FHO. The SHIPS method involves an additional GPS unit to be placed onboard an escort vessel to obtain an estimation of the water level in the direct vicinity of the vessel and eliminates the need to construct a tidal plane from tide gauge measurements.

Data from the 8 measurements indicated that Maersk E-class vessels, such as the Estelle Maersk and Edith Maersk, trimmed more than originally anticipated. Both the Estelle Maersk and Edith Maersk showed significant dynamic trim up to approximately 1.2m by the stern. This is shown in Figure **Error! No text of specified style in document.**-4.

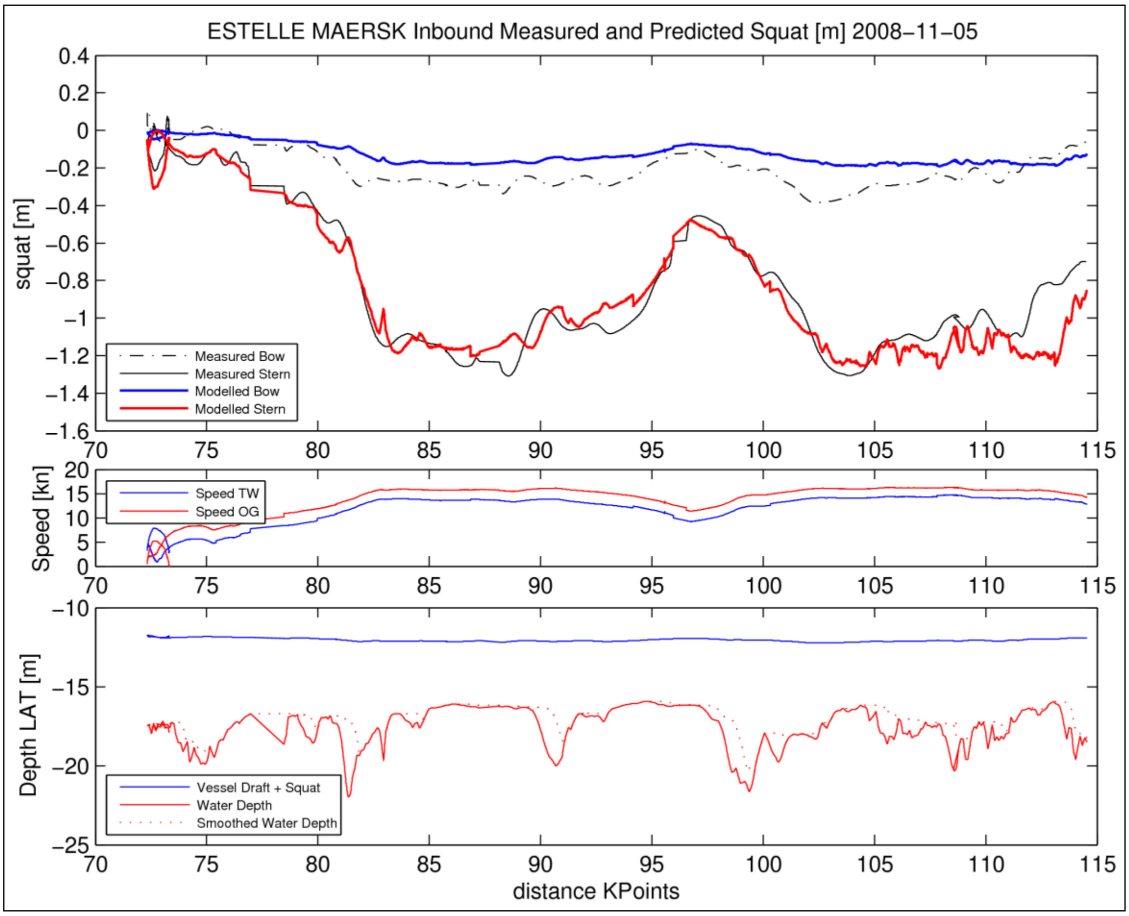

Figure Error! No text of specified style in document.**-4: Recorded and predicted squat for the Estelle Maersk**

Both E-class vessels were lightly laden to a draft of approximately 11.0m. Figure **Error! No text of specified style in document.**-5 shows that at this draft the stern is well clear off the water surface. It is possible that the large dynamic trim is increased by the fine hull form aft (low buoyancy) and increased water flow aft due to propeller action. At deeper drafts the stern will become submerged and provide additional buoyancy and thus resisting dynamic trim.

