IMPACT LOADINGS ON VERTICAL WALLS IN DIRECTIONAL SEAS

N.W.H. Allsop & M. Calabrese *

ABSTRACT

Recent research under PROVERBS has demonstrated that wave impact loads can cause damage or failure of caisson or blockwork breakwaters. Research studies of wave loadings, pulsating or impact, have generally used only 2 - dimensional wave flume experiments, and so most design methods are strongly biased towards 2-d .

This paper describes results from 3-dimensional wave basin tests by Universities of Naples, Sheffield, and HR Wallingford in the UK Coastal Research Facility (CRF). The aim of the study was to quantify effects on wave pressures or forces of oblique or short-crested wave conditions on simple vertical or composite breakwaters.

This analysis has focussed particularly on wave impact loadings as earlier 2-d tests at Wallingford showed them to be potentially severe for some combinations of foundation level and relative wave conditions. New reduction factors are presented.

1. INTRODUCTION

Hydro-dynamic wave loads constitute the main design loading for overall stability of a vertical breakwater. Many wave loads are slow-acting or pulsating, but wave impact loads can be very intense. Research in the UK with support from the EU MAST project PROVERBS has demonstrated that wave impact loads, despite their short durations, can cause failure of caisson or blockwork breakwaters.

Design wave forces on caisson breakwaters and related structures are usually derived as quasi-static loads using methods by Goda (1985) which calculate equivalent loads for sliding. Recent studies on failures of vertical breakwaters by Oumeraci et al.

* Professor (associate) University of Sheffield, c/o HR Wallingford, Howbery Park, Wallingford, Oxon OX10 8BA, U.K. e-mail: w.allsop@sheffield.ac.uk

Assist. Prof. Dr.-Ing., Dipt. di Ing. Idraulica ed Ambientale, Università di Napoli Federico II, Via Claudio 21, 80123 Napoli, Italy, e-mail: calabres@cds.unina.it

(1995) Allsop & Vicinanza (1996), Allsop et al (1996a, b) and others have demonstrated that damage or failure can be caused by wave impacts. These may be triggered by particular combinations of waves and water levels, bed slopc, berm and wall geometries, some of which have been identified in studies by Allsop et al. (1996b), Allsop & Vicinanza (1996) or Calabrese et al. (1996).

Most studies of wave loadings, pulsating or impact, have used 2-dimensional (2-d) wave flume experiments as it has been assumed that long-crested normal wave attack is most damaging. Design methods are therefore strongly biased towards 2-d wave attack, and relatively little information is available on 3-dimensional effects. There are however strong reasons to review this, and to investigate the stability of such structures under 3-d wave conditions:

a) Real waves are highly irregular in space and time, so along particular lengths of wall, thc instantaneous widths of wave fronts are often relatively short.
b) Main breakwaters are often orientated oblique to the largest waves so that the worst wave forces act over only a short length of the structure at any one time.
c) Wave impact pressures are limited spatially, even under long-crested waves, but reduction of effectivc force with length of element has not been quantified.

Methods to evaluate wave forces under oblique and/or short-crested waves have been suggested by the empirical methods of Goda (1985) or theoretical methods of Battjes (1982). Battjes' method estimates wave force reduction coefficients in relation to: angle of attack, β; directional dispersion index, n; and relative length of caisson or wall element L_c/L, where the element length is L_c and wavelength is L. Experiments by Franco et al. (1996), measured effects of long- and short-crested waves with $\beta \leq 60°$ and standard deviation of spreading $\leq 30°$, but did not record impact loads.

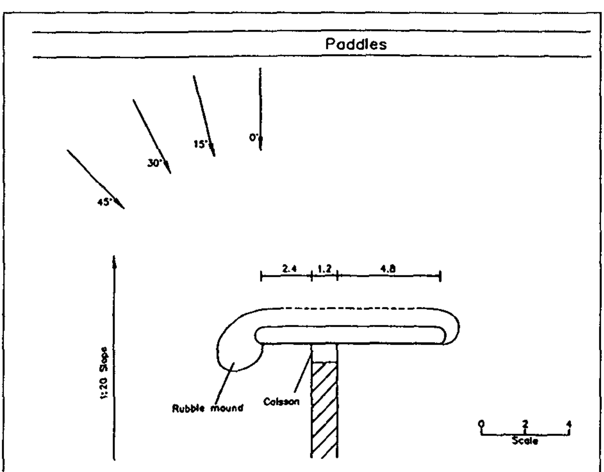

Figure 1 Test set-up in CRF

In contrast, important objectives of the studies summarised here, were to:
a) Identify conditions which lead to impulsive loads on vertical breakwaters under oblique or short-crested waves;
b) Evaluate the influence of wave obliquity, β, and of directional dispersion, n, on the intensity of the wave load;
c) Assess the influence of multi-directionality on the distribution of loads along the wall under pulsating and impact wave conditions.

