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# EXPERIMENTAL STUDY ON THE RESPONSE OF MOORED SHIPS: APPLICATION TO THE LEIXÕES OIL TERMINAL, PORTUGAL

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## Abstract

The paper analyses the influence on the response of moored ships of the test duration and the time series of incident waves, in order to define suitable test durations for this type of physical model studies. In addition, it analyses two interventions on a rubble mound breakwater that intend to improve the operational and security conditions in a Portuguese oil terminal with downtime problems. For this purpose, the behavior of a tanker moored at berth is analyzed for selected wave conditions.

## 1. Introduction

The response of a moored ship to the environmental forcing loads (e.g. waves, currents, wind) is usually complex and nonlinear. Physical modeling may give a valuable insight into moored ship related problems if phenomena governing its response are properly reproduced. Thus, the correct reproduction of wave conditions in the experimental facility is of vital importance. In this context, the test duration (i.e., storm) and the temporal sequence of incident waves have to be carefully selected, as these parameters may influence the behavior of moored ships.

The Port of Leixões is located in the northwest coast of Portugal and has an oil terminal composed of three berths, Figure 1. Berth "A" is the most exposed to environmental conditions, despite the protection offered by the Leixões north breakwater.

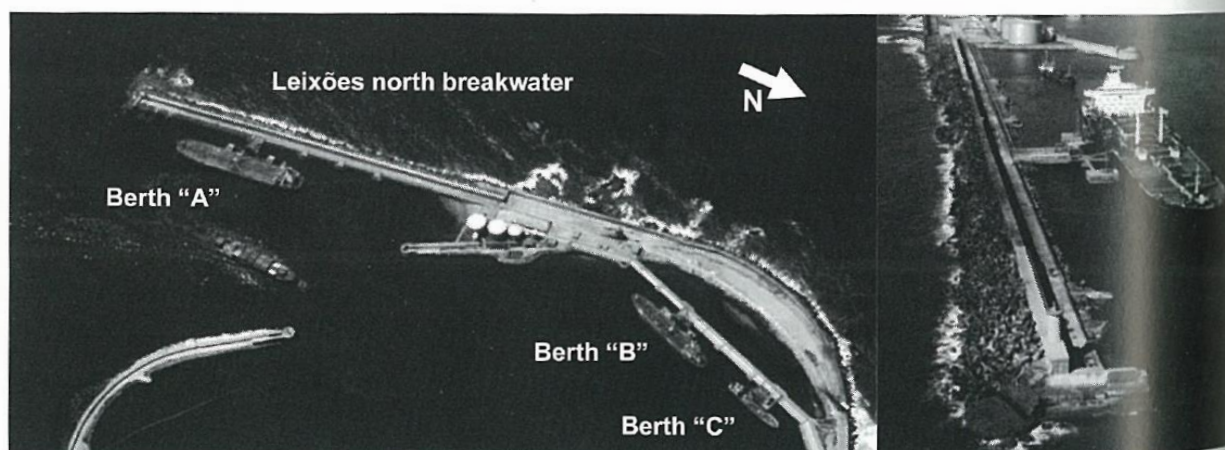


Figure 1. Leixões Oil Terminal (left) and close view of Berth "A" (right).



At Leixões, tides are of semi-diurnal type with amplitudes that range between 2 and 4 m. The wave conditions are highly energetic; during storms significant wave heights may exceed 8 m (about once per year) and wave periods can be on the order of 16 to 18 s. Wave directions between west and northwest prevail. The exposed location of Berth "A" leads, sometimes, to downtime; oil tankers may have excessive movements at the berth and mooring lines may break. In critical situations, on or off-loading operations are difficult or even impossible to carry out.

Operational conditions of port terminals built nearby the external harbor breakwaters may be influenced by wave diffraction. The modification of the Leixões north breakwater may result in lower wave disturbance in its sheltered area and better operational and security conditions at Berth "A". Other phenomena also contribute to Berth "A" downtime (overtopping, mooring system, resonance, etc.) that was estimated in about 20% of total time (IHRH-FEUP/CEHIDRO-IST, 2005).

In this context, two interventions in the north breakwater were studied: one consists in the extension of an upright wall, perpendicularly to the breakwater, and the other corresponds to the construction of a roundhead wave-breaking bank using blocks arranged in a very irregular manner. A comparative analysis of those interventions is carried out based on the moored ship behavior for selected wave conditions.

## **2. Physical modeling**

### **2.1 Experimental facility and equipment**

The study was conducted at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto (FEUP). The wave basin used is 28 m long, 12 m wide and 1.2 m deep. Waves were created by a piston-type multi-element wave generation system, controlled by a HR Wallingford, UK, wave synthesizer and equipped with a dynamic wave absorption system.

