CHAPTER 12

ON THE TESTING OF MODELS IN MULTIDIRECTIONAL SEAS

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Abstract

Although traditional model testing of marine structures in long-crested, uni-directional (2D) waves can lead to conservative results in certain applications, modern multidirectional (3D) wave generators can produce more realistic sea conditions, leading to the design of more accurate, cost-effective and safer structures. This paper justifies the requirements for testing in 3D seas.

Introduction

Although wave simulation has been in use for many decades, the first evolutionary step in wave generation technology started approximately 25 years ago with the simulation of long-crested, uni-directional (2D) random waves. These random waves, varying in height and period, were believed to correspond more realistically to sea states encountered in nature.

The next phase in the evolution of wave simulation techniques addressed the control of non-linear waves. These second order waves, which dominate the frequency bands, both below as well as above the first order waves can, under certain circumstances, be of considerable importance to the response of structures.

The present and possibly final phase in the development of wave generation technology is the introduction of directionality to simulation of sea states by means of wave generators whose wave boards are segmented and are able to move with a "serpentine-like" motion. These three-dimensional (3D) seas are made up of

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waves from several directions, and interact to create so-called short-crested seas. Although this concept has been well known for many decades, the ability to individually control, by computer, a large number of contiguous segments has become practical only over the last 15 years. This capability is now expanding very rapidly. It is estimated that there are now 32 institutes throughout the world equipped with this type of wave generator. Nevertheless, most testing of marine structures is still done by two-dimensional irregular regular or wave tests, because many certification authorities still rely on the results obtained from regular wave tests. It is also widely believed that two-dimensional wave simulations of the natural sea state lead to conservative designs, (i.e. results in forces on or motions of structures somewhat greater than in nature).

Therefore, the question arises if it is necessary to provide an expensive multidirectional wave generation capability either when planning new or upgrading existing laboratory facilities. This paper addresses this question.

Literature Overview

There are now many research publications that compare model tests on marine structures using 2D (unidirectional) or 3D (multidirectional) wave simulation techniques. The results, however, are still somewhat unconvincing, although trends can be identified. Three of the many reasons, which may contribute to a lack of widespread support among design engineers are given below:

- Nearly all laboratories equipped with segmented wave generators for 3D capability, are either totally, or partly, committed to commercial testing work. Consequently, the results of some of the comparative tests are still proprietary to the clients and therefore have not yet been published in the open literature.

- Because multidirectional wave generation technology is relatively recent, there is still disagreement among experts on how best to achieve correct simulations [cf. Sand and Mynett (1987), Miles and Funke 1989 and Miles 1990]. It is difficult and costly to make good quality measurements of the kinematics of three-dimensional waves. In the absence of good measurements, comparisons between multidirectional waves produced in different research institutes are uncertain.

- Many multidirectional sea state simulations have used a spreading index of $s = 1$ with a $\cos^2(\theta)$ formulation. This represents only a very limited perspective of the large variety of conditions that may actually prevail.

The Fourier summation technique of wave synthesis is considered to be one of the more satisfactory methods. There are many versions of this method, which would generally lead to similar results if very long wave simulation records were used. However, for scaled physical model studies, the simulations are generally limited to shorter test periods. As a result, several of these currently used synthesis methods can lead to significant variations in variance and spectral energy distribution, both spatially and temporally. Only the so-called "single summation method", if used over a complete recycling period, will avoid this problem. On the other hand, the single summation method (Miles 1989) also has several variants, some of which may affect the outcome of the test results.

Table 1 summarizes some of the currently available literature on comparative tests between two-dimensional and three-dimensional wave simulations.

Discussion

The following are a few highlights of the research tabulated in Table 1.

Figure 1a describes the model set-up for the work carried out by Mynett, Bosma and van Vliet (1984). In this study wave loading on a simple, relatively long wave barrier was investigated. The barrier represented a partially submerged gate with 44% immersion and supported by two piers. The barrier was tested to investigate the effect of relative structure-length on wave loading, using both long-crested and short-crested waves.

