CHAPTER 101

Influence of Wave Directionality on Stability of Breakwater Heads

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Abstract

An experimental investigation was undertaken to investigate the stability of breakwater heads under uni and multidirectional wave attacks. Waves of normal and oblique incidence were used in the investigations and the stability results were assessed along with relevant measurements of wave surface elevation, measured in the proximity of breakwater heads.

INTRODUCTION

In spite of the growing number of multidirectional wave facilities around the world, breakwater designs are still evaluated using unidirectional regular or irregular waves, because it is widely believed that testing under unidirectional wave provides conservative results (i.e. overdesigned breakwaters). This may be true for the trunk section of the breakwater where the directional spread associated with the multidirectional seas tends to reduce the wave loads imparted on the structure. For the breakwater heads, this assumption is perhaps not valid. Because of the directional characteristics in multidirectional waves (i.e. 3D waves), some sections of breakwater heads may be exposed to larger wave heights than normally encountered under unidirectional waves (i.e. 2D waves).

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Generally, under unidirectional waves of normal or oblique incidence, the head sections of breakwaters are more susceptible to damage than their trunk sections owing to the large wave heights and velocities that result from processes such as refraction, diffraction and shoaling on and around the head sections. Because of this, researchers such as Jensen (1984) and Vidal et al. (1991) suggest that the weight of stones for the heads should be about 1.5 to 4 times the weight of armour stones in the trunk section.

Under multidirectional waves, the wave heights that a breakwater head section encounters through the various processes described above, are possibly made even larger due to waves directly attacking the breakwater from other directions. Therefore more wave loads are expected on the heads, resulting thereby in lower stability.

EXPERIMENTAL SETUP

Layout of the basin

The physical model tests were carried out, at the National Research Council of Canada, in the multidirectional basin of the Coastal Engineering Laboratory of the Institute for Marine Dynamics.

The basin used for this purpose has a length of nearly 20m and a width of 30m. Figure 1 shows a plan view of the experimental set-up. A sixty-segment wave generator is located along one of the 30m sides of the basin. Perforated expanded sheet absorbers, capable of limiting wave

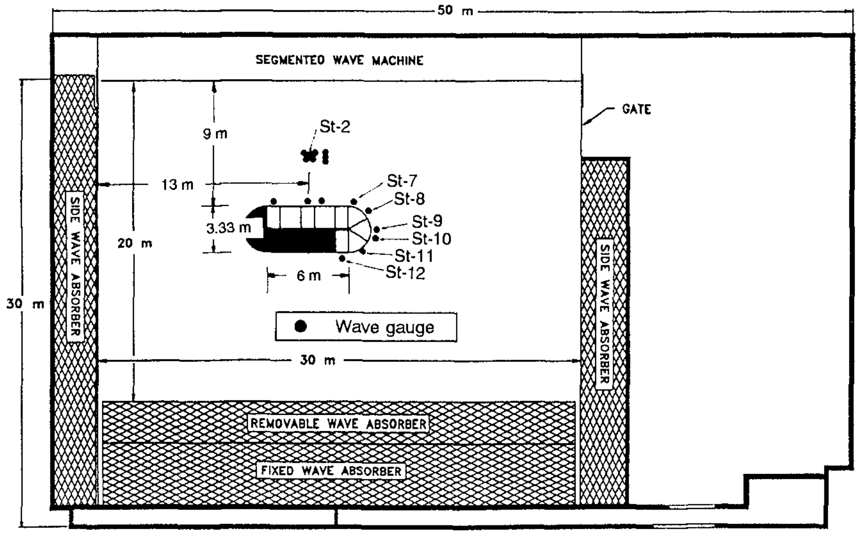

Figure 1. Plan view of the experimental set-up

reflections to 5% for most frequencies of interest, are installed along the remaining three sides of the basin. A 5m long gate and a closure plate of similar length at the two extremities of the wave generator are generally used for techniques that intentionally use corner reflection for increasing the size of the homogeneous area (see Figure 1).

