EXPERIENCE USING UNDERKEEL CLEARANCE PREDICTION SYSTEMS AT AUSTRALIAN PORTS: SELECTED CASE STUDIES AND RECENT DEVELOPMENTS[1]

by

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ABSTRACT

The underkeel clearance (UKC) prediction system discussed in this paper has increased drafts and widened tidal windows at several Australian ports since 1993, without compromising vessel safety. These improvements in port operation have provided economic benefits amounting to millions of dollars in decreased freight costs and increased cargo throughput, at a small fraction of the cost involved in gaining equivalent improvements by dredging.

Since the Dynamic Underkeel Clearance (DUKC) system was first developed in 1993, seven customised versions have been installed in ports around Australia. Research and development of the DUKC system has continued since that time and has been greatly assisted by continuing interaction between Harbour Masters, Pilots, port users and the design team.

Recent major DUKC developments include:

- the application of meteorological and wave forecasting models to provide predictions of maximum drafts and tidal windows up to 36 hours prior to sailing;
- the near real-time modelling of the dynamic motions in waves of each particular ship in its actual loaded condition; and,
- continuous processing of real-time tide and wave data by the DUKC system, allowing predicted changes in maximum draft or tidal windows to be updated automatically during the final hours prior to sailing.

Case studies involving the application of DUKC systems and the associated benefits obtained at three ports are described.

INTRODUCTION

Traditionally, most ports in Australia and elsewhere have operated under fixed rules which govern the minimum underkeel clearance (UKC) to permit safe transit along port approach channels.

UKC requirements are generally calculated to cover a broad range of environmental conditions and vessel parameters. If the requirements are too conservative, ships carry less cargo than they could, and the operation is not as economic as it might be. At the other extreme, inadequate criteria could jeopardise safety.

Because of their geographical situation on the coastline of an island continent, the approach channels of most Australian ports are subject to ocean swells generated by tropical cyclones or Southern Ocean storms. It is therefore essential that UKC requirements include not only vessel squat and the effect of wind and atmospheric pressure changes on predicted tides, but also the dynamic motions of vessels of varying size and stability characteristics.

UKC ALLOWANCES

The major UKC allowances are as follows:

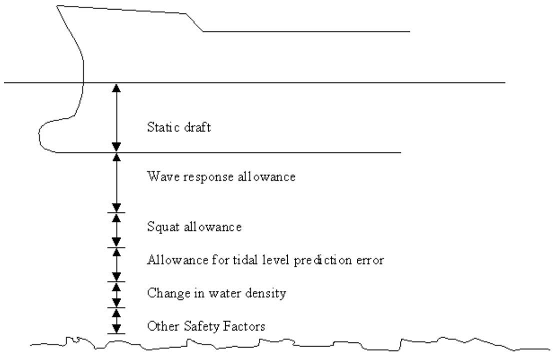

Figure 1: UKC Allowances

Wave Response Allowance

In channels subject to wave action, ships will experience heave, roll and pitch motions which combine to produce vertical displacements of the hull. The magnitude of these dynamic and irregular displacements at each point of the vessel's transit depends on many factors, including:

- Directional wave spectrum (describing wave energy distribution as a function of frequency and direction);
- Ship dimensions, hull shape and stability data;
- Ship speed;
- Water depth/draft ratio.

Squat Allowance

Squat is a combination of bodily sinkage and change in trim of a vessel while sailing. The major factors affecting squat are ship form and initial trim, vessel speed through the water, depth/draft ratio, channel width and depth of cut, abrupt depth changes, changes in fluid density, passing and overtaking vessels.

Changes in Water Level

In addition to the change in water level due to predicted astronomical and seasonal effects, water levels are also affected by meteorological changes in wind speed and direction and in barometric pressure. These changes in water level represent the difference between measured and predicted water levels and are known as the *tidal residuals*. In particular circumstances this difference can be substantial (of the order of ± 40 cm, or greater).

Information regarding the ‘movement’ of high tide is also important, particularly when the port approach channel/canal is quite long and/or subject to large tidal variations. The tidal range and phase needs to be identified and accounted for in the prediction of the ship underkeel clearance along the entire transit.

