Effects of Wave Grouping on Breakwater Stability

by

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ABSTRACT

It has been found that certain sequences of waves, such as occurring within well defined wave groups, can cause greater damage to rubble mound structures, than equally high individual waves dispersed throughout a wave train. It has therefore been necessary to develop a new wave synthesizing technique, which allows control of the phasing of the wave frequencies, so that a similar degree of wave grouping can be produced in the laboratory as is expected to occur at a particular location in the prototype.

Also, during the course of this investigation, an attempt was made to simulate the strength of concrete armour units to the correct model scale. The breaking of armour units, due to their rocking or being displaced, resulted in a much higher percentage of damage, than would have been possible to predict from tests with commonly used model armour units.

INTRODUCTION

Rubble mound breakwaters undoubtedly belong to the oldest type of coastal structures, and therefore their design procedures have a long history. Simple empirical design criteria were originally based on full scale experiences with these structures. In the more recent past, extensive model testing in hydraulics laboratories throughout the world has modified the criteria considerably, mostly by including more parameters, but still making use of a number of empirical coefficients. This stems mostly from the difficulty of being able to define accurately the physical process of waves breaking on a structure.

Magoon and Baird (1) list some nine parameters affecting the stability of a rubble mound structure, while Bruun

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and Gunbak (2) list a total of twelve parameters, which include most of the nine of the previous authors. Gravesen and Sorensen (3) have attempted to include some of the suggested parameters in their proposed design criteria and have further pointed out the importance of the occurrence of wave grouping, similar to a previous paper by Johnson and Ploeg (4) on this subject. As early as 1966, Carstens et al (5) show damage versus wave height curves for regular and irregular wave trains, with the latter differing in the amount of wave grouping due to different spectral shapes. The curves indicate clearly that the grouped wave train causes greater damage than the non-grouped for the same significant wave heights.

Most of the recently proposed breakwater design formulae are based on laboratory experiments using irregular wave generating eguipment. Typically one sees in the literature comparisons between power spectral density functions of naturally occurring sea states and those obtained in wave flumes. Of course the shape of this amplitude spectrum is indeed an essential element in the definition of wave conditions, but if breakwater stability criteria do include a wave period parameter, as well as resonance phenomena as stated by Bruun and Johannesson (6), then the amplitude portion of the power spectral density function alone will not be sufficient to define the sea state. Perhaps somewhat too readily have oceanographers and coastal engineers in the early sixties assumed that a sea state is a continuous random process. Therefore, when a Fourier transform was performed on a recorded wave train, only the amplitude portion of the spectrum was kept and the phase spectrum was ignored as containing no relevant information when dealing with a random process.

It is well known that second order wave forces exerted on floating structures depend heavily on the occurrence of wave grouping. The stability of rubble mound breakwaters appears to be significantly affected by the actual sequence of certain waves in a particular wave train, which tend to occur in wave groups. To test the sensitivity of rubble mound breakwaters to wave grouping, an irregular wave generation technique was developed by Mansard and Funke (7) to allow independent control over the spectrum and the "groupiness" of a wave train, using the information contained in the phase spectrum to control groupiness. With this technique it is then possible to investigate the different modes of failure or stability criteria while maintaining the same energy spectrum, but varying the amount of groupiness. Tests show that different wave trains with similar power spectral density functions and therefore similar RMS values and peak frequencies, and similar wave height statistics, but different wave grouping, do result in rather different stability criteria.

In tests reported previously by Johnson and Ploeg (4), the importance of wave grouping was demonstrated by comparing the effects of a series of artificially constructed wave groups and a non-grouped wave train with the same amplitude spectrum, but randomly assigned phases. These two wave conditions are shown in Fig. 1, and the test results were for a 1:2 slope dolos armoured breakwater, where both wave trains exhibited a significant wave height of 7.6 m, a peak period of 11 s, and a maximum wave height of 11 m. For the non-grouped wave train, some of the dolosse were seen to "rock" in place, but not to the point of being displaced from their locations. However, the sequence of large waves in the artificially grouped wave train (containing no larger wave heights than those encountered in the non-grouped wave train, but consecutively following one another) produced continual displacement of 5 to 7 armour units and severe rocking of most of the armour with each wave group. Since the artificial groups appeared rather unrealistic, the tests