Layout of wave gauges

The water surface elevations were measured at 17 different locations indicated by dots in Figure 1. Eight offshore wave gauges were mounted on two frames as a three-gauge and a five-gauge arrays. The three gauge array was set up to analyze the reflection of unidirectional waves of normal incidence by the methodology of Mansard and Funke (1987). The five gauge array was used to analyze the directional characteristics of normal and oblique incidence multidirectional waves with and without the structure in position. The remaining nine wave gauges were placed in the proximity of the model at a distance of 0.5m away from the toe of the structure, at locations shown in Figure 1. (Note that St stands for wave gauge station).

Layout of breakwater model

The layout of the breakwater model had to be designed carefully in this study, for the reasons indicated below.

Although sophisticated techniques have been developed to simulate the directional characteristics of the natural sea states inside laboratory environments, the area over which the sea state can be homogeneous in a wave basin is limited because of processes such as diffraction and reflection (see Sand and Mynett, 1987). Therefore careful consideration had to be given in order to ensure similar sea state severities along the entire breakwater section. For this purpose, use was made of the WAGEN model which could predict the water surface elevation and kinematics of the sea states prevailing at different locations in the basin. This model, developed by Isaacson (1992), is based on the boundary integral equation and linear diffraction theory and can account for partial reflection from structures such as breakwaters. A sample output resulting from this program is presented in Figure 2. It illustrates the spatial distribution of wave heights in the basin without the breakwater model, under a multidirectional sea state. The expected wave heights presented in this figure were normalized with respect to target wave heights. Note that their maximum value is only 0.9. This is due to diffraction processes and can be increased by applying an amplification factor. It can be seen from this figure that the useful test area, over which the sea state is homogeneous, is limited by a triangular boundary. According to this figure, the best location for the model would be close to the paddle. However, since this wave basin is not yet equipped with active absorption, an optimum location which would simultaneously ensure an homogeneous sea state and minimize re-reflections from the paddle had to be chosen.

Since the model breakwater occupied only a portion of the basin width, reflected waves were expected to dissipate through diffraction processes before they are re-reflected by the paddles. Furthermore, since the proposed breakwater geometry had a symmetrical layout, it was considered justifiable to study only one of its head sections. Based on these different criteria, the model was located, as shown in Figure 1, at a distance of 9m from the paddle, and it was also offset by 2m from the center line.

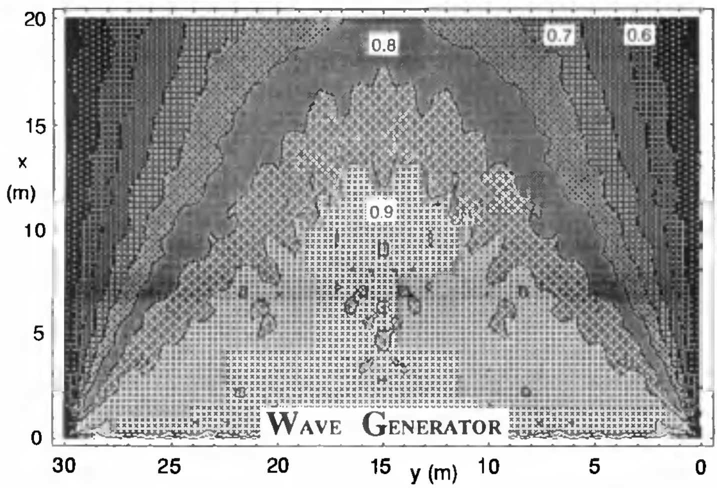

Figure 2. Spatial distribution of wave heights in the basin without the breakwater in place

Characteristics of breakwater model

Figure 3 shows both plan and profile views of the breakwater model. In order to achieve a better insight into the individual performance of the various breakwater components, nine sections of interest were separated from the total structure by using a steel frame with different components. Figure 3 shows the six trunk and the three head sections included in the study. The three head sections, called Front Head (FH), Middle Head (MH) and Back Head (BH), cover an area enclosed by an angle of 60° as shown in Figure 3. The remaining parts of the breakwater were covered with a steel mesh having square openings of 1x1cm in size, in order to avoid rebuilding the entire breakwater after every test.

