HR Wallingford

ROCK ARMOURING FOR COASTAL AND SHORELINE STRUCTURES: hydraulic model studies on the effects of armour grading

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ABSTRACT

This report is concerned with design methods for rock armour or rip-rap protection on coastal or shoreline structures subject to wind waves. It describes a short series of hydraulic model tests on a 1: 2 slope with an impermeable core. The tests were intended to identify whether the use of rock armour of grading wider than D_{85}/D_{15} = 2.25 will lead to armour performance substantially different from that predicted by van der Meer's equations. A secondary purpose was to identify the potential influence of a steep bed slope immediately seaward of the structure.

The test results suggest that very wide gradings such as D_{85}/D_{15} = 4.0, may suffer more damage than would be predicted by methods derived for narrower gradings. The report suggests how this reduced stability might be estimated using revised coefficients for van der Meer's equations. The report also notes the restricted range of conditions for which these conclusions are valid.

This study constitutes part of a collaborative project to produce an engineering manual through the Centre for Civil Engineering Research, Codes and Specifications in the Netherlands (CUR), and the Construction Industry Research and Information Association in the UK (CIRIA). The work reported here was conducted by the Maritime Engineering Department of Hydraulics Research for CIRIA through their research contractor, Robert West and Partners, and for the Department of Public Works in the Netherlands (RWS). For further information on this study the reader should contact Mr N W H Allsop, Manager of the Coastal Structures Section at HR.

Corrigendum

In the first version of this report, the axes in Figures 6-11 were incorrectly scaled. This has been corrected in this version. No other changes have been made.

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1 INTRODUCTION

1.1 Historical context

In 1975 Hydraulics Research (HR), at that time HRS, completed a series of hydraulic model tests on rip-rap protection against wave attack. The results of this work were then published by the Construction Industry Research and Information Association (CIRIA) as CIRIA Report 61 (Ref 1). In 1983 further studies were proposed by HR to address the influence of the width of the armour grading on the armour response (damage); and to quantify the inherent variability of test results. The need for these tests was generally supported and it was widely agreed that the design methods available addressed too narrow a range of possible gradings. That proposal did not however attract funding.

Between 1983 and 1988 a series of studies were conducted in the Netherlands by Delft Hydraulics to quantify rock armour response to a wide range of both hydraulic loading and structure geometry parameters. The test method adopted was based closely on that used by Thompson & Shuttler for the CIRIA work. In analysing the results of the Delft Hydraulics tests, van der Meer included the armour movement results from the CIRIA study. The empirical design method developed by van der Meer therefore used data from both studies (Ref 2).

In the UK further model tests were conducted at HR in a joint study with Queen Mary College, University of London (QMC), now Queen Mary and Westfield College. These tests were intended to explore the effect of particle shape on the armour response (Refs 3, 4). Relatively few tests were possible, so the general empirical description derived by van der Meer (Ref 2) was assumed in analysis.

In 1988 a revised and extended research proposal including some model testing, was prepared by CIRIA, and this attracted support in the UK from the Department of Environment (DOE) and the Ministry of Agriculture, Fisheries and Food (MAFF). This project (CIRIA RP 402) was aimed principally at the compilation of a manual on the use of rock in coastal and shoreline engineering jointly by CIRIA in the UK, and the Centre for Civil Engineering Research, Codes and Specifications in The Netherlands (CUR). Within this project it was agreed that a short series of hydraulic model tests would be conducted by HR to identify the influence of wide grading on the armour response. A relatively restricted test series was devised as funding for testing was limited. These studies were authorised in a sub-contract from the lead research contractor appointed by CIRIA, Robert West and Partners (RWP).

At an early stage in the overall project the purpose and need for these studies had been discussed by the UK and Netherlands research teams. It was noted that the model studies could be extended to explore the effects of other variables at relatively low cost, and the influence of steep approach bed slopes was of particular interest. After discussions between the research teams a set of additional tests were contracted by the Rijkwaterstaat, the Ministry of Transport and Public Works in The Netherlands (RWS). These tests were intended to extend the range of validity of the tests for CIRIA, so it was agreed that the studies for CIRIA and RWS would be reported together.

1.2 Technical context

Rock armouring may be used to protect a rubble mound, reclamation fill, or natural shoreline against erosion by wave action. Rock protection to such structures is generally laid to form an armour layer of around 2 stones thickness, placed typically at porosities in the range 35-40%, and at slope angles from 1:1.5 to 1:6. The roughness and permeability of such armour leads to significantly greater energy dissipation than the equivalent smooth impermeable slope, thereby reducing wave reflections and the levels of wave run-up on the structure.

In the design of rock armouring the main geometric variables are the size or mass of the typical armour unit, and the slope angle at which the protection will be placed. These variables are in part interdependent. The principal tools used to determine minimum stable armour size are empirical design methods developed from hydraulic model tests. The main methods available may be summarised:

a) Hudson formula (Ref 5);
b) CIRIA 61 design graphs (Ref 1);
c) van der Meer's equations (Ref 2);
d) HR/QMC modifications to c) (Ref 3 & 4).

The derivation and use of these methods are discussed in more detail the Manual. The range of validity of these design methods is generally restricted to rock armour layers of relatively narrow size gradings. A convenient description of the size grading is given by the ratio of the 85% and 15% non-exceedance sizes, D_{85}/D_{15}. This ratio may also be taken to be given by the cube root of the equivalent unit masses, or weights, on the grading curve:

$$\frac{D_{85}}{D_{15}} = \left(\frac{M_{85}}{M_{15}}\right)^{1/3} \qquad (1)$$

The methods described previously cover armour gradings within the range $1.25 \leq D_{85}/D_{15} \leq 2.25$. Within this range it is argued by van der Meer that changes of grading do not significantly change the armour response (Ref 2). It has however often been argued that production costs could be reduced if wider gradings were accepted. Such gradings could then give the supplier the opportunity to incorporate a larger proportion of the quarry yield.

The principal purpose of this study was to identify whether the use of armour of a grading wider than $D_{85}/D_{15} = 2.25$ would significantly change the armour response from that predicted by the empirical design methods available. As in the previous study (Refs 3 and 4) the test results were compared with the prediction equations derived by van der Meer (Ref 2). The secondary purpose of these tests was to identify the potential influence of a steep bed slope immediately seaward of the structure on the waves at the structure, and on the armour response.

1.3 Outline of report

The main content of this report is covered by Chapters 2 and 3, supplemented where appropriate by Appendices 1-3. Chapter 2 addresses the scope of the study; the test facilities and procedures; and the design of the armour gradings to be tested. All the test results generated in the study are presented in Tables. The results of the test measurements, and the analysis conducted on them, are discussed in Chapter 3. The conclusions that can be drawn from the study are summarised in Chapter 4.

2 DESIGN OF MODEL TESTS

2.1 Intended use of test results

The principal intention of the tests was to investigate the effect of armour gradings outside of the range previously considered on the armour response to waves. Limited resources were available for the study, so the range of tests was restricted. In discussions with members of the CIRIA and CUR research teams it was agreed that the results of the tests would be compared with the prediction methods derived by van der Meer (Ref 2). It was intended that revised empirical coefficients for those equations (see Appendix 1, equations 4 or 5) might be suggested, but it was noted that the restricted nature of these tests would not allow the derivation of new equations.

2.2 Selection of test parameters

The parameters considered in the hydraulic design of rock armoured slopes may be considered under four headings:

a) structure geometry;
b) hydraulic loadings;
c) structural responses;
d) hydraulic responses.

In the design of rock protection against wave attack a wide range of parameters must be considered under each of these headings. The test programme for these studies only allowed a short series of tests so the range of parameters varied were restricted to a minimum.

The first restriction was in the responses to be quantified. The tests were concerned with armour response only, no hydraulic responses were measured. As for previous work in the UK and Netherlands, the armour response was quantified by measuring profile lines down the test section. Profiles taken before and after each test were compared to generate a damage value.

In testing a particular grading it was clear that a range of wave conditions would be required. As relatively short steep waves tend to characterise design conditions for coastal structures in the North Sea and around the UK, a single wave steepness was used in setting the test wave conditions for series 1-3. For series 4 similar deep water wave conditions were used. The steep approach slope and reduced water depth at the test section caused the wave conditions in series 4 to be rather different. This is discussed further later. Other than the changes between series 1-3 and series 4, the test water depth was kept constant.

The cross-section geometry was also kept essentially constant. Three armour gradings were used, hence changing the armour layer thickness and the filter layer. Otherwise a constant slope of 1:2 was used, with an impermeable core.

Previous studies have explored the influence of test duration. For these tests a constant test duration of 1000 waves was used, unless failure of the test section required the test to be stopped beforehand.

The values of the principal test parameters may be summarised:-

Armour slope (cot α)	2.0
Mound permeability	Impermeable, P = 0.1
Water depth at structure (h_s)	0.5m series 1-3
	0.2m series 4
Bed slope	1:50 series 1-3
	1:10 series 4
Nominal wave steepness (s_m)	0.04
Spectral shape	JONSWAP
Test duration (N)	1000 T_m
Armour rock density (ρ_a)	2710kg/m³
Buoyant mass density (Δ)	1.71
Median rock armour mass (M_{50})	see section 2.5
Filter rock size D_f	see section 2.5

2.3 Test facility

The model tests were conducted in the deep random wave flume at HR. The flume is 52 metres long and 3 metres wide at the wave paddle. Over much of its length it is divided into a central test channel 1.2 metre wide, and two side absorption channels intended to reduce the effects of reflections from the test section. Waves are generated by a buoyant wedge paddle driven by a hydraulic actuator. The random wave control signal is generated by a BBC micro computer using HR software. The wave flume is described more fully in Appendix 1.

2.4 Test section design and construction

Before testing on series 1-3 could commence, an approach section had to be moulded in the central test section of the flume, reducing the water depth to 0.5 metre at the test section. This was installed to give a slope of 1:50 approaching the test section. This slope extended offshore for 19m in the flume. Seaward of that a steeper slope around 1:12 was used to ensure that the moulding did not project into the perforated sections of the side walls. The two slopes were joined by a smooth curve. The moulded bed profile is given in Table 1, and shown in Figure 3.

After completion of test series 1-3, the sea bed bathymetry was re-moulded for series 4. A much steeper approach ramp at 1:10 was installed, and the test section water depth was reduced from 0.5 metre to 0.2 metre. The bed profile moulded for series 4 is also given in Table 1, and Figure 3.

Before construction of the test section, a series of calibration tests were run. An initial set were conducted to define the incident wave conditions for series 1-3. A further set were later conducted on the revised bathymetry for series 4. These calibrations are described in section 2.6, and the results are presented in section 3.1.

The test section itself was constructed on the horizontal section of the moulded floor, within the glazed length of the flume. The test section core was formed in plywood with a seaward face at 1:2.0, attached to the concrete floor. Expanded metal sheet was attached to the slope to simulate the roughness of a granular core. The filter layer was laid directly onto this sheet. The size and thickness of the filter is discussed in section 2.5. The test section is shown in Figure 1.

Two modifications were made from the test section layout used in the HR/QMC tests (Ref 3). The width of the test section filled with the prepared armour grading was reduced from 1.2 metres to 0.7 metres. Perforated divide walls were attached to the sloping plywood face to separate the prepared armour grading within the central measurement section from the rock used in the outer sections. For series 4 it was noted that the incident waves were much reduced. The overall test section height was reduced by 0.203m, commensurate with the reduced likely run-up length. Otherwise the test section was constructed as for series 1.

2.5 Design of armour gradings

2.5.1 Gradings in previous work

In considering the armour gradings to be tested, reference was made to the previous work noted in Chapter 1. In the tests by Thompson & Shuttler (Refs 1 & 6) the grading tested was given by:

$$\frac{D_{85}}{D_{50}} = 1.5, \quad \frac{D_{15}}{D_{50}} = 0.67, \quad \frac{D_{85}}{D_{15}} = 2.25$$

The rock was prepared to a straight line on a log-linear size grading curve. In relating armour unit mass to size, the unit mass was given by:

$$M = 0.55\ \rho_a\ D_z^3\ . \qquad (2)$$

This may be re-written in terms of the sieve size diameter D_z, and the nominal unit diameter, $D_n = (M/\rho_a)^{1/3}$:

$$D_n = 0.82\ D_z \qquad (3)$$

The armour, referred to as rip-rap, was laid to a placement porosity, n_v, around 45%, and a layer thickness, $t_a = 2.44\ D_{n50}$.

Van der Meer (Ref 2) tested two different gradings, each again given by straight line log-linear size curves. The two gradings were given by D_{85}/D_{15}= 1.25 and 2.25. In each instance the armour was placed to a layer thickness, $t_a = 2.22\ D_{n50}$.

