CHAPTER 120

INTERACTION BETWEEN MAIN ARMOUR AND TOE BERM DAMAGE

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ABSTRACT
Wave flume tests were carried out aiming to describe and quantify the interaction between main armour and toe-berm damage up to failure. Experiments are descibed in brief, as well as the qualitative combined damaging process. An interaction scheme is formulated; data and formulae are provided for the quantification of the risk implied in the combined failure.

1. INTRODUCTION

The toe berm of a breakwater is primarily supposed to provide static support to main armour layer, avoiding that its lower units might roll down on the sloping lower surface.

Regarding the effects on the armour layer, if, on one hand, the whole toe-berm upper surface is eroded and erosion undermines the lowest units of the armour layer, the armour units may slide down producing relevant damage of the main armour layer. On the other hand, if the berm is wide enough and almost horizontal, units which are removed from the overlaying armour layer can be retained on the berm itself, reducing the effective slope of the layer and possibly increasing armour resistance to waves. Secondarily and proportionally to its width, the toe berm acts on the water flow, modifying for instance the wave breaking process and the boundary layer evolution at the breakwater surface.

In the case the armour layer is damaged when the berm still shows a significant retaining capacity, armour stones held on the berm can hinder its further erosion.

Some information regarding rubble mound toe protection stability in front of an impermeable vertical wall may be found in the Shore Protection Manual referring to Brebner & Donnelly (1962). Similar information drawn from Japanese experience can be found in Tanimoto & al. (1982) or Goda (1985).
Regarding toe berm stability at a rubble mound breakwater van der Meer (1992) presented a first design formula for depth limited wave conditions desumed from model tests of seven breakwaters with alternatives, whereas Gerding (1993) performed several tests for the specific purpose and derived a verification and design formula valid also for deep water conditions.

No precise information could be found in literature about damaging interaction,

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and only an indirect and qualitative statement, van der Meer (1992), that berm damage greater than 3-10% may cause the berm to loose its functionality and should therefore considered not acceptable.

In order to quantify the outlined interaction between toe-berm and armour layer a set of laboratory experiments was performed aiming:

- to identify the effect of a stable berm on main armour damage;
- to analyse the damaging process of the berm in a wide set of structure and wave conditions;
- to identify the berm damage level which forces the downsliding failure of the armour layer.

Analysing the wide set of experimental data obtained from our tests we have finally

- compared results from our tests and Gerding tests
- derived revised damage formulae for the berm including the effect of factors not variables in Gerding data set or not represented by Gerding formula;
- derived a relation between the berm width and the critical damage level causing main armour failure;
- analysed the statistical errors of Gerding and our revised formulae.

2. PERFORMED TESTS

Tests were performed in Florence. The wave channel used has a 0.8x0.8 m^2 section, is 40 m long and is equipped with a wave paddle of the absorbing type; water depth at the wave paddle is 0.5 m. A 1:100 bed slope reduces water depth to 0.34 or 0.20 m in front of the tested structure. The maximum significant wave height that could be produced in the test section is 0.15 m.
The test section was divided into three parts 0.265 m wide where structures were built with an identical profile, but with stone of different size in the berm. This enabled to test contemporary three berm conditions, but forced also to use a smaller scale than usual. The absence of scale effects was checked reproducing tests T23, T25 and T27 of Gerding (1993) in 1:2 scale. All the geometrical dimensions of the breakwater were accurately reproduced as well as the testing procedure used by Gerding at DH De Voorst: in these tests (only in these) no settling wave attack was run before the nominal ones and berm was rebuilt after each wave attack. Only the foreshore slope, which was yet prepared with a slope 1:100 in our channel, while it was 1:20 in DH experiments, is different. . The milder foreshore slope caused in our tests a reduced wave height at breaking and a slight distorsion of the wave height distribution which was accounted for by assuming as characteristic wave height for stone mobility $H_{2\%}$; no significant scale effects could be observed with this assumption.

