CHAPTER 91

# Oscillatory Motions and Permanent Displacements of Caisson Breakwaters Subject to Impulsive Breaking Wave Loads

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## Abstract

Small-scale model tests were recently conducted in a wave flume at the University of Hannover in order to study in more detail the relationship between impulsive loading induced by waves breaking on a caisson breakwater and subsequent displacements of the latter. These experiments are briefly described and some first results are discussed. Thereby, particular emphasis is put on the relationships between (i) oscillatory motions and permanent displacements, (ii) wave loading and oscillatory motions and (iii) wave loading and permanent displacements.

The findings presented in this paper are intended to improve the understanding of the stability of caisson breakwaters subject to impulsive breaking wave loads and to help developing proper tools for the dynamic analysis of such structures.


## Introduction

When a monolithic breakwater is subject to a sequence of breaking wave loads, both oscillatory and permanent displacements develop. The peak amplitudes of the former may exceed the ultimate resistance of the foundation, thus resulting in relatively smaller but residual deformations. The latter cumulate, leading to large permanent displacements which may cause the structure to collapse.

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In this respect, hydraulic model tests on the impulsive loading and dynamic response of caisson breakwaters using improved measuring techniques for the motions of the structure were conducted at the University of Hannover, SFB 205/TP B3. These tests principally aim at establishing relationships as shown in Fig. 1, i.e. (i) between incident wave parameters and impulsive loading (TF1), (ii) between impulsive loading and dynamic response (TF2), and (iii) directly between incident wave parameters and dynamic response (TF3).

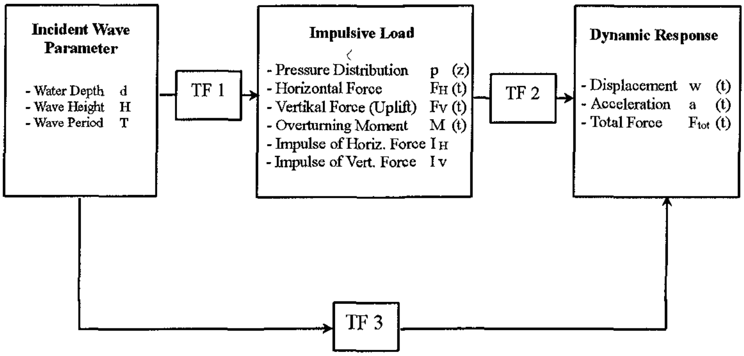


Fig. 1- Definition of Relationships under Study

With the present paper it is intended to discuss some of the results of these investigations, particularly the relationship between the oscillatory motions and the permanent displacements, as well as those between the loading and the response of the structure.

Additional calculations of the safety factor against sliding and overturning and comparison with measurements of the permanent displacements are also presented.

## **Experimental Set-Up, Measuring Techniques, Tests-Conditions and Procedures**

The tests were conducted in a wave flume with 110 m length, 2.2 m width and 2.0 m depth in which both regular and random waves with maximum wave heights up to 40 cm and periods up to 4 s can be generated. The caisson model consists of two distinct parts which can move independently of each other. The first part of the caisson model, for which a cross-section is shown in Fig. 2, is used for the measurement of the impact pressure on the front of the caisson, the uplift pressure on the caisson bottom, as well as the acceleration and displacements of the caisson.

For the pressure measurements piezo-electric pressure transducers of type PDCR 830 from Natec Schultheiss were used which a natural frequency of 28 - 360 kHz and a pressure range from 0.35-5 bar. For the measurement of the acceleration of the caisson three high output accelerometers of type Seitner Model JA-5-M19 with a range of $\pm$ 1 g and $f_{max}$= 200 Hz are installed at the front top (one vertical) and at the rear top (one vertical and one horizontal) of the caisson.

For the measurement of the caisson motions, a displacement meter of type W2 ATK from Hottinger Baldwin Meßtechnik with the range of ± 2 mm and a failure of ± 0.2 %. The displacement transducer is able to record permanent and oscillatory motions of the caisson, while the accelerometers are intended to measure only the latter.