Changes in water density have the same effect as a change in water level in terms of draft and the resulting underkeel clearance. It is important to identify where these changes occur and by how much the density has changed.

In the determination of an accurate underkeel clearance prediction, the changes between predicted and actual tides and any changes in water density need to be taken into account.

Safety Factors

As ports differ in many ways so too do the safety factors that need to be built into an underkeel prediction system. Safety factors may include allowances such as hydrographic survey tolerance, siltation and draft tolerances.

THE DYNAMIC UKC CONCEPT

Dynamic UKC® (DUKC®) is a near real-time underkeel clearance prediction system for use at ports which have draft limitations on import or export ships. The DUKC system takes into account all of the major factors affecting underkeel clearance, together with other allowances such as heel and list which may be required in particular circumstances, as described in O’Brien (1).

The system has two major functions:

- *Maximisation of vessel drafts* (export vessels)

- *Determination of the earliest and latest times for entry into the port approach channel(s)* (import vessels and export vessels sailing at less than maximum draft)

DUKC systems utilise real-time tide and wave measurements taken prior to transit to determine the minimum safe underkeel clearance along the complete transit from berth to deep water, thus taking advantage of favorable conditions and ensuring safety during unfavorable conditions. These systems allow ships to be loaded to greater draft or use wider tidal windows than is possible using fixed UKC rules, which are determined by safety requirements in extreme swells and negative tidal residuals. DUKC systems thus increase port productivity without the need for new port infrastructure or capital dredging and without compromising safety standards.

Wave spectra, ship speed and water depths vary along the transit and the effect of these variations is computed by the numerical ship motion model used in each DUKC system.

In addition, wave spectra and tidal residuals will change over time, and these effects are accounted for in each system. With respect to squat, individual ships and the pertinent characteristics of the complete approach channel are modelled in each DUKC system.

By measuring tide and wave data and using the actual measured values, as opposed to predictions, UKC calculations can be performed with a much greater degree of certainty for the conditions of any given day.

DUKC systems are customised for the vessel type, hydrography, tides and wave climate at each port. The system is designed to provide predictions up to 36 hours ahead to assist vessel loading and sailing scheduling, as explained in Case Studies 1 - 3. In the final hours before departure the DUKC system operates a Windows Monitor, which continuously updates sailing times and maximum drafts prior to sailing, enabling shippers to maximise cargo loadings while providing up-to-the-minute information for the ship handlers.

The magnitude and nature of UKC safety factors are established through consultation with the Harbour Masters and Pilots at each port.

All DUKC systems operate in accordance with internationally-accepted safety criteria for bottom clearance and manoeuvrability requirements.

Three recent extensions of the original DUKC (Series I) concept are described below.

DUKC Swell Forecasting System

Nowcast and 12-hour, 24-hour and 36-hour forecasts of directional wave spectra at deep water sites offshore from each DUKC installation are generated twice daily by the Bureau of Meteorology in Melbourne, using global and regional wind and wave generation models similar to those used by many other meteorlogical forecasting agencies throughout the world. These models have recently been extended to include the ingestion of satellite altimeter data on wave heights, with a significant increase in their predictive accuracy.

The nowcast and forecast wave spectra are downloaded automatically from the Bureau and transformed using site-specific relationships to obtain predicted spectra at the wave measurement sites at each port. The transformed nowcasts are compared with the corresponding measured data at each site and these comparisons are used to adjust the 12-hour, 24-hour and 36-hour forecasts. The adjusted forecast data are then used in each DUKC system for the generation of 36-hour, 24-hour and 12-hour forecasts for maximum draft or tidal window applications. In ports with semi-diurnal tides, these forecasts provide scheduling information for shippers to use up to three high water levels prior to sailing.

DUKC Windows Monitor

Real-time tide and wave data are measured by the DUKC system continuously during the final hours prior to sailing, allowing any changes in conditions to be monitored and displayed, together with any alterations to the sailing time or maximum draft available.

Real-time data regarding all aspects of the factors affecting the underkeel clearance are displayed to assist Harbour Masters, Pilots and Masters make informed decisions. This Windows Monitor feature is particularly useful when weather conditions are deteriorating rapidly (to monitor safety) or improving rapidly (to gain additional draft and/or tidal window).

