Wave Loading and Overtopping on Caisson Breakwaters in Multidirectional Breaking Seas

Grønbech, J.; Hald, Tue; Frigaard, Peter; Burcharth, H. F.

Published in:
Proceedings of the 27th IAHR Congress, San Francisco, 10-15 August 1997

Publication date:
1997

Document Version
Early version, also known as pre-print

Wave Loading and Overtopping on Caisson Breakwaters in Multidirectional Breaking Seas

Grønbech, J.; Hald, Tue; Frigaard, Peter Bak; Burcharth, Hans Falk

Published in:
Proceedings of the 27th IAHR Congress, San Francisco, 10-15 August 1997

Publication date:
1997

Wave Loading and Overtopping on Caisson Breakwaters in Multidirectional Breaking Seas

GRØNBECH J., HALD T., FRIGAARD P. and BURCHARTH H. F.
Hydraulics and Coastal Engineering Laboratory
Dept. of Civil Engineering, Aalborg University, Denmark

ABSTRACT

The present paper concerns the results and findings of a physical study on wave impacts on vertical caisson breakwaters situated in irregular, multidirectional breaking seas. The study has taken place as part of the framework programme "Dynamics of Structures" financially supported by the Danish Technical Research Council, during the period of January 97 to July 97. The tests were carried out in the 3D wave basin at the Hydraulics and Coastal Engineering Laboratory, Aalborg University. The objective of the study was to asses the effects of wave obliquity and multidirectionality on the wave induced loading and overtopping on cassion breakwaters situated in breaking seas. Regarding the wave forces only minor differences between breaking and non breaking waves in deep water were observed, and it was found that the prediction formula of Goda also seems to apply well for multidirectionally breaking waves at deep water. The study on wave overtopping showed that the 3D wave overtopping formula suggested by Franco et al., 1995b, predicts the wave overtopping reasonable well for both non breaking and breaking waves at deep water.

1. INTRODUCTION

Attention has been addressed to the effects of wave obliquity and multidirectionality on wave loads and wave overtopping on vertical caisson breakwaters situated in non breaking seas. Within the joint European (MAST-LIP-TAW) research project, a 3D model investigation was carried out at Delft Hydraulics to asses these effects. The results have been published by several researchers, among them Franco et al., 1995a and Franco et al., 1995b. The effects of wave breaking and impact forces on vertical structures has been investigated by several researchers in the past, and it is still generally acknowledged that the impact loading of vertical structures is the main damage source. Oumeraci et al., 1995. The research work on impact forces has mainly been based on 2D breaking waves. So far, no attention has been paid to the effects of wave obliquity and mulitidirectionality on the wave loads and wave overtopping on caisson breakwaters placed in deep water breaking seas. The effects of wave obliquity and multidirectionality on the wave loads were investigated by measuring the wave induced pressure at 50 locations on a 6.0 meter wide caisson breakwater model, enabling determination of the horizontal force in one section as well as the lateral distribution of the horizontal force. The results and findings on the effects on the lateral distribution of the horizontal force are not included in this paper, but will be published at a later given opportunity. The present paper intends to stress the effects of wave obliquity and multidirectionality on the horizontal force in one vertical section.

The wave overtopping was measured on a 1.0 meter wide section of the caisson breakwater model, and the findings regarding the effects of wave obliquity and multidirectionality of the waves are presented in terms of the mean average overtopping discharge.

2. EXPERIMENTAL SETUP

The cassion breakwater model was constructed in plywood and placed on a smooth one layer foundation berm. Since the wave induced uplift pressures at the caisson bottom was not considered in the study, the foundation berm was constructed in concrete. The cross section of the model is seen in Figure 1, and as it appears a crest element is placed on the top of the model in order to vary the crest height. The size of the model does not refer to any particular prototype structure, however, a Froude scaling of 1:20 - 1:25 seems appropriate for this type of structures. In order to generate a sea state representing breaking waves in deep water in front of the caisson model, a relatively short 1:5 slope was constructed and placed as seen in Figure 1.