Figure 1b gives the measured normalized horizontal forces as a function of ***kl*** (*the wave number multiplied by the barrier length*), and compares these to numerical model predictions according to Battjes (1982). When $s = \infty$, the spreading function is a spike function, and consequently the sea state is virtually long-crested. On the other hand, for $s = 1$, the sea state is short-crested with a broad spreading function [$\cos^2(\theta)$]. As could be expected, a longer barrier is more sensitive to the effects of wave multidirectionality.

As a second example, Figure 2a illustrates a vessel restrained by a single point SALMRA mooring system (Single Anchor Leg Mooring Rigid Arm). The importance of testing such systems in multidirectional seas was first demonstrated by Huntington (1981). His research, which was carried out with an ingenious arrangement of 10 sliding wedge wave generators, placed along a semicircular arch, pointed the way for much of the subsequent development for the testing with realistic sea states.

Figure 2b gives the results that were obtained by Hϕklie, Stansberg and Werenskiold (1983). These graphs illustrate well how the vessel's motions as well as the forces on the various connecting links differ between short and long-crested wave conditions. All results are presented as a ratio of the standard deviation responses in multidirectional seas to those obtained in long-crested seas. Clearly, roll, yaw and sway are much greater in multidirectional seas. Consequently, the transverse force on the tower and the longitudinal force on the tanker are also much larger.

As a third example the second order long wave phenomenon is considered. As is well known, certain structures, particularly large vessels moored in shallow water, have virtually no response to first order waves, but can experience large motions and mooring forces as a consequence of second order long waves. It is therefore fitting to compare the presence of such second order long waves in either the long-crested wave or the short-crested wave situation. This problem was addressed by Sand (1982).

In two-dimensional (long-crested) waves, all waves with different wave periods propagate in the same direction. The second order long waves are derived from the difference terms derived from pairs of wave frequency components. That is to say, for a component of frequency f_1 and another of frequency f_2, a second order long wave term of frequency $(f_1 - f_2)$ is spawned with an amplitude dependent on the water depth and the product of their respective amplitudes, $a_1 \cdot a_2$.

In the multidirectional situation, individual frequency components do not travel in the same direction. Although the second order difference frequencies are, as before, $(f_1 - f_2)$, their wave lengths are now derived from the vectorial difference given in Figure 3a. The difference wave number vector will be $\vec{k}_1 - \vec{k}_2$, and will depend on the directional difference, $\Delta\theta$, between the two components. The larger the wave number of this difference frequency long wave component, the shorter will be its wave length. Another effect will be that the spreading function of these second order terms will broaden out substantially, as is shown in Figure 3b. It can also be shown that the long wave amplitudes in multidirectional waves are reduced by a factor of 5 to 10, depending on the water depth.

Sand (1982) described this phenomenon, as summarized in Figures 3b and 3c. Figure 3c provides information about the reduction in the wave length of the second order long wave components for bichromatic multidirectional waves. This is presented as a ratio of the resultant wave length difference for the multidirectional case to that for the unidirectional case, $\Delta L / \Delta L_U$. The information is given for a normalized frequency, for two frequency ratios $(f_1 - f_2) / f_2$ and for two angular differences of $\Delta\theta$. This result is particularly interesting in connection with natural periods of harbour resonances (i.e. the resonance wave lengths of harbours).

Because the long wave generation process through non-linear wave/wave interaction has been significantly reduced as a result of multidirectionality, it stands to reason that the penetration of this long wave energy into harbours is also reduced significantly. Figure 3d, which was taken from van der Meer (1989) provides an example for two different wave directions relative to the harbour entrance. It also gives the corresponding reductions for a moored vessel's surge motion.

