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# THE EFFECT OF WAVE GROUPING ON ON-SHORE STRUCTURES

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## ABSTRACT

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This paper represents a contribution to the current discussion on whether model tests in waves should be carried out with waves which are, both in time and frequency domaine, reproduced in accordance with field records (and thus conserving the succession of the waves) or whether irregular waves generated solely in accordance with an energy spectrum obtained from field data can be used.

To investigate the importance of the succession of waves to the impact on coastal structures, run-up/down on permeable and impermeable slopes and stability of dolos armour were investigated in model tests by using three different wave patterns. A significant influence of the succession of waves is demonstrated. A jump in wave height seems to be a very important wave pattern which should be included in the analysis of wave grouping. Also the importance of wave period and wave steepness to the relative run-up/down and to the stability of dolos armour is shown.

A proposal to establish a set of universal graphs for the stability of dolos blocks (or any other "interlocking" blocks) is made.

## INTRODUCTION

Today model tests in waves are generally carried out with irregular waves generated in accordance with a certain energy spectrum. The energy spectrum entirely specifies both the probability distribution of the wave heights and the grouping of the waves if the assumptions of the classical theory apply: namely, that the sea is the linear sum of waves with different frequencies, and phases are independent, random variables each with a uniform probability density on the interval $(0.2\ \pi)$. It may be, however, that if there is significant non-linearity in the waves there will be some coupling of the phases of the component waves at different frequency, which might in turn modify the wave grouping.

In many laboratories the wave spectrum is obtained from wave records and the waves are generated using the assumption of relative random phases. Little work has been done to confirm that the wave groupings so produced are those in real seas. The correct grouping is important if coastal structures respond significantly differently when exposed to different wave patterns, i.e. patterns which contain the same size maximum wave. If responses are sensitive to such effects, the laboratory waves should be checked against natural waves to confirm that patterns giving the worst conditions occur with the correct frequency during the storm. The importance of this statement is clear in such characteristic coastal problems as determination of the optimum height of dikes in terms of percentage overtopping by waves and stability of breakwater armour layer blocks, whose stability is known to be dependent to some extent on the duration of the wave attack.

This article presents some preliminary results on the sensitivity of wave run-up and armour block stability to wave grouping.

## EXPERIMENTS

Two experiments representing typical problems were conducted in a wave flume.

(1) To determine run-up and run-down on a 1 in 5.4 smooth impermeable slope.

(2) To determine run-up and run-down and block stability for a 1 in 1.5 slope protected by dolos blocks.

Both models were subjected to the three different wave patterns shown in Fig. 1. Pattern 1 is a regular sinewave which can be regarded as a reference. Pattern 2 consists of a big wave followed by a small wave and it was chosen because one might expect large run-up values due to minimum backwash from the proceeding small wave. Pattern 3, a strongly grouped wave train made of two sinewaves, was chosen because model tests made by Johnson and Ploeg (1977). They have indicated that strongly grouped waves are more critical than random waves.

The three wave patterns used in the experiments described here are arbitrary to some extent and it may well be that other patterns are also important.

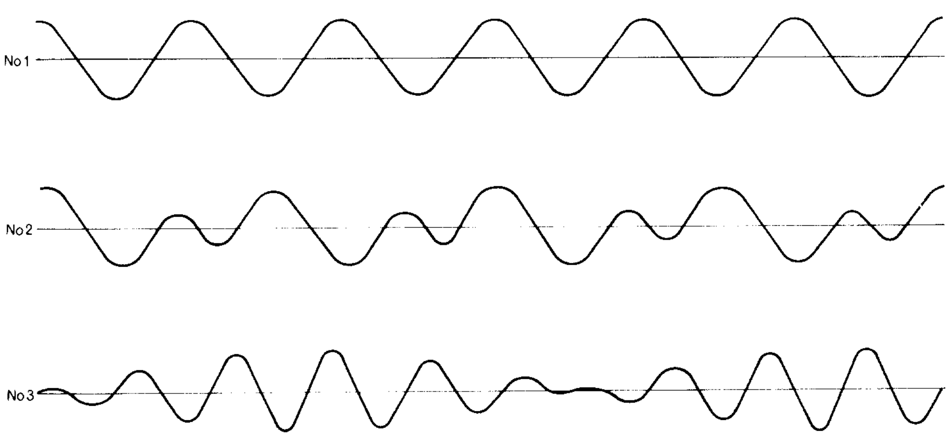


Fig. 1. Wave patterns (vertical scale amplified).