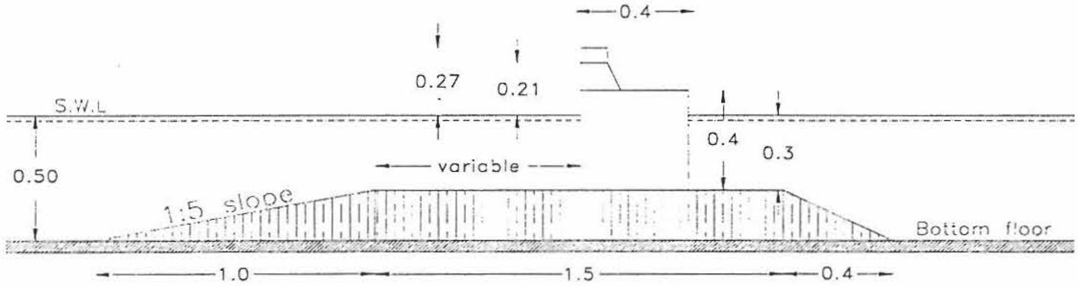

Figure 1 - Cross section of caisson model(s).

For harbor type structures situated at deep water, the percentage of breaking waves in a storm event depends on the structure location and at the wave climate at this location, however, for this study it is decided to keep the number of breaking waves at about 5 to10 per cent of the total number of waves. Using the numerical wave transformation model "Mildsim", developed at the Hydraulics Laboratory at Aalborg University, tests with 2D irregular waves with a significant wave height of 0.18 m and a peak period at 1.2 sec. showed, that about 6 to 7 per cent of the waves are breaking.

Due to the wave diffraction processes around the two ends of the breakwater, the sea states in the vicinity of the ends would be disturbed during the tests, and since the lateral distribution of the horizontal force was to be considered in this study, it was important that the sea state in front of the test section not was influenced by the diffraction at the two ends. The numerical wave transformation tests showed, depending on the wave obliquity, that the sea state at the two ends was disturbed at a distance corresponding to approximately 1-1.5 times the wavelength. Therefore, to take into account the disturbance from the diffraction processes, and to obtain a width of the test section corresponding to one wavelength, the total width of the model should be about 6 meter.