TABLE 1: COMPARISON OF STRUCTURAL RESPONSES IN 2D AND 3D SEAS

TEST STRUCTURE	TYPE OF MODEL	PARAMETERS UNDER STUDY	MAIN CONCLUSIONS FOR TYPICAL CONDITIONS	REFERENCE
Partially submerged barrier supported by two piers	Physical	Horizontal force on the barrier	Reduction in loads up to 50% in 3D seas	Mynett, Bosma and van Vliet (1984)
Haringvliet barrier (Delta project in the Netherlands)	Field study	Fluid dynamic pressures on the barrier	For the highest reliable frequency of the spectrum, the wave load reduction factor due to directional spread could be as small as 0.25.	van Heteren, Botma and Roskam (1989)
Long floating cylinder of arbitrary shape	Theoretical	Wave loads and motions	The 1st order sway and roll force reduction factors could be as low as 0.41 for short-crested seas. Only about 58% of the sway, heave and roll motions obtained under 2D are encountered in 3D situations.	Isaacson and Nwogu (1987)
Forces on a large vertical cylinder	Theoretical and physical	Pressures, forces and moments in 3D seas	The ratio of forces and moments for 3D relative to 2D seas in-line component is: In-line: 0.90 Transverse: 0.45	Huntington and Thompson (1976)
Forces on a pile	Theoretical and physical	In-line and transverse wave forces on a submerged segment	The ratio of RMS values of forces for 3D relative to 2D seas in-line component is: In-line: 0.87 Transverse: 0.50	Isaacson and Nwogu (1988)
Segmented cylinder	Theoretical and physical	In-line and transverse force spectra for a segment above the S.W.L.	The ratio of RMS values of forces for 3D relative to 2D seas is: In-line: 0.83 Transverse: 0.56	Isaacson et al(1988)
Segmented cylinder (submerged segments)	Theoretical and physical	Probability distribution of maxima of resultant forces	Decreasing force maxima with increasing spreading. For instance, the measured values of the ratio of largest force maximum to the standard deviation were 3.98 in long crested and 3.31 in short crested seas.	Nwogu and Isaacson (1989(a))

TABLE 1 (continued 1)

Compliant tower	Physical	In-line, transverse and total response	Directionality has little influence on the total response, but a decrease in in-line response and an increase in transverse response becomes predominant with increasing spreading.	Cornett (1988)
Horizontal acceler-ations	Theoretical	Spectra of 2nd order horizontal accelerations caused by wave set-down	In shallow water, even for a narrow directional spread, the in-line spectral component of the acceleration could be as low as 10% of the 2D response.	Molin and Fauveau (1984)
Harbour and moored ship	Physical	Low frequency energy within harbour and surge motion	Reduction in 3D seas: up to 30% in low frequency activity and more than 75% in surge motion	van der Meer (1989)
Floating barge, moored	Theoretical and physical	Drift motions and mooring loads	The mean value of the low frequency surge motions was reduced by as much as 50% in 3D seas. The mean, standard deviation and maxima of the mooring line loads were reduced by as much as 37%, 25% and 21% respectively.	Nwogu and Isaacson (1989(b))
Single point mooring	Physical	Motions and yoke / tanker hinge force	In 3D, significant increase in sway, roll and yaw motions and in forces at the hinge points.	Huntington (1981)
Moored vessel in open sea	Physical	Motions and mooring loads	In head seas, mooring loads, sway and yaw motions are larger by a factor of 2 in 3D seas. In beam seas the tendency reverses. In quartering seas, the difference between the results of 2D and 3D are small.	Kirkegaard, Sand, Ottesen-Hansen, and Knudsen (1980)
Large offshore floating structures	Theoretical	Transfer functions of motions and forces	Transverse components of force and motion predicted to be negligible in 2D seas are significant in 3D. Typically, the maximum sway motion represents 59 % of the maximum surge.	Isaacson and Sinha (1986)

TABLE 1 (continued 2)