For each wave pattern both the frequency and wave height were varied in small steps. Typical frequency and wave height intervals for the biggest wave in each pattern were 0.3—1.1 $s^{-1}$ and 4—13 cm, respectively. In every test series the increase in wave height was stopped just before wave breaking took place in the flume. The duration of each test corresponded to approximately 200 waves.

The model tests were made in a basin 33 m long, 5.8 m wide with a horizontal bed. By means of walls the flume was subdivided into two test channels, each 20 m long and 0.5 m wide. To minimize reflections a 1 in 20 shingle spending beach was placed at the end of the remaining portion of the flume. The dividing walls were terminated at the paddle end by a section of wall with permeability increasing towards the paddle, which was intended to reduce the reflections caused by an abrupt termination.

The wave generator, which was of the piston type, was controlled by a synthesizer which recycled the input signal. The waveform was defined by 120 ordinates equally spaced over one cycle. Both amplitude and frequency of the output signal could be changed gradually.

The waves were recorded by two twin-wire resistance probes placed 1.5 m from the paddle and 0.6 m in front of the models. (See Fig. 2, which shows the test sections.)

By recording the waves from the start of wave generation it was found that no increase of wave heights took place, i.e. practically no wave energy was reflected back to the paddle. This was due to the drastic reduction of the reflected waves by the expansion of the narrow test section to the wider section of the basin.

The water depth was kept constantly equal to 30 cm (still water condition).

The dolos blocks, having a height of 3.4 cm, a weight of 14.5 g and a specific gravity of 2.32, were placed in two layers on a core of graded quarry stones (see Fig. 2). The laying density was 2180 units per $m^2$, corresponding to a shape factor of 1 and bulk porosity of 63%.

The impermeable slope was constructed of non-lacquered plywood.

Run-up, $R_U$, and run-down, $R_D$, are defined as the maximum vertical

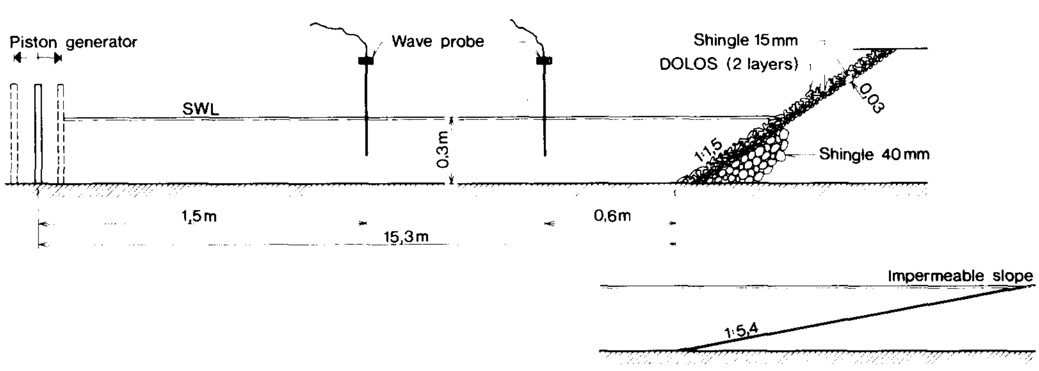


Fig. 2. Model test sections.

distances of solid water on the surfaces measured from still-water level. The observations were done by eye by reading on scales placed on the surface of the slopes.

To improve the accuracy when reading the run-up levels on the dolos slope which has no well-defined surface, a horizontal bar was moved along the top of the blocks until the solid water table just touched the under side of the bar, the level of which was then defined as the operational run-up level.

As a horizontal bar would disturb the flow when measuring the run-down level, it was more difficult to judge this level, but because of the fact that the same wave group was repeated many times in each test the absolute accuracy is assumed to be relatively good.

