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Rocking armour units: Number, location and impact velocity

Jentsje W. van der Meer and Guido Heydra
Delft Hydraulics, P.O. Box 152, 8300 AD Emmeloord, The Netherlands
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ABSTRACT

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As a part of a very extensive research on strength of concrete armour units model tests were performed on breakwater sections armoured with Cubes and Tetrapods. Stability tests resulted in a prediction of the number of moved units and the number of impacts as a function of wave height, period and location on the slope. Measurements on acceleration during impacts resulted in a description of the distribution of impact velocities at the centre of the unit. The expressions are applicable in prototype conditions.

INTRODUCTION

During the late seventies and early eighties several breakwaters were severely damaged along the coast of the European and African countries in the Mediterranean and the Atlantic Ocean. The armour layers of these structures consisted of large concrete units of 20 up to 60 ton. These units had a slender shape and were made of unreinforced concrete. Delft Hydraulics was involved in the rehabilitation studies of some of these projects. Due to the emphasis on the problem of damaged breakwaters with large concrete units basic research project was developed.

This basic research project ran from 1983 to 1989. One of the most encouraging aspects of this project was the collaboration between contractors, consulting engineers and research institutes or universities (see the Acknowledgements for a complete list). Due to the financial support and the organizational aspects all participants were of Dutch origin.

The project was carried out in three phases. During the first phase three items were studied: loadings; the strength of concrete armour units; and concrete technology. In this phase the large failure cases (Sines, Gioia Tauro, Arzew, Tripoli and San Ciprian) were analysed more in depth. Furthermore

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the state-of-the-art in concrete mechanics and in concrete technology was described and priorities in further research were given. Some of the results were given by Ligteringen (1985) and Heydra (1985).

In the second phase another three items were investigated. These items were: measurements of impact velocities together with damage on a schematized breakwater; concrete technology aspects with regard to hardening; and measuring of load-time response of colliding concrete bodies. This phase was finished in 1988 and gave in fact three extensive (Dutch and confidential) reports all concerning different parts in the design process for large concrete units.

The third (and at this moment, final) phase started in 1988. The aim of this study was: an extension of the tests on load-time response of colliding concrete bodies on a much larger scale, an integration of all parts of the previous phases leading to an overall design procedure, and some applications in practical situations. This paper deals with the measurements on impacts and the analysis of the results into an applicable format.

In the second phase a large number of tests were performed on breakwater cross-sections armoured with Cubes or Tetrapods. First test series were performed, measuring damage (displacement out of the layer) and rocking (by overlay- and single-frame-technique). Then impact velocities at a number of locations and under various wave conditions were measured by instrumented units. The instruments measured the acceleration in the centre of the unit during the impact. These accelerations are subject to scale effects in a small scale model. The integrated time signal of the impact, however, gave the velocity at impact for the centre of the unit and this can be scaled according to Froude. The study gave a large number of exceedance curves of impact accelerations (or velocities) as a function of type of unit, location on the breakwater and wave condition.

GOVERNING VARIABLES

A "standard" cross-section was chosen for testing (see Fig. 1). The slope angle amounted to 1 : 1.5 and was armoured with Cubes or Tetrapods. These types of units were chosen for the following reasons. First the slender unit Dolos is part of other investigations, even in spite of the low forces they can bear before they break. The Cube was chosen because it is a massive and strong unit and has quite often been used by Dutch engineers. The Tetrapod has been used extensively since the fifties and this unit can be seen as a transition between the massive Cube and the slender Dolos. The cross-section was designed according to the SPM (CERC, 1984).

The slope of the foreshore amounted to 1 : 50 and the water depth at the structure was 0.32 m. The mass of the Cubes was 0.208 kg with a mass density

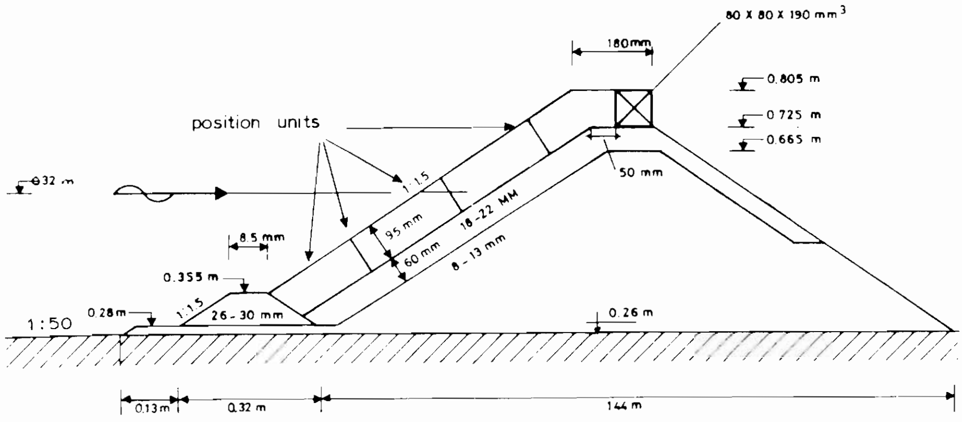

Fig. 1. Cross-section of model.

of 2450 kg/m^3. For the Tetrapods this was 0.200 kg and 2350 kg/m^3, respectively. In both cases the nominal diameter D_n was 0.044 m where D_n is defined by:

$$D_n = (M/\rho_a)^{1/3} \tag{1}$$

with M is mass of the unit and ρ_a is mass density of the unit. The total number of units on the slope per D_n width for the Cubes amounted to 23.5 (or 535 on a 1 m wide section) and for the Tetrapods to 20.7 (or 400 on a 0.85 m wide section). The location of the unit can be described by y/D_n, where y is the vertical distance from the still water level, SWL.

The definition of damage can be given in various ways. The most used definition is a percentage of "a" certain number of units. As the total number of units differs for each design, percentages of various investigations can hardly be compared. Therefore another definition is used here, which was described by Van der Meer (1988a).

