GENERAL CHARACTERISTICS OF SOUTH AFRICAN PORTS AND THE SAFE MOORING OF SHIPS

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ABSTRACT

In this paper, mooring problems in South African ports are discussed. The main cause of these problems is identified as the occurrence of long waves and, to some extent, harbour seiching. The oscillatory characteristics of moored ships are discussed in a simplified but illustrative way. The characteristics of the long waves, based on analysis of measured wave data, are discussed. Unique aspects of a number of ports, as related to the increase or decrease of long-wave height, are presented. Measures to improve long-wave port tranquility and mooring conditions are suggested.

INTRODUCTION

A number of ports in South Africa have experienced problems with moored ships. The first port where significant problems occurred was the Port of Cape Town, especially during the period 1941 to 1944. This concerned naval and general cargo vessels of up to 10 000 dwt. Wilson (1959) and Joosting (1959) have investigated these problems and concluded that the main cause was long-period waves. These waves were amplified in Duncan Dock as standing waves. With later modification to the layout of Duncan Dock and the construction of Schoeman Dock, and proper physical and numerical model testing (Botes *et al*, 1982), the problems in the Port of Cape Town have almost disappeared.

A second South African harbour where significant mooring problems are still being encountered was the Port of Saldanha (see Figure 1). This port was completed in 1976 and was built for the export of iron ore and the import of oil, receiving bulk carriers and tankers of up to 300 000 dwt, moored at an open jetty. During the 1980s the mooring problems are investigated by the CSIR (Moes & Holroyd, 1982). It was concluded that also in this port long waves were the cause of the mooring problems (Moes, 2003). In this case, however, no long-wave resonance did occur in the open bay, but rather a focusing of long-wave energy at the jetty area. The solution was sought and is still being applied in optimization of the mooring lines layout.

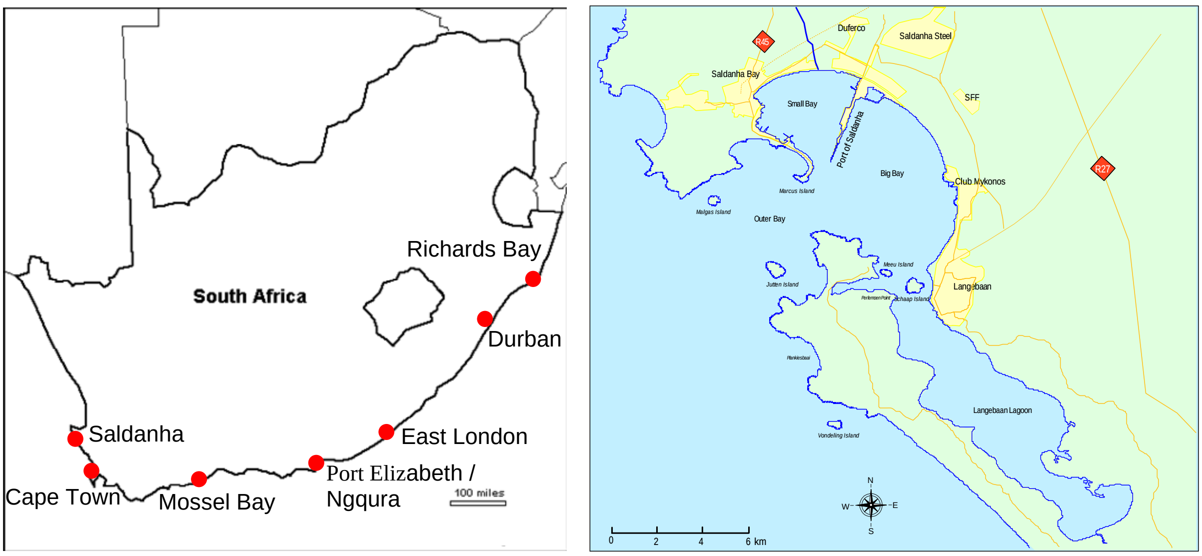

Figure 1: Location of South African ports and layout of Saldanha Bay

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For the design of the new Port of Ngqura (Coega), near Port Elizabeth (see Figure 1), it was concluded from wave recordings that long-wave energy was also present in Algoa Bay. Extensive model studies were undertaken to optimize the mooring conditions for bulk carriers and container vessels in the port.

The above identified adverse mooring conditions have resulted in continuous attention to long waves for mooring conditions in South African ports. Various countermeasures and warning systems have been put in operation. These will be illustrated and discussed in this paper.

