Harbour of Pozzallo

feasibility study on wave penetration, mooring forces and ship motions

AFGEHANDELD

report on model investigation

M 1783

August 1981
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1. Introduction

1.1 Terms of reference

Consorzio A.S.I. di Ragusa authorized the Delft Hydraulics Laboratory to conduct studies on the hydraulic aspects of the proposed breakwater near Pozzallo, cable no. "Ragusa 613", dated February 20, 1981. Under the terms of this commission the studies to be carried out by the Delft Hydraulics Laboratory included:
- model tests on wave penetration, ship motions and wave induced currents (M 1783),
- two-dimensional tests on breakwater trunk stability (M 1781),
- three-dimensional tests on breakwater head stability (M 1782).

These studies are described in three separate reports. The present report deals with the model tests on wave penetration, ship motions and wave induced currents. The tests were executed in the De Voorst Laboratory of the Delft Hydraulics Laboratory, under the supervision of Mr. J. Wouters, who also drew up this report.

1.2 Description of the problem

The existing marine facilities near Pozzallo, Sicily, will be upgraded in order to provide safe berthing and unloading facilities. These facilities must be accessible for general cargo ships with a draught up to 10 m. A detached breakwater will, therefore, be constructed seaward of the existing trestle, and berthing facilities will be provided in the lee of this breakwater.

Wave penetration tests had to be performed in order to determine the optimum alignment of the breakwater to arrive at a proper balance between construction cost and operation cost of the berth. Wave penetration can be determined in terms of heights along the berths. For port operation, however, the wave induced ship motions and resultant mooring line forces are the determinant criteria. Not only the wave heights but also the characteristics of the mooring and the ship are of importance for the resultant mooring forces. So for a
number of selected breakwater alignments, mooring arrangements and ship characteristics resultant mooring forces had to be compared. Wave induced currents can be of importance for the silting of the existing harbour. Visual observations had to be made of this phenomenon, for both the present and future condition.

1.3 Summary and conclusions

A detached breakwater will be constructed seaward of the existing trestle near Pozzallo in order to provide berthing facilities for general cargo ships with a draught up to 10 m. The results of tests on wave penetration, mooring forces and ship motions with this new lay-out are summarized in the present report.

Prior to the tests proper, a desk study was executed to provide the necessary information about the wave conditions near Pozzallo. Two predominant wave directions resulted from this study, viz.: South-East and South-West direction on deep water. A refraction analysis was applied to convert deep water wave statistics into data applicable at the model boundaries. This resulted in directions 150° and 220° with respect to North, respectively at the wave generator on a water depth of 14 m. Tests were performed under both operational conditions (incident wave height $H_{s,i} = 3$ m) and extreme conditions ($H_{s,i} = 5$ m).

A non-distorted model was used for this investigation. The linear scale factor for the model was $n_l = 100$. The model was designed in such a way that parasitic wave reflection against the basin walls and wave board could not affect the wave penetration.

The test programme is described in Table 1. Five different breakwater alignments were tested during the investigation, they are presented on Figure 5. For the shipmotion tests a 15,000 d.w.t. general cargo ship was used. The ship was tested in loaded and ballastved condition. Three different mooring arrangements were tested, the fender arrangement remained unchanged. Separately, tests were performed to determine the existence of wave induced currents in the lee of the breakwater.
From the test results it can be concluded that:

1 In the case of $H_{s,i}^* > 3$ m a seiche can occur alongside the quay wall of the breakwater, which greatly influences the motions and mooring line forces of the moored ship.

2 A 200 m elongation of the breakwater heads with respect to the initial design (Alignment 4, Figure 5) does not affect the wave penetration, ship motions and mooring forces significantly.

3 The use of a perforated quay wall has no influence on the wave penetration, ship motions and mooring forces.

4 The use of (stiff) steel mooring lines can not be recommended, neither under operational nor under extreme wave conditions ($H_{s,i}^* = 3$ m and $H_{s,i}^* = 5$ m, respectively), as the design loads were exceeded.

5 In the case that strong, elastic mooring lines are used the mooring line forces do not exceed the design load under operational wave conditions ($H_{s,i}^* = 3$ m); under extreme wave conditions ($H_{s,i}^* = 5$ m) the design loads were exceeded with 50%.

6 The design loads of the fenders were never exceeded during the tests.

7 Mooring forces are higher in the case of a loaded ship than in the case of a ballasted ship.
2. Boundary conditions

2.1 Harbour location

The existing marine facility near Pozzallo, outmost south area of the Isle of Sicily, will be upgraded. A detached breakwater will, therefore, be constructed approximately 850 m seaward of the existing harbour (see Figure 1). Berthing facilities will be provided in the lee of this protection.

Information on location of the breakwater and on seabed topography of the harbour area was obtained from drawing no. C01 of Consorzio A.S.I. di Ragusa, dated November 19, 1979.

2.2 Wave conditions

The wave heights applied in the tests were deduced from data obtained from ocean-going vessels passing the area 36°-37° North Latitude (N.L.) and 14°-15° Eastern Longitude (E.L.) and from previous studies [1]. The ship observations, collected by the "Royal Dutch Meteorological Institute (K.N.M.I.)", consisted of the following parts:
- observations of sea state,
- swell observations.
A summary of these wave data is given in Tables 2 and 3.

Wave directions of importance for the wave penetration in Pozzallo harbour lie between East (about 105°) and West (about 255°), as can be seen on Figure 1. The cumulative wave height distribution, which is presented in Table 2 is therefore divided in two distributions, viz.:
- distribution for all directions,
- distribution for directions between 105° and 255° (see also Figure 2).

Applying a storm duration of 6 hours the wave height, which can occur once a year and once in five years can be deduced from Figure 2. The wave heights on deep water are:
- once a year \( H_s = 4.50 \) m,
- once in 5 years \( H_s = 5.80 \) m.
The relation between $H_s$ and $T_m$ (the average wave period) used for this investigation was based upon the data from the study of Licata harbour [1]. Lines of combinations of $H_s$ and $T_m$ are plotted in Figure 3. These lines are constructed using the following data sources:
- the Oceanographic Atlas of the North Atlantic Ocean,
- theoretical calculations according to Bretschneider,
- data on waves in the sea areas near Marsa El-Bregha and Misurata (see Figure 1).
For each wave height, observed near Pozzallo, the average of the visually observed wave periods is also given on Figure 3.