The damage number N_o is defined as the actual number of units displaced (moved, or rocking) in a width of one nominal diameter D_n. This damage number is independent of slope angle and length of the slope and can easily be transformed to a percentage if required. Not only units displaced out of the armour layer were counted, but also more or less moving units (with overlay- or single-frame-technique). Therefore the damage number needs a subscript in order to distinguish between these types of damage. In this study the following damage numbers were used:

N_{od} = number of units displaced out of the layer (at least more than $2D_n$)
$N_{o>0.5}$ = number of units displaced more than $0.5D_n$
$N_{o<0.5}$ = number of units displaced less than $0.5D_n$

The wave height can be described by H_s, being the average of the highest one third of the waves. The wave steepness is defined by $s_m = 2\pi H_s/gT_m^2$, where T_m = mean wave period.

TEST PROGRAMME AND EQUIPMENT

The test programme was divided into two parts: stability tests and tests on acceleration measurements. For both cross-sections with Cubes and with Tetrapods one stability test was performed. Each test was performed with random waves and consisted of four steps with a duration of 45 min (about 2000 waves) and with increasing wave height from about 0.08 m up to 0.20 m. The number of units displaced out the armour layer were counted visually. The number of units which displaced more or less than $0.5D_n$, but which remained in the layer were determined by overlay technique. The frequency of rocking of the moving units was determined by single-frame-technique.

The overlay technique consists of a photo before and after each test made from exactly the same location. Comparison of the two photos gives the displacements of the units during that test run. The single-frame-technique employs a wave gauge mounted along the breakwater slope, which sends a pulse to a camera each time the water level passes downward through a selected level (close to the run-down point). By projecting these single frame film exposures with a speed of 10–20 frames per second, the movements and also the frequency of movement of the armour units can be observed very well.

In the second and main part of the programme accelerations were measured of a rocking unit. The unit was placed in such a position that it moved during wave attack. When the unit was displaced out of the layer or when the unit did not move at all, the test was repeated. The test duration was 10 minutes.

The accelerometer was placed in the centre of the unit. This accelerometer was a Bruel & Kjoer, type 4344 and had a natural frequency of 100 kHz. The accelerometer was tested extensively for all kinds of conditions like pendulum tests, drop and turning over tests. For the pendulum tests steel and mortar were used. The pendulum tests with steel balls gave an impact time in the order of 0.1 ms and with mortar units in the order of 0.4 ms. The tests showed that the impact could be measured without being influenced by the properties of the accelerometer itself.

The accelerometer can only measure in one direction. The effect of this limitation was studied in a sensitivity programme. Tests were performed with the accelerometer placed at three well defined directions and other tests with randomly placed directions. Latter tests were repeated ten times. The three defined directions were:
- parallel to the slope and parallel to the axis of the structure;
- parallel to the slope and perpendicular to the axis of the structure; and
- perpendicular to the slope.

In most measurements with the direction of the accelerometer perpendicular to the slope, the exceedance curves showed larger accelerations at a certain exceedance frequency than for the other two directions. The difference was not large, however. The ten repeated tests with random position of the unit showed a large variation in results, which was also due to the more or less loose position of the unit for each test. The exceedance curves of the main test programme containing the random direction of the accelerometer were compared with these ten repeated tests and showed that the accelerations were always in the upper region, giving almost the maximum values which can be expected.

For each unit (Cube or Tetrapod) tests were performed in the main programme for four wave heights and four different locations of the units. These locations were $2D_n$ above SWL, at SWL, and $2D_n$ and $4D_n$ below SWL (measured vertically from SWL). The dimensionless locations therefore were $y/D_n = +2, 0, -2$ and -4.

DATA PROCESSING

The stability tests gave the number of displaced units (out of the layer, more than $0.5D_n$, and less than $0.5D_n$) as a function of the wave height. Moreover, the single-frame-technique gave the number of movements per rocking unit, which was divided into three classes: 1 to 2, 3 to 5 and more than 5 movements.

The analog signals of the accelerometer were recorded on a Racal-Thermonic Store 7 D tape recorder with a frequency range of 200 kHz. For the data processing of the acceleration tests two methods were used. The peak value of all accelerations were established, as this was the easiest way for processing. Each test gave an exceedance curve of these maximum accelerations. As the maximum acceleration is subject to scale effects, the time signal of the acceleration should be integrated, giving the impact velocity.

In order to process the impact velocity a transient recorder of IBM PC with a special card was used to sample the signal with a frequency of 50 kHz. With a special software package it was possible to determine the impacts and to calculate the impact velocity. As this was a time-consuming method, only a part of the data was processed in this way. It gave, however, the relationship between the peak value of the acceleration and the impact velocity and this relationship was used during the analysis.

During the acceleration tests three types of impacts were measured: a single peak, composed peak, and an extended single peak (see Fig. 2). For the location $y/D_n = -4$ only composed peaks were measured. For Tetrapods more single peaks were measured at the other three locations. For Cubes also composed peaks were measured at these locations, but mainly single peaks. For the two lowest wave conditions extended peaks were found for all locations of the unit.

The measured impact time varied depending on the type of impact; for the single peak the time Δt amounted from 0.4 to 1.0 ms; for the extended peak this time was 1–3 ms; and for the composed peak 1–6 ms.

