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Innovative technologies to accurately model waves and moored ship motions

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Abstract

Late in 2009 CSIR Built Environment in Stellenbosch was awarded a contract to carry out extensive physical and numerical modelling to study the wave conditions and associated moored ship motions, for the design of a new iron ore export jetty for BHP Billiton, at Port Hedland in north-west Australia. International consultants WF Baird and Associates are reviewing all technical aspects of the project and also have staff attending the tests. The project had tight deadlines and required extreme accuracy of modelling due to the small nature of the long-period design waves. It is this long-wave energy that has the ability to excite the large moored bulk-ore carrier vessels, which can be in excess of 300 000 Dead Weight Ton (DWT).

A numerical model of the 1:100 scale laboratory wave basin of 35 m by 60 m has also been set up to verify the numerical modelling approach. Direct use of the physical model results for vessel downtime calculations is not realistic since the area of interest is much larger than the modelled domain. Therefore the calibrated numerical model will be used, after verification, to model all the different combinations of extreme wave, wind and current conditions.

Waves in the scale model are generated by a 24-m-long bank of shallow water wave generators (recently imported from the UK). Research was also carried out to ensure that the boundaries of the physical model were covered with a wave-absorbent slope to eliminate erroneous wave reflections. Model waves were also accurately measured (to 0,2 mm) by a CSIR-developed Keofloat system at each berth and in the basin, using video image processing technology. A similar technology was used to measure the moored ship motions. Strain gauges were used to measure mooring and fender forces.

Another aspect of the model study was to physically and numerically model the effect of loaded ships passing close to the moored vessels. This proved to be a critical aspect of the terminal design, as the allowable passing distance would have a significant effect on the area and volume of seabed required to be dredged. The operational safety of the moored vessels during loading also had to be determined as part of the design. Any downtime or delays to these large vessels could be very costly to the terminal operators.

This project highlights the many technologies developed and used by the CSIR to undertake specialist studies, both physical and numerical, to support the design of safe harbours and terminals. This paper will briefly describe those key technologies.

1 Physical modelling

1.1 Wave basins available at the CSIR – deep and shallow, plus flumes – scales

The CSIR's Hydraulics Laboratory at Stellenbosch has one of the largest model halls available worldwide, in comparison with the other top international coastal engineering laboratories. This allows the choice of a larger scale and/or larger coverage of the area to be modelled. The 35 m by 60 m model basin (see Figure 1) represented a prototype area of 3,5 km wide by 6 km long, which covered the whole proposed new dredged basin and approach channels at a 1:100 scale. This is important as it permitted the inclusion of adequate offshore and adjacent bathymetry in front of the wave generators to obtain a true representation of the local wave field, allowing the full effects of free surface gravity waves. Two other large 3-dimensional (3D) basins and a number of 2-dimensional (2D) flumes are also available within the CSIR Hydraulics Laboratory.

Figure 1: CSIR model wave basin

1.2 New wave generators and their capabilities

The basin was orientated so that the main incident wave direction could be generated perpendicular to the 24 m bank of wave paddles (new movable wave generators imported from the UK, see Figure 2). The wave conditions that were tested focused on the long swells that could excite low-frequency ship motions. The paddles are driven by signal-generation software capable of creating short crested waves with set-down compensation to simulate second-order boundary conditions, thereby forming the theoretical bound long waves required to test the motions of the moored ship. The measured target wave spectrum was smoothed such that the spectral shape and total wave height were retained, but the high-frequency tail of the spectrum and any sea waves were discarded, because these waves have little effect on ship motions.

Figure 2: Movable wave generators

1.3 Wave absorption slopes and basin resonance

The wave generators are equipped with active wave absorption, however, this feature was turned off for these particular model tests because the required absorption of very small long waves (2 to 3 mm model wave height) were better absorbed at the model boundaries. This absorption was achieved by placing a wide slope of small stones around the model boundary walls. The optimum width, slope and size of stone were tested in a 2D wave flume before being placed around the 3D basin. The achieved wave reflection off the boundary walls was less than 15%, which allowed accurate simulation of the prototype waves at the moored ship's jetty location. Another strategy to improve the accuracy of the model was to place loose stones behind the wave generators and wave guides on the sides of the model. This had the desired effect of eliminating any spurious basin resonance.

