HYDRODYNAMICS OF A MOORED LNG CARRIER BEHIND A DETACHED BREAKWATER

Wieke Wuisman[1] and Wim van der Molen[1]

Abstract: In order to predict the hydrodynamics of a moored LNG carrier behind a detached breakwater, a rapid assessment tool has been developed. The model is based on linear potential theory. Diffraction around and transmission over and through the breakwater as well as reflection at the coast have been considered. Using the strip theory method for wave force calculations, the strongly varying wave field at the LNG jetty can be taken into account. The results of the assessment tool can be used as input for standard ship motion simulation computer programs. Subsequently, the motions of the vessel and forces in the mooring system can be obtained. Results are presented for various dimensions of the breakwater and coast profiles.

INTRODUCTION

As the worldwide gas market continues to grow and environmental concerns with respect to in-port unloading of gas have increased, there has been a boom of interest in new liquefied natural gas (LNG) import terminals in the past five years. For these terminals, which are more and more located in areas with hostile sea conditions, dedicated provisions are required to create sufficient shelter for the carriers. Proposals have been made to construct a marginal low crested breakwater parallel to the coast protecting a ship moored at a jetty close to the shore. For an optimal economic design of such an LNG marine terminal, the dimensions and orientation of the detached breakwater have to be optimized as a function of the weather related downtime of the moored LNG carrier. Doing so requires adequate simulation tools. However, for the combination of wave and ship motion, a link between an efficient wave simulation tool and a program for ship response calculations is not available at present.

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[1] Delft University of Technology, Faculty of Civil Engineering and Geosciences; P.O. Box 5048, 2600 GA Delft, The Netherlands; W.K.Wuisman@student.tudelft.nl; W.vanderMolen@citg.tudelft.nl

The research on ship behaviour has resulted in the development of various so-called six degrees of freedom (SDF) computer programs. These programs solve the equations of motion of a moored vessel for all six degrees of freedom. As a consequence of the non-linear characteristics of the mooring system the equation of motion is solved in the time domain. The wave force time series are calculated from a homogeneous wave field of irregular, long-crested waves. In case of an open jetty configuration these assumptions are valid. However, considering a carrier behind a detached breakwater, the wave field is not homogeneous, but the wave height varies over the ship length. Consequently the influence of the detached breakwater on the ship motions must be considered. In addition, the reflection of the waves at the coast also has to be taken into account.

This paper describes a methodology to predict the hydrodynamics of a moored LNG carrier behind a detached breakwater. A rapid assessment tool has been developed in order to assess the optimum breakwater dimensions in the preliminary design stage of an LNG marine terminal. In particular the effects of the breakwater dimensions on the hydrodynamic behaviour of the moored LNG carrier are considered. The computational approach for the calculation of ship motions from a given offshore wave field is described. In addition results are presented for different terminal layouts.

COMPUTATIONAL APPROACH

The computational domain is defined by a shallow sea, which is bounded by a partially reflective straight coast. A single breakwater, with length L_b and crest level R_c, is located parallel to the coast and the ship is moored between the coastline and the breakwater, see Fig. 1. The water depth is assumed to be uniform, meaning that wave refraction effects can be neglected. Furthermore, the incident wavelength is presumed to be much larger than the breadth of the breakwater.

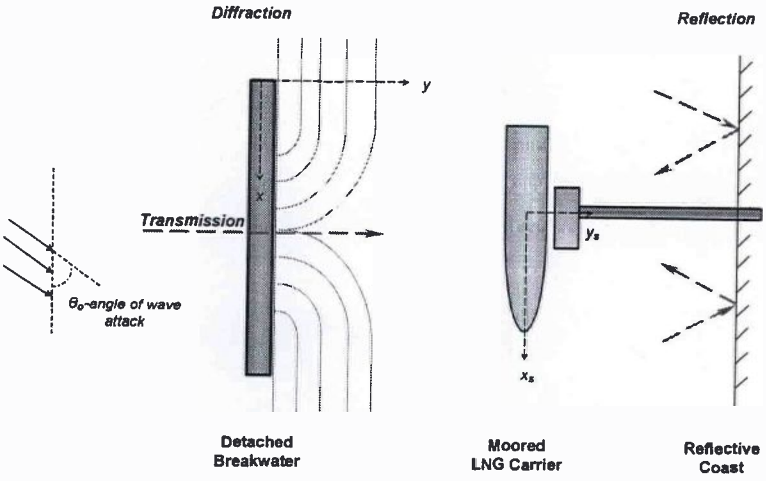

Fig. 1. Definition sketch for an LNG marine terminal

From the offshore wave field, the wave parameters at the jetty are influenced by diffraction, transmission and reflection, see Fig. 1. The wave field, which strongly varies in space behind the breakwater, influences the wave forces acting on the ship's hull, and consequently the motions of the carrier.