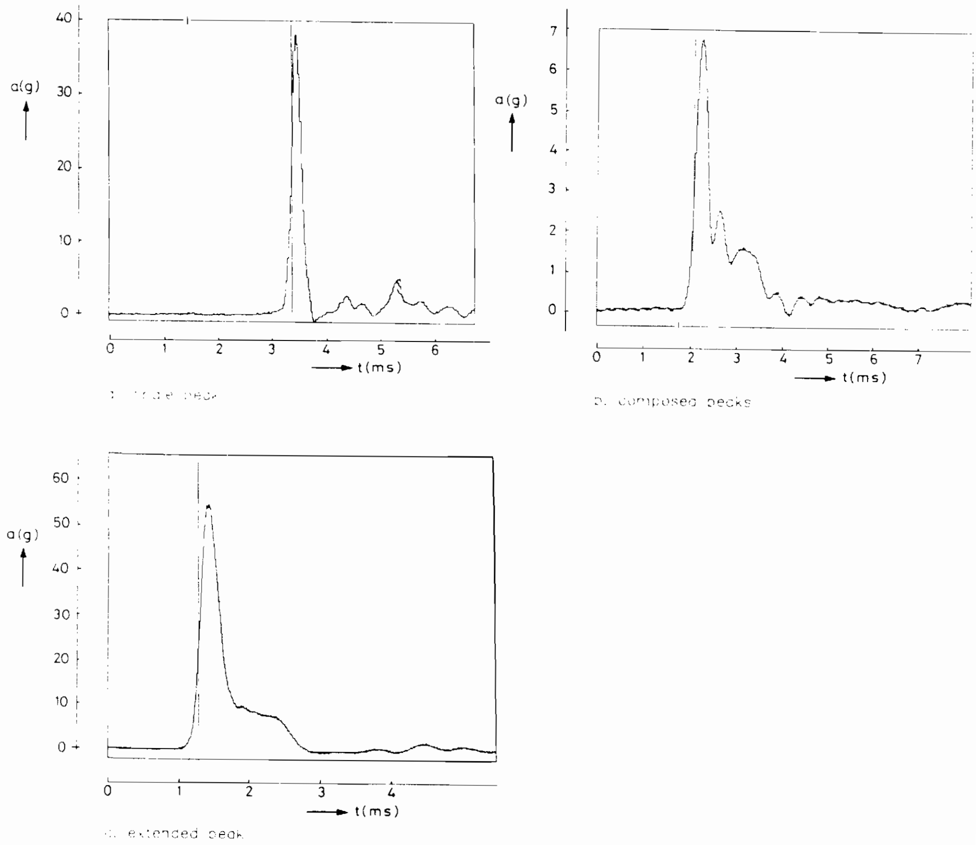

Fig. 2. Types of acceleration signals.

The impacts for the location $y/D_n = -4$ were less than 10 g. The largest impacts were measured near SWL. The maximum recorded peak acceleration for the Tetrapods was about 100 g and for the Cubes about 60 g. In order to determine the impact velocity from the time signal of the accelerations, only the first and largest peak was analysed. The other peaks were smaller due to the reactions of the other units on the instrumented unit.

GENERAL STABILITY FORMULAE

Van der Meer (1988a) derived new stability formulae for Cubes and Tetrapods (and Accropode) based on the results of the extensive research on rock slopes (see Van der Meer (1988b). The stability formulae include the wave period, the storm duration and the damage number N_{od} and apply only for breakwater slopes 1:1.5. This is also the reason why the wave steepness is present in the formulas instead of the often used surf similarity parameter. As it is interesting to compare the test results of the stability tests with these general formulae, they will be summarized here.

The formula for Cubes is given by:

$$H_s/\Delta D_n = b(6.7N_{od}^{0.4}/N^{0.3}+1.0)\ s_m^{-0.1} \quad (2)$$

The formula for Tetrapods is given by:

$$H_s/\Delta D_n = b(3.75N_{od}^{0.5}/N^{0.25}+0.85)\ s_m^{-0.2} \quad (3)$$

where:

H_s = significant wave height at the toe of the structure
Δ = relative buoyant mass density; $\Delta=\rho_a/\rho_w-1$
ρ_a = mass density armour unit
ρ_w = mass density water
b = 1 for the average curve
N_{Od} = number of displaced units out of the layer related to a width of one D_n
N = number of waves
s_m = the wave steepness $2\pi H_s/gT_m^2$
T_m = mean wave period

For the no-damage criterion $N_{0d}=0$ the stability number $H_s/\Delta D_n$ can simply be written as a function of the wave steepness:

$$\text{Cubes: } H_s/\Delta D_n = b\ s_m^{-0.1} \quad (4)$$

$$\text{Tetrapods: } H_s/\Delta D_n = 0.85\ b\ s_m^{-0.2} \quad (5)$$

With $b=1$ the average curve is found. The reliability of the formulas can be described by considering b as a stochastic variable with a normal distribution. It appeared that the standard deviation amounted to $\sigma(b)=0.1$ With for instance $b=0.863$ and 1.164, both 90% confidence levels are found. Figures 3 and 4 give the average damage curves for the Cubes and Tetrapods for the present tests, together with the 90% confidence levels. Figures 3 and 4 are described in the following Section.

RESULTS OF STABILITY TESTS

The wave conditions for the stability tests together with the obtained damage, either displaced units or more or less than $0.5D_n$ moving units, are given in Table 1 and Figs. 3 and 4.

The damage curve with N_{od} for Tetrapods is close to the average curve of the stability formula (see Fig. 4). The curve for Cubes is lower and even out of the 90% confidence band, for the highest wave heights (see Fig. 3). This can be explained by the fact that an amount of Cubes slid downwards, but remained in the armour layer (and were therefore counted as $N_{o>0.5}$). If in

TABLE 1

Test results of stability tests

Unit	H_s (m)	T_m (s)	T_p (s)	N_{od}	$N_{o>0.5}$	$N_{o<0.5}$
Cube	0.082	1.14	1.28	0.14	0.21	0.78
Cube	0.118	1.32	1.58	0.14	0.07	1.13
Cube	0.152	1.34	1.78	0.28	0.21	2.18
Cube	0.183	1.65	1.86	0.66	2.40	3.38
Tetrapod	0.095	1.21	1.36	0.17	0.19	0.63
Tetrapod	0.139	1.41	1.58	0.62	0.56	0.93
Tetrapod	0.171	1.56	1.71	1.24	0.68	1.37
Tetrapod	0.196	1.75	1.86	2.02	0.80	1.74