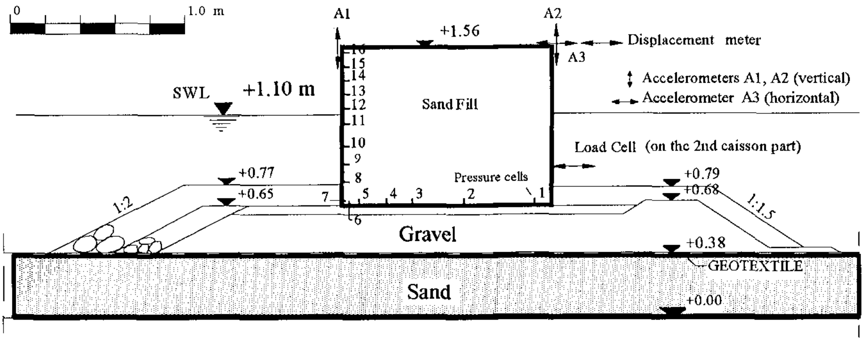


Fig. 2- Instrumented Model Caisson Breakwater

On the second caisson part only total horizontal force measurements behind the structure were performed (shear forces). For this purpose two 20 kN force transducers of type U2 A from Hottinger Baldwin Meßtechnik were used. All these measurements (waves, pressure, total forces, accelerations and displacements), as well as video records were performed simultaneously.

For three different water depths (0.90, 1.00 and 1.10 m) regular and irregular wave tests were conducted with wave heights ranging from 0.10 up to 0.3 m and wave periods from 1.9 - 3.2 s.

## Experimental Results

### (a) Relationship Between Oscillatory Motion and Permanent Displacements

A typical time series of the oscillatory motions and permanent displacements of the model caisson breakwater induced by waves ($H_{max}$ = 0.30 m, T = 2.4 s, d = 1.00 m) plunging on the structure front is shown in Fig. 3. The related horizontal force $F_H$ and uplift force $F_V$ which induce the permanent displacement $a_r$ and the oscillatory motion $x_t$ are shown in Fig. 4.

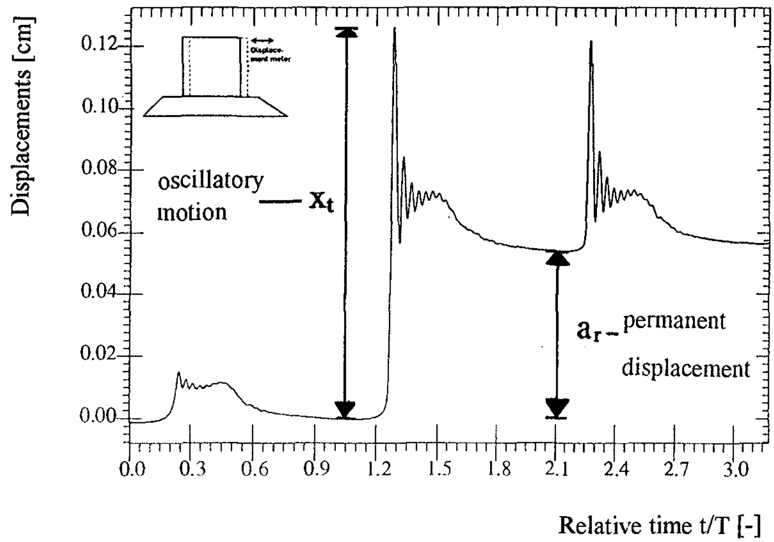


Fig. 3- Oscillatory Motions and Permanent Displacements of the Caisson Breakwater

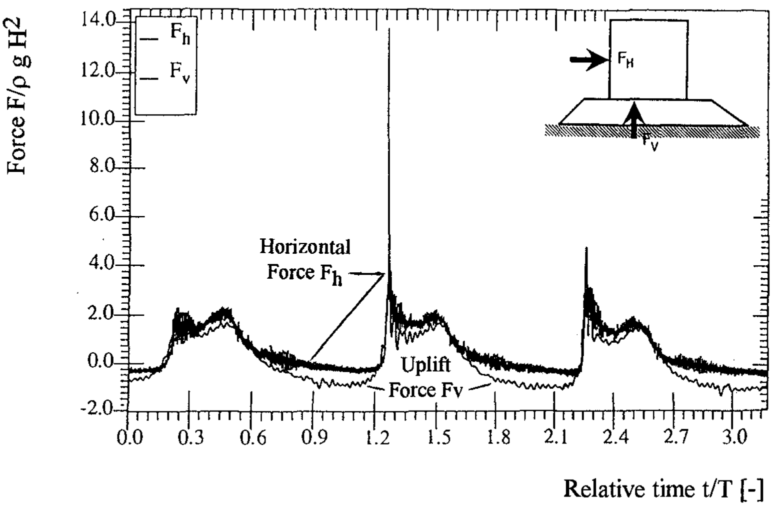


Fig. 4- Horizontal Force $F_H$ and Uplift Force $F_V$ Responsible for Caisson Motion in Fig. 3

In order to get an idea about the relations between $x_t$ and $a_r$, the peak values of the oscillatory motions are plotted against the permanent displacements (Fig. 5).

