HYDROGRAPHIC CONFERENCE
Technical Awareness Seminar 2007
Cape Town, 19 – 21 June 2007

Measurement of vertical motions of bulk carriers navigating in port entrance channels

J Moes
CSIR, PO Box 320, Stellenbosch, South Africa
e-mail : hmoes@csir.co.za

ABSTRACT

Due to developments in shipping, ports are under continuous pressure to accommodate wider and deeper-draught ships. Dredging of the entrance channel provides a solution, but this is an expensive option. The challenge, therefore, is to find the maximum safe draught of a particular type of ship for an existing port entrance channel as a function of the tide, wave conditions and ship speed. For the development of a new port, the minimum safe depth for the "design" ships visiting the port has to be determined with an acceptable percentage downtime. In both cases, the accurate statistical determination of wave-induced vertical ship motions is usually a critical component for entrance channels exposed to wave action.

Because of the dependency of the maximum allowable ship draught on the environmental conditions, these have to be monitored, and preferably be predicted, with an acceptable degree of completeness and accuracy. In addition, the marine staff at the ports need an adequate decision support system to allow them to take ship allowance decisions based on proper and reliable data. Such port operational decision support systems can now be developed based on modern computer technology, ocean monitoring and forecast models and in-depth knowledge of ship behaviour in waves.

This paper presents a description of a decision support system for ship draught allowance, in operation at the Port of Richards Bay, South Africa. This system is partially based on small-scale and numerical model tests, which were verified by local measurements of ship motions with simultaneous recording of tide, wave and ship conditions. The measured wave parameters include the wave height, period and direction. Based on these relationships, the maximum safe draught for Richards Bay can be determined as a function of tide, waves, ship size and ship speed. This is implemented in the PC-based DMAX system.

1. INTRODUCTION

During the period 1975 to 1990 an extensive range of physical and mathematical model studies, as well as prototype monitoring, have been undertaken for the Port of Richards Bay, South Africa (Figure 1). This port is one of the largest coal exporting harbours in the world. The aim of these model studies was to determine the optimum depth and use of the entrance channel to the port for deep-draught coal carriers (Cape Size bulk carriers with draughts exceeding 17 m). This led initially to the development of a PC-based Integrated Port Operations Support System (IPOSS), monitoring the environmental conditions around the port.

The IPOSS has been in use at the Port of Richards Bay during the past decades and has been upgraded steadily with regard to sources and input of environmental data and visual display.

Figure 1: View of the Port of Richards Bay

As part of an ongoing process to improve on the efficiency of port operations, the IPOSS was to be expanded with a sceen to display the safe maximum draught of a particular ship, of which the detail was supplied by the operator. The system should directly display the safe maximum draught of the coal carriers, both for arriving and departing vessels, for the present conditions as well as for some time in the future, based on extrapolated or forecasted environmental conditions. This would allow better decisions on the maximum possible loading of the coal carriers upon departure. The expanded IPOSS would contribute to the greater commercial viability of the port, using the existing channel dimensions.

An important component of the work was to verify the wave-induced ship motions obtained earlier by accurate measurements of ship motions made at the Port of Richards Bay (CSIR, 1991). This was realized by using a dual-frequency differential GPS system, with simultaneous recording of tide and wave conditions (Rossouw *et al*, 2001). The measured wave parameters include the wave height, period and direction.

2. MEASUREMENT OF SHIP MOTIONS

The measurement system for the monitoring of the motions of ships was based on the dual-frequency Differential Global Positioning System (DGPS) technology. With this DGPS the motions of a ship can be determined in all three dimension and in time. The used equipment consisted of four Trimble series 7400 GPS receivers. Three were mounted at strategic positions on the deck of departing and fully laden ships, just before departure from the coal berth. A fourth receiver functioned as a base station for the DGPS system. This reference station is a permanent station, installed at Richards Bay Port Control, which also serves as a base station for a DGPS directional wave buoy (Rossouw *et al*, 1999). A UHF radio link was used to transfer the base station information to the remote mobile stations.