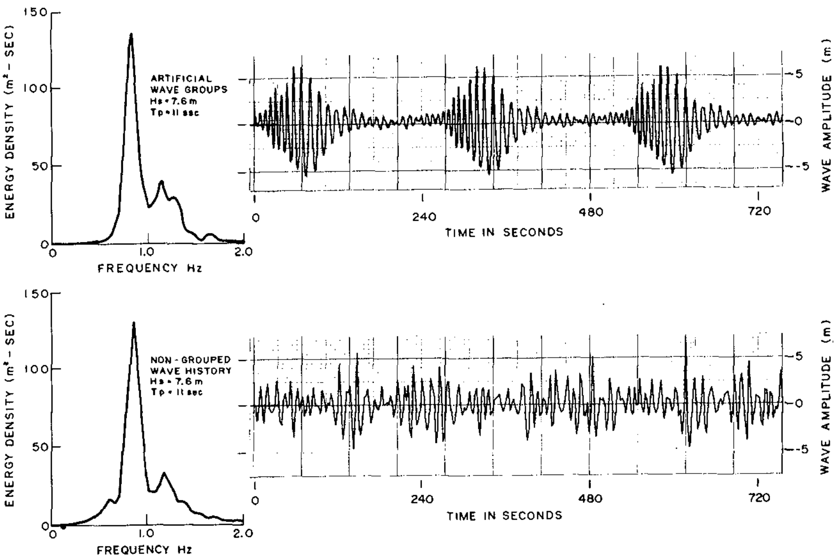

FIG.1 WAVE ENERGY DENSITY SPECTRA
AND GROUPED AND NON-GROUPED WAVE TRAINS

reported in this paper will show a comparison between the effects of a wave train synthesized to have the same degree of groupiness as an actual prototype wave record from a station on the east coast of Canada, and a wave train with the same spectral shape and wave statistics, but randomly assigned phases as commonly used in irregular wave generation.

Of the various types of armour units currently being used for breakwater protection, dolosse seem to be particularly sensitive to certain sequences of waves in a wave train because of the possibility of the units being broken when rocked by wave impact. Visual observations indicate that it appears to be the first wave in a group that loosens the unit, but the second and third waves which produce the damaging motion.

Recently tests have been carried out on a model of the Sines breakwater in Portugal by Ploeg and Mansard (8), where the tensile strength of the concrete in the shank of the dolosse was simulated to the correct model scale, thus allowing a more realistic view of the importance of the breaking of armour units during storm conditions. The tests indicated that for large dolosse, breakage is a key factor in determining a suitable stability criterion and therefore this effect must be taken into consideration when carrying out model tests of rubble mound breakwaters.

FLUME FACILITIES

The wave group effect tests were carried out in a flume described in Fig. 2. A 1:1.5 slope rubble mound breakwater, with dolosse for armour was placed 50 m from the wave board in a 75 m long flume. The 2 m wide flume was divided into a centre channel of 1 m and two side channels each of 0.5 m width. The breakwater was built in the middle channel only. The channel dividers extended from 30 m in front of the breakwater back to the end of a 1:20 slope beach behind the breakwater. The dividers reduced the influence of reflections from the breakwater back to the wave board, and for that reason they were perforated over part of their length. Experiments performed before and after construction of the breakwater showed the arrangement to be quite satisfactory. The hydraulically driven wave machine was computer controlled to generate any specified wave train. Wave height sampling was done with capacitance probes located 2.5 m from the wave board and 3 m in front of the breakwater as shown in Fig. 2. Glass panels in the flume at the location of the breakwater allowed for visual observations and photographic records to be made of the breakwater under wave action. Fig. 3 shows the cross section of the model breakwater, used for these experiments.