The breakwater was of conventional type, composed of two layers of armour, a filter layer and a relatively porous core. Its height was 80cm and it performed as a non-overtopping structure in a water depth of 50cm. The front and rear slopes were 1:2. Similar stone weights were used both in the trunk and head sections intentionally, in order to ensure high damage on the head section. One of the main reasons for this is that an accurate assessment of the wave height that causes small degrees of damage is generally difficult because of the experimental variability associated with effects such as interlocking (see Davies et al., 1994).

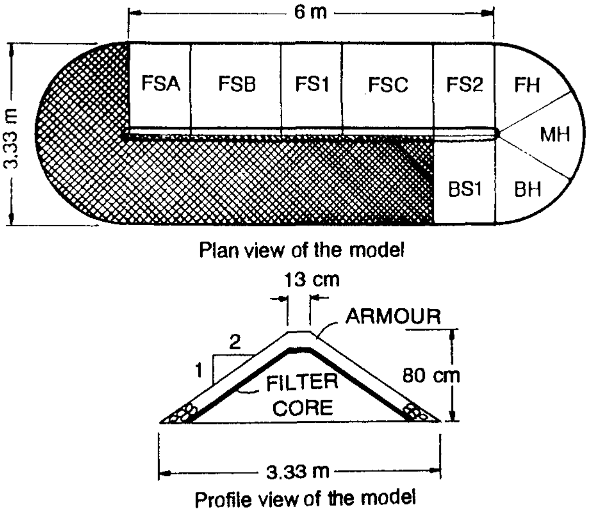

Figure 3. Plan and elevation views of the breakwater model

The characteristics of the core, filter and armour stones used in the experiments are presented in Table 1. The gradations of the armour stone were meticulously checked and the resulting D_{n85}/D_{n15} ratio for the armour was 1.3. In order to differentiate the various layers, each layer of armour stone and the filter layer were painted with a unique color. With this color scheme, the level of damage in each section could be easily ascertained by visual observation and photographs.

Measurement techniques

The profiles of the trunk and head sections of the breakwater were measured using the electro-mechanical profiler described in Davies et al. (1994). The profiles taken in the direction normal to the wave paddle, were generally spaced 10cm apart in the trunk and head sections. The head section profiles were then converted into polar coordinates to obtain profiles every 5°. Since the head was subdivided into 3 sections, each covering an area enclosed by 60°, an average of 11 profiles was used to quantify the damage in these sections.

The eroded area in the head and trunk sections was computed after each test using average profiles of original and final cross-sections. The damage index, S, was then calculated by normalizing the eroded area with the square of the armour stone's nominal diameter.

Besides establishing damage values by profile data, visual observations were also used to classify the degree of damage according to the four classifications suggested by Vidal et al. (1991): Initial damage, Iribarren's damage, start of destruction and destruction.

To further assist the estimation of damage, color photographs of each individual section were taken after each test. In addition, video pictures were used to record the entire experiment.

Table 1. Summary of the breakwater characteristics

W_{50} weight of armour (g)	118
W_{50} weight of filter (g)	15
W_{50} weight of core (g)	2
D_{n50} nominal diameter of armour (cm)	3.54
porosity	0.45
length of trunk (cm)	600
diameter of head (cm)	333
crest breadth (cm)	13
height of breakwater (cm)	80

$D_{n50} = (W_{50} / \rho_s)^{1/3}$, ρ_s : unit weight of armour unit

TEST SERIES

Table 2 indicates the characteristics of the waves used in the experiments. The spectra were of the JONSWAP type with two different peak periods (Tp = 1.4s and Tp = 1.7s). The peak enhancement factor γ was chosen to be equal to 3.3. The multidirectional waves were simulated using the well known Single Summation Method in order to eliminate spatial variability of sea states. Since the objective of this study was to assess the sensitivity of damage to spreading of the wave energy, the commonly used $\cos^{2s}$ model was chosen for directional distribution. Values of s=2 resulting in $\cos^4$ and $s=\infty$ were applied to simulate multi and unidirectional waves respectively. In order to assess the influence of obliqueness, two different mean angles of incidence $\bar{\theta}=0°$ and -15° were used, ensuring at the same time homogeneity of the sea state at all sections of interest.

