WAVE IMPACT PRESSURES ON COMPOSITE BREAKWATERS

by

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ABSTRACT

Wave impact pressures and forces on composite breakwaters have been measured in the laboratory. A solid wall breakwater and a perforated breakwater were instrumented with small pressure transducers in a study designed to estimate the relative effectiveness of perforated breakwaters in reducing impact loads caused by breaking waves.

Experimental results of maximum pressures and forces measured on the breakwater walls are presented as cumulative probability distributions. It is concluded that the perforated breakwater experiences significantly lower breaking wave loads although local impact pressures may be as high as those measured on the solid wall breakwater. Further studies are required on the perforated breakwater and alternative designs to determine the most suitable caisson type for the reduction of wave impact forces.

INTRODUCTION

With the trend in recent years to deep water harbours exposed to unfavourable wave climates, rubble mound breakwaters have become increasingly more expensive relative to composite breakwaters. The massive quantities of rock required for mounds with the gentle slopes necessary for stability, the limited strength of concrete armour units, and the effect of wave groups on armour unit stability, pose problems in the design of rubble mound breakwaters which are not easily solvable. The composite breakwater, consisting of concrete caissons founded on a rubble mound, does not require large quantities of quarry stone and in addition has a considerable advantage at some locations where the wave climate allows only a short construction time, because the caissons are constructed in dry dock and then towed to the site. However, there are also problems in designing composite breakwaters. In the past, composite breakwaters in deep water have been designed assuming total reflection of the waves, but it is now generally recognized that wave breaking can occur even on a composite breakwater with a low rubble mound in deep water. The resulting impact pressures, although occurring infrequently, for an extremely short

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duration and over a very localized area, are enormous. Such pressures can cause severe local damage to the structure, and in the case of lower less localized pressures can cause sliding failure of the breakwater. It is apparent that composite breakwaters should be designed to avoid the possibility of severe impact pressures occurring. Thus, Lundgren and Graveson (3), have proposed breakwaters constructed using vertical cylindrical caissons and also caissons with the upper surfaces sloping away from the wave attack. Measurements of impact pressures on cylindrical caissons are described by Graveson et al. (1). Richert (9) has also shown the effectiveness of a sloping wall in reducing impact pressures. Onishi and Nagai (7) and Nagai and Kakuno (6) have conducted studies in which impact pressures were measured on slit-type breakwaters.

In the laboratory study described in this paper, wave impact pressures were measured on a composite breakwater with plane vertical solid walls. Tests were also conducted on a perforated Jarlan-type breakwater with plane vertical walls in order to determine whether impact pressures are reduced on such a breakwater. Although similar comparative tests have not been carried out previously, many others have measured impact pressures on plane solid walls and Nagai and Kakuno (6) have measured impact pressures on walls with perforations consisting of vertical slits. However, there are many inconsistencies in the experimental data produced from previous studies, mainly because of wide differences in the quality of the experimental equipment used.

EXPERIMENTAL EQUIPMENT

It has been found that the same incident waves breaking on a composite breakwater can produce widely varying magnitudes of impact pressure because of slight differences in timing and position of the breaking wave. This phenomenon has been observed by numerous other researchers such as Mitsuyasu (4) and Moutzouris (5). Therefore, it was essential in order to obtain a valid comparison of caisson designs, to run many tests and plot the results as cumulative probability distributions. The height and period of the regular incident waves were chosen such that every wave in the wave train broke on the vertical walls of the breakwaters. Irregular waves were not used in these tests, nor was any effort made to produce different types of breakers. Thus, the possibility should not be overlooked that the results of this study may not be applicable to situations with breaker types other than the plunging breakers produced in the present experiments.

It is well known that the impact pressures measured on composite breakwaters depend on many design variables such as slope and height of the berm, top width of the berm and water depth above the berm. In addition there are the variables describing the incident waves and the caisson design.

In this study, the berm dimensions were chosen to produce severe wave impact conditions to facilitate the comparison of caisson types.

A sketch of the model breakwater is shown in Fig. 1. The water depth in the wave flume was 75.6 cm and the depth above the berm was 29.2 cm. The berm had a slope of 1:3 and was constructed of stone fill with a cement outer layer approximately 4 cm thick. The model breakwaters were 1.22 m wide and were tested in a wave flume 64 m long and the same width as the breakwaters. The caissons were constructed high enough that no overtopping occurred and were held rigidly in position by a massive concrete and steel structure at the rear of the breakwaters. A solid wall caisson was constructed of wood with walls 3.8 cm thick and internal chambers such that after testing as a solid wall caisson, holes were drilled in the front wall so converting it into a perforated wall caisson. The chamber width from front to rear walls was 30.5 cm, giving a ratio of chamber width to incident wave length of 0.06. This is considerably smaller than the ratio of approximately 0.2 usually recommended to minimize wave reflection; however, it is approximately the ratio suggested by Nagai and Kakuno (6) to reduce impact pressures on slit-type breakwaters. Transverse walls with low porosity were included at 23 cm centres for structural rigidity. One of these walls may be seen through a transparent end wall in the photographs in Fig. 5. The perforations on the front wall of the caisson were circular holes 3.8 cm in diameter spaced at 5.7 cm centres giving a relatively high porosity of 34.9%. Pressure transducers mounted on a thick brass plate were located in the centre of the caisson at elevations as shown in Fig. 2. The locations were the same on the front wall for both the solid and perforated breakwaters, being midway between the rows of holes in the perforated wall. A maximum of seven transducers could be used at any one time, so pressure distributions on the front and rear walls of the perforated breakwaters were measured in consecutive test series.

