CHAPTER ONE HUNDRED NINETY FIVE

Wave Forces and Impacts on a Circular and Square Caisson

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Abstract

The existing breakwater at Civitavecchia Harbour, Italy, will be extended with a part of caissons. In order to investigate wave forces for this caisson, the Ministero dei Lavori Publici commissioned the Delft Hydraulics Laboratory to perform a model investigation on the proposed extension. In the first part of the study quasi-static wave forces on the entire caisson were measured by means of a force measuring frame. In the second part wave impacts were recorded by pressure cells at 22 positions of the caisson.

The investigation contained two main items which are discussed in this paper:

- Comparison of quasi-static wave forces with maximum forces by wave impacts.
- Comparison of forces and impacts for a circular caisson with those measured for a square caisson.

Introduction

The stability of a caisson against wave attack can be described by external parameters (loads) and internal parameters (strength). External parameters are for example, wave height, wave period, foreshore and structure geometry. Internal parameters are dimensions, mass and mass distribution of the caisson and the friction coefficient between the bottom of the caisson and the foundation. If the loads are known for a given external geometry of the caisson, the mass and dimensions required for stability can be calculated. These calculations are simple when quasi-static wave forces are assumed, i.e. forces which vary with the wave period. They can be found in most handbooks.The measuring of the loads and the calculations on stability become more complicated, when also wave impacts have to be considered. For stability calculations which include the time-dependent dynamic forces one is referred to [1].

In this paper an investigation is described on wave forces on a caisson subject to both quasi-static wave forces and wave impacts. Both a caisson with a circular and a rectangular cross-section was examined.

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The main dimensions of the caisson are shown in Fig. 1. Both caissons consisted of a base plate with dimensions of 20x22 m^2 and a curved crest wall with the top elevation 8.5 m above Mean Sea Level (M.S.L.). The cylindrical caisson had a diameter of 19 m, for a square caisson the dimensions were 19x20 m. The caissons were founded on a berm 18.5 m below M.S.L. The water depth in front of the caisson was approximately 30 m.

The design conditions were established at a significant wave height of 8.0 m and an average wave period of 10.5 s. The linear scale factor used for the investigation was 38. All tests were conducted in a 1.0 m wide, 1.2 m deep and 50.0 m long wave flume with the test section installed about 45 m from the random wave generator. This wave generator is capable of performing both translatory and rotational motions by means of a hydraulic actuator, programmed by a closed loop servo-system. The command signal of this loop is obtained from a punched tape, representing a random signal with a predetermined wave energy density spectrum.

Quasi-Static Wave Forces

Sliding and overturning are the failure mechanisms for an entire caisson. This means that only the total horizontal and vertical wave force and the total overturning moment on the caisson are of interest for stability calculations. One is not interested in the distribution of the wave pressures on the caisson. In this case the wave forces can simply be measured by a caisson attached to a force metering frame.

Tests on quasi-static wave forces were performed on one caisson in the middle of the flume with on each side another half caisson. The middle caisson was suspended above the floor of the flume by rigid metal plates attached to the inner section of the Laboratories force metering frame, see Fig. 2. The inner section of the metering frame was supported by a rigidly mounted external frame section through five suspensions with strain gauges, two in the horizontal and three in the vertical planes. A clearance of approximately 3 mm was left around the front and sides of the middle caisson to ensure complete freedom of movement during the force measuring tests. A pressure cell in front of the caisson measured the variation in water level.

Typical signal recordings of the five gauges and the pressure cell are shown in Fig. 3. Impact forces will cause resonance of the suspended caisson at its natural frequency. Second-order low-pass electrical filters of 5 Hz were installed in the force metering recording circuits to eliminate this effect. This means, however, that only the quasi-static forces and no wave impacts were present in the measured signals.