In the case of the impermeable plywood slope, the run-up level was easily observed on the scale. The operational run-down level on the plywood slope was defined as the lowest position of a 2 mm thick waterfilm. This position was determined by moving a vertically held thin bar (which was tapered over 2 mm) along the plywood surface.

An order-of-magnitude estimate of the possible maximum errors is as follows. Dolos slope run-up ± 0.5 cm; run-down ± 1 cm. Plywood slope run-up ± 0.3 cm; run-down ± 0.5 cm.

## RESULTS

Figs. 3—7 show the results which are presented in terms of the Battjes (1974) surf similarity parameter $\xi = T(\frac{g}{2\pi H})^{1/2} \tan\alpha$ (first used by Iribarren and Nogales). In these tests $H$ is the maximum wave height measured at a point 0.6 m in front of the slope (the maximum wave height is defined as the maximum difference in water level between two successive zero-crossings in the downward direction); $T$ is the time elapsing between the same two zero-crossings; $g$ is the gravitational constant and $\alpha$ is the angle of the slope. Applying the deep-water wave length, $L_0$, the parameter can be rewritten as $\xi = (H/L_0)^{-1/2} \tan\alpha$, which can be interpreted as a ratio between slope steepness and wave steepness. Plots of dolos stability, $R_U$ and $R_D$ against $H$ clearly showed the strong influence of the period (which in dimensionless form takes the form of a wave steepness parameter) and with reference to the report on wave run-up and overtopping by the Technical Advisory Committee on Protection against Inundation in Holland (1974) and to Bruun and Gunbak (1976) it was concluded, that the present results were best presented in terms of $\xi$.

In all tests waves broke on the slopes. The breaker types were in excellent accordance with the following transition values (Battjes, 1974):

| | |
|---|---|
| Surging or collapsing | $\xi > 2$ |
| Plunging | $0.4 < \xi < 2$ |
| Spilling | $\xi < 0.4$ |

(As the lower limit of $\xi$ was 0.5 in the tests, the transition value for the spilling breakers could not be checked.)

The ratio of water depth, $d$, to maximum wave height, $H$, in front of the slopes was $2.1 < (d/H) < 8.6$. There was no significant influence of $d/H$ on the test results.

Fig. 3 shows the variation of relative run up and run down with $\xi$ for the smooth slope. It can be seen that as $\xi$ increases from 0.5 to a value corresponding to maximum run-up, wave pattern 2 gives a considerably bigger run-up (regression line $R_U/H = 1.65\xi$ in the interval $0.5 \lesssim \xi \lesssim 1.5$) than patterns 1 and 3 (regression line $R_U/H = 1.1\ \xi$ in the interval $0.5 \lesssim \xi \lesssim 2.3$). The small divergence from Hunt's formula $R_U/H = \xi$, which is regarded as being valid for regular waves such as pattern 1, might partly be due to experimental deviations in bottom contours and the place where $H$ was measured and partly

