CHAPTER 77

Rubble Mound Breakwater Stability Under Oblique Waves : An Experimental Study

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Abstract

A series of model tests was carried out in a wave basin at LNH to quantify the effect of long-crested, oblique waves on rubble mound breakwaters. Four types of armouring units (quarry stone, Antifer cube, tetrapod and ACCROPODE®) were tested, under six angles of wave attack (0°, 15°, 30°, 45°, 60°, and 75°). Overtopping, toe berm and main armour stability were studied as functions of wave obliquity. A method is proposed to reduced the results obtained under oblique waves to those obtained under normal waves, allowing thus for the use of formulae derived under normal waves for the design of a breakwater under oblique wave attack.

Introduction

Scale model tests aimed to define guidance for the design of breakwaters are mainly conducted in wave flumes, because this is the easiest (and then the cheapest) way to vary the numerous structural parameters involved. Therefore, the effect of wave obliquity on the stability of such structures has been hardly investigated so far, and the estimation of the possible influence of that parameter is often based upon conjectures or derived from tests not directly related to breakwater stability (run-up measurements on smooth mild slopes mainly).

A few tests, or re-analysis of tests, have been found in the literature, which give some trends for the stability of rubble mound breakwaters under oblique waves.

Whillock (1977) made tests on a 1:2 slope armoured with dolosse under regular wave attack at a fixed period. Results of his tests showed a slight decrease in stability up to an angle of wave attack β of 60° and then, at β = 75°, quite a large increase in stability.

This trend for dolosse was also mentioned by Gravesen and Sorensen (1977) who, reviewing tests data with random waves, stated a slight decrease in stability when increasing β (with a minimum at β = 45°), although they did not noticed such a large increase for angles higher than 60°. For quarry stone, the same authors found

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that stability was not much affected for β ranging from 0° to 45°, but was then increased a lot at higher angles.

Van de Keeke (1969) performed tests with regular waves (at a fixed period) on rocks for 3 different slope angles (1:1.5, 1:2 and 1:3) and for β = 0°, 30°, 45°, 60° and 90°. He found exactly the same trends as the above mentioned ones.

Gamot (1969) reported tests on a breakwater armoured with tetrapod and stated that the armour stability was increased with increasing angle of incidence, this effect being noticeable as soon as β > 40°. He also mentioned that, once they are initiated, damage increase faster under oblique waves than under normal waves.

Finally, Markle (1989) conducted tests in which toe berm stability was investigated, some of these tests being performed at β = 45°. What he concluded, despite very few tests were conducted, is that there was no great difference in stability associated with different angles of wave attack. Some general trend of higher stability under oblique wave could however be seen, although not well defined.

As only very few papers exist in the literature, a series of model tests was carried out at LNH to quantify the effect of long-crested, oblique waves on the stability of rubble mound breakwaters. Advantage was taken from these tests to study also the influence of oblique waves on overtopping and toe stability. Four types of armouring units - quarry stone, Antifer cube, tetrapod (two layers units) and ACCROPODE® (one layer unit)- were tested, under six angles of wave attack β - 0° to 75°, each 15°. A comprehensive description of these tests is given in Galland (1993).

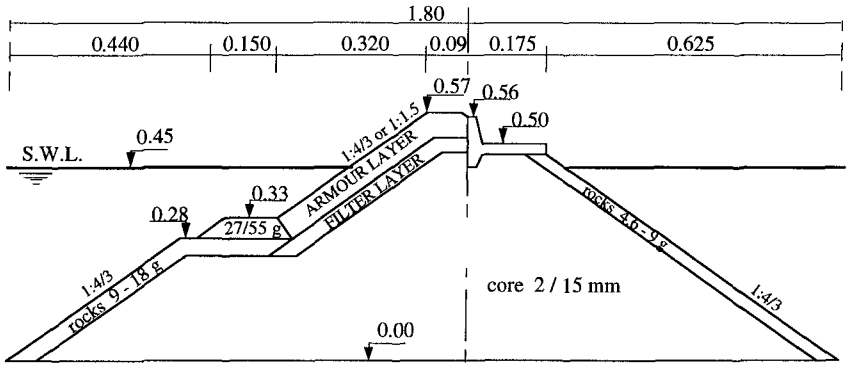


Fig. 1 Breakwater cross-section (measures in m).