2 EXPERIMENTAL STUDY

2.1 Test facilities

These experiments were conducted in the UK Coastal Research Facility (CRF), a large wave and current basin 54m by 27m equipped with 72 paddles to give oblique long-crested or short-crested waves. The model caisson sections were placed in a line in the basin, parallel to the paddles, and on a 1:20 bed slope, see Figure 1.

Oblique or short-crested random waves were produced by adjusting the wave paddle control signals. Absorbing beaches behind the structures reduced wave reflections, and extension walls reduced diffraction distortions. Four different breakwater types were tested: Structure 0 was a simple vertical wall and Structures 1-3 were composite walls with mounds of different geometry. The structures were closely based on those tested by Allsop et al (1996) and McKenna (1997), and used the same measurement caisson, but fitted with eighteen pressure transducers in 3 vertical rows, see Figure 2.

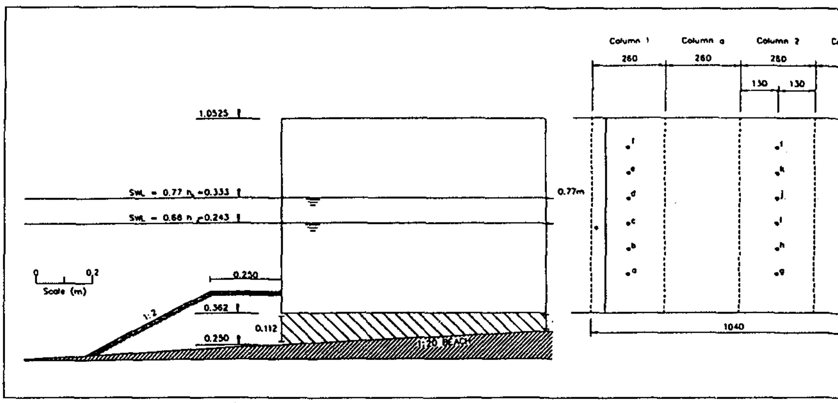

Figure 2 Test caisson and pressure transducers

Most tests were run for 500 waves, but some were repeated for 2000 waves. For Structures 1-3, three different relative height / depth of rock armoured berm in front of the caisson were studied. Test conditions for Structure 0 covered the range tabled below, but restrictions on basin availability limited tests for other structures:

	$s_m = 0.02$	$s_m = 0.04$	$s_m = 0.06$
H_s (m)	T_m (s)	T_m (s)	T_m (s)
0.10	1.8	1.3	1.0
0.20	2.5	1.8	1.5
0.25	2.8	2.0	1.6

2.2. Test Programme

Tests on each structure were conducted in three phases:

a) long-crested waves with $\beta = 0°$;

b) long-crested oblique waves with $\beta = 15°$, 30° and 45°;

c) short-crested waves, β=0° and directional dispersion index of n = 2 or n = 6.

2.3 Pressure Signal Analysis

Pressures were summed by trapezium rule to give horizontal forces on each column, F_h at each timestep (at 400 Hz). The time signal of pressures at static water level was divided into "events" using parameter and threshold definitions developed within PROVERBS, and analysis methods by Calabrese et al (1997) and Allsop et al (1996). Forces and moments were calculated at each timestep. Fictional pressures or forces on imaginary column "a" were interpolated between columns 1 and 2.

Maximum wave forces on each column ("1", "a", "2", "3") were found for each event. Individual column forces were considered as representative of wave loads, $F_h(0)$, acting on an infinitesimal segment, $L_c = \delta l$, of the wall. To simulate longer caissons, average wave forces were calculated for combinations of columns ("2+3"; "1+a+2"; "a+2+3"; "1+a+2+3") giving wave loads, $F_h(\mathrm{n})$, for each caisson length, L_c:

F_h (n)	Caisson length, L_c (m)	Adjacent column combinations
F_h (0)	δl	1; 2; or 3
F_h (1)	0.260	2+3
F_h (2)	0.520	1+a+2; or a+2+3
F_h (3)	0.780	1+a+2+3

For each caisson length, forces, $F_h(\mathrm{n})$, were ranked in magnitude and the average of the 1/250 highest forces, $F_{h1/250}(\mathrm{n})$, was evaluated. For the overall analysis of forces, values of $F_{h1/250}(\mathrm{n})$ for n = 0, 1, or 2 were calculated by averaging across the columns used. This average has been used in the analysis below, except when relative peak to average values are discussed in section 3.2.