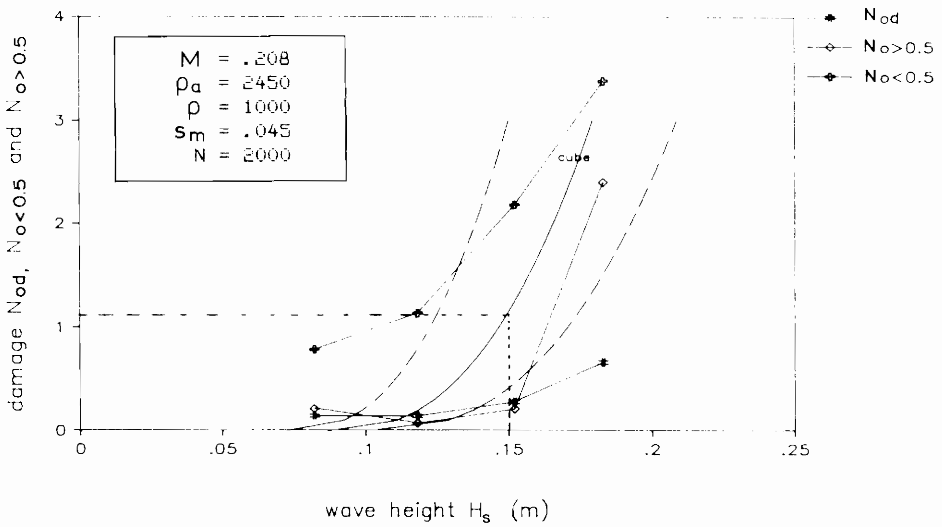

Fig. 3. Stability curve with 90% confidence levels and test results.
Cubes. Slope 1 : 1.5.

this case we take N_{od} and $N_{o>0.5}$ together, the curve will be close the curve of the formula. In general it can be concluded that the damage measured is in agreement with the formulas, except for the remark on the Cubes.

NUMBER OF MOVED UNITS AND IMPACTS

If we take the damage numbers N_{od}, $N_{o>0.5}$ and $N_{o<0.5}$ together, this can be called the total number of moved units, $N_{0,mov}$. Figure 5 gives this curve for the Tetrapods. The curve is more or less parallel to the average curve of the stability formula (taking into account only displaced units), but is shifted to the left. A more detailed analysis showed that for both the Cubes and Tetra-

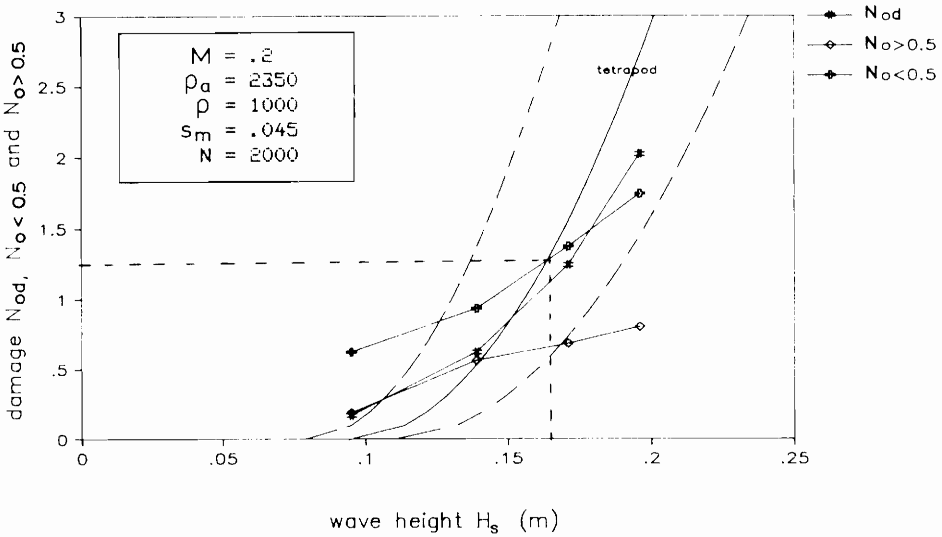

Fig. 4. Stability curve with 90% confidence levels and test results. Tetrapods. Slope 1 : 1.5.

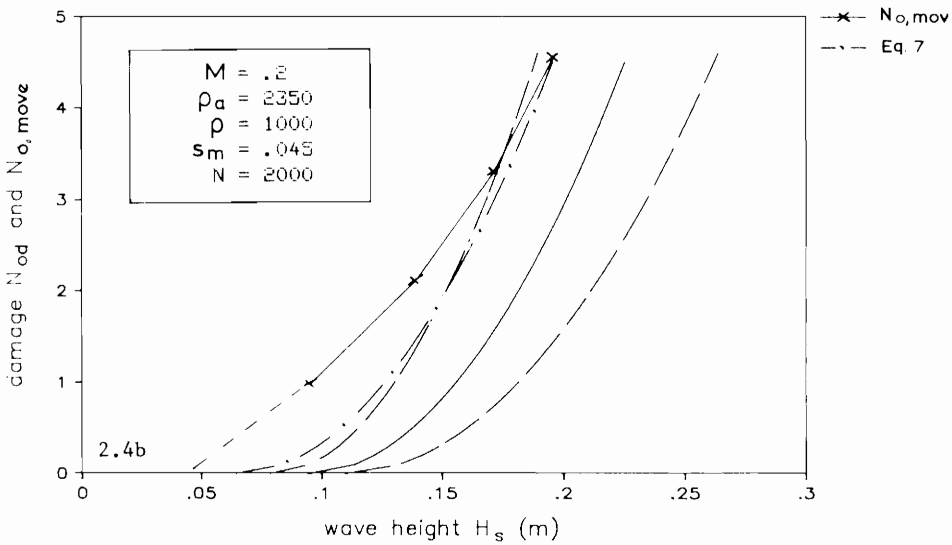

Fig. 5. Stability curves with test results for all moved units. Tetrapods. Slope 1 : 1.5.

pods this shift was more or less equal to $H_s/\Delta D_n = 0.5$. The stability formulas can therefore be transformed in order to describe the number of moved units. Cubes:

$$H_s/\Delta D_n = b(6.7N_{o,mov}^{0.4}/N^{0.3} + 1.0)s_m^{-0.1} - 0.5 \qquad (6)$$

Tetrapods:

$$H_s/\Delta D_n = b(3.75N_{o,mov}^{0.5}/N^{0.25} + 0.85)s_m^{-0.2} - 0.5 \qquad (7)$$

The number of movements per unit was recorded by single frame technique. An extensive analysis showed that about 40% of the rocking units moved only once. The other 60% moved as average about four times which gives that the number of impacts is about three times the number of moving (rocking) units. If it is assumed that units displaced out of the layer cause also about three impacts, the total number of impacts will then be about three times the total number of moved units, or:

$$N_{o,imp} = 3\ N_{o,mov} \qquad (8)$$

where $N_{0,imp}$ is the total number of impacts and $N_{0,mov}$ is calculated by Eqs. 6 and 7.