Individual Ship Modelling (DUKC Series II)

DUKC Series I systems involved modelling the dynamic motions of ships in waves based on classification of ships by their summer deadweight. When the actual ship dimensions and load stability data (including GM_f) are available, the dynamic motions in waves of each particular ship are now modelled in its loaded condition. This recent innovation (termed DUKC Series II) involves coupling the SPMS ship motion model with the DUKC software at each port.

The numerical ship motion model, SPMS (**S**imulation **P**ackage for the **M**otions of **S**hips), has been developed by the author for the analysis of various problems associated with the motions of vessels, either moored, towed or free moving along channels or in deep water. Development of the SPMS model began in 1962 and since then it has been extended to solve a wide variety of maritime projects in Australia and overseas.

Dual frequency DGPS equipment has been used to measure full-scale vessel motions and squat of free moving vessels and validate the accuracy of the predictive models used in the SPMS/DUKC systems installed in several Australian ports (see following Section).

In addition, a major calibration and validation program for the SPMS moored ship model has been completed during 1998/99 for two vessels at Port Taranaki on the west coast of New Zealand. This exercise involved DGPS measurement of moored ship motions, direct measurement of line tensions and collection of short and long wave data at the berth. These data were used to fine tune the model and provide full confidence in its ability to predict moored vessel response in sea, swell and long waves.

HARDWARE & SOFTWARE REQUIREMENTS

Tide and wave measurements are required and must be accessible in real-time. As most ports already have tide gauges installed this minimises hardware costs. Firms with a local or regional base are used to provide tide and wave data, thus allowing any equipment malfunctions to be overcome promptly and at minimum cost. Tide and wave data undergo quality control checks by the DUKC system before use, in addition to the

QA checks applied to the data by the service provider.

The DUKC system is installed for use by the Harbour Master, Pilots and Shipping Officers at each port, using a Windows NT platform. Increasing use is being made of the Internet for E-mailing results to pilots and to provide web sites for data transfers between OMC, Bureau of Meteorology and Port Operations.

Back-up hardware and software systems have been installed at most ports to minimise the possibility of system failure. The reliability of tide and wave measurement devices and DUKC computer hardware and software has been found to be extremely high.

APPLICATIONS

DUKC systems have now been installed at seven Australian ports:

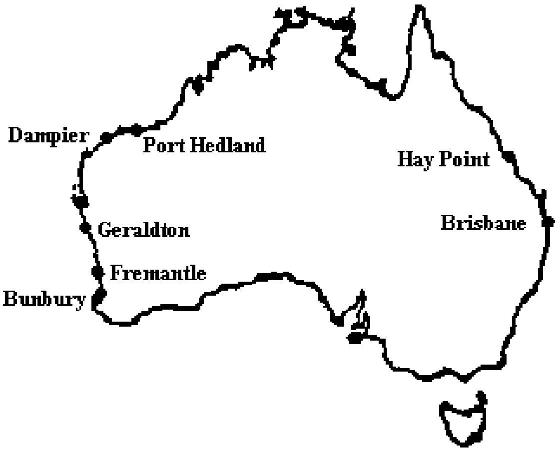

Figure 2: Location of DUKC systems in Australia

- **Hay Point/Dalrymple Bay, Queensland** (1993) - one of the largest coal export ports in the world (approx. 65,000,000 tonnes per annum) - vessels to 230,000 dwt.

- **Fremantle, Western Australia** (1994) - import of crude oil for BP Australia to Kwinana and later extension to Alcoa berth for export of alumina and to Inner Harbour for new generation of container ships (import and export).

- **Port Hedland, W.A**. (1995) - export of iron ore for BHP (approximately 65,000,000 tonnes p.a., vessels to 250,000 dwt).

- **Dampier, W.A.** (1995) - export of iron ore for Hamersley Iron (approximately 55,000,000 tonnes p.a., vessels to 250,000 dwt)

- **Brisbane, Queensland** (1996) - import of crude oil (Post-Panamax vessels) and export of coal (Panamax and Post-Panamax vessels)

- **Bunbury, W.A.** (1996) - regional port, using Handy and Panamax size vessels for export of alumina and import of caustic soda

- **Geraldton, W.**A. (1999) - regional port, using 'Gracht' class and Handy and Panamax size vessels for export of grain and mineral sands and import of petroleum products.