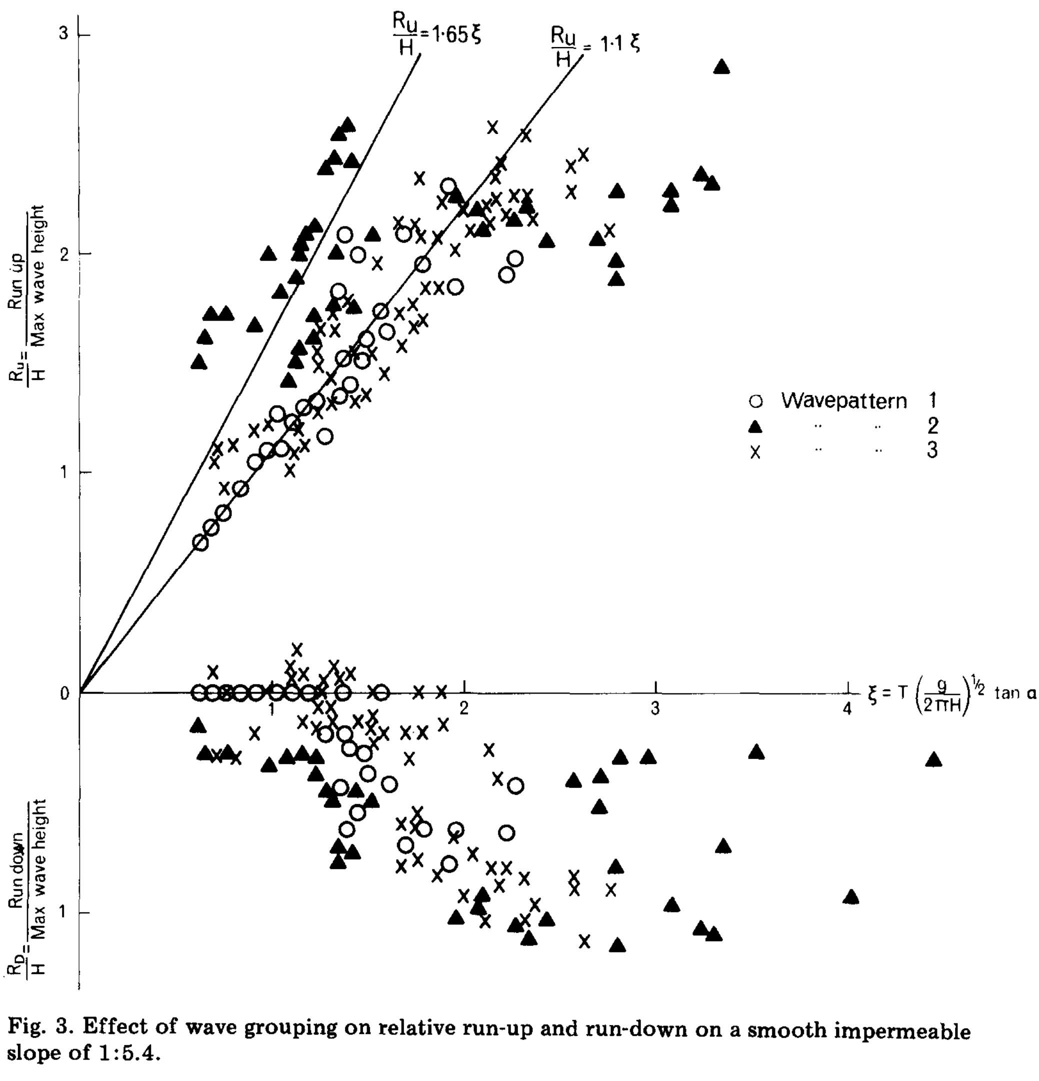


Fig. 3. Effect of wave grouping on relative run-up and run-down on a smooth impermeable slope of 1:5.4.

be due to the fact that $R_U$ in these tests is defined as the maximum run-up and not, as generally used in tests with regular waves, as the average value, the latter being relatively smaller because the experimental run-up for regular waves is generally stochastic in nature with a narrow distribution. From Fig. 3 it can be seen that maximum run-up is approximately the same for patterns 2 and 3 and a little higher than that for pattern 1. The relationship between the three wave patterns described above for run-up also seems to hold for run-down. The negative values corresponding to pattern 3 are due to the variations in mean water level caused by the grouping.

Fig. 4 shows the relative run-up and run-down on the dolos slope and here again it can be seen that pattern 2 gives the highest run-up values. The data clearly shows that run-up increases with $\xi$ until the value $\xi \simeq 8$, and then it