Wave field

Mathematical modelling of the water waves is based on the linear potential theory. The offshore wave field is described as a summation of N first order wave components and $N(N-1)/2$ second order wave components, also known as set-down or bound waves. The bound wave is important because of its contribution to the second order potential in the slowly varying drift forces. On the ocean the bound waves travel with the group speed of the short waves. Behind the breakwater the height of the short waves decreases rapidly though. The bound wave energy becomes free and the long wave travels with the celerity according to the dispersion relation. Because the ship is moored in the lee of the breakwater, the second order wave is treated as a free wave. This means that linear diffraction theory can be applied for the scattering around the breakwater and reflection at the coast.

The wave elevations at the position of the ship are defined by linear superposition of the contribution of the diffracted, transmitted and reflected first- and second order waves to the wave forces. The surface elevation of the water waves at the jetty is determined by the diffraction coefficient K_d, the reflection coefficient K_r and the transmission coefficient K_t.

Following the classical approach of wave diffraction by Penney and Price (1952) for impermeable, semi-infinite breakwaters, several studies to determine the diffraction coefficient K_d by *porous* breakwaters have been carried out, e.g. Yu (1995), McIver (1999) and Lynett et al. (2000). The influence of the breakwater height, and thus overtopping, is not included in these analytical models for porous breakwaters. Since the optimization of the breakwater dimensions is the focus of this study, the effects of the height must be included. In the present work, the diffraction solution of Penny and Price is followed in combination with empirical predictive transmission formulae. The incoming waves, partly diffracted around the breakwater, will be reflected at the coast. The reflected wave height is obtained by calculating the diffracted wave height at the position of the ship mirrored at the coastline and by applying a reflection coefficient. The reflection coefficient K_r depends on the bed slope and the wave steepness. Predictive formulations are available for mild-sloping beaches (Battjes 1974) as well as for rocky coasts (Seelig and Ahrens 1981). These formulations are valid for short waves. The second order long waves are assumed to be fully reflective.

For the determination of wave transmission through porous media analytical methods have been developed. Chwang and Chan (1998) review these analytical solutions. In these studies the loss of energy is affected by two factors: the porosity and the fluid discharge through the porous medium. However, the influence of the relative freeboard on overtopping is not taken into account. The relative freeboard has long been recognized to have a decisive role on wave transmission. In order to investigate its influence, extensive studies with physical models on transmission have been performed over the past years. These tests are all based on waves, approaching the breakwater perpendicularly. From the available predictive formulations the d'Angremond formula (d'Angremond et al. 1996) is chosen in this study. This formulation is most reliable for low-crested rubble-mound breakwaters (Calabrese et al. 2003, Wamsley and Ahrens 2003). In LNG marine terminals the marginal breakwaters are mainly low-crested and emerged, because of visibility considerations. The transmission coefficient K_t decreases with relative crest height and it depends on the shape and permeability of the breakwater. An approximation is made for the transmission of oblique waves. The transmission through the breakwater is influenced by turbulence and geometric nonlinearity. It can be assumed that longer waves travel more easily through the breakwater. A shift in the peak period of the wave spectrum in the lee of the breakwater is to be expected. Additionally it is likely that a phase shift between the wave overtopping and wave transmission through the breakwater occurs. Research on this field is scarce. As a result the change in spectral shape and interaction between wave overtopping and waves transmitted through the breakwater are not taken into account.

