CHAPTER 84

Rock armoured beach control structures on steep beaches

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ABSTRACT

This paper presents the results of a research study to quantify the stability of rock armoured groynes on steep shingle beaches. The research was needed to identify why significant numbers of rock revetments and groynes have suffered greater damage than would be predicted by conventional design methods. The paper describes the design and execution of tests in a large wave basin, at notional scales of 1:10-20, on four types of typical beach control structures. The test structures were constructed on a model shingle beach of slope 1:7, and were subjected to random waves of steepnesses s_m=0.02 or 0.04.

The tests confirmed that armour damage may be substantially greater than predicted by existing methods, even on simple slopes under normal wave attack. The results of the damage analysis have been used to suggest modified coefficients to van der Meer's plunging wave formulae.

1. INTRODUCTION

The use of shingle beaches in a coastal defences increasingly requires control structures to maintain and retain the beach. A variety of structures are in use (Fig 1), including rock groynes and/or breakwaters, and revetments. The main structure types in use, not necessarily in the UK, may be summarised:

a) near-shore, detached, breakwaters;
b) low-crest or reef breakwaters;
c) submerged breakwaters or sills;
d) rock groynes, bastion or inclined;
e) rubble revetments.

Studies at Wallingford on the influence of the control structures on the beach response to wave action, reported by Coates (1994, suggest that rubble groynes are often the most cost-effective of these structures in controlling movements of shingle beaches, and significant research is underway to describe the effect of structure plan configuration and geometry on the plan re-shaping of the beach. As shingle beaches may become depleted without re-nourishment, or may be locally denuded by strong oblique wave attack, back-

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beach rubble revetments may also be required to form a stronger rear defence.

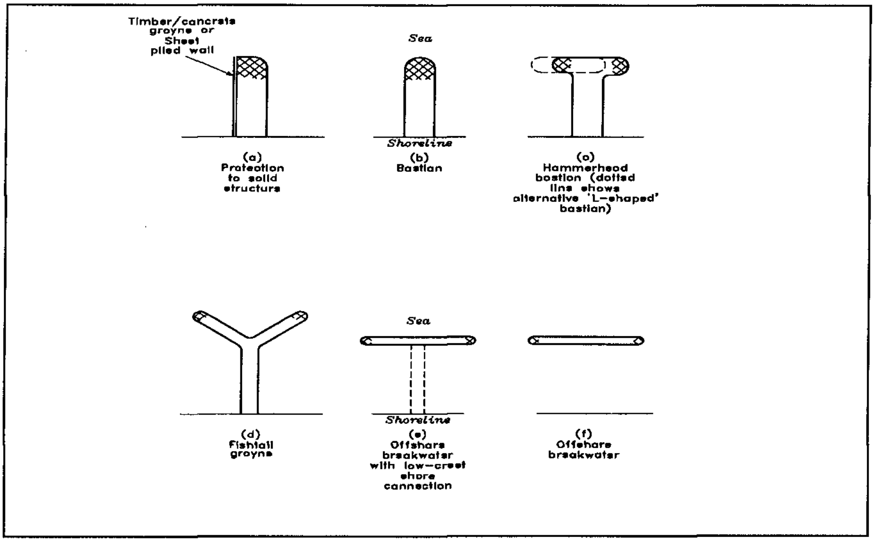

Figure 1 Beach control structures

The main parameter set by structural considerations on all armoured control structures is the median armour size. The armour slope angle chosen interacts with the armour size needed for a given stability level, but is also set by consideration of wave reflections and overtopping. Many other dimensions, and aspects of construction practice, relate closely to the unit armour size. If under-sized, rock armour will move excessively, leading to deterioration of the armour, and/or erosion of fill. Structural changes to the groyne will in turn lead to higher wave overtopping, and/or beach erosion. It is important therefore to ensure that any damage to the structure remains below acceptable limits. Various methods may be used to calculate the armour size, but are only fully valid for normal attack on simple cross-sections. Allsop et al (1995) present evidence where some structures have experienced more damage than expected by their designers, and/or deemed acceptable by their owners.

