CHAPTER 121

WAVE PRESSURE ATTENUATION IN BREAKWATER ARMOUR LAYERS

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<u>Abstract</u>

An experimental investigation was conducted to examine the change in fluid pressure through a breakwater armour layer as a function of the incident wave characteristics, breakwater geometry, armour unit type, number of layers of armour and core permeability. Values of internal pressure were found to decrease with the number of layers of armour. The largest percentage decrease occurred within the first few layers; although this trend was somewhat influenced by armour type.

Introduction

A set of experimental studies were undertaken primarily to investigate the mechanism of wave energy dissipation that occurs throughout the various zones (core, filter and armour) of a rubblemound breakwater subjected to monochromatic wave attack. In addition, information regarding the phreatic surface motion within the various zones of the structure was collected. The influence of the armour unit type, relative geometry of the armour layer, breakwater slope and the material used to construct the various layers of the structure on wave energy dissipation, wave runup and rundown on the outer surface of the structure and the internal flow generated within the structure was assessed.

These studies were undertaken in a two dimensional wave flume in which a rubblemound breakwater, instrumented with pressure transducers and capacitance gauges, was subjected to monochromatic wave attack. The rubblemound structure consisted of a core (constructed using either 3.5 mm angular, 16 mm angular or 14 mm rounded stone), a filter layer (constructed using either 16 mm angular or 14 mm rounded stone), and an armour layer (consisting of 1 to 5 layers of either 50 mm stone, 50 mm steel spheres or 60 mm cubes).

Preliminary work was required to determine the flow resistance characteristics of the porous media used in the study. This work was undertaken in a steady flow parameter.

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Test Conditions

The basic geometry of the test section is shown in Figure 1 The outer slope of the breakwater was tested at 1:3, 1:2, and 1:1.5. The slopes of the core and filter layers were made the same as the outer slope. The structure was instrumented with 10 pressure transducers, five on the outer slope of the structure at elevations of -20, -10, two at 0 and +10 cm (all elevations referenced to the still water level) and five on the outer slope of the core at elevations of -20, -10, -5, 0 and +10 cm placed along the centreline of the breakwater. Miniature stainless steel diaphragm pressure transducers (Data Instruments AB-15psig) capable of measuring gauge pressures ranging from 0 - 100 kPa were used. Five capacitance gauges for measuring the internal water surface movement were located along the centreline of the structure.

All tests were undertaken with the still water level located 30 cm above the flume bottom. Eighteen combinations of wave height and wave period were used for each test structure and are summarized in Table 1.

The wave height, H, is the wave height measured at the location of the rubblemound structure in the flume with no structure present. The surf similarity parameter, ξ , uses the breakwater slope, θ , the wave height at the structure, H, and the deep water wave length, L_0 .

Model Materials

(i) Core and Filter Materials

Three types of core material were used during the experimental studies; 3.5 mm river gravel, 14 mm river gravel and 16mm crushed river gravel. Table 2 lists the characteristic geometric properties and the relative density of each material. A filter layer was used in conjunction with the 3.5 mm core material and consisted of the 16 mm crushed river gravel described in Table 2.

(ii) Armour Units

Three types of armour units were utilized during the course of the experimental studies. These are summarized in Table 3.

(iii) Permeability

The flow characteristics of the core and filter materials were tested in a down-flow permeameter connected to a constant head tank. The results are given in Table 3 which lists the porosity and the Forchheimer constants, a and b, for each material.

During each test, the pressures and internal phreatic surface conditions were





Segment	Т	Н	$\xi = \tan \theta / [(H/L_0)^{1/2}]$ Slope			H/L _o
			1:1.5	1:2	´1:3	
1	0.8	30	3.85	2.88	1.92	0.030
2	0.8	60	2.72	2.04	1.36	0.060
3	0.8	90	2.22	1.67	1.11	0.090
4	1.0	30	4.81	3.61	2.40	0.019
5	1.0	60	3.40	2.55	1.70	0.038
6	1.0	90	2.78	2.08	1.39	0.058
7	1.0	120	2.40	1.80	1.20	0.077
8	1.5	30	7.21	5.41	3.61	0.009
9	1.5	60	5.10	3.82	2.55	0.017
10	1.5	90	4.16	3.12	2.08	0.026
11	1.5	120	3.61	2.70	1.80	0.034
12	2.0	30	9.61	7.21	4.81	0.005
13	2.0	60	6.80	5.10	3.40	0.010
14	2.0	90	5.55	4.16	2.78	0.014
15	2.0	120	4.81	3.61	2.40	0.019
16	1.0	180	1.96	1.47	0.90	0.115
17	1.5	200	2.79	2.09	1.40	0.057
18	2.0	200	3.72	2.79	1.86	0.032