Several test structures were designed keeping fixed some parameters and others variable. Fixed were: armour stones (weight 32 g, density 2.6 g/cm^3, equant shape) breakwater crest elevation (15 cm, irrelevant overtopping), berm base depth (25 cm in deep water, fig 1, and 15 cm in shallow water), shape and grading of berm stones (equant, very well sorted) and, approximately, the wave height likely to produce structure failure (H_{sd}=8 cm). Variable were: water depth at structure toe, armour

slope, toe berm depth and width (the mentioned parameters define a structure shape) as well as wave steepness and toe berm stone size.
The criterion for the choice of variable parameters characterising each test series was to select combinations of reasonably extreme parameters. Each structure shape is identified by four parameters and denoted by four letters specifying in the order:

- water depth at structure toe h_m: D (deep) ⇔ h_m=34 cm, S (shallow) ⇔ h_m=20 cm; in the first case wave are not depth limited, whereas in the second case extreme waves are depth limited;
- berm depth h_t: H (high berm) ⇔ $h_t=H_{sd}$; L (low berm) ⇔ $h_t=1.6H_{sd}$; in the first case berm stones almost as great as armour stone are requested, in the second case almost as great as the underlayer ones;
- berm width b_t: F (no berm) ⇔ b_t=0, the berm depth marks a reduction in armour size; N (narrow) ⇔ $b_t=3D_{n50td}$; W (wide) ⇔ $b_t=10D_{n50td}$; D_{n50td} is our conventional design size of berm stones, i.e. the size satisfying Gerding berm stability formula () with damage $N_{odt}=b_t/D_{n50t}$ (1 in the case of no berm)
- armour slope: S (steep) ⇔ $cotg\alpha$=1.5; M (mild) ⇔ $cotg\alpha$=2.5; it was supposed that milder slopes could hinder armour sliding even in the case of severe berm erosion.

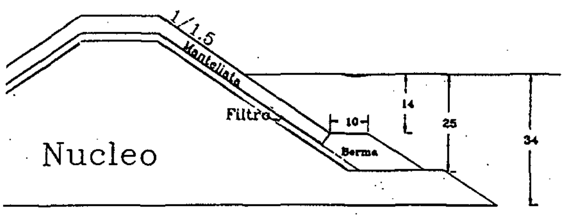

Fig. 1 Section of the tested structure DLWS

Figure 1 shows the DLWS structure.

Different berm stone size were tested corresponding to more and less stable berms than provided by the design criterion. The actual number of stones in the berm width can be significantly different from one of the nominal values (0,3,10), ranging actually from 0 to 25.

Each structure was attacked with waves of increasing intensity up to failure. Wave conditions were drawn from a fixed wave signal set providing a wave height increase around 10-12% per step. For each test series the wave spectrum shape was kept constant and in all cases each wave attack lasted 3000 waves. Two combinations of wave steepness and spectral shape were used: a PM spectrum giving H_s/L_{om}=0.05 (short waves, identified by a 5th letter S in test series code) and a JONSWAP spectrum with γ=5 and H_s/L_{om}=0.02 (long waves, L).

12 structure shapes (8 in deep water and only 4 in shallow water conditions, since low berm are unrealistic in this case) and 73 test series, i.e. combinations of structure shape, wave steepness and berm stability conditions, were tested systematically.

Waves were generated using the same signals and target wave conditions were preliminarily measured at structure toe in the absence of any structure. Measurements were repeated during tests for control purposes but target values were used for analysis.

Damage to the armour layer and to the berm was measured:

- by profiling the structure with a rod array after each wave attack and deriving erosion area (A_e) from profiles (erosion damage $S \equiv A_e/D_{n50}^2$) and
- by counting over a certain observation area (the relevant part of the structure times an observation width B_o) the number of stones (N_d) displaced from the armour layer or removed from the berm ($N_{od} \equiv N_d/(D_{n50} \cdot B_o)$.

3. QUALITATIVE RESULTS AND CLASSIFICATION OF FAILURE PROCESS

Figure 2 shows some typical results of one test series.