Coupled, articulated tower/ship system	Theoretical	Wave loading on the yoke and motions of the coupled system	Response in 3D seas: maximum structural response values are about 20-25% lower than those predicted with 2D seas.	Helvacioglu and Incecik (1989)
Bi-articulated mooring column	Physical	Tanker motions and forces on the yoke connections	Head-on conditions: the high frequency motions of sway, roll and yaw are nearly twice as large in 3D as in 2D. The tanker/yoke hinge force is 2 to 2.5 times larger in 3D.	Römeling, Marol and Sand (1984)
Single point moored tanker	Physical	Force on tanker/yoke hinge connection and motions	The longitudinal hinge force is generally increased by a factor of 2.5 in 3D seas while the significant sway and yaw motions are up by a factor of 4.	Høklie, Stansberg and Werenskiold (1983)
Semi-submersible, moored	Physical	Motion and mooring loads	In the low frequency domain, near natural frequencies, heave, pitch and roll motions are reduced by as much as 30% in 3D seas. Similar reduction is also found for the in-line and transverse forces. However, no simple relationship exists between 2D and 3D responses.	Sand, Römeling and Kirkegaard (1987)
Jacket structure on a barge for transportation	Theoretical and physical	Motions of the barge, accelerations at the system's and jacket's centres of gravity and at a mud-mat.	Directional spreading sometimes increases motions, loads and accelerations, and 2D waves may not always provide a conservative approach for design.	Standing, Rowe and Brendling (1986)

Conclusions

Based on the experience gained with the segmented wave generator system at the Hydraulics Laboratory of the National Research Council of Canada, and on the information available through the published literature or verbal communications, the following statements with regard to the merits of testing in multidirectional waves can be made:

- Whenever significant non-linearities are present in the response of structures to waves, the principle of superposition is not valid. Consequently, it is essential to evaluate such structures through the use of realistic simulations of the natural sea state. Two-dimensional wave simulations are not realistic for this purpose.
- Group-bound long wave activity is significantly lower in three-dimensional than in two-dimensional seas. For the investigation of large floating structures, such as tankers, landing strips, floating plants, which will be subject to wave group-induced drift loads, this will be a significant factor. Three-dimensional waves will lead to smaller drift displacements and mooring loads.
- The excitation of harbour seiches will be smaller with three-dimensional than with two-dimensional waves.
- Structures, which have small torsional resistance, will be subject to larger yaw motions when subjected to three-dimensional seas. Typical examples of such structures are compliant towers or tension leg platforms (TLPs) as well as semi-submersibles.
- Motions of vessels with single point moorings are greater in three-dimensional than in two-dimensional seas, resulting also in larger mooring loads. In particular, "fishtailing" motions will be accentuated.
- Dynamic positioning systems for floating structures will be more difficult to operate in multidirectional than in unidirectional waves.
- Wave loading on fixed, long structures can be assumed to be generally smaller in multidirectional seas.

In summary, the absence of correct three dimensional wave simulations can grossly underestimate design requirements. Although two-dimensional wave simulations can sometimes produce reasonably conservative (i.e. large) results, in many cases it would result in excessive over-design. Therefore, model testing in multidirectional seas is strongly recommended to improve designs of marine structures for cost-effectiveness and safety.

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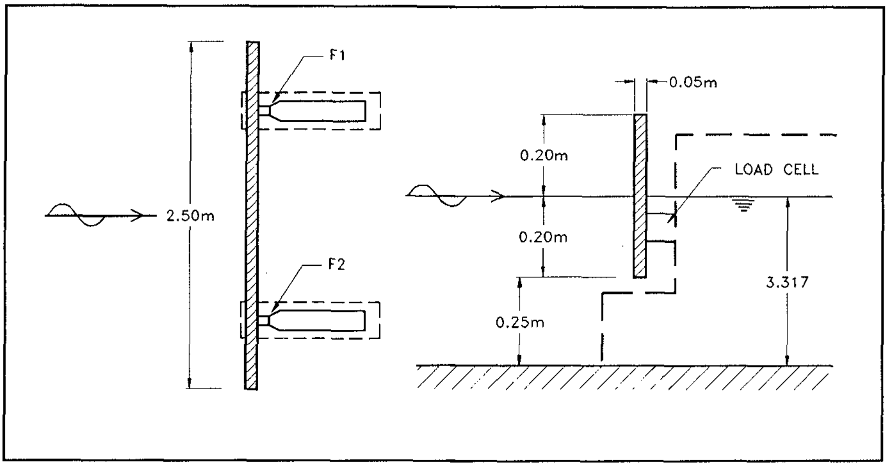