The signals of the strain gauges were recorded by a HP 1000 computer with a sampling frequency of 25Hz. The time histories of the total horizontal force (Fh), the total vertical force (Fv) and the total overturning moment (M_A) were calculated from the signals of the strain gauges, using the equations given in Fig. 2. The maximum force and moment for each wave crest were calculated from these time histories and with these data exceedance curves were calculated. Fig. 4

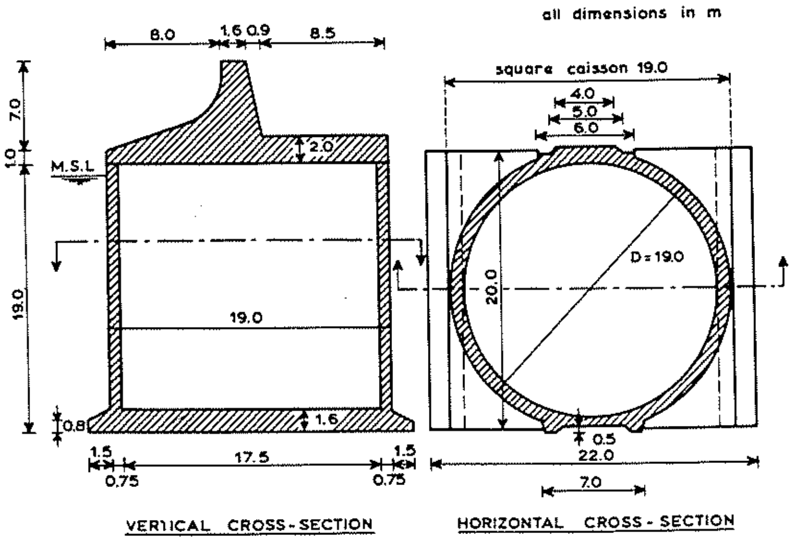
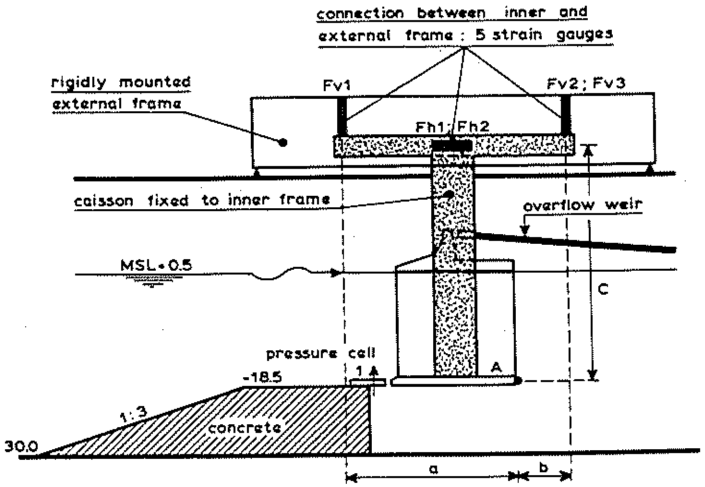
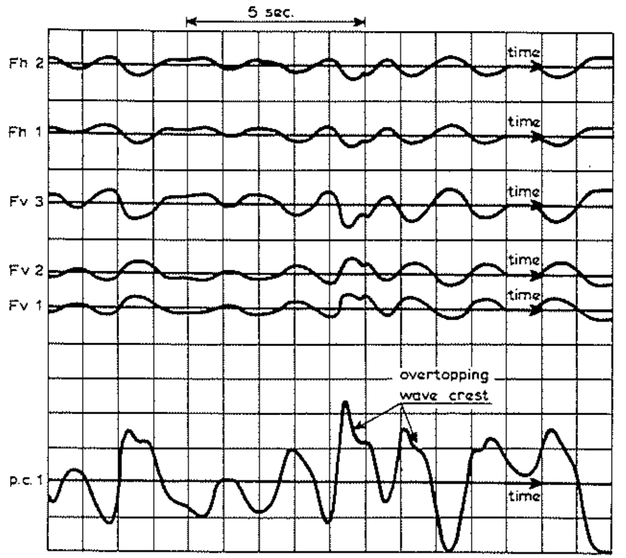