Figure Error! No text of specified style in document.**-5: Edith Maersk transit – Stern well above water surface**

The opposite effect has been noted by Uliczka and Kondziella[ii] for Yang Ming container vessels (on the River Elbe) which trimmed by the bow. They speculated that the wide transom, combined with the slender bow of these vessels provide a trimming moment to the bow.

The operational squat model used by the DUKC® was modified to include improved squat estimations for lightly laden container vessels. Figure **Error! No text of specified style in document.**-4 shows the DUKC® squat prediction for the Estelle Maersk after modelling improvements.

5.2 PORT OF MELBOURNE (AUSTRALIA)

To ensure the safety of vessels transiting the Port of Melbourne, the Port of Melbourne Corporation (PoMC) engaged OMC to configure and install a DUKC® system. The transit through the Port of Melbourne Channel (see Figure **Error! No text of specified style in document.**-6) takes approximately 4 hours. Depending on conditions UKC can control at with a number of critical points along the channel. These points are:

1. The Yarra River and Port of Melbourne Channel where the tidal range is approximately 0.5m and the container vessels are transiting up to 8 knots.
2. The South Channel where the tidal range is approximately 0.6m and the container vessels are transiting at times in excess of 18 knots
3. The Port Phillip Heads (PPHs), one of the most treacherous stretches of water in the world, where the narrow entrance to Port Phillip Bay acts as the conduit for tidal flow into and out of the bay. There is a tidal range of 2.5m outside PPHs and 0.6m inside resulting in very strong tidally driven currents up to 6-8 knots acting through this relatively narrow opening. The currents interact with long Southern Ocean swells of up to 5m significant wave height over a complex and hard bathymetry producing wave/current interaction effects that are complex and highly variable both spatially and temporally. Accurate determination of UKC in such conditions is difficult but critical for ensuring safe passage. For squat prediction through this critical region, accurate modelling of the tidal currents (where speed over the ground can vary between 6 to 18 knots for the same speed through the water), water depths over the large tidal gradient is required.

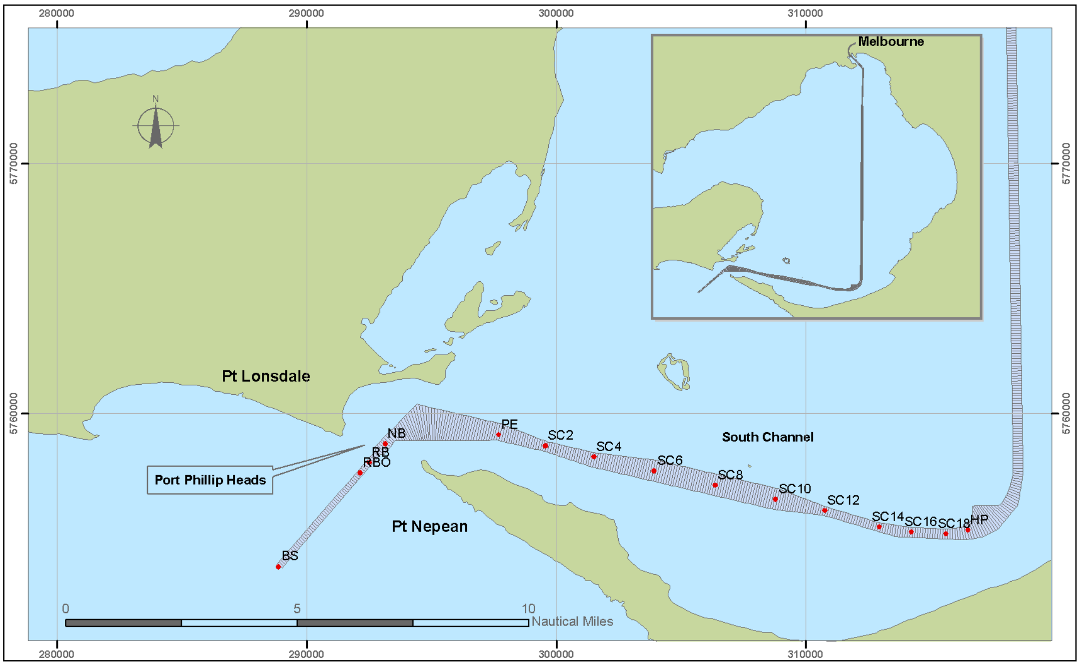

Figure Error! No text of specified style in document.**-6: Map of the Port of Melbourne DUKC® extent including key locations**

As well as the considerable variation in tidal height along the transit through the Port of Melbourne waters, there is also a significant tidal phase lag, with high tide in the Yarra River lagging high tide in the PPHs by up to 3 hours. Depending on the wave conditions at PPHs, the time of the transit in relation to the tidal phase throughout the transit, and the direction of the transit (i.e. travelling with or against the tide), the characteristics of the vessel and the planned vessel speed profile, a transit may control at any one of the above control points.