1.4 Wave gauges – capacitance probes and Keofloats

Due to the small size of the waves (long waves as small as 0,2 mm model scale) and the extreme accuracy of measurement required, two separate wave-measurement systems were employed in the physical model. Capacitance probes were used for the larger waves closest to the wave generators, while Keofloats were used for the smaller waves close to the moored vessels and at the back of the dredged basin. Figures 3A and 3B show a capacitance probe and a Keofloat on the left and right, respectively. Capacitance probes have an accuracy of about 0,5 mm and consist of twin wire gauges attached to an amplifier. Through calibration, the voltages obtained as output are coupled to the corresponding water level.

Figure 3A: Capacitance probe

Figure 3B: Keofloat

When it became necessary to measure waves much smaller than 10 mm in the model, for which the noise levels on the signal become significant for traditional resistance and capacitance wave gauges, a new system was developed by the CSIR, consisting of small lightweight floating blocks, called Keofloats (see Figure 3B. These floats are tracked by a standard video camera and are insensitive to erratic gauge drift. Noise levels are therefore very low and they do not require separate calibration. The accuracy is estimated at 0,2 mm. The Keofloat system has been tested in a flume and compared with capacitance probes (Terblanche et al., 2009). It was concluded from the flume tests that the Keofloats are superior to traditional wave gauges for wave heights of less than 5 mm. Keofloats are equivalent to wave gauges for wave heights between 5 mm and 20 mm. The results of the flume test comparison are shown by the plots in Figure 4.

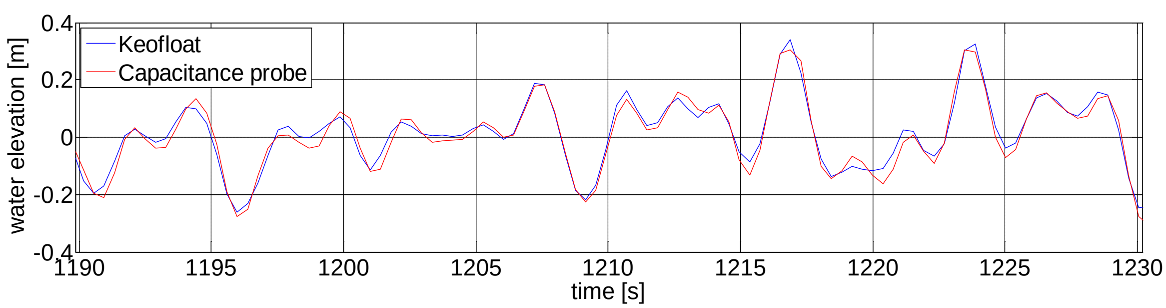

Figure 4: Results of the flume test comparison

1.5 Model ship set-up

The CSIR has a number of scaled model ships available, but for the Port Hedland model study, three new model ships were constructed. These were 150 000 DWT, 205 000 DWT and 320 000 DWT bulk carrier vessels. Line drawings of the ship's hull are loaded into a computer-controlled cutting machine, which cuts the exact hull shape from a block of high-density polyurethane foam. The foam is then covered with a thin waterproof layer of smooth fibreglass. The ships are made hollow and ballasted with lead blocks to achieve the correct mass and weight distribution. The vertical placement of blocks is calibrated such that the centre of gravity is at the correct height, while the horizontal placement is chosen such that the moments of inertia for pitch and roll are correct. The model ship is placed in a cradle (Figure 5) to determine the longitudinal moment of inertia from the period of free oscillation. The transverse moment of inertia is measured from the free roll period in water.