FIGURE 1. DIMENSIONS OF THE CAISSON



vertical force : Fv = Fv1 + Fv2 + Fv3
horizontal force : Fh = Fh1 + Fh2
moment : M_A = Fv1 a − (Fv2 + Fv3) b + (Fh1 + Fh2) c

FIGURE 2. FRAME FOR MEASURING QUASI-STATIC WAVE FORCES



p.c. 1 - pressure cell 1, see figure 2
Fv 1, Fv 2, Fv 3 - vertical forces of the measuring frame, see figure 2
Fh 1, Fh 2 - horizontal forces of the measuring frame, see figure 2
total vertical force Fv = Fv 1 + Fv 2 + Fv 3
total horizontal force Fh = Fh 1 + Fh 2

FIGURE 3. TYPICAL RECORDINGS OF THE FORCE MEASURING FRAME

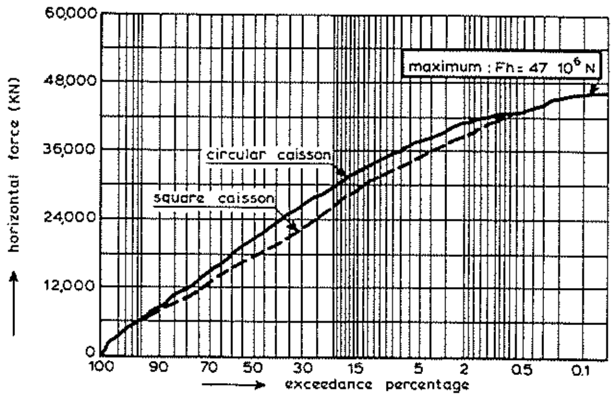


FIGURE 4. EXCEEDANCE CURVE FOR THE TOTAL HORIZONTAL FORCE

gives the exceedance curve for the horizontal force, both for a circular and a sqaure caisson.

Although a small difference exists for the two exceedance curves, the maximum horizontal force is the same for a circular and a square caisson. This maximum horizontal force amounted to 47 MN, full scale value. It can be concluded that the shape of the caisson has hardly any influence on the quasi-static horizontal wave forces.

Wave Impacts

Wave impacts can cause very high local pressures, exceeding the hydrostatic pressures by a factor 10-50. The parts of a structure where impacts occur should be designed for these high pressures. For this reason wave impacts were measured on the caisson.

The front side of one caisson with on each side another half caisson was constructed of 10 mm thick steel, see Fig. 5. The rear side was strengthened by steel diaphragms to ensure a rigid model construction. The caissons were founded on a rigid steel base, the berm in front of the caisson was constructed of concrete. Six or seven pressure cells were applied for each test to measure wave impacts simultaneously along a vertical or horizontal axis. A front view of the positions of the pressure cells is given in Fig. 6. In this way impacts were measured at 22 positions of the caisson. Tests 1...4 refer to the circular caisson. In test 5 the square caisson was investigated. To maintain a constant water level the overtopped water at the rear side of the caisson was pumped back to the sea side.

For the tests 0.8 cm diameter DRUCK PDCR 10 miniature pressure transducers were used, each having operating pressure of 100 kPa with 400% overpressure capability. The pressure cells were mounted on a brass plate. The transducer calibrations supplied by the manufacturer were confirmed by static pressure tests. The natural frequency in air was 28,000 Hz and mounted on the caisson and in water approximately 10,000-15,000 Hz. Outputs from the pressure transducers were fed into a RACAL magnetic tape recorder for off-line processing. Seven data channels were available for the RACAL tape recorder. For a recording speed of 15 inch/s (0.38 m/s) the recorder had a 100% frequency response up to 4000 Hz and up to 5000 Hz for an accuracy of 70%. The ten highest impacts, determined from a Honeywell oscillographic visicorder (model 1858) were recorded on a second RACAL tape recorder with a time expansion of 16 times. These analog signals were used, again with a time expansion of 16 times, for sampling by means of a HP1000 computer with a sampling frequency of 100 Hz. Therefore the sampling frequency of the original pressure outputs was 16x16x100 = 25,600 Hz. The overall frequency of the measuring system was about 4,000 Hz.