Figure 1a: HYDRAULIC MODEL FOR A STORM SURGE BARRIER

Mynette et all (1984)

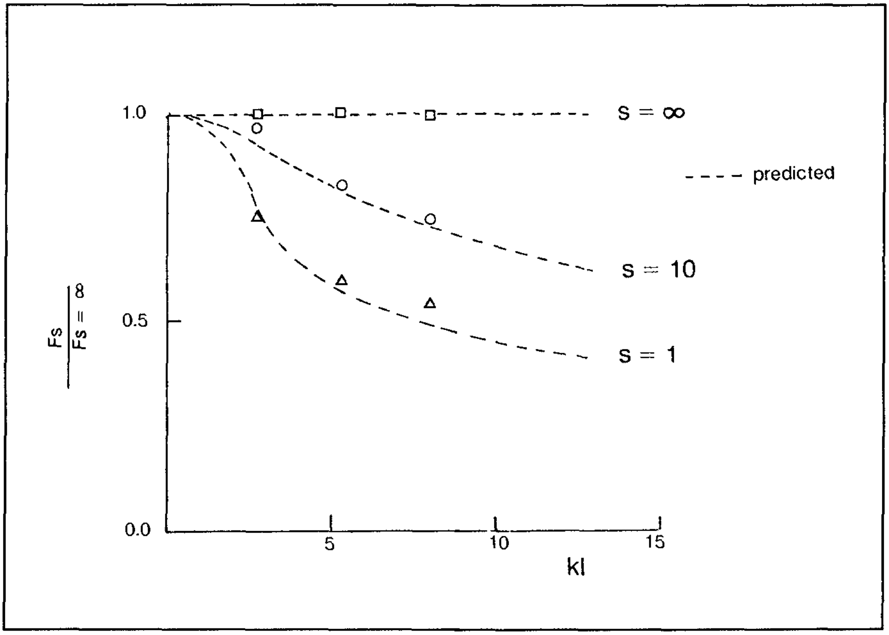

Figure 1b: MEASURED AND COMPUTED FORCE REDUCTION FACTORS

(Mynett et al (1984)

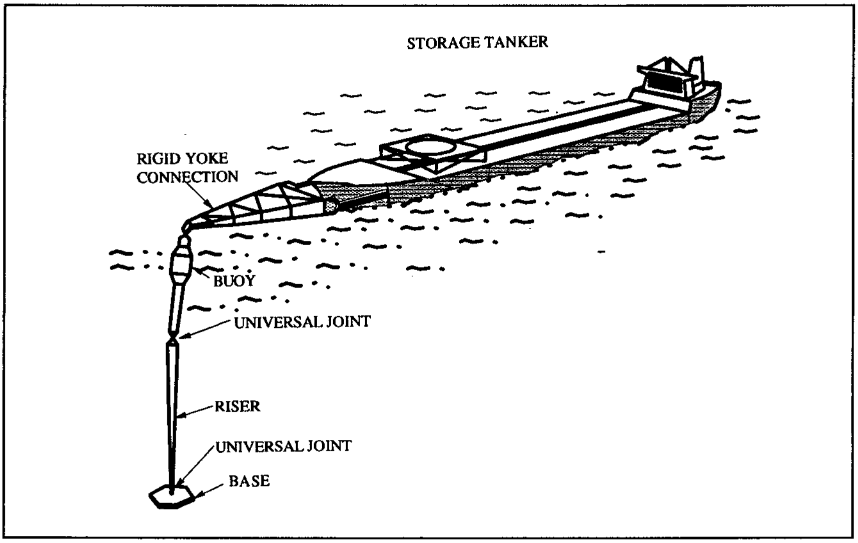

Figure 2a: CONCEPTUAL DESIGN OF SALMRA MOORING SYSTEM

Høklie et al (1983)