The system operated as a DGPS system with Real-Time Kinematic (RTK) and On-The-Fly (OTF) technology that can position (moving) objects in the x-, y- and z-plane. Depending on the position of the satellites at the time of measurements, the accuracy of the system can be about 3 cm (Trimble, 1996; Davies, 1996). The horizontal co-ordinates are directly produced in the WGS-84 grid system, where the position of the DGPS base station has to be accurately surveyed. The horizontal and vertical accuracy of the local land survey grid is obtained by taking the height and position readings of a few well established survey benchmarks in the area.

The ship-bound equipment was made as light and portable as possible and consisted of the GPS receiver, GPS antenna, a laptop PC, a UHF radio and a battery pack. One receiver was mounted on the longitudinal center line at the bow of the ship, while the other two were mounted on either side of the bridge extremities (i.e. at port and starboard).

A typical bridge set up is shown in Figure 2. The equipment on board a loaded departing ship was switched on as soon as the ship left the berth. The system recorded data until the ship was approximately two nautical miles outside the main breakwater, which is the end of the dredged port entrance channel. After the equipment was dismantled it was taken to the helipad on the ship's central deck for departure back to shore by helicopter.

Figure 2: Placement of GPS sensor and computer on board a ship

The mobile receiver-units were configured to output a standard string of data every second (i.e. 1 Hz recording interval). This data string was directly recorded by the laptop PC. Each exercise, of a ship transit recording, produced data sets of about 40 to 50 minutes.

The horizontal motion of the ship, or rather of the three GPS sensors, was defined by their varying latitude and longitude. The vertical displacement, between the base station and the GPS sensor on the ship, was represented by the ellipsoidal height.

As part of the study, an accurate survey of the centre line section of the entrance channel was also undertaken. The survey data provided the necessary information to determine the channel bed profile, which is required to establish the relationship between the vertical ship motions and underkeel clearance at any position in the channel. By using the same DGPS sensors for the channel survey and the ship motion measurements, with benchmark checks, the possibility of making an error in the reference datum was minimised.

3. SHIP MOTION ANALYSIS

The DGPS measurement system, as described Section 2, provided the necessary data to allow the analysis of the principal motions of the ship in six degrees of freedom (i.e. surge/speed, sway, heave/squat, roll/list, pitch/trim and yaw/heading/crab angle), as function of time. The measurement exercise focused on ships with a draught of at least 16 m, leaving the port. Ship manoeuvres and vertical motions of 12 fully laden bulk carriers of 150 000 dwt to 180 000 dwt were monitored in this way.

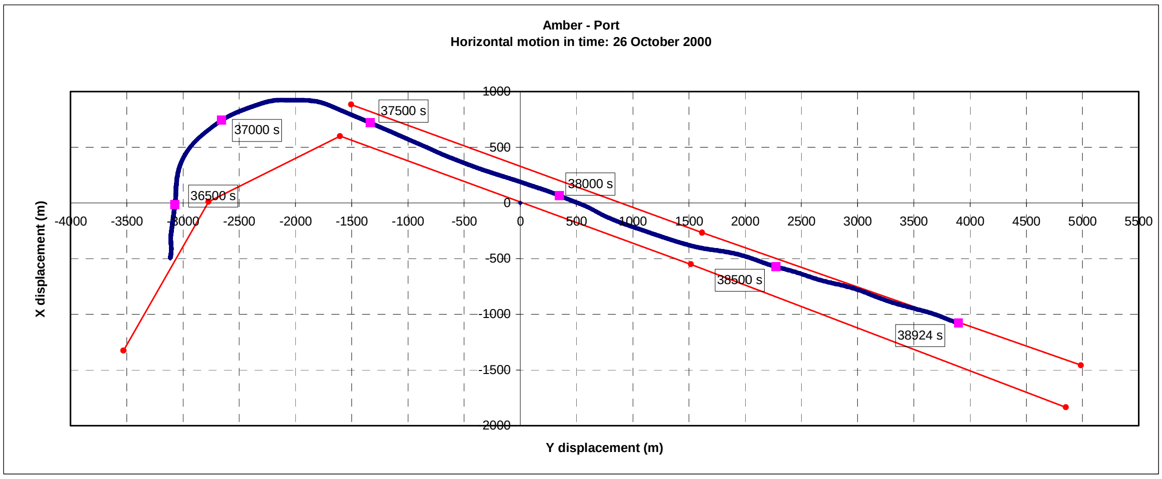

Figure 3: Relative plot of the port-side GPS position of a ship leaving the Port of Richards Bay