Figure 5: Model ship in cradle

1.6 Moored ships and Keoship measurement system

The motions of the moored ships are measured with the Keoship video monitoring system developed by the CSIR (Van der Molen & Hough, 2009). Two light metal strips are placed on the deck of the model ship, one at the bow and one at the stern (see Figure 6). Two mirrors are placed at 45°, extending from the quay above the metal plates, and two video cameras are placed alongside the ship at a distance of about 10 m (model scale) to focus on the metal strips. The cameras then track the movements of the black and white interfaces painted on the strips, from which the six degrees of motion of the ship are calculated by computer. The determined accuracy of the Keoship system is 0,1 mm model scale or 10 mm prototype scale at 1:100. The accuracy of the measurement of angular ship motions is 0,04° for roll and 0,01° for pitch and yaw.

Figure 6: Light metal strips placed on the deck of the model ship

1.7 Fender and mooring line force measurements

Besides the measurement of moored ship motions and the calculation of forces in fenders and mooring lines, the forces in the fenders and mooring lines are measured directly as well. The model fender pads and mooring lines are connected to calibrated cantilevered metal strips, fitted with strain gauges. Each strip has the correct linear load-deflection characteristics of each scaled fender or mooring line.

The fenders are modelled as Teflon pads (with the correct friction coefficient) attached to the calibrated metal strips, which are firmly fixed at the correct spacing on the model berth (Figure 7). The resolution of the measured fender forces is 0,3 mN model scale or 300 N prototype scale. The mooring lines are modelled as thin, but stiff, synthetic ropes, along with a spiral spring with a known stiffness factor. The ropes run over correctly positioned pulleys on the berth to the cantilevered metal strips with mounted strain gauges. Forces in the fenders and mooring lines can also be calculated from the measured ship motions.

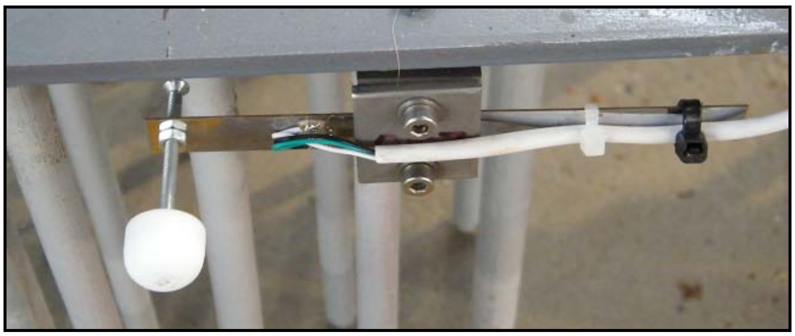

Figure 7: Fenders modelled as Teflon pads attached to the calibrated metal strips

1.8 Passing ship tests

After the tests to study wave propagation and moored ship motions, model tests were conducted to study the effect of passing ships. For these tests a ship was pulled along a rail according to a predefined straight track along the jetty at a certain distance from the moored ship. The waves and water flow generated by the passing ship would interact with the moored ship, causing it to move. Similar to the other ship motion tests, the motions of the moored ship were measured with the Keoship video monitoring system and the forces in fenders and mooring lines were recorded with strain gauges. About 40 model tests were executed to test different passing distances, speed and orientation of the passing ship, for ships in ballast entering and loaded ships leaving the port.

2 Numerical modelling of ship motions

Research at the CSIR's Coastal Engineering and Port Infrastructure Group over the last two years has led to the development of three new numerical models for moored ship response and wave-ship interaction. These models are:

- WAVESCAT, which is a boundary-integral equation model (BIEM) to compute wave forces and hydrodynamic forces on a ship or other floating bodies
- PASSCAT, which is a BIEM to compute hydrodynamic forces on a moored ship due to another ship passing in a channel or a fairway
- QUAYSIM, which is a time-domain ship motion simulation model to compute the ship motions and mooring line forces of a ship moored at a quay or a jetty due to waves, current and wind.

These models are interconnected in such a way that the results of PASSCAT and WAVESCAT feed into QUAYSIM to determine the motions of a moored ship in irregular short-crested waves or due to a passing ship. Brief descriptions of the three models with application to the Port Hedland Iron Ore Project are given in the following subsections.