GENERAL STATISTICS OF SOUTH AFRICAN PORTS

The eight main ports of South Africa are operated by a central South African ports authority Transnet NPA. The eight ports, indicated in Figure 1, are from west to east: Saldanha Bay, Cape Town, Mossel Bay, Port Elizabeth, Ngqura, East London, Durban and Richards Bay. The cargo handling statistics of these ports are given in Table 1 together with the ports of Walvis Bay and Maputo, which also take a share of the import and export of South Africa. Measured in cargo volume Richards Bay is the largest port of South Africa; measured in economic value Durban is the largest port. The main export ports for the South African mines are Richards Bay and Saldanha Bay, while the other ports are used more for industry products and fishery. Saldanha Bay and Richards Bay are designed for the largest bulk carriers in the world. The design vessel for the Port of Saldanha is a 250 000 dwt bulk carrier with a draught of 20.5 m. The entrance channel to the Port of Durban is currently being widened, so that the near-largest Post-Panamax container ships with a capacity of 9 000 TEU, a draught of 14.5 m and a beam of 49 m can call at the port.

The main requirements of a port are important input for a port designer and hydrodynamic modeller. The criteria for movements of moored ships are much stricter for container ships and car carriers than for bulk carriers and tankers, with a related difference in the criteria for wave penetration in the harbour. Therefore, the Port of Saldanha Bay can be relatively open to the sea and the oil berths in Mossel Bay and Durban can be located outside the harbour basins.

Table 1: General statistics of Southern African ports

Port	Main functions	Throughput[1]	
		Bulk (Mton)	Containers (x1000 TEU)
Walvis Bay	Fish, containers	3.0[2]	71[2]
Saldanha Bay	Iron ore	46.5	-
Cape Town	Containers, fish, marine repair works	3.2	768
Mossel Bay	Fish, oil products	2.0	-
PE / Ngqura	Containers, fish	5.4	424
East London	Cars, containers	2.0	57
Durban	Containers, oil, cars, grain	41.4	2 642
Richards Bay	Coal	84.5	9
Maputo	Coal, aluminum, sugar	5.3[3]	100[3]

[1] Statistics of South African ports based on 2008
[2] Statistics from 2005
[3] Statistics from 2007

METEOROLOGICAL CONDITIONS

Problems with excessive motions of moored ships are most often related to waves from the ocean. The most notorious are waves generated in meteorological low pressure systems (extra-tropical cyclones) that pass through the southern Atlantic Ocean and impact on the south-western shores of the continent during the winter months May to September. The ports of Saldanha, Cape Town, Mossel Bay and Port Elizabeth/Ngqura are all located such that they are sufficiently protected against large swells from the south-west.

The design condition for Richards Bay is for tropical cyclone waves originating from the warm waters of the Indian Ocean, although such a cyclone does not occur as frequent at Richards Bay as along the shores of Mozambique and Madagascar.

Wave-driven currents in the surf zone are strong along the shores near Durban and Richards Bay and have a major impact on the design of the breakwaters and the shipping channel. However, the current at the berths inside the harbour is insignificant.

Strong winds can be factor on tall ships such as container ships and car carriers. Mooring problems have been reported at the Port of Cape Town, also concerning oil rigs docked for repair, during storm winds.

AMPLIFICATION OF MOORED SHIP MOTIONS

A moored ship can be considered as a simple mass-spring system with an oscillatory forcing due to waves. The equation of motion is

$$(M+a)\ddot{X}+b\dot{X}+kX=F\cos(\omega t+\varepsilon_F) \quad (1)$$

where X is the motion of the ship, M is the displacement of the ship, a is the added mass of the oscillating water mass surrounding the ship, b is the damping, k is the spring stiffness which refers to the stiffness of the mooring lines and fenders for the horizontal ship motions, F and ε_F are the amplitude and phase, respectively, of the wave force oscillating with angular frequency ω.

The natural frequency of such a mass-spring system is defined as $\omega_0 = \sqrt{\{k/(M+a)\}}$ with the natural period $T_n = 2\pi/\omega_0$. The response of the ship for different frequencies is presented in Figure 2. The added mass and damping are assumed constant for simplicity, but they are dependent on frequency in reality. The damping consists of wave radiation damping due to waves radiating away from the oscillating ship and viscous damping in the fluid and in the mooring system. It is noted that all these terms are small for low-frequency horizontal motions.

The natural frequencies of the vertical motions heave, roll and pitch are in the order of 8 to 25 s for sea-going ships and hence in the range of swell periods. However, these motions are usually not important for the loads in the mooring lines and fenders which are mainly determined by the horizontal motions, surge, sway and yaw. The natural periods of these motions are as large as 2 to 3 minutes for large bulk carriers and about 1 minute for container ships.