In order to minimize statistical variability associated with short lengths of wave records, a recycling period of 20 minutes (in model scale) was used in the synthesis by the Random Phase Method. This length corresponded to about 1000 waves when T_p=1.4s and 850 for T_p=1.7s. The ratios of diameter of the head over wave length and length of trunk over wave length are indicated in Table 2.

Eight test series were carried out using different combinations of spreading index and mean angle of incidence. In each series, the spectrum-based significant wave heights H_{m0} were increased from 5 to 15cm in steps of 2.5cm. Most of these sea states were pre-calibrated in the basin without the structure in position, while keeping all 17 gauges in place.

Tests under each value of H_{m0} were run until the stabilization of damage. This was achieved in about 2000 to 5000 waves.

Table 2. Characteristics of waves in experiments

Spectrum	T_p (s)	γ	$\bar{\theta}$ (deg.)	s	T_R (min.)	N	D/L	T_L/L
JONSWAP	1.4	3.3	0, -15	2, ∞	20	1028	1.3	2.3
JONSWAP	1.7	3.3	0, -15	2, ∞	20	847	1.0	1.8

RE-REFLECTIONS IN THE TEST SET-UP

The reflection characteristics of the breakwater were estimated by the NRC algorithm, under unidirectional waves of normal incidence. Figure 4, which summarizes these results, shows the reflection coefficient, Cr, to be in the order of 20 to 25%. Although the steepness parameter, H_{m0}/L, used in the abscissa of the figure, incorporates the relevant wave length of the sea state, longer periods result in higher reflection coefficients.

Table 3 provides a summary of wave heights measured under different experimental combinations for one particular severity of the sea state (i.e. H_{m0}=12.5cm).

The description of the various parameters presented in this table is given below.

H_{m0} is the target significant wave height;
H_{m0_no} is the significant wave height measured without the structure at the gauge 2. (This is the middle gauge in the 5 probe array);
H_{m0_with} is the significant wave height measured during the experiments by the gauge 2; and
$H_{m0,i}$ is the incident wave height resolved by reflection analysis.

This table shows that the estimation of the incident wave heights is within an accuracy of 2.5%, while the build-up of wave heights due to re-reflections is in the order of 3.6%. (This small degree of re-reflection was also confirmed by running some regular wave tests and monitoring the build-up). Because the reflection and the re-reflection were small in this set-up, it was considered justifiable to use the wave heights measured by gauge 2 with the structure in position, as the reference wave height in the stability analysis.

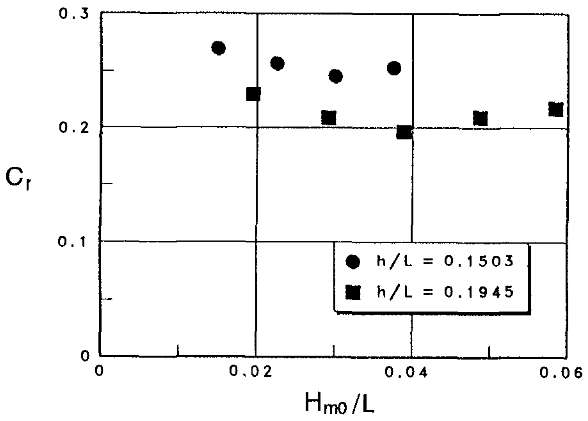

Figure 4. Reflection characteristics of the breakwater

Table 3. Comparison between different estimates of the significant wave heights when the target H_{m0}=12.5cm

Wave condition	H_{m0} (cm)	H_{m0_no} (cm)	H_{m0_with} (cm)	$H_{m0,i}$ (cm)
2D normal waves	12.5	12.83	13.30	12.53
2D oblique waves	12.5	12.83	13.71	-----
3D normal waves	12.5	12.81	12.33	-----
3D oblique waves	12.5	13.04	13.25	-----

RESULTS OF BREAKWATER STABILITY

The analysis of the results from these eight test series, on the stability of the relatively large number of test sections is still proceeding. This paper presents some of the first findings on the stability of head sections. A complete presentation of the results will be given in Matsumi et al. (1995).