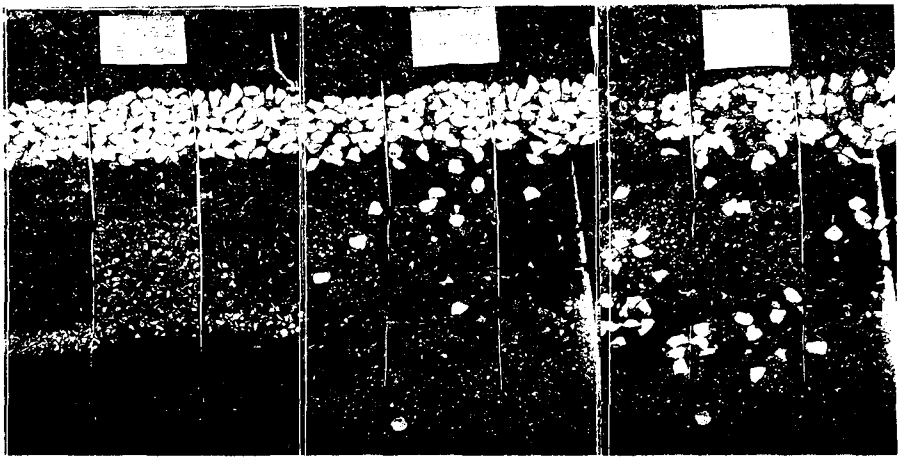

Fig. 2 Structure DHNS at start of test and after the 3rd and last wave attacks. Remark in the central photo how a moderate berm damage in the left structure (dark-coloured stones removed) does not induce any incremental damage on main armour compared to the central structure, whereas the rightt photo shows how a relevant berm damage forces the armour down sliding in the left structure and a significant incremental damage in the central structure, where the narrow flattened berm is unable to stop falling units, compared to the right structure.

Since every stone moved on the armour layer is displaced downwards and almost certainly removed from it, erosion and displacement damage of the armour are strictly linked and represent a single damaging process.

This is not the case for the berm when the armour layer is damaged, see fig. 3, since profiles do not distinguish armour from berm stones, whereas the distinction was natural while counting removed stones. Berm apparent erosion usually decreased when the armour layer was severely damaged, whereas the number of stones displaced from it is regularly increasing with wave height. As index of damage to the berm the displacement damage is therefore used in principle. A qualitative description of the damaging process must however accompany the damage quantification in order to avoid anbiguities.

Referring to failure conditions the following classification was used:

1. stable and wide berm: the berm mantains its initial shape up to armour layer failure, most of falling armour stones are stopped by the berm causing a reduced damage increase with wave intensity;
2. stable but narrow berm: the berm mantains its initial shape but most of the armour stones fall below it;
3. wide berm less stable than the armour layer but effective in retaining falling units;
4. berm less stable than the armour layer and ineffective in retaining falling units;
5. severely unstable berm: the armour layer fails due to lack of support provided by the berm.

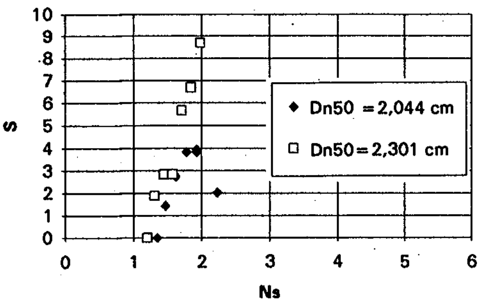

Fig. 3 Damage progress for a typical structure: DHNS, long waves, $D_{n50t} = 2.04$ cm

By decreasing berm stability wide berm structures move from type 1 to 3 ending at 5; narrow berm structures normally follow the sequence 2, 4 and 5.

Figure 4 shows schematically the damage progress in berm and main armour for a non effective (left) or effective (right) berm. The three progress lines represent in left to right order a stable berm, a moderately unstable and a severely unstable one. The right figure shows also how a stable and wide berm retards the damaging of the main armour, the effect being cancelled in a weak berm, and how, hypothetically, main armour damage can retard the berm damage causing armour down sliding.

Since the damage causing main armour failure is well documented in literature

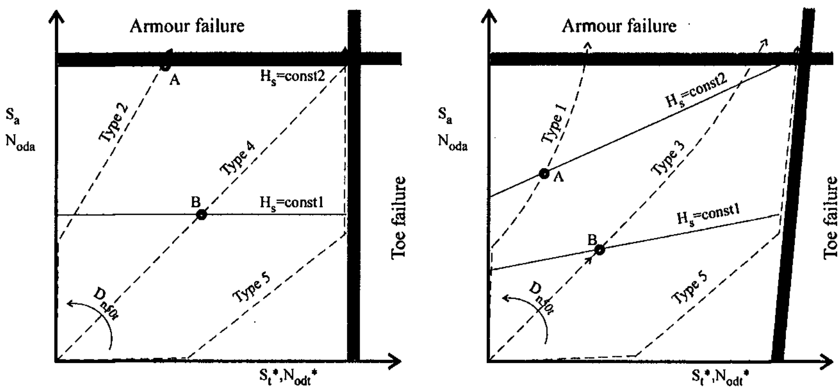

Fig. 4 Damage progress in a non effective berm case (left side) and in an effective berm case (right)

($S_a = 8 \div 12$ depending on slope, van der Meer 1988), the main aspects requiring quantification are:

- the benefit of a stable berm if any,
- the berm damage threshold causing armour down sliding
- a reliable relation providing berm damage (in the stable armour case at least).

