CHAPTER 195

Scale effects of wave impact pressures on cob armour units

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Abstract

Froudian scaling laws are often used to convert model wave impact pressures to prototype scale. However, although many model studies have been performed in the past, the effects of scale on the magnitude and duration of wave impact pressures have yet to be determined.

Wave impact pressures were monitored on a Cob armoured breakwater at LaCollette Harbour, Jersey, UK, throughout the Winter of 1993/94. In addition, a 1:32 scale model of the prototype breakwater was constructed at the University of Bristol and subjected to a similar wave climate as was measured at prototype scale. A comparison of the pressures measured at the 2 scales has allowed the scale effects present in the wave impact process to be determined.

Introduction

Wave impact loading has long been of interest to designers and researchers, as it can be the most severe form of loading on coastal structures (e.g. Rouville 1938). Despite this, there is still considerable uncertainty about the magnitude of these loads and the physical processes which govern them. Although many model studies have been carried out, the scale effects present in the impact process remain uncertain.

Traditionally, Froudian scaling is used to convert model wave loads to prototype scale, as it is generally accepted that wave loads are gravity dominated. However, during the wave impact process the compressibility of the wave front may be the dominating factor in determining the magnitude of the pressure generated (Führböter 1988, Kamel 1970). Many researchers have recognised that small scale experiments may overestimate the pressures measured at prototype scale when Froudian similarity is used. Very little research, if any, has adequately shown this to be the case by carrying out experiments at model and prototype scales and comparing the results.

In this study, impact pressures were measured on a typical hollow cube armour unit (a Cob unit) at LaCollette Harbour, Jersey. In addition, a 2-dimensional model of the breakwater at LaCollette Harbour was constructed at 1:32 scale in the small wave flume at the University of Bristol. The wave and tidal conditions measured at LaCollette Harbour were recreated as closely as possible in the laboratory. Any differences in the pressures measured at model and prototype scales are likely to be due to the scale effects present in the impact process.

Prototype pressure measurement

LaCollette breakwater was constructed in the early 1970s, and forms part of the outer coastal defence of St. Helier Harbour, Jersey. The breakwater is protected by Cob armour units, placed in a single layer, protecting a rubble core. The main axis of the breakwater runs WNW to ESE, and is subjected to wave loading from the South-west. A typical cross-section of the breakwater is shown in Figure 1.

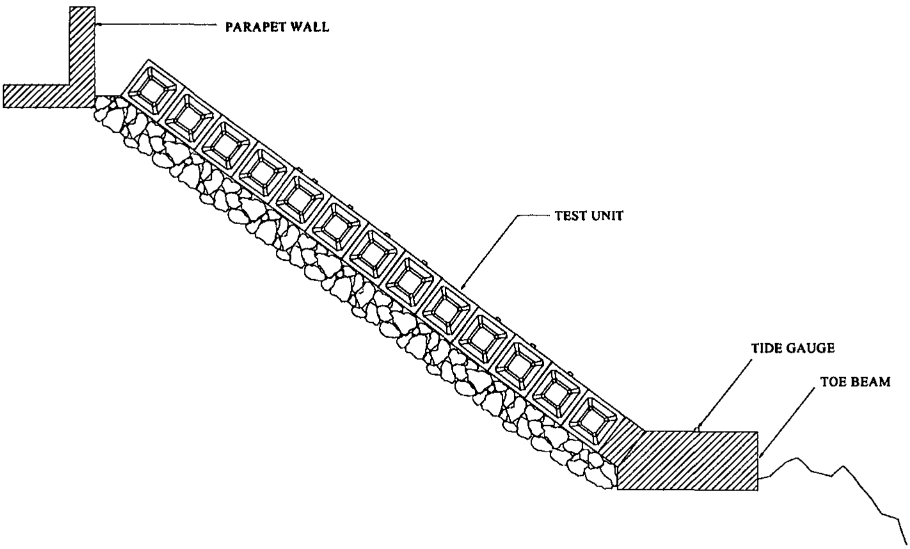

Figure 1: Typical cross-section of LaCollette Breakwater, Jersey, UK

Wave impact pressures were measured at 8 points on the surface of a single unit on row 5 of the breakwater. The unit was chosen as it received wave impact loading on every tide whilst being far enough up the breakwater slope to be relatively unaffected by the toe beam. Data Instruments AB pressure transducers were used to measure impact pressures. The transducers were placed flush with the surface of the Cob unit to ensure that the pressures measured were the same as those experienced by the unit. The pressures were sampled at 500Hz, which was adequate to ensure the vast majority of impact pressures were accurately captured. Wave height and tidal level were measured at the breakwater toe.