The pressure transducers were 7.6 mm in diameter with semi-conductor strain gauges mounted on a thin metal diaphragm. Temperature compensation was provided but was not entirely satisfactory. The linear range of the transducers was 0-25 psi or 0-172 kPa (kN/m^2) with a combined non-linearity and hysteresis of ±0.25%. The transducer calibrations supplied by the manufacturer were confirmed by static pressure tests. The resonant frequency in air was 20 000 Hz and in water approximately 12 000 Hz.

Outputs from the pressure transducers were amplified one hundred times by amplifiers with a frequency response of 15 000 Hz, before going to two transient recorders. Basically, these recorders are high speed analog to digital converters which have a resolution of 10 bits or 1 in 1000. Each transient recorder has four data channels each capable of storing in memory 1024 data words. The sampling rate can

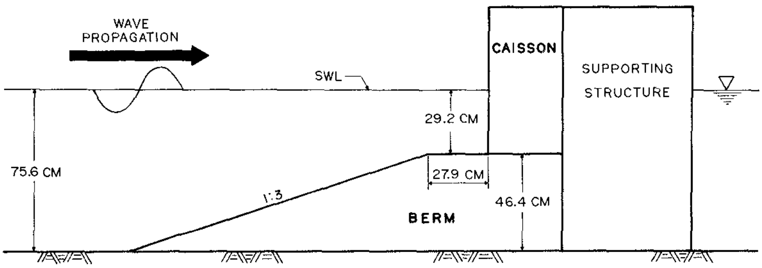
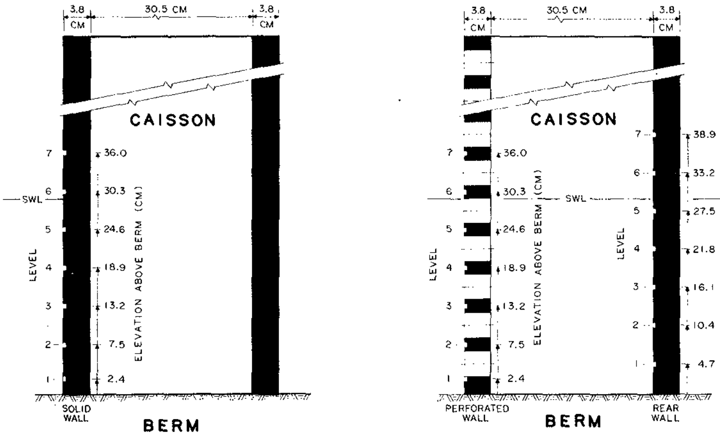


FIG. 1 SKETCH OF MODEL COMPOSITE BREAKWATER



(A) SOLID WALL CAISSON (B) PERFORATED CAISSON

FIG. 2 LOCATIONS OF PRESSURE TRANSDUCERS be chosen as high as 100 000 samples per second, which corresponds to a sample interval of 0.01 ms. At this sample interval the total record length is 0.01 s.

Because fast sampling rates are necessary for accurate measurement of sharp pressure peaks, total record lengths are short. Thus, it is important to commence sampling immediately before a pressure peak occurs, to ensure its inclusion in the record. This is possible using the pre-trigger function of the transient recorders. In this mode of operation the recorders sample the pressure transducer outputs continuously and the data simply overflows from the memory. When a rise in pressure exceeding a certain pre-set level is sensed at any input channel, the recorders interrupt sampling after continuing to sample for a pre-set length of time referred to as the pre-trigger delay. For example, in the present experiments with the pre-trigger delay set at 0.90, the recorders continue to sample and store 0.9 times 1024 data words after the pressure rise is sensed. Then on completion, the channel memory contains 0.1 times 1024 data words recorded previous to and 0.9 times 1024 data words recorded following the increase in pressure. The two transient recorders are interconnected so that the time base is identical for all channels and a pressure rise on any one channel will trigger both recorders simultaneously. After the data from one wave is stored in the memories of the two recorders, it is transmitted to the disk of a digital computer for storage. The transfer of 7168 data words is accomplished fast enough that the system is ready for sampling the pressures caused by the next wave impact.

The rate of sampling by the transient recorders must obviously be chosen sufficiently fast that the peak pressures measured are not attenuated. However, because the memory of each data channel is limited to 1024 words, fast sampling rates result in short records. If the record length is too brief, then pressure rises at locations distant from the point of initial contact of the wave will not be recorded. This in turn means that when the pressures are integrated over the breakwater, the resulting force record may not contain the maximum force on the breakwater. Thus, the choice of sample rate is quite important.

Pressure records measured at different sample rates are shown in Fig. 3. The well-known form of the records of wave impact pressure can be seen when the rate of sampling is slow. A rate of 1000 samples per second conveniently includes the complete pressure record for this wave period of 2.1 seconds; however, this speed is not sufficient to accurately define pressure peaks. For the present experiments, a rate of 20 000 samples per second was chosen, that is, a sample interval of 0.05 ms. The total record length is therefore approximately 0.05 s and this length is illustrated on all the pressure records in Fig. 3 to show the relatively small part of the total record being sampled.