Figure 5 shows the comparison of main armour damage over berm of different stability. In the presented cases the sudden damage increase due to berm flattening is evident. A curve is shown representing van der Meer formula, i.e. the usual increase of damage with increasing incident wave height. Erosion damage is converted to displacement damage dividing by 2.0.

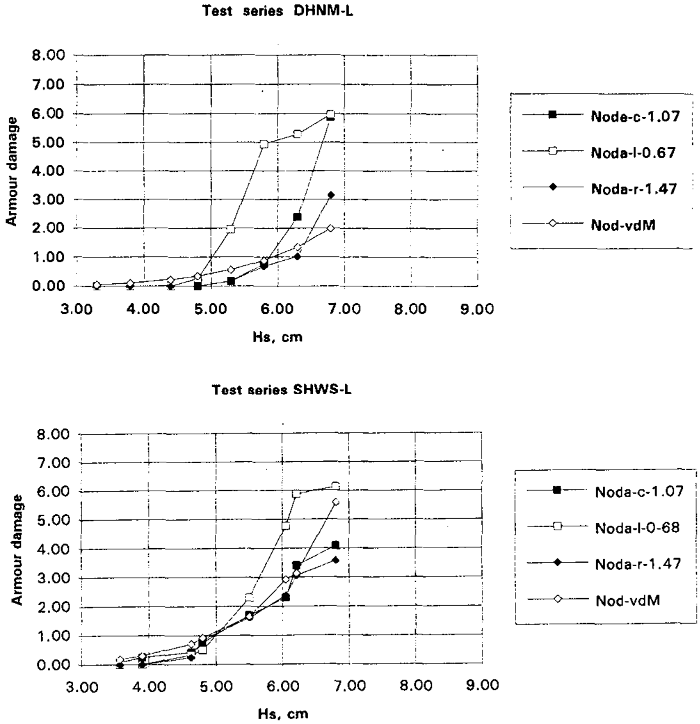

Fig. 5 The effect of berm stability on main armour damage in two tested structures

4. POSITIVE EFFECTS OF A STABLE BERM ON THE ARMOUR LAYER

The positive effect of a stable berm can be desumed from the comparison of observed armour damages over a certainly stable berm with damage estimates obtained from van der Meer (1988) formulae. This formula is actually deduced mostly from experiments on slopes, i.e. in the absence of any berm; the comparison with the formula is quantified by evaluating the average ratio of observed and

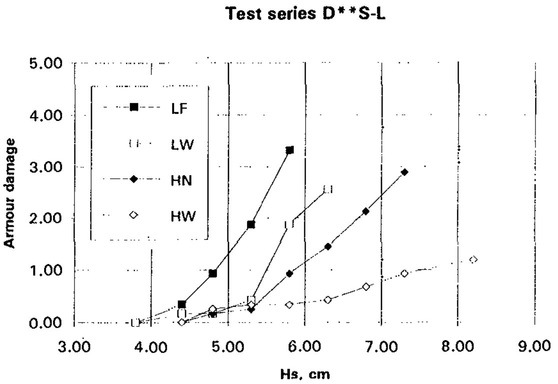

Fig. 6 Comparison among experimental displacement damages due to long waves in deep water acting on steep armour slopes over berms of varying width and depth

computed damages presented in table 1. Since formulae include the effects of wave and of armour layer parameters (wave height and period, armour slope, stone size and density) the ratio even if not constant is less variable than the damage itself and can characterize the damage relation below the threshold.