Bradbury et al (Ref 3) tested rock in 5 different shape categories. For the fresh rock, the category most closely matching that used in previous work, the grading was given by:

$$\frac{D_{85}}{D_{50}} = 1.10, \quad \frac{D_{15}}{D_{50}} = 0.87, \quad \frac{D_{85}}{D_{15}} = 1.26$$

The main other difference with previous studies was that the armour, laid in two layers, gave a total layer thickness for fresh rock of $t_a = 1.61\ D_{n50}$, and equant rock $t_a = 1.69\ D_{n50}$.

2.5.2 Specification of gradings

At an early stage in the study design it was considered that gradings tested might fall in the range $1.25 \leq D_{85}/D_{15} \leq 5.0$. It was hoped that each grading could be prepared to the same median size, D_{n50}, and laid to a uniform layer thickness of say $t_a = 2.0\ D_{n50}$. During more detailed planning it was realised that only some of these objectives could be attained. Resources for the study dictated that only 3 gradings could be prepared.

In discussion within the CIRIA/CUR research team it was agreed that a narrow grading should be tested to maintain some continuity with the earlier studies, and to give a well defined control case. It was hoped that the test results for this grading, series 1, would agree well with previous test data, allowing the user greater confidence in the overall reliability of the test data. To maintain the closest possible continuity with earlier work, the grading for series 1 was specified as a straight line log-linear size grade, with D_{85}/D_{15} = 1.25. This armour was laid to a layer thickness of $t_a = 2.2\ D_{n50}$. This grading was used for both series 1 and 4.

The design of the widest grading presented a less well defined problem. Initially gradings of D_{85}/D_{15} of 3.0, 4.0, and 5.0 were considered. It was noted that for the wider gradings the size of the largest stone would exceed the suggested layer thickness. It also became apparent that the very wide gradings, $D_{85}/D_{15} > 4$, would be very difficult to handle and place. An upper limit of $D_{85}/D_{15} = 4$ was therefore proposed.

The merit of testing an intermediate grading, say around 2.5 or 3, was considered. It was noted that analysis of van der Meer's and Thompson & Shuttler's data suggested that the performance of gradings between 1.25 and 2.25 was very similar. It therefore seemed more useful to concentrate the investigation on the wide grading, $D_{85}/D_{15} = 4.0$, for both series 2 and 3.

The gradings used in previous studies had generally conformed to a straight line log-linear grading. It was noted however that quarry production curves seldom approach a straight line. A more typical form for armour rock is given by the Schuman equation giving the unit mass, M_y, not exceeded by the fraction y:

$$y = \left(\frac{M_y}{M_{100\%}}\right)^{m_s} \qquad (4)$$

where the index m_s gives the steepness of the curve. The Schuman grading can be plotted as a straight line on log-log axes.

In considering the shape of the grading curves it was decided to select one grading prepared to the idealised log-linear straight line, and the other to the Schuman equation. For series 2 the Schuman grading, given by equation 4, was suggested, where for D_{85}/D_{15} = 4.0, m_s = 0.4712. This grading was still compatible with the suggested layer thickness t_a = 2.2 D_{n50}. The straight line grading at D_{85}/D_{15} = 4.0 for series 3 would however include some stones markedly bigger than 2.2 D_{n50}. The grading for series 3 could not therefore be laid at a layer thickness less than about 2.7 D_{n50}.

The original proposal had been that each grading would be prepared to give the same median nominal diameter D_{n50}. Consideration of the larger stone sizes in series 2 and 3 quickly demonstrated that this would not be practical. Maximum stone sizes of many kilograms would result, and this was not compatible with the resources available to prepare the gradings, or to re-build the armour slope after each test. It was therefore decided that the common size for each of the gradings would be D_{n85}. The resulting grading curves are shown in Figure 2, and are listed in Table 2. The main parameters for each grading may be summarised:

	Series		
	1, 4	2	3
D_{n50} (mm)	50.0	36.6	27.9
D_{n85} (mm)	55.9	55.9	55.9
D_{n15} (mm)	44.7	14.0	14.0
M_{50} (grams)	340.0	133.0	59.3

The placement thickness, and the underlayer specification, were then related to these parameters for each test series. As noted previously the target layer thickness was t_a = 2.2 D_{n50}. These could be achieved for series 1, 4 and 2 with t_a = 110.0mm and

80.5mm respectively. However for series 3 the larger rocks would exceed this thickness, giving a minimum layer thickness around $t_a \geq 2.7\ D_{n50}$. After some consideration, it was decided that the armour in each of series 2 and 3 should be placed to the same layer thickness of 80.5mm, being equivalent to $t_a = 2.89\ D_{n50}$ for series 3.

Each armour layer was placed on a granular underlayer or filter related in size and thickness to the armour layer. Previous work had used a relationship between the median diameter for the armour and filter layers given by

$$\frac{D_{n50}\ \text{(armour)}}{D_{n50}\ \text{(filter)}} = 4.5. \tag{5}$$

This gave a median nominal diameter of the filter for series 1 of 11.1mm. This was prepared to a grading D_{85}/D_{15} of 2.25, and laid to a thickness of 25mm. For series 2 and 3 a similar filter was prepared to D_{n50} of 8.1mm and laid to a thickness of 18mm.

For series 1, and later for series 4, each armour unit was laid individually. In the first instance the toe berm was formed across the full width of the test section, see Figure 1. The armour layer was then formed in two layers from the toe berm, and working diagonally upwards and across the section face. Each stone was placed by hand against its predecessor. No preference was given to orientation, and the operator was careful not to fit stones closely together, rather leaving each in its initial position and attitude on placement. One test section differed slightly from this. During armour placement for test 1C it was noted that the placement technique used for test 1B had been slightly more fastidious than had been intended. It was therefore possible that armour interlock had been higher in test 1B than in other tests in the series. The layer porosity for tests 1B and 1C were slightly lower than for the rest of series 1, but only by relatively small margin.

Placement of the wide graded armour (series 2 and 3) differed significantly from the method described above. Before placement the armour was carefully mixed to reduce any size segregation. The armour was then laid in bulk by pouring it in rough rows across the section. The surface was then levelled approximately to the layer thickness indicated by the perforated divide walls, see section 2.4. Large stones lying loosely on the surface of the armour were pushed upslope until they were within the depth of the armour layer. More armour was then added along the construction edge as before, and the process was repeated until the test section was complete. During placement the operator intentionally refrained from fitting or selecting stones.

2.6 Wave measurements

The waves incident upon the test sections in these experiments were measured using HR twin wire wave probes. The output from each wave probe control module was scaled, then logged, using a Compaq micro computer with a proprietary A/D converter board. Representative parameters were derived by spectral and/or statistical analysis using, where possible, standard HR software. All wave measurements were made in the absence of the test sections, using an absorbing beach at the end of the moulded bathymetry to ensure minimal corruption by reflected waves. Wave measurements were conducted in three phases.

Phase I was conducted before test series 1-3, using the 1:50 approach bathymetry, see Table 1, and a paddle water depth of 1.5m, giving a depth at the test section of 0.5m. The waves used for series 4 were measured in phase II, after the construction of the revised 1:10 bathymetry. A paddle water depth of 1.5m gave a depth at the test section of 0.2m. These bathymetries are shown in Figure 3.

Both statistical and spectral analysis were used to derive representative parameters. In each instance waves were measured at the setting out line for the toe of the test section, and in deep water. In these tests the toe of the section was placed 5m from the end of the wave flume, Figure 3. In phase I the generator settings were adjusted to achieve the desired wave conditions at the inshore wave probe, when the measurements were analysed by spectral analysis. Further measurements were then made over 1000 waves to give the main statistical properties. Precisely the same wave generator settings were used for phase II as for phase I.

Phase III wave calibrations were conducted for the Rijkwaterstaat to provide comparison data for a numerical model ENDEC. These measurements were made with the bathymetry moulded for series 4, but with the water depth reduced by 0.1m. This gave a depth at the paddle of 1.4m, and over the horizontal section of the moulding at the inshore end 0.1m. Nine wave probes were used. One was placed offshore as before. Six probes were placed at intervals along the slope, and two more on the inshore horizontal bed. These positions may be summarised:

Probe number	Distance seaward from top of 1:10 slope (m)	Chainage from end of flume (m)	Water depth (m)
1	Offshore	~30	1.4
2	6.5	12.5	0.75
3	4.0	10	0.50
4	3.0	9	0.40
5	2.0	8	0.30
6	1.0	7	0.20
7	0	6	0.10
8	-1.0	5	0.10
9	-2.0	4	0.10

The results of these tests are summarised in Table 4, but are not discussed further in this report. The analysis and comparison of this data is described by Van der Meer in Reference 7.

2.7 Armour profile measurements

The principal measurement of the armour response made in this study was of the surface profile of the armour layer. Profile measurements were made with an automated profiler which touched the armour surface at set intervals. Damage to the test section was then calculated by comparing the profiles measured before and after the test. Example profiles are shown in Figure 4.

A computer-controlled bed profiler running on a moveable beam above the test section was used to measure the armour profile along 9 sample lines. The profiler was adapted from the HR automatic bed profiler to incorporate a touch-sensitive foot, and is described in more detail in Appendix 2. For this study the touch-sensitive foot was fitted with a hemisphere of diameter 0.025m. The profiler ran along a beam in increments of 0.030m. The beam itself could be located at each of 9 positions across the wave flume at 0.050m centres.

During profiling the voltages corresponding to the x, y, and z co-ordinates of each sampling position were scaled to model dimensions, and logged for later processing. Where interpolation was required a cubic spline was fitted through the adjacent points. All levels were recorded relative to a fixed datum, and the starting position reading was checked before each run. A series of instrument check tests were conducted to quantify the accuracy of repeat profile measurements. In each instance the discrepancies between repeat surveys remained within an error band of ± 0.3%.

The profile results were used to calculate the armour layer thickness, t_a, and to determine damage values, S and S_{md}. The armour layer thickness was calculated by differencing the mean profile of the surface of the underlayer from the armour profile.

The calculation of armour damage followed closely the method used in the previous study at HR (Ref 3). The dimensionless damage, S, is related to the area of erosion, A_e, and the nominal armour diameter, D_{n50} :

$$S = A_e/D_{n50}^2 \qquad (6)$$

In determining the erosion area, A_e, a mean profile is calculated from the 9 profiles measured. The mean profile after the test is subtracted from the mean profile before the test. The erosion area is then calculated by summing all areas of the final profile below the original (before test) profile. Values of S calculated for each test in this study are given in Table 5. An alternative approach was also used in the previous study at HR (Ref 3). Here the order of calculation was changed. Firstly each of the before and after profiles were differenced, giving values of A_e, and hence S, for each of the 9 profile lines. The nine values of S were then averaged giving S_{md}. Values of S_{md} calculated in this study are also given in Table 5. A more detailed discussion on the derivation of damage values has been given previously in Reference 3.

2.8 Test procedures

For each test a consistent procedure was adopted:

(a) Construct test section, re-laying armour to given layer thickness;

(b) Profile the armour surface along 9 survey lines;

(c) Set test wave conditions on generator, flood wave flume to fixed water level;

(d) Run waves for duration of 1000 T_m;

(e) Drain working section of the flume, re-survey test section;

(f) Calculate damage values S and S_{md}, input to results file.

For each of the test series, five wave conditions were selected for testing. In some instances alternative wave conditions were substituted in the light of the damage measured in the early tests in the series. In a few instances a wave condition was repeated. All tests were run for a duration of 1000 T_m, except test 3E which was stopped early due to the very high level of damage.

3 TEST RESULTS

3.1 Waves

The derivation of input wave conditions has been discussed earlier in Chapter 2, as have the methods of wave measurement and analysis. The wave conditions measured with the bathymetry for test series 1-3 are listed under phase I in Table 3. The revised bathymetry used for test series 4 caused significant changes to the inshore wave conditions, even though the same offshore conditions were produced. The wave conditions with the series 4 bathymetry are listed under phase II in Table 3.

Comparing the offshore conditions measured in phases I and II good repeatability is seen. At the inshore position, conditions with the revised bathymetry are much changed, particularly at the longer wave periods.

3.2 Armour damage

3.2.1 Observations during testing

The main results of these tests were the measurements of erosion area, and hence of damage, made at the end of each test. Values of the damage parameters S and S_{md} calculated from these measurements are summarised in Table 5, and are discussed in more detail later. These results however only record the state of the armour at the end of the test. Observations of the behaviour of the armour were therefore recorded during testing to supplement the measurements, and these are discussed briefly below.

The narrow-graded material, series 1 and 4, performed much as might be expected from previous work by van der Meer (Ref 2) and Bradbury et al (Ref 3). Those armour units that moved, usually did so as individual units after being loosened by a wave up-rush. Generally armour was carried down slope. There was no apparent correlation between units moved and their size. It appeared that units were more likely to be displaced because they were loosely placed. Most damage occurred close to the static water level, but was not otherwise particularly concentrated. Relatively few waves caused armour movement.