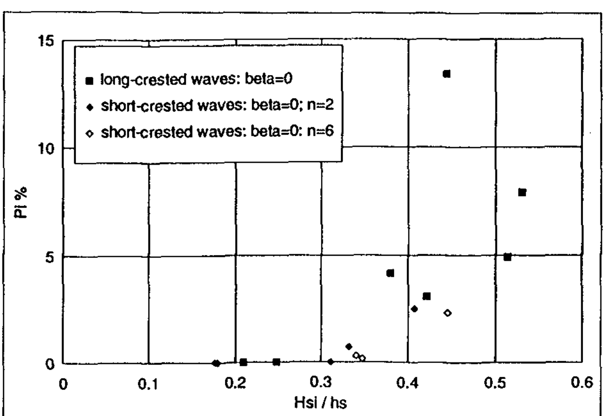

Figure 3 Effect of short-crested waves on impacts

3. RESULTS

3.1 Occurrence of impacts

The aim of the initial analysis was to identify conditions which lead to impulsive loads and to evaluate their occurrence P_i. Work by Allsop et al (1996) and McKenna (1997), distinguished between "pulsating" and "impact" loadings using probability distributions of wave forces. Individual forces were ranked and plotted on Weibull axes, and any significant departure above the Weibull line was taken as indicating an impact. The probability level at which forces started to diverge from the Weibull line gave percentage of impacts P_i (%) for each column of transducers.

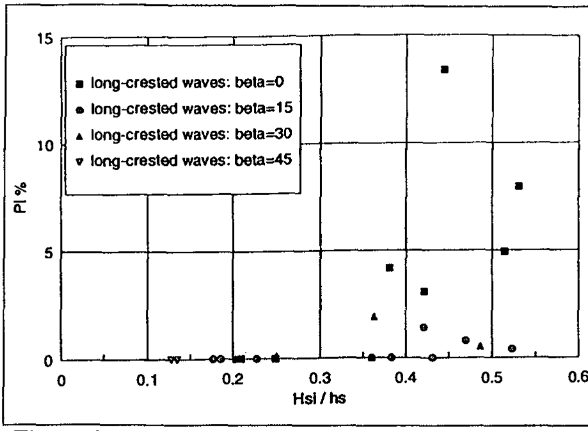

Figure 4 Effect of oblique wave attack on impacts

This paper generally discusses average values of P_i across three columns. Evaluations of P_i were checked by evaluating impacts from video recordings of the experiments.

<u>Simple vertical wall</u> Impacts under <u>long-crested normal</u> waves were compared with results from 2-d tests by Allsop et al (1996) with only slight variation. The onset of impacts was reached at about $H_{si}/h_s = 0.35$ in both experiments for long-crested waves at β=0°. For <u>short-crested</u> waves at β=0°, P_i again showed no changes in comparison with long-crested waves. Again, impacts begin at conditions close to $H_{si}/h_s = 0.35$, although there are some indications in Figure 3 that impacts do not increase as rapidly with increasing H_{si}/h_s in short-crested waves as for long-crested waves.

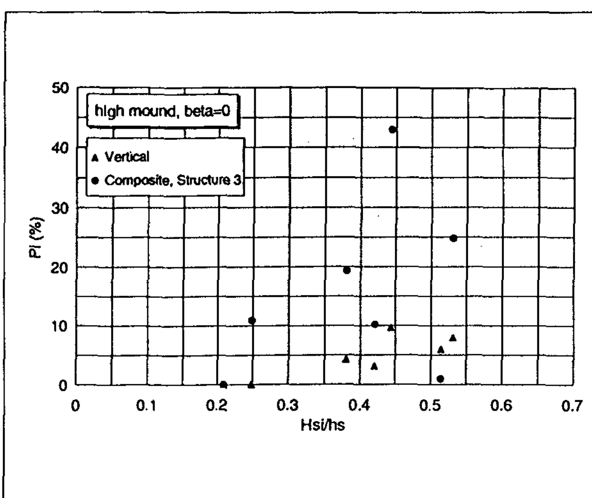

Figure 5 Effect of H_{si}/d on P_i, high mound

For <u>oblique long-crested</u> waves, β = 15°, 30° and 45°, there were much fewer impacts than for normal long-crested waves, Figure 4. For larger waves, $H_{si}/h_s > 0.35$, impacts were less frequent with oblique waves than for normal attack, β=0°.