DISTRIBUTION OF NUMBER OF IMPACTS ALONG THE SLOPE

The single-frame-technique gave also the location of the rocking units. Most units moved in a wide band around SWL. The movements above SWL were restricted to a certain height which was depending on the wave height. The technique was not able to determine the movements more than $0.5 - 1.0H_s$ below SWL.

During the investigation on general stability formulas (Van der Meer (1988a) profiles of the breakwater slopes were measured. Figure 6 gives one of these profiles. It shows that, due to displaced units, the profile changes below SWL have the same order of magnitude as around SWL. Displaced units will give impacts below SWL, up to the toe.

From the total analysis on movements it was concluded that although most of the **rocking** will be concentrated around SWL, the distribution of the **impacts** will be more or less uniform from SWL to the toe.

From all measured profiles as shown in Fig. 6 the upper level of movement was determined. Figure 7 shows the results where this level was plotted versus the significant wave height H_s. The various symbols give the mean wave periods which were used. The straight curve gives the relationship where the upper level is equal to H_s. Therefore, it was concluded that the upper level of movement was 1 H_s above SWL. Furthermore it was (arbitrarily) assumed that the number of impacts above SWL was linearly decreasing from SWL to 1 H_s above SWL. Figure 8 gives the assumed distribution of impacts along the slope.

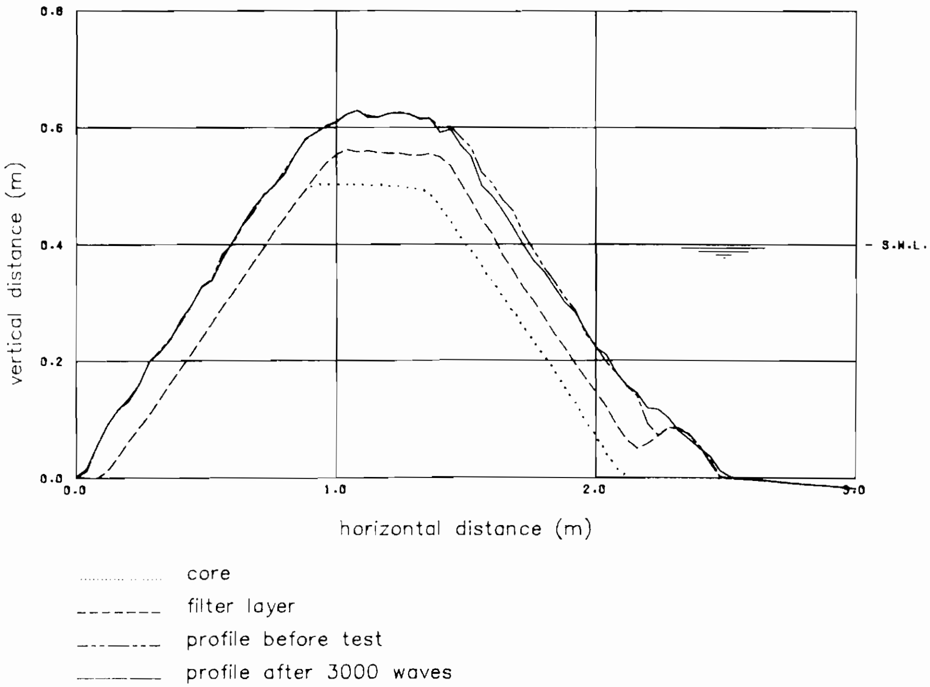

Fig. 6. Profiles measured for a breakwater armoured with Tetrapods.

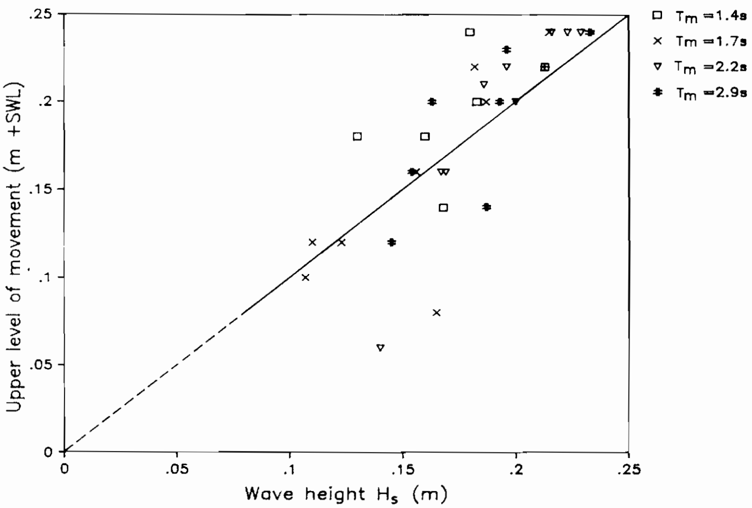

Fig. 7. Relationship between upper level of moving units and wave height.

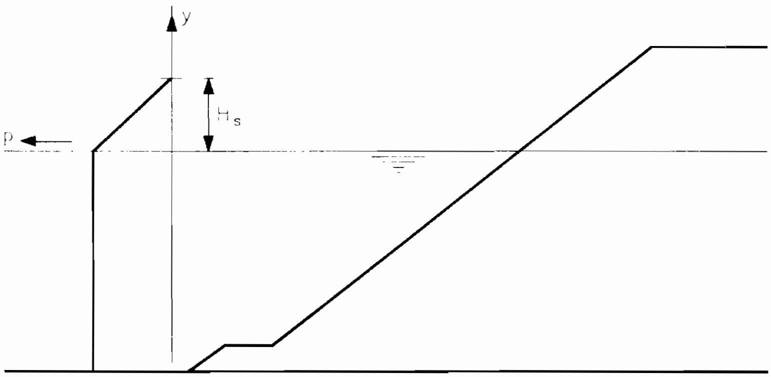

Fig. 8. Assumed distribution of number of impacts along the slope.

PEAK ACCELERATION VERSUS IMPACT VELOCITY

All tests on acceleration measurements were processed in such a way that for each impact the peak value was determined. For a part of the tests the time signal of the acceleration was integrated which gave the impact velocity. The relationship between the peak acceleration and the impact velocity will be given first. This relationship is only valid for these specific tests on a small scale.