Armour damage was measured both as erosion and as displacement damage. The two damage estimates are well correlated: we have observed $S_a = 2.5 \cdot N_{oda} \pm 0.8$; but, while the first is subject to the evaluation error due to the limited number of profiles and includes structure settlement, the second is not subject of any measurement error, since counting is exact and displaced stones are clearly recognizable. Displacement damage was therefore preferred. Figure 6 shows the comparison of armour damages due to long waves on steep armour slopes in deep water. The compared results are derived from cases where the berm was very stable and show the effect of berm width and height. Every existing formula, as e.g. Van der Meer's formula, returns equal damages for the four structures. The effect is comparable to discrepancy observed between data in extreme conditions and van der Meer formula were observed also by Mase & al. (1995). The effect is in this case out of discussion: both the height and width of the berm have evident and positive effects. The effect is similar but smaller for mild armour slope and/or in shallow water, supporting the interpretation that the positive effect is due to reshaping of the armour layer sustained by the berm in the most severely attacked zone.

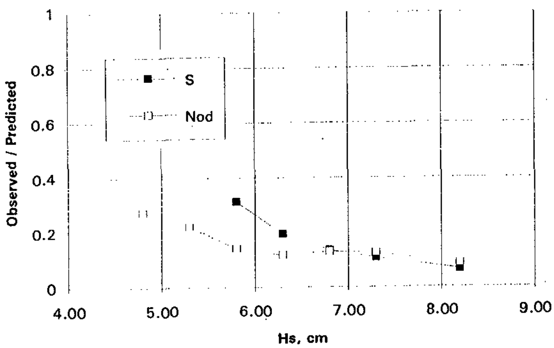

Fig. 7 Typical ratio of observed damage to the damage derived from van der Meer eq.. Structure DHWS with long waves (most effective berm among tested ones)

Figure 7 presents a typical behaviour of the ratio between observed damage and the damage estimated by van der Meer formulae.

Table 1 shows the average ratio between the observed damage and the damage foreseen by the formula. Due to the recognized inaccuracy of the formula (6-7% on H_s) and due to the recognized lack of reproducibility of armour strength (≅30% on damage) only discrepancies greater than 40% are singularly evident.

Table 1. Average reduction factor to be applied to van der Meer equation below the negative effect threshold

	Long waves						Short waves					
	FS	NS	WS	FM	NM	WM	FS	NS	WS	FM	NM	WM
DH	---	**0.4**	**0.2**	---	0.8	**0.4**	---	0.5	**0.4**	---	0.9	0.6
DL	1.0	---	0.5	1.6	---	1.0	0.5	---	0.7	---	---	0.8
SH	1.2	0.9	0.8	---	---	0.8	0.8	1.1	0.6	---	---	0.6

Some conclusions may be drawn:

- positive effects are evident only in deep water;
- the effect normally increases with berm height and width;
- the effect is greater for steep armour slopes;
- strong positive effects are possible only when the berm can retain displaced stones from falling to a depth where they would be of no use for the portion of the profile that is attacked by waves.

5. NEGATIVE EFFECTS OF AN UNSTABLE BERM ON THE ARMOUR LAYER

In most cases armour damage increased quite abruptly as a consequence of berm flattening, see fig. 5. In a few others it raised more gradually. The damage increase shows always some irregularity due to the limited number of armour stones in the test area, and this makes the identification of small deviations questionable.
As long as the berm damage is significantly below the critical threshold no evident correlation between armour and berm damage could be observed.
Actually the erosion and flattening of the berm is supposed to cancel progressively the beneficial effect of the stable berm, but this is covered by the "noise" in most cases.

On the oher side, when the armour is severely damaged and armour stones cover the berm, the conditions for experimental evaluation of the berm damage are the worst and only the order of magnitude of the damage can be assessed. Visual inspection showed also that armour stones were never covering with sufficient and uniform density the berm, so that a compensation between the shelter effect of a dense armour stone cover and the erosive effect of isolated stones is likely to occur.
When eventually erosion undermines the armour layer, a rather sudden incremental damage $\Delta N_{od} = 3 \div 4$ takes place.