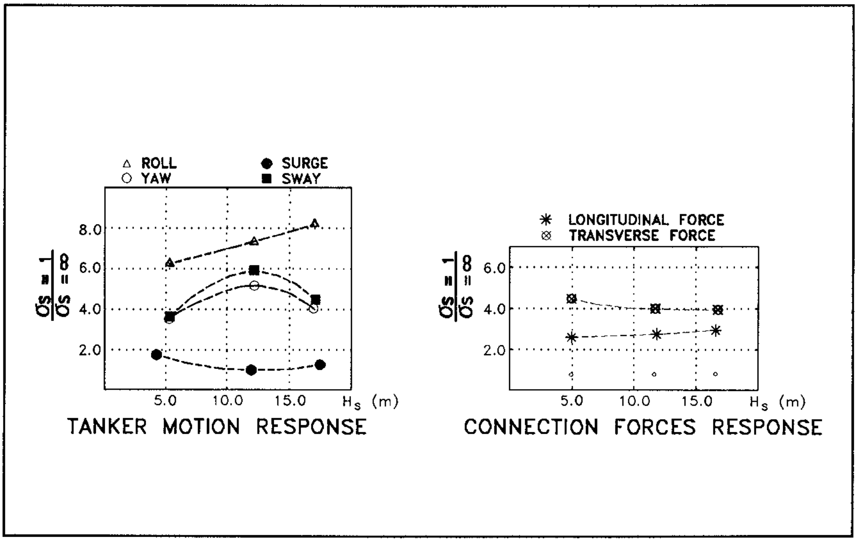

Figure 2b: RESPONSE OF THE MOORING SYSTEM Høklie et al (1983)