The performance of the wide-graded material, series 2 and 3, differed in a number of important aspects from that of the narrow-graded armour. During test series 2 and 3 it became clear that the smaller fractions in the armour were moved quite frequently, by waves smaller than could move the median size stones. The rate and form of damage was strongly influenced by the position and local proportion of the larger stones, from around which the smaller material was eroded. This process was highly variable, and led to some apparently anomalous results. This is best illustrated by the results of tests 3A and 3B, both run with the same wave conditions, see Table 5. In test 3A fine material was eroded from around a number of larger stones close to the static water level (swl). These large stones remained relatively stable during the test, and were seen to trap small material that would otherwise have been washed further down slope. In test 3B however the larger stones were less stable, and were undermined by the preferential erosion of the small material. The movement of these larger stones then allowed further small material to be eroded, and the erosion area tended to spread up slope. In other tests, and particularly in 3E, erosion around the water level then promoted sliding failures within the armour layer, essentially a geotechnical phenomenon.

3.2.2 Measurements of damage

Two parameters have been advanced for the description of damage, S and S_{md}, and their derivation has been covered in section 2.7, and previously in Reference 3. Previous work by van der Meer has used only S to describe damage, so this parameter has been calculated, and will be used in most of the following discussion. The parameter S_{md} is however probably a better measure of damage, particularly at lower levels of damage, so some comparisons will also be made with that parameter.

Three stages of analysis have been attempted within this study. The test results have been presented graphically, see Figures 5 to 11. These are described in more detail below. Then values of the damage parameter S were compared with the appropriate formula derived by van der Meer to explore whether new coefficients could be justified. Finally some comparisons were made using the 15th and 85th percentile values of the armour size distributions rather than the median values.

Generally the most useful description of test data of this form is given by appropriate dimensionless parameters. Previous work has related the damage given by the dimensionless parameter S to the dimensionless wave height $H_s/\Delta D_{n50}$. The wave height used in this calculation was that measured at the position of the structure toe during the calibration phase and analysed statistically. Where the number of waves varied, S was scaled by $N^{0.5}$. In considering the results of the study however, there was some uncertainty as to the most appropriate parameters to use. The first method used simply plots the erosion area, A_e, against the significant wave height at the toe of the test section for all of the test results, Figure 5. As expected the lack of data on the relative size of the armour unit to the wave height renders this presentation most unclear.

A more useful approach is given by plotting the erosion area against the dimensionless wave height $H_s/\Delta D_{n50}$. This is done in Figures 6 and 7, using the alternative ways of calculating the erosion areas A_e and A_{emd}, see section 2.7. The study results now span a much-reduced range. It may be noted that the erosion areas defined using the "mean of differences" approach, A_{emd}, are greater than those calculated by "differences between means", A_e.

The major limitation in presenting the damage results in the form of Figures 6 and 7 lies in the dimensional nature of A_e, or A_{emd}. This prevents results presented in this form being applied easily to prototype situations. This problem has been overcome previously by calculating the damage parameter S, or S_{md}, using the nominal median diameter of the armour,

D_{n50}, as in equation 6. Damage defined by S, or S_{md}, is plotted against $H_s/\Delta D_{n50}$ in Figures 8 and 9 respectively.

3.2.3 Further analysis

The test results have been analysed further to explore the possibility of generating new design coefficients and/or to test whether D_{n15} or D_{n85} better represents the performance of a wide graded material than D_{n50}. The analysis was conducted in two stages. The data was compared with an equation of the general form:

$$\frac{H_s}{\Delta D_{n50}} = A\ P^{0.18} \left(\frac{S}{\sqrt{N}}\right)^{B} Ir^{-0.5} \qquad (7)$$

where van der Meer's data yields values for the empirical coefficients A = 6.2 and B = 0.2. By transforming equation 7 it was possible to perform a regression analysis to yield values of A and B for the data in this study. A second stage of analysis was also explored. For series 1 to 3 the value of either D_{n15} or D_{n85} was substituted for D_{n50}, and the results re-plotted to see whether the change in typical size selected was sufficient to explain any differences in armour response. In considering all further analysis from these tests it must be noted that each data set contained no more than 5 values. This size data set is wholly insufficient to support either new formulae or new coefficients with acceptable certainty for design purposes. It was felt however that this analysis would indicate whether such an approach might be worthwhile with more data.

The results of test series 1, 4, 2 and 3 are considered further below. In each instance the test results are presented as $S/\sqrt{N}$ against $H_s/\Delta D_{n50}$, preserving consistency with previous studies. Test series 1 was conducted to check the performance of a narrow grading as tested previously by van der Meer (Ref 2). Over the range of $H_s/\Delta D_{n50}$ up to 2.0, there is good qualitative agreement between the damage measured and that predicted by van der Meer's equation for plunging waves, see Figure 10. An attempt to perform a regression analysis was not however successful. The regression coefficient calculated suggested that the data were not well correlated.

Test series 4 was conducted to explore the effect on armour performance of the revised bathymetry. The results are shown in Figure 10. Again the data are scattered, but in good qualitative agreement with van der Meer's prediction. The regression analysis for equation 7 gave very similar values for A and B as were derived for series 1, although the regression coefficient calculated was less than 0.5, again indicating that the data were not well correlated. These results suggest that van der Meer's equation can be used for the alternative bathymetry considered, provided that the significant wave height can be predicted at the position of the toe of the structure.

Test series 2 and 3 were conducted to explore the influence of wider gradings. In both of these test series the damage measured was generally greater than would be predicted. The results of the regression analysis may be summarised:

	A	B
van der Meer	6.2	0.2
series 2	4.8	0.15
series 3	5.2	0.13

It should be noted however that the regression coefficients calculated still suggest a very poor fit.

A final comparison was made to test the influence of D_{n50} in the dimensionless wave height parameter $H_s/\Delta D_n$. Noting that the rock in series 2 and 3 had been produced to similar D_{n15} or D_{n85}, but different D_{n50}, the data in Figure 11 was re-plotted using D_{n15} or D_{n85} in place of D_{n50}. The use of D_{n85} shifts the results to slightly smaller values of $H_s/\Delta D_n$. The use of D_{n15} shifts the results to rather larger values of $H_s/\Delta D_n$. In neither instance is agreement improved over that given by the use of D_{n50}.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

A short series of hydraulic model tests has compared the stability under wave action of wide-graded rock armour, $D_{85}/D_{15} = 4$, with that of narrow-graded armour, $D_{85}/D_{15} = 1.25$. The tests were restricted to a 1:2 structure slope with an impermeable base, to a duration of 1000 waves, and to a limited set of plunging wave conditions. Damage was measured by profiling, and the results were compared with predictions by van der Meer's formula for plunging waves. For test series 1-3, a 1:50 bed slope was used. For series 4 the test section was placed on a level bed fronted by a 1:10 slope.

During tests on the wide-graded material, Series 2 and 3, it was noted that armour movement was variable in location and rate. Generally the smaller fraction was moved preferentially, often leaving larger rocks un-supported. This was highly variable, and led to widely differing values, even for repeated wave conditions! The very wide gradings used for Series 2 and 3, $D_{85}/D_{15} = 4.0$, mitigated against the successful construction of a truly homogeneous armour layer. On site it is likely that this will lead to very variable armour construction with wide differences in the armour size parameter along any sample length.

Analysis of the damage measured in these tests suggest that the damage to Series 1 and 4 using the narrow-graded armour, $D_{85}/D_{15} = 1.25$, was generally less than or equal to that predicted by van der Meer's formula. The effect of shallow water and a steep approach slope did not alter this, provided that the wave height used in the prediction was that incident at the toe of the structure.

Damage experienced by the wide-graded material in Series 2 and 3 was generally greater than or equal to that predicted by van der Meer's formula using D_{n50}. Better agreement was not given by using either D_{n85} or D_{n15} in the comparison.

4.2 Recommendations

Wide-graded armour may suffer greater damage than would be predicted by present design methods valid for gradings $1.25 < D_{85}/D_{15} < 2.25$. The composition of an armour layer formed from a wide-graded material is extremely difficult to control, and it is probable that the size properties of such material will vary significantly during the construction process, and hence along the structure. Damage experienced by such gradings under wave action will be more variable, and at a mean level greater than for a narrow-graded armour. The use of gradings wider than $D_{85}/D_{15} = 2.25$ is not supported by the results of these tests.

5 ACKNOWLEDGEMENTS

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TABLES.

TABLE 1 Bed profiles for series 1-3 and series 4

Chainage from end of test flume (m)	Floor height above mean flume floor level (m)
Series 1-3	
1.95	1.00
5.00	1.00
7.00	0.96
9.00	0.92
11.00	0.88
13.00	0.84
15.00	0.80
17.00	0.76
19.00	0.72
21.00	0.62
23.00	0.52
25.00	0.42
27.00	0.25
29.00	0.084
30.00	0.00
Series 4	
0.30	1.30
3.00	1.30
6.00	1.30
8.00	1.10
10.00	0.90
12.00	0.70
14.00	0.50
16.00	0.30
18.00	0.10
19.00	0.00

TABLE 2 Armour size grading curves

Unit mass (grams)	Nominal diameter Dn(mm)	Percentage Passing Series 1	Series 2	Series 3
1156.0	75.2			100.0
817.0	67.0			94.2
701.0	63.6		100.0	91.6
578.0	59.7		92.3	88.3
548.0	58.6	100.0	90.2	87.4
510.0	57.2	92.5	87.6	86.2
475.0	55.9	85.1	85.0	85.0
410.0	53.2	69.6	80.0	82.5
350.0	50.5	53.0	74.9	79.9
340.0	50.0	50.0	74.0	79.4
310.0	48.5	40.3	71.2	77.8
270.0	46.3	25.8	67.2	75.5
240.0	44.5	13.5	64.0	73.5
211.0	42.6	0.0	60.6	71.4
175.0	40.1		56.1	68.2
133.0	36.6		50.0	63.6
124.0	35.7		48.6	62.4
88.0	31.9		42.1	56.6
62.0	28.3		36.4	50.7
59.3	27.9		35.7	50.0
44.0	25.3		31.5	45.0
31.0	22.5		27.2	39.1
22.0	20.1		23.6	33.3
16.0	18.1		20.7	28.0
11.0	15.9		17.6	21.6
7.4	14.0		15.0	15.0
6.6	13.4		14.2	12.9
5.5	12.6		13.2	9.9
4.5	11.8		12.2	6.5
4.0	11.4		11.6	4.6
3.3	10.7		10.8	1.6
3.0	10.4		10.3	0.0
2.7	10.0		9.9	
2.2	9.4		9.1	
1.9	8.9		8.6	
1.4	8.0		7.4	
1.0	7.1		6.4	
0.8	6.7		5.9	
0.7	6.3		5.5	
0.5	5.6		4.8	

TABLE 3 Wave measurements, phases I and II

Spectrum file name	Gain setting	Nominal wave conditions		Spectral analysis				Statistical analysis					
				Offshore		Inshore		Offshore			Inshore		
		H_s (m)	T_m (s)	H_s (m)	T_m (s)	H_s (m)	T_m (s)	$H_{1/3}$ (m)	$H_{0.1\%}$ (m)	T_m (s)	$H_{1/3}$ (m)	$H_{0.1\%}$ (m)	T_m (s)
Phase I													
CIR11	151	0.076	1.1	0.087	1.13	0.076	1.11	0.082	0.151	1.13	0.072	0.140	1.13
CIR12	190	0.090	1.2	0.106	1.22	0.090	1.21	0.100	0.177	1.24	0.086	0.172	0.21
CIR13	241	0.106	1.3	0.124	1.33	0.105	1.30	0.117	0.230	1.32	0.099	0.197	0.29
CIR14	310	0.122	1.4	0.146	1.42	0.122	1.38	0.142	0.264	1.42	0.121	0.227	0.40
CIR15	387	0.141	1.5	0.167	1.50	0.142	1.49	0.158	0.301	1.50	0.136	0.248	0.50
CIR16	492	0.160	1.6	0.191	1.62	0.160	1.60	0.183	0.326	1.61	0.156	0.338	0.57
CIR18	817	0.202	1.8	0.258	1.82	0.200	1.78	0.250	0.388	1.81	0.203	0.312	0.81
CIR19	940	0.225	1.9	0.275	1.91	0.218	1.91	0.263	0.407	1.92	0.208	0.321	2.00
Phase II													
CIR11	151	0.076	1.1	0.090	1.12	0.072	1.10	0.088	0.158	1.12	0.075	0.114	0.12
CIR12	190	0.090	1.2	0.107	1.22	0.082	1.18	0.104	0.192	1.22	0.088	0.121	0.22
CIR13	241	0.106	1.3	0.124	1.32	0.086	1.24	0.122	0.223	1.32	0.094	0.126	0.32
CIR14	310	0.122	1.4	0.146	1.41	0.089	1.35	0.145	0.264	1.41	0.102	0.143	0.41
CIR15	387	0.141	1.5	0.166	1.51	0.094	1.42	0.165	0.277	1.50	0.106	0.154	0.50
CIR16	492	0.160	1.6	0.189	1.60	0.099	1.58	0.189	0.345	1.60	0.111	0.177	0.60
CIR18	817	0.202	1.8	0.256	1.82	0.113	2.00	0.252	0.432	1.81	0.121	0.187	0.81
CIR19	940	0.225	1.9	0.268	1.90	0.121	2.09	0.265	0.46	1.90	0.128	0.189	0.90