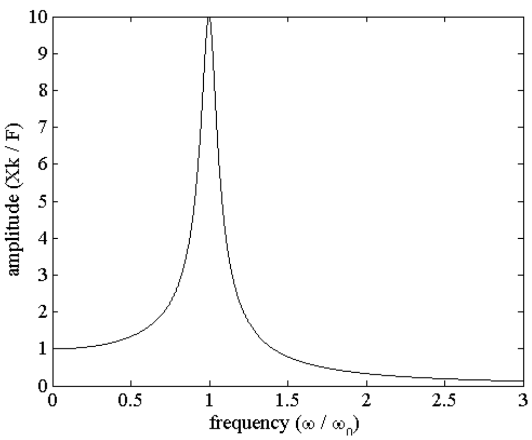

Figure 2: Response amplitude of the ship as function of the frequency relative to the natural frequency. The assumed damping is 0.05 times the critical damping

LONG-WAVE CHARACTERISTICS

Over the past 50 years, mooring problems have been experienced even with well-designed harbours. Quite a number of these mooring problems can be attributed to low-frequency environmental forcing, especially long waves. Many old harbour basins have a fairly rectangular plan shape, with a relatively constant depth. Such basins have well-defined natural periods of water oscillation (see e.g. Wilson, 1959). If the water levels in such basins are agitated by forcing of similar frequencies, this leads to resonance or seiching.

Resonance in harbour basins is caused by long waves, generated by the ocean weather systems and by wave-wave interaction. Basically, two types of long waves are distinguished, bound long waves and free long waves. Bound long waves are associated with the groupiness of swell and have the same length as the group length. Free long waves are generated directly by ocean weather systems. They can also be generated at the surf zone, where the swell breaks and the bound long waves are set free and reflect from the breaker zone.

A particular aspect of long waves, which renders it difficult to mitigate their effect, is their large wave length. For example, in a typical harbour situation, with a water depth of 20 m, a long wave with a period of 100 s will have a wave length of 1.4 km. For a wave height of 0.2 m, the maximum slope of such a wave will be about $44 \cdot 10^{-3}$. Since the long-wave lengths are so large and the slopes are so small, it is very difficult to absorb these waves with artificial structures. A ship with a mass of 100 000 tons, if moored in such conditions, will experience a horizontal force of about 440 kN. This will then be the amplitude of the cyclic horizontal forcing on such a vessel, leading to surge, sway and yaw motions of the ship, depending on the ship's orientation relative to the long waves.

A typical example of a wave spectrum is given in Figure 3. This spectrum has been measured near the shore at a water depth of 10 m with a wave height of 2.4 m. The wave energy is plotted against the wave frequency. Most wave energy is concentrated around a frequency of 0.06 Hz (T = 16.7 s) which is a typical long swell. However, the driving force for horizontal ship motions is due to the wave energy concentrated near the small peak at f = 0.005 Hz (T = 200 s). This low-frequency peak is rather wide in open water, but there can be a few sharp peaks in a harbour basin, coinciding with the resonance periods of the basin.

When moored ships are exposed to bound or free long waves (directly or indirectly through basin resonance), and their natural period of oscillation is close to the period of the long waves or harbour oscillations, large vessel motions can occur, even though the wave height of the long wave may only be a couple of decimeters. This has been experienced specifically with the present development to build harbours, ports and terminals near the open ocean (near deep water). A good understanding of these long waves and their effect on moored ships is important to avoid or alleviate long-wave problems on moored ships.

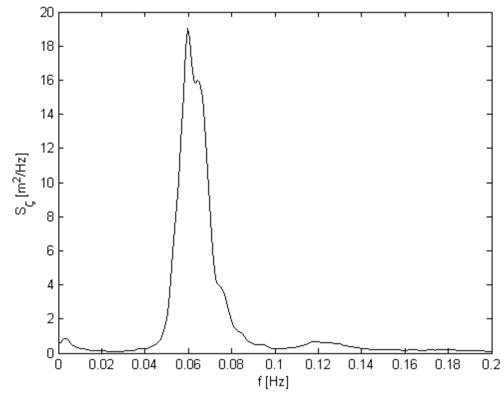

Figure 3: Typical measured swell and long wave spectrum

COUNTERMEASURES APPLIED IN SOUTH AFRICAN PORTS

There are a number of potential ways to improve mooring conditions in the case where long waves cause adverse conditions. It should, however, be realized that changing the long-wave frequency range is almost impossible. Therefore, the local long-wave energy distribution (the shape of the spectrum) has to be accepted as a given, while the long wave height, resulting from wave groupiness, can be influenced. Each particular harbour will have different options to mitigate possible problems with moored ship motions. Examples of such measures or conditions for a number of South African ports are briefly discussed below.