The main analysis will then be based on the peak accelerations which are also only valid for these tests. The derived equations for the peak accelerations and the relationship between peak acceleration and impact velocity together, will finally give the equations for the impact velocity. And these equations will be general applicable for prototype conditions.

Figure 9 gives all results for tests where both peak acceleration and impact velocity were determined. The figure shows that the highest peak accelerations were found for Tetrapods, but the highest impact velocities were found for the Cubes. This was due to different shapes of the acceleration signal for Cubes and Tetrapods.

The relationship between peak acceleration and impact velocity can be described by a linear function for the Cubes and by a power function for the Tetrapods. The relationships are:
Cubes:

$$v/\sqrt{gD_n} = 0.0040\ a/g \tag{9}$$

Tetrapods:

$$v/\sqrt{gD_n} = 0.0081\ (a/g)^{0.7} \tag{10}$$

where: v is impact velocity, a is peak value of the acceleration and g is the gravitational acceleration. Although the relationships are given in dimension-

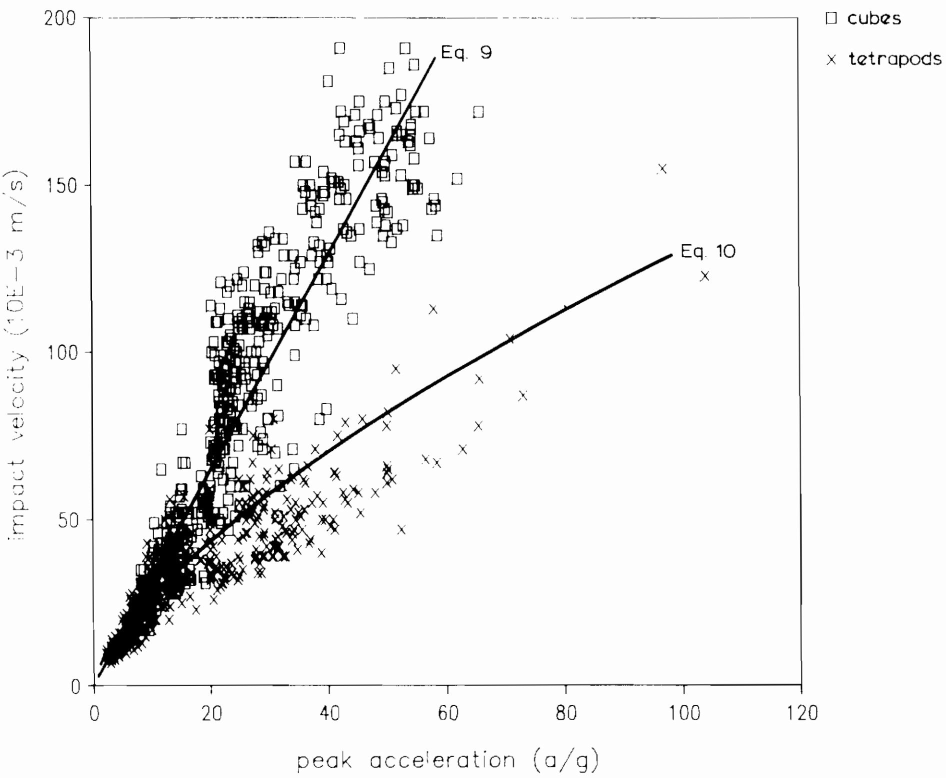

Fig. 9. Relationship between peak acceleration and impact velocity.

less terms, again they are only valid for the present tests. The coefficients in Eqs. 9 and 10 can be assumed as stochastic variables with a normal distribution. The variation coefficient for both equations amounted to about 20%.

DISTRIBUTION OF PEAK ACCELERATIONS

Figure 10 gives an example of distributions of peak accelerations which were found for Cubes, for three wave conditions and at the location $y/D_n = +2$. Identical plots were established for the locations $y/D_n = 0$; -2 and -4 and for Tetrapods.

The Figure shows that:

- the curves are not straight on a Rayleigh scale, so the peak accelerations are not Rayleigh distributed.
- lower wave heights gave lower peak accelerations. The lowest wave height of 0.12 m gave many low peaks which were not really caused by impacts, but by a (very) small movement of the unit. These small peaks were also present for the higher wave heights, but were not analysed.

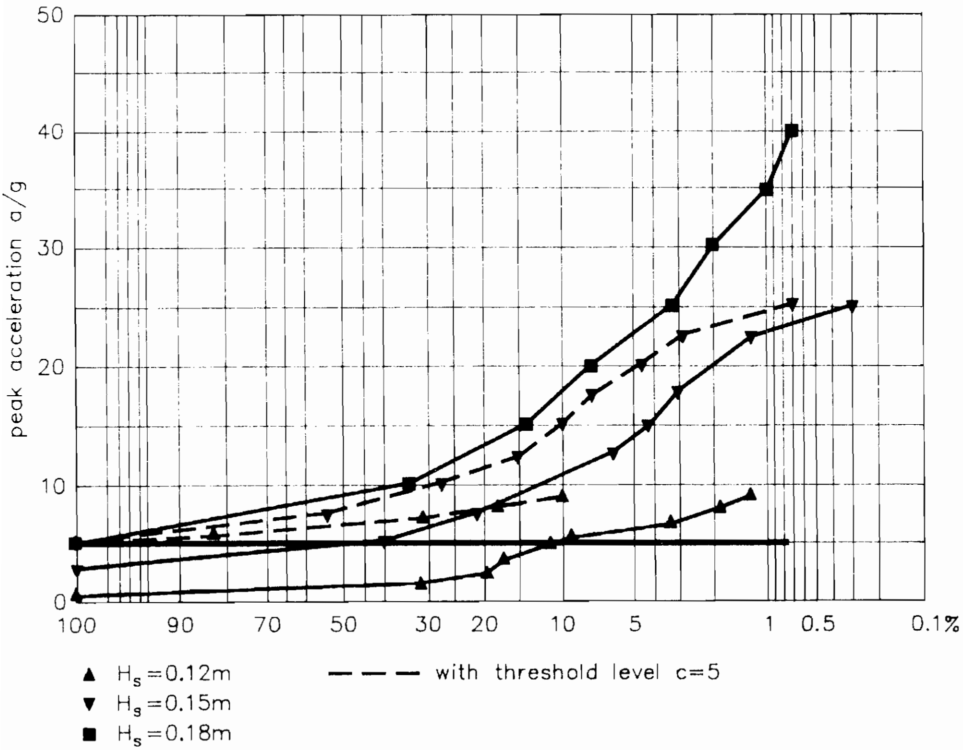

Fig. 10. Example of exceedance curves measured for the peak acceleration. Location $y/D_n = +2$. Cubes.