Since the flattened berm has an almost constant shape (slope 1:4÷5), the corresponding berm damage level measured either as erosion or as displacement damage should depend only on the nodimensional berm width: berm damage, represented by either the erosion area A_e (volume of erosion per unit length) or by the number of displaced stones N_{dt} (proportional to the length where removed stone are

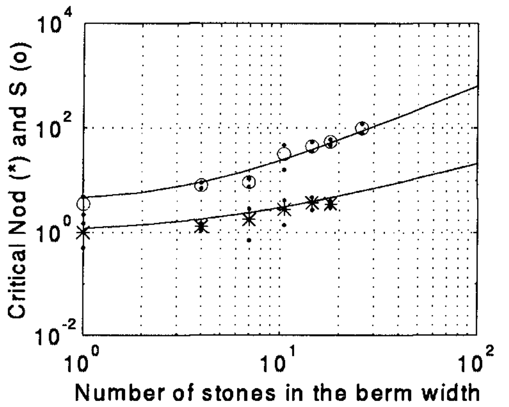

Fig. 8 Empirical relation between the critical berm erosion and the relative berm width

counted), should depend only on berm width B_t and stone size D_{n50t}, the nondimensional version of this relation is a relation between N_{odt} or S_t and B_t/D_{n50t}.

Figure 8 shows the two average empirical relations. For each substructure the critical damage was assessed (either as a value, when sliding was observed, or as a bound, when sliding was not observed) and statistics were evaluated for berm-width classes. Figure 8 shows the average values and the 2 standard deviation range.

The two lines represent relations fitted to the average raw values; from these a unique corrected relation for the damage can be derived (following paragraph describes the correction):

$$S_t^c \equiv 2.0 \cdot N_{odt}^c = 3 + 0.7 \cdot \left(B_t/D_{n50t}\right)^{5/4} \tag{1}$$

The final interaction scheme is:

- if the berm damage is below critical threshold, the effect on the armour is normally weak; it can be:
    - disregarded (traditional approach, using e.g. van der Meer formulae) increasing parallely the estimate error;
    - pointed out by some new method (e.g. Mase & al., 1995) or derived from tests; in this case the benefit should be reduced progressively to zero with incresing berm damage up to the critical value;
- if the berm damage reaches the critical value the upper layer of the armour will slide down causing a considerable increase of damage and reaching, for any reasonably safe design, armour failure ($N_{oda} \cong 4$).

6. RELIABILITY OF OUR DAMAGE ESTIMATES

For several reasons raw estimates of the berm damage S_t and N_{odt} are only moderately correlated and show an average ratio far greater than 2.0. If every removed stone causing erosion is counted in N_d and if no other mechanism but erosion causes profile modification, then the relation between the two variables would be

$$S \cdot (1 - n) = N_{od} \quad , \tag{2}$$

where n is the void fraction near the suface (≅0.5), expressing in non dimensional form the fact the eroded part of the initial profile was occupied by stones and by interstitial void.

But actually settlement do occur, particularly for the berm since it was reconstructed after each test series, and some error in conting the removed stones could not be avoided. Berm stones were made recognisable by colouring the top layer, and removed stones were counted only when they were removed outside the berm including its face. Some berm stones were removed from the berm and not counted, because maybe they were hidden by fallen armour stones or among armour stones (particularly when in order to obtain a very unstable berm berm stones were smaller than those in the underlayer), some more eroded by the second layer were not counted because they were uncolored and confused with stones of the lower layers, some others were not counted because they moved within the berm.

The best experimental relation between the two variables in our experimental set-up and procedure was

$$S_t = 5.2 \cdot N_{odt} + \frac{0.5 \cdot B_t}{D_{n50t}^2}^{\text{cm}} \qquad \text{c.det.} = 0.76$$

It can be interpreted as:

- the average structure show a berm settlement of approximately 0.5 cm;
- on the average only 38% of berm stones contributing to erosion are positively counted as removed.

The first assumption corresponds to observations. The second was controlled in some final tests series where the upper first three layer of the berm where coloured differently from the front face, eliminating the second and partly the third cause of counting errors. It was observed that stones of the upper first layer transported out of the berm were on the average 45% of those that were counted as moved, i.e. that were moved outside they colour area. The difference (45-38%) can be easily explained by the remainin error causes.

The above empirical relation was used to correct raw berm damage estimates and combine them into "true" berm eroson and displacement damage indexes

$$S_t^* \equiv 2.0 \cdot N_{odt}^* \equiv avg\left(S_t - \frac{0.5 \cdot B_t}{D_{n50t}^2}^{\text{cm}} \;,\; 5.2 \cdot N_{odt} \right)$$

The relation compensates for some systematic errors performed in the evaluation but shows also the errors present in the raw estimates.

Likely errors of compensated values are about 40% (less or more depending on the number of original raw estimates available: in some cases counting was impossible, in some others berm stones erosion area could not be assessed).