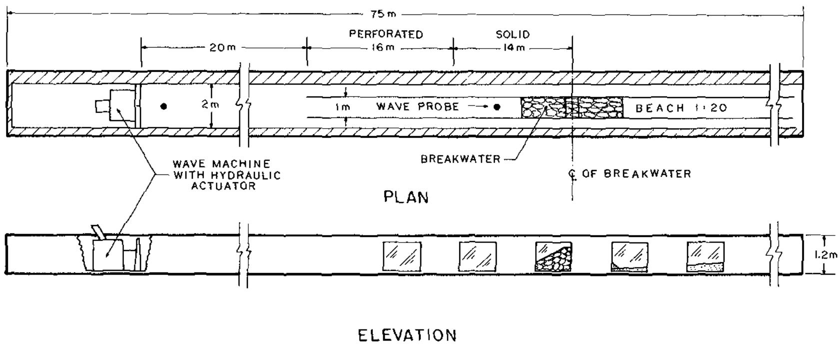

FIG. 2 WAVE FLUME-EXPERIMENTAL SET-UP

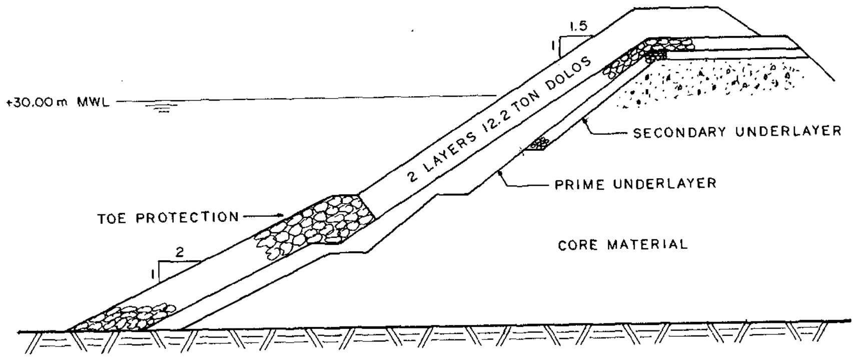

FIG.3 CROSS-SECTION OF THE MODEL BREAKWATER

WAVE GENERATION

An essential part of this study has been the capability to generate at the test section in the wave flume a desired wave train. This has been achieved by means of a phase and amplitude compensated technique described by Mansard and Funke (9). It has also been necessary to use the synthesis technique, referred to earlier (7) which allows control over the phasing of the frequencies and therefore the groupiness of the wave conditions in the flume. The phase spectrum of a wave train has proven to be an important factor and if reproduced can lead to a predetermined amount of wave groupiness in any wave record.

Any periodic time record can be described as a Fourier series with the linear combination of all those cosine and sine functions which have the same period, say as

$$f(t) = a_0/2 + \sum_{n=1}^{\infty} a_n \cos \frac{2\pi n t}{T} + \sum_{n=1}^{\infty} b_n \sin \frac{2\pi n t}{T}$$

where:

$a_0/2$ - mean value

a_n, b_n - Fourier coefficients for the frequency component of the order 'n'

From these Fourier coefficients, the values of the amplitudes A_n, and the phase angles ϕ_n, associated with each frequency component can be derived as follows:

$$A_n = \sqrt{a_n^2 + b_n^2} \quad \text{and} \quad \phi_n = \tan^{-1}\frac{b_n}{a_n} \quad \text{for } n=1,2,3,\ldots\infty$$

The variation of these amplitudes over the frequency is referred to as the "Amplitude Spectrum" and that of the phase angles over the frequency as the "Phase Spectrum". Hence any periodic time record can be represented by its Amplitude and Phase spectrum in the frequency domain.

In a laboratory simulation of sea states, very often, importance is attributed to the amplitude spectrum alone, thereby reproducing only the amplitude associated with each frequency component and disregarding the importance of its phase spectrum. One of the main reasons is that the phases appear to be randomly varying within $-\pi$ to π, and are assumed to contain no useful information.

It has been found that the phases can be important and that the use of the amplitude spectrum alone does not give a unique description of the wave record associated with it. A combination of the same amplitude spectrum with different phase spectra can result in entirely different wave trains (grouped or ungrouped). Hence if it is required to reproduce a particular wave record, say as found in the prototype, it is necessary to reproduce the phase spectrum associated with it and it is not sufficient to use randomly selected phases as most of the presently available synthesis techniques do.

In order to illustrate that identical amplitude spectra (Fig. 4a) can lead to different time functions depending on the particular choice of a phase spectrum, the following two, perhaps somewhat extreme, cases are presented. In the first case, the phase spectrum is defined by means of a random selection via a noise generator with uniform distribution of numbers from $-\pi$ to $+\pi$ and in the second case, the phase is made to vary linearly over a limited range as illustrated in Fig. 4b. The time functions derived from these two identical amplitude spectra, but different phase spectra are, as shown in Fig. 4c, quite different. Further considerations of the relevance of the phase spectra are given in Funke and Mansard (10).