These tests were in intermediate depths: $0.05 \leq h_s/L_{pi} \leq 0.18$. Conditions which gave impacts fell in $0.03 \leq s_p \leq 0.06$. Lower steepnesses, $s_p = 0.02$, showed no impacts.

Composite walls, low and high mounds

Addition of even a small rock berm or slope in front of a simple wall has been shown to increase substantially the number and severity of impacts. In the previous 2-d study, Allsop et al (1996) argued that the onset of impacting for low mounds, $0.3<h_b/h_s<0.6$, occurred at $H_{si}/h_s = 0.35$, but that P_i increases rapidly at higher values of H_{si}/h_s. Results from long-crested waves at $\beta=0°$ from these tests support the earlier conclusions, , but suggest that impacts for low mounds might start to occur at lower relative wave heights than suggested previously, perhaps $H_{si}/h_s \leq 0.30$.

The 2-d tests by Allsop et al (1996) showed that impacts increase further with high mounds, $0.6<h_b/h_s<0.9$. Impacts start at smaller values of H_{si}/h_s, and become much more frequent with increasing relative wave height. Tests on high mound composite walls in the CRF at $\beta=0°$ substantially confirmed this, with impacts starting at values of H_{si}/h_s as low as 0.25. These are shown against H_{si}/d in Figure 5. Whilst there are substantially fewer results than in the 2-d tests, and the general trend is very similar, it may be noted that the % of impacts in the 3-d tests all fall below the outer limit of the results for the 2-d tests. This confirms the expectation that, even when using nominally perpendicular and long-crested waves, inherent perturbations and instabilities are likely to develop, and these will reduce the level of wave impacts from those predicted from 2-d wave flume tests.

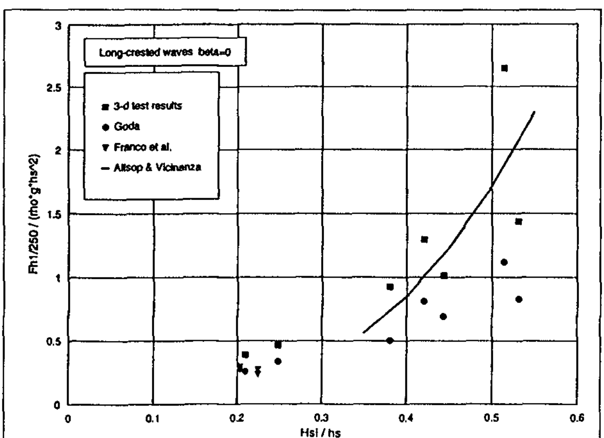

Figure 6 Dimensionless wave force for vertical walls, normal wave attack

3.2 Horizontal forces

Values of $F_{h1/250}$ are compared in Figure 6 with results from earlier 2-d tests, and predictions using Goda's method. The predictions do not take account of caisson length, L_c, so measurements used in this analysis were those of $F_{h1/250}(0)$, thus giving three sets of measurements representative of wave forces over a narrow vertical strip, $L_c=\delta l$.

Forces for long-crested normal waves in Figure 6 have been non-dimensionalised as $F_{h1/250}/\rho g h_s^2$, and plotted against relative wave height H_{si}/h_s. Summary results from the 3-d tests by Franco et al (1996), are included, for which $H_{si}/h_s = 0.20$. These forces are very similar to those measured here for the lower values of H_{si}/h_s where there are no impacts, only pulsating loads. Comparisons with Goda predictions show relatively good agreement over the pulsating zone, but use of Goda's method seems inappropriate in the impact zone ($0.35 < H_{si}/h_s < 0.55$) where Goda's method would not be expected to match the measured wave loads.