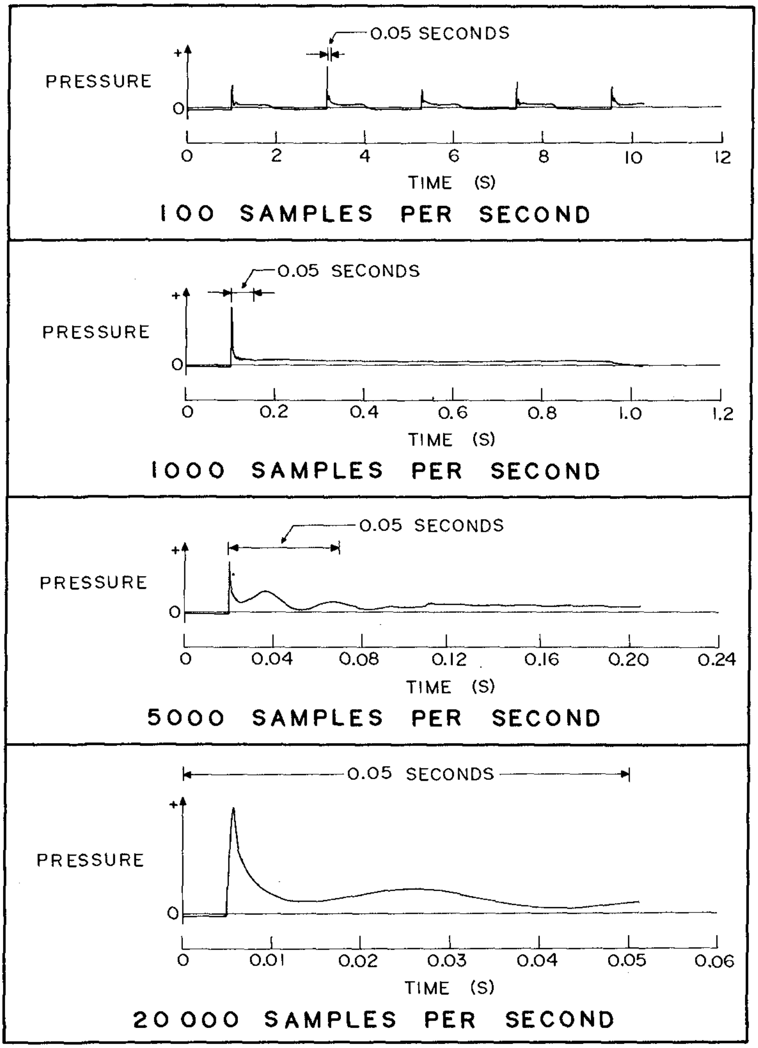


FIG. 3 PRESSURES AT DIFFERENT SAMPLE RATES

TEST PROCEDURE

Scale factors and bias values for the transient recorders were determined at the start of each day. Trigger levels of the recorders were set at approximately 3.5 kPa so that each breaking wave would trigger data collection. Zero readings for the pressure transducers were taken when the water in the wave flume was calm at the beginning of each test series. Thus, zeros were taken with hydrostatic pressure on the transducers so the pressure records produced were the dynamic pressures of the wave impacts.

A train of regular waves was generated using voltage signals produced by a digital computer as input to the wave machine, to ensure repeatable sequences of waves from start-up to finish. A short series of waves was produced so that there would be no disturbance caused by secondary reflections returning from the wave generator board. The height of the incident waves was 37 cm and the wave period was 2.1 s. Wave reflection from the solid wall breakwater was approximately 60% and from the perforated breakwater was 30%.

Ten wave impacts were measured in each wave train, after which it was necessary to allow the agitation in the wave flume to settle before running more tests. The data from sixty wave impacts or 430 000 words were stored on disk before it was necessary to transfer the data to magnetic tape. Because of the wide variation in wave impact pressures even when incident waves varied in height by only ±4%, approximately 300 tests were run with pressure transducers on each breakwater wall so that the results could be treated statistically. To estimate the total force on a perforated breakwater, it is necessary to know the pressures on the interior walls of the chamber. Thus, pressures were also measured on the rear wall of the chamber, although it was assumed that pressures on the interior side of the perforated wall were negligible. In all, approximately 900 tests were run to obtain pressure distributions on the solid wall breakwater and the front and rear walls of the perforated breakwater.

The series of photographs in Fig. 4 show how the incident waves broke against the solid wall breakwater. The numerals on the right hand side of each photograph show the locations of the pressure transducers on the brass plate which is just visible in the centre of the breakwater. The first two photographs show the approach of a wave crest to the caisson wall and the instant before impact. An air pocket is just beginning to form and it appears that the maximum pressure in this case will occur where the crest first hits the wall at level 4. Immediately after the wave impact the water surface begins to rise and large pockets of air can be seen plastered against the caisson wall. The remaining photograph shows the wave run-up and the high density of air bubbles in the water caused by the wave breaking.