Froude similitude was used to ensure that the correct relationship is maintained between inertial and gravitational forces when the prototype is scaled down to model dimensions. The geometrical scale of 1:100 was selected in accordance with the experimental facility dimensions, size of the coastal area of interest, expected quality of results (*i.e.*, scale effects), operational and economic issues. Usual scales for this kind of studies are between 1:80 and 1:120 (Hughes, 1993).

The experimental equipment used consisted of resistive wave gauges to measure the water free surface elevation (accuracy of  $\pm 0.4\text{mm}$ ), ten cantilever force transducers with built-in strain gauges prepared to measure the loads applied on mooring lines and fenders (accuracy of  $\pm 1\%$ ) and a motion capture system. This system is composed of three digital infrared cameras and is capable of measuring the motions of moored ships, in its six degrees of freedom (surge, sway, heave, roll, pitch and yaw), without contact with the model (accuracy of  $\pm 0.5\text{mm}$  - translational motions and  $\pm 0.1^\circ$  - rotational motions). Two different setups of the forces transducers were prepared to allow the simulation of the mooring lines and the fenders.

A sampling frequency of 24 Hz was selected to avoid aliasing in data spectral analysis and to provide a satisfactory accuracy to the parameters determined based on time domain analysis.

### **2.2 Physical model**

The physical model was built based on the characteristics of the Leixões oil terminal. The port breakwaters, the berthing structure and neighboring beaches were reproduced as faithfully as possible to allow the development of realistic wave conditions near Berth "A". In fact, those

conditions depend much on the diffraction of waves around the head of the north breakwater and reflections on the south breakwater and Matosinhos Beach.

The bottom was assumed uniform and at a level of -16 m CD. Therefore, the water depth near the berth was 20 m for the high tide condition. The set-up of the model in the facility is sketched in Figure 2. Dissipative beaches were installed to minimize unwanted reflections of incident waves from the basin sidewalls and other physical model boundaries.

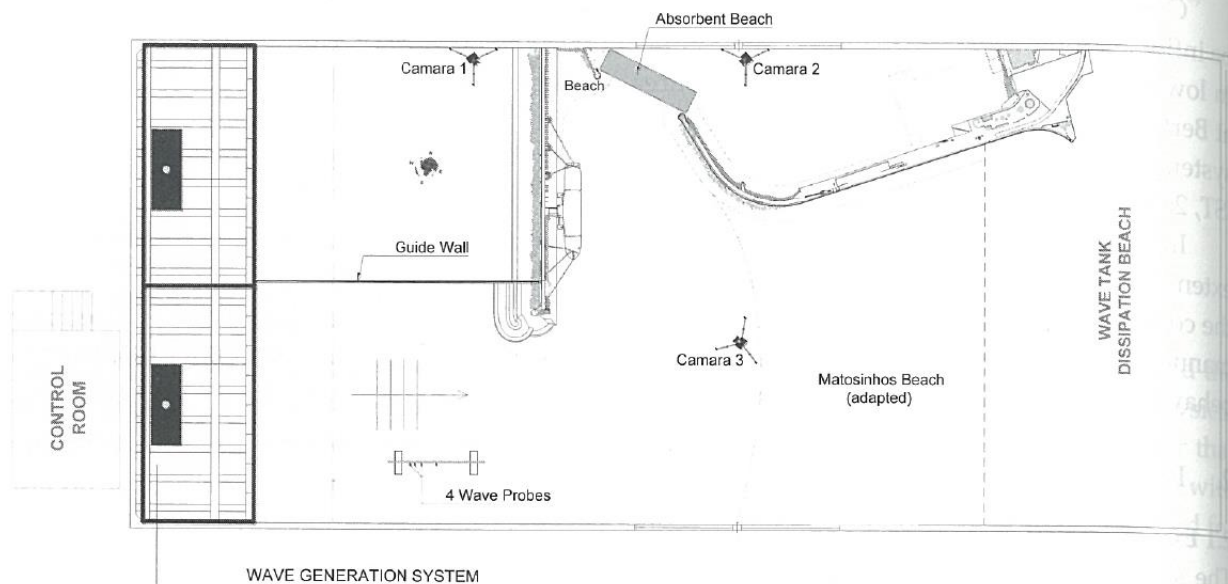


Figure 2. Physical model set-up in the wave tank.

The wave conditions selected for the study had a direction of propagation perpendicular to the north breakwater (at the wavemaker). This direction is one of the most problematic for the Berth "A" operational conditions (IHRH-FEUP/CEHIDRO-IST, 2005) and minimizes wave reflections from the basin sidewalls. Wave conditions were calibrated before starting the tests with the moored ship and later verified in all tests performed. The incident wave conditions were determined based in a development of the least squares technique proposed by Mansard and Funke, 1980, that uses simultaneous records of free surface elevations measured by four aligned wave gauges. An absorbent beach was designed and installed at the entrance to the inner harbor basin, Figure 2.