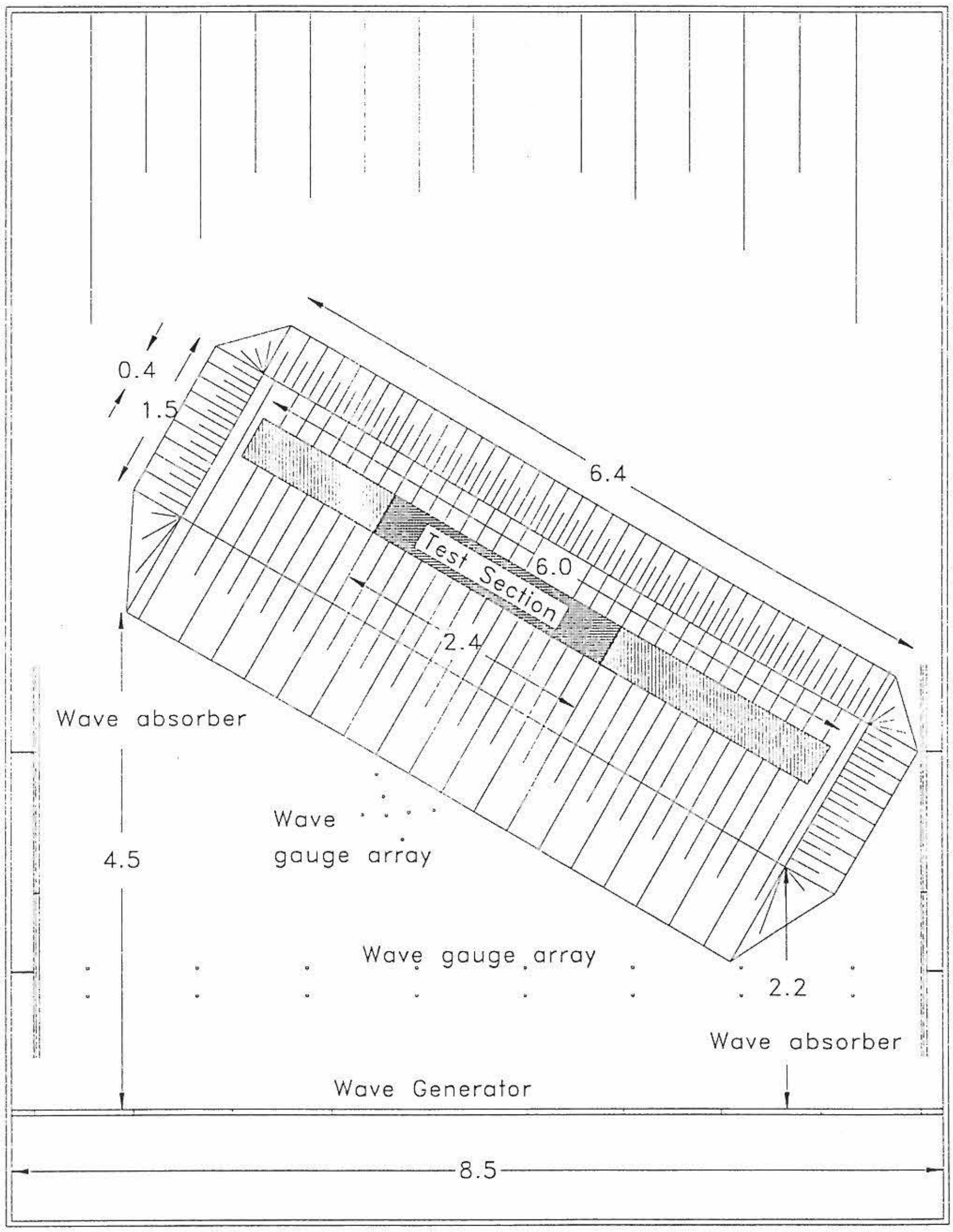

Figure 2 - Plan view of the 3D Wave Basin layout. Measures in meters.

The experiments were carried out in the 3D deep water wave basin at Aalborg University, Denmark. The basin is a multidirectional wave basin capable of generating irregular multidirectional waves. A plan view of the wave basin and the caisson model is seen in Figure 2. Although the amount of wave energy passing through the gabs between the caissons and the side walls of the basin is small compared with the reflected wave energy, the rear end of the basin is equipped with a spending beach constructed of gravel material. Along the side walls of the basin, vertical steel absorbers are placed to damp any cross modal activity occurring during the tests. Due to limitations in the wave generation, the obliquity of the generated waves should be kept less than 30°, and therefore the model was placed under 60° with the wave paddles of the wave generator, as seen in Figure 2. Due to the high reflection from the caissons, a three dimensional active wave absorption system is applied to avoid too much re-reflected wave energy in front of the caissons. The active absorption system operates on-line by digital filtering of surface elevations measured in 16 individual positions in the wave field in front of the wave generator. The 16 wave gauges are arranged along two parallel lines in front of the wave paddles, as seen in Figure 2.2. The wave absorption system is in its complete form outlined in Hald and Frigaard, 1997. In front of the model the wave field is measured by an array of 7 wave gauges, see Figure 2. The wave gauges are placed at deep water, i.e. in front of the 1:5 slope, which is about 1.5 meter, seaward the model. The incident wave field was estimated based on the Bayesian Directional spectrum estimation Method (BDM).

The wave pressures were measured by a set of 50 pressure transducers placed as shown in Figure 3. The position of the pressure transducers enables the study of the vertical distribution of the horizontal pressure in different sections along the caisson model. By means of these vertical distributions of the horizontal pressures, the lateral distribution of the horizontal forces can be studied, and not only the lateral distribution of the horizontal pressures. This is important due to the unknown correlation between the lateral distribution of the horizontal pressure and the lateral distribution of the horizontal force.

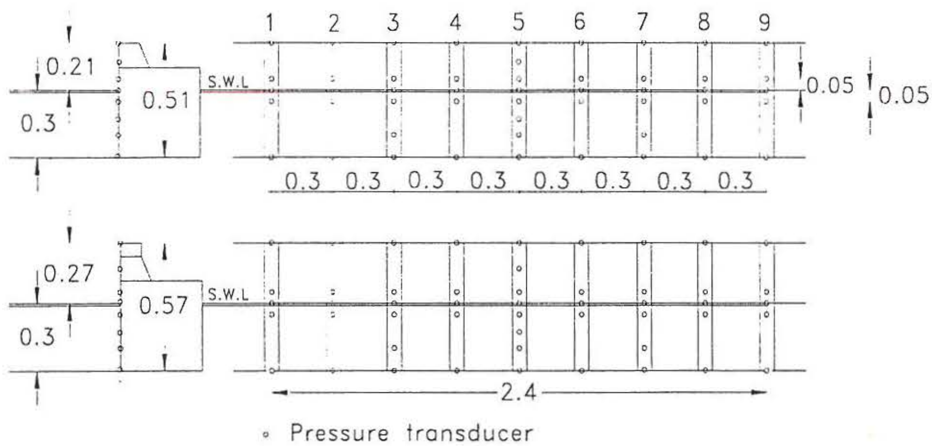

Figure 3 - Instrumentation of the caisson model. Measures in meters.