DUKC systems will be set up in early 2000 at the ports of New York/New Jersey (USA), Richards Bay (South Africa) and Taranaki (New Zealand).

Port Characteristics

The system is capable of allowing for all port characteristics. Some of the major variations which have occurred in the various DUKC applications to date are as follows:

- Channel lengths from 3 km to 70 km

- Tidal ranges from 1.0 m to over 7.0 m

- Swells from near zero up to significant wave heights in excess of 5.0 m and with peak periods ranging from 10 sec to 22 sec

- Currents up to 2 - 3 knots in some channels, very small in others

- Dynamic ship motions modelled in near-real time for vessels ranging in size from 17,500 dwt to 250,000 dwt

- Differences between measured and predicted tides exceed positive 40 cm (or higher, during storm surges) to negative 40 cm during events involving very high pressure systems and offshore winds.

SYSTEM VALIDATION AND MAINTENANCE

Until recently it has been very difficult to validate the existing squat formulae with any degree of confidence as there has been no method of accurately measuring full-scale vessel squat. Advances in the area of dual-frequency Differential GPS have overcome this problem, making full-scale squat testing not only possible but also highly accurate.

DGPS equipment with On-The-Fly technology has been used to measure full-scale dynamic motions and squat and provide further validation of the predictive models used in the DUKC systems installed at several ports, as described by Hatch(2) and Rolph et al (3).

Full-Scale Squat Testing

Since 1997 OMC has conducted full-scale squat measurements on over 50 vessels in six different ports around Australia.

The vessels tested have primarily been bulk carriers, up to Cape size, and tankers. The range of conditions at each of these ports varies considerably, including narrow channels, undulating sea floors and variations in tide and wave conditions. Each study has highlighted the sensitivity of squat to the local conditions and individual channel configuration.

Both fore and aft squat have been measured, as this allows for the separate sinkage and trim components of squat to be quantified.

Ship squat at the bow and stern of a bulk carrier measured by the DGPS equipment is shown below in Figure 3. The oscillations shown indicate the dynamic motions (heave and pitch) of the vessel. The vessel squat is taken to be the mean of these oscillations.

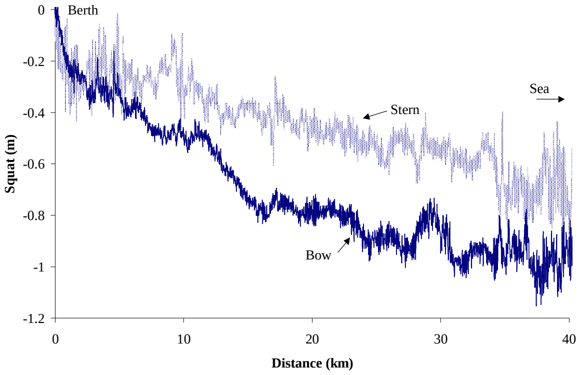

Figure 3: Measured Bow and Stern Squat

Clearly the bow of the vessel experiences greater squat than the stern.

During the initial three kilometers of the transit the bow and stern squat are similar in magnitude, indicating that bodily sinkage is occurring. After this distance the ship begins to increase speed considerably and the vessel's trim alters to produce maximum squat at the bow.

The results of the validation testing have highlighted the sensitivity of squat to particular channel configurations and provided an excellent record of actual vessel squat. Such testing also proves some of the fundamentals of squat, such as full form vessels squat by the bow.

In addition to squat and dynamic motion data, the test programs also provide valuable data regarding ship speed along the various channels. This has enabled the DUKC systems to be further refined to better reflect the actual vessel speeds in the approach channels.

The full-scale testing results have lead to operational changes which have increased economic benefits as well as improved safety at several DUKC ports.

Monitoring and Maintenance

All systems are maintained and monitored remotely by OMC, with occasional site visits as required. Tide and wave measurement devices are maintained by local or regional consultants.