Model design and layout

Although these tests do not refer to any field study, the cross-section of the breakwater was defined in such a way that it could represent an actual one. With reference to the maximum significant wave height to be tested (H_s = 0.135 m), the depth of the toe berm below the water level (h_t = 0.12 m) was chosen so that the toe was under strong influence of hydrodynamic forces and the crest elevation (h_c = 0.12 m) so that overtopping was allowed at the same time as damage should start (under normal waves). Doing this way also ensures that the armour layer (which is the main element under study) has a realistic number of units rows, and then a behaviour similar to the one that could occur in the field.

The breakwater consisted in four trunks, each one being 3 m long and armoured with one of the studied units. The total length of the breakwater, including two roundheads, was about 16 m. The rear slope and the crown wall blocks were artificially stabilised, in order to prevent destruction of the breakwater by rear slope degradation and/or crown wall tilting.

Breakwater cross-section

The cross-sections for concrete units were identical and a 1:4/3 slope was chosen (fig. 1). For quarry stones however, the slope was changed into 1:1.5, which is a more realistic value for that armouring unit.

The crown wall blocks, the core, the toe berm, the rear armour layer and the lower part of the front cover layer were identical for all armour units.

Characteristics of the units

Characteristics of the armouring units and toe rocks are given in table 1. The weights and mass density are mean values over at least 30 dry units. In the following, Δ is the relative mass density and D_n the nominal diameter of the unit considered.

Block	ρ_r (kg/m^3)	W (10^{-3} kg)	ΔD_n (10^{-2} m)
ACCROPODE®	2310	44.7	3.51
Antifer block	2400	48.6	3.82
Tetrapod	2540	61.6	4.48
Armour rock	2850	(W_{50}) 90.0	5.85
Toe rock	2500	(W_{50}) 38.0	3.75

Table 1. Characteristics of units.

Grading characteristics of the rocks used for that study are presented in table 2, together with their mass density.

Rock	W_{min} (10^{-3} kg)	W_{max} (10^{-3} kg)	W_{50} (10^{-3} kg)	W_{85}/W_{15}	ρ_r (kg/m^3)
Armour layer (main)	55.0	145.0	90.0	2.05	2850
Underlayer	1.8	9.3	5.0	1.83	2650
Toe berm	27.0	55.0	38.0	1.34	2500
Rear slope	2.8	10.0	6.6	1.57	2660
Cover-layer (lower part)	5.0	17.0	10.0	1.93	2630

Table 2. Characteristics of rocks.

Placement of armouring units was realised according to the procedure relative to each unit : for concrete units, this means that the prescribed mesh was respected and, for quarry stones, that they were tipped on the slope. A cover layer armoured with a given armouring unit was always built by the same person, to ensure a good reproducibility in the way of placing the units.

Test conditions

The programme included 6 series of tests, each one being defined by its angle of wave incidence (0°, 15°, 30°, 45°, 60° and 75°). The normal wave test was aimed to

be the reference when analysing the results. To limit the number of investigated stability parameters, the breakwater was placed on a flat bottom (water depth h = 0.45 m) and, as one test consisted in 8 steps with increasing wave height, the peak wave period was tuned at each step so that the wave steepness remains a constant (s_{0p} ≅ 4 %). The steps duration was adapted so that the total number of waves in each one was 2000. It was large enough a number to ensure both a suitable statistical distribution of waves and a stabilised damage evolution at the end of each step. Targeted wave characteristics are presented in table 3.

Step	1	2	3	4	5	6	7	8
H_S (m)	0.030	0.045	0.060	0.075	0.090	0.105	0.120	0.135
Tp (s)	0.71	0.87	1.00	1.12	1.22	1.32	1.41	1.50
L_{0p} (m)	0.78	1.18	1.56	1.96	2.32	2.72	3.10	3.51
Duration (')	22	26	30	34	37	40	42	45

Table 3. Targeted wave characteristics.

Test facilities

The tests were performed in a wave basin (fig. 2) which overall dimensions are 33 m x 28 m x 1 m, the maximum water depth being 0.45 m. This basin is fitted out with a hydraulic flap-type wave maker, which paddle is 17 m long, 0.85 m high and can move round the basin, allowing this way for a 180° rotation. The four walls of the basin were equipped with wave absorbers in order to avoid re-reflection.