The motion data, consisting of the GPS (WGS-84 and Chart Datum) co-ordinates were transformed to x-, y- and z-directions relative to an arbitrarily selected location along the entrance channel. Figure 3 is a typical example of the horizontal motion (x and y) of the port-side GPS sensor on one of the ships from where it left the quay. The boundary lines of the navigation area are also shown. The vertical displacement of this same port-side bridge position, as a function of time, is plotted in Figure 4.

In this figure, the time-average squat has been separated form the wave-induced vertical motions. The increase in vertical motion when the ship leaves the protection of the main breakwater can be clearly seen from Figure 4. The sudden effect of the southerly waves and cross current on the ship, with a resulting drift to portside, when the ship leaves the protection of the main breakwater can be seen from Figure 3.

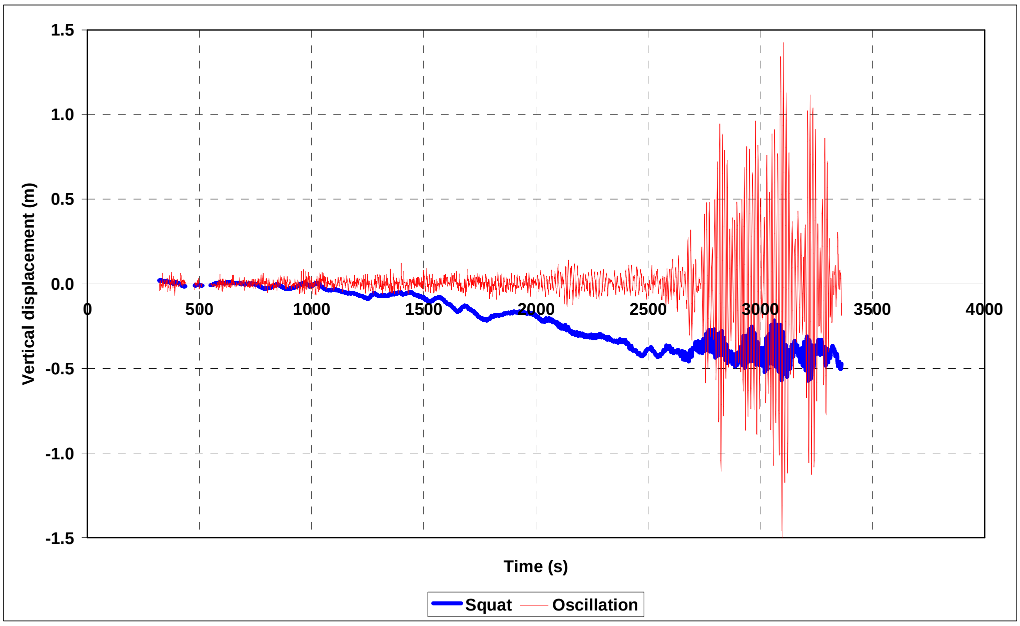

Figure 4: Squat and vertical oscillations as determined from the GPS sensor as function of time

Based on the vertical oscillation data, the principal vertical motions (heave, roll and pitch) can be determined as functions of time. These principal motions can be used to determine the vertical motions of characteristic keel points. The vertical keel point motions, together with the tide, squat and their x- and y-position, can now be compared with the points trajectory along the channel depth chart. The difference between the vertical motion and the channel depth constitutes the actual underkeel clearance.

4. SHIP MONITORING RESULTS

The ship motion data obtained during the measurement exercise provided results specifically indicating ship speed, squat, the three vertical principal ship motions, i.e. heave, roll and pitch, and the vertical keel point motions. From these results, relationships between the dynamic ship motions and the waves can now be established with a high degree of accuracy. The relevant wave parameters available include the significant wave height, wave period and direction.