2.1 WAVESCAT – wave forces on ships

The boundary-integral equation model WAVESCAT is used to compute the forces on a ship in regular waves and to compute the hydrodynamic coefficients due to a ship oscillating in still water. The ship's hull and the submerged surface of other nearby structures are covered with a large number of flat quadrilateral panels on which the pressure and the velocity in the fluid is computed. Integration of the pressures over the submerged hull gives the total wave force on the ship. An example of a panel description of a container ship moored at a quay is shown in Figure 8.

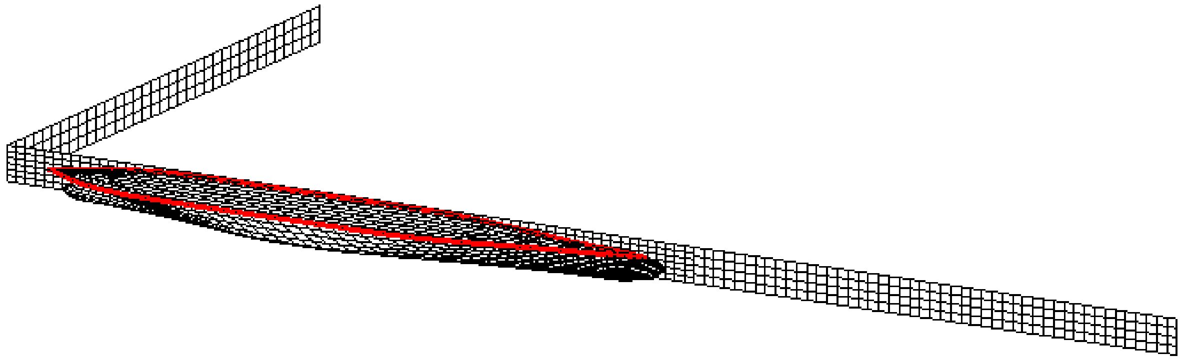

Figure 8: Panel description of a container ship moored at a quay (WAVESCAT model)

2.2 PASSCAT – forces due to a passing ship

Ships sailing in a channel in a port can cause problems for ships moored at berths alongside the channel. The passing ship induces a return flow with an inherent pressure drop, due to which a ship can be pulled off the berth. Ships breaking away from a berth have been reported in the past, causing huge damage and fire (for an oil or gas terminal).

Model tests in the past have led to the development of empirical design formulae for the forces on a moored ship due to a passing ship. However, these formulae are only valid for specific situations. For a different range of ship sizes or water depths, numerical models should be used to compute the passing ship effects accurately for these particular conditions. The model PASSCAT has been developed to compute the flow generated by the passing ship and to compute the resulting hydrodynamic forces on the moored ship. The model is comparable to WAVESCAT, but with a simplified boundary condition at the free surface and with the inclusion of a constant speed of the passing ship. A panel description of one ship passing another is shown in Figure 9.

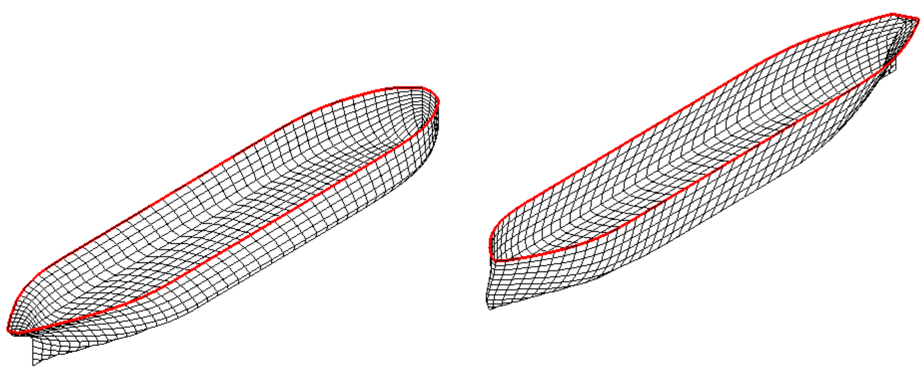

Figure 9: Panel description of one ship passing another (PASSCAT model)