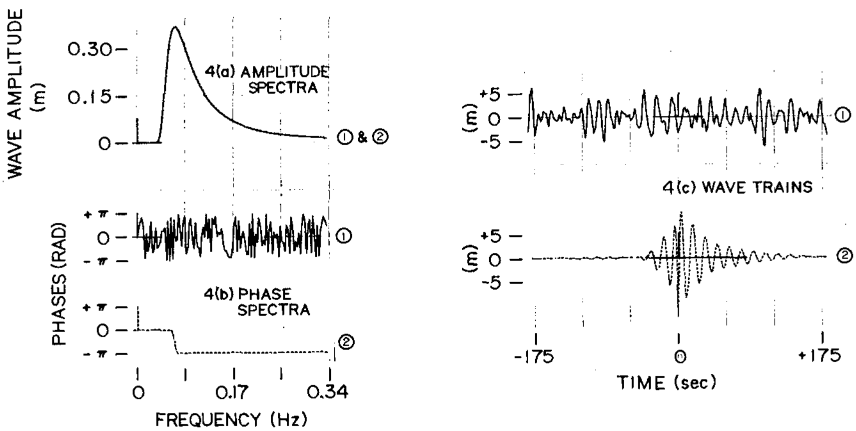

FIG. 4 EFFECT OF THE PHASE SPECTRA ON WAVE TRAINS

A measure of wave groupiness can perhaps be obtained by plotting the "instantaneous wave energy history" (IWEH) of a wave record. This function represents the square of the instantaneous water surface elevations, smoothed by taking a running average over a time interval equal to the period associated with the peak frequency of the energy density spectrum.

There are several steps involved in synthesizing a wave history with the same amount of grouping as observed in a prototype wave record. Sinusoidal waves of a frequency equal to the desired peak spectral frequency are modulated by the prototype IWEH. This modulation will produce a time series similar in grouping to that of the original wave record and may be analysed for the phase spectrum by Fourier analysis. The phase spectrum is then used with the desired amplitude spectrum in an inverse Fourier transform to produce a wave record with the proper wave height statistics and with the frequencies phased to also give the specified wave grouping. This technique is described in full detail in the earlier referred to report of Funke and Mansard (7).

Three wave generation techniques were applied in the tests reported here. The first followed the technique briefly described above where a wave train was synthesized to have the same degree of wave grouping as a prototype wave record, but with a JONSWAP amplitude spectrum. The result is a well grouped wave history, shown in Fig. 5 with its IWEH, and which realistically simulates a prototype situation. The acutal prototype wave record, with the corresponding IWEH is also shown in the same figure. For convenience, this synthesized wave train will be referred to as "grouped".

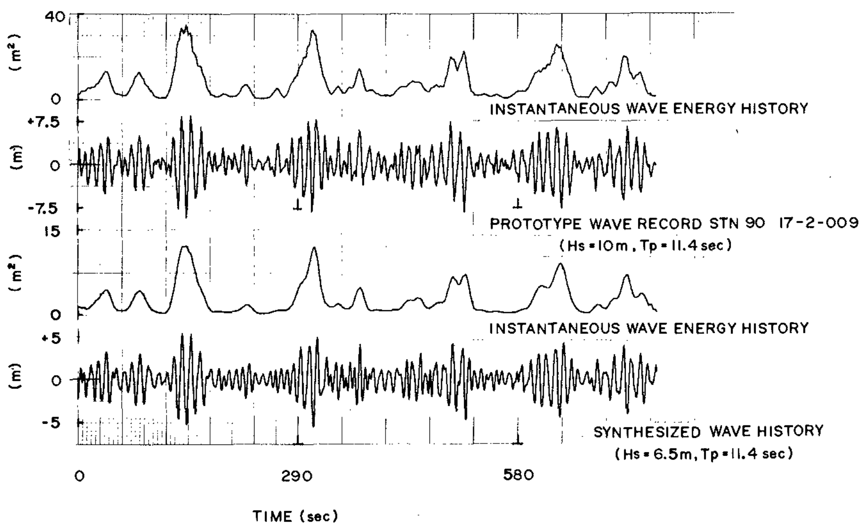

FIG.5 SYNTHESIS OF WAVE GROUPING FROM A PROTOTYPE WAVE RECORD

The second and more common technique, combined a randomly assigned phase spectrum with the same JONSWAP spectrum in an inverse Fourier transform to obtain a wave history of undetermined wave grouping. In this particular case the result is a wave train with little apparent grouping (Fig. 6), and will for convenience be referred to as "non-grouped". Again the IWEH of this non-grouped wave train has been calculated and is also shown in the figure. Fig. 7 presents a comprehensive comparison of the two wave trains and their corresponding energy density spectra. It can clearly be seen, that whereas the two amplitude spectra are nearly identical, the wave trains are very different, as far as the degree of wave grouping is concerned. It is important to emphasize that using a randomly assigned phase spectrum can produce wave trains with either more or less grouping than a particular prototype record.