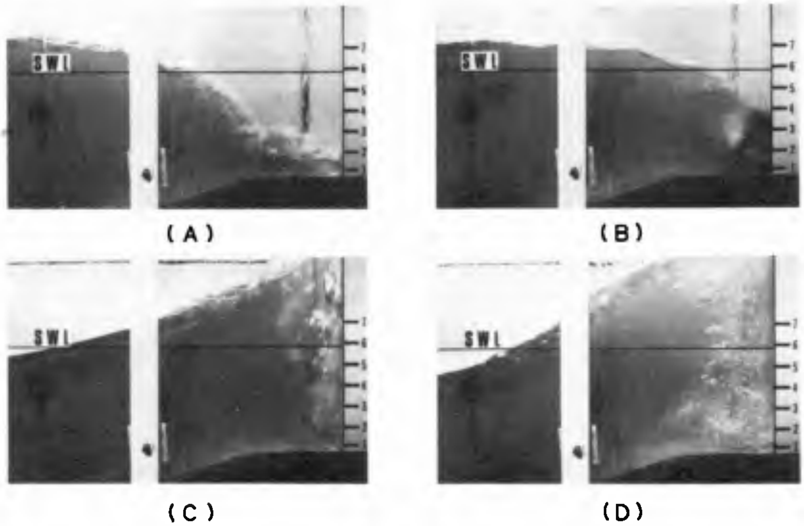


FIG.4 WAVE BREAKING ON SOLID WALL BREAKWATE

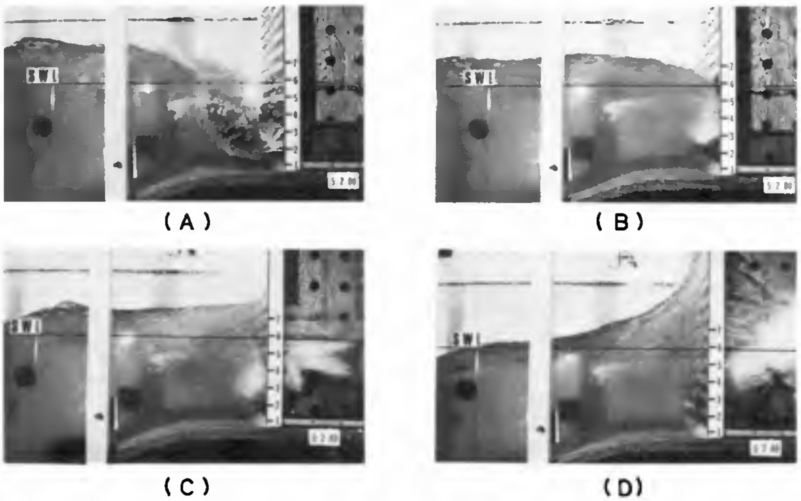


FIG.5 WAVE BREAKING ON PERFORATED BREAKWATER

A wave breaking against the perforated breakwater is shown in Fig. 5. The first photograph shows the wave crest approaching the caisson and the water still draining from the caisson chamber. The water level inside the chamber does not reach level 3 before the crest hits the wall as seen in the second photograph. A small air pocket is formed between levels 1 and 3. The third photograph shows an instant after the initial impact of the wave crest. Water jets have not yet contacted the rear wall and the water surface inside the chamber has been deformed by jets entering between levels 1, 2 and 3. The remaining photograph shows the continued run-up against the front wall of the caisson with water jets entering at higher levels and the extreme turbulence and high air entrainment of the flow against the rear wall.

EXPERIMENTAL RESULTS

Wave impact pressure records are shown in Fig. 6(a) for tests on the solid wall breakwater and the perforated breakwater. The pressure on the solid wall in this particular test reached a maximum of 122 kPa (17.6 psi) at level 4. The pressure records at levels 1, 2 and 3 show the characteristics of compression shocks caused by the presence of an air pocket, that is, a slow rise and fall of pressure. The record at level 4 is somewhat unusual because it apparently is a combination of a sharp pressure increase caused by a hammer shock and the smoother curve of a compression shock. The similarities in the lower four pressure records indicate that in this case the spacing of the transducers was sufficiently close for a relatively accurate determination of the total force on the wall. The pressure records from levels 4 to 7, in which the pressure increase occurs at progressively later times, show the effect of the run-up of the wave crest on the caisson wall.

Pressures recorded in a test on the front wall of the perforated breakwater are shown in Fig. 6(b). The most obvious difference to the previous records is that compression shocks are absent because of the rapid dissipation of air pockets through the perforations in the wall. However, there is a very large hammer shock present at level 5 with a magnitude of 125 kPa (18.1 psi) and a rise time of 0.25 ms indicating that the perforated wall does not completely eliminate the occurrence of high impact pressures. In fact the highest impact pressure recorded in all tests was 142 kPa (20.6 psi) and occurred on the front wall of the perforated breakwater. Fortunately, such high pressures do not occur over a wide area. In Fig. 6(b) the peak pressure is recorded at level 5, but at level 4 this peak has already dropped to one third and at level 6 it is even less. The high frequency oscillations in these records are due to structural vibration of the breakwater. They are not the compression oscillations measured by many investigators

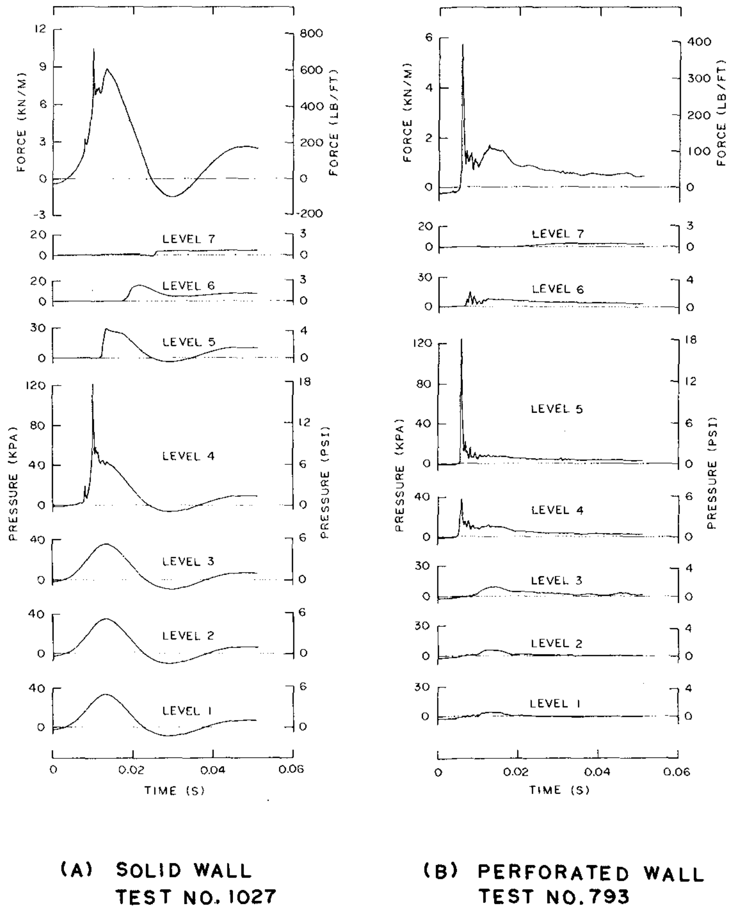


FIG.6 WAVE IMPACT PRESSURE AND FORCE RECORDS

(Mitsuyasu (4) and Ramkema (8)) because such oscillations are generally at frequencies less than 500 Hz, although in the present tests similar low frequency oscillations were occasionally observed.