By combining the vertical keel point motions of each ship with the bathymetric channel bed data the underkeel clearances are being determined. An example of this is given in Figure 5, for the starboard quarter keel point.

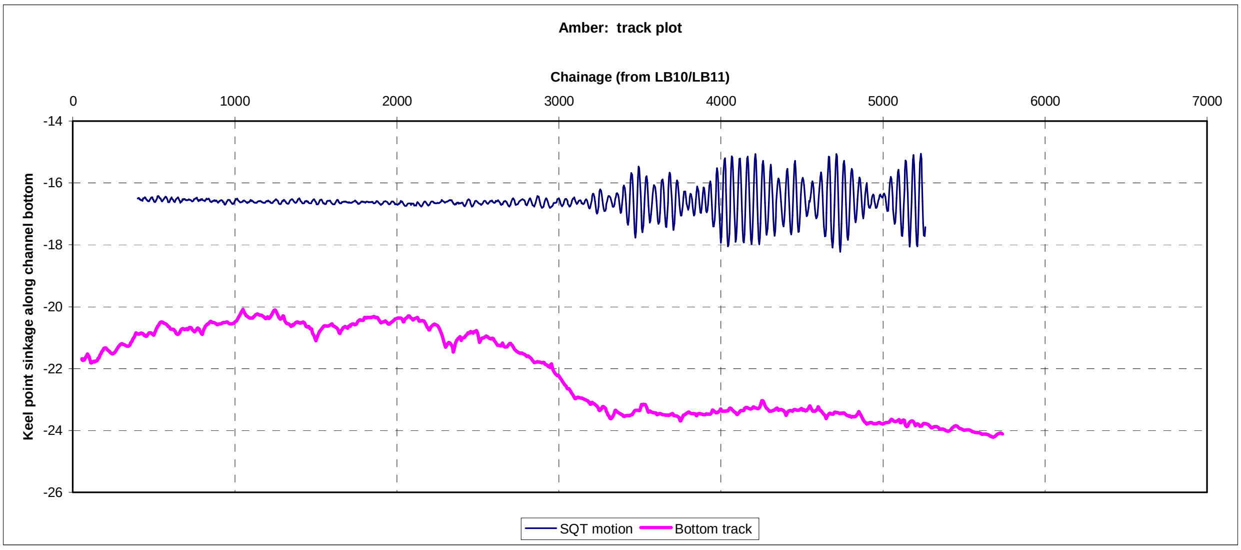

Figure 5: Total vertical motion of starboard-quarter point of ship along channel bed profile

The oscillatory motions represent the total vertical motion of this keel point along the corresponding channel bed profile.

Based on this information it is now possible to determine for each ship, at all six keel points, the underkeel clearance. From these records the minimum instantaneous underkeel clearance can be selected, which is indicative of the safety of the particular channel transit. It is also now possible to develop relationships where the maximum safe draught for ships leaving the port can be determined as a function of tide, wave conditions, ship's draught and ship speed. Some typical results of two of the monitored ships, the Amber and the Ferosa, are listed in the table below.

Ship name	L_{oa} (m)	Beam (m)	Draught (m)	H_{mo} (m)	Direct (deg)	Z_{max} (m)	V_{ship} (m/s)	T_p (s)	T_e (s)	Squat (m)	Tide (m)	UKC (m)
Amber	290,0	46,0	17,5	2,64	154	1,66	4,0	12,8	10,1	0,59	1,33	5,58
Ferosa	298,2	44,7	17,7	2,51	156	1,61	4,6	12,2	9,5	0,62	2,13	6,20

GEOMETRIC SHIP DATA AND VERTICAL RESPONSE OF MONITORED SHIPS

The wave-induced vertical keel point motions Z_{max} have to be assessed for many deep-draught vessels, in view of earlier prototype measurements, small-scale physical model studies and numerical model simulations. During the last monitoring exercise values for Z_{max}/H_{mo} of up to 0,64 were found. The computed underkeel clearance (UKC) has to be related to the time that the ship is in the channel to establish the safety of the manoeuvre with regard to touching the channel bed. For this approach, the safety practice of the Port of Rotterdam is followed (Savenije, 1996). The safety criterion for a single transit of a ship in a confined navigation channel is formulated as : "the chance that a vessel during transit touches the channel bottom must always be less than 1% for all weather conditions". The underkeel values are being assessed in the same way as in the earlier photographic study of ship motions (CSIR, 2001).