7. REVISION OF TOE BERM DAMAGE FORMULAE

Tests were programmed making use in a predictive sense of Gerding formula,

$$\frac{H_s}{\Delta_t D_{n50t}} = \left(1.6 + 0.24 \cdot \frac{h_t}{D_{n50t}} \right) \cdot N_{odt}^{\;0.15} \qquad (3)$$

The results of the tests substantially confirm the formula.

Comparing the two sets of experimental results and or the derived formulae a few differences must be remarked. Formula (3) is based on a series of tests expressly designed for the evaluation of berm damage under a fixed armour layer, whereas our tests were primarily focused on the influence on armour damage and were therefore carried in a more complex and difficult experimental environment. The berm in Gerding's tests was reconstructed every time and damage are the damages of the wave attack, whereas in our tests the berm was reconstructed at the beginning of the test series and the observed damage is the cumulated effect of all the wave attacks in the current progression. Foreshore slope was different in the two experiments, as mentioned before. Armour slope in Gerding test was fixed: 1:1.5. Wave steepness in Gerding tests varied in {0.02, 0.03, 0.05} with preference with the central steepness, i.e. varied significantly less than in our experiments.
The main differences we observed are:

- the average exponent of displacement damage was higher: 0.2;
- the average sensitivity to berm depth was lower 0.15;
- a systematic effect of wave steepness (or wave period) was evident as in Benoit & Donnars (1996).

A formula similat to (3) that fits our results is:

$$\frac{H_s}{\Delta_t D_{n50t}} = \left(1.1 + 33 \cdot s_m + 0.15 \cdot \frac{h_t}{D_{n50t}}\right) \cdot N_{odt}{}^{0.20} \tag{4}$$

We have also reanalysed berm damage data with a more free approach since some aspects of formulae (3) and (4) did not convince us.
Let $u_c \equiv \sqrt{g \cdot H_s}$ be the conventional reference velocity (the velocity scale in the breaker area), let u_t be the maximum velocity at the toe-berm i.e. the real cause of damage, and let $\upsilon_t \equiv u_t / u_c$ be the non dimensional velocity at the berm. The erosion of toe berm stones depends on the ratio between the hydrodynamic force on the stones and their submerged weight

$$N_{odt}^{*} = funct\left(\frac{H_s}{\Delta_t D_{n50t}} \cdot \upsilon_t^2\right) \tag{5}$$

where 1) *funct* should be a monotonic increasing function with no upper bound, and 2) υ_t should depend only on what influences the flow field and not on Δ_t.
The non dimensional velocity at the berm should depend on:

- a location parameter specifying where the berm is located with special refence to breakers: h_t / H_s;
- a roughness ratio, ratio between the flow field dimension and the surface roughness: h_t / D_{n50t} ;
- wave period and armour slope, determining wave penetration into depth, reflection, run down: s_m and $tg\alpha$
- berm width: B_t / D_{n50t}.

Formulae (3) and (4) conform to the above scheme but represent the influence of the roughness ratio which seems of secondary importance compared to the location parameter. Making use of the fact that Δ_t was practically constant in Gerding tests, formula (3), for instance, can be easily transformed into an equivalent relation involving the location parameter:

$$\frac{H_s}{\Delta_t D_{n50t}} = \left(1.6 + 0.4 \cdot \frac{h_t}{H_s} \cdot \frac{H_s}{\Delta_t D_{n50t}}\right) \cdot N_{odt}^{0.15} \tag{6}$$

This relation however shows un upper limit in the damage $\left(\frac{H_s}{0.4 \cdot h_t}\right)^{1/0.15}$ which was almost reached in some of our experiments.

We have therefore interpreted also our data according to a power regression equation returning toe berm damage as function of the independent variables described above. The relation is fitted on our data and checked with Gerding's results.

The best representation is obtained with different equations fitting for h_t/H_s greater and smaller than 1.35; the separation value is empirical but not far from the condition that berm emerge at extreme run down; in the tested conditions the average run-down according to van der Meer (1992) is $R_{d2\%}/H_s = 0.75$.