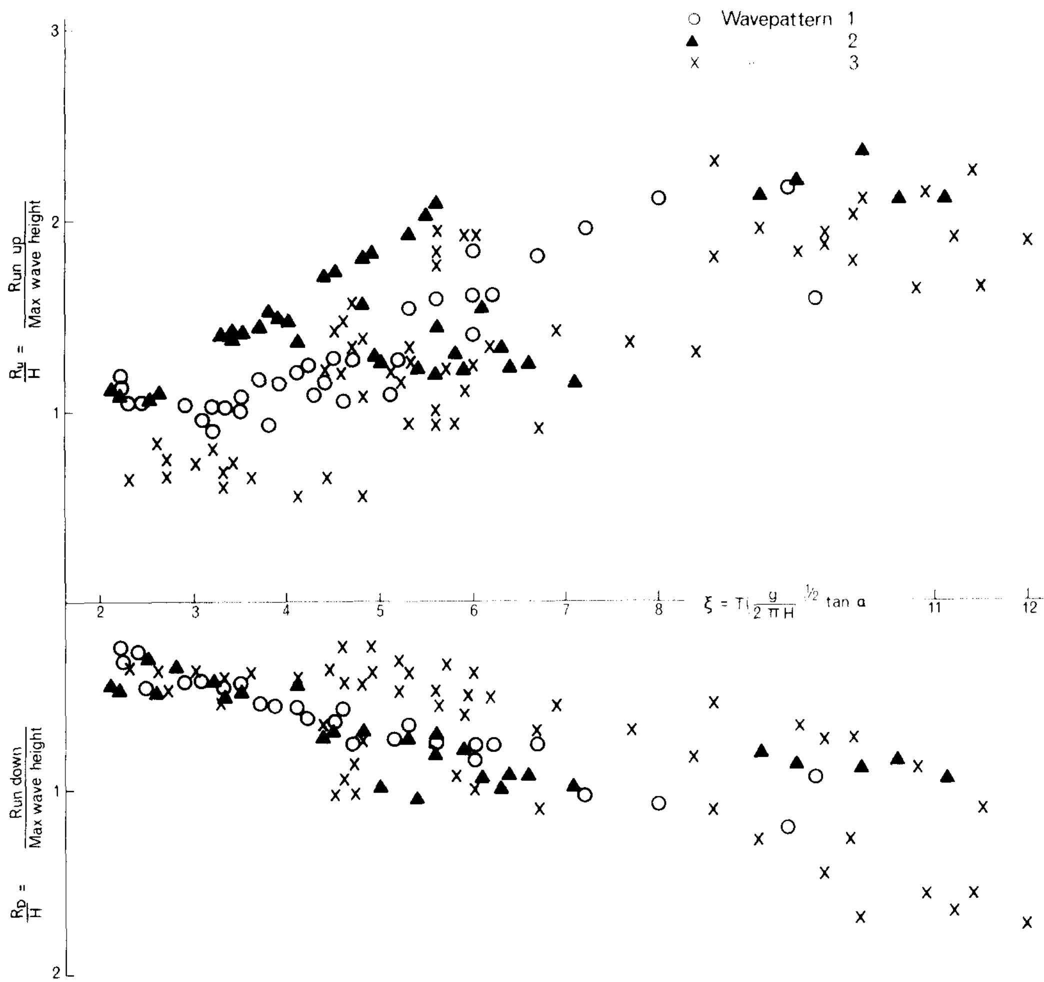


Fig. 4. Effect of wave grouping on relative run-up and run-down on a Dolos slope of 1:1.5.

becomes constant with a remarkably high value of 2.1. The run-down for all patterns is grouped around the same mean ($R_D/H = \xi/7$) for $\xi < 7$. For higher $\xi$-values run-down for pattern 2 seems to become nearly constant while run-down for patterns 1 and 3 increases with $\xi$ with surprisingly big values ($R_D/H = 1.7$) being recorded. The considerable scatter related to pattern 3 is due to variation in the mean water level caused by the strongly grouped wave train. Maximum values of run-up and run-down on dolos slopes are usually assumed to be much smaller than the values recorded in these experiments. In a paper by Bruun and Gunbak (1976) for example, $R_U/H$ and $R_D/H$ are considered constant for $\xi > 4$, with values of 1.2 and 0.75, respectively, but this conclusion is based on tests carried out solely for $\xi < 5.3$.

In order to investigate the absolute run-up caused by waves with the same height and period the absolute run-up, $R_U$, was plotted against $\xi$. For each pattern graphs were drawn through points of equal wave periods, as shown in Figs. 5 and 6. From these figures it may be concluded that for normal design wave conditions ($\xi < 1.6$ for the smooth slope and $\xi < 5$ for the dolos slope) the same wave (specified values of $H$ and $T$ or $\xi$ and $T$) gives the highest run up when it is part of pattern 2 and it is clear that this run-up is considerably bigger in all cases than run-up corresponding to pattern 3. For larger values of $\xi$ the picture is less clear as the differences between the different patterns seem to diminish. From all the above described tests it is seen that (except for the large $\xi$ values) wave pattern 2 gives the biggest run-up values. The physical explanation of this is that the big waves in this pattern only interfere with the backrush from a small preceding wave. In the case of both patterns 1 and 3 the big waves have to run up against a considerable stream of water flowing back from a preceding big wave.