The long logging periods and the high sampling rates involved in measuring wave loads on a prototype breakwater can mean a huge volume of data can be collected, with relatively few impact 'events' occurring during that time. Intelligent monitoring techniques were used in an attempt to limit the volume of data stored whilst retaining all significant impact data. This was achieved by sampling pressure data for 1 hour as the tidal level increased towards the instrumented unit, and for 1 hour as the tidal level fell back below the unit. The logging period was sufficiently long to ensure that all impacts which occurred on the instrumented unit were measured. An analysis program was then implemented to detect the wave impacts measured during the logging period and to determine the magnitudes and rise times of the pressures. The details of each impact were then stored in a text file with the time and the tidal level at the time of impact. This process greatly reduced the amount of data stored whilst retaining all useful impact pressure information.

Pressure and wave data was monitored almost continuously between November 1993 and February 1994.

Model Pressure Tests

A 2-dimensional model of the LaCollette breakwater was constructed at 1:32 scale. A 1:50 slope was constructed in front of the breakwater, representing the average slope of the bathymetry at Jersey. Impact pressures were measured on the top limb of the Cob unit, as this was the position at which the largest pressures at prototype scale were measured. The pressure on the top limb was sampled at 10kHz. This is a faster sampling rate (to scale) than that used at prototype scale, as it has previously been found that wave impact pressures measured in the laboratory, using fresh water, can have an extremely short duration (e.g. Oumeraci 1993, Kirkgöz 1995). The pressure transducer used was the EP-101W-50 transducer supplied by Entran Ltd., chosen for its excellent frequency response and small size. The diameter of the sensing face roughly represented the diameter of the prototype scale transducer used in Jersey. The size of the sensing face of a pressure transducer is likely to affect the magnitude and rise time of the impact pressure measured, resulting in smaller magnitude, longer duration pressures being recorded. If accurate scaling between model and prototype scales is to be achieved it is likely that the linear dimensions of the transducer face should be subject to the same scale factor as the rest of the model. If inappropriate transducers are used then the effects of scale in the impact process may not be detected (e.g. Führböter 1986).

The model breakwater was subjected to similar random wave conditions as those measured at LaCollette Harbour. The waves were always applied normal to the breakwater, which was not necessarily the case for the prototype structure. Despite this, it is thought that the waves applied to the model were a good representation of the prototype wave climate.

Prototype results

The site deployment at LaCollette Harbour was extremely successful. More than 4000 impact pressures above 1m head of water were recorded, with more than 3000 impacts measured on the vertical face of the top limb. Figure 2 shows pressures measured on instrumented unit caused by a typical wave - transducer 6 was situated on the vertical face of the top limb. In this case transducer 6 has measured an impact pressure equivalent to 3.5m head of water, whilst the other transducers have measured 'quasi-hydrostatic' pressures. The impact pressures measured exhibited typical wave impact features: a rapid rise in pressure (with a rise time generally below 30ms) as the wavefront impinged on the unit, followed by a longer duration pressure formed as the unit is submerged.