CASE STUDIES

Case Study 1 - Hay Point, Queensland

The Port of Hay Point is located on the north-east coast of Australia. It consists of two offshore loading terminals, each comprising two berths. The berths are located 4km offshore and are subject to swells approaching from near the beam.

For vessels sailing to maximum draft, a 24-hour prediction is performed and used as an *indication* for the Master and shipping agent of the maximum expected draft and optimum sailing time. The 12-hour prediction is usually adopted as the *confirmed* draft and departure time, after approval by the duty pilot. For export vessels sailing to less than maximum draft, a similar procedure is followed with respect to initial indication and later confirmation of earliest and latest sailing times.

The DUKC system at Hay Point has been continually developed and extended since its installation in March 1993. Currently, Stage VIII of the DUKC system is in operation. Typical increases in draft due to the application of the DUKC system range from 50cm to 1.0m, depending on the tidal residuals and wave conditions.

In the 1996/97 financial year the Hay Point system enabled 123 vessels to load an additional 743,246 tonnes of coal (an average 6042 tonnes per vessel); the freight savings from these increased shipments amounted to approximately US$7,500,000, the increased value of export earnings amounted to approximately US$30,000,000. Increases in the number of vessels using the system since 1996/97 (due to berths increasing from three to four) and from additional cargo loaded per ship (due to new refinements in the DUKC system) have led to annual coal shipments being increased by more than 1,000,000 tonnes per annum *due to use of the DUKC system alone.*

Two additional dynamic systems that have been developed and installed at the Port of Hay Point are as follows:

a) DUKC system for maximising loading time of vessels over low water. Two of the four berths have insufficient depth in their berth pockets to allow vessels to continue loading during low water. Use of the DUKC system has enabled loading to continue over a longer portion of the low tide cycle than was previously possible with fixed-rule procedures.

b) Berth Warning System is a real-time berth warning system designed for use at ports subject to cyclones or to ocean swells. The Port of Hay Point experiences tropical cyclones in summer and long-period swells from storms in the Southern Ocean in winter. The Berth Warning System monitors the effects of swell growth, using hourly wave measurements to compute the expected dynamic motions of moored ships. The computations take into account the size of the ship, its loading condition (unladen, 50% laden, fully laden) and the orientation of the berth in relation to incident swells.

Case Study 2 - Fremantle, Western Australia

The Port of Fremantle is located in the south-west of Australia and has a small tidal range of around 1m. Fremantle imports crude oil, exports alumina and is a busy container port.

Fremantle has an inner and an outer harbour consisting of three separate channels, all of which are modelled in the DUKC system. The DUKC system was originally customised for Post-Panamax oil tankers entering the Outer Harbour. Following the success of the system with these vessels the DUKC was extended to include container ships entering the Inner Harbour and Panamax bulk carriers sailing from the Alumina berth in the Outer Harbour.

Import vessels have their drafts set at their previous port of departure and hence use the tidal windows facility.

Because the DUKC systems can be run shortly before the ship enters the approach channel, there is minimum time for tidal residuals and swells to change and tidal windows will generally be very much greater than those corresponding to fixed rules set for worst-case conditions. This means that waiting vessels can enter port earlier than would otherwise be possible and, at the other end of the tide cycle, gain entry on occasions when they might otherwise have to wait for the next suitable tide. Alternatively, the gains obtained from reduction of UKC allowances can be translated into increased arrival drafts by decreasing the Gross UKC formulae used to schedule such drafts.

The increased tidal windows made available by the DUKC system at Fremantle has allowed the Gross UKC for import tankers to be reduced by 3% of vessel draft (approximately 42 cm), with additional draft increases up to 1.0 m for tankers with beams in excess of 40 m.

On average, approximately 5,000 tonnes of additional crude oil is carried per voyage. As each shipment involves approximately 100,000 tonnes of oil, the importer saves one complete charter voyage in twenty. Savings in ship charter costs, especially from the

Middle East, are significant.

In addition, the system allows ships to berth earlier, optimise terminal operations and clear the berth earlier than would have been possible without the system.