Wave forces

Since the length of the ship is not negligible with respect to both the wavelength and the length of the breakwater, the wave height is not constant over the ship's length. To account for this wave height distribution, the wave elevations and forces are calculated per cross-sectional strip using a strip theory approach. Within strip theory the wave forces are determined per cross-sectional strip separately, where each section is treated as if it were part of an infinitely long cylinder with constant cross-section. Hence diffraction of waves by the ship is considered to be entirely underneath the ship. Diffraction around the bow and the stern is neglected. Although this seems quite a rude assumption, comparison of strip theory calculations with model tests on slender hulls (e.g. Journée 1992) have demonstrated that the results are well enough for quick first design solutions. Integration of the cross-sectional forces over the ship length provides the total wave force.

The strip theory approach is used because it is computationally much faster than a full body diffraction model, such as a panel model. Compared with the prototype situation, the inaccuracies of strip theory are presumably smaller than the uncertainties due to the constant depth assumption and the difficult modelling of wave overtopping of the breakwater. Strip theory is a linear method, so that the wave components due to diffraction and transmission by the breakwater and reflection from the coast can be treated separately. The diffracted and reflected second order waves are also treated as free waves interacting with the ship, so that only the drift force components due to product terms of first order quantities are missing in the linear computations. To account for the contribution of these slowly varying drift forces, the force is estimated based on full body diffraction calculations in long-crested regular waves, known as Newman's approximation (Newman 1974). A linear panel model is used to provide the drift force transfer functions as well as for the determination of the added mass and damping coefficients.

Ship motions

The wave forces are the exciting forces on the ship. The subsequent vessel motions and forces in the mooring system are obtained by solving the equation of motion

$$\sum_{j=1}^{6}\left\{\left(M_{kj}\right)\cdot \ddot{X}_j(t)\right\} = F_k^{hydrodynamic}(t) + F_k^{moor}(t) + F_k^{waves}(t) + F_k^{current}(t) + F_k^{wind}(t) \qquad k = 1,2,\ldots 6 \tag{1}$$

in which the left-hand side contains the inertia matrix M and the rigid body motions X_j in the six degrees of freedom (surge, sway, heave, roll, pitch and yaw). The right-hand side contains hydrodynamic reaction forces incorporated in the added mass, (viscous) damping and hydrostatic restoring coefficients and several linear and nonlinear components such as forces due to waves, wind, current and forces in mooring lines and fenders. Only exciting forces due to waves are considered in this paper. The computer program TERMSIM (Van Oortmerssen et al. 1986), developed at MARIN, has been used to integrate the equation of motion. The model takes into account the nonlinear characteristics of the mooring system and low-frequency hydrodynamic damping.

RESULTS

Several simulation runs have been carried out for a 130,000 m^3 LNG carrier moored at a jetty behind a breakwater. The rubble-mound breakwater, with length L_b = 800 m and crest height R_c = 2 m, and the jetty are situated at 600 m and 350 m from the coast respectively. The water depth is assumed constant, h = 14 m. For the determination of wave reflection a bottom slope of 1:40 is assumed in the surf zone. A typical mooring arrangement is used. The ship is equipped with 16 steel wire ropes with 11 m polypropylene tails. Table 1 shows the dimensions of the LNG carrier.

Table 1. Dimensions of a 130,000 m^3 LNG carrier

Designation	Symbol	Unit	Value
Length between perpendiculars	L_{pp}	m	276.15
Breadth	B	m	41.15
Draft	T	m	11.00
Displacement	Δ	m^3	96,361

The results presented in this section are for the terminal dimensions as described above and for different breakwater lengths, crest heights and bed slopes of the coast to investigate the influence of these parameters on the moored ship behaviour. The results are given for the horizontal motions of the carrier, surge, sway and yaw. These degrees of freedom are chosen because they are critical for the safe mooring of the ship. The ship is able to move rather freely in heave, roll and pitch. The mooring system prevents the ship from large horizontal motions. If these motions still become large, line-breaking accidents can occur.