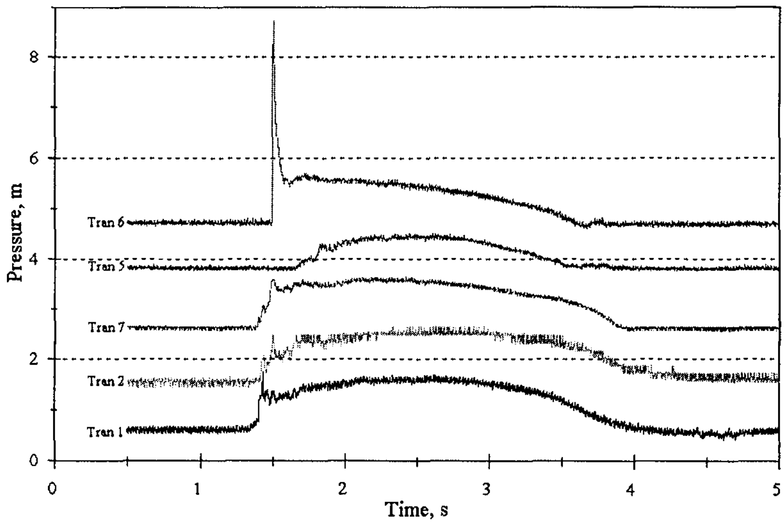

Figure 2: Typical pressure traces measured at prototype scale

All the impact pressures measured throughout the winter on the vertical face of top limb are plotted against probability of non-exceedence in Figure 3. The pressures followed a log-normal distribution very closely. The largest pressure measured was 14.6m head of water. The excellent correlation with a log-normal distribution suggests that more extreme impact pressures may be accurately predicted by extrapolating the graph.

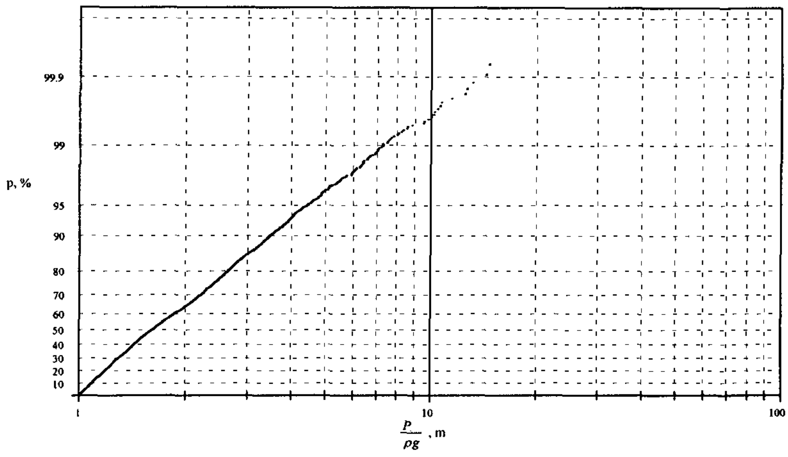

Figure 3: Log-normal distribution of impact pressure, prototype

The distribution of the rise times measured for each impact, plotted on log-normal axes, is shown in Figure 4. It can be seen that impact rise time follows a log-normal distribution well. Approximately 30% of the impact pressures measured had a rise time less than 10ms.

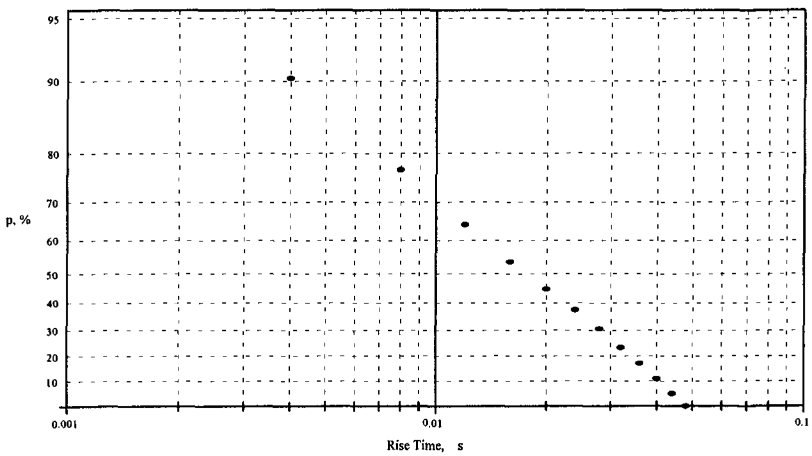

Figure 4: Log-normal distribution of impact pressure rise times, prototype

Model Test Results

The pressure transducer used in the model test programme performed excellently, and was found to be capable measuring the very rapid impact pressures found at small scales. The impact pressures measured exhibited similar features as those found at prototype scale. A typical impact pressure is shown in Figure 5. The pressure rise times were often very short, with many impacts being lower than 0.5ms.