Influence of wave periods

Given the difference in wave lengths under the two peak periods, substantially different patterns of wave diffraction were found in the two cases. In fact, along the trunk section, the non-uniform pattern of damage reported by Vidal et al. (1991) was also found in this study under unidirectional waves. (All results related to trunk sections will be presented in Matsumi et al., 1995). For the head sections, the difference in stability between uni and multidirectional waves was relatively small when Tp was equal to 1.4s. Numerical simulation of wave heights and kinematics is required to provide a better insight of the influence of wave period. Therefore in the next section, only those results that correspond to 1.7s will be discussed.

Comparison between the damage under unidirectional waves with normal and oblique incidence

In order to facilitate the interpretation of stability results, the significant wave heights measured at different locations in the proximity of the heads were computed and normalized with respect to the significant wave height measured at gauge 2. (The rationale for using the 2nd gauge was discussed earlier).

Figure 5 shows the results of the wave height ratios and the resulting stabilities for unidirectional waves under normal and oblique incidence. Although the difference in the values of significant wave heights realized under normal and oblique wave conditions is small, the stability results show more damage under oblique waves with $\bar{\theta}$=-15°.

In order to achieve a better understanding of these results, the numerical model WAGEN, described earlier, was used. Assuming a partial reflection of 30% from the breakwater, the horizontal velocity components in the x and y directions were computed using a regular wave of 1.7s. (Note that x direction is normal to the wave machine, and y direction is parallel to it).

Figures 6a and 6b show the resolutions of the dominant directions of velocity components under normal and oblique wave conditions respectively. It can be seen that these are directed towards the FH section under oblique waves, while under normal waves they wrap around the section. This focussing pattern is believed to be responsible for causing higher damage in FH section when $\bar{\theta}$=-15°.

In order to explore the reasons for similar increase in the damage of MH and BH sections, a refraction analysis was carried out using simple cases of regular waves. The intervals between wave rays were found, in this analysis, to be narrower under oblique waves, implying more concentration of energy and thus resulting in lower stability.

The higher damage on the front head under unidirectional waves is however not common for traditional structures. According to Jensen (1984)