TABLE 4 Wave measurements, phase III

GAUGE	DEPTH	SPECTRAL		STATISTICAL			
		H_s	T_m	$H_{0.1\%}$	$H_{1/10}$	H_s	T_m
	(m)	(m)	(s)	(m)	(m)	(m)	(m)
T_p = 3.1s							
1	1.4	0.126	2.653	0.209	0.152	0.123	2.465
2	0.75	0.133	2.707	0.222	0.161	0.13	2.436
3	0.5	0.141	2.714	0.286	0.182	0.145	2.465
4	0.4	0.141	2.738	0.276	0.192	0.151	2.451
5	0.3	0.147	2.734	0.312	0.223	0.172	2.465
6	0.2	0.137	2.755	0.242	0.205	0.178	2.446
7	0.1	0.116	2.942	0.196	0.148	0.123	2.147
8	0.1	0.067	3.254	0.112	0.078	0.066	2.128
9	0.1	0.08	3.56	0.113	0.086	0.073	2.342
T_p = 2.2s							
1	1.4	0.156	1.886	0.252	0.191	0.153	1.863
2	0.75	0.158	1.927	0.299	0.2	0.156	1.9
3	0.5	0.16	1.936	0.323	0.215	0.166	1.925
4	0.4	0.162	1.948	0.326	0.225	0.173	1.938
5	0.3	0.158	1.951	0.29	0.234	0.187	1.962
6	0.2	0.146	1.995	0.243	0.203	0.183	1.933
7	0.1	0.1	2.113	0.171	0.134	0.116	1.62
8	0.1	0.067	2.396	0.098	0.072	0.062	1.874
9	0.1	0.066	2.597	0.118	0.077	0.063	1.804
T_p = 1.8s							
1	1.4	0.2	1.58	0.339	0.251	0.199	1.551
2	0.75	0.205	1.621	0.347	0.259	0.206	1.606
3	0.5	0.197	1.604	0.336	0.265	0.209	1.617
4	0.4	0.194	1.616	0.324	0.261	0.212	1.618
5	0.3	0.183	1.63	0.289	0.239	0.209	1.654
6	0.2	0.159	1.666	0.224	0.197	0.178	1.63
7	0.1	0.107	1.795	0.174	0.134	0.115	1.513
8	0.1	0.071	2.1	0.099	0.073	0.061	1.773
9	0.1	0.074	2.329	0.097	0.076	0.065	1.741
T_p = 1.8s							
1	1.4	0.148	1.557	0.251	0.182	0.146	1.548
2	0.75	0.152	1.577	0.278	0.19	0.15	1.58
3	0.5	0.147	1.601	0.299	0.189	0.149	1.585

GAUGE	DEPTH (m)	SPECTRAL H_s (m)	SPECTRAL T_m (s)	STATISTICAL $H_{0.1\%}$ (m)	STATISTICAL $H_{1/10}$ (m)	STATISTICAL H_s (m)	STATISTICAL T_m (s)
T_p = 1.8s							
4	0.4	0.148	1.6	0.241	0.19	0.152	1.585
5	0.3	0.145	1.589	0.246	0.199	0.163	1.605
6	0.2	0.134	1.588	0.209	0.185	0.165	1.611
7	0.1	0.094	1.695	0.167	0.123	0.108	1.435
8	0.1	0.059	1.986	0.085	0.064	0.054	1.604
9	0.1	0.061	2.143	0.097	0.068	0.057	1.583
T_p = 1.8s							
1	1.4	0.106	1.55	0.163	0.129	0.103	1.54
2	0.75	0.107	1.577	0.224	0.13	0.104	1.548
3	0.5	0.105	1.587	0.207	0.129	0.104	1.589
4	0.4	0.106	1.597	0.192	0.132	0.105	1.556
5	0.3	0.106	1.6	0.203	0.142	0.112	1.595
6	0.2	0.105	1.592	0.2	0.155	0.125	1.624
7	0.1	0.085	1.639	0.14	0.117	0.103	1.515
8	0.1	0.049	1.806	0.073	0.056	0.049	1.483
9	0.1	0.048	1.904	0.08	0.059	0.051	1.458
T_p = 1.55s							
1	1.4	0.156	1.374	0.278	0.2	0.155	1.36
2	0.75	0.152	1.407	0.265	0.196	0.154	1.414
3	0.5	0.146	1.408	0.249	0.189	0.15	1.404
4	0.4	0.144	1.415	0.249	0.188	0.151	1.423
5	0.3	0.143	1.398	0.229	0.196	0.159	1.431
6	0.2	0.132	1.403	0.202	0.174	0.153	1.437
7	0.1	0.09	1.496	0.148	0.116	0.099	1.345
8	0.1	0.054	1.718	0.087	0.055	0.047	1.473
9	0.1	0.058	1.875	0.091	0.063	0.053	1.511
T_p = 1.27s							
1	1.4	0.103	1.136	0.186	0.131	0.103	1.139
2	0.75	0.097	1.152	0.177	0.125	0.097	1.15
3	0.5	0.094	1.151	0.182	0.124	0.093	1.122
4	0.4	0.092	1.157	0.196	0.124	0.093	1.132
5	0.3	0.092	1.166	0.173	0.126	0.095	1.165
6	0.2	0.089	1.156	0.159	0.126	0.098	1.191
7	0.1	0.073	1.149	0.105	0.095	0.085	1.187
8	0.1	0.041	1.168	0.055	0.044	0.04	1.12
9	0.1	0.041	1.139	0.067	0.051	0.045	1.051

TABLE 5 Armour response results

Test	D_{85}/D_{15}	D_{n50} (m)	t_a/D_{n50}	T_m (s)	H_s (m)	N	$H_s/\Delta D_{n50}$	S_{md}	$\sigma(S_{md})$	S	$\frac{S_{md}}{\sqrt{N}}$	$\frac{S}{\sqrt{N}}$
1A	1.25	0.050	2.20	1.3	0.099	1000	1.151	2.513	0.635	1.909	0.079	0.060
1B	1.25	0.050	2.10	1.4	0.121	1000	1.407	1.121	0.428	0.758	0.035	0.024
1C	1.25	0.050	2.10	1.5	0.136	1000	1.581	0.254	0.123	0.045	0.008	0.001
1D	1.25	0.050	2.20	1.6	0.156	1000	1.814	3.800	1.739	2.989	0.120	0.095
1E	1.25	0.050	2.20	1.8	0.203	1000	2.360	10.091	2.070	9.066	0.319	0.287
2A	4.00	0.037	2.14	1.1	0.072	1000	1.144	3.366	1.311	2.157	0.106	0.068
2B	4.00	0.037	2.09	1.2	0.086	1000	1.366	5.570	1.775	4.111	0.182	0.130
2C	4.00	0.037	2.05	1.3	0.099	1000	1.573	14.329	5.162	12.872	0.453	0.407
2D	4.00	0.037	2.07	1.3	0.099	1000	1.573	4.471	0.904	2.236	0.141	0.071
2E	4.00	0.037	2.12	1.4	0.121	1000	1.922	13.198	4.385	10.918	0.417	0.345
3A	4.00	0.028	2.76	1.1	0.072	1000	1.500	3.079	1.155	1.752	0.097	0.055
3B	4.00	0.028	2.76	1.1	0.072	1000	1.500	11.579	3.258	10.397	0.366	0.329
3C	4.00	0.028	2.71	1.2	0.086	1000	1.792	7.579	4.954	5.784	0.240	0.183
3D	4.00	0.028	2.75	1.3	0.099	1000	2.063	11.655	3.072	8.532	0.369	0.270
3E	4.00	0.028	2.74	1.4	0.121	429	2.521	55.349	14.539	54.301	2.674	2.623
4A	1.25	0.05	2.20	1.4	0.102	1000	1.186	0.534	0.163	0.131	0.017	0.004
4B	1.25	0.05	2.27	1.5	0.106	1000	1.233	3.258	0.75	2.915	0.103	0.092
4C	1.25	0.05	2.27	1.6	0.111	1000	1.291	0.788	0.387	0.362	0.025	0.011
4D	1.25	0.05	2.26	1.8	0.121	1000	1.407	2.904	0.948	2.433	0.092	0.077
4E	1.25	0.05	2.27	1.9	0.128	1000	1.488	3.036	0.628	2.666	0.096	0.084

FIGURES.