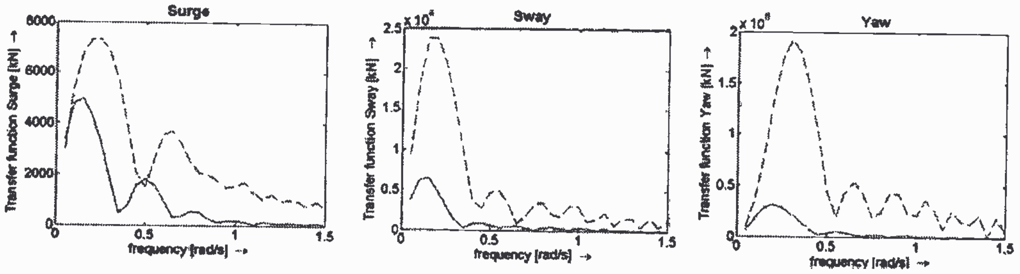

Fig. 2. First order transfer functions, $\theta_0 = 45°$; (- - -) no breakwater, (—) $L_b = 800$ m

First order Transfer Functions (FTF) are given in Fig. 2 to provide more insight in the dependence of the ship behaviour on the wave frequency. The FTF is defined as the ratio between the offshore wave amplitude and the wave force on the ship. Fig. 2 shows the reduction due to the presence of an 800 m long impermeable breakwater for an incident wave direction $\theta_0 = 45°$. Only diffraction is considered here to get a better insight in this contribution. The effects due to reflection and transmission are neglected. For low-frequency waves there is only minor reduction, whereas for higher frequencies the reduction is about 90% for sway and yaw. A remarkable fact is the frequency shift comparing the graphs with and without the breakwater. This shift is due to the change of wave direction in the diffracted wave pattern behind the breakwater.

The results for ship motions presented in this section are for irregular waves. The offshore wave field is defined by a Pierson-Moskowitz wave spectrum, with a significant wave height $H_s = 2.5$ m, peak period $T_p = 13$ s and the calculations have been carried for two different wave directions $\theta_0 = 45°$ and 90°, where the latter corresponds to waves perpendicular to the breakwater. The vessel motion spectra in Fig. 3 and the significant values of the motion amplitudes in Fig. 4 are for a wave direction $\theta_0 = 45°$ and different breakwater lengths. The surge motions are dominated by low-frequency behaviour, mainly due to diffracted bound waves. Higher frequencies have no effects on the motions, because the mooring system is very soft in surge. Evidently, a very long breakwater would be necessary to protect the terminal against these long waves. The sway and yaw motions are influenced by both first and second order wave forcing. The breakwater is much more effective for these motions.

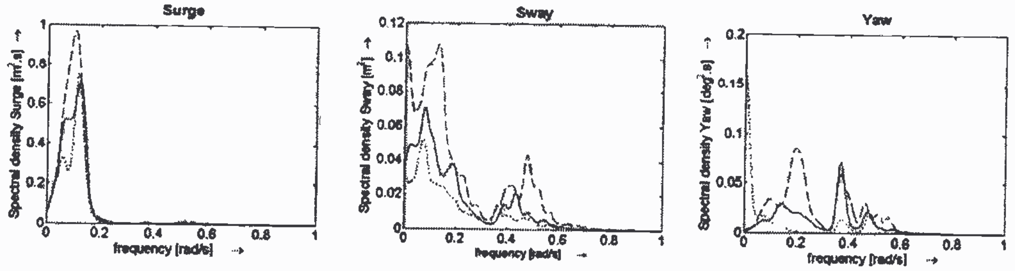

Fig. 3. Ship motion spectra, $\theta_0 = 45°$; (- - -) $L_b = 600$ m, (—) $L_b = 800$ m, (· · ·) $L_b = 1000$ m

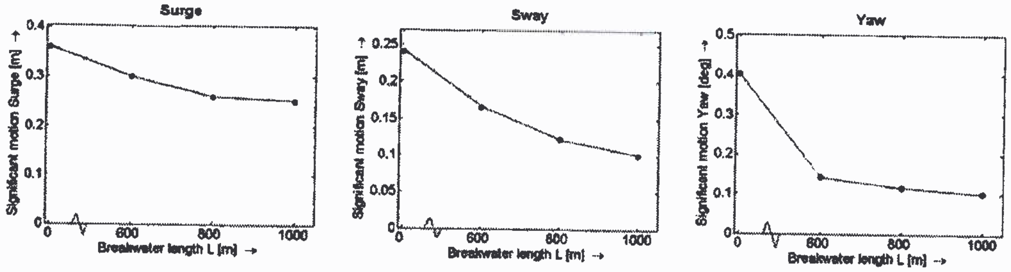

Fig. 4. Significant motions for increasing breakwater length L_b, $\theta_0 = 45°$

The investigation of the influence of the crest height and thus the effect of overtopping has been carried out for normally incident waves, see Fig. 5. The influence of transmission is in the range of the first order wave frequencies, as the empirical transmission formulae are formulated for first order waves only. Surge motions are low for these transverse waves. Regarding the results for sway and yaw the influence of transmission is large for low crest elevations. In these cases with dominant transmission the model gives an approximation of the ship motions and one should be aware of the necessary rude assumptions on transmitted waves.