The introduction of DUKC to the container berths at Fremantle has allowed drafts of container ships to be increased by 35 cm, with at least a 95% probability of berthing without a delay. The increase in draft that can be accepted relates to approximately an increase in freight of 120 TEUs. The maximum draft acceptable at Fremantle for container vessels is now 12.80 m, which guarantees the port first and last port of call status.

The chemical tankers sailing to the alumina refinery have also benefited from the DUKC at Fremantle. The tankers have been able to increase their draft by a minimum of 35cm. This is a specific benefit to the refinery operator as these vessels previously had to lighten at an alternate berth prior to transiting this channel.

Case Study 3 - Port Hedland, Western Australia

Port Hedland is located on the north-west coast of Australia and exports around 65 million tonnes of iron ore each year.

Like Hay Point, Port Hedland is subject to tropical cyclones from December through to March and long-period swells from storms in the Southern Oceans in winter. During these events, the DUKC system offers added safety to shipping operations; by calculating the vessel motions in waves the system can accurately predict safe sailing times or drafts for vessels, even in extreme conditions.

Port Hedland has a large tidal range of up to 7.5m during spring tides. This is both an advantage and a problem for the port as the ships can sail with a larger draft at high water provided they can clear the channel (approximately 4 hours sailing time) before the water level drops too low. The transit out of the port is 42km in a channel with depths ranging from 14.1 m - 16.0 m. Ships in excess of 220,00 dwt are common callers to the port.

The port was the third DUKC installation but the first to be extended to include DUKC swell forecasting, *individual* ship modelling (Series II) and DUKC Windows Monitor, as described above.

Port Hedland was also the first port to undertake full-scale squat testing to validate the empirical formula used in the DUKC system.

The DUKC system at Port Hedland operates with multiple redundancies in tide and wave measurement equipment, all of which are programmed into the system.

At Port Hedland, the DUKC system has increased maximum drafts by an average of 55 cm. For typical Cape size vessels, this draft increase amounts to approximately 7,500 tonnes, which translates into US$75,000 in freight savings and US$200,000 in increased export earnings per vessel.

The DUKC system has provided the port with the largest result for port throughput since capital dredging was carried out in 1994/96, at a small fraction of the cost.

CONCLUSIONS

DUKC systems offer a number of advantages over existing Static UKC rules including:

- Prediction of maximum sailing draft for export vessels, with forecast maximum drafts available from up to 36 hours prior to sailing and final drafts available as close to sailing as shiploading operations allow. Such predictions have enabled increases in maximum drafts of 30 cm - 1.0 m to be obtained at Australian ports during the last six years, translating into cargo increases ranging from 3,000 to more than 10,000 tonnes per vessel.

- Prediction of earliest and latest sailing times for import and export vessels with forecast tidal windows being available from 36 hours prior to channel transit and final times being available up to the commencement of transit. This facility has expanded tidal windows by several hours, thereby allowing export vessels to load more cargo and both import and export vessels to benefit by more flexible channel entry times. In addition, the system allows ships to berth earlier, optimise terminal operations and clear the berth earlier than would have been possible without use of the system.

- DUKC systems include numerical ship motion modelling of vessel motions in waves along the approach channel, using real-time wave data, together with forecast changes in these data. This predictive modelling is used to enable all UKC allowances to be reduced to the minimum possible, consistent with the requirement to maintain adequate margins for manoeuvrability and to protect against grounding. The system has recently been extended to allow the dynamic motions of individual ships to be modelled, using their actual dimensions and load stability data.

- DUKC systems are not expensive to install and operate and do not require use of expensive DGPS receivers mounted on each vessel; DGPS equipment with On-The-Fly technology is used for system validation, but is not required for system operation.

- DUKC systems are simple to operate and have been used by a wide number of port operators and users. Arrangements to support the operation, monitoring and continuing refinement of each system include remote access to the DUKC software, environmental data and system report files, combined with local maintenance of tide and wave recording equipment.

DUKC systems have been operational since 1993 and a wide body of experience has now been accumulated at seven Australian ports. Harbour Masters, Pilots, Shipping

Superintendents and port users have all been involved in the progressive development of each system and many of the developments since 1993 have arisen as a result of this interaction between users and designers. Experience has shown that this continuing interaction is vital to the successful operation of predictive UKC systems.

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