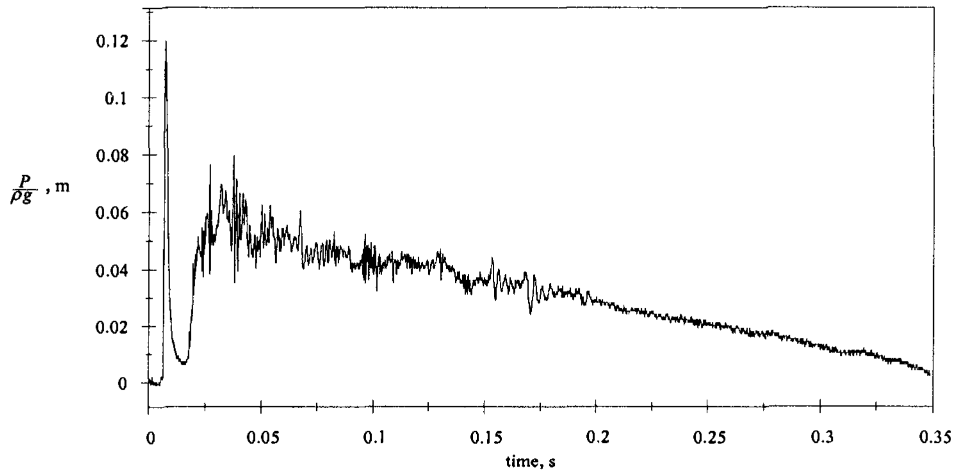

Figure 5: Typical impact pressure trace at model scale

The pressures measured during each test were plotted on statistical axes. It was found that a log-normal distribution accurately described the impact pressures measured in each test. The rise times of all the impact pressures measured during the test programme are shown in Figure 6. Log-normal axes have been used. It can be seen that the impact pressure rise times are accurately described by a log-normal distribution. It can also be seen that approximately 50% of the pressures measured exhibited a rise time of less than 1ms. A small number of impacts, approximately 1%, had a rise time of less than 0.1ms, equal to the sampling interval used throughout the test programme. Ideally, a higher sampling frequency would have been used so that even the most rapid impact pressures that occurred could have been accurately captured. However, an increase in the sampling rate would have lead to increases in the already large volume of data recorded, and in any case the percentage of impact pressures which were affected by the sampling rate was small.

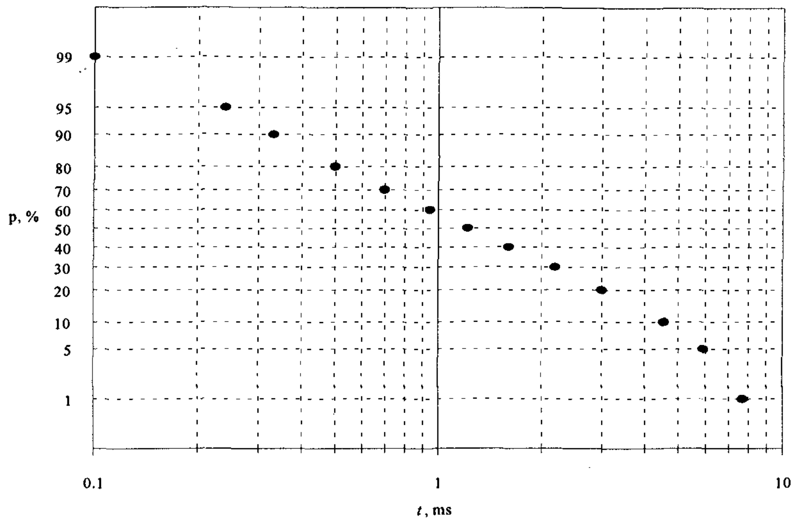

Figure 6: Log-normal distribution of impact pressure rise times, model

Scale Effects

The breakwater at LaCollette Harbour was modelled as closely as possible at 1:32 scale. The wave conditions measured at Jersey were reproduced accurately in the laboratory. The size of the pressure transducer was scaled as accurately as possible from prototype to 1:32 scale. Hence it can be assumed, with reasonable confidence, that any differences in the impact pressures measured at model and prototype scales are due to the scale effects present in the impact process.

It has generally been predicted by previous researchers (e.g. Führböter 1984) that Froudian scaling *overestimates* the magnitude of prototype impact pressures and *underestimates* their rise times. These results have been found in this research. It may be expected, therefore, that the magnitude of wave impact impulses will scale relatively accurately using Froudian scaling, since impulse is assumed to be the product of pressure magnitude and rise time.