By integrating the pressure over the vertical height of the caisson, the total horizontal force on the wall is obtained in units of kN per metre width of caisson. Thus, the force records for the solid and perforated walls are also shown in Fig. 6. The effect of the compression shock pressures on the solid wall is to produce a force record with a relatively slow rise time. The maximum force is obviously caused by the hammer shock recorded at level 4, but it is important to note that the peak of the force caused by the compression shock is almost 90% of the maximum force. The total force on the model breakwater which is 1.22 m wide is 12.76 kN (2870 lbs) which emphasizes the importance of the massive supporting structure. The maximum force measured in all tests on the solid wall breakwater was 14.78 kN/m or a total force for the width of the model of 18.03 kN (4050 lbs).

The force record in Fig. 6(b) for the perforated wall test has a peak force due to the hammer shock pressure at level 5 which occurs for a short duration of approximately 1 ms. It should be noted in this case that a correction has been made for the porosity of the wall. Thus, the pressure has been integrated only over the solid area of the wall and the resulting force is therefore only 65% of the force that would have been obtained if the wall contained no perforations.

To determine the total force on the perforated breakwater, it is necessary to take into account the additional pressures on the internal walls of the chamber. However, pressures on the interior side of the perforated wall were not measured, as it is thought that these pressures would be small. In any event, it is conservative to omit these pressures as they act in the opposite sense to those on the other surfaces. Approximately 300 tests were conducted with seven pressure transducers located on the rear wall of the perforated breakwater as shown in Fig. 2(b). An example of the type of pressure records measured is in Fig. 7(a). The initial impact of the water jets produced by the perforated wall is sensed at level 4 on the rear wall. The pressure peaks at levels 5 and 6 are displaced in time slightly and are much smaller in magnitude. In a number of the pressure records measured on the rear wall, the rise times were very fast indeed. In fact several were measured with a rise time approaching that of the sample interval. This obviously means that the sampling rate was not nearly fast enough to measure such pressure peaks accurately. In addition, when the pressure rose so rapidly, the transducer diaphragm vibrated giving an oscillation on the pressure record that was unmistakably due to the excitation of the resonant frequency of the transducer.