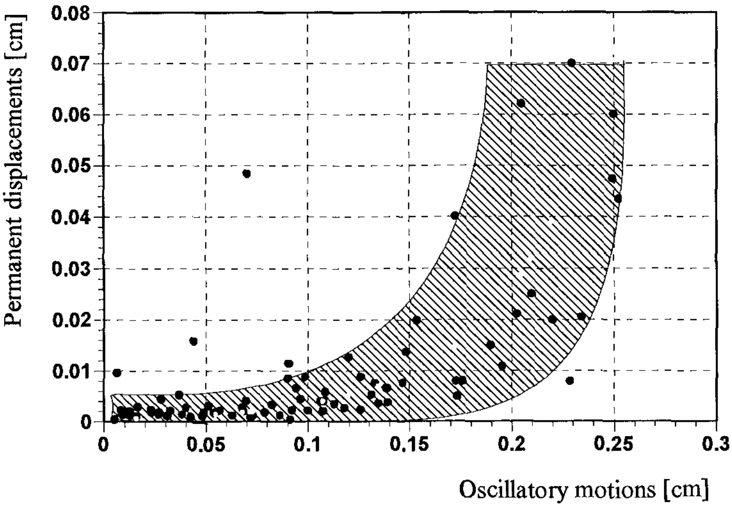


Fig. 5- Peak Values of Oscillatory Motions vs. Permanent Displacements

It is seen from Fig. 5, that:

- for smaller peak amplitudes $x_t$ of the oscillatory motions (generally $x_t < 0.1$ mm), almost no permanent displacements $a_r$ occur;
- for amplitudes $x_t$ > 0.1-0.15 cm, relatively larger permanent displacements $a_r$ start to occur, suggesting that there is some threshold value of $x_t$ for which a permanent displacement is initiated;
- despite the scatter of the recorded values, there is a clear tendency of the amplitudes $a_r$ of the permanent displacements to increase "exponentially" with increasing peak amplitudes $x_t$. This relationship strongly depends on the weight of the caisson.

## (b) Relationship Between Wave Loading and Oscillatory Motions of Caisson Breakwater

A typical result is given by Fig. 6 showing the horizontal impact force, the uplift force, the total overturning moment around the caisson heel and the resulting motions of the caisson in non-dimensional form (H = 0.30 m, T = 2.4 s, water depth d = 1.00 m)