Table 1 Incident wave conditions for testing

Sample	D _{min} (mm)	D ₅₀ (mm)	D _{max} (mm)	Relative Density	Porosity (as tested) percent	$a(\frac{800}{cm})$	b(<u>cm²</u>) sec²)
Α	1	3.5	8	2.62	35	0.144	0.182
В	2	16	20	2.65	36.5	0.049	0.0109
С	3	14	20	2.65	33.7	0.0951	0.0355

 Table 2

 Characteristic Properties of Core and Filter Materials

Table 3 Summary of Armour Units

Armour Type	Mass (grams)	Relative Density	Nominal Size (mm)
Stone	$M_{50} = 121$	2.65	$D_{50} = 50$
	$M_{min} = 80$		
	$M_{max} = 180$		
Steel spheres	M = 557	8.0	50
Cubes	M = 330	2.0	60

monitored until steady state conditions were obtained. Time series records of pressure fluctuation at each gauge location were recorded. Post processing was incorporated to decrease the requirement for data storage.

The pressure was measured at a sampling rate of 50 Hz for a total recording length of ten wave periods. Earlier trials in which pressure was sampled at rates of 20 to 50,000 Hz provided sufficient evidence that a sampling rate of 50 Hz would enable determination of peak pressure. The data were subsequently phase-averaged so that each test segment (wave height-wave period combination) was characterized by a time series having a record length equal to the wave period. For the purpose of further analysis, each phase-averaged time series was characterized by a maximum differential pressure head, ΔP , which describes the maximum variation in recorded pressure over the period of the wave divided by ρg , where ρ is the fluid density and g is gravitational acceleration. Therefore, all pressure measurements were reported in terms of the equivalent head of water. The ratio of maximum differential pressure head, ΔP , to wave height, H, was used to provide a nondimensional expression.

<u>Results</u>

In order to compare the attenuation of pressure between the various layers as a function of the test variables, the percent attenuation of pressure relative to one layer of armour, $\%\Delta P_1$, was calculated where

$$\% \Delta P_1 = \frac{\left(\frac{\Delta P}{H}\right)_n}{\left(\frac{\Delta P}{H}\right)_1} = \frac{\frac{\Delta P}{H} \text{ for } n \text{ layers}}{\frac{\Delta P}{H} \text{ for } 1 \text{ layer}}$$

Values of $\% \Delta P_1$ were calculated for each wave height-period combination. Table 4 shows values of the average and standard deviation of $\% \Delta P_1$ as a function of the number of layers of armour and elevation of the pressure recording.

In order to reduce the number of variables, the data was refined one step further. For each test series, the differential pressure head for a specified number of layers is presented as a percentage of differential pressure head for one layers, that is

$$\overline{\Delta P / \Delta P_1} - \sum_{\substack{i=1\\j=1}}^J \left(\frac{\Delta P_{nj}}{\Delta P_{1j}} \right) / J$$