The problem of increased damage armour appears to have been most severe on steep shingle beaches, typically in the UK at slopes between 1:5 to 1:10, with the average near to 1:7. It is likely that such steep slopes have significant influences on the form and strength of wave breaking onto any structure constructed on the beach, thus modifying the waves from the form of deep or intermediate depth waves for which most design methods have been derived. Most of this paper therefore describes hydraulic model studies conducted to measure armour damage on beach control structures on steep beaches, and the analysis then conducted to devise appropriate design methods.

2 METHODS TO CALCULATE ARMOUR STABILITY

Design methods for rock armour focus on calculation of the median armour unit mass, M_{50}; or the nominal median diameter D_{n50} defined in terms of the median unit mass and rock density ρ_r: $D_{n50} = (M_{50}/\rho_r)^{1/3}$. The most common calculation methods are the Hudson formula given in the Shore Protection Manual by CERC (1984); or equations by Van der Meer (1988). Hudson developed a simple expression for the minimum armour weight for regular waves which may be written in terms of the median armour unit mass, M_{50}, and wave height, H:

$$M_{50} = \rho_r H^3 / (K_D \cot\alpha\ \Delta^3) \tag{1}$$

where ρ_r is the density of rock armour (Kg/m^3); ρ_w is the density of (sea) water; Δ is the buoyant density of rock, = (ρ_r/ρ_w)-1; α is the slope of angle of the structure face; and K_D is a stability coefficient to take account of the other variables. Values of K_D corresponded to the wave height giving least stability in tests with regular waves on permeable cross-sections subject to little overtopping. Slight re-shaping of armour was expected, and values of K_D correspond to "no damage" where 0-5% of the armour was displaced.

An alternative method was derived by Van de Meer (1988) who included model data by Thompson & Shuttler at Wallingford, extended this by further tests at Delft, and derived new formulae for armour damage which include the effects of random waves, range of core / underlayer permeabilities, and distinguish between plunging and surging wave conditions respectively:

$$H_s/\Delta D_{n50} = 6.2\ P^{0.18}\ (S/\sqrt{N_z})^{0.2}\ \xi_m^{-0.5} \tag{2a}$$

$$H_s/\Delta D_{n50} = 1.0\ P^{-0.13}\ (S/\sqrt{N_z})^{0.2}\ \sqrt{\cot\alpha}\ \xi_m^{P} \tag{2b}$$

where the parameters not previously defined are:

- P notional permeability factor
- S design damage number = A_e/D_{n50}^2, and A_e is erosion area
- N_z number of waves
- ξ_m Iribarren number = $\tan\alpha/s_m^{0.5}$
- s_m wave steepness = $2\pi H_s/gT_m^2$, and T_m is the mean period;

and the transition from plunging to surging is given by a critical value of ζ_m:

$$\xi_m = (6.2\ P^{0.31}\ (\tan\alpha)^{0.5}\ )^{1/(P+0.5)} \tag{2c}$$

Damage to armour on a range of core / underlayer configurations were analysed. Values of P given by Van de Meer vary from 0.1 for armour on underlayer over an impermeable slope, to 0.6 for a homogeneous mound of armour, with intermediate values of 0.4 and 0.5 also described. These formulae were derived for normal wave attack, and do not include corrections for roundheads or junctions.

3. DESIGN OF MODEL STUDIES

3.1 Test structures and facility

The objective of the physical model tests was to quantify the stability of rock armour on four typical rock armoured structures on a 1:7 beach slope:

a) a breakwater or groyne roundhead, Type 2, (Fig 2);
b) an L-shaped groyne, formed from a) above;
c) an inclined groyne, Type 1, (Fig 3); and
d) a simple 1:2 rubble sea wall slope.

The 1:2 sea wall section was tested primarily as a control structure, damage to which could be compared directly with predictions by the existing design formulae.