The reason why the differences between the different patterns seem to diminish for larger values of $\xi$ might be that the run-down process is in any case completed before the next wave arrives, which means that the behaviour of a wave on the slope tends to be independent of the preceding wave, which again equalizes the effect of a wave, even though it is a part of different patterns.

The stability of the dolos slope when subject to different wave patterns is shown in Fig. 7 where the minimum value of $H/h$ (wave height over dolos height) giving rise to a certain degree of damage is plotted against $\xi$.

As Brorsen et al. (1974) found that the stability of the dolos blocks is nearly independent of the slope for $1 < \cot\alpha < 3$, and as the density and the specific density of the blocks were kept constant during the tests, the parameter $H/h$ can be regarded as a degree of damage stability number. The definition of the degree of damage is given in the figure. As the normal design condition for a dolos armour layer is chosen between degrees of damage 2 and 3, it can be seen that also in this case wave pattern 2 is the most critical, giving $H/h$ values which are about 25% less than those corresponding to patterns 1 and 3 for $\xi < 5$, (normal design wave conditions). This is of course due to the bigger lift forces created by the higher run-up and run-down velocities related to pattern 2.

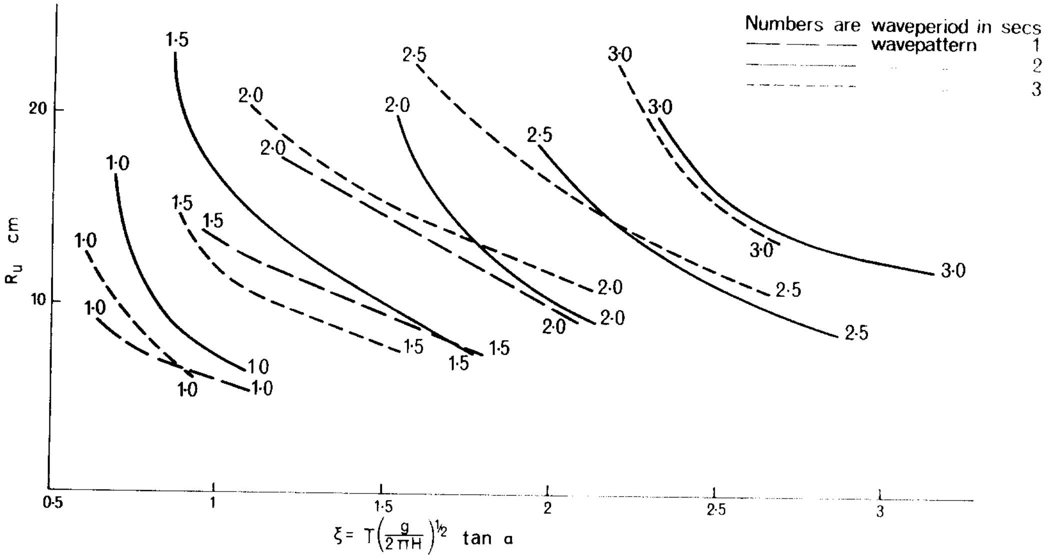


Fig. 5. Effect of wave grouping on run-up on a smooth impermeable slope of 1:5.4.