All the independent variables were initially included in the regression; the less influent were progressively discarded until the loss of of determination (percentage of explained variance) became greater tha 0.01. The final regression are:

- for $h_t/H_s < 1.35$

$$N_{odt}^* = 3 \cdot 10^{-6} \cdot \left(\frac{H_s}{\Delta_t D_{n50t}}\right)^{4.0} \cdot \left(\frac{H_s}{L_{om}}\right)^{-3.1} \cdot \left(\frac{B_t}{D_{n50t}}\right)^{-0.4} \tag{7}$$

on our data the coeff. of determination is 0.75 and r.m.s. log deviation is 0.48; on Gerding data r.m.s. log deviation is 0.85;

- for $1.35 < h_t/H_s$

$$N_{odt}^* = 9 \cdot 10^{-6} \cdot \left(\frac{H_s}{\Delta_t D_{n50t}}\right)^{3.5} \cdot \left(\frac{H_s}{h_t}\right)^{1.9} \cdot \left(\frac{H_s}{L_{om}}\right)^{-3.0} \cdot (tgh\, kh_m)^{4.8} \cdot \left(\frac{B_t}{D_{n50t}}\right)^{-0.3} \tag{8}$$

on our data the coeff. of determination is 0.73 and r.m.s. log deviation 0.71; r.m.s. log deviation is 1.43 on Gerding data. As a comparison the r.m.s. log deviation of N_{odt} in Gerding's relation is 1.50 on our data, and 0.75 on Gerding's data.

Figure 9 gives an impression of data fitting to equation (7).

8. CONCLUSIONS

An effective berm (high, wide and stable) can reduce significantly the damage progress of a steep armour layer, particularly in deep water conditions;

The effect is significantly greater than the error range usually attributed to design formulae, particularly to van der Meer's one, which is quoted as providing estimates with a 6-7% error on H_s. The effect may be as great as 40 % on H_s at start of damage level ($N_{oda} = 1$) and is in several tested cases above 20%.

A berm damage above a critical threshold causes the rapid regressive erosion of a one stone layer (sliding) and the failure of the armour layer for every tested conditions ($tg\alpha \geq 1/2.5$). The threshold damage value increases with berm width; a graph representing the critical damage is provided.

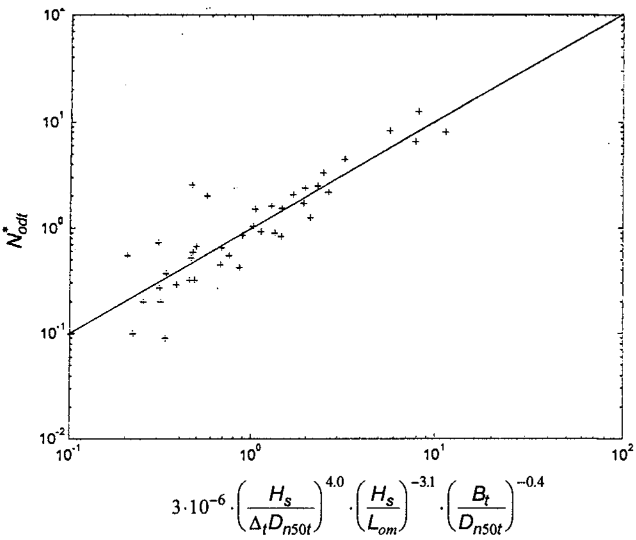

Fig. 9. Comparison of our experimental data with damage relation (7)

The armouring process of an unstable berm by displaced armour units, visually observed, does not produce evident effects in our tests, mainly because the surface armouring layer never was so dense everywhere to induce an effective protection of the underlaying berm stones.

The test showed that wave steepness has an evident effect on berm damage.
The berm depth influence is secondary if the berm is struck by breakers ($h_t/H_s < 1.35$ in our tests or berm above run-down level in a more general case), whereas it becomes predominant if the berm is deeper.
Secondary effects of berm widt and of of depth at structure toe are recongnizable.

A formula for toe-berm damage is provided representing principal and secondary effects. In all tested conditions Gerding's formula gives however reasonable results. Correction terms in Gerding formula are provided in order to represent all the principal effects.

The design criterion "failure of the main armour (i.e. filter visible) and of the berm (i.e. erosion undermining armour units) for the same wave conditions" provides a balanced design. The criterion used for programming the tests, "failure of the main armour for wave conditions that, according to Gerding formula, cause as many displaced stones in the berm as they are in the top layer", lead to failure types 2 or 3 and can also be considered a balanced criterion, showing only minor unrepresented effects of wave steepness and berm width.

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