The ship selected for the study is a 105,000 dwt tanker and intends to represent the largest class of ships that can use Berth "A". Prior to testing, the ship model was ballasted to obtain the hydrostatic and hydrodynamic characteristics of the full-scale tanker for the maximum loading condition, Table 1. During calibration, several weights were placed inside the ship to reproduce displacement, draft, metacentric heights and natural periods of oscillation (Rosa-Santos, 2010).

Table 1. Characteristics of the selected 105,000 dwt oil tanker.

Designation	Unit	Full-scale
Length overall	m	245.1
Length between perpendiculars	m	236.0
Breadth	m	43.0
Draft (maximum)	m	14.1
Displacement	t	122,714
Transverse metacentric height	m	5.83



The usual mooring arrangement for large oil tankers is sketched in Figure 3 and consists of four headlines, four breast lines, four spring lines and four stern lines. Steel mooring lines with a synthetic tail are often applied. All mooring lines with the same orientation were reproduced by equivalent cables. The floating fenders (pneumatic) installed on the berth have a maximum energy absorption capacity of 1300 kJ for a reaction force of 2450 kN.

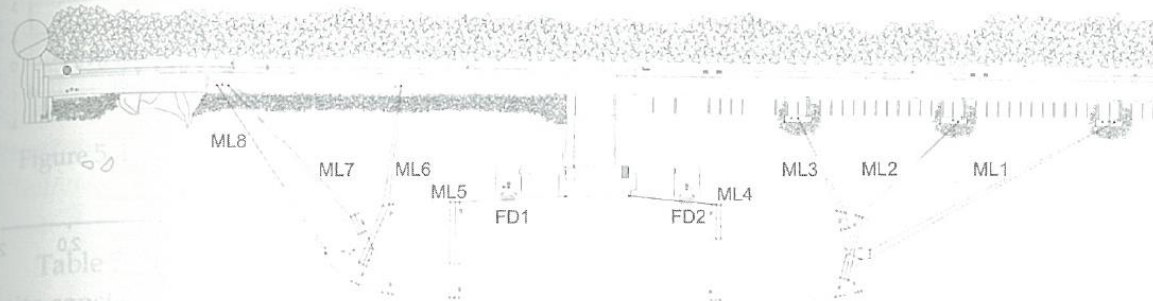


Figure 3. Typical mooring arrangement of a 105,000 dwt oil tanker at Berth "A".

The load-elongation relationships of fenders and mooring lines were simulated by a set of coil springs. The weak non-linear behavior of mooring lines was linearized, *i.e.*, these elements were reproduced by equivalent linear lines with constant stiffness (that does not depends on its elongation) and the same energy absorption capacity of the non-linear mooring lines up to its maximum elongation (Rosa-Santos, 2010). Because the pneumatic fenders are highly non-linear, a bilinear approach was used to reproduce its load-elongation relationships. The mooring line lengths and the (bi) linearized stiffness of each mooring system element are presented in Table 2 (full-scale values). The load-elongation curves of ML3, ML8 and FD1, and their equivalents in the model, are shown in Figure 4. The stiffness of each mooring system component was verified before each test series. The ship model was moored to the berth using inelastic kevlar® strings.

Table 2. Characteristics of mooring lines (ML) and fenders (FD).

Designation	length (m)	stiffness (kN/m)
ML1	150	457.8
ML2	90	598.1
ML3	55	696.6
ML4	55	697.3
ML5	82	611.2
ML6	82	610.4
ML7	90	583.5
ML8	120	518.5
DF1	--	587.5 (first stretch)
		2146.7 (second stretch)
DF2	--	576.3 (first stretch)
		2114.6 (second stretch)

Pretension loads applied on mooring lines were verified and adjusted with special devices to ensure that results for different test conditions could be compared. In this study, pretension loads were fixed in the range 100 – 120 kN (prototype values for each individual mooring line). The friction coefficient between the ship hull and the fenders was reproduced in the model and assumed equal to 0.45 - 0.48 (interface steel-rubber). A set-down compensation was introduced in the wave generation system to ensure a realistic propagation of bound long waves.