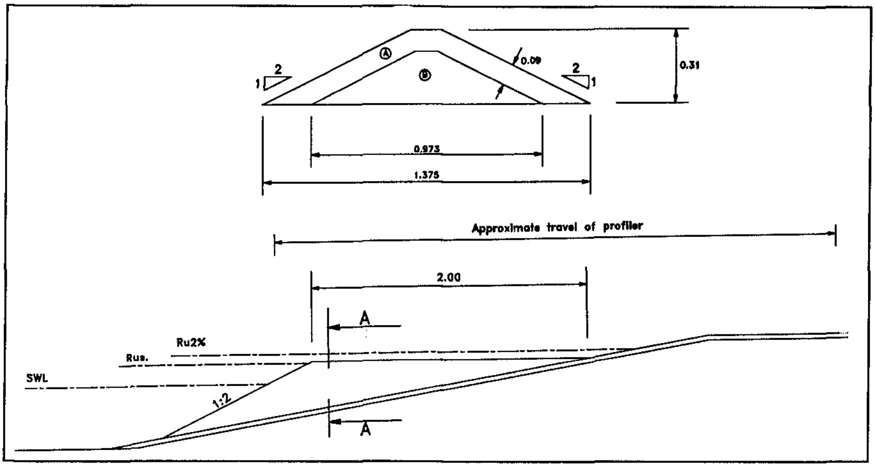

Figure 2 Type 2 roundhead groyne

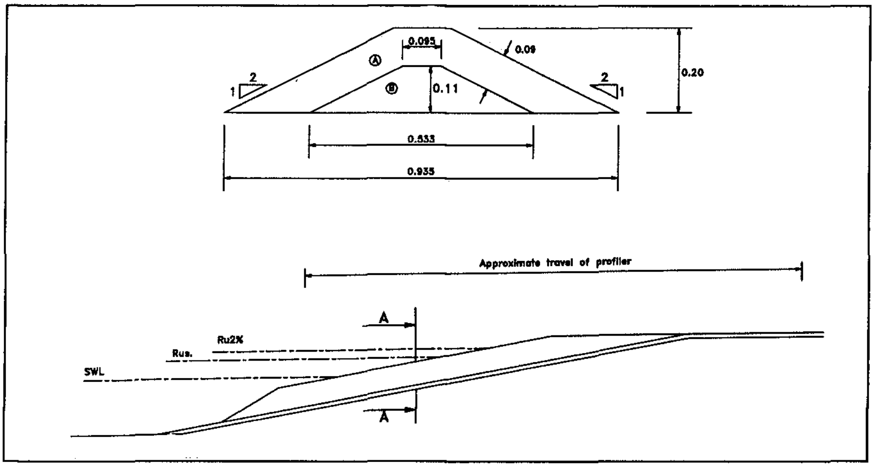

Figure 3 Type 1 groyne

Early in the research, a review of prototype structures suggested that the crest level should allow overtopping, and often fell between significant and 2% run up levels. The 2% run-up level was calculated using empirical prediction methods in CIRIA (1991). The principal test parameters may be summarised:

Water and bed levels	0.0m; -0.7m
Target wave height	H_s = 0.13m, ($H_s/\Delta D_{n50}$ = 1.7)
Mean sea steepnesses	s_m = 0.02 and 0.04
Test duration	N_z = 1000 and 3000 waves
Armour and core size	D_{n50} = 0.045m; D_{n50} = 0.024m
Side slope angles	Cot α = 2.0
Toe and crest levels	-0.36m, (-8D_{n50}); +0.22m, (+5D_{n50})