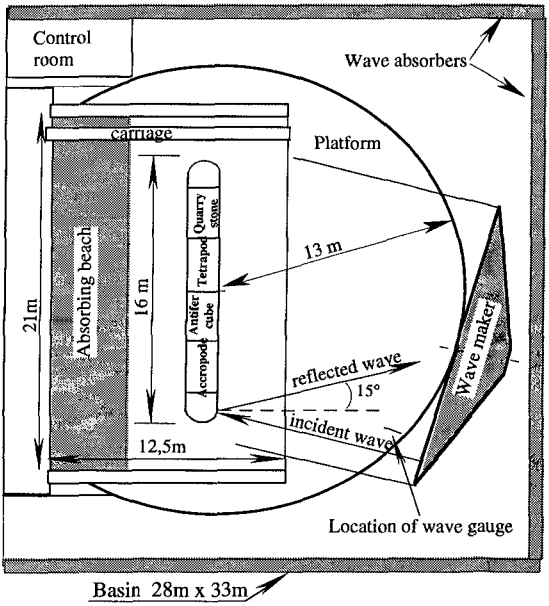


Fig. 2. Test set-up and location of surface elevation measurement for oblique wave attack (example, β = 15°).

Test procedures

Generation and measurement of waves

Random waves were generated according to a JONSWAP type spectrum, with $\gamma = 3.3$. The wave signals were calculated following the "Deterministic Spectral Amplitude" method, by adding 100 sinusoidal components. They covered the whole steps duration and were computed prior to the tests, which ensured a good reproducibility in the succession of waves during a given step for all tests.

Evaluation of the wave heights is of prime importance for such a study. Under normal waves, water surface elevation was measured with three gauges, which enables to separate incoming and reflected waves by mean of a spectral analysis. Incoming waves characteristics (peak period T_P and significant wave height H_s) were determined this way.

Under oblique waves however, it was not possible to separate incoming and reflected waves. It has then been decided to measure only a "global wave height" (incoming+reflected) at a location in the wave basin that was not optically under direct influence of reflection (cf. fig. 2).

Surface elevations were also measured in front of each test section to ensure that the wave field was homogenous. Wave measurements and their analysis were performed over the whole duration of each step, i.e. over 2000 waves.

Damage evaluation

Damage level to the armour layer D_a was determined by counting, at the end of each step, both blocks that were removed out of the cover-layer and blocks that were distinctly displaced. Armouring units were coloured and the armour layer consisted in a succession of horizontal coloured stripes, the width of which was two blocks (two median diameters for rock), so that displaced blocks were those displaced out of their coloured band, while still standing in the cover layer. All displaced or removed blocks were counted at the end of each step, so that *cumulated* damage was evaluated.

Cumulated damage to the toe berm D_t was determined in the same way, but by counting the number of removed bloeks only (reshaping not considered).

Damage measurements were made on a 1 m wide section in the centre part of each trunk, called the test section in the following, in order to avoid side effects at the junction of two trunks when oblique waves are performed. Before counting, the water level was lowered to the toe mound. Damage levels are expressed as the percentage of displaced and removed units in the test section.

Overtopping measurement

The number of overtopping waves was recorded on a paper-recorder, over the whole duration of each step, at the centre of each trunk by use of a wave gauge placed on top of the structure. Calibration enabled to discriminate between green water and broken spray. Overtopping was expressed as the percentage of overtopping waves N_{ov}.

Experimental results

Wave field

The main problem here is the impossibility to separate incoming and reflected waves for the tests under oblique waves, which makes questionable the comparison

between the results of these tests, and even more with those under normal waves. To clear up that point, all steps 7 were re-run with normal waves after all tests had been performed, ensuring very carefully that waves were measured in strictly identical conditions : same wave signal, same location of the wave gauges, same position for the wave guides as during the tests. The global wave height measured under oblique wave was then compared to the incident normal wave height. As their relative difference is expected to grow up with increasing wave height (the reflected wave becoming higher), the comparison between these two values for step 7 is a good evaluation of the accuracy of the global wave height as an estimate for the incident wave height under oblique waves. As this relative difference was lower than 6% for all tests, the global wave height as measured under oblique waves was thus considered as a reasonable approximation of the actual incident one.

Armour stability

The curves shown hereafter present the percentage of moved armour blocks D_a as a function of the non-dimensional significant wave height $H_s/\Delta D_n$, and are limited to $D_a < 20\%$, which is their most significant part.

Table 4 below gives the relative variation in wave height with respect to normal wave when increasing obliquity, corresponding to several given damage levels (start of damage, $D_a = 5\%$ and $D_a = 10\%$).