To manage these conditions, DUKC® technology has been integrated onto Portable Pilot Units (carried by all 35 pilots) and into VTS centres to enable vessel speed and predicted under keel clearance for the remainder of a transit to be monitored onboard and ashore. This provides the pilots with the ability to optimise their planned speed profile in real time throughout the transit to ensure they have sufficient UKC throughout the transits. This on-the-fly control requires accurate and efficient squat modelling considering the spatial and temporal variation of all factors influencing squat.

Given the complexity of the PoMC DUKC® System, an extensive trial and validation process was required to confirm that the system was capable of delivering the improved safety benefits that were required. This included installing the latest state-of-the-art environmental instruments to provide data of the highest quality.

In 2007/08 a series of full-scale ship motion and under keel clearance measurements were undertaken by PoMC for 12 vessels transiting the Port of Melbourne channels. OMC's system was run prior to each transit and the results were provided to PoMC for their independent validation of the accuracy of OMC's ship motion predictions. Comparisons of the DUKC® predictions against the precise GPS measurements confirmed that the system accurately predicted squat and turning heel in the Yarra River and South Channel as well as the vessel wave response and squat in Port Phillip Heads under a wide range of wave/tidal current conditions, vessel types, sizes and transit speeds.

An example of the measured and predicted vessel squat using the Port of Melbourne DUKC® system is shown in Figure **Error! No text of specified style in document.**-7.

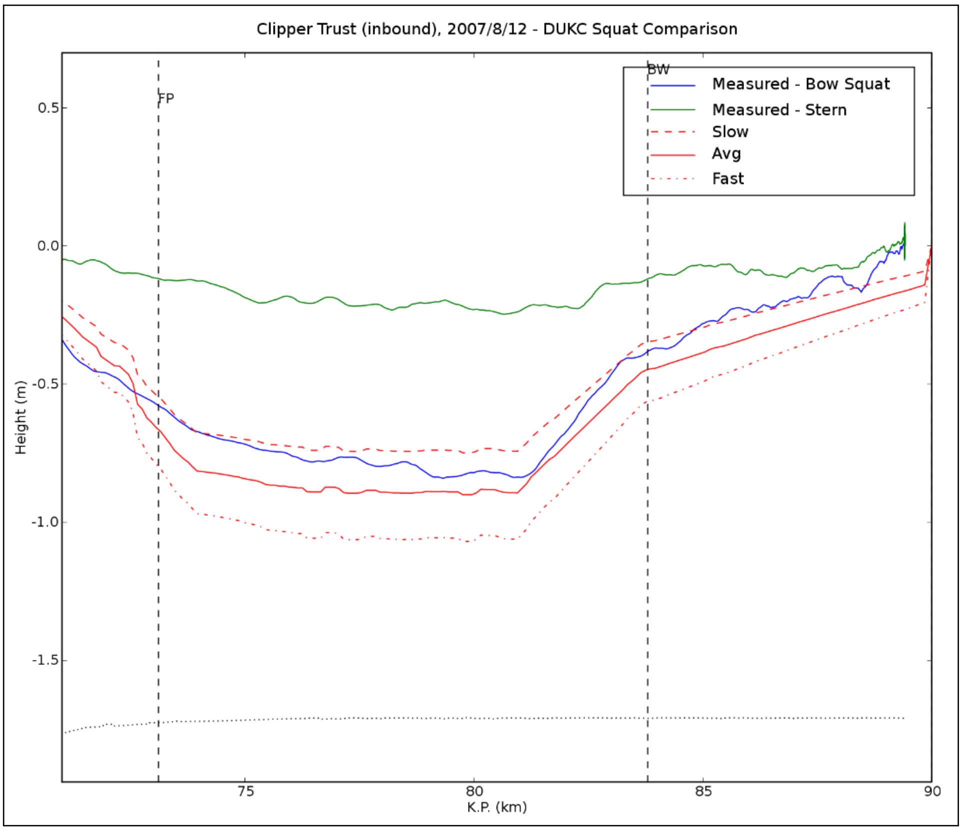

Figure Error! No text of specified style in document.**-7: Example recorded and modelled maximum squat using the PoMC DUKC® system.**

Following satisfactory completion of this external validation process, PoMC approved the customisation of a full DUKC® system for Melbourne for both vessel passage planning and for in-transit monitoring and control.