A mean period of 8.5 s and 9.5 s was chosen from this information for the once a year and the once in 5 years wave conditions, respectively. A ratio between the peak period ($T_p$) and the average period ($T_m$) of 1.28 was chosen for the spectrum used during the tests, the so-called JONSWAP spectrum (see Figure 4).

Two wave directions were chosen for the model investigation:
- SW (or 225° with respect to North),
- SE (or 135° with respect to North).

The waves were generated in model on a water depth of M.S.L. -14 m, due to refraction and shoaling these wave directions changed into:
- 220° with respect to North, for deepwater direction 225°,
- 150° with respect to North, for deepwater direction 135°.

The wave heights, which had to be generated on a water depth of 14 m have to be corrected also for refraction and shoaling; for both a wave direction of SE and SW the combined refraction and shoaling factor is about 0.88 so:
- once a year wave condition at MSL -14 m will be $H_{s,i} = 4$ m and $T_p = 10.9$ s,
- once per 5 years wave condition at MSL -14 m will be $H_{s,i} = 5.1$ m and $T_p = 12.2$ s.

During the course of the study, the client decided to use less severe wave boundary conditions viz.:
- operational condition $H_{s,i} = 3$ m and $T_p = 9$ s,
- extreme condition $H_{s,i} = 5$ m and $T_p = 10.8$ s.
This change of condition was based mainly on experience in this area.
Unless otherwise stated, the wave boundary conditions at M.S.L. -14 m will be used in this report.

A storm duration of 6 hours was simulated in model.

2.3 Waterlevel

Variations due to tide action are between M.S.L. +0.5 m and M.S.L. -0.5 m. For the model investigation only M.S.L. was used.
3. **Berthfacilities and ship's characteristics**

3.1 **Breakwater alignment**

The main purpose of this study was to determine the optimum breakwater alignment. This optimum should be related to:

- the motions and the forces in the hawser of the moored vessel,
- the wave height in the manoeuvring area.

Five different alignments were tested in total; they are represented on Figure 5. In order to determine the reduction on the wave penetration due to the breakwater head, it was necessary to execute a test without any breakwater head initially (Alignment 1). The influence of an elongation of the western breakwater head was checked with the Alignments 2 and 3. The western breakwater head for Alignment 2 was in agreement with the initial design; for Alignment 3 the western head was lengthened by 200 m. In the case of Alignment 4 the total breakwater was in agreement with the initial design; in the case of Alignment 5 the western breakwater was lengthened with 50 m and the eastern one was lengthened with 100 m with respect to the initial design.

A cross-section of the breakwater and the quay is given on Figure 6. The length of the quay will be about 600 m.

3.2 **Mooring arrangement**

3.2.1 **Fenders**

The fenders in nature will consist of sets of two rubber fenders with the following particulars:

- inner diameter = 0.60 m
- outer diameter = 1.00 m
- length = 1.00 m
- maximum load = 420 kN

The centre to centre distance between the sets of two fenders is 9 m.
3.2.2 Hawsers

Two different arrangements of mooring lines can be used for a 15,000 d.w.t. general cargo ship, viz.:
- two spring lines together with one sternline and one bowline.
- two spring lines together with two sternlines and two bowlines.
Both steel wires and artificial fibres can be present on this type of ships. The absolute minimum is steel wire Ø 22 mm, while steel wire Ø 32 mm and polypropylene Ø 80 mm is more common. Whenever the size of the line is to small it is usual to double that particular line.

3.3 Ship

A 15,000 d.w.t. general cargo ship, being the maximum size to be accommodated at the new berth, has been chosen for model testing. The model was constructed of wood according to the body-plan given on Figure 7. The model tests were performed for a fully laden ship and for a ballasted ship. The particulars of the design ship are:

<table>
<thead>
<tr>
<th></th>
<th>fully laden</th>
<th>ballasted</th>
</tr>
</thead>
<tbody>
<tr>
<td>water displacement</td>
<td>19.270</td>
<td>10.010</td>
</tr>
<tr>
<td>length between perpendiculars</td>
<td>149</td>
<td>149</td>
</tr>
<tr>
<td>moulded breadth</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>moulded depth</td>
<td>11.1</td>
<td>11.1</td>
</tr>
<tr>
<td>moulded draught (aft)</td>
<td>8.87</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>8.87</td>
<td>4.0</td>
</tr>
<tr>
<td>centre of gravity KG</td>
<td>6.1</td>
<td>4.4</td>
</tr>
<tr>
<td>metacentric height GM</td>
<td>2.15</td>
<td>4.5</td>
</tr>
<tr>
<td>centre of gravity measured from last perpendicular</td>
<td>74.50</td>
<td>72.40</td>
</tr>
<tr>
<td>longitudinal radius of gyration, kψ</td>
<td>37.25</td>
<td>37.25</td>
</tr>
<tr>
<td>transversal radius of gyration kΦ (in air)</td>
<td>7.0</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>8.4</td>
</tr>
</tbody>
</table>
The water displacement, the centre of gravity, the longitudinal and transversal radius of gyration as well as the metacentric height have been adjusted in model by lead blocks.
4. The model

4.1 Model scales

Physical processes reproduced in a small scale model should be similar to those in nature. A number of similarity laws has to be obeyed to achieve this. Apart from geometrical and kinematical similarity most of all dynamic similarity is required. This implies for instance that corresponding masses of fluid exposed to forces will behave in a similar way in model and nature. To achieve dynamic similarity the ratio of the inertial force to other active forces such as gravity, viscosity, surface tension, elasticity etc. must remain constant. However, as the resulting dimensionless numbers yield different scale laws, generally complete similitude cannot be achieved. Nevertheless often one force predominates and by proper selection of the scales the other forces can be minimized.

As far as the hydraulic processes within a wave are concerned, in nature gravity forces predominate. Consequently, a wave disturbance model should be designed in such a way that gravity forces are correctly reproduced, which implies application of the so-called Froude law to formulate scale relationships.

It can be easily demonstrated that a correct reproduction of wave generated ship motions and mooring forces is only possible in a non-distorted model. As a result, following scale relationships resulting from the Froude law can be expressed in the length scale $n_L$ of the model:

- time  \[ n_t = \sqrt{n_L} \]
- velocity  \[ n_v = \sqrt{n_L} \]
- acceleration  \[ n_a = 1 \]
- spring stiffness  \[ n_k = n_L^2 \]
- mass  \[ n_m = n_L^3 \]
- force  \[ n_f = n_L^3 \]
- energy  \[ n_e = n_L^4 \]

Since other dimensionless numbers are consequently different in model and nature, it should be checked whether their influence is sufficiently small to avoid scale effects. The ultimate choice of the scale is determined by the
classical trade off between construction cost and the degree of accuracy required for generation and measurement of waves. A length scale factor of \( n_L = 100 \) was chosen as an acceptable compromise.