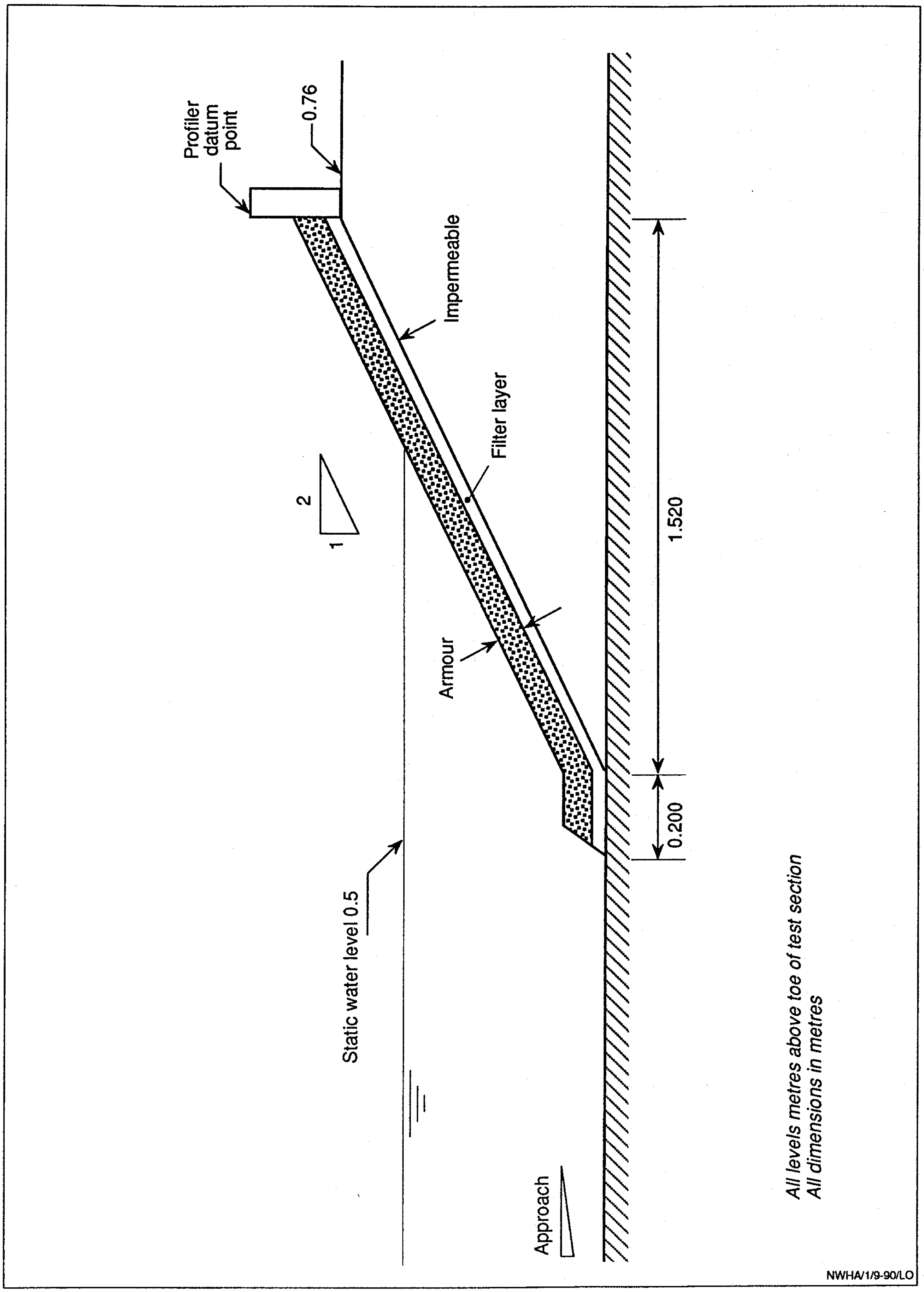

Fig 1 Cross-section through model test section, series 1-3

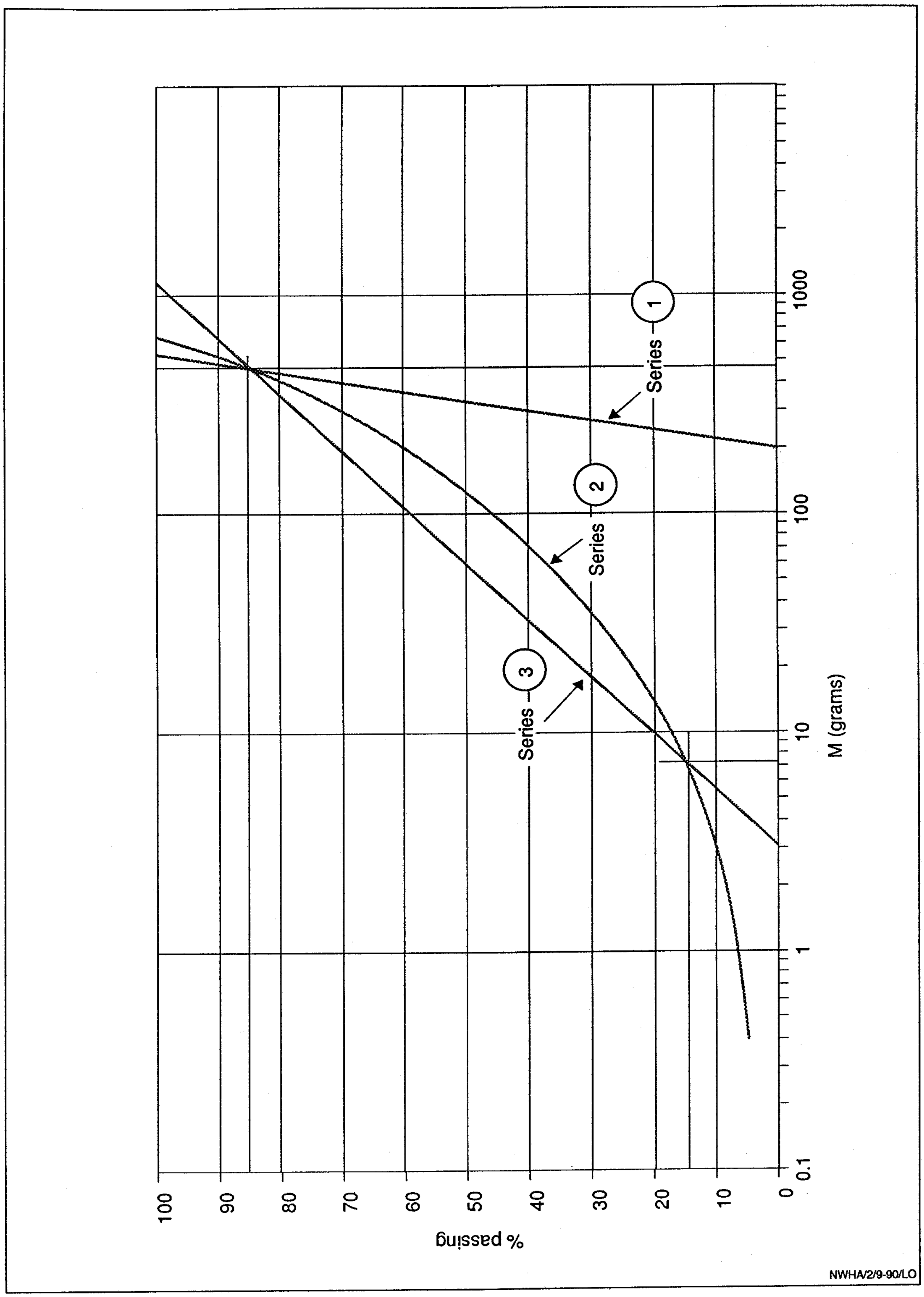

Fig 2 Size grading curves, series 1/4, 2 and 3

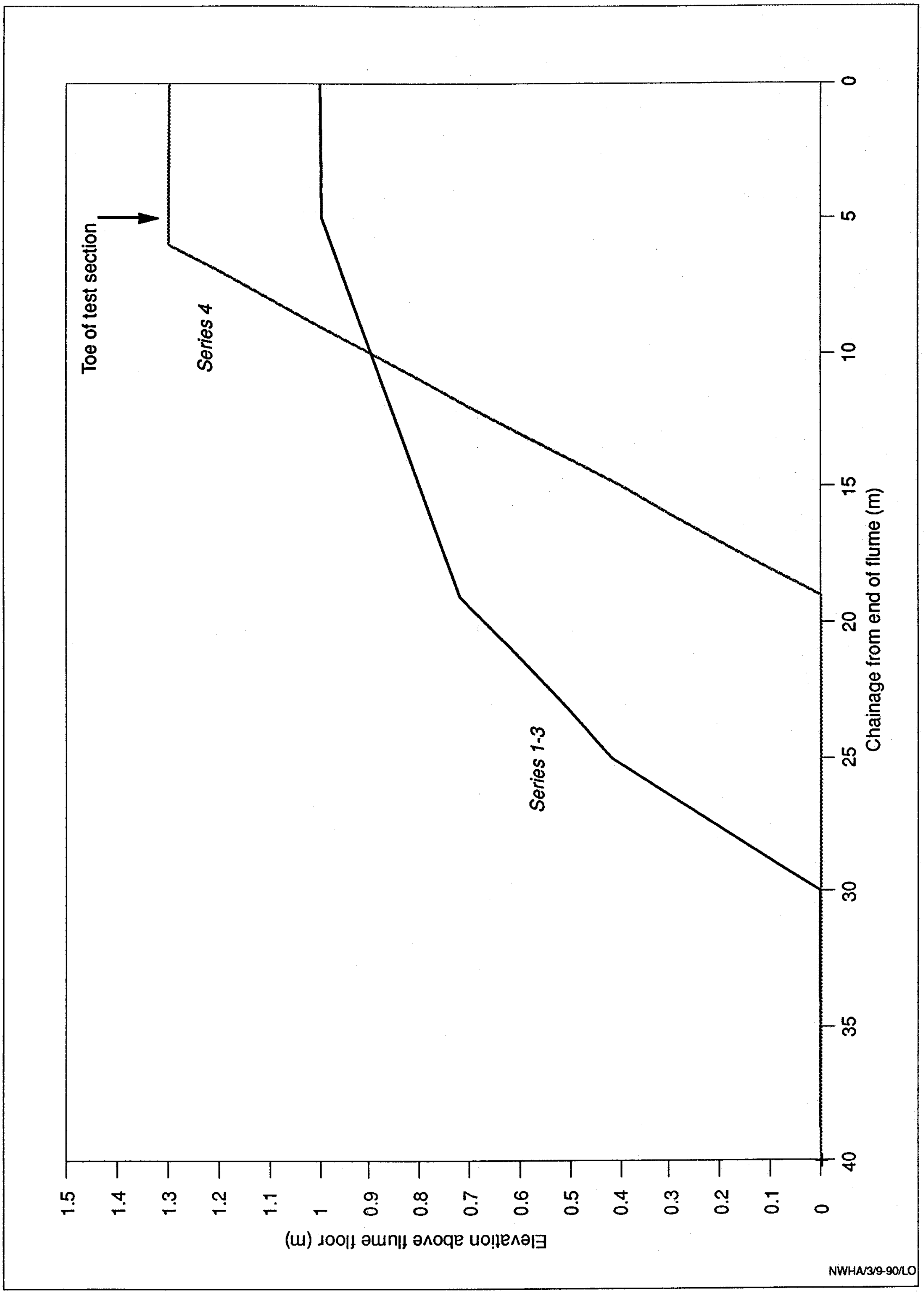

Fig 3 Bathymetry for test series 1-3, 4

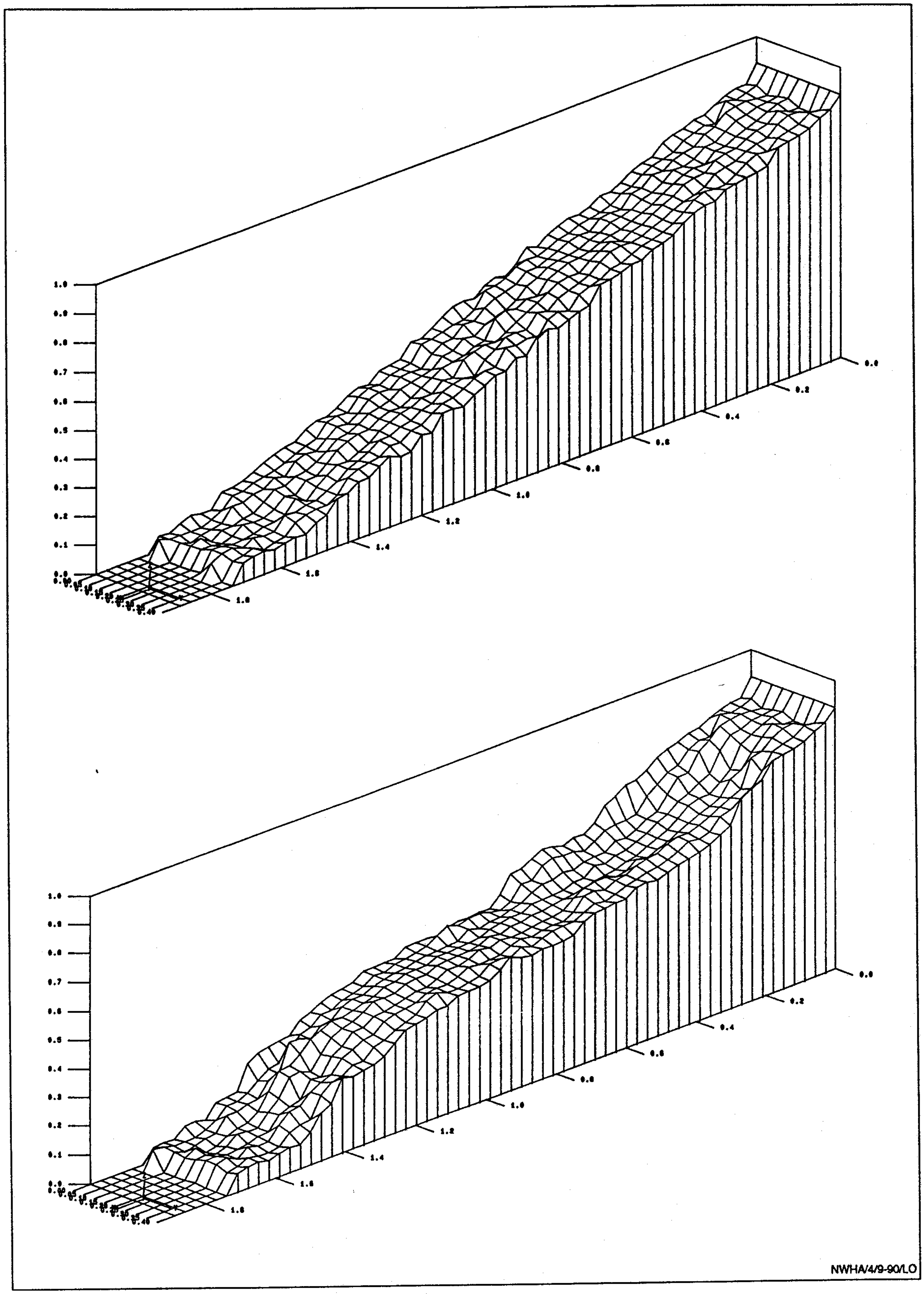

Fig 4 Example profile measurements