Digital processing of data give a fast method to combine all pressure signals into a total force by multiplying with different factors, representing the respective working area. Two impacts, plotted at different time scales, are shown in Fig. 7.

For each test and for each pressure cell the ten highest impacts were plotted. The schematization and the location of these impacts on

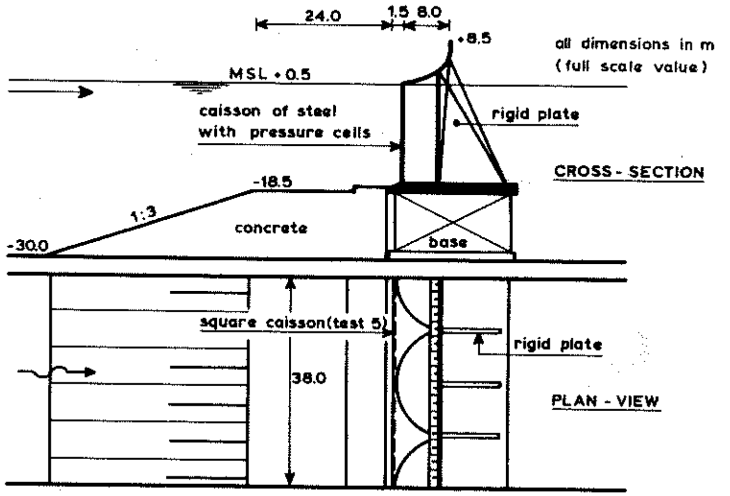


FIGURE 5. TEST SET - UP FOR WAVE IMPACT STUDY

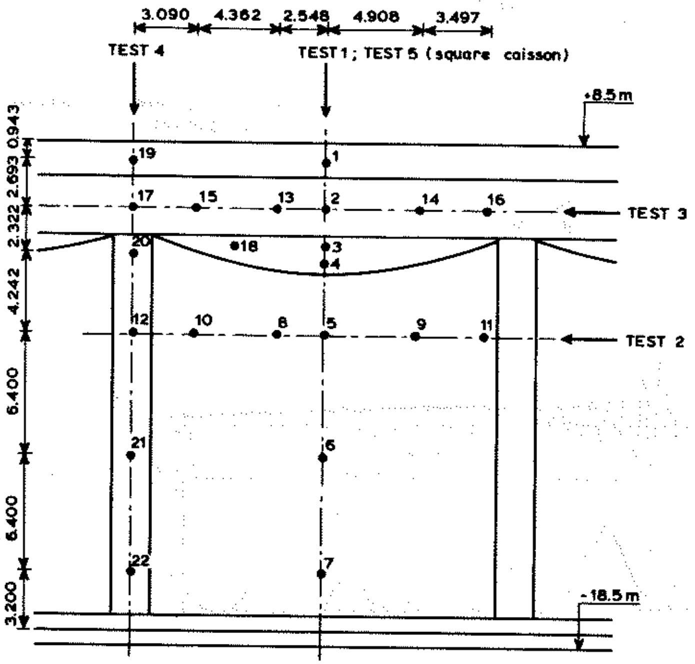


FIGURE 6. FRONT VIEW OF CAISSON WITH POSITIONS OF PRESSURE CELLS

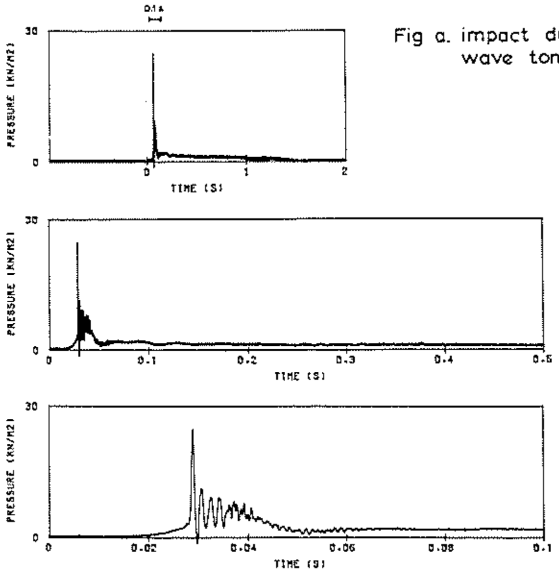


Fig a. impact due to wave tongue

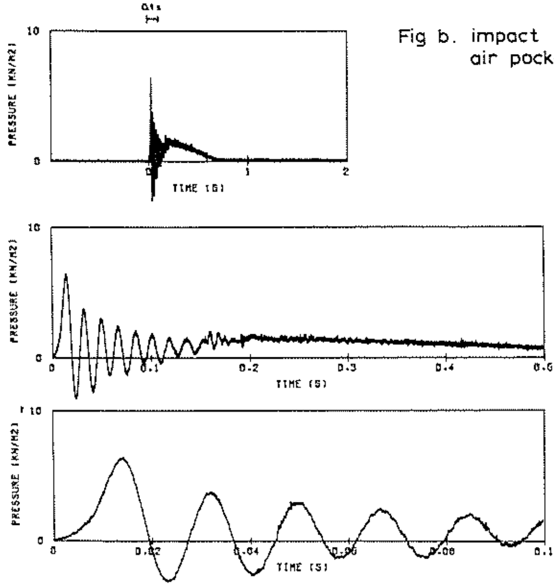


Fig b. impact due to enclosed air pocket

FIGURE 7. IMPACTS AT DIFFERENT TIME SCALE

the caisson are shown in Fig. 8. All local impacts could be described by four diagrams, two with the shape of one or two triangles and two with the shape of a damped oscillation. Fig. 8 shows also the moment just before the impacts occurs. The wave front rises along the vertical wall and a wave tongue falls on the upper part of the crest wall, whilst an air pocket is formed for the lower section of the crest wall. At the upper part