Port of Saldanha

The port is situated in a bay that is open to the ocean, with a relatively wide entrance (see Figure 1). Long-wave energy enters the bay mainly bound to the incoming swell. It had been considered to construct an additional breakwater at the entrance, but this appeared to be too costly, while its effect could not yet be quantified with sufficient accuracy. The wave heights at the jetty are reduced mainly by refraction and energy dissipation at the entrance to about 15% of the wave heights in the open ocean. Long-wave heights of up to 0.45 m have been recorded at the jetty. It has been established that for long-wave heights exceeding 0.15 m, mooring problems can be expected.

The swell breaks along the inner shores of the bay and the freed bound long waves are reflected from these shores to focus on the central area of the bay, where the terminal is located. This forms a very unfavourable condition, which should be avoided by future port expansions. Surge motions of up to 8 m have been recorded for ore carriers of up to about 250 000 dwt, while at one incident a ship broke 12 of its mooring lines (CSIR, 1987).

The emphasis has been on optimizing the mooring line layout, by ascertaining that the loads in the mooring lines are evenly distributed over the available mooring lines. Also an additional fender support point at the bow location of the tanker terminal has been constructed. This has led to some improvement, while simultaneously the general size of ore carriers using the port has reduced, with a reduction of general mooring resonant periods. A vessel monitoring program is being set up with which the forces in mooring lines will be monitored continuously at the mooring hooks and the motions of the ship are tracked by a digital video camera placed on top of a chimney at the jetty. With this system the berthing master can be warned in time and he can take appropriate action, such as checking the tensioning of the lines to reduce large sway motions or even order the ship to leave the berth due to hazardous mooring conditions.

Port of Cape Town

The port has been notorious for basin resonance in Duncan Dock. However, after the modifications in the layout of the Dock in 1966 and especially after the construction of Schoeman Dock in 1977, the problems of resonance have almost disappeared. These conditions were realized after extensive prototype measurements and small-scale physical and numerical model studies (Botes *et al*, 1982). Therefore, moving away from a rectangular basin shape and de-tuning basins with each other appears to have been an effective solution to the mooring problems in the Port of Cape Town.

Port of Ngqura (Coega)

Ngqura is a new port. The construction has been completed in 2007. The lessons learned from the long wave problems at the Ports of Saldanha and Cape Town were applied to this port and its layout design. Early during the feasibility studies for the port, a wave pressure sensor (S4) was deployed at the site in about 17 m water depth. Spectral analysis of the data revealed the (expected) presence of long waves and quantified its correlation with local swell conditions. Numerical model studies were undertaken to optimize the port layout with respect to resonance. Resonant conditions were identified with the initial conceptual layout and these conditions were mitigated where possible.

Subsequently, an extensive series of small-scale physical model studies were carried out, with particular emphasis on the effect of long waves on the moored ships. An innovative moored ship monitoring system was developed, based on digital video image analysis (Moes & Hough, 1999). These investigations have resulted in the design of a port that will be able to accommodate container vessels with very strict requirements on maximum moored ship motions (in this case 0.3 m as maximum horizontal motion for 6 000 TEU vessels, with acceptable forces in the prescribed stiff Dyneema mooring lines).

Port of Durban

The Port of Durban has developed over the past 150 years into the Natal Bay. Due to the sand banks in the bay, the port facilities have only been developed in the deeper part of the port, and at a relatively irregular layout shape. However, this has had the advantage that (unkonowingly) long wave energy in the port has been damped by the sand banks, while the irregular shape of the port has prevented long-wave resonance. Due to the more benign wave climate off the coast of KwaZulu-Natal, it is expected that the long-wave conditions will be much less severe than at the South African west and south coast. However, recent measurements, in connection with the planned port extension, have confirmed the presence of long wave energy in this port as well.

Port of Richards Bay

The Port of Richards Bay is the most northerly port of South Africa. It has been developed in the Mhlatuzi River Estuary. This estuary and the present port are also characterized by the presence of shallow sand banks. Due to reported mooring problems in the port, a long-wave recorder has been installed in the port for some time. However, it appeared that the occurrence of long waves is very incidental and that in general the mooring conditions in the port are not affected by the presence of long waves.