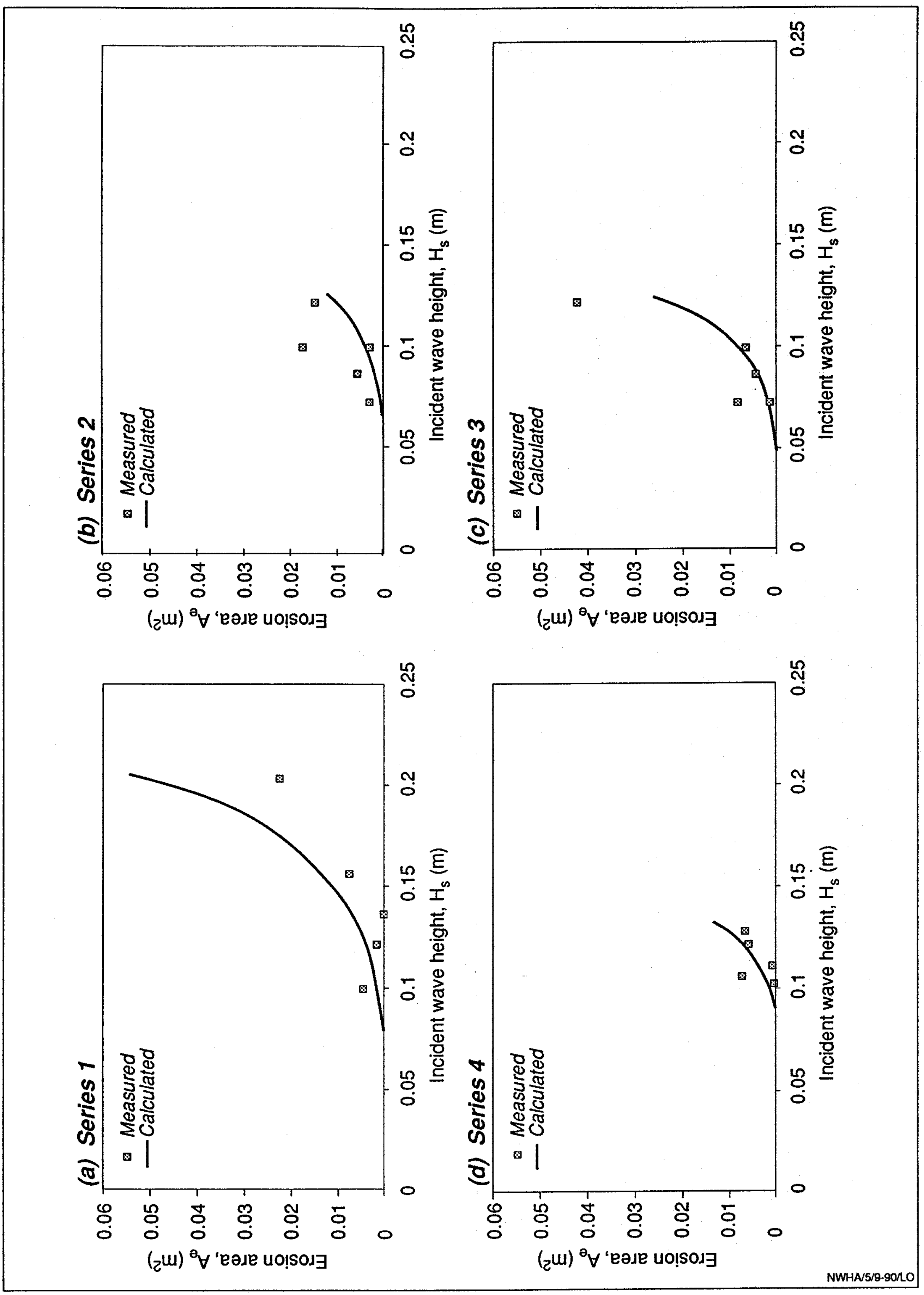

Fig 5 Erosion area, A_e, against wave height H_s

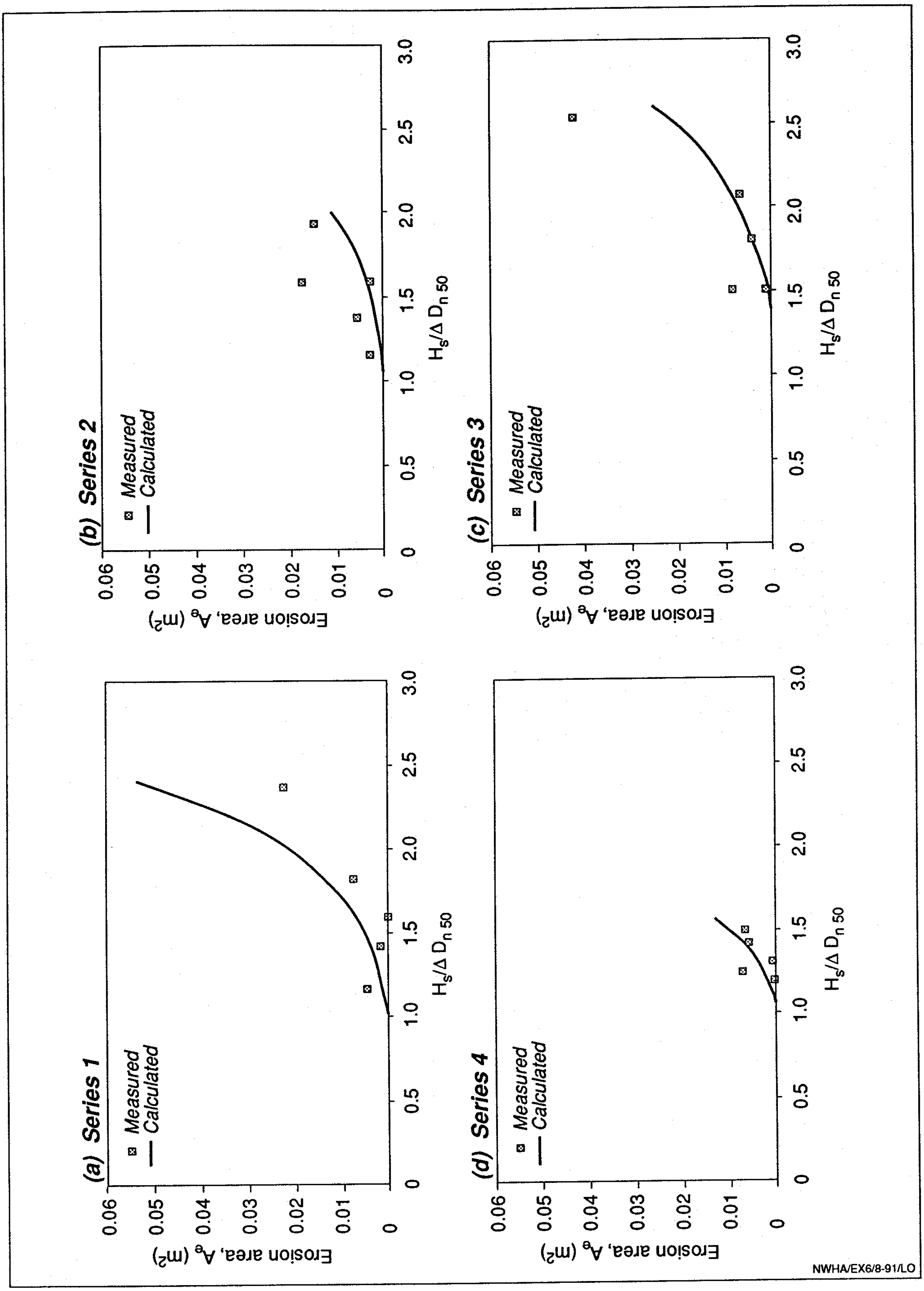

Fig 6 Erosion area, A_e, against $H_s/\Delta D_{n50}$

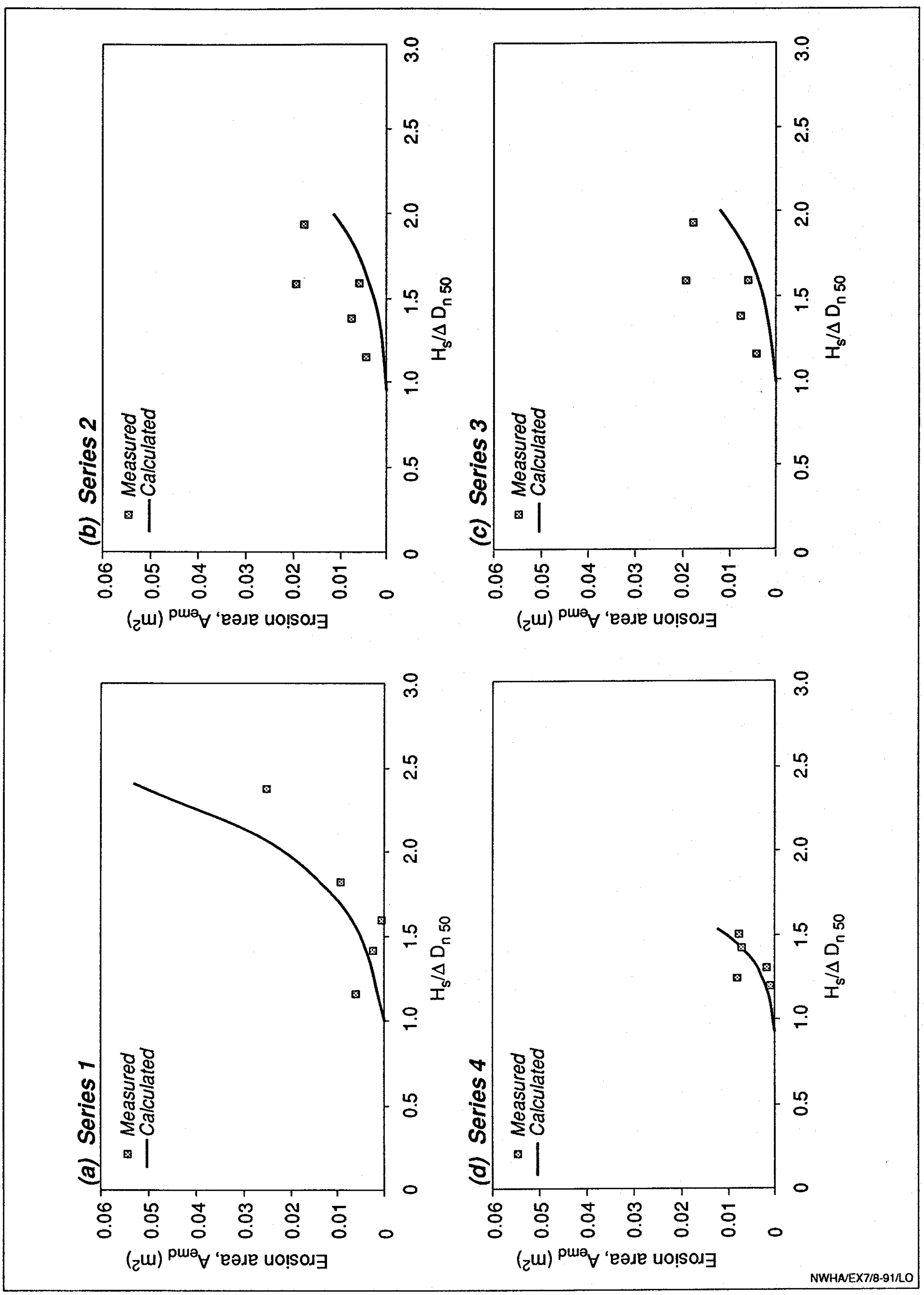

Fig 7 Erosion area, A_{emd}, against $H_s/\Delta D_{n\,50}$

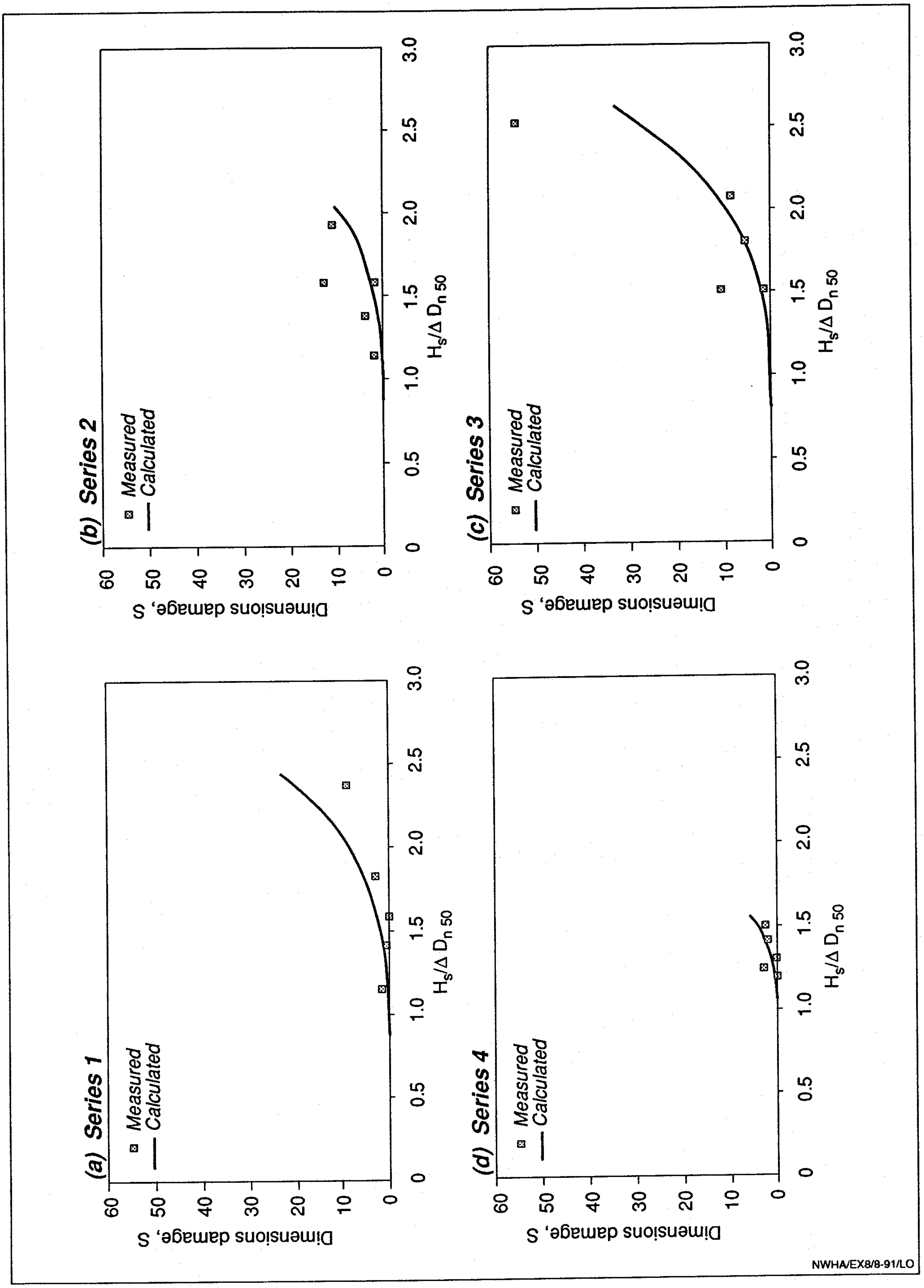