The relationship between ship speed and squat can also be derived. It is expected that squat will be related to the square of the ship speed : Squat = $C_{sq}.V_{ship}^2$ (Appendix C of PIANC, 1997). It appears that such a relationship varies with increasing speed and is not the same for all ships. It would appear that in the inner channel the value of C_{sq} is about 0,025 s^2/m, while in the outer wave-exposed channel the value can increase to about 0,035 s^2/m.

5. DMAX SYSTEM

The DMAX system is directly coupled to the IPOSS, installed at Port Control. The IPOSS is set up to collect, amongst others, actual wave heights, periods and directions from the wave buoy offshore, predicted wave heights, periods and directions obtained from the SA Weather Service, and the actual and predicted tide levels for the port (the latter obtained from the South African Tide Tables).

Other port-related data are incorporated in the DMAX computer program. Such data are the proclaimed depths of the four channel sections and the expected ship speeds in these channel sections. The specified wave conditions are directly applicable to the outer channel. According to wave refraction studies, the wave heights in the next less exposed channel section can be taken as 10% of the wave height outside, while the wave directions are taken as being in line with the channel. No wave action is accepted in the other two inner channel sections.

The DMAX system receives the environmental information from the IPOSS, the forecast wave conditions and the user supplied information from the ship (size and speeds) and the siltation or erosion in the entrance channel sections. The siltation levels have to be specified carefully, reflecting the representative and actual siltation level in those parts of the channel where the ship is expected to pass. A good background knowledge of the siltation patterns in the channel is required, for estimates in between hydrographic surveys. This is then used to compute the wave-induced vertical motions of the vessel, as function of tide as predicted for the next few days, for the four sections of the entrance channel.