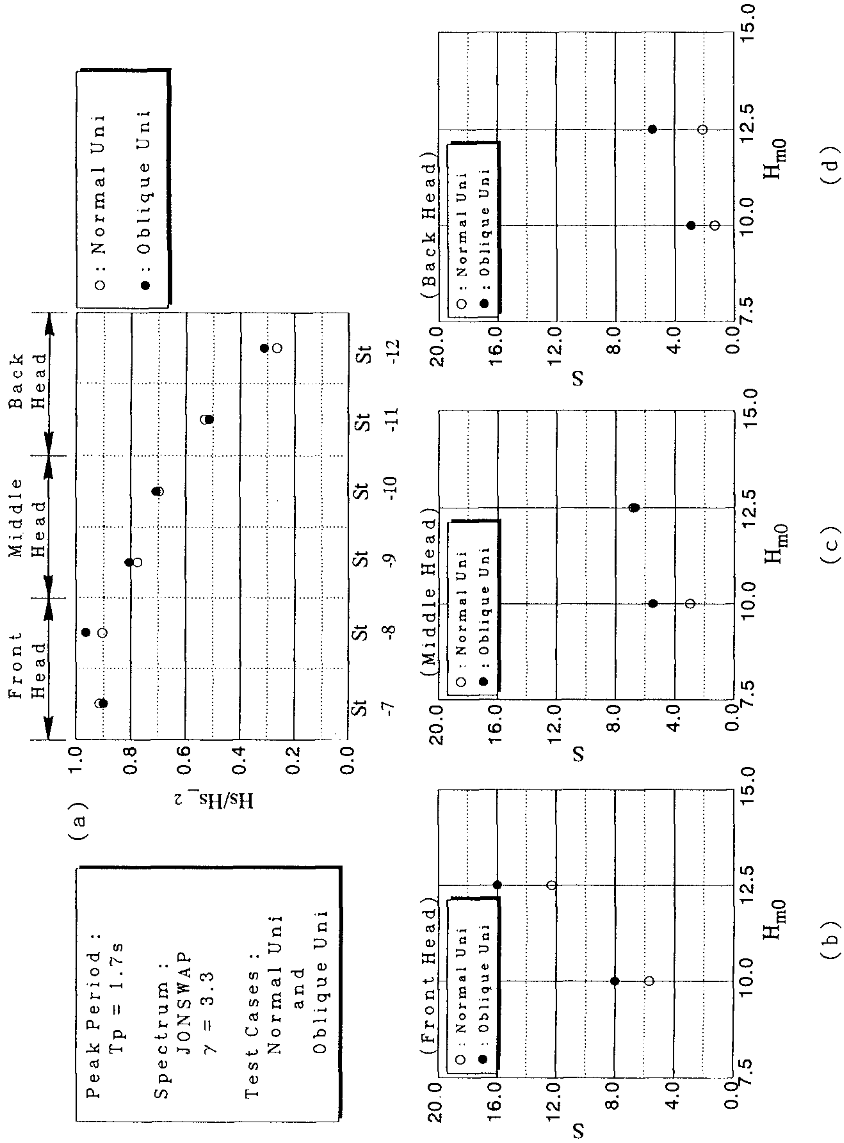

Figure 5. Comparison of significant wave heights around the head, and of damage index, under unidirectional normal and oblique waves

the most susceptible section for damage is at angle of about 90° to 135° relative to the incident wave direction. However for berm breakwaters, which are generally composed of smaller stones than those used in conventional structures, Jensen and Sφrensen (1991) report damage to the front head sections. It is therefore possible that the reason for the higher damage in this study is the small gradation of stones used intentionally to cause larger degrees of damage.

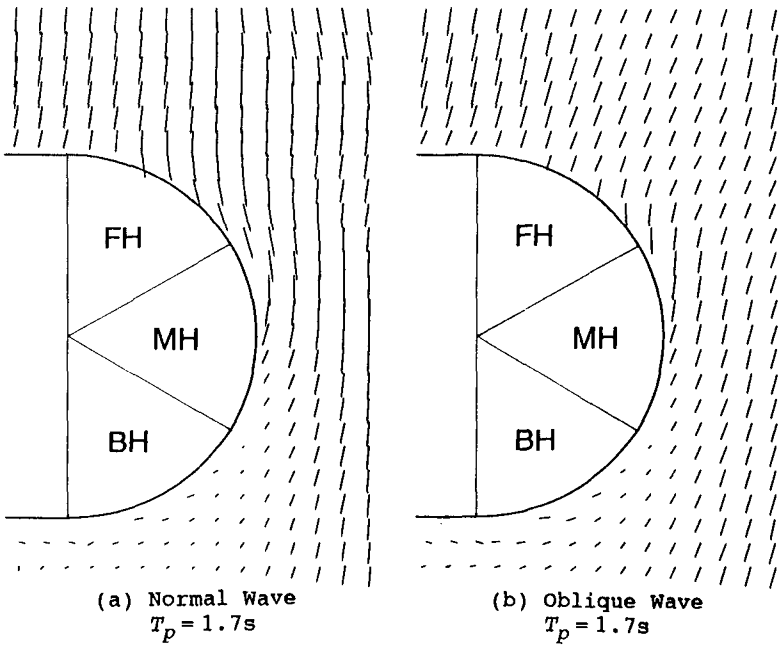

Figure 6. Dominant directions of velocity components under normal and oblique waves (Regular wave T=1.7s)

Comparison between damage under normal uni and multidirectional waves

Figure 7 shows a comparison of the significant wave heights around the head for normal uni and multidirectional waves. It can be seen that the directional spread under multidirectional waves has increased the wave heights on the head sections. This implies higher wave loading under these waves, and the stability results presented in this figure also confirm this fact. However, the difference in damage between uni and multidirectional waves is largest in the MH section when H_{m0} was equal to 12.5cm. Under