Sideways, the pressure transducers are placed within a distance of 0.3 m enabling the study of the vertical distribution of the horizontal pressure in 9 sections along the 2.4 meter wide test section. A row of pressure transducers are placed at still water level. Furthermore, a row of transducers are placed 5 cm above and 5 cm below the still water level.

The wave overtopping measurements concern the determination of the mean discharge of a test sequence, the number of wave overtopping events and finally the determination of the water volume in each of the individual overtopping events. In this study, the wave overtopping is determined by recording the water level in a water tank, in which all the overtopping water is collected. The collected overtopping water corresponds to a width of 1.0 m of the test section. The amount of water collected in the tank is determined by recording the water level in the tank during the tests. The water level is measured by a set of two wave gauges placed in the water tank. Due to the irregularity of the waves, the amount of overtopping water varies from wave to wave, and in order to obtain reasonable increments of the water level in the tank even for the smallest wave overtopping events, the cross section area of the tank must be kept relatively small.

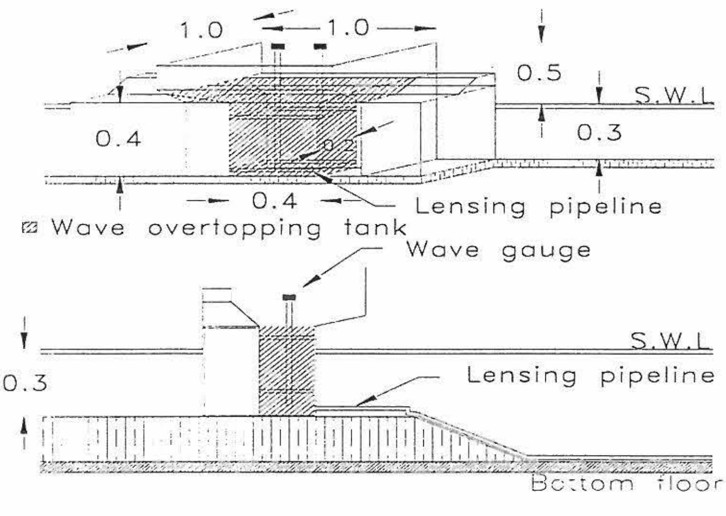

Figure 4 - Wave overtopping measuring device. Measures in meters.

3. TEST CONDITIONS

As the main objective of the study was to assess the effect of wave obliquity and multidirectionality the changes on test conditions were mainly the incident mean direction of the waves and the directional spreading of the waves, i.e. the energy distribution around the mean direction of the waves. The mean direction, or the incident angle of wave attack was varied from 0° (head on waves) to 50° for some of the tests. A cosine squared $(\cos^{2s}(\theta/2))$ spreading function with fixed s-values of 10 and 29 was used in the tests, which corresponds to standard deviations of 25° and 15°, respectively. See Frigaard et al., 1997. The incident target wave height was fixed at

0.16 m for the non breaking waves and 0.18 m for the breaking waves. A JONSWAP wave spectrum with a peak enhancement factor of 3.3 and a peak period of 1.2 sec was applied in all the tests, giving a steepness at 0.07 for non breaking waves and 0.08 for breaking waves. To obtain an adequately statistically validity of the test results, rather long test series were performed with no test series having less than 1800 waves. In table 1, the various target parameters of the test series are shown.

Wave spectrum	JONSWAP, $\gamma = 3.3$
Peak period, T_p	1.2 sec
Significant wave height	0.16 m to 0.18 m
Crest freeboard, R_c	0.21 and 0.27
Water depth, h_d	0.3 m
Angle of wave attack , θ	0°, 15°, 30°, 45°, (60°)
Type of spreading	Cosine squared, with s=10 and s=29

Table 1 - Wave parameters.