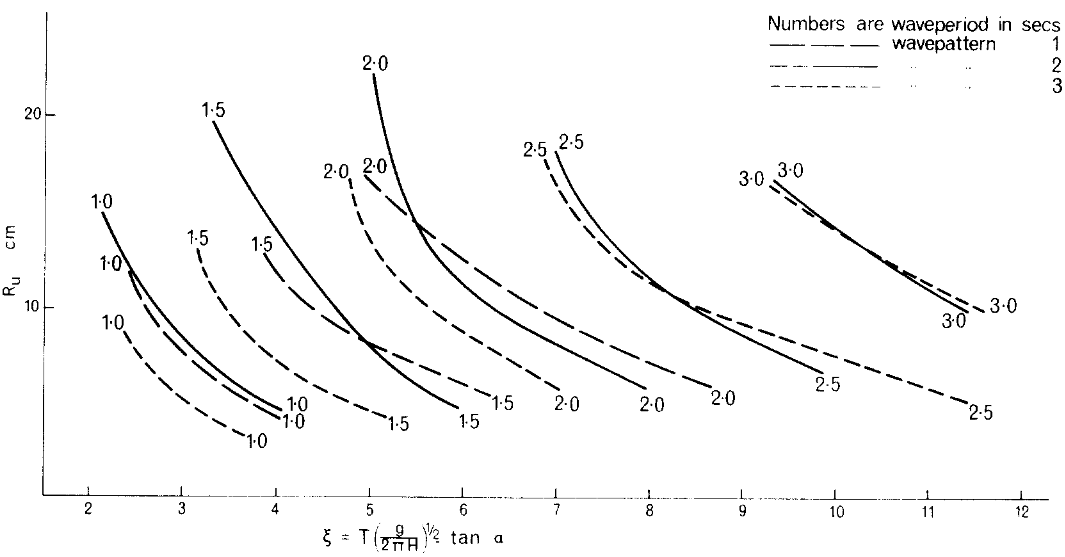


Fig. 6. Effect of wave grouping on run-up on a Dolos slope of 1:1.5.

Another important conclusion that might be drawn from the graphs is that stability decreases steadily with increasing $\xi$. This means that the wave period plays a role and that long waves with a small steepness might sometimes be more dangerous than higher, but steeper waves. This is in accordance with practical experience where damage to breakwaters very often occurs towards the end of storms in which wave heights have decreased but, where periods

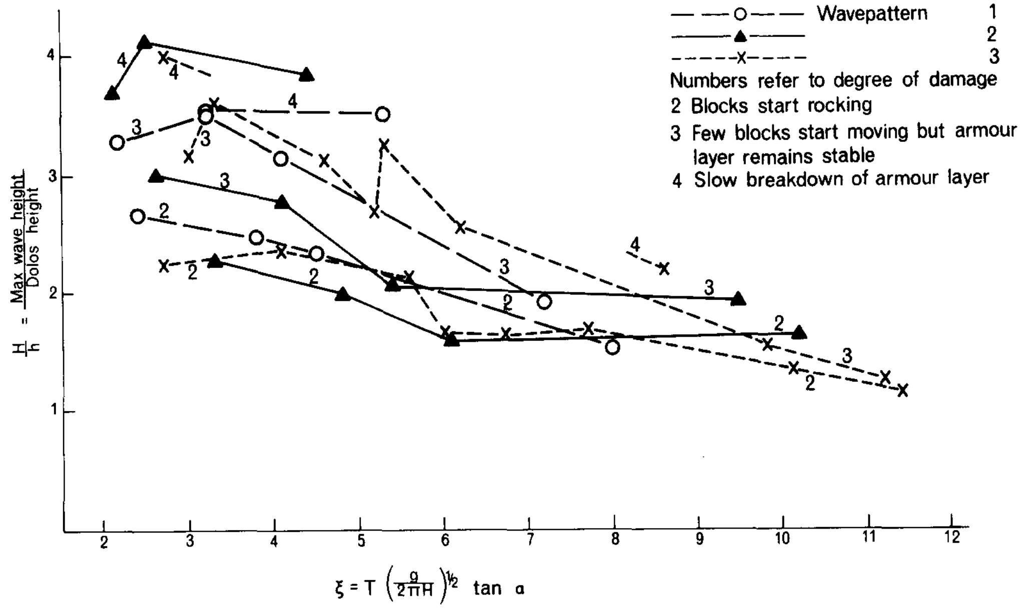


Fig. 7. Effect of wave grouping on stability of a Dolos slope of 1:1.5.

have increased (see also Bruun and Gunbak, 1976). It should be noticed that the graphs do not indicate a stability minimum corresponding to the so-called resonance condition as mentioned by Bruun and Gunbak (1976) for rubble-mound breakwaters when $2 < \xi < 3$.