2.3 QUAYSIM – simulation of ship motions

QUAYSIM is a time-domain ship motion simulation model. The wave forces are determined from the wave force transfer functions as computed with WAVESCAT, and the effect of radiated waves formed by the oscillations of the ship are included using impulse response functions. The interaction of the ship with non-linear mooring lines and fenders is also included. An example of a schematised mooring layout of the ship with mooring lines and fenders is presented in Figure 10. In this way the non-linear behaviour of the moored ship can be computed and the maximum ship motions and forces in mooring lines can be compared with criteria for the safe loading and unloading of ships.

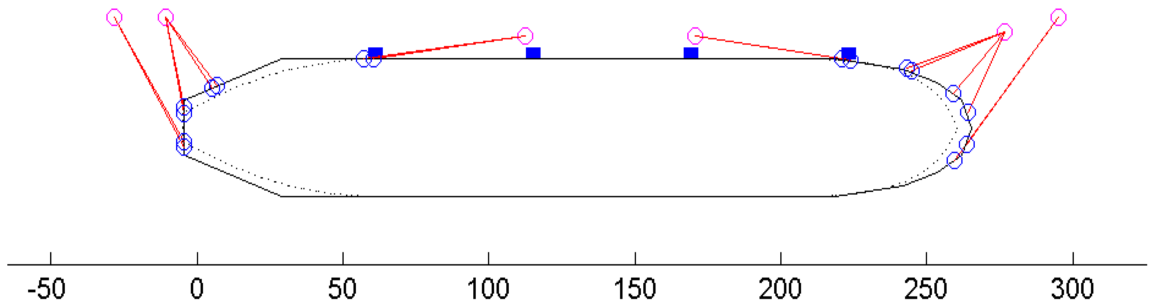

Figure 10: Schematised mooring layout of ship with mooring lines and fenders (QUAYSIM model)

2.4 Modelling of long waves

Long waves associated with non-linear properties of the propagation of short-wave groups in shallow water are the main concern for large ships moored in coastal waters. The effects of the bathymetry, the shape of dredged basins, oscillation in harbour basins and reflections of long waves from the shore can play a significant role. This means that the modelling of long waves is not straightforward and that an area much larger than the berth should be considered. The long-wave model Delft3D-Surfbeat, developed at Deltares in the Netherlands, was used to determine the wave propagation in the shallow areas and propagation of long waves into the dredged areas for the Port Hedland project. Subsequently, the forces on the ships could be computed from the calculated long-wave elevations and velocities at the berth (Van der Molen, 2006). These wave forces feed into QUAYSIM to determine the ship motions and the forces in mooring lines and fenders.

3 Validation

The main objective of the physical modelling study was to validate the numerical modelling procedure. For this purpose the wave basin area was modelled in Delft3D-Surfbeat. The same wave conditions were modelled numerically and the results compared with the model test measurements. In this way, a direct comparison could be made for the specific terminal environment, under controlled conditions and with the availability of wave measurements at about 30 locations. The wave forces on the moored ships and the resulting ship motions could be calculated from the Delft3D-Surfbeat results, and the motions and forces in fenders and mooring lines compared with the physical model measurements.

The main objective of the passing ship model test series was also to validate the numerical modelling procedure. The hulls of the two ships were included in PASSCAT, along with the bathymetry of the dredged basin and the passing ship progressing in the model according to the orientation and speed of the ship along the rail in the physical model. The resulting moored ship motions and forces in mooring lines and fenders could be compared with the physical model test measurements.

4 Conclusions

Several new measurement techniques for small-scale physical modelling and new numerical models were applied successfully at the CSIR's Hydraulics Laboratory to assist with the moored ship response studies for one of the largest bulk terminal projects. The combination of new state-of-the-art (or better) numerical models in combination with highly accurate physical model measurements guaranteed good confidence in the results, which in turn contributes to the safety and economically efficient design of the new iron ore terminal. Although these techniques were developed for a study for a client in Australia, they will also be available to benefit port and terminal applications in Africa.

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