Regarding this paper, the results are all based on the test cases listed below and with a crest freeboard of 0.27.

- 3D non breaking waves, $H_s = 0.16$ m, $\sigma = 15°$, $\theta = 0°$ to $40°$
- 3D non breaking waves, $H_s = 0.18$ m, $\sigma = 25°$, $\theta = 0°$ to $40°$
- 3D breaking waves, $H_s = 0.16$ m, $\sigma = 15°$, $\theta = 0°$ to $48°$
- 3D breaking waves, $H_s = 0.18$ m, $\sigma = 25°$, $\theta = 0°$ to $40°$

4. WAVE FORCE ANALYSIS

The horizontal wave forces are determined by a linear integration of the measured pressure time series. The horizontal forces presented below are all based on the pressure measurements of section 5, see Figure 3, where 8 pressure measurements are assumed to represent the vertical distribution of the horizontal pressure. In Figure 5, a plot of the measured horizontal pressure is shown along with the calculated force time series. The plot shows 10 sec of the test series with head on breaking waves and a spreading corresponding to σ=25°.

The pressure time series are sampled at 800 Hz, and only the maximum peaks within one wave period are used in the determination of the probability distribution of the horizontal forces.

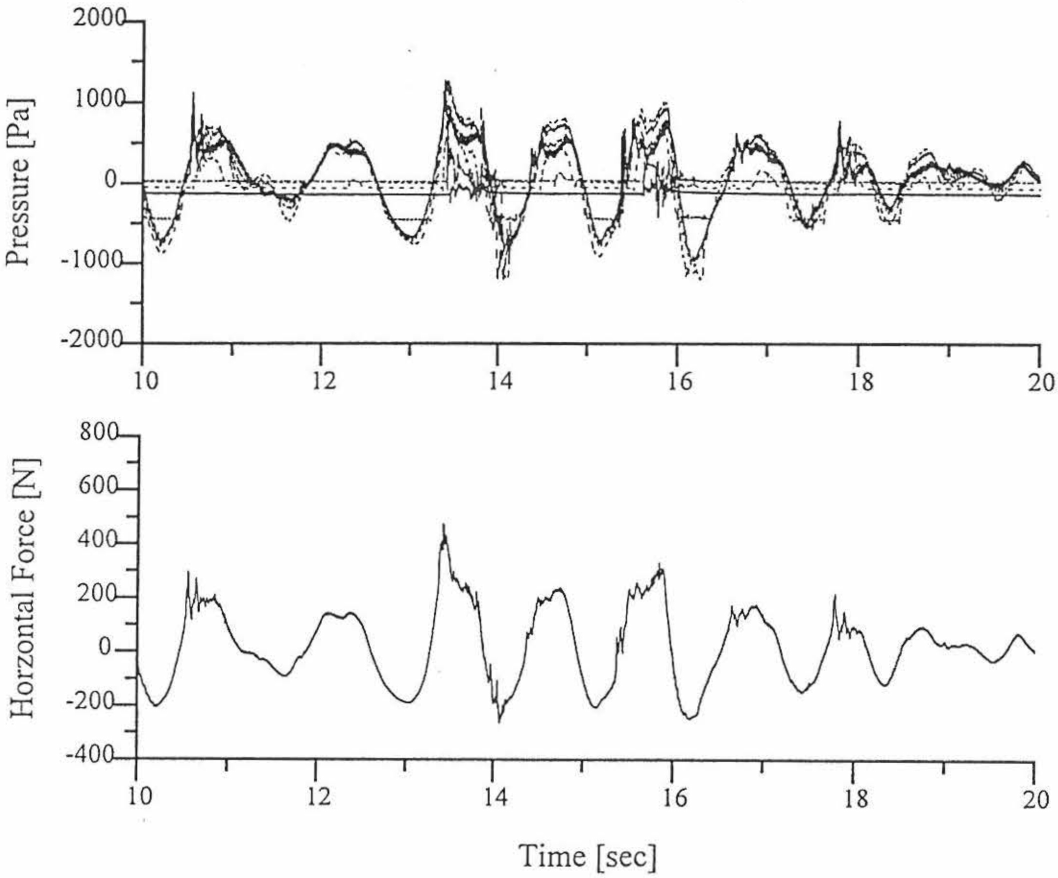

Figure 5 - Pressure record with corresponding force time series.