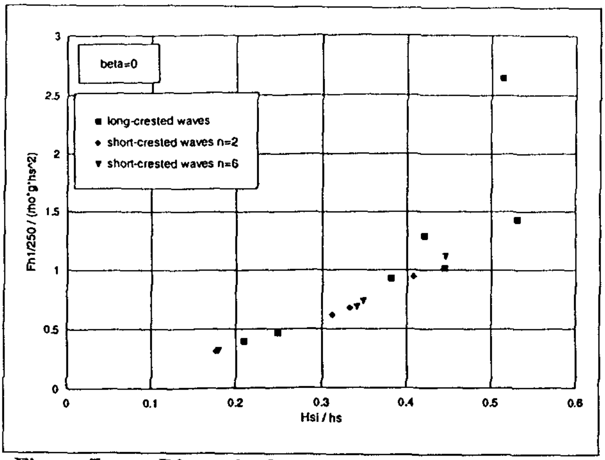

Figure 7 Dimensionless wave force for vertical walls, short-crested wave attack

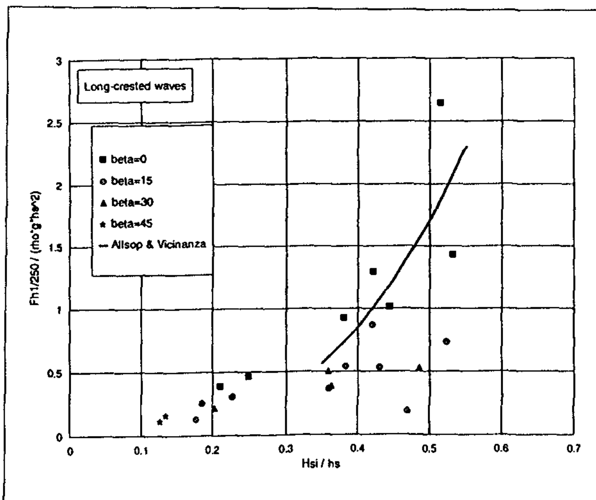

Figure 8 Dimensionless wave force for vertical walls, oblique wave attack

The simple prediction line by Allsop & Vicinanza (1996) in Figure 6 indicates an upper limit, with a few results above the line. This may be due to the greater possibility of extreme loads under impacting conditions, particularly when sampled by more than one column of transducers, and illustrates the essential variablity of impact loads, even under similar hydro-dynamic and geometric conditions.

For short-crested waves, values of $F_{h1/250}/\rho g h_s^2$ are again plotted against relative wave height H_{si}/h_s in Figure 7. The results appear to show no significant change in local force for the range of conditions tested, dispersion index (n = 2 or 6), compared with loads generated by long-crested waves of the same height.

The influences of oblique long-crested waves on forces on any narrow strip of the caisson are more significant in Figure 8. Over the pulsating zone, $H_{si}/h_s \leq 0.35$, forces are very similar to those for normal approach, even though the component of force perpendicular to the caisson might have been expected to reduce. In the impact region however, wave loadings diminish considerably under oblique attack.