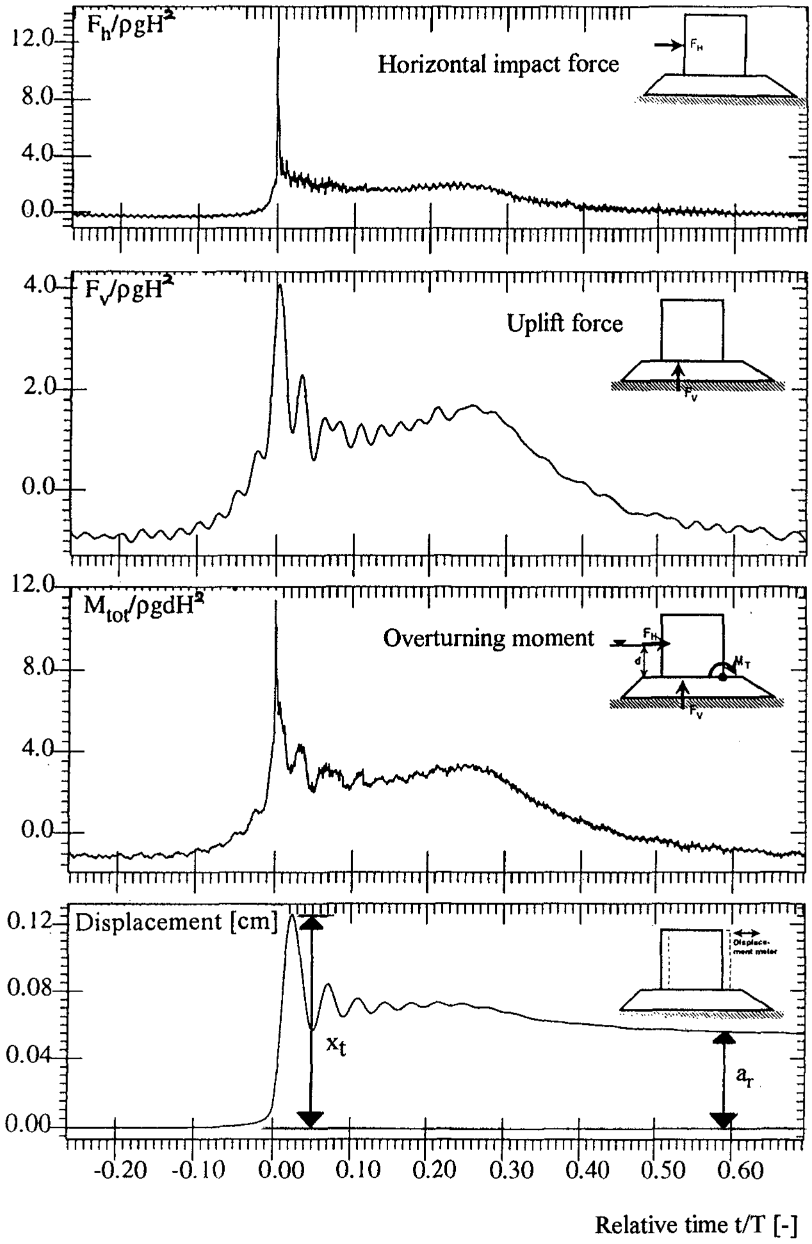


Fig. 6- Simultaneously Recorded Impact Loading and Motions of Caisson Breakwater

For the study of the relation between wave loading and the magnitude of the peak amplitude of the caisson motions $x_t$, the horizontal impact force, the uplift force and the total overturning moment around the caisson heel are considered.

Despite the large scatter of the measured values it is seen from Fig. 7 that the peak amplitude $x_t$ first increase at a higher than at a lower rate with increasing peak of the horizontal force $F_{hmax}$.