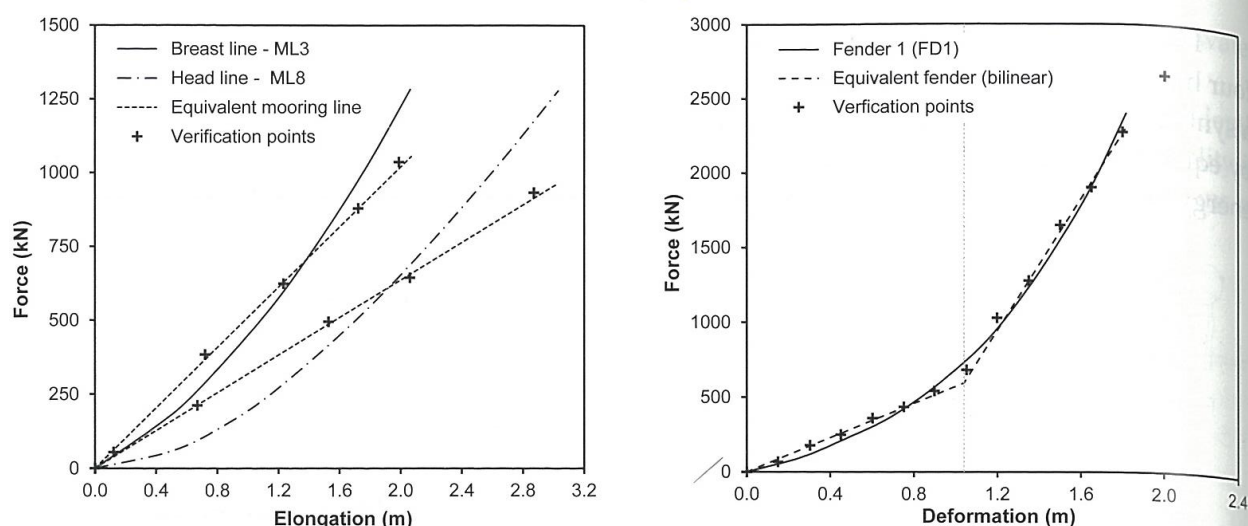


Figure 4. Load-elongation curves of ML3, ML8 and FD1, and their equivalents in the model.

### 3. Influence of the test duration on the moored ship behavior

The reproduction of selected sea states in an experimental facility by generating random time series of waves using the white noise method is a sound basis for studying the hydrodynamic behavior of harbor basins and the response of moored ships. Nevertheless, the length of those series has to be sufficiently large, so that the different patterns of wave grouping may occur during the test, especially when long period waves and the effects associated to wave groups are important. If the random sequence of waves is too short, the results may be inclusive as the response of harbor basins to long period forcing or the behavior of moored ships may change with the modification of the test duration (length of the random sequence of waves). It follows that the greater the length of the random sequence, the more closely sea states are reproduced, particularly its low-frequency components. Furthermore, the maximum wave height in a wave time series is a function of its length (Kirkegaard, 2007).

Therefore, the influence of the test duration, on the low-frequency energy content of the reproduced sea conditions and on the parameters characterizing the response of moored ships, is analyzed for the test conditions presented in Table 3. It is important to mention that all tests were carried out for the same JONSWAP spectrum (peak factor equal to 3.3), characterized by a significant wave height,  $H_{Si}$ , of 3.0 m and a peak wave period,  $T_P$ , of 16 s.

Table 3. Test conditions: length of random sequences, test duration, recorded wave height.

$n$		10	11	12	13	14	15
$2^n$		1024	2048	4096	8192	16,384	32,768
Minimum number of waves		150	300	625	1250	2500	5000
Test conditions ( $T_P=16$ s) ( $H_{Si}=3.0$ m)	Duration (h)	0.57	1.14	2.28	4.55	9.10	18.20
	$H_{Si}$ (m)	3.03	3.04	3.07	3.00	3.02	3.03
	$m_{0,lp}$ (m <sup>2</sup> )	0.0185	0.0107	0.0151	0.0140	0.0140	0.0131
	$H_{max}$ (m)	5.26	5.15	5.34	5.51	5.69	5.56

Test durations corresponded to the cycle time, so random and non-repeating time series of waves, of varying durations (number of waves), were generated in the facility using the white noise (digitally filtered) technique. The same time series of waves was used in the tests carried out for the same peak wave period. Figure 5 clarifies the concepts of time series of random waves (without repetition) and time series of waves obtained from repetition of a random base.



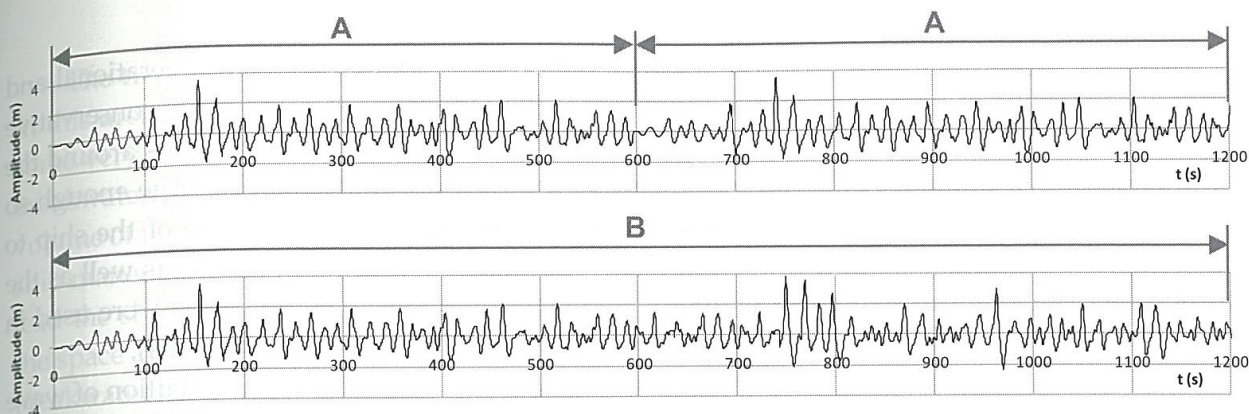


Figure 5. Examples of surface elevation time series: repetition of random sequence "A" (top), random sequence "B" without repetition (bottom). Tests with the same total duration.