Impulse data collected at model and prototype scale, scaled to prototype using Froudian scaling, is shown in Figure 7. The impulses are plotted on log-normal axes. It can be seen that for low probabilities of non-exceedence the values of model and prototype impulses differ significantly, with the model results underestimating the impulses measured at prototype scale. For more extreme impulses, however, the model and prototype data correlate well, suggesting that for the most severe impact events Froudian scaling can reasonably be used to predict prototype impulses from small scale data. Impulse is related to the wave momentum destroyed in the impact process. Wave momentum can be accurately scaled using Froudian similarity, and hence the value of impulse in the impact process can be modelled using Froudian scaling. The difference in data at small values of impulse may be caused by the higher sampling rate (to scale) used in the laboratory, which allowed impact pressures with an extremely short rise time to be measured.

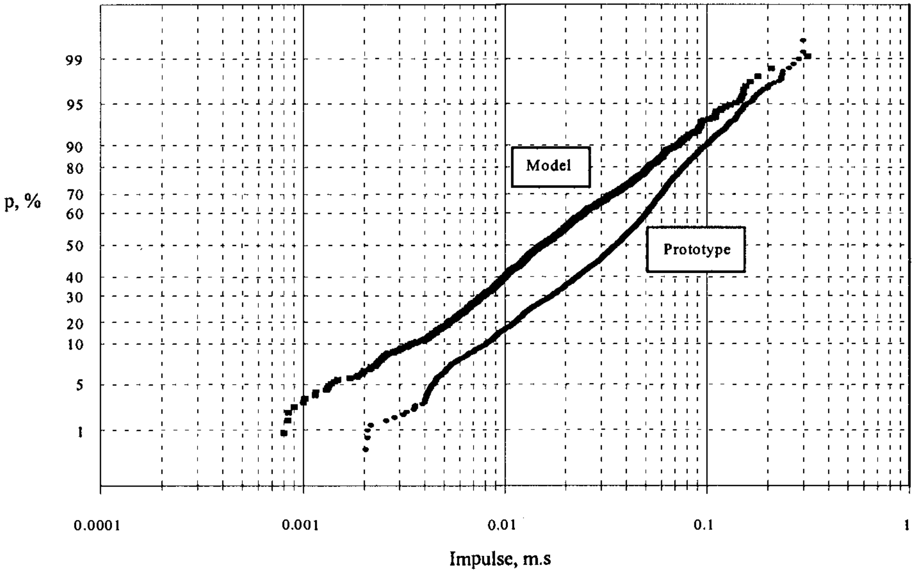

Figure 7: Comparison of impact impulses using Froudian scaling

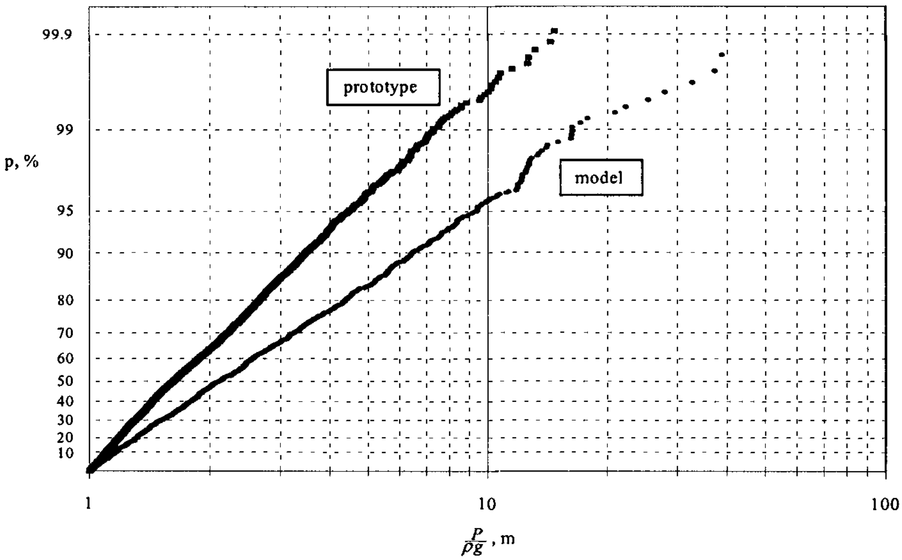

Figure 8: Comparison of pressure magnitudes using Froudian scaling

The distribution of all the impact pressures measured at prototype and model scale is shown in Figure 8. The model pressures have been scaled to prototype using Froudian similarity. It can be seen that the pressures at both scales follow a log-normal distribution extremely well. The distribution of pressures both start at 1m head of water as this was used as the threshold pressure magnitude for both scales. The pressures measured in the laboratory were generally larger than those measured at prototype scale. Although the magnitude of the pressures are different, the excellent correlation in the type of distribution data from both scales follow suggests that very similar processes are present at both scales.