5.3 PORT HEDLAND (AUSTRALIA) – IRON KING GROUNDING

Port Hedland (Western Australia) is one of the largest iron ore ports in the world and the largest within Australia. Approximately 154 million tonnes of iron ore was exported in the 2008-2009 financial year. The Port Hedland Port Authority (PHPA) has been using DUKC® for over 10 years and recently upgraded their system to include real-time UKC monitoring and speed control.

On 31/July/2008 the bulk carrier 'Iron King' departed the port with approximately 160,000 tonnes of iron ore. Shortly after departure the vessel experienced steering failure and ran aground near beacon 44 (see Figure **Error! No text of specified style in document.**-10 and Figure **Error! No text of specified style in document.**-11). The vessel blocked the Port Hedland approach channel and consequently the port had to be closed.

The PHPA used the real-time DUKC® system to determine if the vessel could be safely towed out to sea and if so, how this could be achieved. The following describes the events:

TIME (AWST)	EVENT
2230	Vessel grounds due to steering failure.
0830	PHPA ballasts vessel to 18.35m by the stern to refloat the vessel. Vessel speed is planned to be constrained to 6 knots as structural damage is suspected.
1000	Vessel refloated. DUKC® VTS starts tracking vessel using AIS broadcast positions. DUKC® VTS advises that vessel (ballasted to 18.35m & constrained 6kn) should return to berth or proceed no further than lay-by as underkeel clearance will be insufficient 24 nm further offshore as the tide was falling. See Figure Error**! No text of specified style in document.**-8. This figure shows the planned vessel speed, the predicted underkeel clearance and the predicted water level along the planned route. As tide was falling, the water level at the end of the planned route would be insufficient (indicated red in Figure Error**! No text of specified style in document.**-8).
1015	PHPA uses the DUKC® VTS system to determine at what draft and speed the transit can be completed safely. DUKC® VTS indicates that if the vessel was de-ballasted to 17.54m and increased its speed to 8 knots that the transit can be completed safely. Figure Error**! No text of specified style in document.**-9 shows the updated UKC prediction based on the 8 knot vessel speed and 17.54m draft.

1256	Transit successfully completed using DUKC® VTS monitoring and speed control.

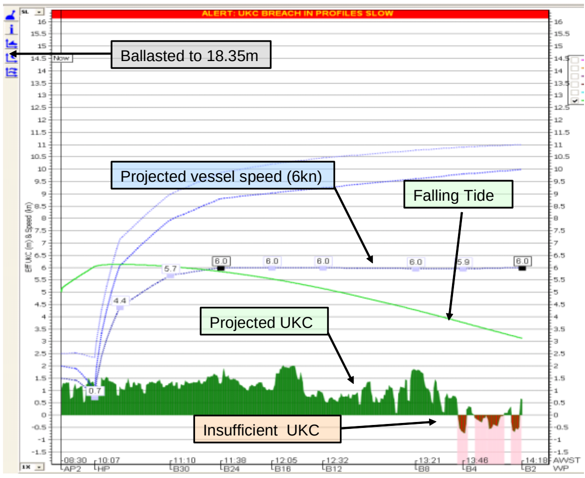

Figure Error! No text of specified style in document.**-8**

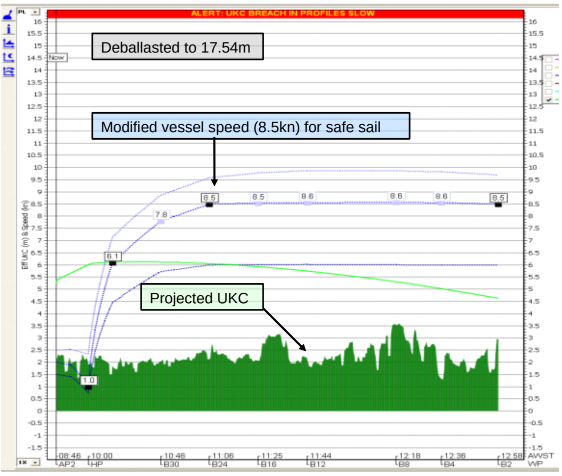

Figure Error! No text of specified style in document.**-9**

In this instance the ability to control and monitor in real-time the effect of changes in vessel speed to optimise vessel squat against the loss in tidal plane throughout the transit was critical to ensuring the safe passage of the vessel in this emergency situation.