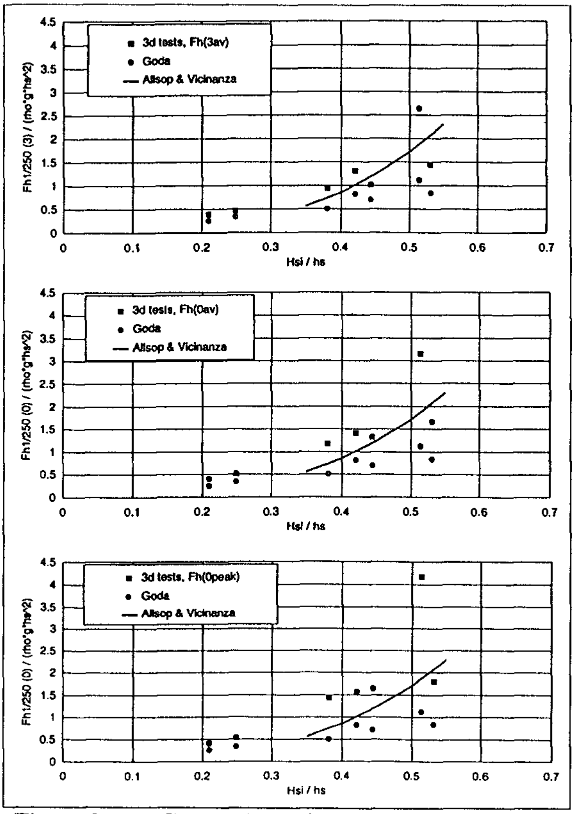

Figure 9 **Comparison of peak v average forces**

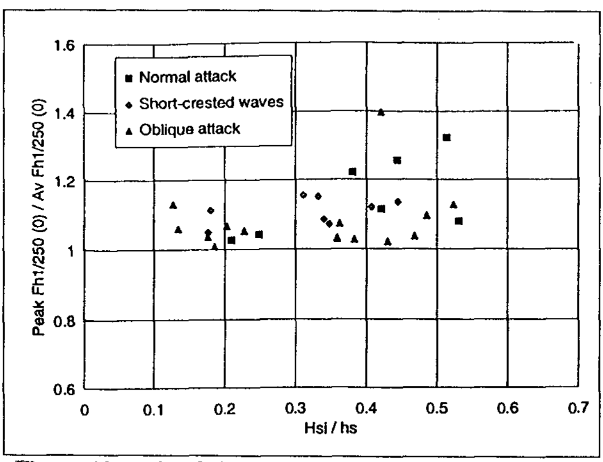

Figure 10 **Peak / average forces**

3.3 Variability of forces

With these data, it is possible to estimate variations of peak force by comparing results from the 3 columns of transducers. Values of F_h, including the "Goda" force ($F_{h1/250}$) can be calculated using three alternative methods, giving successively less averaged values:

a) from the average force calculated at each timestep across all three columns;

b) from peak forces on each column, averaged event by event, but not neccesarily at the same point in time;

c) from peak forces on any individual column, irrespective of event or timestep.

Most analysis has been based on averages by methods a) or b). These are necessarily smaller than the peak values calculated using method c). Some estimates of increase in "local" force may therefore be derived from comparison of these values, plotted as dimensionless forces in Figure 9a)-c).

These comparisons show consistent increases in $F_{h1/250}$, with reduced averaging, methods a) –

c). Allsop & Vicinanza's simple formula gives a reasonable representation of forces averaged over typical caisson widths of 10-20m, but under-estimates the "local" force over a single narrow strip, even for normal and long-crested wave attack.

Peak valucs in c) have been compared with average forces in a) as $F_{h(peak)} / F_{h(av)}$ plotted against H_{si}/h_s in Figure 10. Values of $F_{h(peak)} / F_{h(av)}$ reached 1.2-1.3 for normal long-crested attack. Under long-crested oblique attack, most results were much lower, not exceeding $F_{h(peak)} / F_{h(av)} = 1.15$, but with a single test giving 1.4. Under short-crested waves the ratio $F_{h(peak)} / F_{h(av)}$ never exceeded 1.15, suggesting that peak forces are unlikely to exceed those analysed in this research by any substantial margin, except under conditions of normal attack.

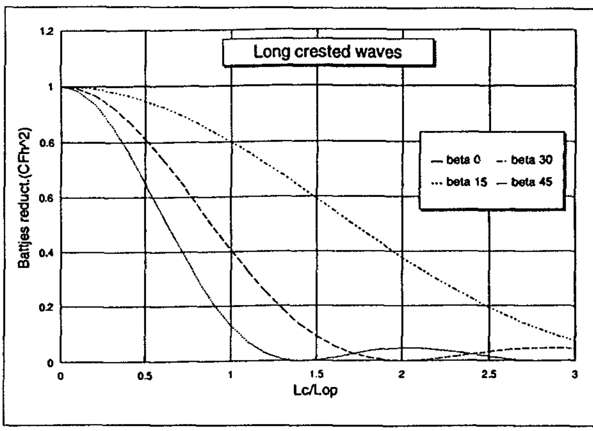

Figure 11 Battjes prediction of force decay with wave obliquity

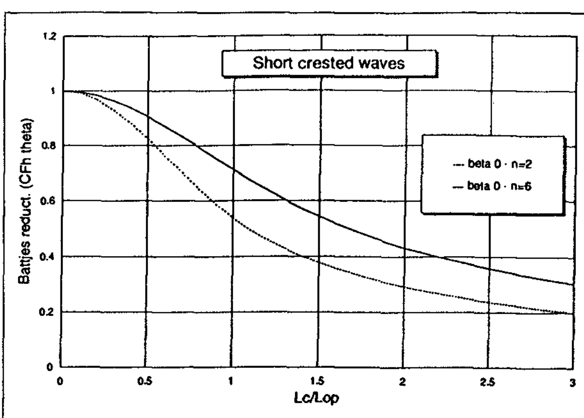

Figure 12 Battjes prediction of force decay with short-crested waves

3.4 Effect of caisson length

Battjes (1982) argued that oblique or short-crested wave attack on caisson of length L_c will give further reductions in effective force relative to normal and/or long-crested attack, and relative to loads on a narrow strip (modelled here as a single column of transducers.