In order to compare the results with the prediction formula of Goda, the statistical force parameter $F_{1/250}$ are calculated from the force time series. Due to the applied number of waves this force is calculated as an average value of 7 estimates. In order to compare the results of the tests with non breaking waves with the tests with breaking waves, i.e. results with different wave heights and wave steepnesses, the calculated $F_{1/250}$ forces are normalized by the predicted Goda force corresponding to the actual wave obliquity and wave height. For the above mentioned tests, this is shown in Figure 6.

Despite the observed scatter, the formula of Goda seems to apply well for both the non breaking as well as the breaking waves. Most of the calculated forces are seen to deviate less than 10% from the Goda predicted forces. Apparently, the Goda formula applies best in case of waves within the range of 0 to 35 degrees. However, the pronounced scatter for waves with larger obliquity than 35 degrees could also be due to the relative error of these forces.

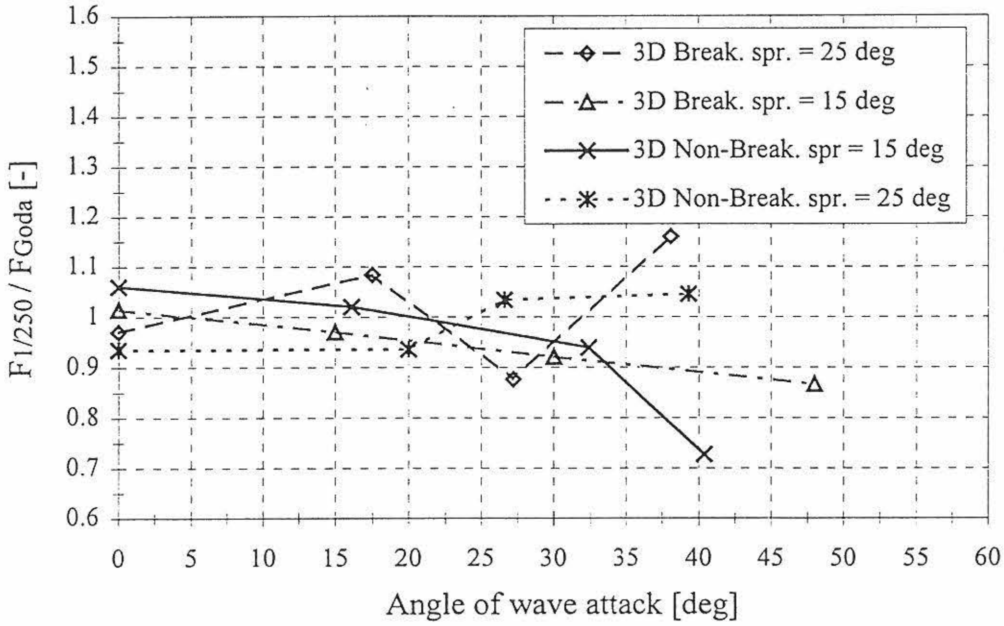

Figure 6 - Comparison with Goda predicted forces.

Franco et al. 1995a found that the forces predicted by the formula of Goda, which does not take into account the multidirectionality of the waves, should be reduced with about 10%. This trend is, however, not seen in the results of this study.

One would expect the breaking waves to produce higher forces than the non breaking waves due to the impact forces. However, it must be kept in mind that the generated breaking waves represent deep water breaking waves, meaning that the highest waves do not necessarily break on the caisson breakwater model, but break seaward to the model, i.e. on the slope. Thereby, a lot of the energy of the waves is lost in the breaking process.

5. WAVE OVERTOPPING ANALYSIS

For each test series, the wave overtopping was determined by recording the water level in the overtopping tank. The water levels were measured by a set of two wave gauges during the tests, and each of the overtopping events were recorded as a small (or large) increase in water level. In Figure 7 the measured overtopping rate is shown for the test with head on non breaking waves, and a spreading corresponding to $\sigma=25°$. The total amount of water collected in the water tank during a complete time series is determined by calculating the water volume of each of the individual over-topping events.