Table 3 also presents measured incident significant wave heights, which can be considered quite constant despite the test duration modification, and estimates of the low frequency energy content, defined as the zero order moment of the wave spectrum, for frequencies between 0.00 and 0.04 Hz. This parameter did not increase with the test duration and seems to stabilize for the longer duration tests.

Figure 6 presents maximum and significant peak-to-peak amplitudes of the ship motions, as a function of the test duration, for the conditions presented in Table 3. It also presents the trend lines that result from performing a linear fit to the results, by the least squares method. Test durations result from using sequences of lengths from  $2^{10}$  to  $2^{15}$ , without repetition.

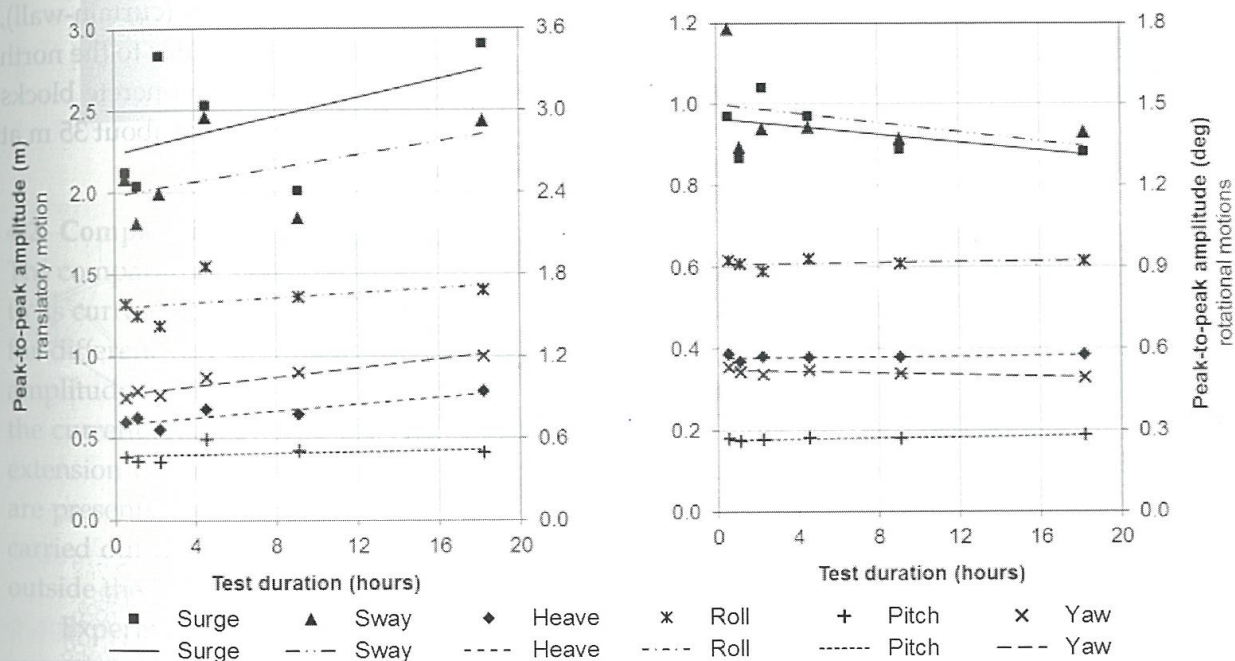


Figure 6. Motion amplitudes as a function of the test duration (prototype values): maximum amplitude (left) and significant amplitude (right). Linear fit to the experimental data.

Despite significant wave heights and variance spectra of incident waves being identical in all tests, maximum amplitudes of ship motions may significantly vary with the test duration, showing a tendency to increase (other conditions unchanged), in opposition to what happened with the low frequency energy content of variance spectra. The significant amplitude variations are smaller, especially when considering only the longer tests.

Since the maximum motion amplitudes are the most limiting in terms of operational and security conditions of port terminals, it follows that the longer the test, the more conservative results will be. However, reference has to be made to the notable spread of results around the trend lines shown in Figure 6. It can be concluded that test duration must be large enough so that the different wave groups are reproduced in the model and the response of the ship to those groups is recorded and then analyzed. Having these conclusions in mind, as well as the study objectives, random sequences of about 1250 waves (sequence length of  $2^{13}$ ) were used in the tests carried out to evaluate the interventions on the north breakwater (section 4).