Fig 8 Dimensionless damage, S, against $H_s/\Delta\ D_{n\ 50}$

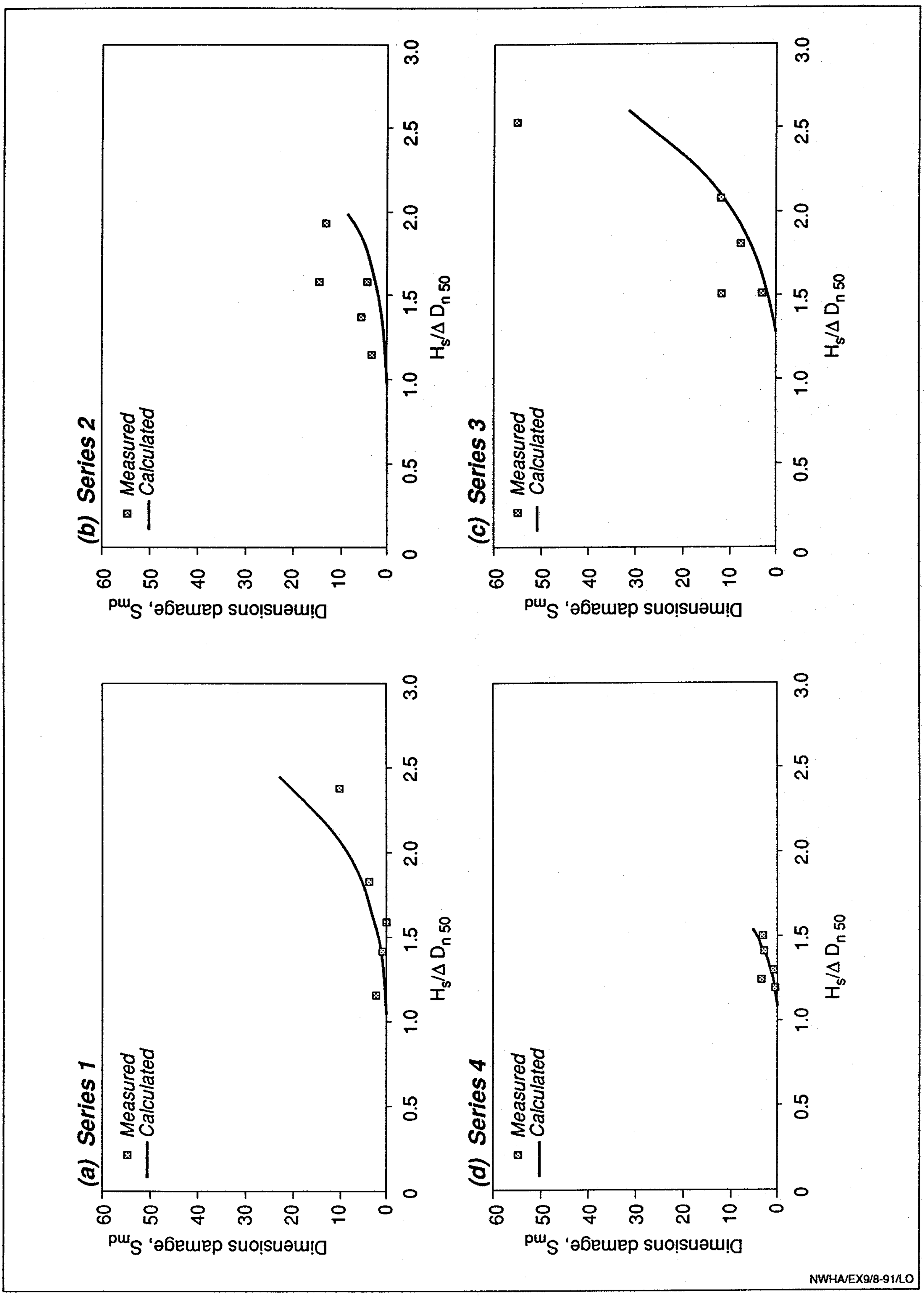

Fig 9 Dimensionless damage, S_{md}, against $H_s/\Delta D_{n50}$

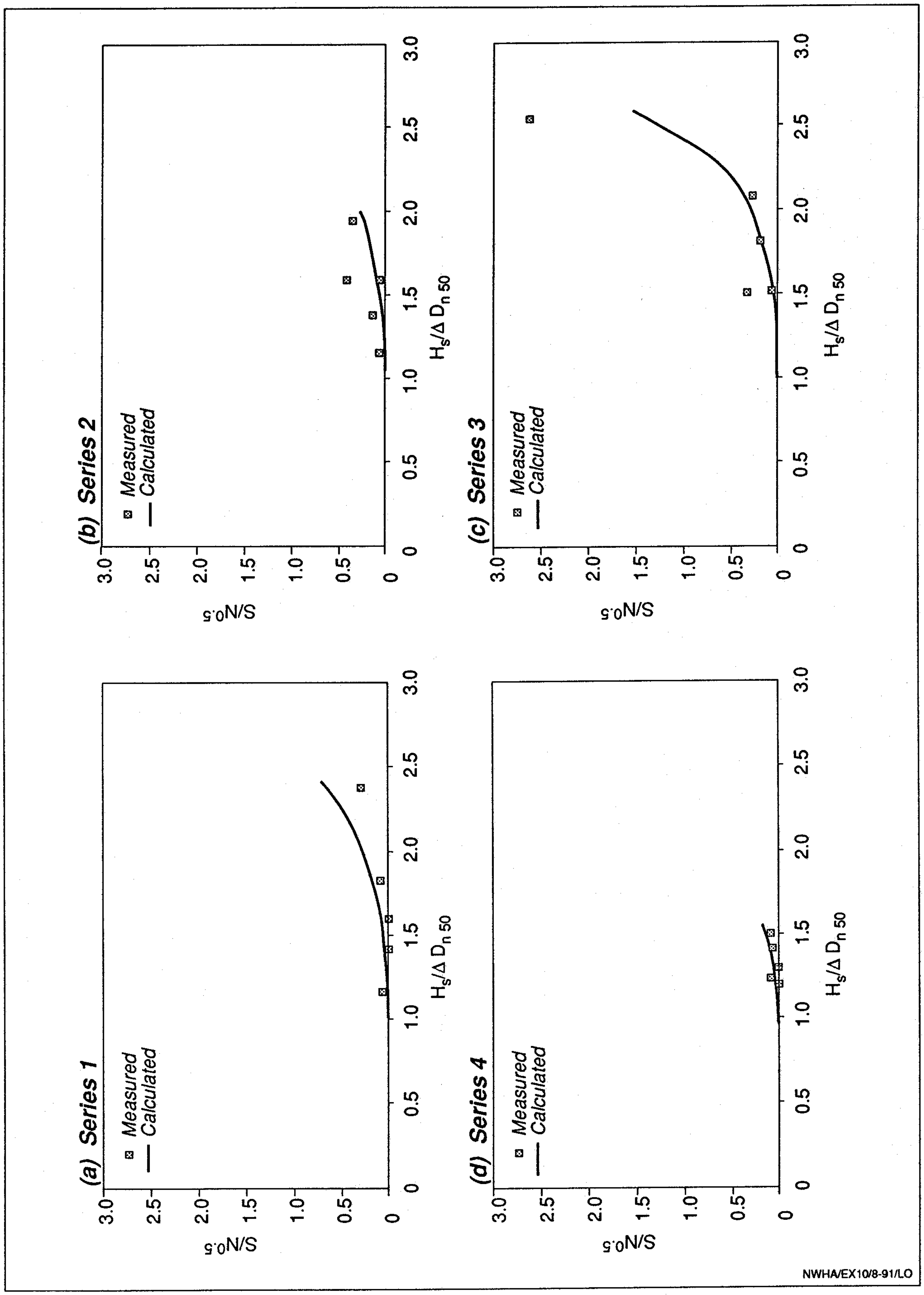

Fig 10 $S/\sqrt{N}$ against $H_s/\Delta D_{n50}$

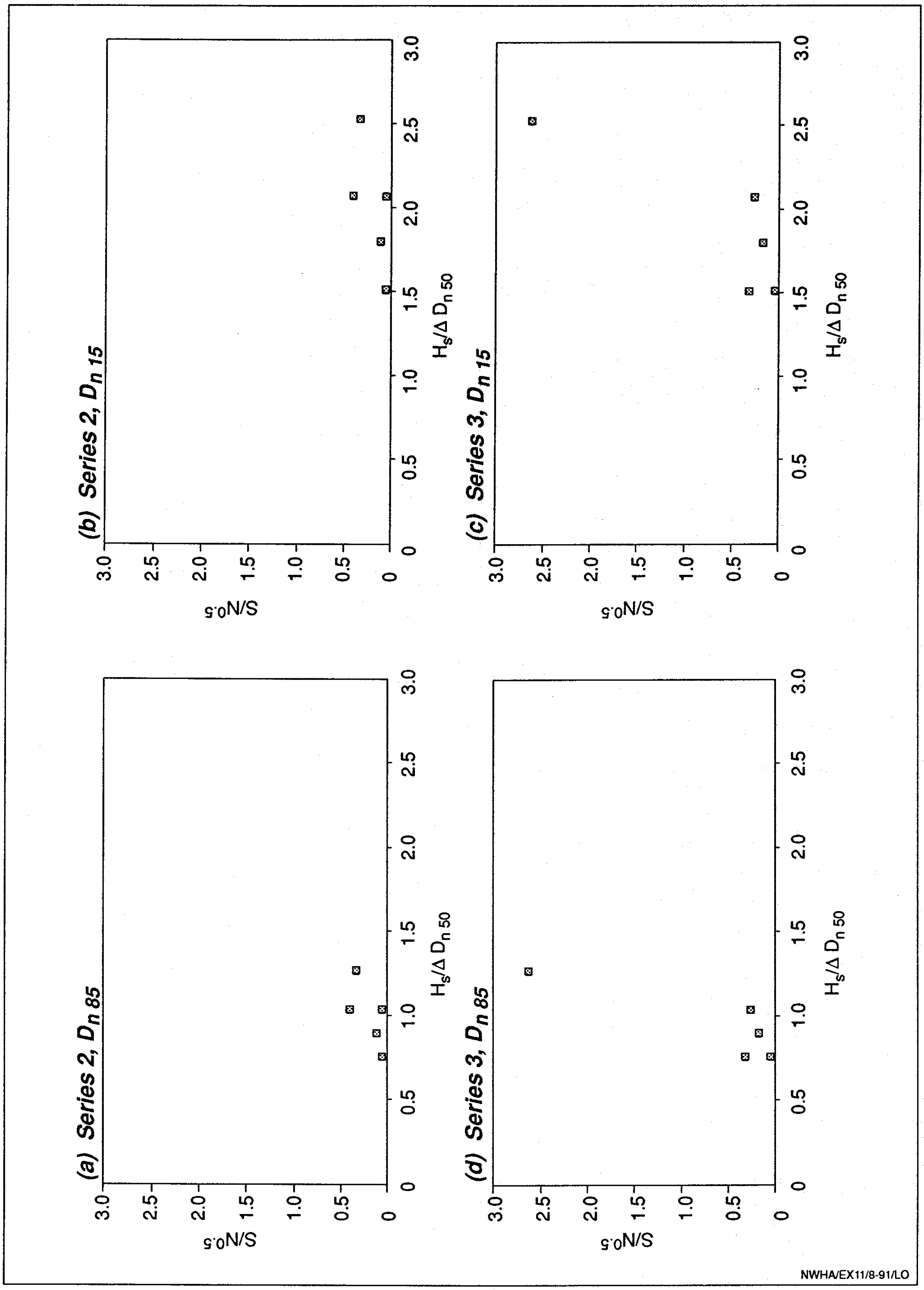

Fig 11 Comparison of use of $D_{n\,85}$ or $D_{n\,15}$

APPENDICES.