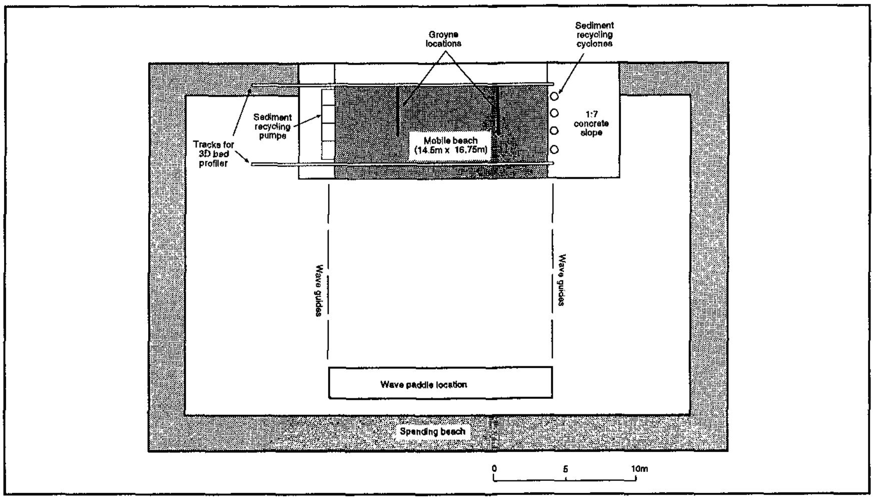

Figure 4 Roundhead Basin test facility

The structures were constructed and tested in a large wave basin which measured 40m by 27m (Fig 4). The models were not to a particular scale, so analysis of measurements used dimensionless terms, but the structures may be viewed as modelled at ratios of between 1:10 and 1:20. Two structures were tested at one time. Type 1 and 2 groynes were tested in the first series. The Type 1 groyne was then replaced by the sea wall, and the Type 2 groyne was modified to the "L" shape (Fig 5).

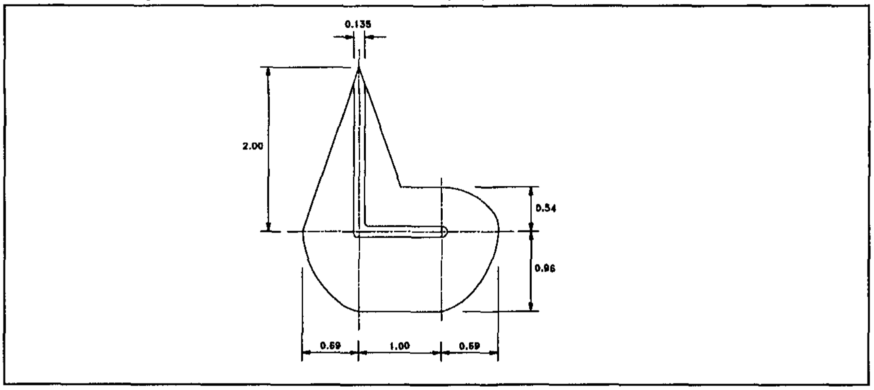

Figure 5 Plan of L-shaped groyne

The 1:2 slope sea wall section was 1.0m wide (equivalent to 22 D_{n50}). The toe was set at the same level as the toe of the "L" shaped and roundhead groynes.

The low level groyne, Type 1, was 4.7m long (105 D_{n50}), 0.94m (21 D_{n50}) wide at the base, and reached a height of 0.2m (4.4 D_{n50}) above the beach. The armour was laid to a thickness t_a=2D_{n50}, slopes of 1:2, and crest width of 3D_{n50}.

The high level roundhead groyne, Type 2, was shorter and wider than the Type 1 groyne at 2.95m (66 D_{n50}) long and 1.38m (31 D_{n50}) wide at the widest part of the roundhead. The crest was 0.31m (6.9 D_{n50}) above the beach at the seaward end.

The "L" shaped groyne was formed by extending from the roundhead of the Type 2 groyne. The groyne was 2.96m (66 D_{n50}) long, with a side limb of 2.38m (53 D_{n50}). A straight section of 1.0m (22 D_{n50}) formed the "L" shape.

Three 5m random wave paddles produced normal wave attack for these tests. The 1:7 slope beach used by Coates (1994) measured 12.5m by 8m, and this area was covered by an automatic three-axis bed profiler. Profile measurements of the structures were recorded on a personal computer, allowing armour displacements to be quantified by comparing profile lines over selected areas of each model. The measured damage was compared with damage predicted by the Van der Meer method for simple sections.

3.2 Test conditions

These tests were designed to give useful data over a wide range of structural and environmental variables. The experiments were intended to give intermediate armour damage at wave heights less than the maximum possible in the basin, equivalent to $H_s/\Delta D_{n50}$=2.6 for armour of D_{n50}=0.045m. The "target" wave height was equivalent to $H_s/\Delta D_{n50}$=1.7, and this wave height was used in the design of the model structures.

Around European coastlines, storm wave conditions are generally steep and narrow-banded, often described well by the JONSWAP spectra. Storm waves are relatively steep, but armour damage also depends upon sea steepness. These tests used two steepnesses, s_m=0.02 and 0.04 to explore the possible effects of longer waves. Each test was planned to be run for N=1000 and 3000 waves duration.