4.2 Description of the model and instrumentation

4.2.1 Model lay-out

The harbour and adjacent seabed was reproduced in a fixed bed model as shown on Figure 8. A general view of the model is given on Photograph 2.

The breakwater used in model was constructed as a rubble mound. No overtopping was allowed in model. The berthing quay in model was made of wood, incidentally a perforated quay wall was used (see Figure 6).

Waves were generated from two directions \( 220^\circ \) and \( 150^\circ \) with respect to North, respectively. The purpose of the tests with a wave direction \( 220^\circ \) was to find an optimum design of the western breakwater head. Only diffraction around this head was taken in account therefore. A wave conducting wall had to be used during the tests with this wave direction.

The model was designed in such a way, that, parasitic wave reflection against basin walls and wave board could not affect wave penetration.

The ship was berthed at the western end of the quay, during the tests with a wave direction \( 220^\circ \) and at the eastern end of the quay during the tests with a wave direction \( 150^\circ \) (see Figures 8 and 9).

Waterlevels in the model were measured to \( \pm 0.01 \) prototype metres using a point gauge located in a stilling well (see Figure 8).

4.2.2 Waves

The model was equipped, which a random-wave generator to simulate irregular waves, from a direction \( 150^\circ \) and \( 220^\circ \), respectively. Generation of irregular waves enables a true reproduction of conditions in nature. This factor has proven to be essential for obtaining reliable test results for mooring forces and ship motions. The wave board has one degree of freedom, viz. a translatory motion. A punched tape was used for the drive of the wave board. The signal on
the punched tape was not recorded in nature. As mentioned in Section 2.2, for
the present investigation only one shape of the variance density spectrum was
used, the so-called JONSWAP-spectrum (see Figure 4).

In order to enable the generation of the required wave heights, the waves were
generated on an extra deepened part of the basin.

The incident waves were measured during each test at the stations 1 or 10,
respectively. The wave penetration was measured by means of several other wave
gauges, which were placed at characteristic places in the model, shown on
Figures 8 and 9.

The wave gauges used in the tests are of the resistance type, which have an
accuracy of 0.5% of the full scale.

4.2.3 Fenders

The fender structure in nature will consist of sets of two rubber fenders
600/1000. The centre to centre distance between the sets of fenders will be
9.0 m in nature. Linear springs on a centre to centre distance of 0.18 m
simulated the fender structure in model. So one fender in model simulates
2x2 rubber fenders 600/1000. The fender characteristics of the fenders in
both nature and model are presented on Figure 10.

Two of the fenders in model were equipped with strain gauges in order to
measure the forces in these fenders (see Figure 11). The accuracy of the
fenders is 2.10^{-3} N (model). Drag between the fenders and ship hull was
minimized by use of teflon at the point of contact.

4.2.4 Hawser

Three different hawser arrangements were tested during the investigation viz.
(see Figure 11).
- Arrangement A : one double sternline (l = 20 m)
  : two single springlines (l = 30 m)
  : one double bowline (l = 20 m)
The lines which were used were steel lines φ 22 mm
breaking load = 210 kN
design load = 92 kN
- Arrangement B: two single sternlines (1 = 20 m)
  : two double springlines (1 = 30 m)
  : two single bowlines (1 = 20 m)
The lines which were used were steel lines $\phi$ 32 mm
breaking load = 661 kN
design load = 290 kN.

- Arrangement C: two double sternlines (1 = 20 m)
  : two single springlines (1 = 30 m)
  : two double bowlines (1 = 20 m)
The lines which were used were polypropylene $\phi$ 80 mm
breaking load = 650 kN
design load = 286 kN*.

The force-deformation characteristics of these lines are represented in Figure 10. The mooring line characteristics were simulated by wires connected to force-measuring springs. Springs were applied to give the appropriate elongation versus force ratio for the varying diameters and materials of the mooring lines simulated. Mooring line forces were measured to $2.10^{-3}$ N (model).

4.2.5 Ship motions

The six motion components of the ship have been measured with a set of seven potentiometers, by which displacements are converted into electrical tensions. The accuracy of the potentiometers is $1.10^{-4}$ m (model). The signals were added and subtracted directly to derive translations and rotations respectively (Figure 12).
The meters for vertical displacements were placed on a frame around the ship, whereas the meters for horizontal displacements were placed on small tables (see Photographs 1 and 3).

4.3 Recordings and elaboration

Electrical signals from the wave gauges were fed into a computer for analysis and presentation of both percentage wave height exceedance and relative amount of wave energy at various periods in the spectra.

*The same relationship between breaking load and design load has been used for polypropylene ropes as for steel ropes in this report. No general accepted rule for this relationship in the case of polypropylene has been found in literature.
The recorded ship motion signals were also fed into the computer. Exceedance curves for both the negative and positive ship motions were elaborated.

For the hawser- and fender forces both exceedance curves of the peak forces and time exceedance curves of a certain force level are given.

4.4 Wind load

A calculation method for the effect of the wind on the mooring forces is given in [3]. The following equations are presented in this article.

Longitudinal wind force (tf\(^*\)) \(F_x = C_x \left(\frac{\rho_w}{7600}\right) v^2 A_T\)

Lateral wind force at aft perpendicular \(F_yA = C_yA \left(\frac{\rho_w}{7600}\right) v^2 A_L\)

Lateral wind force at forward perpendicular \(F_yF = C_yF \left(\frac{\rho_w}{7600}\right) v^2 A_L\)

in which:

\(C_x\) = longitudinal force coefficient 
\(C_y\) = transverse force coefficient 
\(\rho_w\) = density of air \(\text{(kgf s}^2/\text{m}^4)\)
\(v\) = velocity of wind at 10 m elevation \(\text{(knots)}\)
\(A_T\) = transverse (head-on) area \(\text{(m}^2)\)
\(A_L\) = longitudinal (broadside) area \(\text{(m}^2)\)

In the case of a fully laden ship the deck of the ship is almost at the same level as the quay so: \(A_L = 0\), while \(A_T = 44 \text{ m}^2\). The value of \(C_x\) is represented in [3] as a function of the wind angle of attack (\(\theta\)) and is maximum at \(\theta = 0^\circ\) and \(180^\circ\) (parallel with the length axis of ship) \(C_x = 1\). The most extreme wind condition that can effect the longitudinal wind force is a wind from western direction, up to windforce 8 Beaufort (40 knots).

\[F_x = 1 * \frac{0.13}{7600} * 40^2 * 44 = 1.2 \text{ tf (= 12 kN)}.\]

* In the present reference the S.I. (Système International) was not used for the units
In the case of a ballasted ship the deck lies about 2.6 m above the quay so in this case

- $A_L = 2.6 \times 149 = 387 \text{ m}^2$
- $A_T = 6.1 \times 20 = 122 \text{ m}^2$.