The filtered white noise technique determines implicitly the statistical distribution of wave groups. So, provided that tests are sufficiently long, the availability of information about wave groups on the real sea states it is not an essential requirement. Other results (not presented in the paper) shown that there is no advantage in carrying out very long tests if the time series of incident waves consists of the repetition of a base random sequence of waves.

## 4. Interventions on the north breakwater

### 4.1. Description

In order to improve operational and security conditions at Berth "A", two interventions in the head of Leixões north breakwater were developed and analyzed comparatively. They intend to improve tranquility conditions in the Berth "A" surroundings and were developed based on the following assumptions: maintaining the area currently available for the approach, rotation and berthing of ships; constructability; and having a low cost (not estimated).

The interventions studied consisted of: extension of an existing upright-wall (curtain-wall), in a length of about 30 m (crown elevation at +11.5 m), in a direction perpendicular to the north breakwater, and the construction of a roundhead wave-breaking bank using concrete blocks arranged in an irregular manner, Figure 7. The roundhead outside diameters are about 35 m at the top and 60 m at the base. The weight of the blocks was variable.

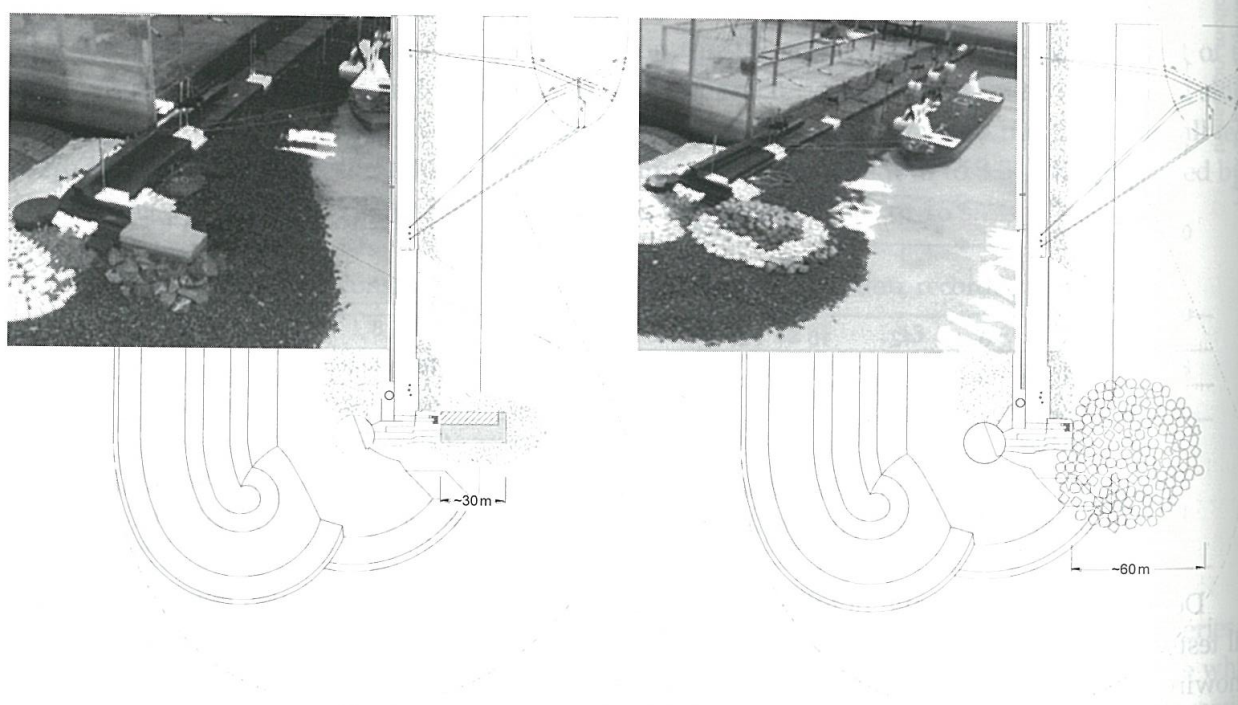
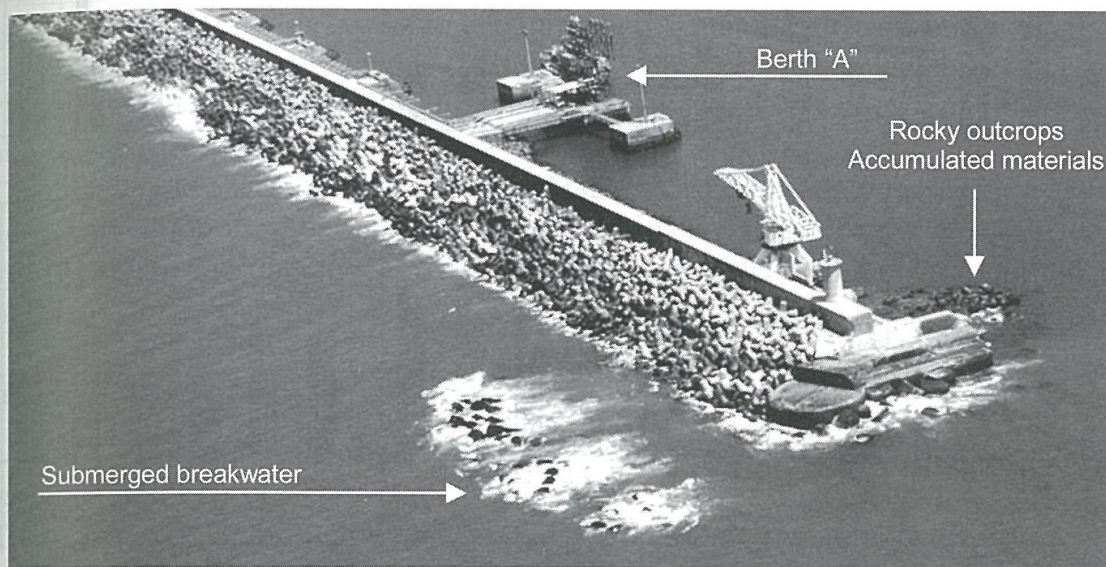