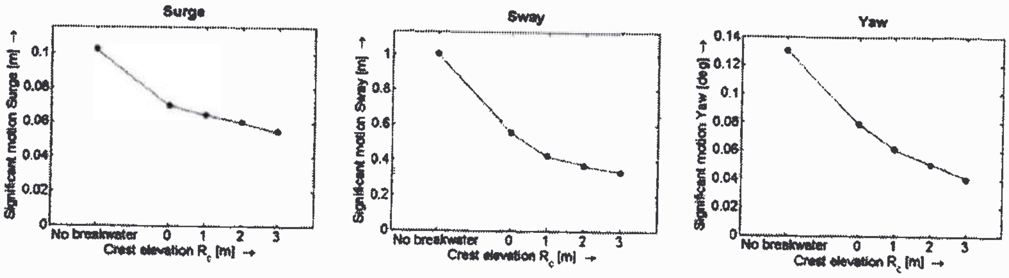

Fig. 5. Significant motions for increasing breakwater crest height R_c, $\theta_0 = 90°$

Regarding the reflection at the shore the (second order) low-frequency waves have higher reflection coefficients, and thus dominate the ship motions due to reflection, only in case of a rocky coast there is also considerable short-wave reflection. Results for different bed slopes and for a rocky coast are given in Fig. 6. The large difference between a rocky coast and a mild-slope beach shows that reflection can play an important role. In case of oblique waves, the waves reflected from the coast are hardly reduced due to the presence of the breakwater and in case of normally incident waves, where the ship is perfectly sheltered against diffracted waves, the reflected wave energy is dominant for rocky coasts.

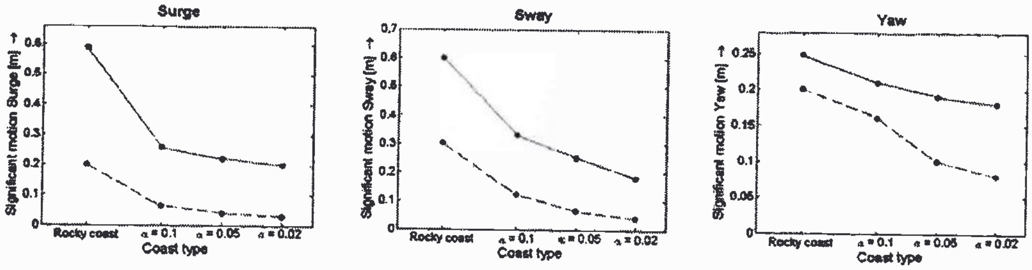

Fig. 6. Significant motions for different shore types; (—) $\theta_0 = 45°$, (- - -) $\theta_0 = 90°$

CONCLUSIONS

A computer model has been developed to calculate the motions and subsequent mooring forces of a ship moored behind a breakwater. Analytical formulations for diffraction of first- and second order waves by a breakwater are combined with empirical formulations for wave transmission over and through the breakwater and reflection at the shore. Quick computations can be carried out to investigate the influence of varying breakwater dimensions and terminal layouts. This is especially useful in the preliminary design stage of a LNG terminal. The calculations give good approximations of the behaviour of the ship, although model testing remains necessary for particularly the difficult modelling of wave overtopping. Hence, the numerical results can be used as a preparation to the model tests.

The results presented in this paper show that a detached breakwater of approximately three times the vessel length efficiently protects the berth against diffracted short waves. However, the protection against long waves is less effective and in case of steep coasts the influence of wave reflection at the shore is dominant. Marginal overtopping over the breakwater can be allowed, although the lack of knowledge about the deformation of the wave spectrum behind the breakwater has to be kept in mind.

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