The value of $C_x = 0.8$ and $C_{yA} = C_{yF} = 0$ in the case of $\theta = 0$.
So in this case the extreme value of $F_x = 2.7 \text{ tf} (= 27 \text{ kN})$.

In the case of $\theta = 90^\circ$ (perpendicular to the ship) the value of $C_x = 0$ and $C_{yA} = 0.5$ and $C_{yF} = 0.3$. The most extreme wind condition, that can effect the lateral wind force is a wind from south-western direction, up to wind force 7 Beaufort (30 knots).

- $F_{yA} = 3.0 \text{ tf} (= 30 \text{ kN})$,
- $F_{yF} = 1.8 \text{ tf} (= 18 \text{ kN})$.

These forces are so small, that it was not possible to simulate the wind effect in the model.
5. Test procedure

5.1 Test programme

Test programme and conditions are given in Table 1. The general sequence followed during the study was:
i. Optimization of western head of the breakwater with a direction $220^\circ$ of the incident wave,
ii. Optimization of mooring arrangement,
iii. Optimization of total breakwater alignment with a direction $150^\circ$ of the incident wave,
iv. Determination of influence of a perforated quay wall,
v. Wave height measurements for the wave penetration, which were executed during the ship motion tests.

The sequence of the tests was disturbed by an error in the simulation of the mooring line characteristics of the mooring lines $\phi$ 32 mm. These tests had to be repeated at the end of the investigation with an incident wave direction of $150^\circ$.

A number of tests was repeated in order to check the reliability of the test results.

5.2 Ship motion tests

In advance of the tests, the mooring lines of the 15,000 d.w.t. ship were pretensioned individually. A set of double lines was simulated in model by one line with the characteristics of two lines in nature; so a double pretension was used for such a double set of lines in model.
The instruments for the measurement of the ship motions were brought in their zero position after pretensioning the mooring lines.

The incident wave height and the wave height in several selected stations in the basin were measured during a ship motion test (see Figures 8 and 9). After the test the tension in the mooring lines was measured and compared with the pretension before the test.
All ship motion and mooring- and fender force signals were fed into a computer to plot exceedance curves.
The maximum, 1% exceedance, 5% exceedance, 10% exceedance and significant values for each ship motion and mooring force were then determined and tabulated.

5.3 Wave induced currents

Separately from the ship motion tests some tests were executed to get a qualitative impression about the occurrence of wave induced currents. This was done by photographing the position of floats with a time interval camera.
6. Test results

6.1 Presentation of results

The mooring forces, fender forces, the ship motions and wave height measurements in the model are described in Tables 4...7. The mooring- and fender forces and the ship motions are presented in these tables in the following form, viz.:
- maximum value (m),
- the value, which was exceeded by 1%, 5% and 10% of the peakvalues, respectively,
- significant value (s); the mean value of the highest \( \frac{1}{3} \) part of peakvalues.

Not only the exceedance percentages of the peak values were calculated, the exceedance values with respect to the time, that a certain level was exceeded, was calculated too. The difference between both ways of presentation was very small. Therefore, only the peakvalues will be used for the present study.

Wave heights measured in the wave gauge positions indicated in Figures 8 and 9, are presented in Table 4...7 too. The results are characterized with the following parameters:
- \( H_s \) = significant wave height; mean value of the \( \frac{1}{3} \) highest part of the wave heights,
- \( T_M \) = mean wave period,
- \( T_p \) = peak period of the high frequency part of the spectrum,
- low part \( 4\sqrt{m_o} \) = indication of the significant wave height of the long waves,
- \( m_o \) = total energy density of the low frequency part of the spectrum,
- low part \( T_p \) = peak period of the low frequency part of the spectrum.

The maximum mooring- and fender forces and ship motions, measured during each test, are summarized in Table 8.

The wave penetration during the tests 9 and 10, 12 and 13, 7 and 8, 9 and 11 is compared in Figures 13 and 14. Two different penetration coefficients were used for the comparison, viz.:
- \( H_s / H_{s, i} \) = ratio of the significant wave height in the concerned wave gauge position and the incident significant wave height,
- \( 4\sqrt{m_o} / (4\sqrt{m_{o, i}}) \) = ratio of the \( 4\sqrt{m_o} \) value of the low frequency part of the wave spectrum in the concerned wave gauge position and the \( 4\sqrt{m_{o, i}} \) value of the low frequency part of the incident wave spectrum.
In Figures 15..19 the measured mooring forces, surge motion and wave penetration are compared for different, comparable sets of tests. The development of the spectrum shape in the different wave gauge positions during Test 9 and Test 10 are presented in Figure 20 and 21, respectively.

6.2 Model calibration

6.2.1 Incident wave

The irregular wave generator was controlled as to wave period and significant wave height by varying both the speed of a punched tape signal fed into the computer and the amplitude of the computer response signal. The incident wave height was defined by the wave height measured in wave gauge positions 1 and 10 for a wave direction of $220^\circ$ and $150^\circ$, respectively. The influence of wave reflection against the breakwater was very small on the incident wave height, as the calibration test showed.

6.2.2 Second order long waves

It has been generally accepted during recent years that a correct reproduction of the second order group-induced long waves is imperative for physical model tests dealing with, for instance harbour resonance and slow drift oscillations of moored ships. The fact that short period waves induce longer waves with periods near those of the wave groups was first stated by Longuet-Higgins and Stewart. Sand [2] gives the transfer function between the amplitude of the second order long waves and the generated short waves. Within the scope of the calibration tests the development of the low frequency energy of the energy density spectra was studied as a function of the waterdepth and compared with theoretical calculations [2]. The difference between the measured and calculated amount of low frequency energy was manifest in the spectra, measured at waterdepth, varying from $d = 12.5$ m to $d = 8$ m, for a wave direction of $220^\circ$. The measured amount was lower than the calculated one; the difference increased in the case of a decrease of the waterdepth.