The difference in the maximum pressures likely to occur at model and prototype scales increases as the likelihood of occurrence decreases. This is illustrated below:

Probability of non-exceedence, %	Model pressure, m	Prototype pressure, m	P_{model}/P_{proto}
50	2.13	1.68	1.27
90	6.35	3.26	1.80
99	18.1	7.20	2.51
99.9	40.4	12.50	3.24

As the impacts become more severe then the model pressures increasingly overestimate the magnitude of the pressure which will occur at prototype scale. The prototype and model pressures may be related, once Froudian scaling has been used, by the empirical equation:

$$\frac{P_{prototype}}{\rho g} = \left(\frac{P_{\text{mod}\,el}}{\rho g}\right)^{0.684}$$

It may be suggested that as the impact loading becomes more severe the effect of wave compressibility dominates over Froudian (gravity) forces. Hence, the increasing differences between model and prototype pressures is due to the increasing effect of wavefront compressibility on the impact process.

The largest non-dimensionalised pressure *likely* to occur in 100 waves, denoted by $P_{100}/\rho g H_s$, has been used to compare results from different model tests as well as being used in the prototype analysis. The value of $P_{100}/\rho g H_s$ is a good measure of the severity of wave impact loading, as it is a function of both the frequency of occurrence and the statistical distribution of the pressures measured. The effect of the still water level on the value of $P_{100}/\rho g H_s$ is shown in Figure 9. It can be seen that, for both scales, the most severe wave impacts occur when the still water level is below the level of the transducer. The pressures measured in the laboratory are much greater than those measured at prototype scale at this still water level, suggesting that compressibility effects are most important for the most severe loading. As the water level rises towards the transducer then the pressures become less severe, with the pressures measured at both scales converging. This suggests that compressibility effects are less than Froudian effects for less severe impact pressures.