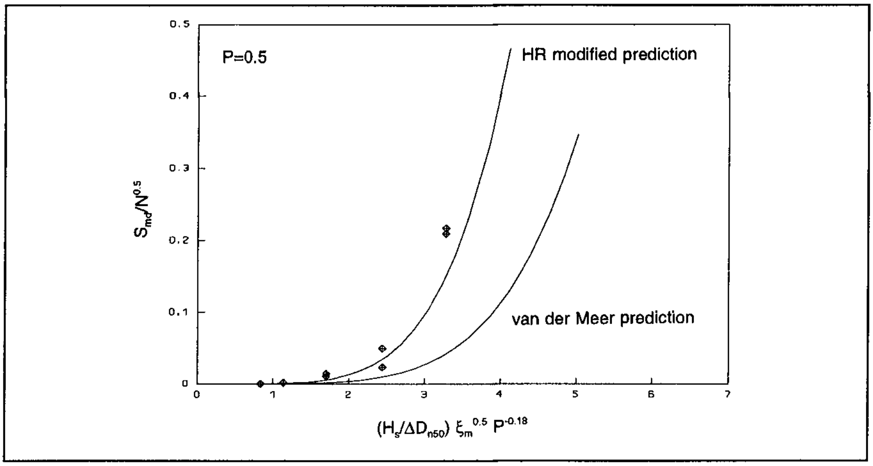

Figure 6 Sea wall damage, s_m=0.04, P=0.5

3.3 Test procedures

The first part of each test used 100 waves, during which close observations were made of the structures. If no movement was seen in these 100 waves, the test was stopped. If any damage (including rocking) was observed, then the test continued to 1000 waves when each profile line was re-surveyed. The test then continued for a further 2000 waves. After each test the structures were re-surveyed and photographed. If they had been damaged such that repair was necessary, the armour was re-built around the zones damaged. Testing was stopped when the structures needed re-building.

Profiling covered set lines over each of the groynes under test. The profiler incorporated a touch-sensitive foot of diameter equivalent to $0.8D_{n50}$, and took observations at $0.5D_{n50}$ intervals along each profile line. The profile results were used to calculate the area of erosion on each profile line, A_e, and hence the damage parameter S defined in section 2.

4. TEST RESULTS

4.1 Simple slopes

The test results were initially very surprising, as virtually all of the profiles showed significantly more damage than predicted by conventional formulae (Fig 6). Some local increases in damage had been expected, but not the consistently greater damage found here. Analysis attention was focused first on the 1:2 sea wall slope, and equivalent section on the L-shaped groyne, but even these simple cases showed significantly greater damage than predicted by the Van der Meer equations. During the analysis period, additional data on the performance of armoured groynes on two bed slopes became available from tests at CEPYC in Madrid. Initial analysis of these had been presented by Baonza & Berenguer (1992), and their test data were further analyzed by Allsop & Franco (1992) as part of the EC MAST project G6-S. These data also indicated that the sea bed slope might be significant in increasing armour damage.

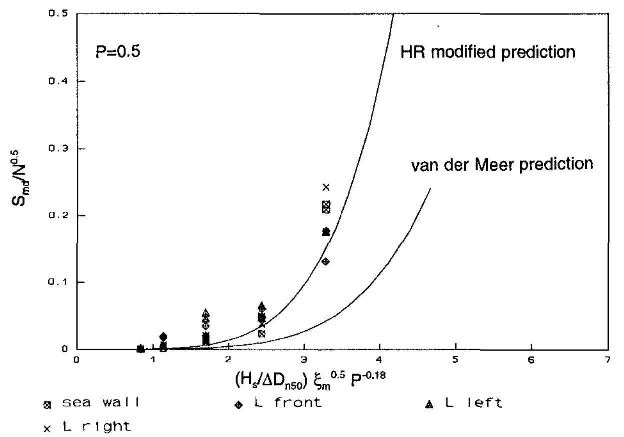

Figure 7 Sea wall and front face of "L" shaped groyne

Damage results for the sea wall section alone are summarised in Figure 6, using axes based on equation (2a) that allow results for each wave steepness and test duration to be presented together. The standard Van der Meer equation for plunging waves is shown, together with a version of the equation with a revised coefficient:

$$H_s/\Delta D_{n50} = 4.8\ P^{0.18}\ (S/\sqrt{N_z})^{0.2}\ \xi_m^{-0.5} \tag{3a}$$

The fit of the data to this modified equation is good over the area of main interest. Further support for the revised equation is given by the comparison of damage on the front face of the "L" shaped groyne with the sea wall, shown in Figure 7.