For a wave direction $150^\circ$ the calculation was in good agreement with measurements up to a depth of $d = 11.6$ m; when the depth decreased further the same difference appeared as in the case of a wave direction $220^\circ$. Previous studies at the D.H.L. showed also differences between measured and calculated
amounts of low frequency energy, which appears to indicate that especially for shallow water, the theory is still not adequate. The use of a compensation signal (based on \[2\]) for the wave generator did not result in a relevant chance of the development of the wave spectra. It was decided, therefore, that the use of such a compensation programme for the wave generator would not be desirable.

6.3 Wave penetration

6.3.1 Influence of wave height

The wave penetration in the case of an incident wave height of approximately 3 m and 5 m are compared in Figures 13 and 14. No influence of the incident wave height on wave penetration can be distinguished for the case that the wave penetration is presented as the penetration coefficient \[\frac{H_s}{H_{s,i}}\]. The wave penetration coefficient \([H_s/H_{s,i}]\) near the quay is between 10\% and 20\%, which is very well in agreement with theoretical estimates of the wave penetration due to diffraction.

The development of the low frequency part of the wave spectrum is more remarkable (see Figure 20 and 21). The influence of the incident wave height demonstrates itself in the amount of low frequency energy in the incident wave spectrum. The amount of low frequency energy (in this report presented by the \(4\sqrt{m_o}\) value, in which \(m_o\) = 0-th moment of the spectral density) is more or less proportional to the square of \(H_s\). The development of the wave penetration coefficient of the low frequency part of the spectrum \(4\sqrt{m_o}/(4\sqrt{m_o})_i\) shows, that there is only a slight reduction as a result of diffraction. No significant influence of differences in incident wave heights can be determined in the development of this wave penetration coefficient \((4\sqrt{m_o}/(4\sqrt{m_o})_i)\), neither. The latter is very important for the behaviour of moored vessels in the lee of the breakwater.

An extra peak in the spectrum measured in wave gauge position 5 appeared during Test 10 (see Figure 21) and 13. The period is approximately \(T = 65\) s. This extra peak points to the existence of a so-called "seiche" along the quay wall (a seiche is a long period harbour oscillation) with a wave length equal to the length of the breakwater. A certain threshold value of the incident wave height has to be exceeded in order to create this seiche. The threshold value of the incident wave height will probably lie between 3 m and 5 m, during the tests with \(H_{s,i} = 3\) m this seiche did not appear, during the tests with \(H_{s,i} = 5\) m it is obvious.
6.3.2 Influence of breakwater alignment

As a wave passes the end of an obstacle, for instance a breakwater, the head of the breakwater may be considered as a source, which generates arc shaped waves in the lee zone behind the breakwater. The wave height decreases as we proceed along a wave crest into the shadow zone. The rate of decay depends on the distance between the breakwater head and the measuring station and the period of the wave. The decrease in wave height will be small for a short distance away from the breakwater head and will reduce for shorter wave periods.

It appears from the development of the specific wave coefficients, that the low frequency part of the spectrum, which was considered to be coupled to the high frequency part, manifests itself after diffraction as an independent wave of a considerable length.

The influence of the presence of the western breakwater head on the wave penetration is presented on Figure 15. The influence of the elongation of both the western and the eastern head in comparison with the initial design is presented in Figures 16 and 17. The elongation of the distance between the breakwater heads and the wave gauges was too small in these cases. So it did not have any influence on the penetration of waves with these periods.

6.3.3 Influence of perforated wall

The wave penetration during comparable tests with and without perforated quay wall (Test 9 and Test 11, respectively) is presented in Figure 14. Only a slight improvement can be determined as a result of the perforated wall in the wave penetration.

6.3.4 Conclusions

With respect to the wave penetration in the proposed lay-out it can be concluded from this study that:

1. In the case of $H_{S,i} > 3$ m a seiche can occur alongside the quay wall of the breakwater.
2 A limited elongation of the breakwater heads does not have any significant influence on the wave penetration in the lee of the breakwater.

3 The use of a perforated quay wall has no influence on the wave penetration.

6.4 Ship motions and mooring forces

6.4.1 Influence of wave height

The influence of the height of the incident wave on the ship motion and mooring forces is large, as is illustrated in Table 6.1. The relation between the maximum surge motion (negative or positive direction) and the incident wave height may be expressed as:

\[
\frac{\text{max. surge (Test } x)}{\text{max. surge (Test } y)} = \left( \frac{H_{s,1} \text{ (Test } x)}{H_{s,1} \text{ (Test } y)} \right)^n
\]

The same expression can be used for the significant surge motion and for the \(4\sqrt{m_o}\) value of the low frequency part of the spectrum. For the various tests the value of \(n\) is respectively:

<table>
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<tr>
<th>(x)</th>
<th>Test 7 and Test 8</th>
<th>Test 9 and Test 10</th>
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<th>Test 12 and Test 13</th>
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<td>(wave gauge)</td>
<td>(1)</td>
<td>(4)</td>
<td>(10)</td>
</tr>
</tbody>
</table>

Table 6.1

The value of \(n\) for these four sets of comparable tests is both for the maximum surge motion and for the significant surge motion 3.5, approximately. The expectation was that the surge motion would be proportional to the \(4\sqrt{m_o}\)
value ("wave height") of the low frequency part of the spectrum, which is proportional to the square of the wave height as can be seen in Table 6.1. This unexpected high value of \( n \) (for the surge motion) was caused by the existence of the seiche along the quay wall (see Paragraph 6.3.1). The ship was situated during the tests near the nodes of the long wave. The period of the seiche appears also in the "forced" surge period of the moored ship. A reduction of the surge motion can be expected in the case of a ship moored at the antinodes of the seiche; for instance in the centre position of the quay.

6.4.2 Influence of breakwater alignment

The influence of the western breakwater head is very well illustrated on Figure 15. Notwithstanding the fact, that the wave penetration is not affected by the presence of this head, the forces in the hawsers and the surge motions are significantly reduced. The reduction is caused by the difference in the direction of the diffracted wave near the ship, resulting from the presence of the head.