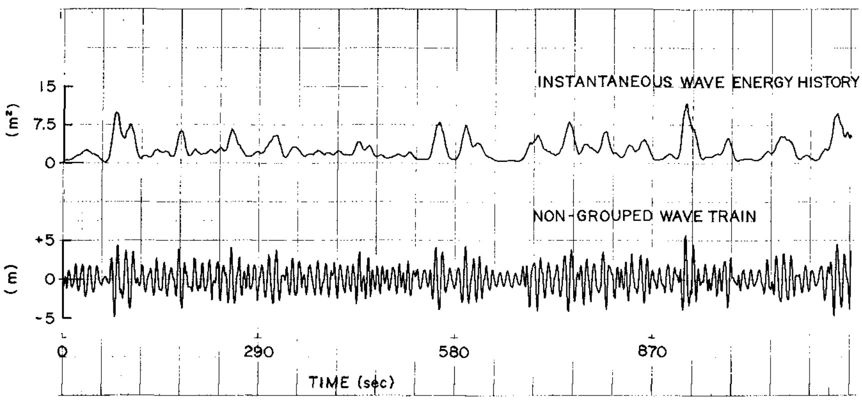

FIG.6 NON-GROUPED WAVE TRAIN AND ITS INSTANTANEOUS WAVE ENERGY HISTORY

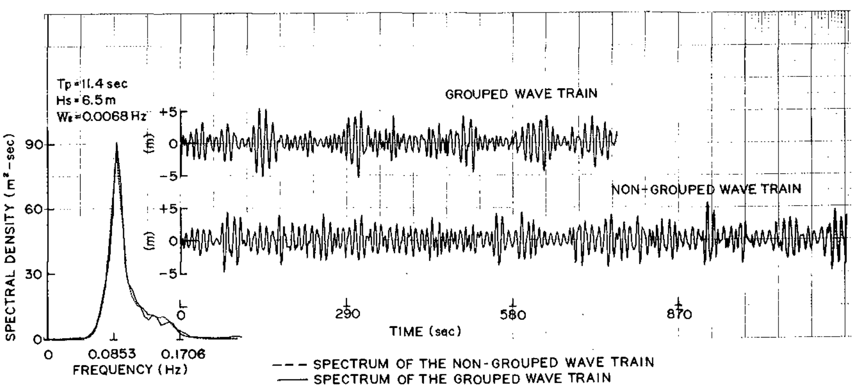

FIG.7 COMPARISON OF THE GROUPED AND NON-GROUPED WAVE TRAINS

The third technique as presented in the earlier paper by Johnson and Ploeg (4) generated an accentuated and rather artificially grouped wave train, synthesized by an algorithm described by Funke (11) which phases consecutive waves in such a manner that they all focus at a predetermined distance from the wave maker. For convenience, this wave train was referred to as "artificially grouped" and is shown in Fig. 1.

TEST RESULTS AND DISCUSSION

The two examples of the grouped (synthesized to correspond to an observed wave record containing wave grouping) and the non-grouped (generated using a randomly assigned phase spectrum) wave trains, as recorded in deep water conditions, have been shown in Figs. 5, 6 and 7. Both wave trains have a peak period of 11.4 secs and a significant wave height of 6.5 m. To attempt to define the degree of wave groupiness, the RMS value of the instantaneous wave energy history (IWEH) is being proposed. The RMS value of the IWEH of the grouped wave train (Fig. 5) is 0.7 m, while for the non-grouped wave train this value is 0.57 m. The investigation indicates that the breakwater response to the two wave trains is quite different, with the grouped wave train causing severe rocking of the armour and several units to be completely displaced with every wave group (failure mode of 4), but the non-grouped wave train producing only some minor rocking and no displacements (failure mode of 2). A description of modes of failure is given by Baird and Paul (12).