high impacts occur under the wave tongue with impact type 1 or 2. At the lower part of the crest wall, oscillation of the air pocket was observed. Pressures are less high and the -rising time longer (type 3). This oscillation generates pressure waves which travel trough the water and give impact pressures at the pressure cells below M.S.L. (type 4) with a fast damping. Impact types 1 en 2 have been found for breaking waves on a slope and type 3 was found by Ramkema [2].

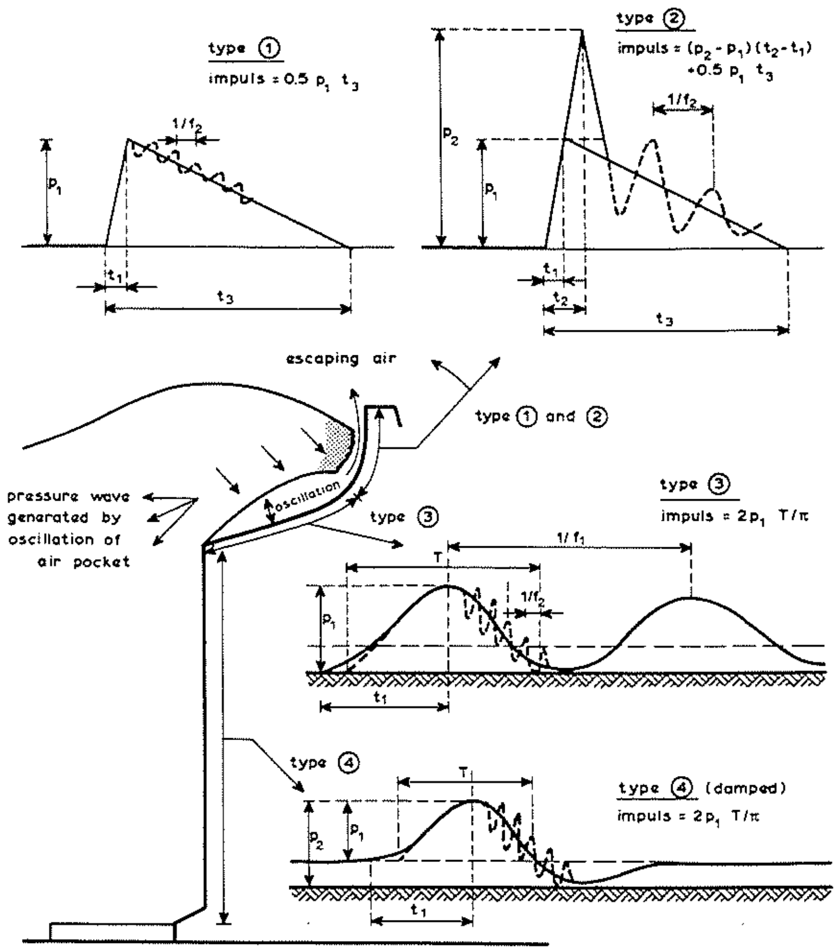
Every impact is completely described by the pressure p_1 and p_2, the rising times t_1 and t_2, the impact duration t_3, the duration T of the first half oscillation (type 3), the frequency of this oscillation f_1 and the frequency f_2 of oscillations during the decrease of the pressure. The impulse of the impact can be calculated with the above mentioned characteristics and formulae are given in Fig. 8. The impact by the wave tongue (type 2) gives the highest pressures, up to 44.5 kN/m^2, model value. The frequency of the oscillation of the air pocket is within the range of $33 < f_1 < 80$ Hz. Oscillation of little air bubbles was observed with frequencies in the range of $200 < f_2 < 2000$ Hz.