Figure 7. Extension of an upright-wall in a direction perpendicular to the north breakwater (left) and construction of roundhead wave-breaking bank using blocks arranged in an irregular manner (right).



The two interventions were planned to the leeside of the north breakwater, near its head. In this area there are rocky outcrops, as well as materials resulting from damages caused by some very violent storms in the main breakwater (prior to the construction of the submerged breakwater in the early eighties), which have accumulated there. Therefore, on one hand, the volume of material required for the interventions is very small. Moreover, the space available for ship maneuvering is not reduced. More extensive interventions in the alignment defined would lead the sheltering structures to larger water depths and would result in a likely reduction of the space available for ship manoeuvring. Figure 8 presents the head and the trunk of the north breakwater for a water level near low spring tide and shows the intervention area (leeside) and the submerged breakwater aimed to protect the head of the main breakwater (seaside).



(a) ber Figure 8. Head and trunk of the north breakwater of the port of Leixões.

#### 4.2. Comparative analysis

The comparative analysis of interventions on the north breakwater is performed with reference to its current condition and is based on the study of the behavior of a ship moored at Berth "A", for different test conditions. Figure 9 presents the significant peak-to-peak amplitudes (mean amplitude of the one-third highest motions) of the ship motions, in its 6 degrees of freedom, for the current situation and the reduction of those amplitudes for both interventions considered: extension of the upright-wall and construction of a roundhead wave-breaking bank. Results are presented as a function of the peak wave period,  $T_P$ , in prototype values, and refer to tests carried out for incident significant wave heights of 3.0 m (*i.e.*, representative wave conditions outside the port that are a frequent threshold for the occurrence of operational problems).

Experimental results show that both interventions on the north breakwater improve the operational conditions at Berth "A" compared to the current conditions. Indeed, it can be seen that the amplitudes of surge, sway and yaw (*i.e.*, the motions with more influence on the safety and efficiency of operations performed in a terminal for oil tankers (Bruun, 1983)) are smaller for those test conditions, with the larger reductions occurring for surge. Heave and pitch have similar trends. The roll motion is the exception, as it may present a slight increase in amplitude for some peak wave periods, as a result of the changes in the north breakwater head.

Construction of the round-head wave-breaking bank seems to be more effective than the extension of the upright-wall (*e.g.*, reductions of surge amplitudes are in the range of 14 to 26% in the first case and between 11 and 17% in the second case). These results may be explained by



the slightly larger dimensions of the round-head bank as well as its higher porosity and surface roughness that will promote wave energy dissipation during diffraction around the head of the breakwater. It can also be concluded that amplitudes of ship motions tend to increase with the peak wave period regardless of the characteristics of the breakwater head.