APPENDIX 1

WAVE FLUME FACILITY

The deep random wave flume is a dual-function facility serving both the offshore and coastal divisions of Hydraulics Research. It has mainly been used for coastal engineering research (almost exclusively rubble-mound breakwaters and sea-walls) and has been adapted accordingly. A false floor is installed in the centre channel and perforated dividing walls have been fitted for most of the length of the flume. These walls allow wave reflections from the modelled section to dissipate gradually, thus reducing re-reflection and inhibiting the formation of cross-waves. Breakwater and sea-wall models are tested in the 1.2m wide glazed section of the 10m long finger flume. This part of the flume may be separated from the main body by a removable gate. The finger flume may then be pumped dry to allow model construction and armour stability measurements to be conducted in the dry when appropriate.

The wave paddle is a sliding wedge intended to operate around a single mean depth of immersion. However, different water levels are needed to accommodate changes in model scale, prototype sea bed level or water level, as well as the non-optimal setting of the false floor. Tests have therefore been carried out to determine the performance characteristics of the wave generator at a number of water depths, thereby producing a set of transfer coefficients for each of those depths.

The signal for the wave paddle is produced by a Hydraulics Research BBC wave spectrum synthesiser which acts as a digital white noise generator with variable digital filter. The noise is generated by logical feedback in a shift register and is, consequently, psuedo-random. The shape of the noise spectrum is controlled by the digital filter which is set up by fourier transforming the required spectrum. The computer calculates and stores the weighting factors required for the production of random waves from the required spectral shape, using the set of transfer coefficients for the relevant depth range. White noise is then generated and the weighting factors are applied to produce the appropriate position derived signal for the paddle. The length of the repeating signal produced may be varied by the operator. In these tests the repeat length was much longer than the tests.

Due to the need to reproduce the required wave conditions at the site of the test section (rather than offshore in deep water) the settings required cannot always be predicted. In particular the gain or amplitude setting cannot be predicted for a given wave height at the test section. For this reason a calibration exercise must be performed to determine the correct amplitude setting to be used for each of the sea states required in the subsequent model testing. This calibration procedure has been described in the report.

APPENDIX 2

PROFILE MEASUREMENT

The HR bed profiler is required to make accurate measurements of the height of solid or granular surfaces. It consists of a sounding probe controlled by a servo motor, driving a gear wheel, and a potentiometer to measure the rotation of the gear wheel. The probe consists of a hollow metal tube, typically one metre in length, with a serrated outer surface into which the teeth of the gear wheel marry. By commanding the servo motor to rotate in one direction or the other the probe will move vertically up or down. The position of the probe tip relative to its starting position can be measured using the potentiometer fitted to the gear wheel.

To measure the height of a particular surface the probe must be driven downwards until it is a given distance from the surface, the potentiometer read, and the probe driven back upwards. To stop the probe at a given height above the surface an infra red beam is emitted from the probe tip, any reflected energy is sensed by infra red receivers mounted next to the emitters. The strength of the reflected signal controls the servo motor. A threshold signal is present in the profiler such that when the reflected signal matches the threshold signal the probe stops moving. When the tip is far away from the reflecting surface little or no signal is reflected. When the tip is too close to the reflecting surface a strong signal is reflected. Too weak a signal and the probe is driven down towards the reflecting surface- too strong and the probe moves away. The probe therefore always finds a constant height above the surface. In this mode of operation the probe never comes into contact with the surface, and there can be no disturbance of the surface.

Unfortunately many of the surfaces to be profiled are made up of materials which are poor reflectors for the purposes of the probe. They either have a poor reflection coefficient or they are multi-faceted and so do not reflect light directly back. This is particularly true of rubble mound structures. To overcome this problem a foot may be placed on the end of the probe tip. This consists of a sleeve which fits tightly over the probe tip and which holds a small piston. The top of the piston is covered in reflective material to reflect the maximum amount of infra red light. In use the probe descends until the end of the piston (a hemisphere of diameter $D_{50}/2$) comes into contact with the surface, which moves the reflecting surface of the piston closer to the probe. Since the piston is made as light as possible and can move freely there is no disturbance of the material being profiled. The foot of the piston can be of any size according to the size of material being profiled.

Horizontal movement of the profiler is achieved by attaching the profile to a movable carriage. This runs on a horizontal beam across the section to be measured. The carriage is moved by a drive wheel attached to a servo motor. The position of the servo motor is measured by a potentiometer.

The horizontal position is controlled by a Compaq PC, which moves the carriage according to the sampling internal chosen by the greater. The horizontal position of the carriage is recorded by the computer as is the vertical height measured by the probe. These results are stored in files to Wallingford Format 2.2 for later analysis.

APPENDIX 3

WAVE/STRUCTURE INTERACTIONS, DRAFT STANDARD NOTATION

The notation used in this report is drawn from a standard list presently proposed for the UK/Dutch manual on the design of coastal and shoreline structures. The notation is based upon the recommendations of a joint 1AHR/PIANC working group. Where possible notation has been incorporated without change from the Shore Protection Manual published in the USA, and from relevant Dutch and British standards.

A_c	Armour crest freeboard, relative to still water level;
A_e	Erosion area on profile;
a,b	Empirical coefficients;
B	Structure width, in horizontal direction normal to face;
B_{wl}	Structure width at still water level;
C, C_1, C_2, C_i	Empirical or shape coefficients
C_i	Compression index
C_{pi}, C_{si}	Primary, or secondary, compression index
C_r	Coefficient of wave reflection
C_t, C_{to}, C_{tt}	Coefficient of total transmission, by overtopping, or transmission through
$C_r(f)$	Reflection coefficient function
c'	Soil cohesion
c_v	Consolidation coefficient (has units of m^2/s)
D	Particle size, or typical dimension
D_e	Effective particle diameter
D_n	Nominal block diameter = $(M/\rho_a)^{1/3}$
D_{n50}	Nominal diameter, $(M_{50}/\rho_a)^{1/3}$
D_p	Diameter of profiler or survey head
D_z	Sieve diameter
D_{50}	Sieve diameter, diameter of stone which exceeds the 50% value of sieve curve
D_{85}	85% value of sieve curve
D_{15}	15% value of sieve curve
D_{85}/D_{15}	Armour grading
d	Thickness, min. distance between 2 parallel lines
E_i	Incident wave energy
E_r	Reflected wave energy
E_t	Transmitted wave energy
E_d	Energy absorbed of dissipated
e, e_o	Void ratio = $\frac{n_v}{1-n_v}$, initial void ratio
F	Factor of safety, defined $\frac{\text{ultimate resistance}}{\text{required resistance}}$
F_c	Difference of level between crown wall and armour crest = $R_c - A_c$
F_l	Fetch length

F_s	Shape factor = $M/\rho_a D_z^3$
F_*	Dimensionless freeboard parameter = $(\frac{R_c}{H_s})^2 (\frac{s}{2\pi})^{1/2}$
G_c	Width of armour berm at crest
g	Gravitational acceleration
H	Wave height, from trough to crest
H_o	Offshore wave height, unaffected by shallow water processes
H_{mo}	Significant wave height calculated from the spectrum = $4m_o^{1/2}$
H_s	Significant wave height, average of highest one-third of wave heights
H_{max}	Maximum wave height in a record
$H_{2\%}$	Wave height exceeded by 2% of waves
$H_{1/10}$	Mean height of highest 1/10 of waves
h_c, h_c'	Armour crest level relative to sea bed, after and before exposure to waves
h	Water depth
h_f	Height of crown wall over which wave pressures act
h_s	Water depth over ½ wavelength seaward of structure toe
Ir	Iribarren number = $\tan\alpha/s_m^{1/2}$
Ir	Modified Iribarren number = $\tan\alpha/s_p^{1/2}$
K	Hydraulic conductivity
K_D	Stability coefficient in Hudson formula
K_{RR}	Stability coefficient for rip rap
K_{1c}	Fracture toughness
k	Wave number, $2\pi/L$,
k_t	Layer thickness coefficient
L	Wave length, in the direction of propagation
L_o	Deep water or offshore wave length, $gT^2/2\pi$
L_m, L_p	Offshore wave length of mean, T_m, and peak, T_p, periods respectively
L_s	Wave length in (shallow) water at structure toe
L_{ms}, L_{ps}	Wave length of mean or peak period at structure toe
M	Mass of an armour unit
M_{50}, M_i	Mass of unit given by 50%, i%, on mass distribution curve
m	Sea bed slope
m_o	Zeroth moment of wave spectrum
m_n	nth moment of spectrum
N	Number of waves in a storm, record, or test, = $\frac{T_R}{T_m}$
N_a	Total number of armour units in area considered
N_d	Number of armour units displaced in area considered
N_{od}, N_{or}	Number of displaced, or rocking, units per width D_n across armour face
N_r	Number of armour units rocking in area considered
N_s	Stability number, = $\frac{H_s}{\Delta D_{n50}}$
N_s^*	Spectral stability number = $\frac{(H_{mo}^2 L_{ps})^{1/3}}{\Delta D_{n50}}$
n_a	Area porosity, void area as proportion of total projected area
n_v	Volumetric porosity, volume of voids as proportion of total volume

O, O_i	Opening size in geotextile, i% opening size
P	Notional permeability factor, defined by Van der Meer
P_f	Fictitious porosity = $1-(\rho_a/\rho_b)$
P_o	Proportion (or %) of incident waves given by N overtopping
P_n	Fourier noncircularity, based on the harmonic amplitudes from 1 to ∞
P_S	Fourier shape factor based on the 1st to 10th harmonic amplitudes
P_R	Fourier asperity roughness based on the 11th to 20th harmonic amplitudes
p	Pore water pressure, or wave pressure
Q	Overtopping discharge, per unit length of sea wall
Q^*	Dimensionless overtopping discharge = $Q/T_m\ g\ H_s$
q_o	Volume of overtopping, per wave, per unit length of structure
q_s	Superficial velocity, or specific discharge, discharge per unit area, usually through a porous matrix
R_u	Run-up level, relative to still water level
R_c	Crest freeboard, level of crest relative to still water level
R_{us}	Run-up level of significant wave
$R_{u2\%}$	Run-up level exceeded by only 2% of run-up crests
R^*	Dimensionless freeboard = $R_c/T_m\ (g\ H_s)^{½}$
R_a	Average roughness of a surface from profile data
$R_{d2\%}$	Run-down level, below which only 2% pass
r	Roughness value, usually relative to smooth slopes
S	Dimensionless damage, A_e/D_{n50}^2, may be calculated from mean profiles or separately for each profile line, then averaged
S_c	Settlement or compression distance
s	Wave steepness, H/L_o
s_m	Wave steepness for mean period, $2\pi H_s/g\ T_m^2$
s_p	Wave steepness for peak period, $2\pi H_s/g\ T_p^2$
T	Wave period
T_m	Mean wave period
T_p	Spectral peak period, inverse of peak frequency
T_R	Duration of wave record, test or sea state
t	Time, variable
t_a, t_f, t_x	Thickness of armour, filter, or other layer in direction normal to face
U_c	Coefficient of uniformity, D_{60}/D_{10}
U_{10}	Wind speed 10 metres above sea surface
u, v, w	Local velocities, usually defined in x,y,z directions
W	Armour unit weight, = Mg
x, y, z	Distances along orthogonal axes
α (alpha)	Structure front face angle
β (beta)	Angle of wave attack
γ (gamma)	Weight density = ρg
Δ (delta)	Relative buoyant density of material considered, eg for rock = $(\rho_r/\rho_w)-1$
ϵ (epsilon)	Strain, relative displacement
η (eta)	Instantaneous surface elevation
Θ (theta)	Mean direction of waves, usually to grid north

λ (lambda)	Geometric scale ratio in physical models; or penetration length in set-up calculations
μ (mu)	Coefficient of friction
$\mu(x)$	Mean of x
ν (nu)	Coefficient of kinematic viscosity
ξ (xi)	Surf similarity parameter, or Iribarren number , $= \tan\alpha/s_m^{1/2}$
ξ_p	Modified surf parameter, $= \tan\alpha/s_p^{1/2}$
ρ (rho)	Mass density, usually of fresh water
ρ_w	Mass density of sea water
ρ_r, ρ_c, ρ_a	Mass density of rock, concrete, armour
ρ_b	Bulk density of material as laid
σ (sigma)	Stress
σ'	Effective stress in soil or rubble $= \sigma - p$
$\sigma(x)$	Standard deviation of x
τ (tau)	Shear strength of rubble or soil
Υ (upsilon)	Dimensionless damage $= N_d/N_a$, may be expressed as %
ϕ (phi)	Angle of internal friction of rubble or soil