Comparison Wave Impacts for Circular and Square Caisson

For each test six or seven impacts were recorded simultaneously, see Fig. 6. The sum of the signals was calculated, taking into account the area corresponding to each cell, the direction of the resultant force and the scale of the model. No correct scaling laws are available for all types of impacts observed for the tests. Maybe the model law given by Ramkema [2] may be applied for impact types 3 and 4, the higher impacts types 1 and 2 are not scaled correctly with this law. The common relationship (Froude) is $n_p = n_l$ and $n_t = \sqrt{n_l}$. As this relationship gives the most conservative results it was used for all impacts. The scale factor for the pressure was $n_p = 38$ and for the time $n_t = 6.16$. The time history of the total force per meter width for test 1 (circular caisson) and test 5 (square caisson) is shown in Fig. 9 for the highest impact. From this figure the following conclusions can be derived for the maximum horizontal force per meter width:

The maximum horizontal force for the circular and square caisson are almost the same and amounted to 4.4 MN/m and 5.0 MN/m respectively. The impulse, however, was 1.8 times larger for the square caisson (i = 0.188 MNs/m and i = 0.347 MNs/m for the circular and square caisson, respectively).

For the circular caisson the impacts on 22 pressure cells were measured. Combination of these signals obtained from tests 1...4 gives the total horizontal signal for the circular caisson. The total horizontal force per meter width for test 5 (see Fig. 9) multiplied by 20 m gives the total horizontal force for the square caisson. The time history of the horizontal force for the circular caisson and for the



t_1 ; t_2 = rising time
t_3 = impact duration
p_1 ; p_2 = maximum pressures
Δ tf = phase lag between maximum of two pressure cells

f_2 = frequency of air bubble oscillation in the wave front
f_1 = frequency of air pocket enclosed by overtopping wave
T = duration of half a sine