β (°)	15	30	45	60	75
			Antifer Cube		
$D_a < 0.1$ %	+ 56 %	+ 52 %	+ 54 %	+ 130 %	+ 140 %
$D_a = 5$ %	+17 %	+ 31 %	+ 31 %	-	-
$D_a = 10$ %	+ 4 %	+ 13 %	+ 18 %	-	-
			Tetrapod		
$D_a < 0.1$ %	+ 52 %	+ 50 %	+ 44 %	+ 48 %	+ 140 %
$D_a = 5$ %	+ 8 %	+ 4%	+ 5 %	+ 22 %	-
$D_a = 10$ %	- 3 %	- 4 %	+ 2 %	+ 16 %	-
			Rock		
$D_a < 0.1$ %	- 17 %	+ 65 %	+ 35 %	+ 49 %	+ 98 %
$D_a = 5$ %	0 %	+ 10 %	+ 6 %	+ 6 %	-
$D_a = 10$ %	- 4 %	+ 6 %	+ 15 %	+ 18 %	-
			ACCROPODE ®		
$D_a < 0.1$ %	- 23 %	+ 23 %	+ 38 %	+ 21 %	-
$D_a = 1$ %	+ 12 %	+ 19 %	+ 26 %	-	-

Table 4. Relative variation of $H_s/\Delta D_n$ with β, with respect to normal waves, for start of damage ($D_a < 0.1$ %), $D_a = 5$ % and $D_a = 10$ %, or $D_a = 1$ %. (- indicate that the corresponding damage level was not reached).

Some trends can be seen in table 4 which indicate an increase in stability with increasing angle of wave incidence. Results are detailed below for each unit.

Antifer cube

Four trends can be observed from table 4 and fig. 3 :
- stability increases with increasing wave obliquity,
- start of damage is delayed under oblique waves : it corresponds to a wave height 50 % higher for $\beta = 15°$, 30° and 45° than under normal waves,

- damage, once initiated, increases faster under oblique waves than under normal waves : about two times faster for $\beta = 15°$, 30° and 45°,
- For $\beta > 45°$, the increase in stability is so high that nearly no damage occurs.

Tetrapod

Exactly the same trends (cf. table 4 and fig. 4) as for Antifer cube can be noted, although they are somewhat less pronounced and valid mainly for $D_a < 10$ %

These results (increasing stability with increasing obliquity, faster damage increase under oblique waves) are consistent with those reported by Gamot (1969).

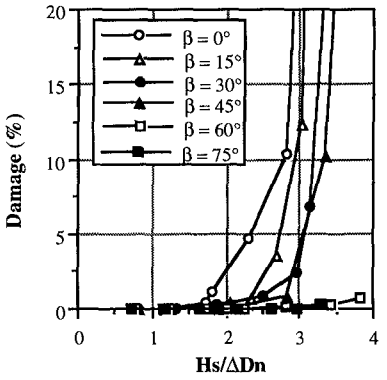


Fig. 3. Armour stability - Antifer cube

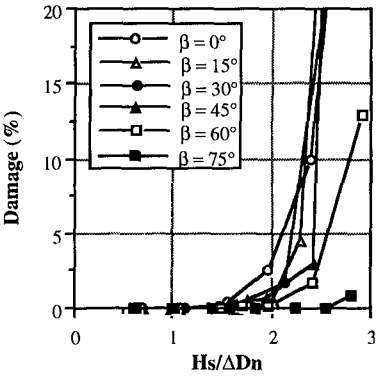


Fig. 4. Armour stability - Tetrapod

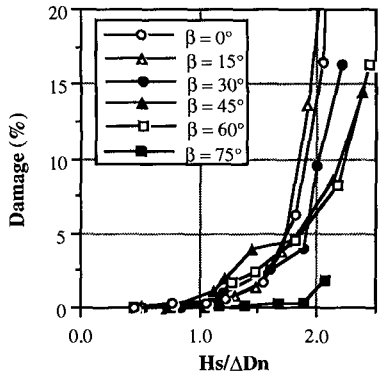


Fig. 5. Armour stability - Quarry stone

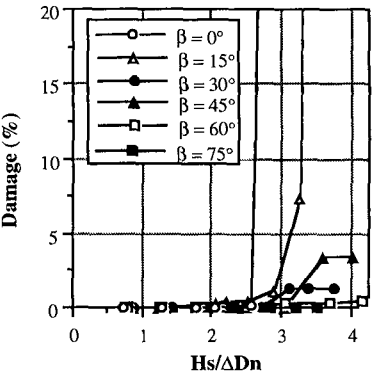


Fig. 6. Armour stability - ACCROPODE®

Quarry stone

From fig. 5 and table 4, start of damage seems to be slightly delayed under oblique waves, but quarry stone is seen to be not very sensitive to wave obliquity, at least at low damage levels ($D < 5$ %). For higher damage levels and $\beta \geq 30°$, some trend is noticeable that could indicate an increasing stability for increasing angle of incidence. However, stability strongly increases at $\beta = 75°$ only.