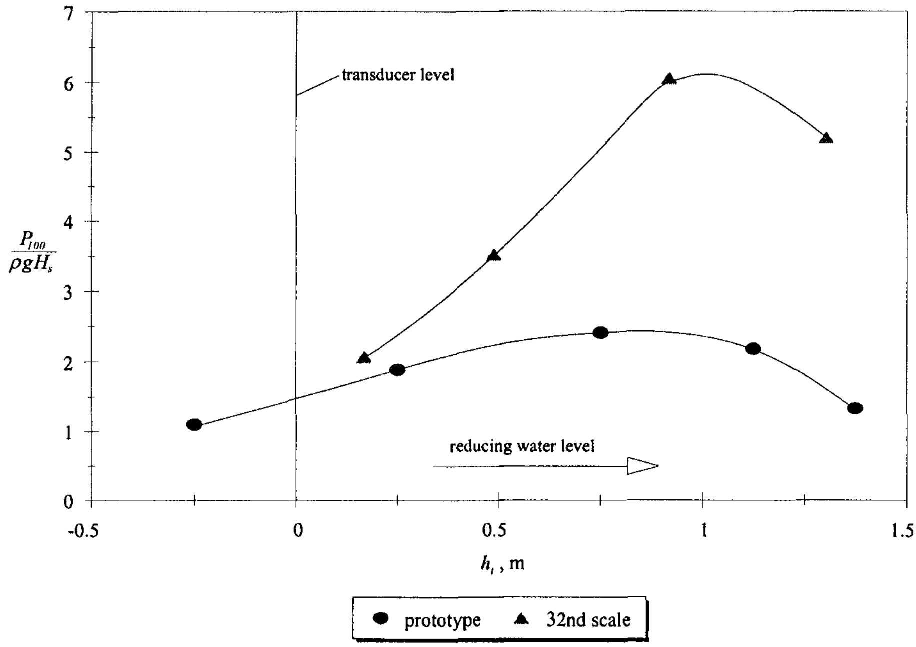

Figure 9: $P_{100}/\rho g H_s$ vs. relative water depth, h_t

It has been suggested previously (e.g. Oumeraci 1991) that impact pressures measured at small scales tend to have shorter rise times than would have been predicted using Froudian scaling. Figure 10 shows the percentage of impacts which occurred for given rise times. The data has been scaled to prototype scale using Froudian similarity. The results from both scales can be directly compared as the same definition of an 'impact event' was used at both scales. It can be seen from Figure 10 that a much higher proportion of impact pressures measured at 1:32 scale have short rise times compared to those measured at prototype scale.

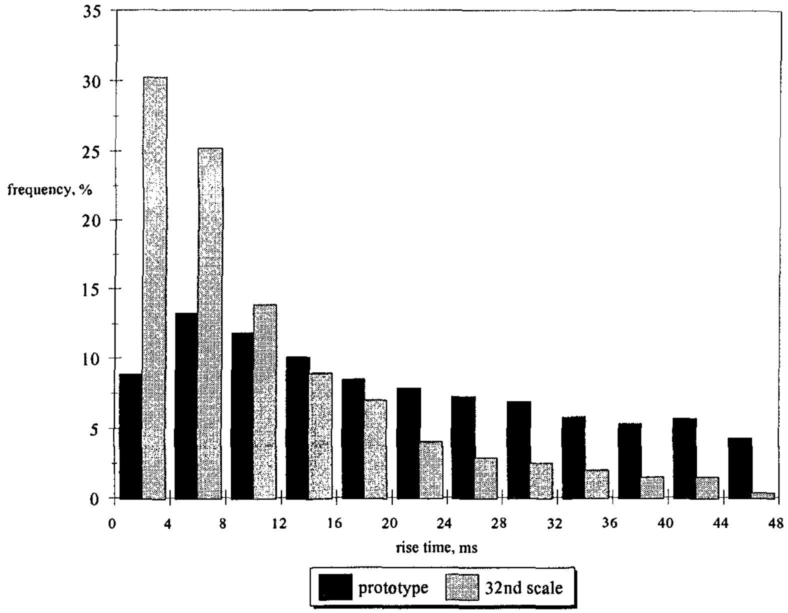

Figure 10: Comparison of impact pressure rise times using Froudian scaling

Figure 10 shows that great care must be taken when performing model wave impact tests. For example, it may be decided in the design of a coastal structure that impact pressures with a rise time below 5ms (for example) need not be considered, as it might be assumed that pressures of a shorter duration will have little effect on the prototype structure. However, Figure 10 shows that if model tests were carried out to determine the pressures likely to occur at prototype scale, rise times of less than this value (scaled down using Froudian scaling laws) should be considered. The short rise times which occur at small scales represent longer duration pressures at prototype scale which may be structurally important.

Conclusions

It has been shown that the physical effects present in model wave impact tests are similar to those found at prototype scale. For example, typical impact pressure traces are similar, the relationship between impact severity and still water level is similar, and pressures from both scales accurately follow a log-normal distribution. However, significant scale effects present in the wave impact process have been found:

The use of Froudian scaling to convert model impacts to prototype scale is likely to overestimate the pressures which will occur on the structure by up to 500%. The error in the predicted pressures increases as the severity of the impact loading increases.

The rise times of impact pressures are underestimated at model scales if Froudian similarity is used. The reduced compressibility of the wavefront at model scale leads to sharper impact pressures with short rise times and large magnitudes. The reduction in compressibility is caused by less air entrainment present in the model waves, which in turn is caused by the use of fresh water in the laboratory as well as differences in the Weber number at the two scales.

Impact impulses scale reasonably well when Froudian scaling is used. The impulse generated in the impact process is principally related to the momentum of the wave, which may be accurately scaled using Froudian similarity.

A relationship between model and prototype pressures has been deduced. This allows Froudian scaling to be used to convert model data to prototype scale, as long as the appropriate adjustment is made to take scale effects into account.

References

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