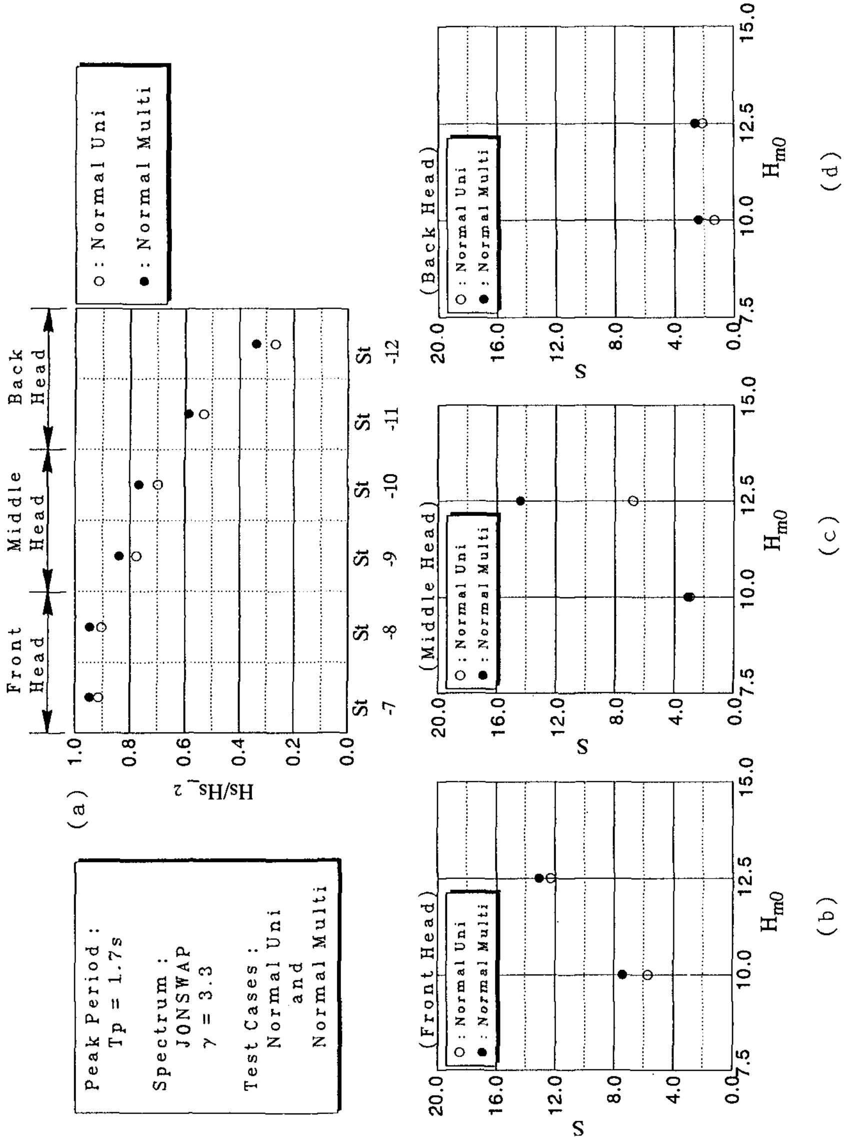

Figure 7. Comparison of significant wave heights around the head, and of damage index, under uni and multidirectional normal waves

Figure 8. Uniform damage pattern in MH section under unidirectional normal waves

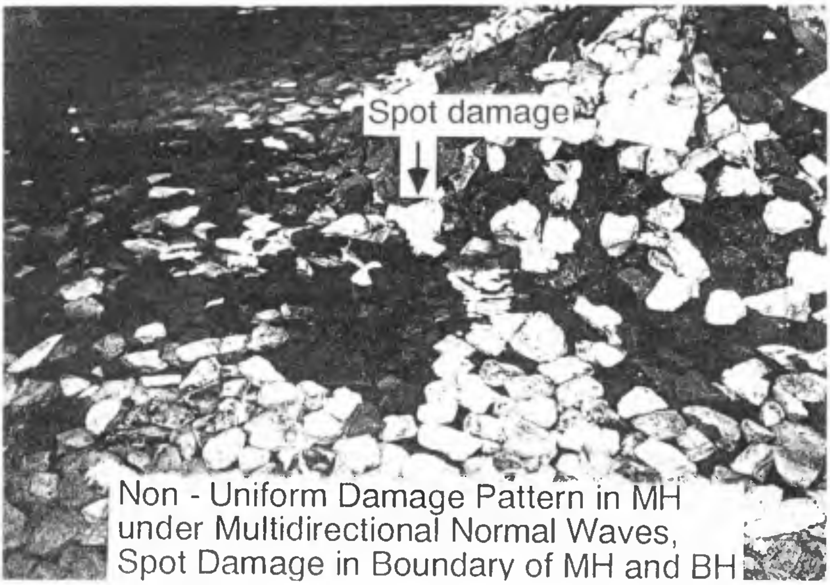

Figure 9. Spot damage pattern in near boundary between MH and BH sections under multidirectional normal waves