These points are in accordance with the results of previous works (Gravesen and Sorensen (1977), Van de Keeke (1969)), although the increase in stability was noticed as soon as $\beta \geq 60°$.

ACCROPODE®

Evolution of ACCROPODE® stability with increasing wave obliquity (fig. 6) is quite different from those observed till now. At $\beta = 15°$, the armour layer behaves similarly as under normal wave attack, with a very sudden failure (characteristic of a one layer unit) which has led to retain a zero-damage criteria for the design of breakwaters armoured with this unit. At higher angles, its behaviour however significantly differs : after some damage, units rearrange so that the armour is stable again and no more damage occur. This could be explained by the high interlocking of this one layer unit.

Toe berm stability

The curves shown below present the percentage of removed toe blocks D_t as a function of the non-dimensional significant wave height $H_s/\Delta D_n$.

A distinction can be made here between the results for Antifer cube and tetrapod on one hand, and quarry stone and ACCROPODE® on the other hand.

Toe berm at Antifer cube and Tetrapod armour layer

The same trends as for the corresponding armour unit can be made (fig. 7 and 8) :
- stability increases with increasing wave obliquity,
- start of damage is delayed under oblique waves : it corresponds to a wave height 45 % higher for $\beta = 15°$, 30° and 45° than under normal waves,
- damage, once initiated, increase faster under oblique waves than under normal waves : about 1.6 time faster for $\beta = 15°$, 30° and 45°,
- For $\beta = 75°$, the increase in stability is so high that nearly no damage occurs.

What could be add is that, provided that high damage levels to the toe are accepted, a 15° wave incidence could be more dangerous than normal wave.

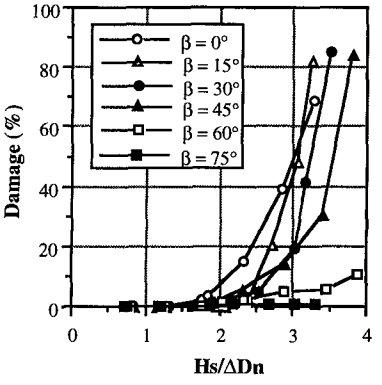


Fig. 7. Toe stability - Antifer cube

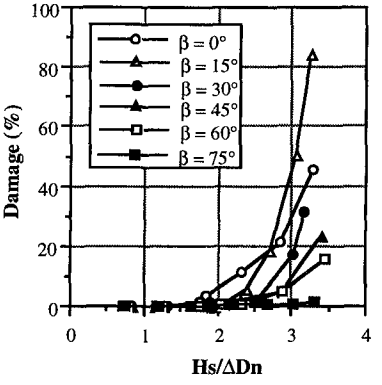


Fig. 8. Toe stability - Tetrapod

Toe berm at quarry stone and ACCROPODE armour layer

The behaviour of toe berm at quarry stone and ACCROPODE® armour layer (fig. 9 and 10) is rather atypical. Initiation of damage is not so much delayed under oblique

waves, and the only marked trend is an increase in stability with increasing wave incidence for $\beta \geq 30°$. However for ACCROPODE®, the same trend as for Antifer cube and tetrapod can be noticed, that is that damage could possibly be higher at 15° than under normal waves.

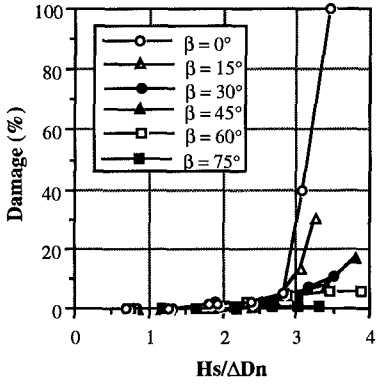


Fig. 9. Toe stability - Quarry stone

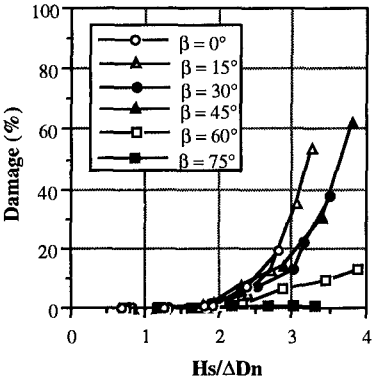


Fig. 10. Toe stability - ACCROPODE®

Out of the scope of this study but important to notice, is that very high damage levels to the toe berm were reached without endangering the stability of the armour layer.