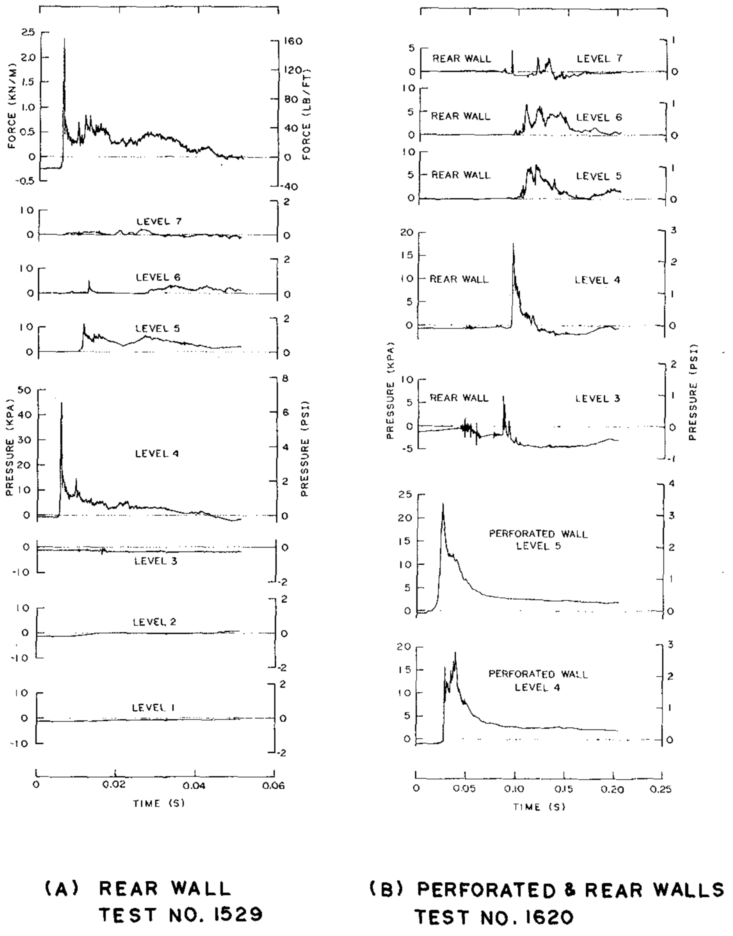


FIG.7 WAVE IMPACT PRESSURE AND FORCE RECORDS PERFORATED BREAKWATER

The pressure records measured on the rear wall of the perforated breakwater were not always as clean as shown in Fig. 7(a). The turbulent fluid motions occurring on the rear wall after the initial wave impact, caused irregular pressure records such as shown in Fig. 7(b). This figure illustrates the time difference between pressure peaks occurring on the two walls of the perforated breakwater. Because pressures could not be measured simultaneously at 14 locations on the perforated and rear walls, an accurate estimate of the total force on the perforated breakwater could not be obtained. However, to help understand how the total force is produced, two pressure transducers were placed at levels 4 and 5 on the perforated wall, and the remaining five at levels 3 to 7 on the rear wall. Triggering of the transient recorders was initiated by either of the two transducers on the perforated wall, and tests were conducted to determine the most suitable sampling rate. The sample interval of 0.05 ms used for the earlier tests was too fast in this case because the water jets did not reach the rear wall within the 0.05 s record length. A sample interval of 0.20 ms was chosen and approximately 60 tests were conducted with the pressure transducers located as described above. A typical set of pressure records is in Fig. 7(b). There is a pronounced time difference between the occurrence of peak pressure on the perforated wall and that on the rear wall. This time difference varies between different records, but it can be estimated as approximately 0.075 s and is the time taken for the jets of water formed by the perforated wall to reach the rear wall. The resulting displacement of pressure records appears to be large enough that as a result of integrating pressure over the two walls, the peak total force on the breakwater would not be significantly greater than the maxima recorded separately on either the front or rear walls. However, further investigations are necessary to obtain accurate estimates of total force on the perforated breakwater. It is important to note that the maximum force on the breakwater will depend on the chamber width, not only because of the effect of wave reflection but because if the rear wall is too close to the perforated wall, peak pressures will occur at approximately the same time.

For comparison of breakwater types, approximately 300 tests were conducted on each of three walls, that is, the solid wall breakwater, and the front and rear walls of the perforated breakwater. For each test the maximum pressure at each transducer was extracted along with the maximum force from the force record. Using these figures, cumulative probability distributions were plotted for the maximum pressures occurring at each level on the walls and also for the maximum forces. Since the transducer elevations for the solid and perforated walls are identical and in order to provide a direct comparison, probability distributions for these two walls are plotted together in Fig. 8. As an exam-

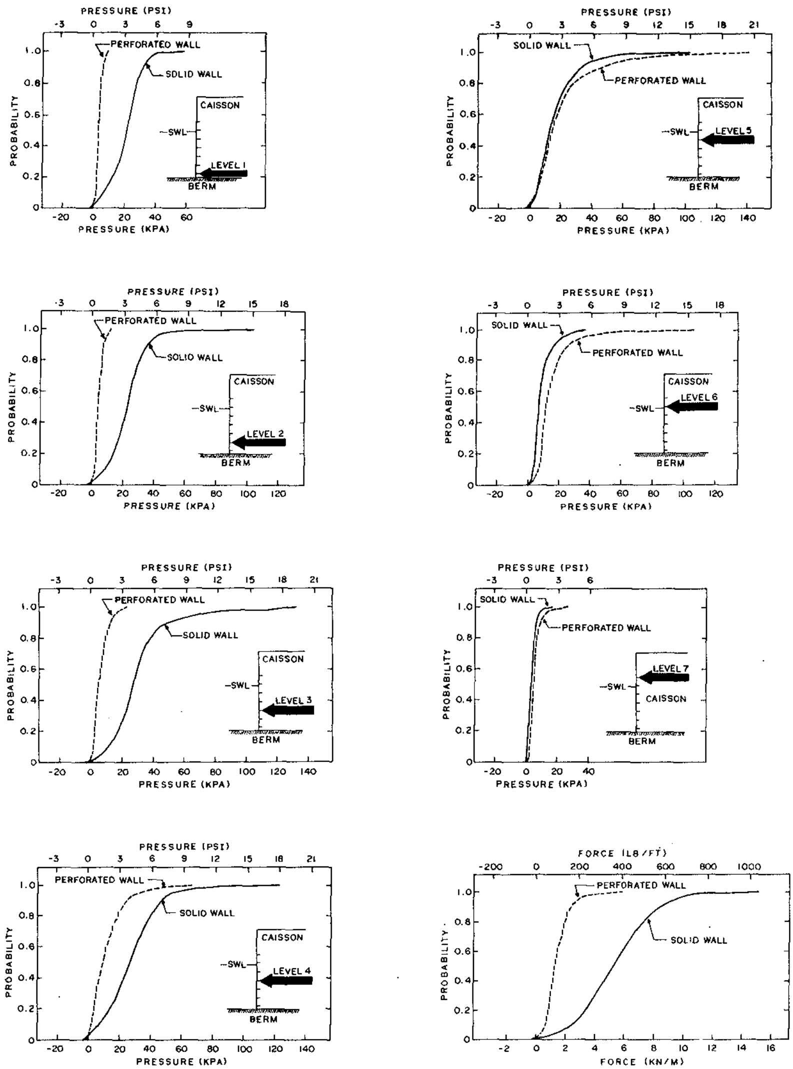


FIG. 8 CUMULATIVE PROBABILITY DISTRIBUTIONS SOLID AND PERFORATED WALLS

ple of how these figures may be read, taking a probability of 0.9 at level 1 on the solid wall shows that 90% of the maximum pressures measured at this location were less than approximately 31 kPa (4.6 psi).

From levels 1 to 4 in Fig. 8, the pressures on the solid wall are considerably larger than those measured on the perforated wall, but from levels 5 to 7 the pressures are larger on the perforated wall. The maximum pressure occurs at level 5 on the perforated wall and is 142 kPa (20.6 psi). However, because the pressures are more localized, the cumulative probability distribution curves show that the force on the perforated wall is very much less than that on the solid wall. At probabilities of 0.5 and 0.9 the maximum force on the perforated wall is consecutively 25% and 29% of that on the solid wall.