These reductions are illustrated in Figures 11 and 12 where Battjes methods give prediction curves of the decay coefficient, C_{Fh} in relation to relative caisson length, L_c/L_{op}. These curves, show that these theoretical considerations predict only small reductions in effective force over caisson lengths around 10-25m, the largest caisson constructed to date being a single example in Japan of 100m long. In contrast waves of T_p=7-15s would cover wave lengths of L_{op}=80-350m.

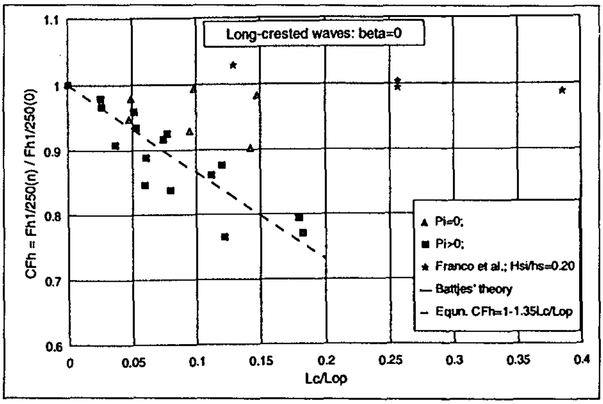

Figure 13 Force decay for long-crested / normal waves

Battjes methods were developed for simple vertical walls, so the comparisons here are based on tests with Structure 0, the simple vertical wall. The first results considered here are therefore for normal, long-crested waves in Figure 13. Results from these tests have been combined with results from Franco et al (1996), which show little decay over caisson lengths L_c/L_{op} up to 0.4. Measurements from the CRF however show up to 10% decay, ie C_{Fh} down to 0.9 for non-impact conditions for relative caisson lengths up to L_c/L_{op}=0.15. Wave impact conditions (H_{si}/h_s>0.35), however, gave substantially greater reductions in the effective force, even over short caisson lengths, 0.005 <L_c/L_{op} <0.2. A simple regression line gives the reduction factor C_{Fh} in terms of relative caisson length with a coefficient B = 1.35 for long-crested waves and $\beta = 0°$:

$$C_{Fh} = 1 - B\,(L_c/L_{op}) \tag{1}$$

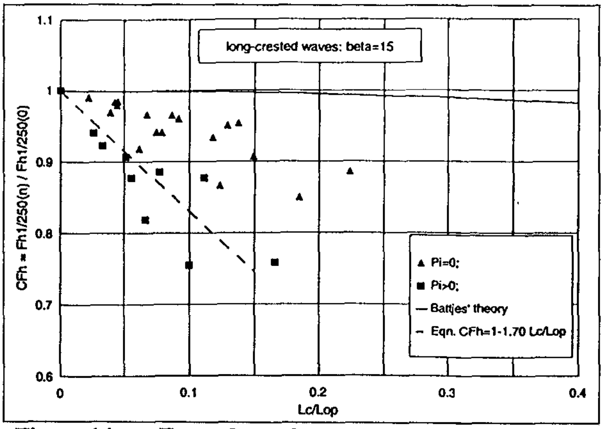

Figure 14 Force decay for long-crested waves and oblique attack, β = 15°

Under slightly oblique attack, β = 15°, forces in Figure 14 for non-impacting conditions show more significant reductions than for β = 0°, but there is only slightly greater change for impact conditions. The same simple form of regression line gives C_{Fh} in terms of L_c/L_{op}: for β = 15°, yielding B = 1.70:

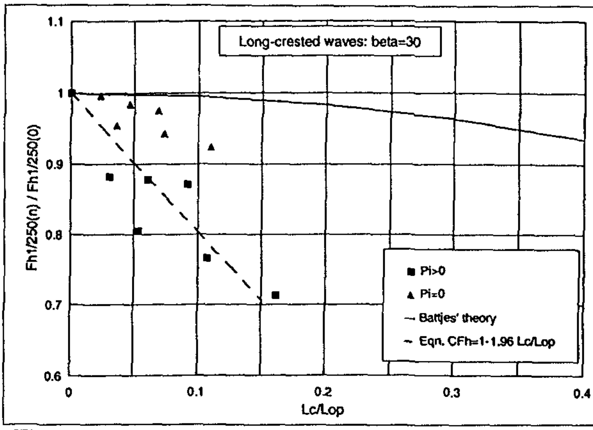

Figure 15 Force decay for long-crested waves and oblique attack, β = 30°

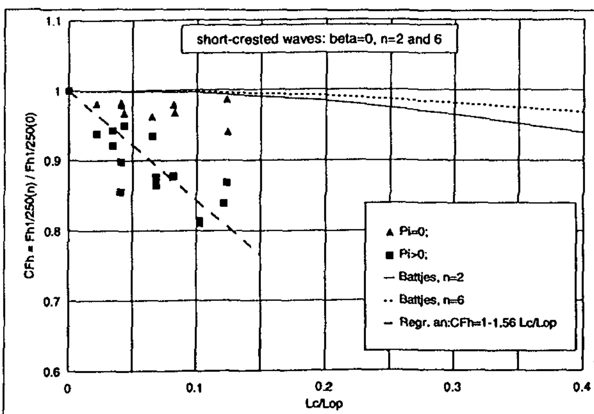

Figure 16 Force decay for short-crested waves

At greater obliquities, the force reduction is more marked for pulsating conditions. Measurements at β= 30° in Figure 15 also show slightly greater reduction for impacts.

Effects of short-crested waves in Figure 16 show no significant effect of spreading between n=2 and n=6. The regression for β = 0° gives B = 1.56, steeper than for long-crested waves at β = 0°, but less severe than for long-crested waves and β = 15°.

These results suggest that Battjes' model may be used to give conservative predictions in the pulsating zone, but that force reductions under impacts are much more significant than predicted by linear methods. Calculations of the mean decay function on F_h for impacting conditions can be summarised by the simple equation relating decay to relative caisson width, L_c/L_{op} given in equation (1) where coefficient B is defined for each test case below.

Impact force reduction coefficients

Wave condition	Coefficient B	Coef. Varn. (%)	Correlation r^2
Long-crested, β = 0°,	1.35	6.6	0.82
Long-crested, β = 15°,	1.69	9.2	0.77
Long-crested, β = 30°,	1.96	10.4	0.79
Short-crested, n= 2,	1.55	10.6	0.76
Short-crested, n= 6	1.58	9.3	0.77
Short-crested, n= 2, 6	1.56	6.8	0.77

4. CONCLUSIONS

Initial conclusions from these studies may be summarised:

a) There is good agreement between results from 2-d tests in 1994 with 1:50 approach bed slope, and results from tests with normal long-crested waves in the CRF with 1:20 approach bed slope.

b) Impacts on composite walls follow trends identified previously at Wallingford. There are however indications that impacts might start at slightly lower relative wave heights, perhaps $H_{si}/h_s \leq 0.30$,. The data also suggest that higher levels of impacts for some configurations may be reduced under 3-d conditions, even if only normal wave attack is used.

c) Under oblique long-crested waves, the occurrence of wave impacts on vertical walls are substantially reduced at β=15°, 30° and 45°. This is repeated for high mounds at β=15°, 30° and 45°, and low mounds for β=30° and 45°.

d) Effects of short-crested waves of dispersion index 2 or more do not appear to vary significantly with increased spreading.

e) Under oblique or short-crested waves, the variation of peak forces relative to those averaged over a short length equivalent to a single caisson of about 20m are relatively small, not exceeding a ratio of 1.2.

f) The variation of peak force on a single narrow strip under normal wave attack is more substantial, with peak forces up to 1.3 times greater than the average.

g) Battjes' method for estimating the decay of average force with longer caissons gives very small reductions for most practical caisson lengths. The tests with pulsating conditions show that Battjes' predictions are generally conservative.

h) For impact conditions, average forces reduce significantly with caisson length, giving reductions of 25% or so over relative caisson lengths of only 0.2.

i) A simple reduction factor for F_h under impacting conditions as a function of L_c/L_{op} has been developed. Values of a coefficient B have been presented here in Table 1 for long-crested waves at different obliquities, and for short-crested waves.

The results of these studies also suggest the following initial conclusions on spatial correlation of impact forces under oblique / short-crested waves:

j) For heavy impacts ($F_{Impact}/F_{Goda} >> 2.5$), and small obliquity or spreading: - assume a typical coherence length $\leq L/16$;

k) For light impacts ($F_{Impact}/F_{Goda} < 2$), normal wave attack ($\beta = 0°$) and little spreading: - assume a typical coherence length $\leq L/4$;

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