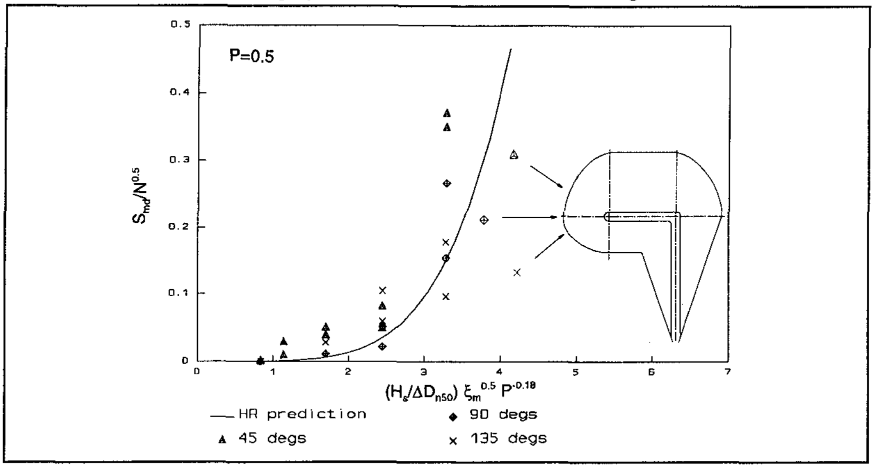

Figure 8 Damage to curved parts of "L" shaped groyne

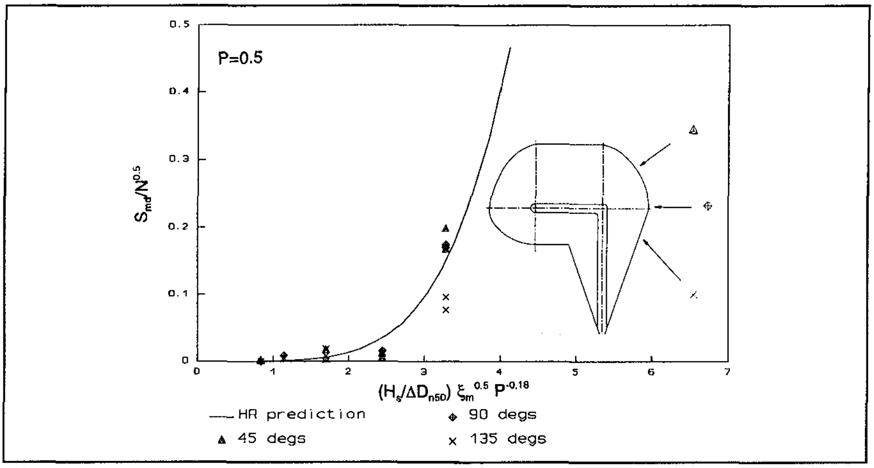

Figure 9 Damage to curved parts of "L" shaped groyne

The first result from this analysis was therefore the conclusion that damage is significantly increased by steep (local) beach slopes, even for simple slopes subject to normal wave attack. A modification to the Van der Meer equation for plunging waves is given in equation (3a), and a similar increase for surging waves would be given by:

$$H_s/\Delta D_{n50} = 0.77\ P^{-0.13}\ (S/\sqrt{N_z})^{0.2}\ \sqrt{\cot\alpha}\ \xi_m^{P} \tag{3b}$$

4.2 Roundhead and "L" shaped groynes

Once the effect of the steep beach slope had been accounted for, the test results suggest that some sections of the more complex 3-dimensional structures experience greater damage than the simple slopes under normal wave attack, but that the spread of damage spatially is somewhat variable. This is shown in Figures 8 and 9 where damage on the opposing sides of the "L" shaped groyne are contrasted with the new equation (3a). For most positions, the modified prediction method in eqn (3a) gives a reasonable estimate of the damage, but for the zones shown in Figure 8, damage at larger wave heights is still greater than would be predicted by the new method. In itself, this is not surprising, as it is well known that breakwater roundheads require larger armour units, and/or shallower slopes for the same stability as trunk sections.