An additional elongation of the head with 200 m does hardly affect the mooring forces and ship motions (Test 3). So for a further reduction of the wave height 200 m is insufficient, as a further change of the wave direction near the ship is only possible by a much larger extension of the initial western breakwater head.

The influence of both an elongation of the eastern and of the western breakwater head is represented on Figures 16 and 17. The influence of these elongations (Test 12 and 13) is very small. Only a slight reduction in the wave penetration, mooring line forces and surge motions can be determined.

6.4.3 Influence of perforated wall

The influence of the perforated wall is represented on Figure 18. It can be stated that for the hawsers 3, 4, 5 and 6 and for the surge motion, no difference can be seen in the results for a solid and for a perforated wall. Hawser 1 and 2 show a reduction in the forces for which there are no obvious physical reasons.
6.4.4 Influence of mooring arrangement

Three different mooring arrangements were tested during the study, viz.: Arrangement A, B and C (see Figure 11 and Paragraph 4.2.4).

Mooring arrangement A was tested during the tests 1, 2, 3 and 4. The forces in the mooring lines were far above the design loads of the mooring lines during the tests \( H_{s,i} = 3.9 \text{ m} \) and \( 4.8 \text{ m} \), respectively). Only an approximation of the mooring forces can be made for an incident wave height of \( 3 \text{ m} \); for this wave boundary condition the forces will exceed the design load, too.

Mooring arrangement B was tested during the tests 5 and 6. The mooring line forces during Test 5 are about two times higher than the design load in the case of this very stiff mooring arrangement. In spite of the reduction of mooring forces and ship motions, which appears in the case of a ballasted ship instead of a fully laden ship (see Figure 19), the mooring line forces exceeded the design load in the case of a ballasted ship (Test 6), too. The forces in the spring lines, however, are considerably smaller than those in the bow- and sternlines; so the doubling of the springlines does not seem to be a good choice. The surge motion is very small in the case of mooring arrangement B. The use of thicker steel wires instead of \( \phi 32 \) will of course increase the design load of the lines, but it will increase the stiffness of the mooring arrangement, too and consequently the forces in the mooring lines will increase.

A more elastic material for the mooring lines seems to be more correct for this ship. Mooring arrangement C was tested during the tests 7...13. For this arrangement polypropylene lines were used. The design load of these lines was not exceeded during the tests with an incident wave height \( H_{s,i} = 3 \text{ m} \); during the tests with a wave height \( H_{s,i} = 5 \text{ m} \) the mooring line forces exceed the design load with about 50%. Interpolation between the results of the tests 7 and 8 results in an incident wave height \( H_{s,i} = 3.90 \text{ m} \) for which the design load is reached; interpolation between the results of the tests 9 and 10 results in an incident wave height of \( H_{s,i} = 4.02 \text{ m} \) for which the design load is reached.

6.4.5 Fender forces

The design load of the fenders of 420 kN per fender was never exceeded during the tests (note: In the model one fender simulated 4 fenders in nature, so per modelfender the design load is \( 4 \times 420 \text{ kN} = 1680 \text{ kN} \)).
6.4.6 Conclusions and recommendations

With respect to the ship motions and mooring forces, it can be concluded from this study that:

1 The ship motions and mooring forces increase considerably due to the presence of the seiche along the quay wall in the case of $H_{s,i} = 5$ m (a reduction of the mooring forces and ship motions can be expected during the extreme wave conditions, if the ship will be berthed more in the centre of the quay wall).

2 A limited elongation of the breakwater heads with respect to the initial design will not have any significant influence on the mooring forces.

3 The use of a perforated quay wall does not reduce the mooring forces.

4 The use of (stiff) steel mooring lines can not be recommended, neither under operational nor under extreme wave conditions ($H_{s,i} = 3$ m and $H_{s,i} = 5$ m, respectively), as the design loads will be exceeded.

5 In the case that strong, elastic mooring lines are used the mooring line forces do not exceed the design load under operational wave conditions ($H_{s,i} = 3$ m); under extreme wave conditions ($H_{s,i} = 5$ m) the design loads were exceeded with 50%.

6 The design loads of the fenders were never exceeded during the tests.

7 The mooring forces are larger in the case of a loaded ship than in the case of a ballasted ship.

6.5 Wave induced currents

A summary of the patterns of the floating objects in the harbour area are presented on Figures 22, 23 and 24. The current pattern in the case of a wave direction 220° is given on Figure 22. A circulation current arises in the lee of the western breakwater head. Near the mouth of the small harbour hardly any current can be determined. The flow pattern in this mouth is not influenced
by the existence of the breakwater at all. The flow patterns in the case of a wave direction of 220° are presented on the Figures 23 and 24; on Figure 23 the flow pattern without the breakwater is presented, while the flow patterns in the case with breakwater are presented on Figure 24. The existence of a large circulation current in the lee of the breakwater is obvious on the last figure. In the mouth of the small harbour a circulation exists as well in the case without as with the breakwater. The flow pattern near the harbour is, however, rather confused.
REFERENCES

1 Harbour of Licata
   Wave penetration and harbour oscillations
   Delft Hydraulics Laboratory, report M 1586. 1979

2 Sand, S.E.
   Long wave problems in laboratory models
   A.S.C.E. Journal of the waterway, Port, Coastal and Ocean Division,
   February 1981

3 Guidelines and recommendations for the safe mooring of large ships at
   piers and sea islands
   O.I. Companies International Marine Forum
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<th>Test</th>
<th>Breakwater alignment</th>
<th>Incident wave (M.S.L. -14 m)</th>
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*Tests were executed at the end of the programme.

Note: Three reproduction tests were executed, viz.: Test 5r, 9r and 10r.