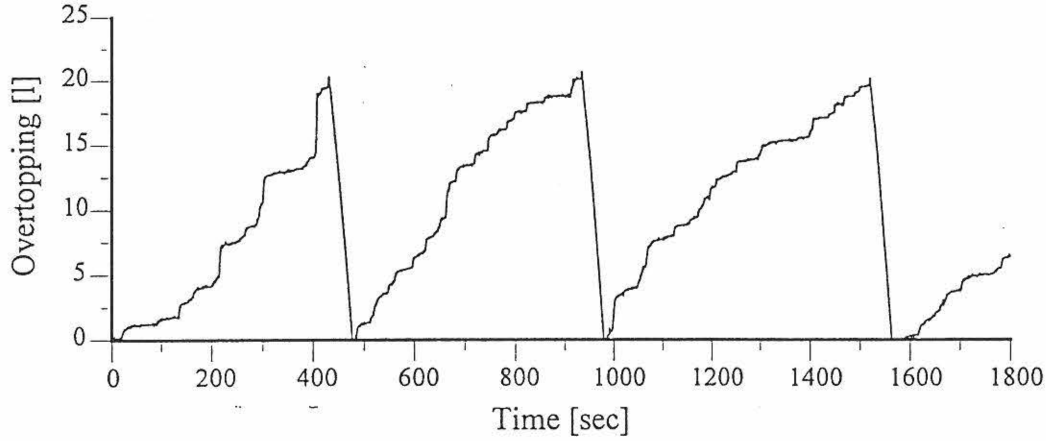

Figure 7 - Recorded wave overtopping time series.

The non dimensional mean overtopping discharge is defined as :

$$Q = \frac{q}{\sqrt{g H_{os}^{3}}}$$

where q is the average wave overtopping discharge per meter structure length, H_{os} is the significant wave height at deep water and g is gravity acceleration.

The basic assumption, confirmed by many researchers, is that the main parameters influencing the wave overtopping performance, i.e. the significant wave height, the crest height and the average wave overtopping discharge are related through a exponential function as:

$$Q = a\, e^{\left(-b \frac{R_c}{H_{os}}\right)}$$

Based on more than 80 hydraulic model tests performed in the Directional Wave Basin at Delft Hydraulics, Franco et al., 1995b, suggested the use of a=0.082 and b=3.0 for plain vertical structures exposed to head on waves. To take into account the effects of wave obliquity and multidirectionality a reduction factor was introduced to the non dimensional expression.

$$Q_P = a\, e^{\left(-\frac{b}{\gamma} \frac{R_c}{H_{os}}\right)}$$

Through best fit regression analysis Franco et al., 1995b suggested the following relation between γ and the wave obliquity for multidirectional waves.

$\gamma = 0.83$ for $0° \leq \theta \leq 20°$
$\gamma = 0.83 \cos(20° - \theta)$ for $\theta \geq 20°$

In Figure 8 the results of the 4 test cases are shown. The wave overtopping is expressed in terms of the measured average overtopping discharge Q_m normalized by the predicted average wave overtopping discharge Q_p.