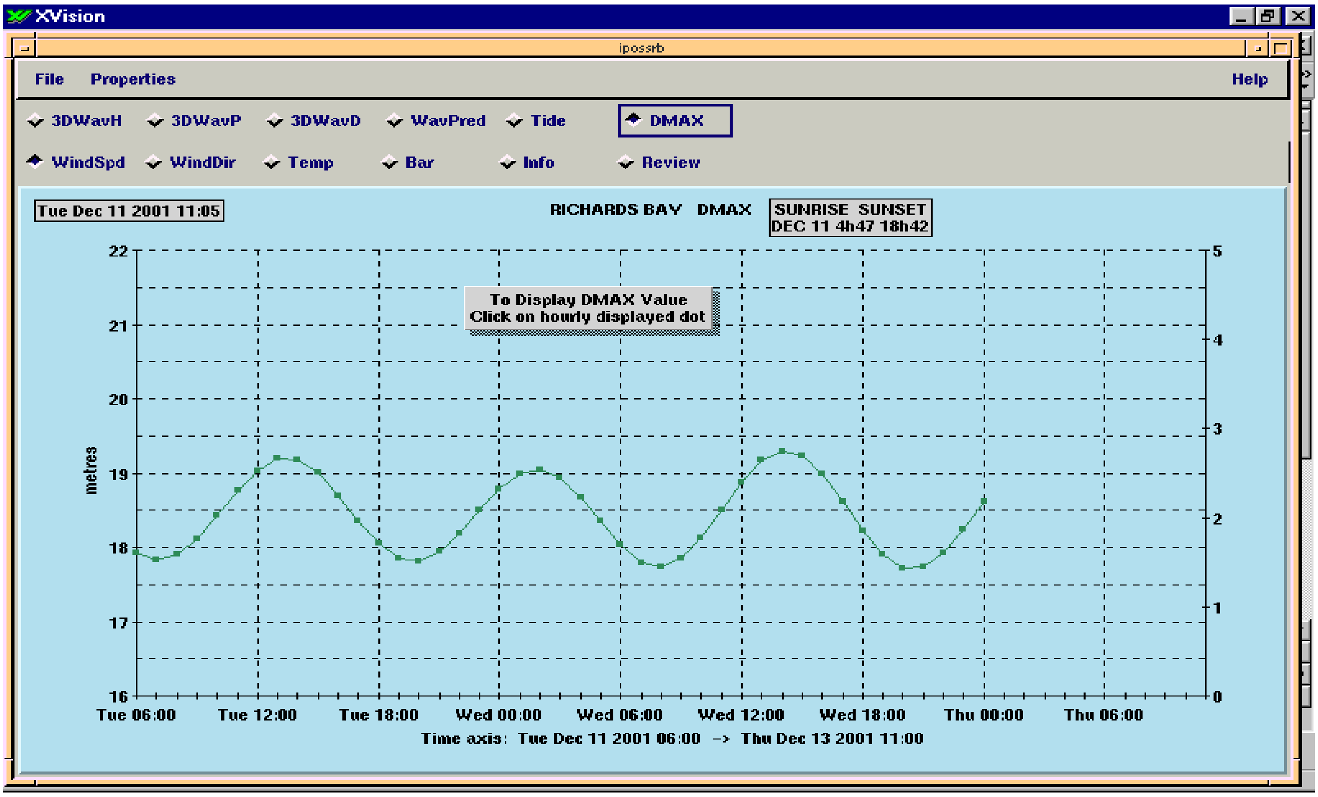

Figure 6: DMAX screen indicating the maximum allowable draught of a ship as function of time

The maximum allowable overall draughts are displayed on the DMAX output screen. The operation and application of the DMAX system is described in a User's Manual (CSIR, 2001). The DMAX results are displayed as shown on Figure 6. The green line displays the maximum allowable draught of that particular ship, using the conditions supplied by the user together with the present and forecast environmental conditions.

6. CONCLUSIONS

An effective DGPS-based method has been used to determine ship motions in a port and its entrance channel with a high degree of accuracy. This allows accurate assessment of the use of existing harbour channels by deep-draught ships. Such measurements are very useful in verifying the results of small-scale physical or numerical models.

By incorporating the ship response characteristics due to waves, the environmental conditions at the port and the particular conditions of the port and the entrance channel into a computer system, such as DMAX, an effective decision support system for the marine staff for the allowance of individual deep-draught ships can be created. Reliable allowance policies, such as at the Port of Richards Bay, can be established in this regard, which will benefit the economic use of the port.

In addition, downtime computations can be made to determine the best long-term policy for the port with regard to advertised ship size and draught for the port.

ACKNOWLEDGEMENT

The work reported in this paper was commissioned and financed by the National Ports Authority (NPA) of South Africa. The author kindly acknowledges this support, as well as the active co-operation of various NPA staff members in the Port of Richards Bay.

REFERENCES

CSIR (1991). Ship Motion Studies : Optimum use of the Port of Richards Bay by larger ships : Executive summary report. CSIR Report EMA-C 90158, January

CSIR (2001). DMAX User Manual : A system for the determination of the maximum allowable draught of bulk carriers. CSIR Report ENV-S-C 2001-111, December

Davies, J (1996). Wave simulation measurement with GPS: a revolutionary way to monitor wave energy, direction, tidal changes using DGPS. Sea Technology, pp 71-72, Reprint : ENV/S-R9603

PIANC, 1997. Approach channels : a guide for design. Supplement to PIANC Bulletin No 95, June.

Rossouw, M, Davies, J, Coetzee, L and Kuipers, J (1999). The wave recording network around the South African Coast. Proceedings of the 5th International Conference on Coastal and Port Engineering in Developing Countries. Cape Town, April

Rossouw, M, Moes, J, Kuipers, J and van Loon, F (2001). Ship motions in wave-exposed port entrance channels. Proc Inaugural Int. Conf. On Port and Maritime R&D and Technology, Singapore, October, pp 307-312

Savenije R Ph A C (1996). Probabilistic admittance policy (for) deep-draught vessels. PIANC Bulletin No 91, June

Trimble (1996). Series 7400 Operation Manual. Revision: A. Part number: 31463-00. Surveying & Mapping Division, Trimble Navigation Limited, USA. November