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<td>3.94</td>
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<td>9.87</td>
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Table 2 Distribution of wave height and wave direction according to K.N.M.I. data
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<th>0 - 0.25</th>
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<th>0.75 - 1.25</th>
<th>1.25 - 1.75</th>
<th>1.75 - 2.25</th>
<th>2.25 - 2.75</th>
<th>2.75 - 3.25</th>
<th>3.25 - 3.75</th>
<th>3.75 - 4.25</th>
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<th>5.75 - 6.25</th>
<th>6.25 - 6.75</th>
<th>6.75 - 7.25</th>
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<td>6.02</td>
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<td>0.19</td>
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<td>0.97</td>
<td>0.92</td>
<td>0.63</td>
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<td>0.02</td>
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<td>.02</td>
<td>.05</td>
<td>.07</td>
<td>.10</td>
<td>.13</td>
<td>.07</td>
<td>.05</td>
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<td>.02</td>
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<td>.02</td>
<td>.02</td>
<td>.02</td>
<td>.02</td>
<td>.02</td>
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<tr>
<td>12 - 13</td>
<td>.02</td>
<td>.02</td>
<td>.05</td>
<td>.07</td>
<td>.10</td>
<td>.13</td>
<td>.07</td>
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<td>100%</td>
<td>100%</td>
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<td>100%</td>
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Table 3: Distribution of wave height and wave period according to K.N.M.I. data
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<td>5%</td>
<td>10%</td>
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<td>5%</td>
<td>10%</td>
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<td>Mooring 1 (kN)</td>
<td>1334 809 570 446 383</td>
<td>1067 652 427 300 260</td>
<td>847 639 454 352 302</td>
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<td>Mooring 2</td>
<td>1510 852 493 316 245</td>
<td>643 325 184 100 84</td>
<td>643 443 280 183 141</td>
<td>798 564 399 284 226</td>
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<tr>
<td>Mooring 3</td>
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<td>723 524 398 338 295</td>
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</tr>
<tr>
<td>Mooring 4</td>
<td>1518 1135 685 516 482</td>
<td>1093 827 608 478 444</td>
<td>1023 790 409 323 273</td>
<td>1135 754 524 403 342</td>
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<td>Mooring 5</td>
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<td>- - - - -</td>
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<tr>
<td>Mooring 6</td>
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<td>- - - - -</td>
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<tr>
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<td>1507 1350 784 646 331</td>
<td>1273 749 422 269 188</td>
<td>1407 896 537 351 260</td>
<td>1507 1131 763 554 381</td>
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<tr>
<td>Fender 7</td>
<td>1207 691 258 132 108</td>
<td>1248 697 350 142 144</td>
<td>916 511 211 309 95</td>
<td>1256 520 177 86</td>
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**Wave direction**

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<th>220°</th>
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<td>low part</td>
<td>Hg</td>
<td>Tm</td>
<td>Tp</td>
<td>Hg</td>
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<td>wave gauge</td>
<td>220°</td>
<td>220°</td>
<td>220°</td>
<td>220°</td>
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<td>3.93 9.3 10.8 0.80 55.9</td>
<td>3.91 9.4 10.8 - -</td>
<td>4.75 10.5 12.5 1.13 87.8</td>
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<td>location 2</td>
<td>3.98 9.4 9.2 0.69 61.4</td>
<td>4.19 9.5 10.8 0.73 47.3</td>
<td>4.10 9.5 11.0 - -</td>
<td>5.32 10.3 12.3 1.21 87.8</td>
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<td>- - - - -</td>
<td>- - - - -</td>
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<td>- - - - -</td>
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<tr>
<td>location 11</td>
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</table>

**Breakwater alignment**

<table>
<thead>
<tr>
<th>Breakwater alignment 1</th>
<th>Breakwater alignment 2</th>
<th>Breakwater alignment 3</th>
<th>Breakwater alignment 4</th>
</tr>
</thead>
</table>

Note: For the double mooring lines the presented mooring force has to be divided by 2 in order to get the force per mooring line.

Table 4 Results of Tests 1, 2, 3 and 4
<table>
<thead>
<tr>
<th></th>
<th>TEST 5</th>
<th>TEST 6</th>
<th>TEST 7</th>
<th>TEST 8</th>
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</thead>
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<tr>
<td></td>
<td>max.</td>
<td>1%</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>Mooring 1 (kn.)</td>
<td>495</td>
<td>335</td>
<td>248</td>
<td>209</td>
</tr>
<tr>
<td>2</td>
<td>562</td>
<td>386</td>
<td>291</td>
<td>244</td>
</tr>
<tr>
<td>3</td>
<td>449</td>
<td>354</td>
<td>297</td>
<td>264</td>
</tr>
<tr>
<td>4</td>
<td>657</td>
<td>440</td>
<td>374</td>
<td>340</td>
</tr>
<tr>
<td>5</td>
<td>555</td>
<td>350</td>
<td>272</td>
<td>234</td>
</tr>
<tr>
<td>6</td>
<td>468</td>
<td>350</td>
<td>272</td>
<td>236</td>
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<tr>
<td>Tender 3 (kn.)</td>
<td>568</td>
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<td>134</td>
<td>105</td>
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<td>7</td>
<td>213</td>
<td>115</td>
<td>75</td>
<td>52</td>
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**Surge neg. (m):**
- 0.15 (n), 0.11 (m), 0.09 (n), 0.07 (m), 0.06
- 0.10 (n), 0.07 (m), 0.05 (n), 0.03 (m), 0.02 (n), 0.01 (m), 0.00 (n), 0.00 (m)

**Pos. (m):**
- 0.19 (n), 0.12 (m), 0.09 (n), 0.08 (m), 0.07 (n), 0.05 (m), 0.03 (n), 0.03 (m), 0.02 (n), 0.01 (m), 0.00 (n), 0.00 (m)

**Sway neg. (m):**
- 0.27 (n), 0.18 (m), 0.13 (n), 0.11 (m), 0.10
- 0.29 (n), 0.13 (m), 0.10 (n), 0.09 (m), 0.08

**Pos. (m):**
- 0.19 (n), 0.13 (m), 0.11 (n), 0.09 (m), 0.08 (n), 0.07 (m), 0.06 (n), 0.05 (m), 0.04 (n), 0.03 (m), 0.02 (n), 0.01 (m), 0.00 (n), 0.00 (m)

**Heave neg. (m):**
- 0.34 (n), 0.27 (m), 0.21 (n), 0.17 (m), 0.16
- 0.40 (n), 0.27 (m), 0.20 (n), 0.17 (m), 0.15

**Pos. (m):**
- 0.31 (n), 0.23 (m), 0.18 (n), 0.15 (m), 0.14

**Roll neg. (deg):**
- 1.53 (n), 0.86 (m), 0.60 (n), 0.52 (m), 0.45 (n), 0.35 (m), 0.32 (n), 0.29 (m)
- 1.19 (n), 1.00 (m), 0.90 (n), 0.87 (m), 0.77 (n), 0.64 (m), 0.59 (n), 0.47 (m)