Fig. 9 shows the cumulative probability distributions for the maximum pressures measured on the rear wall of the perforated breakwater. These pressures are generally much smaller than those occurring on the front wall; however, peak pressures of up to 100 kPa (14.5 psi) were measured. The probability distribution for force also shows that the force on the rear wall is less than that on the perforated wall. At a probability of 0.9, the maximum force on the rear wall is 58% of that on the perforated wall, and 17% of the force on the solid wall breakwater.

The distributions of maximum pressure in Fig. 10 have been plotted by taking the maximum pressures at probabilities of 0.5, 0.9 and 1.0 for each transducer location from the cumulative probability distributions. The pressure distributions for the three walls are superimposed. The curves for probabilities of 0.5 and 0.9 show that the pressure on the solid wall is usually a maximum at level 3, while that on the perforated wall is usually a maximum at level 5. This is a result of the different characteristics of the breakers striking the two walls. Although the incident wave is the same in both cases, the reflection from the perforated breakwater is about half that from the solid breakwater, causing the wave to trip slightly closer to the perforated wall. The pressure distributions at a probability of 0.9 show pressure peaks similar in magnitude for both the perforated and solid walls, but the solid wall has a higher pressure over a greater area of wall. Pressures are lower at the base of the perforated wall because of the absence of compression shocks. The plot for a probability of 1.0 shows the maximum pressures measured at the pressure transducer locations and so the curves are not as smooth as the previous plots. Also, Fig. 10(d) shows examples of instantaneous pressure distributions. The pressures plotted are from tests 1027, 793 and 1529 for which the pressure records are in Figs. 6 and 7, and are the pressures occurring at the same time as the maximum pressure on the wall which also corresponds to the pressures at the time of maximum force. However, it should be pointed out that in some tests the