unidirectional wave attack, the damage is found to be uniform near the waterline because of the high velocities generated by refraction, shoaling and diffraction processes. In the case of multidirectional waves, the co-existence of the above processes added to the incidence of oblique waves, has resulted in severe spot damage near the boundary between the MH and BH sections (i.e. 90° to 135°). Figures 8 and 9 present the photographs corresponding to these damages.

For H_{m0}=10cm, it is difficult to find any difference between the results of uni and multidirectional waves. The reasons for it are unclear, but are possibly due to experimental variabilities found under low degrees of damage.

To achieve a better insight into the reasons for the increased damage, some velocity measurements were made at St9 and St11, as a continuation of the present study, by the principal author at the Tottori University. The results indicate that the y-component velocities under 3D waves are larger by nearly 1-1/2 to 2 times the values measured under 2D waves. These findings support the stability results presented above.

Comparison between damage under oblique uni and multidirectional waves

Under oblique incidence, the multidirectional waves result in large significant wave heights on the middle and back head sections in comparison to the heights obtained under 2D seas. The resulting damages do not display a consistent trend except in the MH section where higher damage was observed under 3D waves when H_{m0} was equal to 12.5cm. However, the velocity measurements described earlier clearly display larger y-component velocities under 3D waves.

For the FH section, the damages under unidirectional waves are larger than those caused by multidirectional waves (see Matsumi et al. 1995).

CONCLUSIONS

In this particular test program, some correspondence was found between the wave heights measured in the proximity of the heads and the resulting damage. A clearer picture emerged when the x and y components of the velocity field were analyzed.

The front head section of the breakwater suffered substantial damage under all combinations of sea states owing to the small gradation of stones used in the tests. For waves of normal incidence, damage on FH section was larger under 3D waves due to directional spreading. However, with $\bar{\theta}$=-15°, the trend was opposite (i.e. unidirectional waves induced more damage).

The MH section is more prone to damage under 3D waves because of the co-existence of processes such as refraction, diffraction and shoaling, along with the possibility of direct attack from other directions.

Further analysis of wave kinematics at the Tottori University as a continuation of this test program is expected to provide a better insight into the damage pattern.

ACKNOWLEDGMENTS

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REFERENCES

Davies, M.H., Mansard, E.P.D. and Cornett, A.M. (1994), "Damage Analysis for Rubble-Mound Breakwaters", Proc. 26th int. conf. on Coastal Engineering, Kobe, Japan.

Isaacson, M., (1992), "Diffraction Model of Directional Wave Generation in a Basin with Partially Reflecting Boundaries", Report prepared for National Research Council of Canada.

Jensen, O.J., (1984), "A Monograph on Rubble Mound Breakwaters", Danish Hydraulics Institute, Denmark

Jensen, O.J. and Sϕrensen, T., (1992), "Hydraulic Performance of Berm Breakwater Heads", J. of Hydraulic Research, IAHR, Vol.29, No.6.

Mansard, E.P.D. and Funke, E.R., (1987), "On the Reflection Analysis of Irregular Waves", Hydraulics Laboratory Tech. Report TR-HY-017, National Research Council of Canada.

Matsumi, Y. Mansard, E.P.D. and Rutledge, J. (1995), "Influence of Multidirectional Waves on Breakwater Stability", National Research Council of Canada, Tech. Report (in preparation).

Sand, S.E. and Mynett, A.E. (1987), "Directional Wave Generation and Analysis", Proc. IAHR Seminar on Wave Analysis and Generation in Laboratory Basins, 22nd IAHR Congress, Lausanne, Switzerland.

Vidal, C., Losada, M.A. and Medina, R., (1991), "Stability of Mound Breakwater's Head and Trunk", Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol.117, No.6, Nov/Dec.