Because the somewhat subjective nature of defining modes of failure, it is difficult to record the results of rubble mound breakwater stability tests precisely, and usable for later reference. The most comprehensive documentation of the results is probably a 16 mm film, made during this study. An edited version of this film was shown at the conference, clearly indicating the differences in the response of the breakwater to the non-grouped and the grouped wave trains.

As mentioned earlier, there does appear to be a mechanism by which the first wave in a group loosens up a unit, the second causes it to be pulled (or pushed) a little out from the armour layer, while the third wave rolls the unit up and down the face of the structure. The non-grouped wave train does not have the same sequence of waves and is therefore not as damaging. It may be possible to relate this partially to the build-up of pressure in the filter layers, and perhaps even the breakwater core, and the resultant stronger down rush.

In Fig. 8 damage factors have been plotted for two types of wave trains, versus the significant wave heights

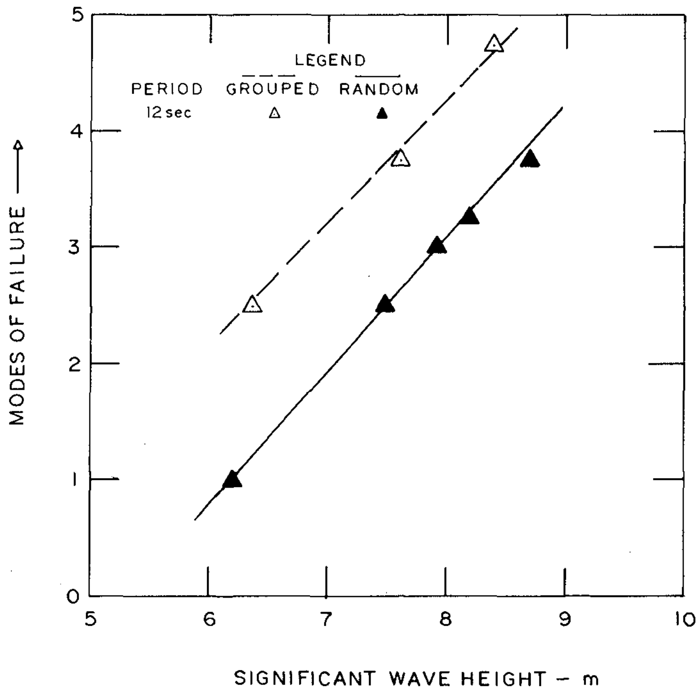

FIG.8 DAMAGE CURVES FOR GROUPED AND NON-GROUPED WAVE TRAINS VERSUS SIGNIFICANT WAVE HEIGHTS

for the case of a peak period of 12 s. The dolos weight is 12.2 t (metric) modelled to a scale of 1:34.3 on a slope of 1:1.5 (Fig. 3). For equal damage factors the non-grouped wave train clearly permits a considerably higher design wave condition than the grouped.

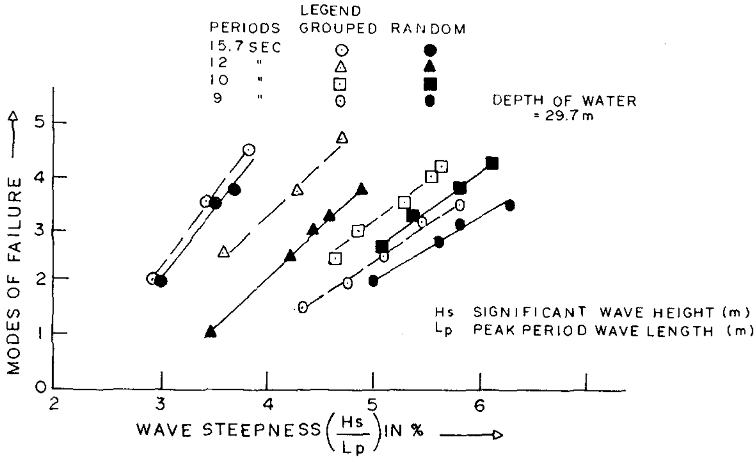

FIG. 9 DAMAGE CURVES FOR GROUPED AND NON-GROUPED WAVE TRAINS VERSUS WAVE SLOPES

More extensive tests for different peak periods, dolos weights, water depths and model scales have been carried out and the results are consistently showing a marked difference between the response of grouped and non-grouped wave trains. Fig. 9 is a typical plot of damage factor against wave condition, expressed here as a wave slope parameter in order to include effects related to wave period and water depth. At the time these experiments were performed, however, the method for synthesizing wave grouping was not yet available and the tests were run directly with digitized prototype records, similar to the practice of the Danish Hydraulics Institute (Ref. 13). This means that the peak period variations were achieved by either stretching or compressing the wave history somewhat unrealistically, thus leaving the tests at long and short periods difficult to interpret.