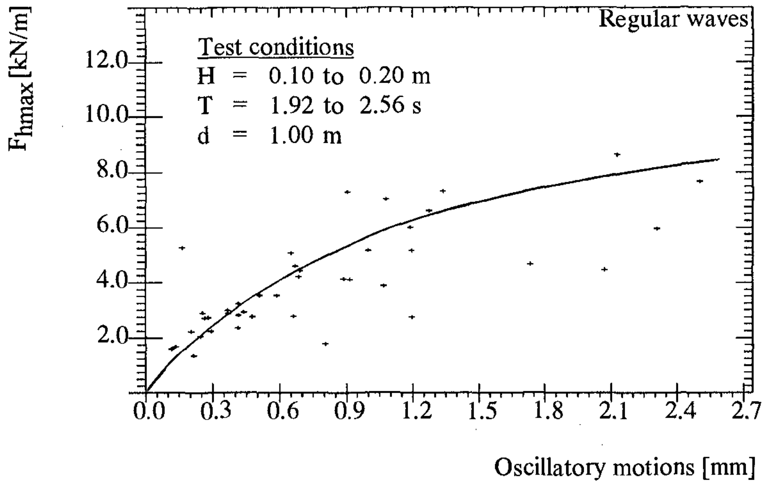


Fig. 7- Peak Amplitude of Oscillatory Motions vs. Horizontal Impact Force

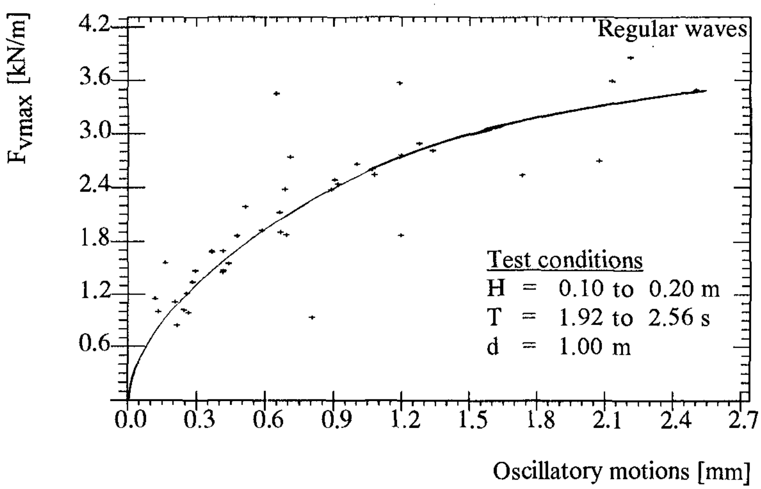


Fig. 8- Peak Amplitude of Oscillatory Motions vs. Uplift Force

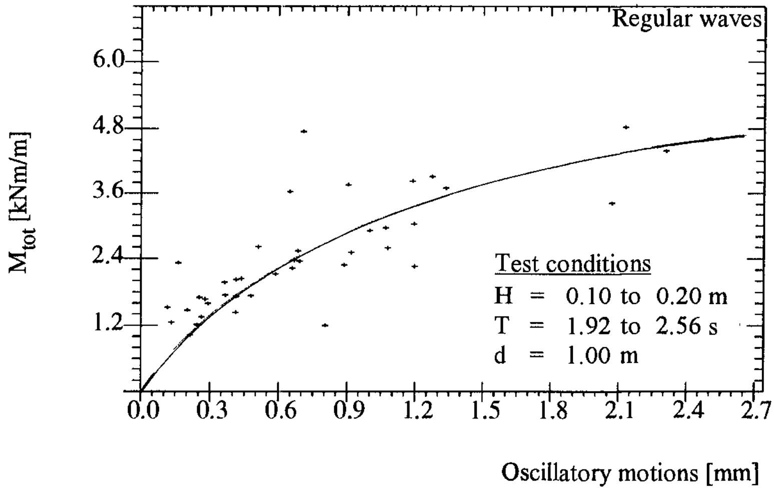


Fig. 9- Peak of Oscillatory Motions vs. Peak of Total Overturning Moment

Almost the same tendency is depicted in Fig. 8 for the relationship between the peak values of the oscillatory motions and the peak values of the uplift forces. The resulting effect of the uplift and the horizontal impact force is shown in Fig. 9 as peak values of the total overturning moment vs. the peak amplitudes of the permanent displacements.

**(c) Relationship Between Wave Loading and Permanent Displacements**

For the study of the relationship between wave loading and permanent displacements $a_r$, the horizontal impact force, the uplift force and the total overturning moment around the caisson heel are considered.

The permanent displacements $a_r$ are plotted against the peak amplitudes of the horizontal impact force, the uplift force and the total overturning moment in Figs. 10, 11 and 12, respectively.

As compared to Figs. 7, 8, and 9 for the oscillatory motion there is no clear relationship between the wave loading and the permanent displacements. A large scatter is present on the peak values of the critical loading at which a permanent displacement starts to occur, illustrating the fact other characteristics of the loading may also be determinant for the initiation and the magnitude of the permanent displacements.