**Pos. (deg):**
- 1.61 (n), 1.64 (m), 1.64 (n), 1.64 (m), 1.64 (n), 1.64 (m), 1.64 (n), 1.64 (m)

**Pitch neg. (deg):**
- 0.25 (n), 0.14 (m), 0.12 (n), 0.10 (m), 0.10 (n), 0.09 (m), 0.08 (n), 0.07 (m), 0.07 (n), 0.06 (m), 0.05 (n), 0.04 (m), 0.03 (n), 0.02 (m), 0.01 (n), 0.00 (m)

**Pos. (deg):**
- 0.25 (n), 0.14 (m), 0.12 (n), 0.10 (m), 0.10 (n), 0.09 (m), 0.08 (n), 0.07 (m), 0.07 (n), 0.06 (m), 0.05 (n), 0.04 (m), 0.03 (n), 0.02 (m), 0.01 (n), 0.00 (m)

**Wave direction:**
- 150°
- 220°

**Wave gauge location:**
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

**Loaded Ballast:**
- 5
- 6
- 7
- 8
<table>
<thead>
<tr>
<th>TEST 9</th>
<th>TEST 10</th>
<th>TEST 11</th>
<th>TEST 12</th>
<th>TEST 13</th>
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<tr>
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<td>SE</td>
<td>TIE</td>
<td>(\times)</td>
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<td>163</td>
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<td>113</td>
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<td>60</td>
<td>50</td>
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<td>99</td>
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**Fender 3** (set 1.91)

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<th>SE</th>
<th>TIE</th>
<th>(\times)</th>
<th>max.</th>
<th>IE</th>
<th>SE</th>
<th>TIE</th>
<th>(\times)</th>
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<tr>
<td>797</td>
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<td>282</td>
<td>237</td>
<td>208</td>
<td>1600</td>
<td>837</td>
<td>534</td>
<td>399</td>
<td>305</td>
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<tr>
<td>620</td>
<td>176</td>
<td>25</td>
<td>25</td>
<td>37</td>
<td>468</td>
<td>316</td>
<td>238</td>
<td>198</td>
<td>175</td>
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**wave direction**

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<th>location</th>
<th>(see Fig. 9)</th>
<th>(\times)</th>
<th>(\times)</th>
<th>(\times)</th>
<th>(\times)</th>
<th>(\times)</th>
<th>(\times)</th>
<th>(\times)</th>
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<td>1.17</td>
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<td>3.64</td>
<td>9.9</td>
<td>11.8</td>
<td>1.01</td>
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</tbody>
</table>

**Loaded Ballast**

| l | l | l | l |

**Breakwater alignment**

| l | l | l | l |

**Note:** For the double morring lines the pressure of morring force has to be divided by 2.

In order to get the force per morring line.

**Table 6 Results of Tests 9, 10, 11, 12, 13**
<table>
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<th>TEST 5r</th>
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<td>5% 10%</td>
<td>max. 1%</td>
</tr>
<tr>
<td>1 (kn.)</td>
<td>254</td>
<td>199</td>
<td>162</td>
</tr>
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<td>2 -</td>
<td>219</td>
<td>146</td>
<td>124</td>
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<tr>
<td>3 -</td>
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<td>117</td>
<td>64</td>
</tr>
<tr>
<td>4 -</td>
<td>129</td>
<td>97</td>
<td>76</td>
</tr>
<tr>
<td>5 -</td>
<td>234</td>
<td>167</td>
<td>130</td>
</tr>
<tr>
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<td>252</td>
<td>163</td>
<td>130</td>
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<tr>
<td>Fender</td>
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<td>58</td>
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Table 8  Summary of main results of the ship motion tests
WAVE HEIGHTS

STATISTICAL DISTRIBUTION OF SIGNIFICANT

SHIPS OBSERVATIONS IN THE AREA 36° - 37° NL AND 14° - 15° EL

Hs at deep water

times per year

1/10 1/6 3/4 3/2 1 2 3 4 5

exceedance percentage of time (%)

1 2 3 4 5 6 7 8 9 10

directions 0° - 360°

directions 105° - 255°
RELATION BETWEEN $H_S$ AND $T_m$ [1]

DELFORD HYDRAULICS LABORATORY M 1783 FIG. 3
MODEL OF THE 15,000 DWT. GENERAL CARGO SHIP

DELFT HYDRAULICS LABORATORY

M 1783 FIG. 7

scale 1 : 10  (model)
scale 1 : 1000  (nature)
measures in metres
MOORING ARRANGEMENT A

MOORING ARRANGEMENT B

MOORING ARRANGEMENT C

MOORING ARRANGEMENTS
**DEFINITION OF SHIP-MOTION COMPONENTS**

- $\chi$ = surge
- $y$ = sway
- $z$ = heave
- $\varphi$ = roll
- $\theta$ = pitch
- $\psi$ = yaw
- $G$ = centre of gravity

**SCHEMATIC SET-UP POTENTIOMETERS**

- $\chi : P_1$
- $y : (P_2 + P_3)/2$
- $z : (P_4 + P_7)/2$
- $\varphi : (P_5 - P_6)/a$
- $\theta : (P_4 - P_7)/b$
- $\psi : (P_2 - P_3)/b$
TEST RESULTS: DIFFERENT BREAKWATER ALIGNMENTS

DELFT HYDRAULICS LABORATORY

T9, T9r, T12

M 1783 FIG. 16

\[ H_g = 3.1 \text{m} \]
\[ T_p = 8.8 \text{s} \]

- test 9
- test 9 reproduction
- test 12
- alignment 4
- alignment 4
- alignment 5

m = maximum value
s = significant value
# = double mooring line
TEST RESULTS: DIFFERENT BREAKWATER ALIGNMENTS

DELTFT HYDRAULICS LABORATORY
TEST RESULTS; INFLUENCE PERFORATED WALL

DELFT HYDRAULICS LABORATORY

M 1783 FIG. 18
FLOW PATTERN, WAVE DIRECTION 150°
(WITHOUT BREAKWATER)
DELFT HYDRAULICS LABORATORY
M 1783  FIG. 23
FLOW PATTERN, WAVE DIRECTION 150°
(WITH BREAKWATER)

DELFt HYDRAULICS LABORATORY

M 1783 FIG. 24
1 View on the model of the moored ship
(ballast condition, wave direction 150°)
2 General view model lay-out
(wave direction 150°)

3 View on the model of the moored ship
(ballast condition, wave direction 220°)