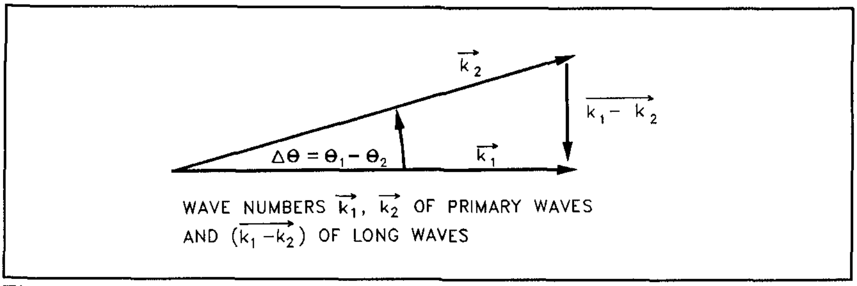

Figure 3a: WAVE NUMBERS OF SHORT AND LONG WAVES

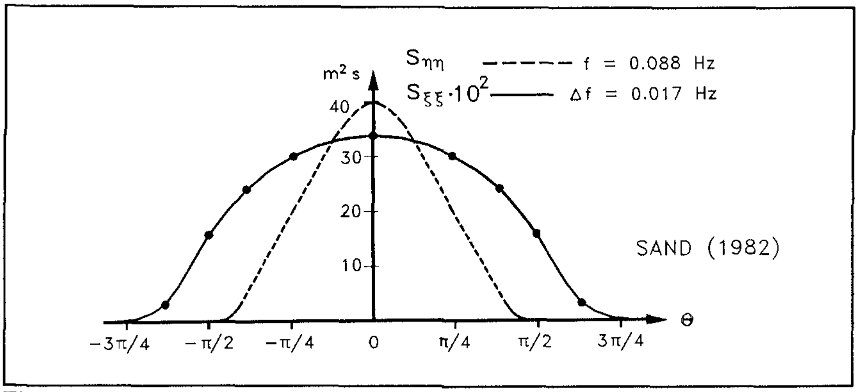

Figure 3b: SPREADING FUNCTIONS OF SHORT AND LONG WAVES

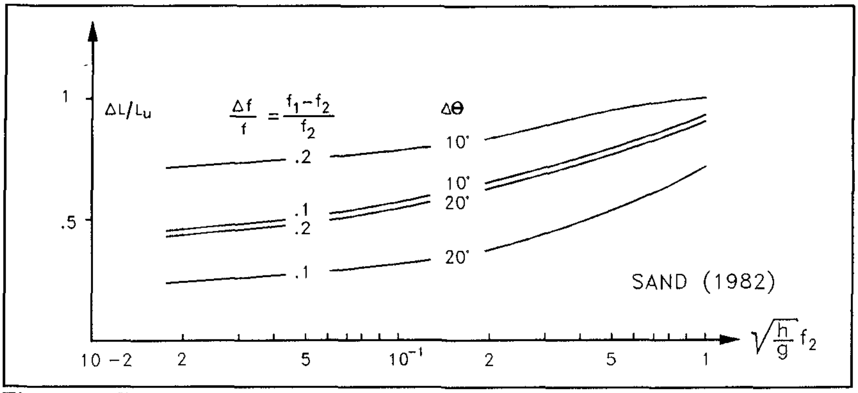

Figure 3c: REDUCTION OF WAVE LENGTH OF DIRECTIONAL LONG WAVES

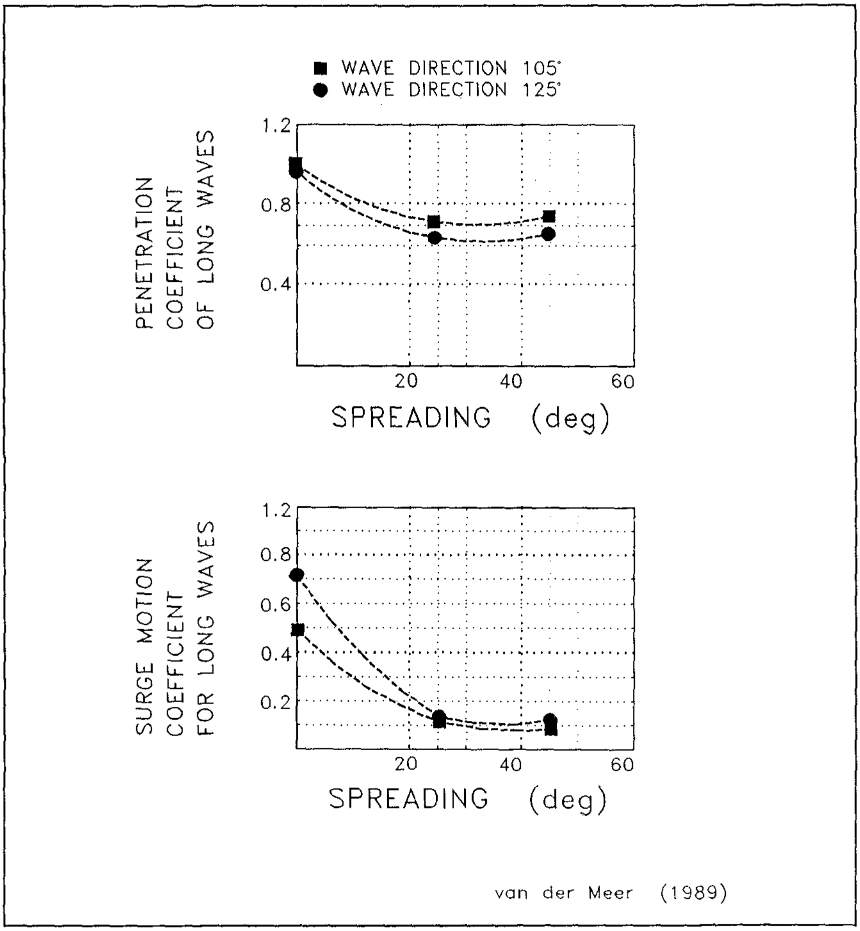

Figure 3d: WAVE DIRECTIONALITY EFFECTS ON LONG WAVE PENETRATION AND SURGE MOTION

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