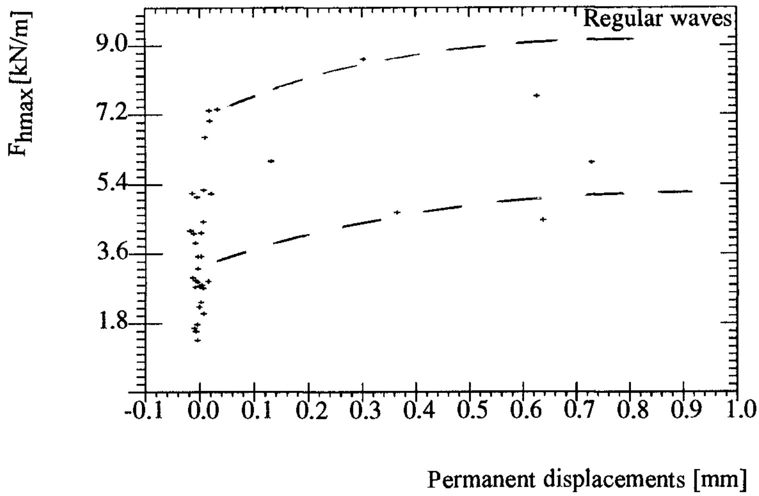


Fig. 10- Permanent Displacements vs. Horizontal Impact Forces

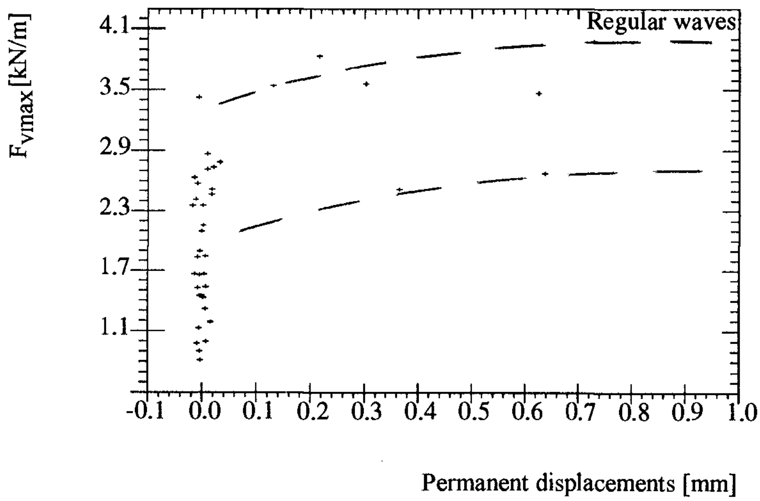


Fig. 11- Permanent Displacements vs. Uplift Forces

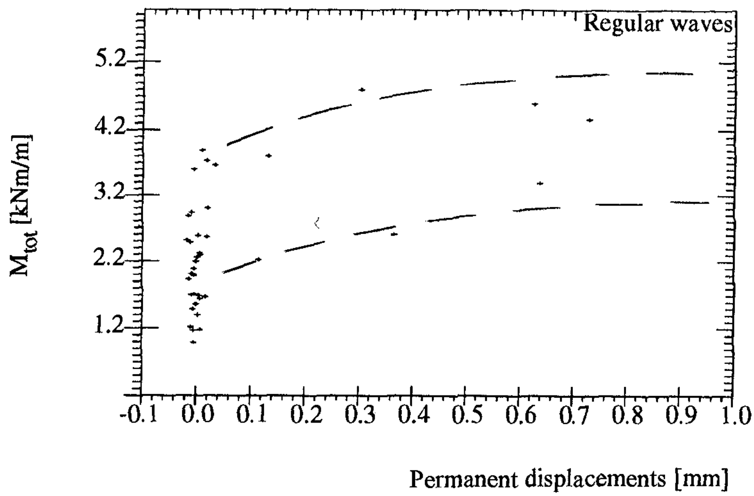


Fig. 12- Permanent Displacements vs. Peak of Total Overturning Moment

**d) "Safety Factor" against Sliding**

A kind of "safety factor" against sliding $\eta_s$ is defined as the ratio of $F_R/F_{hmax}$ in which the shear resistance or friction force is expressed as

$$F_R = \mu \cdot (W_{cai} - F_V),$$

where $\mu$ is a "dynamic" friction coefficient ($\mu$= 0.5), $W_{cai}$ is the weight of the caisson (dry and submerged part) and $F_V$ is the maximum uplift force (Fig. 13). The horizontal impact force $F_{hmax}$ is obtained by integrating the pressure recorded on the front face of the caisson.

Plotting the related time history of the measured caisson motions (scaled on the left y-axis) and the calculated safety factor $\eta_s$ (right y-axis) in Fig. 14 for one event, it can be seen that the displacement of the caisson is initiated for $\eta_s < 1$.

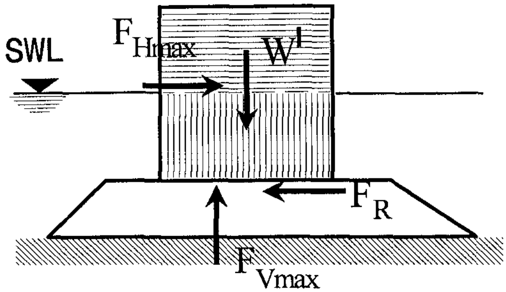


Fig. 13- Definition Sketch

Plotting the related time history of the measured caisson motions (scaled on the left y-axis) and the calculated safety factor $\eta_s$ (right y-axis) in Fig. 14 for one event, it can be seen that the displacement of the caisson is initiated for $\eta_s < 1$ (test conditions: H= 0.30 m, T= 2.4 s, d= 1.0 m).