Overtopping

The curves shown hereafter present the percentage of overtopping waves N_{ov} as a function of the significant wave height H_s.

For all the units studied here, the percentage of overtopping wave N_{ov} is seen to present the same features (fig. 11 to fig. 14):

- overtopping is equivalent under normal waves and a 15° incidence,
- overtopping then decreases with increasing wave obliquity,
- at $\beta \geq 60°$, overtopping is reduced to nearly zero, except for quarry stone.

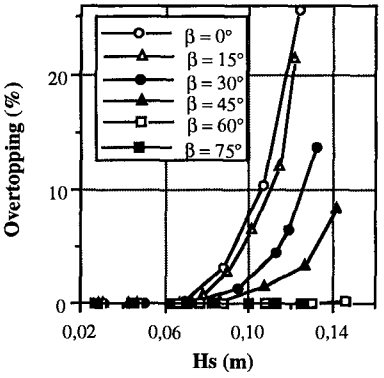


Fig. 11. Overtopping - Antifer cube

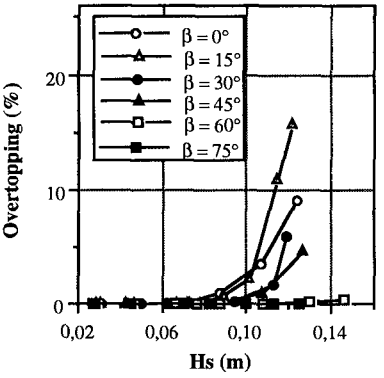


Fig. 12. Overtopping - Tetrapod

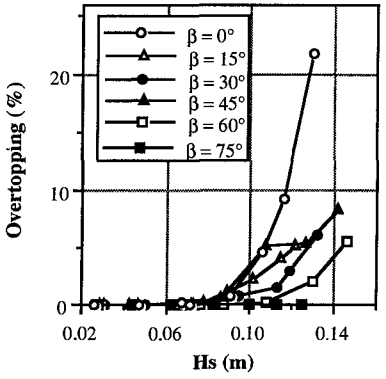


Fig. 13. Overtopping - Quarry stone

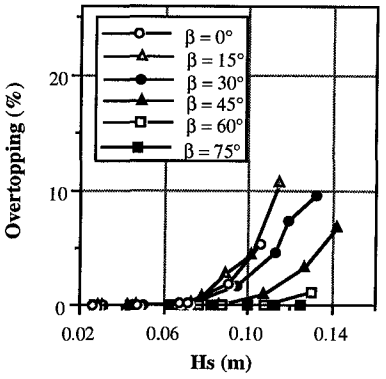


Fig. 14. Overtopping - ACCROPODE®

Discussion

The aim of this study was not to derive new formulae for the design of rubble mound breakwaters armour layer and toe berm or for the evaluation of overtopping rates, but to provide a better idea of the influence of wave obliquity and also to propose a way for taking into account that influence in existing formulae.

In this idea, and as the apparent slope of the breakwater turns from tgα under normal waves into tgα.cosβ under a β angle of wave attack, it is of interest to study all the above mentioned phenomena as functions of $H_s\cos\beta^x$ instead of functions of H_s only, $H_s\cos\beta^x$ being then an *equivalent normal wave height.*

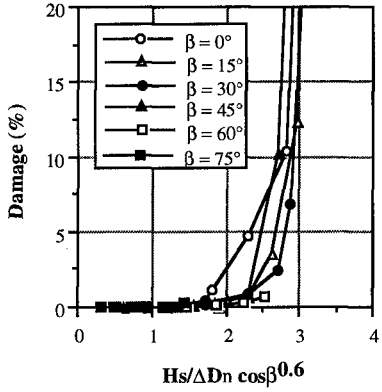
The remaining problem is of course to determine the coefficient x : results are not numerous enough to allow for the use, from a scientific point of view, of a numerical "best fit" method and the evaluation of x has then to be derived by visual adjustment, being thus subject to some interpretation.

All the curves for armour, toe berm stability, and overtopping have been re-plotted against $H_s\cos\beta^x$, with the best estimates for x (fig. 15 and fig. 16). A summary of the values obtained for x is given in table 5 below.

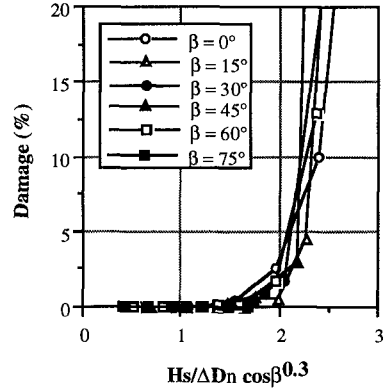
Such an approach is not fully satisfactory : first because, in some cases, the adjustment is not very good and second because it can not represent the change in the slope of some of the curves that occurs under oblique wave. Nevertheless it could be very useful for the preliminary design of breakwaters.