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TABLE 4

Summary of ZAP, versus Number of Layers of Armour

Series	$\frac{EL}{Avg} = 0$	$\frac{EL}{Avg} = -5$	$\frac{EL}{Avg} = -10$	$\frac{EL}{Avg} = -20$
ST13A 2-1	1.0 (.0)	.58 (.15)	.73 (.09)	.91 (.12)
3-1	1.0 (.0)	.57 (.25)	.64 (.15)	.83 (.20)
4-1	1.0 (.0)	.44 (.27)	.53 (.12)	.78 (.24)
SP13A 2-1	1.17 (.3)	•93 (•36)	.97 (.11)	.97 (.27)
3-1	.98 (.45)	•65 (•35)	.76 (.15)	.87 (.34)
4-1	.94 (.53)	•54 (•36)	.59 (.19)	.78 (.30)
CU13A 2-1	1.51 (.33)	•68 (•39)	.77 (.64)	.94 (.39)
3-1	1.46 (.34)	•76 (•42)	.52 (.28)	.84 (.25)
4-1	1.03 (.23)	•62 (•35)	.42 (.23)	.65 (.23)
5-1	.96 (.31)	•55 (•38)	.35 (.20)	.40 (.20)
ST12A 2-1	.88 (.14)	.85 (.59)	.86 (.06)	.96 (.15)
3-1	.68 (.14)	.69 (.43)	.75 (.08)	.87 (.26)
4-1	.60 (.15)	.56 (.35)	.61 (.07)	.81 (.27)
5-1	.50 (.16)	.47 (.34)	.51 (.09)	.76 (.25)
ST12B 2-1	.38 (.18)	.66 (.13)	.71 (.08)	.85 (.17)
3-1	.31 (.10)	.59 (.13)	.60 (.08)	.76 (.18)
4-1	.23 (.05)	.48 (.08)	.48 (.08)	.69 (.17)
5-1	.27 (.08)	.41 (.14)	.39 (.08)	.58 (.17)
ST12C 2-1	.77 (.11)	.73 (.11)	.80 (.09)	.98 (.18)
3-1	.71 (.15)	.37 (.10)	.58 (.07)	.83 (.22)
4-1	.58 (.13)	.28 (.09)	.46 (.08)	.78 (.23)
5-1	.53 (.15)	.21 (.06)	.36 (.08)	.65 (.21)
SP12A 2-1	.82 (.13)	.93 (.08)	.87 (.07)	.95 (.17)
3-1	.66 (.16)	.75 (.11)	.76 (.07)	.83 (.26)
4-1	.59 (.14)	.64 (.12)	.67 (.09)	.79 (.29)
CU12A 2-1	.72 (.17)	.74 (.10)	.76 (.10)	.89 (.22)
3-1	.49 (.08)	.53 (.14)	.67 (.13)	.92 (.37)
4-1	.37 (.11)	.37 (.10)	.44 (.12)	.64 (.21)
5-1	.33 (.09)	.29 (.08)	.32 (.11)	.49 (.19)
ST15A 2-1	.56 (.16)	.84 (.22)	.79 (.21)	.86 (.24)
3-1	.47 (.09)	.80 (.09)	.76 (.10)	.89 (.18)
4-1	.35 (.05)	.70 (.08)	.64 (.09)	.90 (.19)
5-1	.26 (.10)	.58 (.10)	.49 (.12)	.76 (.23)
SP15A 2-1	.85 (.07)	.83 (.07)	.83 (.08)	.95 (.15)
3-1	.71 (.11)	.72 (.11)	.73 (.10)	.93 (.23)
CU15A 2-1	.74 (.10)	.83 (.11)	.79 (.13)	.91 (.20)
3-1	.53 (.12)	.48 (.09)	.51 (.12)	.78 (.21)
4-1	.43 (.07)	.34 (.08)	.37 (.10)	.61 (.17)

^{*} the y-l column represents the difference between tests with y layers and 1 layer.

LEGE	ND	ST	13A	
Armour I	уре 🛥	Slope		Core Type
Stones	ST	1:3	13	А
Spheres	SP	1:2	12	В
Cubes	CU	1:1.5	15	С

where $\Delta P / \Delta P_1$		average value of ratio of differential pressure head for n layers to differential pressure head for one layer.
ΔP_{lj}	-	differential pressure head for one layer
ΔP_{nj}	=	differential pressure head for n layers
n	=	number of layers
j	=	test segment number
J	=	total number of test segments
Thus plots of	$\overline{\Delta P / \Delta P_1}$	provide a graphical representation of the data in Table
4		

Influence of Elevation

The largest reduction in internal pressure as the number of layers was increased occurred at the still water level, whereas the pressure measured at an elevation of -20 cm showed the smallest reduction as the number of layers of armour was increased. This is illustrated in Figure 2.

Influence of Core Type

The influence of the type of core material on the internal differential pressure head was assessed only for a structure with 50 mm stones in the armour layer and a front slope of 1:2.

Figure 3 provides an example of the variation of $\overline{\Delta P/\Delta P_1}$ with the number of layers of armour as a function of core type. At all elevations, the internal pressure measured in core type A ($D_{50} = 3.5$ mm) were the highest. At all elevations, the internal pressures measured in core type B were approximately 15-20 percent lower than those measured in core type A. The internal pressures measured in core type C varied from being equal to those measured in core type A at elevations of the still water level and -20 cm to a 30 percent reduction at elevation -5 cm and a 15 percent reduction at elevation -10 cm. The reason for this variation with elevation is not quite clear, although it may be a consequence of non-homogeneity in core type C. It was suspected that core material C was non-homogeneous because two separate loads of material were used and these may have had slightly differing characteristics.