- a threshold level is present for the higher wave heights.

An exponential distribution with a threshold level describes the type of curves shown in Fig. 10. The general expression is:

$$p(a/g) = \exp[-(a/g - c)/b] \tag{11}$$

where:

$p(a/g)$ = the probability of exceedance;
c = the threshold level; and
b = the scale parameter.

The low wave heights not only gave impacts but also peaks caused by small movements, without impacting another unit. Therefore it was assumed that an impact was only present if a certain peak value was exceeded. This peak value (the threshold level c) was assumed not to be influenced by the wave height, but only by the location of the unit. Curves as shown for $H_s = 0.12$ and 0.15 m in Fig. 10, therefore, were replotted according to the assumed threshold level for that location. This gave the dotted curves in the Figure.

Analysis showed that the threshold level was only a function of the location of the unit on the slope, with its maximum at SWL and similar above and below SWL. Figure 11 gives a general plot of the threshold level. The following expression was derived for this threshold level:

$$c = 10 \exp[-d_1 |y/D_n|] \quad (12)$$

where $|y/D_n|$ = the absolute value of y/D_n. (See for d_1 the Acknowledgements.)

The parameter b in Eq. 11 determines the location of the curve. From Fig. 10 it was already concluded that a lower wave height gave a lower curve. Therefore b is dependent on the wave height or on the stability number $H_s/\Delta D_n$. Figure 12 gives these b-values as a function of $H_s/\Delta D_n$ for the four locations and the two unit types. A linear relationship between b and $H_s/\Delta D_n$ is a good assumption. Furthermore, it can be concluded from Fig. 12 that the highest impacts were measured at SWL (curves 3 and 7) and lower impacts above and below SWL. This means also that b will be highest at SWL. It can also be assumed that b is similar at the same locations above and below SWL (for example at $y/D_n = +2$ and -2, the curves 2, 4, 6 and 8). The relationship between b and $H_s/\Delta D_n$ can be described by:

$$b = a_1 \times H_s/\Delta D_n, \quad \text{with } a_1 = f(y/D_n) \quad (13)$$

The values for a_1 were determined from Fig. 12 and were plotted versus the location on the slope, y/D_n, in Fig. 13. In this Figure the average value is given with an acceptable range where an analytical description of this average value should lay within this range. The complete analysis led to the final description of b which is in fact more or less similar to the one for the threshold level c. This expression is shown in Fig. 13 and in a general way in Fig. 14 and is described by:

$$b = 5\, H_s/\Delta D_n \times \exp[-d_2 |y/D_n|] \quad (14)$$

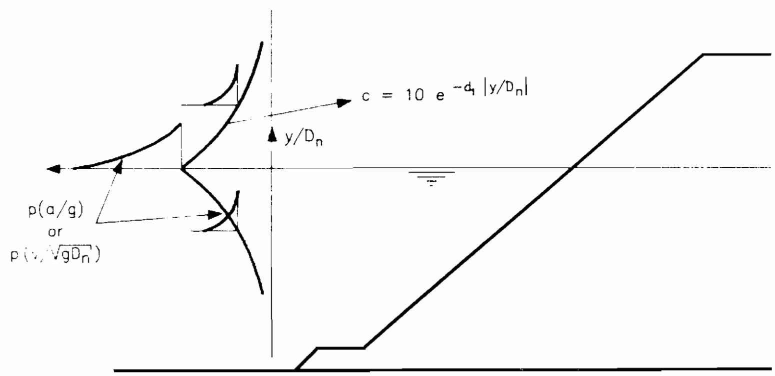

Fig. 11. The threshold level c with three examples for the distribution of a or v.

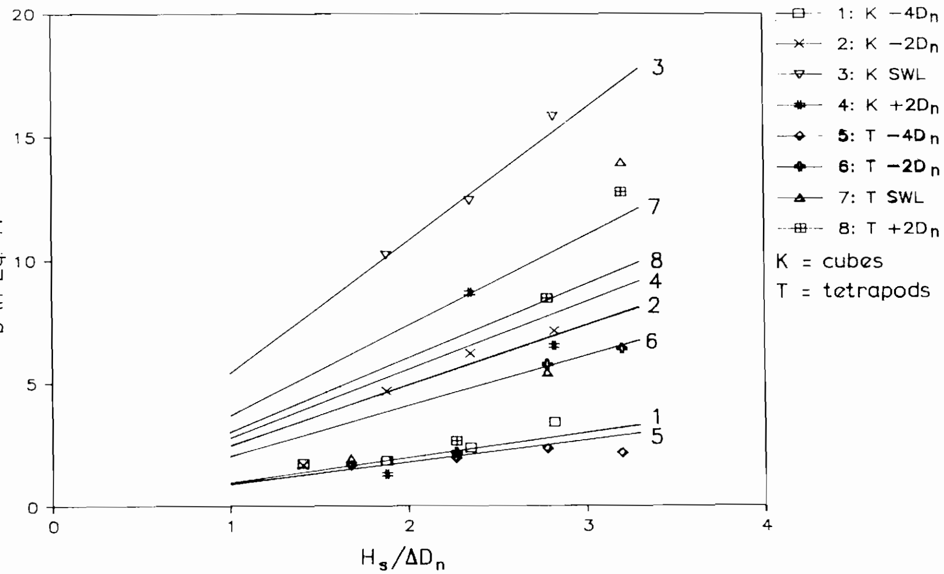

Fig. 12. b-values in Eq. 11 as a function of $H_s/\Delta D_n$ and location on the slope.