This discrepancy and the steady decrease in stability to relatively low stability levels for big $\xi$-values might be explained by the experiments done by Brebner (1978), in which he found that the stability of dolos layer and rock armour layer was the same for a steady flow over a horizontal bed formed by dolos blocks and quarry blocks having identical mass and density. As $\xi$ increases, the relative importance of inertia and impact forces will decrease and a growing part of the run-down will take place as a flow over (parallel to) the surface, thus creating a situation with dominating drag forces as in the case of Brebners tests. This relation between the flow characteristics corresponding to big $\xi$-values and the relative sensibility of dolos blocks to a steady parallel flow prevents a rise in stability with increasing $\xi$-values (and thus a stability minimum). Fig. 8 is a qualitative illustration of the relation between the stability of quarry rock and dolos.

From Fig. 7 it can be seen that the experiments seem to show a tendency of decreasing distance between degrees of damage 2 and 3 as $\xi$ increases. This again might be explained by comparing the run-up and run-down flow to a steady flow over a horizontal bottom, i.e. formed by sand or gravel, in which case it is known that hardly any movement takes place before a critical velocity, which cause a displacement of the bed material, is reached.

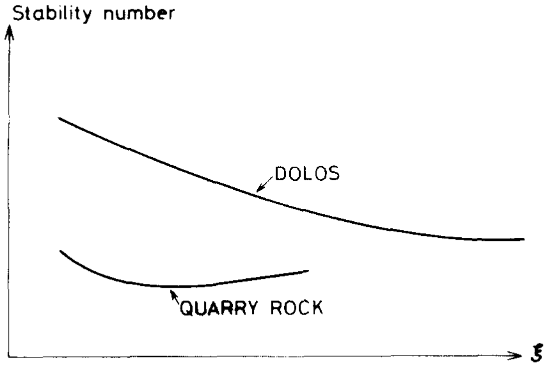


Fig. 8. Qualitative illustration of the relation between the stability of quarry rock and dolos.

## A PROPOSAL FOR ESTABLISHING A SET OF UNIVERSAL GRAPHS FOR THE STABILITY OF DOLOS BLOCKS

A diagram similar to Fig. 7, but based on more extensive tests, could replace the Hudson equation, which is not valid for dolos blocks. It would then be appropriate to plot against ξ, a stability number defined as:

$$\frac{H}{\left(\frac{W}{\gamma_D}\right)^{1/3}\left(\frac{\gamma_D}{\gamma_W}-1\right)}$$

where $W$ = the weight of the block, $\gamma_D$ = specific weight of blocks, and $\gamma_W$ = specific weight of water. It might be seen that this stability number can be derived from Hudson's formula as $\sqrt[3]{K_D \cot\alpha}$ ($K_D$ is Hudson's stability factor). This reflects the results from experiments by Brorsen et al. (1974) where it was found that the stability is nearly independent of the slope angle for $1 < \cot\alpha < 3$.

ξ should probably be defined as $\tan\alpha(H/L)^{-1/2} = \tan\alpha\left(\frac{H}{TU}\right)^{-1/2}$, where $H$, $L$, $T$ and $U$ are characteristic values of wave height, wave length, wave period and wave phase velocity corresponding to conditions in front of the structures and related to the wave spectrum and water depth. The relations should be obtained from experiments in which the duration of wave attack and core and filter layer permeability and roughness should be specified.

## CONCLUSIONS

Coastal structures respond differently when exposed to different wave patterns that contain the same maximum wave, i.e. there is a significant influence of the succession of the waves. This means that research into the occurrence and frequency of characteristic patterns in wave records should be undertaken and the results incorporated into sea conditions used in model tests. It also underlines the importance of using irregular waves instead of regular waves in model tests.

The experiments showed the significant effect of a discontinuity in wave trains, i.e. a jump in wave heights where a small wave is followed by a big wave. Such wave groups should therefore be included in the analysis of wave grouping.

It has also been shown in model tests of a dolos slope of 1 in 1.5 that the relative run-up and run-down ($R_U/H$, $R_D/H$) and the relative stability of dolos armour layers are affected by the wave period. Very big values of the relative run-up and run-down and a reduced stability and safety margin of the dolos armour layer may be expected when long waves with small steepness are present.

A proposal for establishing a set of universal graphs for the stability of dolos blocks (or any other blocks with similar interlocking or interknitting characteristics), meant to replace the use of the Hudson formula, is made.

## ACKNOWLEDGEMENTS

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