Recent development of a novel mooring system

It should also be mentioned that a novel system for the mooring of ships has been developed in New Zealand. The mooring lines at the quay are replaced by vacuum suction units installed on the quay, which are connected to the ship's hull. These hold the ship firm in horizontal position, while freely allowing vertical (loading and tidal) movements. This MoorMaster system has been applied to local ports, as well as to a container terminal in the Port of Salalah in Oman. Severe mooring problems due to long waves were experienced at this container terminal, but with the MoorMaster system these problems have almost been eliminated. The operational conditions of this system are being monitored and the system is improved continuously.

TOOLS FOR HARBOUR DESIGN

For the identification and quantification of long waves in a (proposed) port, it is essential to monitor the local wave conditions for the full frequency range of 0.0025 Hz (400 s) to 0.2 Hz (5 s). This is typically done by pressure or acoustic sensors. The relationship between swell height and long wave height (bound long waves) has to be determined from the measured wave signals. For existing ports, this can lead to an integrated early warning system, like the IPOSS system installed in the Port of Saldanha.

Numerical models have evolved significantly and are a useful tool for the port designer. Models such as Delft3D-Surfbeat (Deltares, the Netherlands) or Mike21 BW (DHI, Denmark) are capable to handle the complex interaction between swell, long waves and an irregular bathymetry and harbour geometry. With these tools it is possible to evaluate different design alternatives for different wave conditions. Besides the modeling of (long) waves, the interaction between the waves and the moored ship needs to be treated carefully as well (Van der Molen, 2006).

For the (re-)design of harbours, the use of small-scale physical modeling is (still) indispensable in the final design stage of the harbour. This is due to the complicated interaction between swell, long waves and moored ships. Physical models may also be required for other aspects of port design (e.g. breakwater stability), which together more than justify the relatively large expenses associated with these models.

It should be realized that both physical and numerical models have to be calibrated and verified. For this purpose, prototype data from actual mooring conditions are essential. Prototype studies will also reveal specific harbour conditions which can play a significant role in identifying the optimum solution to mooring problems for the specific port.

CONCLUSIONS

South African harbours are exposed to relatively high levels of (long) wave energy. This has led to significant mooring problems in some of these harbours. The tendency is to develop some of these harbours in a seaward direction, where exposure to long waves will increase. This requires an in-depth investigation of the consequences for the mooring conditions. Prototype monitoring and analysis of local swell and long-wave conditions over several years is essential in this regard. For existing harbours, also prototype monitoring of adverse mooring conditions is extremely useful. The development, application and experience with the novel MoorMaster system should be followed closely, as such a system may also be successfully applied to the safe mooring of ships in South African ports. However, at present there does not appear to be a single uniform solution to mooring problems associated with long waves, as each harbour is different.

The recommended approach is to:

- analyse the local long-wave climate in detail and quantify the energy distribution over the low-frequency range;
- investigate whether harbour basin resonance could occur and what the locations of nodes and anti-nodes of such standing long waves would be;
- establish the ship size and mooring line and fender conditions or options for the harbour and determine the natural period range of the moored ships;
- correlate the period sensitivity range of the moored ships with the local long-wave conditions;
- assess the various options for mitigation of the negative long-wave effects and for optimizing the mooring conditions;
- use numerical and physical modeling to quantify the problem and the potential solutions, supported by prototype measurements in case of existing harbours or after construction in case of new harbours.

References

Botes, WAM, Russel, KS and Huizinga, P (1982). Resonance in South African harbours. Proc. 18th ICCE, Cape Town, pp. 439-453

CSIR (1987). Moored ship studies at Saldanha Bay Harbour – Field studies interpretation report. CSIR Report C/SEA 8750, Stellenbosch, August

Joosting, WCQ (1959). The troubled waters of Table Bay harbour. The Civil Engineer in South Africa, October, pp. 211-222

Moes, J (2003). Storm conditions and long waves along the coast of South Africa. Proc. Long Wave Symposium, held in parallel with the 30th IAHR Congress, Thessaloniki, August, 10 pp

Moes, J and Holroyd, SG (1982). Measurement techniques for moored ship dynamics. Proc. 18th ICCE, Cape Town, pp. 2641-2661

Moes, J and Hough, G (1999). Measurement of Moored Ship Motions Using Video Imaging Technology, Proc. 12th International Harbour Congress, Antwerpen, KVIV.

Van der Molen, W (2006). Behaviour of a moored ship in a harbour. PhD thesis. Delft University of Technology.

Wilson, BW (1959). Research and model studies on range action in Table Bay Harbour, Cape Town. The Civil Engineer in South Africa, issues of June pp. 131- 148) and July (pp. 153-177), with discussion in the issue of May 1960 (pp. 79-96)