FIGURE 8. SCHEMATIZATION OF WAVE IMPACTS AND CORRESPONDING LOCATION

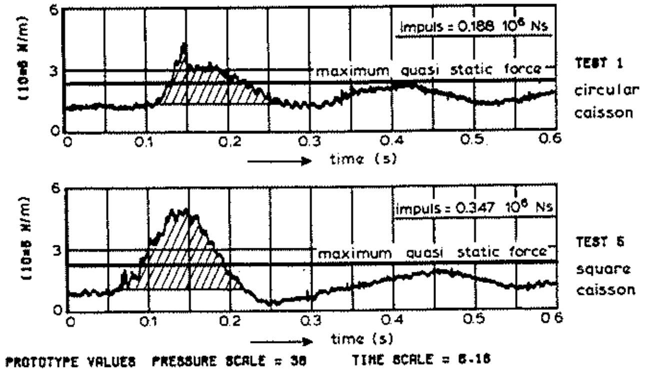


FIGURE 9. TIME HISTORY OF THE MAXIMUM HORIZONTAL IMPACT FORCE FOR TESTS 1 AND 5

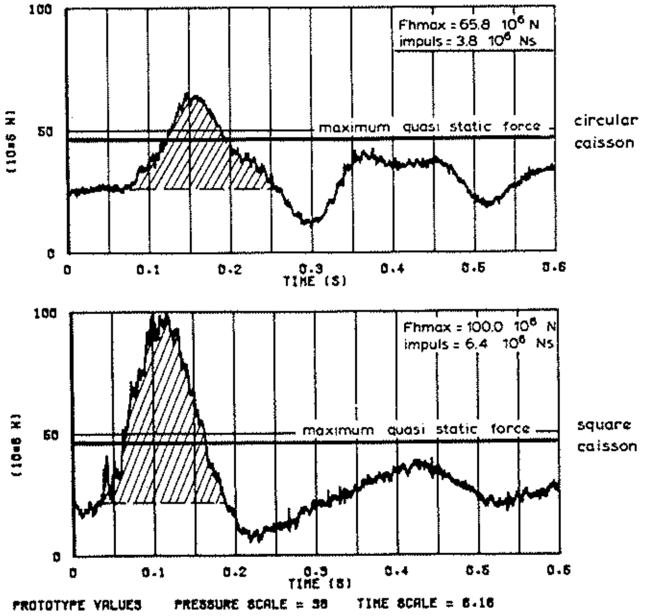


FIGURE 10. TIME HISTORY OF THE MAXIMUM TOTAL HORIZONTAL IMPACT FORCE FOR THE ENTIRE CAISSON

square caisson are shown in Fig. 10 for the highest impact. From this figure the following conclusions can be derived for the total maximum horizontal impact force for the entire caisson:

- The maximum horizontal forces for the square caisson are 1.5 times higher than for the circular caisson. The average maximum horizontal force was Fh = 65.8 MN for the circular caisson and Fh = 100.0 MN for the square caisson.
- The impulse is also about 1.5 times higher for the square caisson. The impulse for the circular caisson was i = 3.8 MNs and for the square caisson i = 6.4 MNs.
- Rising time and duration of the impacts are almost the same for the circular and square caisson. The rising time is about t_1 = 0.07 sec and the total duration of the impact t_3 = 0.17 sec.

Comparison Quasi-Static Wave Forces and Wave Impacts

The maximum quasi-static froce was established at 47 MN for both the circular and square caisson. This value is also given in Fig. 10. Scaling impact forces according to the Froude number, as was done in Figs. 9 and 10, gives maximum impact forces which are 2 times higher for the square caisson and 1.3 times higher for the circular caisson than the maximum quasi-static force.

The model law for iso-thermal compression, described by Ramkema [2] can be used for impact types 3 and 4. Although this law is not correct for impact types 1 and 2 it will be used in order to calculated a lower boundary for the impact force. In this case the maximum impact for the square caisson was used, where even the highest located impacts could be described by impact type 3, see Fig. 11. Results are given in Fig. 12 for the impact pressures and in Fig. 13 for the total maximum impact force for the caisson. The force signal of Fig. 10 (Froude scaling) has been added to Fig. 13.

Scaling according to the model law for iso-thermal compression shows much lower impacts than for scaling to the Froude number. The maximum horizontal force is about 40 MN for the compression model, whilst a force of 100 MN was calculated according to the Froude number. The actual maximum force in nature will be within this range and probably close to 50 MN, as impact types 1 and 2 are only present on a small part of the caisson.