The classification of grouped and non-grouped wave trains is at the present time not clearly defined. It relies mostly on interpretation only. An actual measure of the degree of wave groupiness would ideally come from a spectral analysis of the IWEH thereby identifying the groups by amplitude, length and frequency of occurrence (and therefore for a given peak frequency, also an indication of the number of waves per group). However, the length of commonly available wave records is usually too short to give an adequate spectral distribution.

With the synthesis technique it is possible to construct wave histories of equal grouping regardless of the width of the power spectral density function, thus showing that spectral width alone cannot be a unique way of determining wave grouping. However, there does seem to be a relationship between the width of the spectrum and the way the amount of groupiness changes with propagation. Further tests are presently under way to consider this aspect.

The tests reported here are all for a dolos armour layer, but the conclusions apply in varying degrees to other types of armour also. The experiments with dolosse did, however, highlight an aspect which applies specifically to this type of unit.

Observing the severe rocking and indeed displacement of dolos units in the model, especially when exposed to the grouped wave trains, leads to the obvious question, how such units will perform when not only the hydraulic parameters are scaled, but also the structural ones. No material has unfortunately been found so far, which has all the correct physical properties to simulate unreinforced concrete (density, elasticity, tensile and compressive strength, friction, etc.) to the correct model scales. Prototype failures of dolos units occur most often through the shank; if it is assumed that this type of failure is mainly caused by exceeding the tensile bending strength of concrete, the model dolos units can be cut and a thin wafer of a material with the correct tensile strength can be inserted. The recent tests on the Sines breakwater (8) were run with a scale of 1:52. To simulate a concrete tensile strength in bending of 35 kg/cm^2 and using the Froude scaling law, a material needed to be used with a tensile strength of about 0.7 kg/cm^2. A synthetic material, consisting of a mixture of stearic acid and polypropylene, used for artificially modelling the behaviour of ice in the laboratory, has approximately a strength of 0.75 kg/cm^2. An extensive series of simple and cantilever beam tests was performed to establish the adequacy of inserting a thin wafer of this synthetic material within a much stronger material, to simulate the desired tensile bending strength correctly. Using this simulation technique with the dolos units, the Sines breakwater tests led to an extremely good comparison between prototype and model performance. The results of similar tests, but with commonly used model units, i.e. without scaling any of the strength parameters, were much more difficult to interpret. The actual breaking of the model units caused immediately the breakage of many other dolosse and a very rapid, general deterioration of the structure. It became quite apparent, that the accepted philosophy of allowing a certain percentage of damage to a rubble mound breakwater as a design condition, can not be relied on when large artificial armour units are used. A 16 mm film of the behaviour of the two types of model units illustrates the differences very clearly. A photograph of the final profile (Fig. 10) shows in the foreground, the completely failed section where dolos units were used which simulated the tensile strength of concrete, but the apparently less damaged section in the background, where the commonly used units were placed.

FIG. 10 PHOTOGRAPH OF DAMAGE TO MODEL BREAKWATER USING MODIFIED DOLOS UNITS

CONCLUSIONS

Firstly, wave grouping has been shown to be an essential parameter in the correct model testing of rubble mound breakwater stability. Since both wave trains considered here had similar spectra and wave statistics, it is evident that one must define the degree of wave grouping as actually observed in nature or as may be expected to occur at a particular location. The typical wave parameters used so far, including a spectral width parameter, are not deemed to give sufficiently accurate description of a particular sea state to allow adequate reproduction in a laboratory wave flume. It is expected that a "groupiness" factor will have to be multi-dimensional, not only taking account of the presence of such groups, but also of the periodicity of their occurrence and their widths.

Secondly, without correctly scaling the strength of concrete of the armour units in model tests of rubble mound breakwaters, it is extremely difficult to determine accurately the percentage of damage. It is not possible to interpret correctly the motions of the armour units, without being able to establish when they will break. As soon as breakage begins to occur, the response of the structure changes drastically, leading very quickly to failure conditions.

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