	Antifer cube	Tetrapod	Quarry stone	ACCROPODE®
Armour stability	0.6	0.3	0.25	1
Toe stability	0.6	0.4	0.6	0.4
Overtopping	1	0.6	1/3	0.75

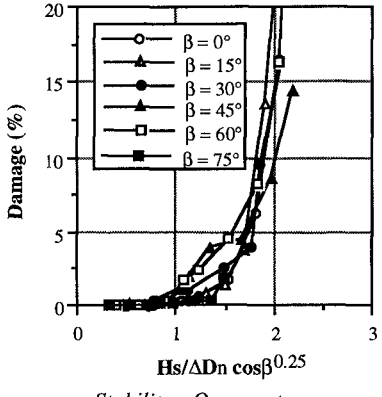
Table 5. Coefficient x for the equivalent normal wave height $H_s\cos\beta^x$.



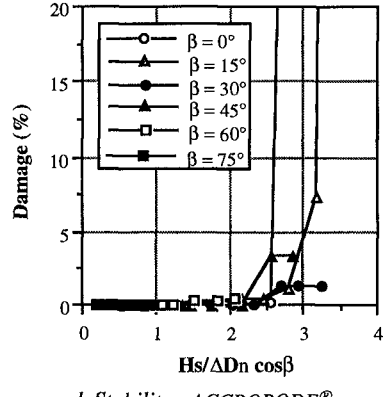
a. Stability - Antifer cube



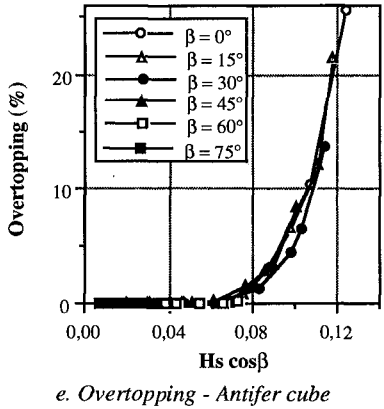
b. Stability - Tetrapod



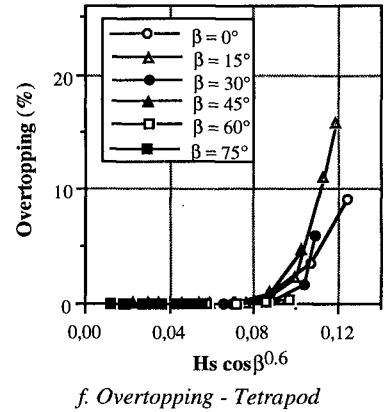
c. Stability - Quarry stone



d. Stability - ACCROPODE®

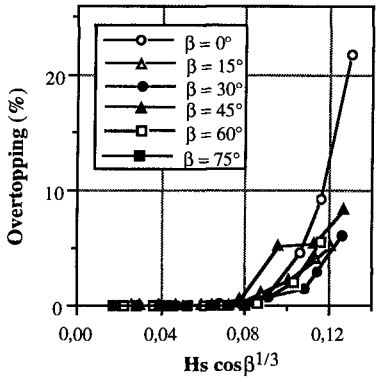


e. Overtopping - Antifer cube

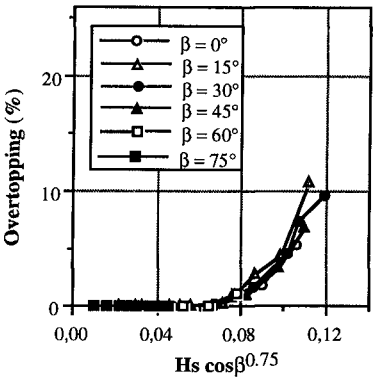


f. Overtopping - Tetrapod

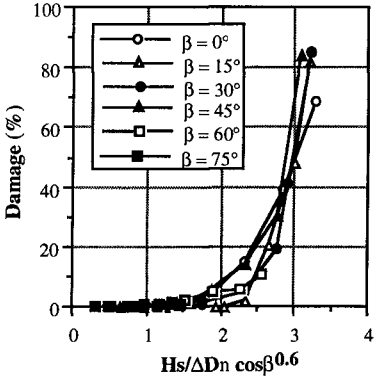
Fig. 15. Re-plot of the results against the equivalent normal wave height