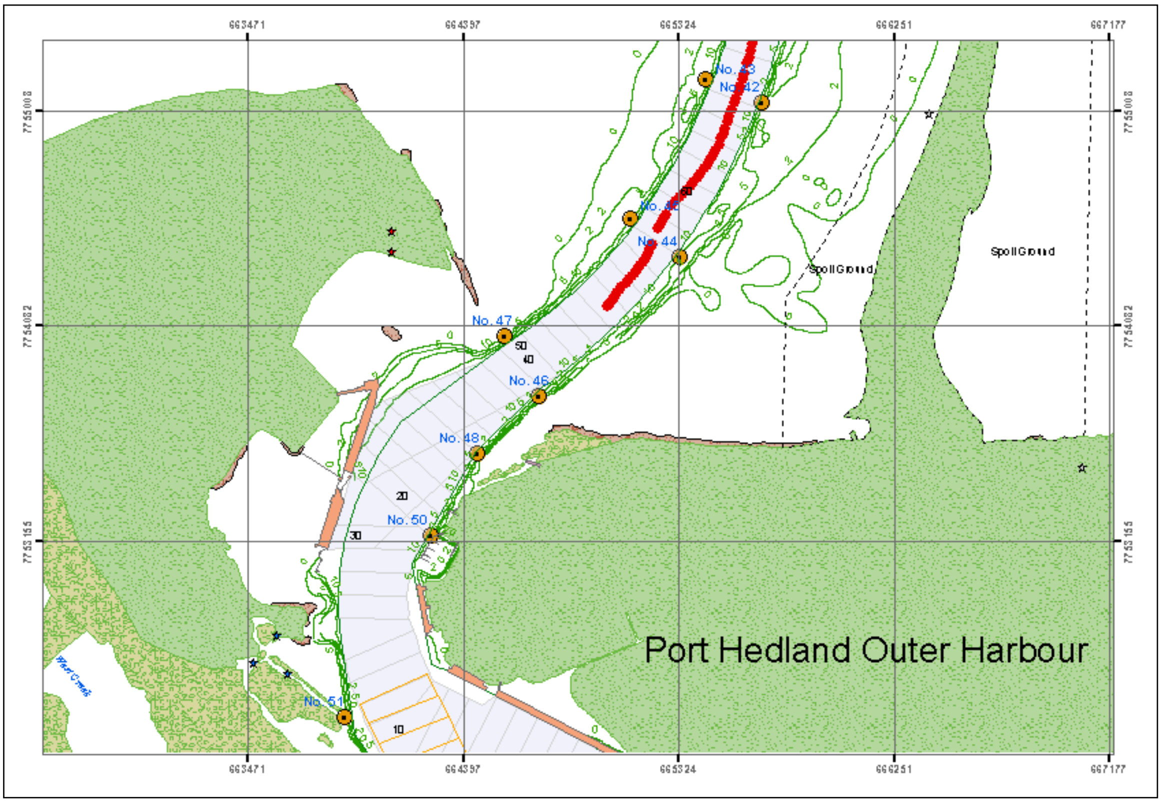

Figure Error! No text of specified style in document.**-10: Iron King track after refloating**

Figure Error! No text of specified style in document.**-11: Iron King aground near beacon 44 (picture by Mike Cummins)**

CONCLUSIONS

- A squat model needs to be sufficiently accurate, reliable and conservative if it is to be used under operational conditions such as within an underkeel management tool.
- A decision based squat model, which incorporates many different sub-models and manages risk, is suitable for an operational UKC management system.
- Real-time underkeel clearance makes it possible to assess the impact of operational decisions, such as changes in speed, on vessel squat and underkeel clearance.
- OMC has successfully deployed real-time underkeel clearance systems to various ports around the world, including a system for vessels travelling on the Lower and Outer Weser.

REFERENCES

[1] Dunker, S. Gollenstede, A. Härting, A. Reinking, J. FH Oldenburg/Ostfriesland,Wilhelmshaven, *Analysis and comparison of SHIPS derived squat*.

[1] Uliczka, K. and Kondziella, B., 2006. *Dynamic response of very large container ships in extremely shallow water*. 31st PIANC conference, May 2006, Estoril Portugal.