The influence of core type was found to be relatively linear with the number of layers of armour.



Influence of Armour Type

The influence of the type of armour unit used in the armour layer on the internal pressure field at the four internal gauge locations is shown in Figure 4 which shows

the variation of $\overline{\Delta P/\Delta P_1}$ with the number of layers for a given breakwater slope and pressure gauge elevation.

In general it appears that randomly placed cubes provided the greatest reduction in internal pressures at all elevations on all slopes (with the exception of a few instances). The internal pressures measured for armour layers consisting of stones and spheres exhibited fairly similar trends. Typically cubes provided an additional

10-30 percent reduction in internal pressure, although this usually occurred across

the second layer. The rate of change of $\Delta P/\Delta P_1$ with the number of layers of armour was similar for all three unit types.

For a breakwater slope of 1:1.5, armour stones exhibited the greatest ability to dissipate internal pressure at the still water level. Cubes exhibited the same trend at all other gauge locations (-20, -10 and -5 cm), with a typical average internal pressure reduction 25-50 percent greater than that of stones, depending upon the number of layers of armour.

For a breakwater slope of 1:2 the greatest internal pressure reduction at all elevations was achieved by using cubes in the armour layer.

As the slope became flatter (1:3), stones and cubes exhibited similar capabilities in providing a reduction in internal pressure, particularly with decreasing gauge elevation.

Influence of Breakwater Slope

Examples of the influence of breakwater slope on the variation of $\Delta P / \Delta P_1$

with the number of layers of armour is shown in Figures 5 to 7. One graph is presented for each type of armour unit. An elevation of -10 cm was chosen as representative.

The variation in $\overline{\Delta P / \Delta P_1}$ as a result of slope change was not significant in

tests undertaken with armour layers comprised of stones, except at the still water level. A slope of 1:3 consistently provided the greatest internal pressure reduction, although this was only of the order of 5-10 percent greater than that for the other slopes.

This was also true for tests in which the armour layer was constructed of spheres.





For these tests, the variation of $\Delta P / \Delta P_1$ with slope was not significant at any

gauge location. This trend was also observed in tests in which the armour layer was constructed with cubes, except at the still water level.

There were two cases in which the trend described above did not occur. These cases were for measurements made at the still water level. Since the internal pressure at this elevation will be influenced by local variations in the phreatic surface, this may provide an explanation for this effect. The phreatic surface elevation for given test conditions was typically much higher for spheres than for stones or cubes. In tests undertaken with spheres, minor fluctuations in the phreatic surface creates a dynamic pressure component which makes up only a small percentage of the total internal pressure at the still water level. The hydrostatic component was far more significant since the phreatic surface elevation was consistently well above the still water level. However, for tests undertaken with stones and cubes, the local variations in phreatic surface often had a magnitude equal to the average set-up of the phreatic surface. Thus the local variations in phreatic surface elevations were a function of breakwater slope and may indicate why a large variation in

 $\overline{\Delta P / \Delta P_1}$ with slope occurred at the still water level in tests undertaken using stones and cubes.

Summary of Findings

- the external pressure response curves were characterized by sharp peaks and rapid rise times whereas internal pressure response was somewhat smooth and gradual as a result of damping within the armour.
- the elevation at which the maximum $\Delta P/H$ on the external slope of the breakwater occurred was found to vary with wave period
- the rate of change of pressure during wave uprush was found to increase with increasing wave height at all gauge elevations
- the core material type had no significant influence on the external pressures but had a marked influence on the internal pressure field. As the number of layers of armour was increased, the magnitude of the peak pressure decreased while the rise time between trough and peak pressures increased
- the number of layers of armour had no influence on the external pressures but had a marked influence on the internal pressure field. As the number of layers of armour was increased, the magnitude of the peak pressure decreased while the rise time between trough and peak pressures increased.

- the type of armour unit used in the armour layer was found to have a small influence on the external pressure field. Using cubes produced the highest value of $\Delta P/H$.
- the maximum $\Delta P/H$ was found to increase with decreasing wave steepness.
- values of internal maximum $\Delta P/H$ were found to decrease with increasing armour layer thickness. The largest percentage decrease was found within the first few layers of armour. This trend was more evident with tests undertaken with stones and cubes in the armour layer. (this is primarily a permeability effect)
- a net downward propagation of wave energy and pressure was found by analyzing phase and elevation relationships between gauge locations
- internal pressures were found to be the highest for tests undertaken using spheres and lowest for tests undertaken using cubes.