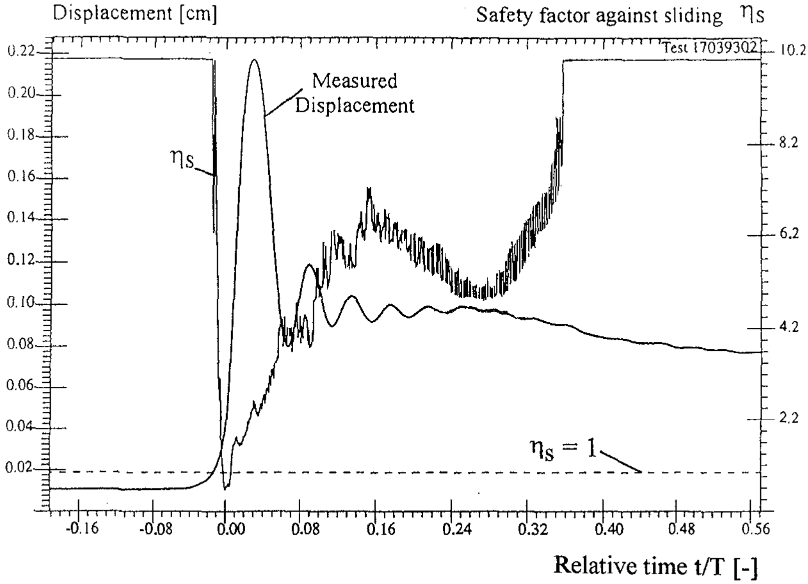


Fig. 14- Related Time History of Measured Displacement and Calculated "Safety Factor" $\eta_s$

This result is confirmed by a set of more than 40 impacts caused by regular waves where the ratio of $F_R$ and $F_{hmax}$ is plotted against the permanent displacement of the caisson (Fig. 15). It is seen that permanent displacement occurs only for $\eta_s < 1$.

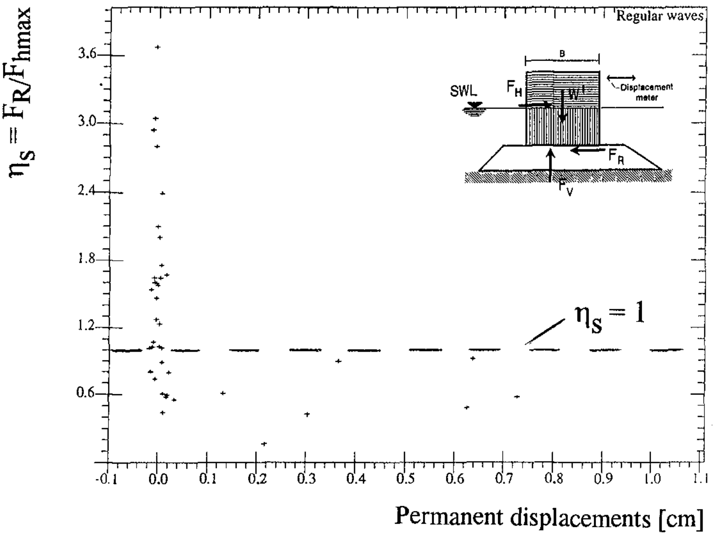


Fig. 15- "Safety Factor" vs. Permanent Displacement

The ratio $\eta_R = M_R/M_{tot}$ is also considered in analogy to the safety coefficient against overturning, where $M_R$ is the resistive moment (due to the weight of the caisson) and $M_{tot}$ the maximum overturning moment around the caisson heel induced by the horizontal peak force $F_{hmax}$ and the maximum uplift force $F_{vmax}$. It can be seen from Fig. 16 that permanent displacement may occur even for values $\eta_R > 1$.

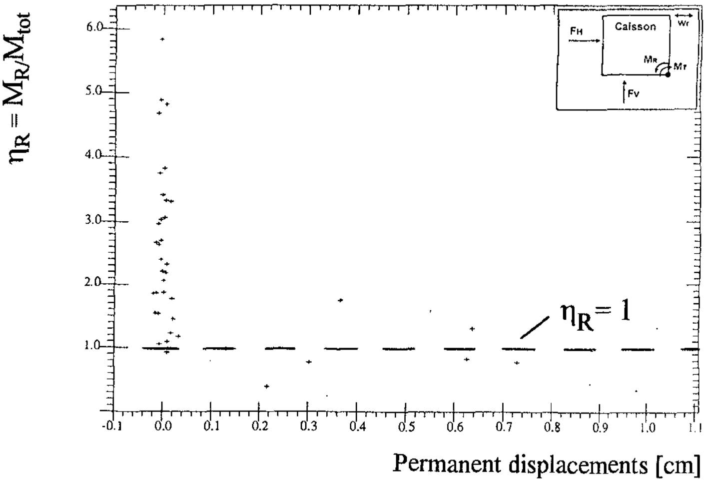


Fig. 16- "Safety Factor" $\eta_R$ against vs. Permanent Displacements of the Caisson

**e) Cumulative Effect of Permanent Displacements**

As already mentioned above the effect of the impulsive loading induced by waves breaking on the structure is not only limited to small amplitude oscillatory motions of the caisson breakwater. It also consists in incremental small permanent displacements which may cumulate and lead to the collapse of the structure.