4.3 Inclined, Type 1, groyne

Damage to the inclined groyne, Type 1, varied along its length, with the location of greatest damage depending on wave height and period. The mean level of damage taken over the active length of the groyne, and derived by averaging the erosion areas from each profile, fits the general prediction given by eqn (3a), and is summarised in Figure 10.

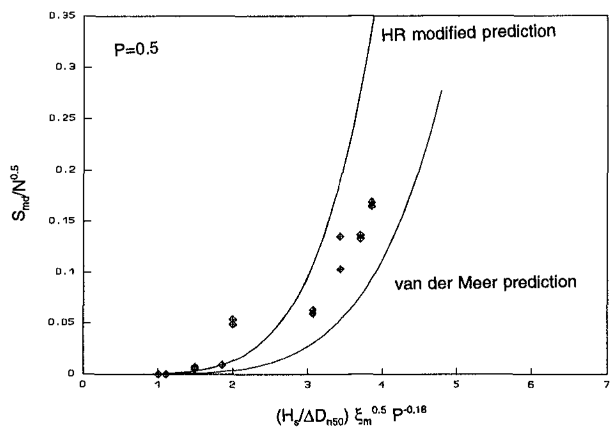

Figure 10 Summary of Type 1 groyne results

Peak values of (local) damage along the length of the groyne however often reached twice the mean, often at the wave run-up and run-down limits along the groyne, and this is illustrated in Figures 11-13 which show local levels of damage plotted against position along the groyne from the landward end for increasing relative wave heights. For $H_s/\Delta D_{n50}$ up to 1.72 (Figures 11-13), damage only exceeds S=5 at 1000 waves over small regions. For $H_s/\Delta D_{n50}$=2.16 (Fig 14) however, damage over most of the length of the structure has exceeded this criterion.

8 CONCLUSIONS

These tests have shown that the stability of armour on beach control structures depends critically on the local sea bed slope. Results from tests using a beach of 1:7 were used to develop a modified coefficient for use in the Van der Meer equation. The changes to the coefficients are equivalent to increasing the mean armour mass by a factor of 2.2 to maintain armour stability.