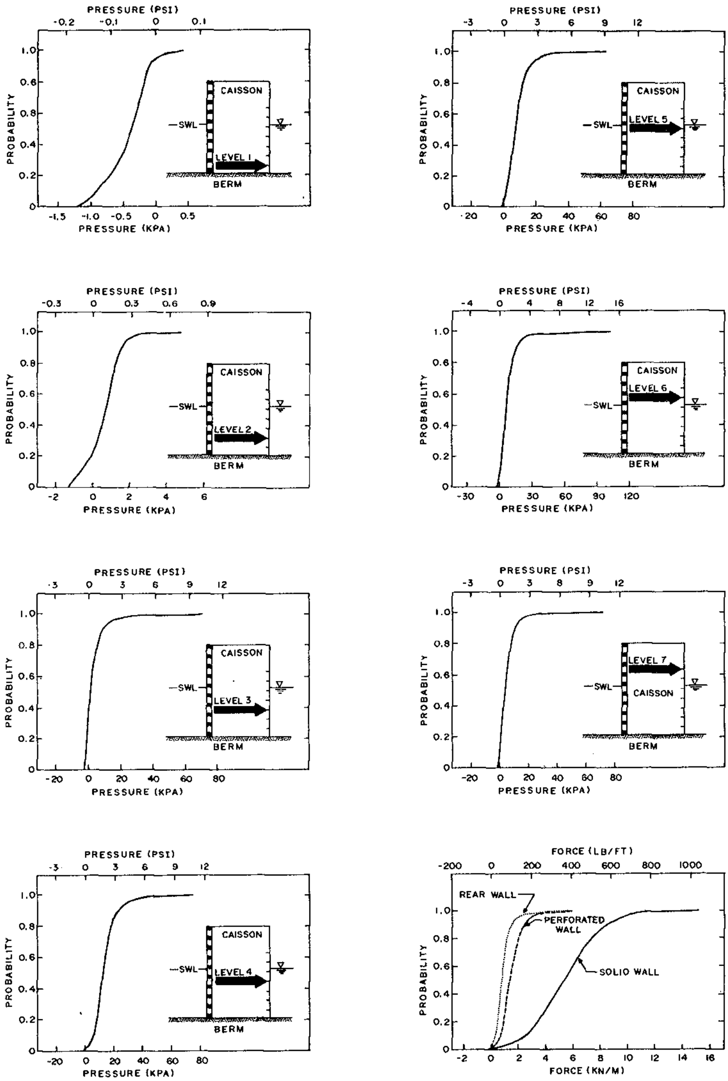


FIG.9 CUMULATIVE PROBABILITY DISTRIBUTIONS
REAR WALL OF PERFORATED BREAKWATER

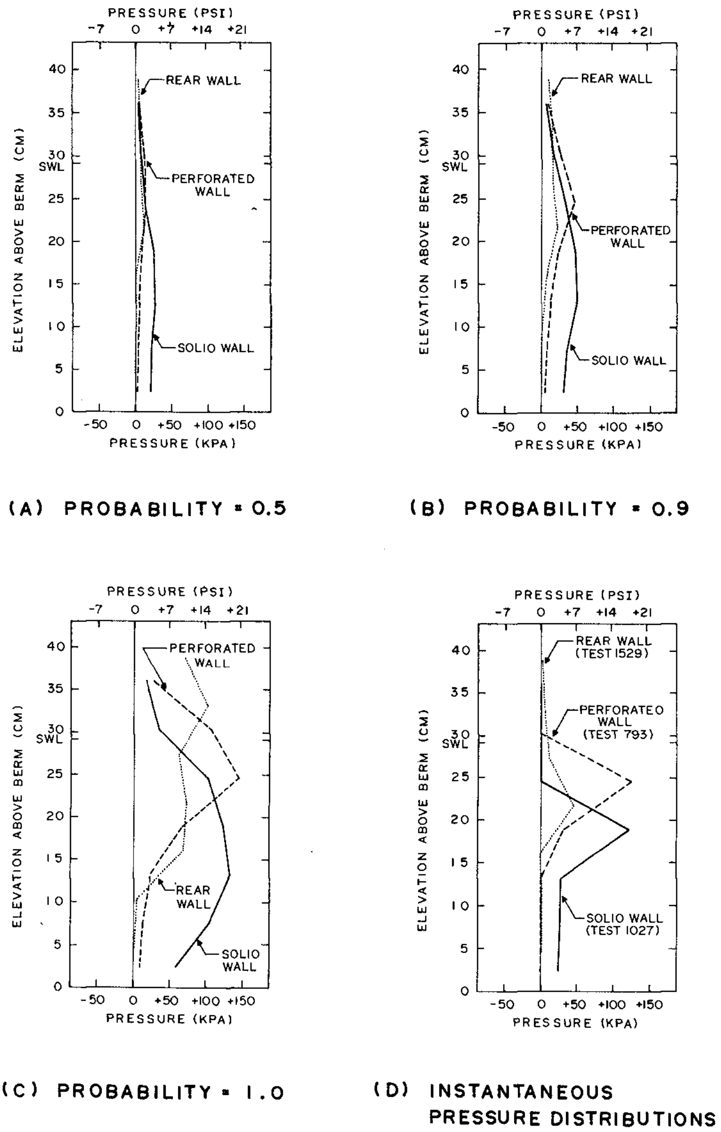


FIG. 10 PRESSURE DISTRIBUTIONS

maximum force occurs at a different time to the maximum pressure and therefore would not result in the same pressure distributions.

RESEARCH PROBLEMS

The experimental results clearly show the importance of good instrumentation, since the peak pressures measured are much higher than in many previous studies in which inferior instrumentation was used. The frequency response of all components must be fast enough that resonance problems are eliminated and pressure peaks are not significantly attenuated. Even with the present equipment, these difficulties were obviously present in a number of tests, particularly on the rear wall of the perforated breakwater. However, it is essential to make a decision as to how fast peak pressures need to be measured in view of the probability that breakwaters are not adversely affected by high pressures if the duration of pressure is extremely brief. Evaluation of the relative importance of high frequency pressures and forces is necessary, but unfortunately the response of breakwaters to wave impact loads has received little attention in the literature. However, breakwater response must be considered using the latest wave impact pressure data before more highly sophisticated instrumentation is deemed necessary.

The estimation of total force on breakwaters as complex as the perforated breakwater, requires numerous pressure transducers to give reasonable accuracy. This could be an unnecessarily expensive proposition when it may be possible to design force dynamometers which are sufficiently stiff for high frequency response. Also an alternative to the use of pressure transducers is the possibility of strain-gauging the structure itself, as described by Graveson et al. (1).

There is still no generally accepted method of scaling impact pressures from model to prototype conditions. The compression laws of Lundgren (2), Mitsuyasu (4) and Ramkema (8) may improve predictions but still rely on measurements in models which are not dynamically similar to the prototype. Consideration should be given to very large model tests and the measurement of impact pressures on existing full-size breakwaters.

The data presented in this paper demonstrates the extreme variability of impact pressures and forces under controlled conditions, when attempting to reproduce exactly the same incident waves. Natural sea states are so much more complex that the frequency of occurrence of high impact pressures in real seas is still largely a matter of speculation.

CONCLUSIONS

1. A large variation was observed in the impact pressures caused by incident waves with a variation in height of only ±4% at the most. For example, extremes of maximum pressure occurring at a single location on a breakwater were as much as ten times the average peak pressure. Means and standard deviations (S.D.) of maximum pressures and forces are as set out in Table I.

TABLE I

MEANS AND STANDARD DEVIATIONS

OF MAXIMUM PRESSURES AND FORCES

Pressure (kPa) at Level	Solid Wall		Perforated Wall		Rear Wall	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	21.2	9.6	3.4	2.0	-0.4	0.3
2	23.9	11.6	4.5	2.5	0.7	0.8
3	32.6	20.6	7.1	4.8	3.6	6.2
4	29.8	17.2	12.5	10.7	14.7	8.2
5	17.8	13.0	22.2	19.9	9.2	6.9
6	9.2	5.9	16.4	11.7	9.5	9.6
7	3.9	2.4	6.0	3.3	5.7	6.0
Force (kN/m)	5.5	2.4	1.6	0.8	0.9	0.6

2. The perforated wall virtually eliminated compression shocks caused by the entrapment of air pockets.
3. Although impact pressures were generally lower on the perforated wall than on the solid wall caisson, there were locations where the pressures recorded were higher than on the solid wall. In fact, the highest pressure recorded in all tests, that is 142 kPa (20.6 psi), was measured on the perforated wall. However, the frequency of occurrence of high pressures on the perforated wall was lower than that on the solid wall.
4. Peak pressures measured on the rear wall of the perforated breakwater were significantly less than those occurring on the front wall and occurred at a time displaced from the peaks on the front wall dependent on the chamber width.
5. The mean force measured on the perforated wall was only 28% of that on the solid wall caisson. The total force on the perforated breakwater was not measured but is estimated to be considerably less than the force on the solid breakwater.

6. This experimental study has enabled an evaluation of the advantages of the perforated breakwater over the solid wall breakwater, but further investigations are necessary before it can be concluded that the structurally complex perforated caisson would be preferable to other alternative caisson designs.

ACKNOWLEDGEMENTS

Although the task of high speed transmission of data from two transient recorders a distance of 120 m to a digital computer, may not seem difficult, it caused much grief particularly for Arnold Wiegert and Tony Edwards. The authors appreciate their perseverence in developing a data acquisition system which made possible the rapid processing of vast quantities of experimental data.

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