Fig. 17 shows the total overturning moments calculated from the horizontal and uplift forces on the caisson induced by a sequence of breaking wave loads and the resulting oscillatory motions and permanent displacements.

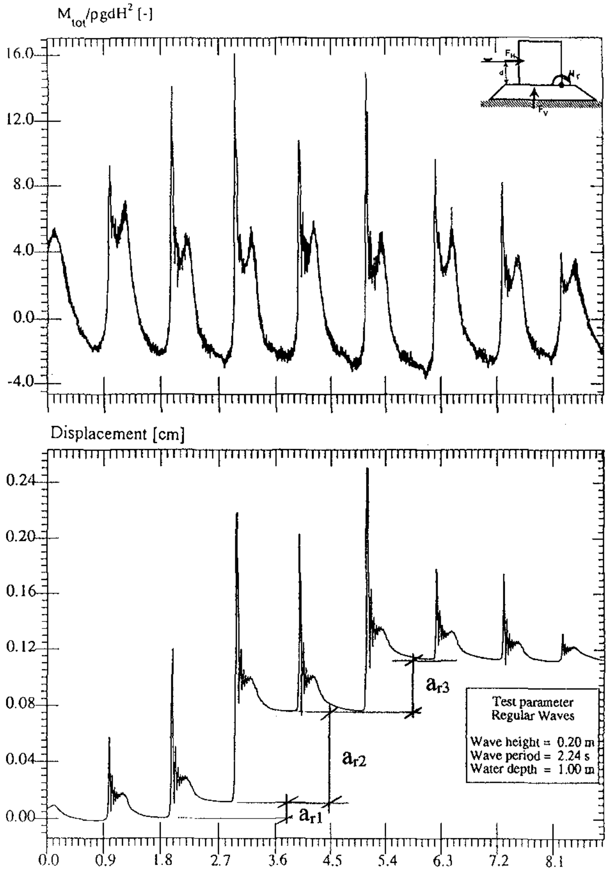


Fig. 17- Cumulative Effect of Permanent Displacements Induced by a Sequence of Breaking Wave Loads (see Fig. 18)

The cumulative effect of permanent displacements may lead to a stepwise failure of the caisson (Fig. 18). This effect is very important and should be taken into account in future design methods, analysis and numerical modelling.

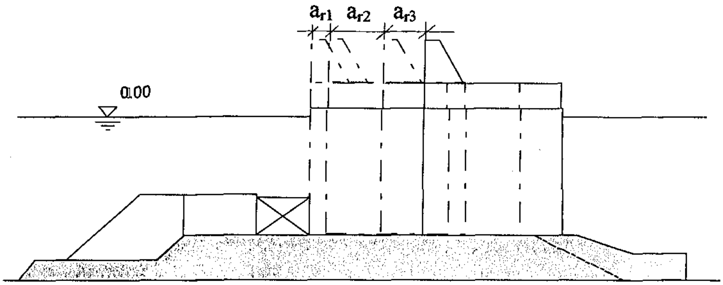


Fig. 18- Stepwise Failure of Caisson Breakwaters Induced by a Sequence of Breaking Wave Loads (see Fig.17)

## 4. Concluding Remarks

Although the analysis of the results of the hydraulic model tests is not yet completed they clearly show that the effect of the impulsive loading induced by waves breaking on the structure is not only limited to small amplitude oscillatory motions of the caisson breakwater. It also consists in incremental small permanent displacements which may cumulate and lead to the collapse of the structure.

On the other hand, these first results show that future analysis and numerical models to be developed for the prediction of the stability of caisson breakwaters should also necessarily account for the stepwise failure resulting from the incremental residual displacements (plastic deformations) induced by successive breaking waves on the structure.

## 5. Acknowledgements

This study is part of a research programme on breakwaters within the Coastal Engineering Research Unit "SFB 205" at the University of Hannover which is supported by the German Research Council (DFG), Bonn.

Additional support by the European Union within MAST II-Research programme (MAS2-CT92-0047) is also gratefully acknowledged.