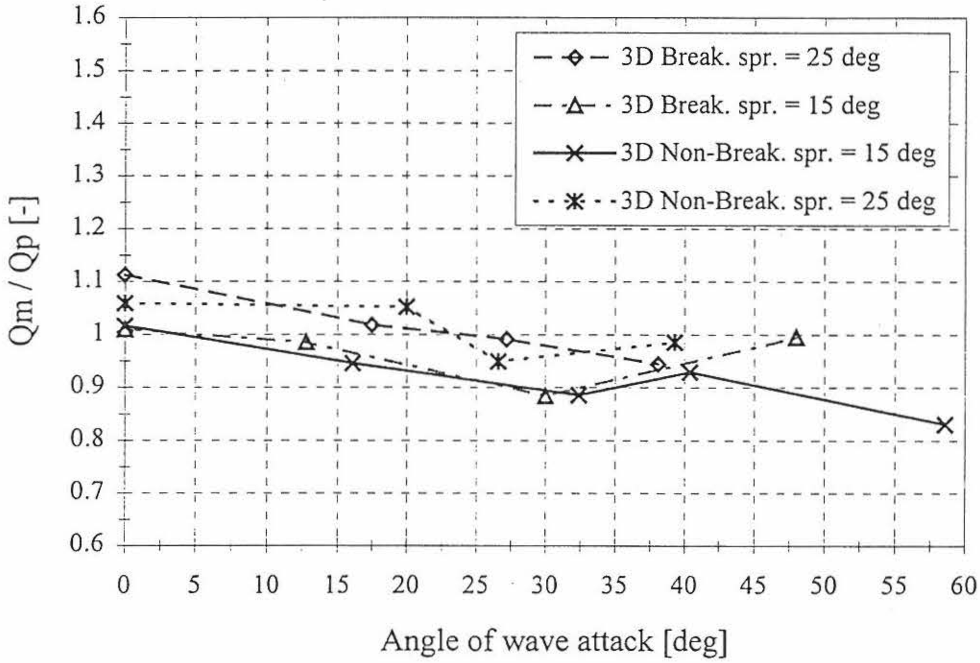

Figure 8 - Comparison of measured and predicted wave overtopping.

As it appears, the suggested prediction formula of Franco et al., 1995b seems to apply well with most of the compared data deviating less than 10%. It is, however, observed that for angles of wave attack smaller than approximately 20°, the predicted wave overtopping tends to be smaller than the measured wave overtopping, whereas, the wave overtopping seems to be over predicted for angles of wave attack larger than approximately 20°.

Comparing the results of non breaking waves to the results of breaking waves, it is seen, that no apparent difference exist, indicating that in terms of 3D waves, it is not necessary to distinguish breaking waves from non breaking waves. However, it was visually observed during the tests with breaking waves, that the breaking process causes a significant increase in spray, which of course should be considered in the prototype case.

6. CONCLUSION

Regarding the effects of wave obliquity and multidirectionality on wave loading and wave overtopping on caisson breakwaters only minor differences were observed between breaking and non breaking waves.

The insignificant differences between the measured forces from breaking waves and the forces from the non breaking waves might appear odd. However, kept in mind that the present study concerns deep water breaking waves (spilling breakers) and not shallow water breaking waves (plunging breakers), which have a completely different physical behavior, these findings seem reasonable. Although some scatter was observed between the measured forces and the predicted forces, the formula of Goda seems to apply well for breaking waves as well as for non breaking waves at deep water.

Despite the observed amount of spray during the tests, the measured overtopping rates for breaking waves seem to agree well with the prediction formula for 3D non breaking waves given by Franco et al., 1995b.

7. ACKNOWLEDGEMENTS

This work has been carried out with support from the frame work programme *Dynamics of Structures* of the *Danish Technical Research Council.*

8. REFERENCES

Battjes, J. A. and Jansen, J. P. F. M. (1978). *Energy loss and set-up due to breaking of random waves*, Proceedings of the 16th International Conference on Coastal Engineering, Hamburg.

Hald, T. and Frigaard, P. (1997). Alternative Method for Active Absorption in Multidirectional Waves. To be published at the IAHR seminar on Multidirectional Waves and their Interaction with Structures, San Francisco.

Franco, C., Franco, L., Passoni, G., Restano, C., van der Meer, J.W. (1995a). *The effect of wave obliquity and short-crestedness on the horizontal and uplift forces on caisson breakwaters.* In: Final proceedings, MAST II, (MAS2-CT92-0047), MCS-Project: Monolithic (Vertical) Coastal Structures, Paper 4.8, 22 pp.

Franco, C., Franco, L., Restano, C., van der Meer, J.W. (1995b). *The effect of wave obliquity and short-crestedness on the overtopping rate and volume distribution on caisson breakwaters.* In: Final proceedings, MAST II, (MAS2-CT92-0047), MCS-Project: Monolithic (Vertical) Coastal Structures, Paper 4.9, 37 pp.

Frigaard, P., Helm-Petersen, J., Klopman, G., Stansberg, C. T., Benoit, M., Briggs M. J., Miles, M., Santas, J., Schäffer, H.A., Hawkes, P.J. (1997). IAHR List of Sea State Parameters. To be published at the IAHR seminar on Multidirectional Waves and their Interaction with Structures, San Francisco.

Oumeraci, H., Hewson, P., Juhl, J. and van der Meer, J.W. (1995). MCS-Project: *Multi-Disciplinary Research on Monolithic Coastal Structures*, Final proceedings, MAST II, (MAS2-CT92-0047), MCS-project: Monolithic (Vertical) Coastal Structures. Papers Task 1-2.