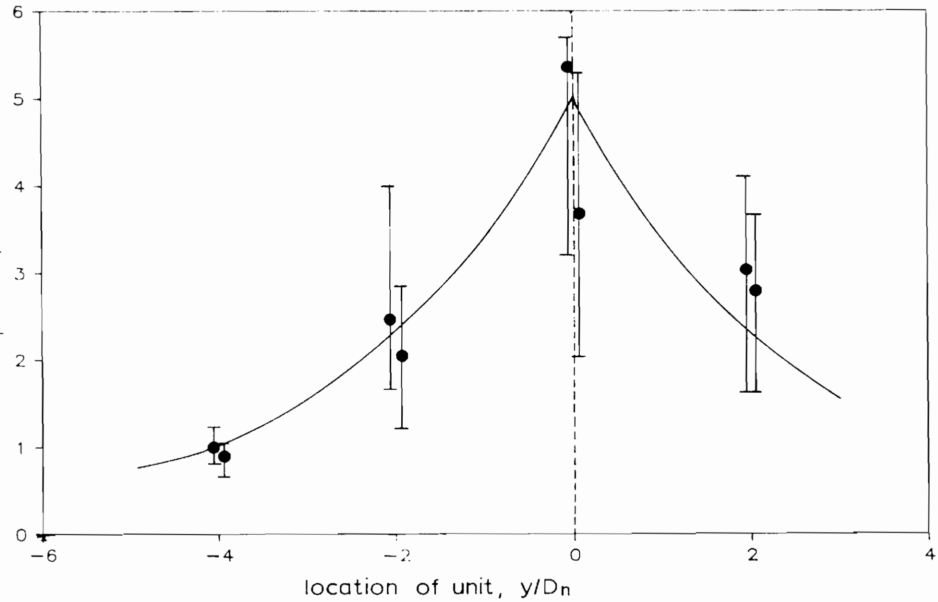

Fig. 13. a_1-values in Eq. 13 as a function of the location on the slope.

(See for d_2 the Acknowledgements.)

The peak accelerations showed no great differences for Cubes and Tetrapods. Therefore the above-described Eqs. 11 (the general exponential curve), 12 (the threshold level c) and 14 (the parameter b) are valid for both Cubes

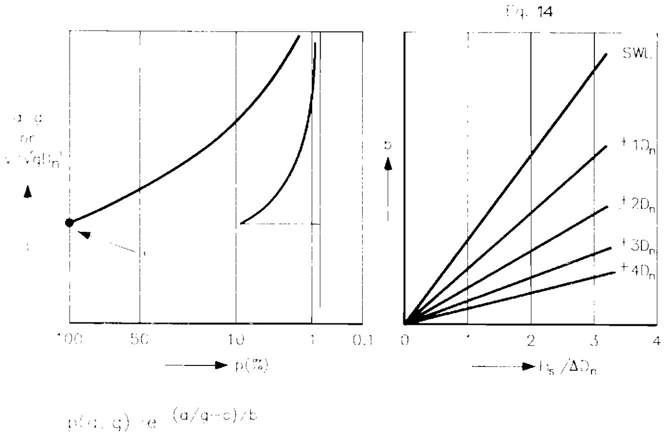

Fig. 14. The distribution curve for impacts with the scale parameter b.

and Tetrapods. The equations are, however, only valid for the present small scale tests, due to scale effects for the peak accelerations.

DISTRIBUTION OF IMPACT VELOCITIES

Substitution of the relationships between peak acceleration and impact velocity (Eqs. 9 and 10) in the relationships for the distribution, finally gives the expressions for the distribution of the impact velocities at the centre of the units. These expressions become:
For Cubes:

$$p(v/\sqrt{gD_n}) = \exp\{-[(v/\sqrt{gD_n} - c)/b]\} \qquad (15)$$

with:

$$c = 0.049 \exp[-d_1 |y/D_n|]; \qquad (16)$$

$$b = 0.025\, H_s/\Delta D_n \times \exp[-d_2 |y/D_n|] \qquad (17)$$

For Tetrapods:

$$p(v/\sqrt{gD_n}) = \exp\{-[((v/\sqrt{gD_n})^{1.43} - c)/b]\} \qquad (18)$$

with:

$$c = 0.0103 \exp[-d_1 |y/D_n|] \qquad (19)$$

$$b = 0.0051\, H_s/\Delta D_n \times \exp[-d_2 |y/D_n|] \qquad (20)$$

The above-given expressions, Eqs. 15–20 are applicable in prototype conditions.

SUMMARY AND CONCLUSIONS

The research on impact velocities, a part of a more extensive research, resulted in the description of two main items:

- the description of the number of displaced and moved units, the number of impacts and the distribution of impacts along the slope; and
- the description of the distribution of the impact velocities.

General stability formulas 2 and 3 which give the number of displaced units as a function of wave height, steepness and storm duration, were modified to describe the number of moved units (Eqs. 6 and 7). The number of impacts was assumed to be three times the number of moved units. The distribution of impacts along the slope can be described by a uniform distribution from SWL to the toe and a linear distribution from SWL to 1 H_s above SWL (Fig. 8).

The analysis of the peak accelerations finally produced expressions for the distribution of the impact velocities (at the centre of the unit). These distributions are described by an exponential function with a threshold level and are dependent on the type of unit, the location of the unit on the slope and the wave height. Equations 15–20 give the expressions for Cubes and Tetrapods.

APPLICATION

The above results can be used in a general and integral approach:

Calculate the number of moved units and the number of impacts using the modified stability formulas. Apply the given distribution of impacts along the slope of the structure.

Calculate the probability density functions of the impact velocities using the developed formulas.

Calculate the load-time history in prototype conditions using the developed model in another stage of the research, for a large number of impact velocities.

Calculate the maximum stresses in the units and the number of units that will break, including a possible distribution of loading conditions, the hardening of concrete (internal stresses) and the effect of impacts on the tensile strength of concrete.

The procedure given above was applied in the final phase of the research project, but only for Cubes and Tetrapods. The complete procedure was implemented on a personal computer using a probabilistic approach (Monte Carlo simulation). Results will be described elsewhere.

Finally it can be stated that the procedure is complementary to that proposed by Burcharth and Howell (1988) as they proposed to measure the stresses directly.

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