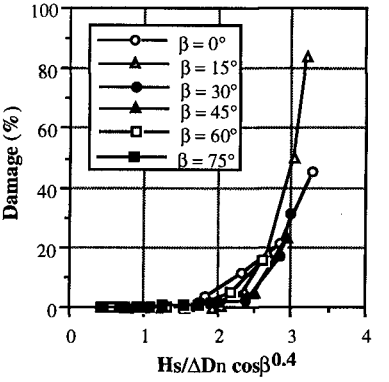
a. Overtopping - Quarry stone



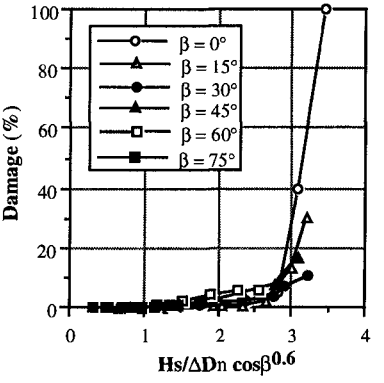
b. Overtopping - ACCROPODE®



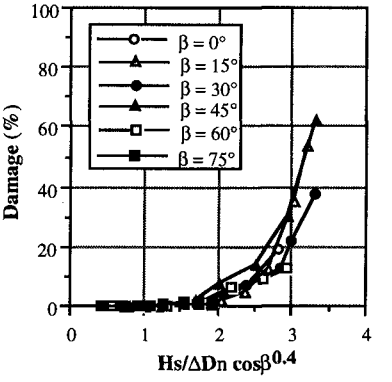
c. Toe stability - Antifer cube



d. Toe stability - Tetrapod



e. Toe stability - Quarry stone



f. Toe stability - ACCROPODE®

Fig. 16. Re-plot of the results against the equivalent normal wave height

As a general remark, it should be noted that the results obtained within this study do not support the vague belief in a lower stability at small angles of wave incidence (say β = 10°-30°). Such a belief is mainly based on run-up measurements, which have been shown to be maximum at β = 10°-30° on smooth, mild slopes (Tautenhain et al. (1982), CUR/CIRIA (1991)).

The numerical values derived within this study are to be taken with great care, as they result from a single test at each wave angle. Many authors (Jensen (1984), Burcharth et al. (1986), Galland and Manoha (1991) for instance) have indeed stated a large scatter in results of such tests, so that a well-defined characterisation of the influence of wave obliquity should be derived from series of identical tests.

But what is important here, is that the results are not drowned into the scatter but *do really define* the trends reported above ; only the actual values of the gains obtained under oblique waves are not known exactly.

Conclusions

Under the conditions tested :
- flat bottom (no shoaling effect),
- JONSWAP spectrum, γ = 3.3 (no influence of spectrum width or wave groupiness),
- constant wave steepness, $s_{0p} \cong 4$ % (constant surf similarity parameter ξ_{op}),
- 2000 waves per step (no influence of storm duration),
- one series of tests per angle of wave incidence (scatter not considered),

the following conclusions can be drawn :

Armour stability

Concrete units
- armour stability increases with increasing angle of incidence,
- initiation of damage is delayed under oblique waves,
- once initiated, damage increases faster under oblique waves (Antifer cube, tetrapod).

Quarry stone
- armour stability is not much influenced by wave obliquity at damage levels lower than 5%,
- at higher damage levels and at incidence higher than 15°, armour stability slightly increases with increasing wave obliquity.

Overtopping

All units
- overtopping is equivalent under normal waves and at a 15° angle of wave incidence,
- then, it continuously decreases with increasing incidence.

Toe berm stability

Concrete units
- toe berm stability is equivalent, and can even be lower, at a 15° angle of wave attack and under normal waves,
- then it increases with wave obliquity.

Quarry stone
toe berm stability continuously increases with increasing obliquity.

Equivalent normal wave height

Results obtained at an angle of wave attack β and a wave height H_s are equivalent to those obtained under a normal wave height $H_s.\cos\beta^x$, x being a coefficient which depends on the phenomenon and the unit under consideration. This way, it is possible to use formulae derived under normal wave attack to take into account wave obliquity, for preliminary design of breakwaters.

However it is important to keep in mind that these conclusions result from a single series of tests at each wave incidence, and therefore do not take into account the scatter often reported. Trends presented in this paper are assessed because of the continuity in the evolution of the phenomena they represent, but numerical values should be taken just as estimates. Further testing is still required in order to derive reliable laws taking into account the influence of wave obliquity on the stability of rubble mound breakwaters.

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