Main Conclusions

1 Horizontal quasi-static wave forces on a circular and square caisson are almost the same.

2 All local impacts could be described by four diagrams, two with the shape of one or two triangles and two with the shape of a damped oscillation, see Fig. 8. The triangular types are caused by the impact of the wave tongue and can be compared with a wave breaking on a slope. The damped oscillation is caused by the compression of an enclosed air pocket as found by Ramkema [2]. The impact by the wave tongue gives the highest pressures, (up to 44.5 kN/m^2). The frequency of the oscillation of the air pocket is within the range

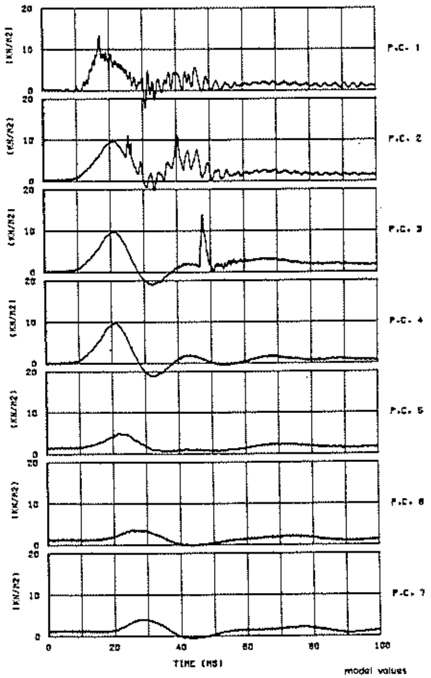


FIGURE 11. MAXIMUM IMPACT PRESSURES FOR THE SQUARE CAISSON

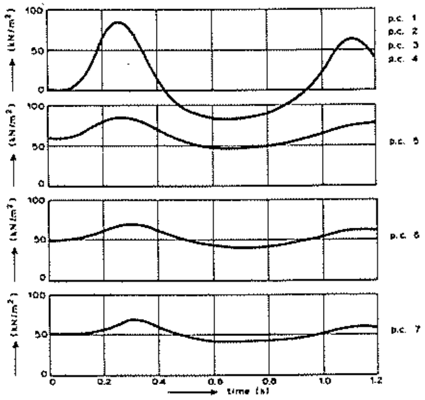


FIGURE 12. PRESSURES OF TEST 5 SCALED ACCORDING TO THE COMPRESSION MODEL

of $33 < f_1 < 80$ Hz. Oscillation of little air bubbles was observed with frequencies in the range of $200 < f_2 < 2000$ Hz.

3 Total impacts forces for a square caisson are 1.5 times higher than for a circular caisson, whilst also the impulse is about 1.5 times higher. Rising time and duration are almost the same for the circular and square caisson, see Fig. 10.

4 Scaling impact pressures according to the Froude number gives maximum impact forces which are 2 times higher for the square caisson and 1.3 times higher fpr the circular caisson than the maximum quasi-static force. Scaling according the model law for iso-thermal compression (Ramkema [2]) shows impact forces with the same values as the maximum quasi-static wave force.

References

1 BENASSAI, E., The stability against sliding of breakwaters under the action of breaking waves. PIANC Bulletin No. 21, 1975.

2 RAMKEMA, C., A model law for wave impacts on coastal structures. Proc. Coastal Engineering Conf., Hamburg, 1978.

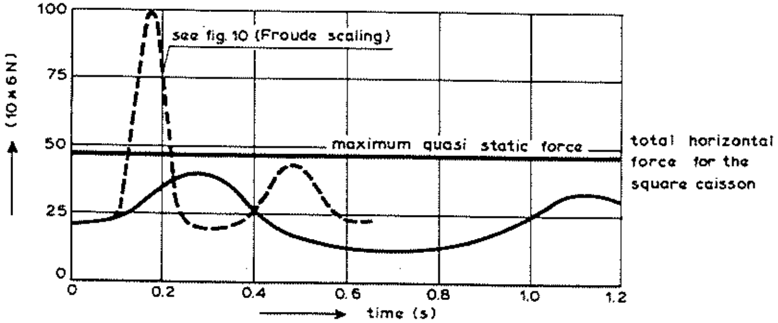


FIGURE 13. TIME HISTORY OF THE MAXIMUM HORIZONTAL FORCE, SCALED ACCORDING TO THE COMPRESSION MODEL