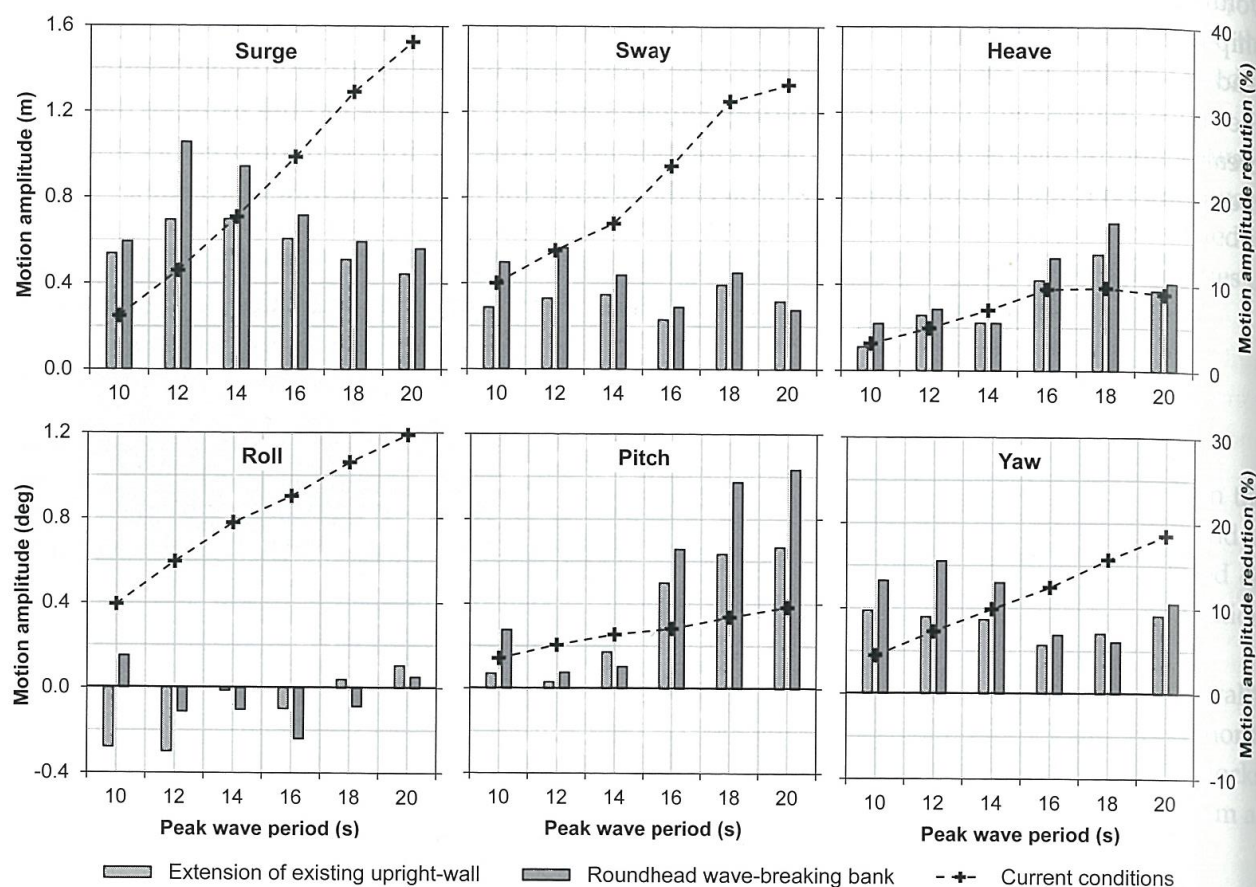


Figure 9. Significant motion amplitudes (peak-to-peak values) for the current conditions and reduction of those amplitudes for the two interventions on the breakwater considered.

Summing up, results obtained are in accordance with expectations, given the nature of the interventions studied. The study compared them based on their efficacy to attend the proposed objectives. Optimization of those interventions, or development of more extensive interventions on the north breakwater, may result in higher efficacy with regard to Berth "A" operational and safety conditions and, eventually, better access conditions to the port of Leixões inner basins.

It is worth mentioning that improvement of sheltering conditions to short waves, through the modification of breakwaters (*e.g.*, length or configuration), is not always favorable for the behavior of moored ships. If modifications results in a narrower port entrance, inner harbor basins may become more exposed to resonant phenomena. The interventions analyzed, due to its minimalist nature, did not seem to have a noticeable influence on the resonance conditions near Berth "A", so in this case the increase of sheltering corresponds to an overall improvement of the behavior of moored ships.

## 5. Conclusions

The work carried out showed that maximum amplitudes of the ship motions increase with the test duration (other conditions unchanged). The significant amplitude variations were smaller.



Thus, test duration must be large enough so that the different wave groups are reproduced in the facility and the response of the ship to those groups is recorded. In addition, there is no advantage in carrying out very long tests if the time series of waves consists of the repetition of a base random sequence of waves.

The study analyzed two different interventions in the head of Leixões north breakwater. In their implantation site, there are some rock outcrops and accumulated materials, which would minimize the required amount of materials for construction and costs. Furthermore, due to the minimalist nature of the studied interventions, the space available to perform the approach, rotation and berthing manoeuvres would not be changed.

Both interventions improved operational conditions at Berth "A" since they lead to smaller amplitudes of ship motions. The construction of a roundhead wave-breaking bank with blocks arranged in an irregular way seems to be more effective than the extension of a curtain-wall. However, even for the most favorable conditions, motion amplitude reductions did not exceed 25%. The higher efficacy of the roundhead bank may result of its greater extension and higher porosity and surface roughness.

This initial study was based on results obtained under a R&D project and a PhD thesis. The development (optimization) of the interventions may result in higher efficacy with regard to Berth "A" safety and operational conditions and, eventually, better access conditions to the port of Leixões inner basins.

### Acknowledgments

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