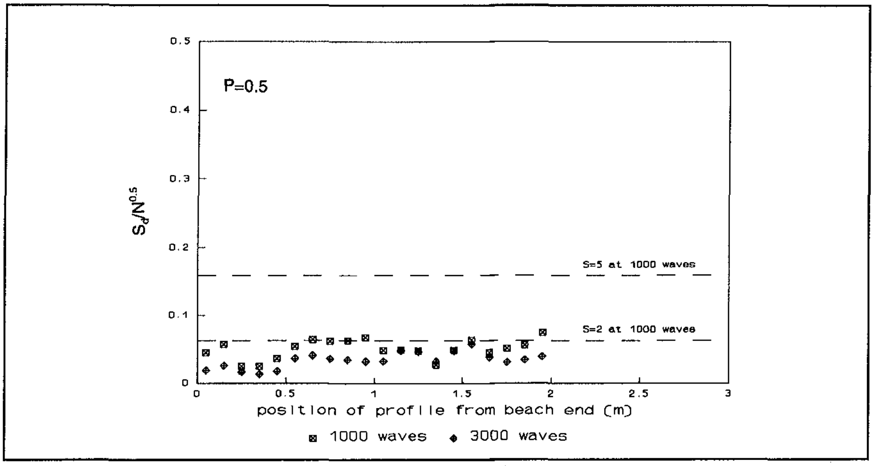

Figure 11 Type 1 groyne, s_m=0.04, $H_s/\Delta D_{n50}$=0.83

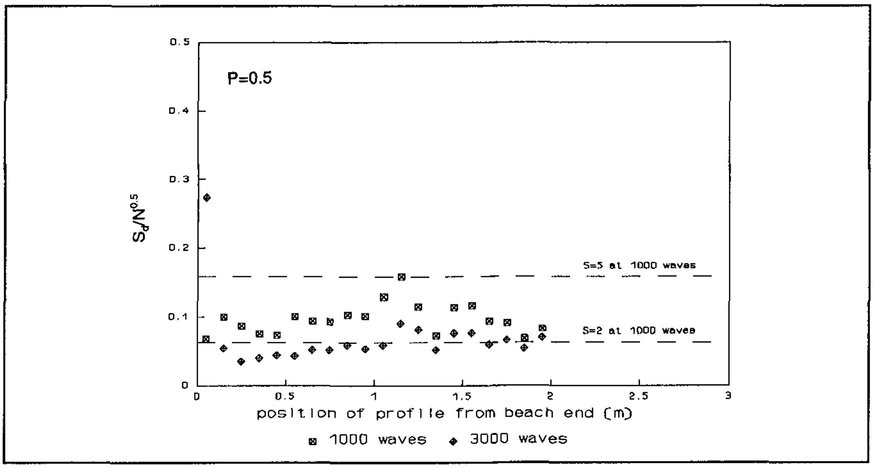

Figure 12 Type 1 groyne, s_m=0.04, $H_s/\Delta D_{n50}$=1.12

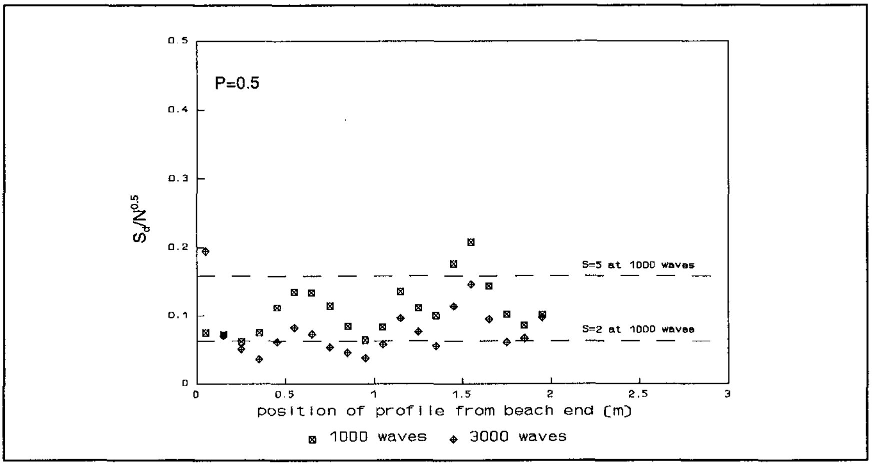

Figure 13 Type 1 groyne, s_m=0.04, $H_s/\Delta D_{n50}$=1.72

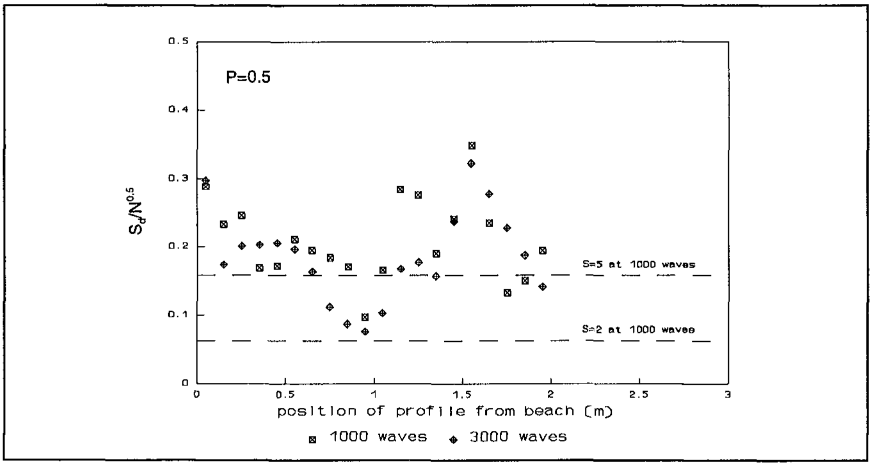

Figure 14 Type 1 groyne, s_m=0.04, $H_s/\Delta D_{n50}$=2.16

This study has identified some unusual effects, and some unexpected conclusions. The tests suggest that steep beach slopes may change the form of wave breaking such that the performance of structures in or behind steep (beach) slopes should be reviewed to identify whether a more general effect may lead to problems.

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