CHAPTER 108

Rock Armour Stability Formulae-Influence of Stone Shape and Layer Thickness

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Abstract

A series of hydraulic model tests of armour rock stability have been carried out on a 1:2 slope armoured with rock of each of 5 different shape types. Results of these tests have been compared with damage predicted by van der Meer's stability formulae. Coefficients are suggested to describe the influence of armour shape and layer thickness in revised stability formulae.

1. Introduction

Coastal structures may be protected from the effects of wave action using rock armour with a variety of rock types, each of different grades and shape properties. The shape characteristics of quarried rock are governed largely by natural jointing and fracturing, and by production techniques. Many quarries can only produce flat slabby armourstone due to the limitations of the bedding. Under circumstances where the bedding and joint characteristics of the source permit, and where special production techniques are used, near equant blocks of armour can be produced.

During service, rock armour may suffer changes to both its shape and size. Previous research by Queen Mary College, and Hydraulics Research (Refs 1,2,3) has demonstrated the importance of rock quality and shown that degradation of armour in service constitutes a major problem for many coastal structures worldwide. Degradation of the armour may occur by fracturing, spalling or abrasion. These may be particularly important in severe wave climates, where there are abrasive sediments, or where the rock is of low grade, or where the rock is too small for the incident wave

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conditions. Recently some structures have been designed for dynamic stability. In such cases the armour will also be more susceptible to degradation due to its movement under wave action.

2. Previous Work

Recent work in the UK and the Netherlands has highlighted the shortcomings of the Hudson formula (Ref 4), traditionally used for the design of rock armour for static stability. The omission of several fundamental hydraulic parameters in the Hudson formula has been addressed by van der Meer (Refs 5,6). These studies included the data from Thompson & Shuttler's work on rip-rap stability (Ref 7), in addition to the results from many other irregular wave tests. The new design formulae are based upon a more comprehensive empirical framework, and allow the designer to explore the influence of mound permeability, storm duration and acceptable damage levels. These formulae do not give quantitative advice on the effects of armour shape stability. Neither do they allow for variations in construction which may result in loose interlock, or armour layers of variable thickness.

The influence of armour shape and placement on stability has been discussed by a number of researchers. The Shore Protection Manual (Ref 4) suggests different stability coefficients for smooth and angular rock. Jensen (Ref 8) and Bergh (Ref 9) have tested rock armour of various shapes, and identified significant influence of armour shape on stability.

Van der Meer did not consider gross shape and roundness as variables in his static stability programme. However, a number of interesting observations arose during his tests which may be related to armour shape. Rounding of material during the extensive testing programme seems to give a likely explanation of some anomalous results. Two repeat tests at the beginning and end of the test programme resulted in 2.5 times more damage in the second test. Tests to investigate the effects of relative mass density identified a systematic effect, apparently uncorrelated to rock density. These differences may have arisen from variations in roundness and surface texture.

These suggest that gross shape and roundness, together with placement technique, have an important effect on stability, but no clear guidance is given to the designer on these effects. This study sought therefore to identify the influence of rock shape on armour stability, for inclusion in empirical design methods.

3. Test Programme

The framework of this study was based on the parameters defined in van der Meer's design formulae. A systematic series of random wave stability tests were carried out on each armour shape, including the effects of wave period, significant wave height and mean wave steepness, for a range of surging and plunging wave conditions. A number of variables were kept constant throughout these tests:

Median armour weight W_{50} = 323g +/- 2%
Relative mass density of rock = 1.73
Armour slope cot α = 2
Armour grading (D_{85}/D_{15}) = 1.25
Spectral shape = JONSWAP
Approach beach slope = 1:52
Filter size D_{50} = 11mm
Construction method, crest level, wave angle
Water depth at the toe of the structure, h_s = 0.5m

Measurements were made of the armour slope profiles, using a computer driven bed profiler, sampling at intervals of approximately 0.5 D_{n50} along each of 10 profiles across the test section. Damage to the test sections was expressed by the dimensionless damage parameter, S, defined:

$$S = A_e / D_{n50}^2 \quad (1)$$

An important variation between this study and previous work was the method of construction of the armour layers. Studies by both van der Meer and Thompson & Shuttler used armour layers constructed to a thickness of 2 - 2.4 D_{n50}, with bulk placement of rock. Whilst bulk placement is common for rip-rap with a wide armour grading, this study used armour with a narrow grading ratio of D_{85}/D_{15} = 1.25. This study therefore used individual placement of the armour blocks to give two layers. The effect of this placement method was that the measured armour layer thickness was about 1.5 - 1.7 D_{n50}.

Five contrasting shapes of rock were selected to represent the full range of armour shapes. Categories of rock defined in this study are: fresh, equant, tabular, semi-round, and very round. Fresh, crushed rock is used in many model tests and is generally typical of much quarried rock. This shape was initially selected as a base condition for comparison with van der Meer's work. Flat or slabby rock was excluded from this category. Equant or nearly cubic rock was selected as the second armour shape. Flat, slabby or tabular rock, with maximum to minimum lengths in excess of 2, was selected as a third shape, typical of much quarried limestone presently excluded from many design specifications. The effects of changing shape whilst in service were also examined by testing two grades of rounded rock, prepared by tumbling in a concrete mixer. Rounding to a weight loss of 5-10% and 20-25% represented materials subject to varying degrees of abrasion.

4. Shape Analysis

A study has been carried out at Queen Mary College to develop methods for the description of particle shape (Ref 3, 11), and this has allowed a number of shape parameters to be examined. The median value of the X/Z ratio (maximum and minimum dimensions of the enclosing cuboid) has been used in the past to give a basis for comparing the gross shape of the samples. Recently Latham et al (Ref 11) have developed shape descriptors based on Fourier and/or Fractal analysis of particle outlines and armour slope profiles. These include the Fourier shape factor, P_C, which describes gross shape, and the Fourier asperity roughness, P_R, which is sensitive to roughness, but is also influenced by gross shape. The most useful of these shape descriptors was the Fourier asperity roughness factor, P_R. Blocks that have not undergone rounding but are tabular and elongate will give higher values of P_R than ones that are equant.

5. Test Results

For each test, values of the damage parameter were calculated from the profile data. In the preliminary analysis, damage was compared directly with that predicted by Van der Meer's formulae with a permeability coefficient of P = 0.1. For the purposes of further analysis, van der Meer's formulae were re-arranged, replacing the fixed coefficients in the original formulae by variables. The plunging wave formula was rewritten:

$$S^* = H^* / C_{pl} \qquad (2)$$

where

$$S^* = (S/\sqrt{N})^{0.2} \qquad \text{and} \qquad H^* = H_s/\Delta D_{n50}\sqrt{\xi_m}\, P^{-0.18}$$

where C_{pl} replaces 6.2 in the original.

The surging wave formula was rewritten :

$$S^* = H^{**} / C_{su} \qquad (3)$$

where

$$H^{**} = H_s/\Delta D_{n50}\, \sqrt{\tan\alpha}\, P^{0.13}\, \xi_m^{-P}$$

where C_{su} replaces 1.0 in the original equation.

Curve fitting regression coefficients for C_{pl} and C_{su} were calculated, for a permeability of P = 0.1 and are given in Table 1. Results from this study for plunging waves are compared with predicted damage from van der Meer's equation in Figure 1. Comparisons with van der Meer's equations indicated that very round rock performed worse than predicted, as did the partially rounded rock. However, equant and fresh rock also performed somewhat worse than predicted. Tabular rock surprisingly performed better than any other shape. Throughout the test programme, the threshold of damage for virtually all conditions was lower than that predicted by van der Meer's formulae. There

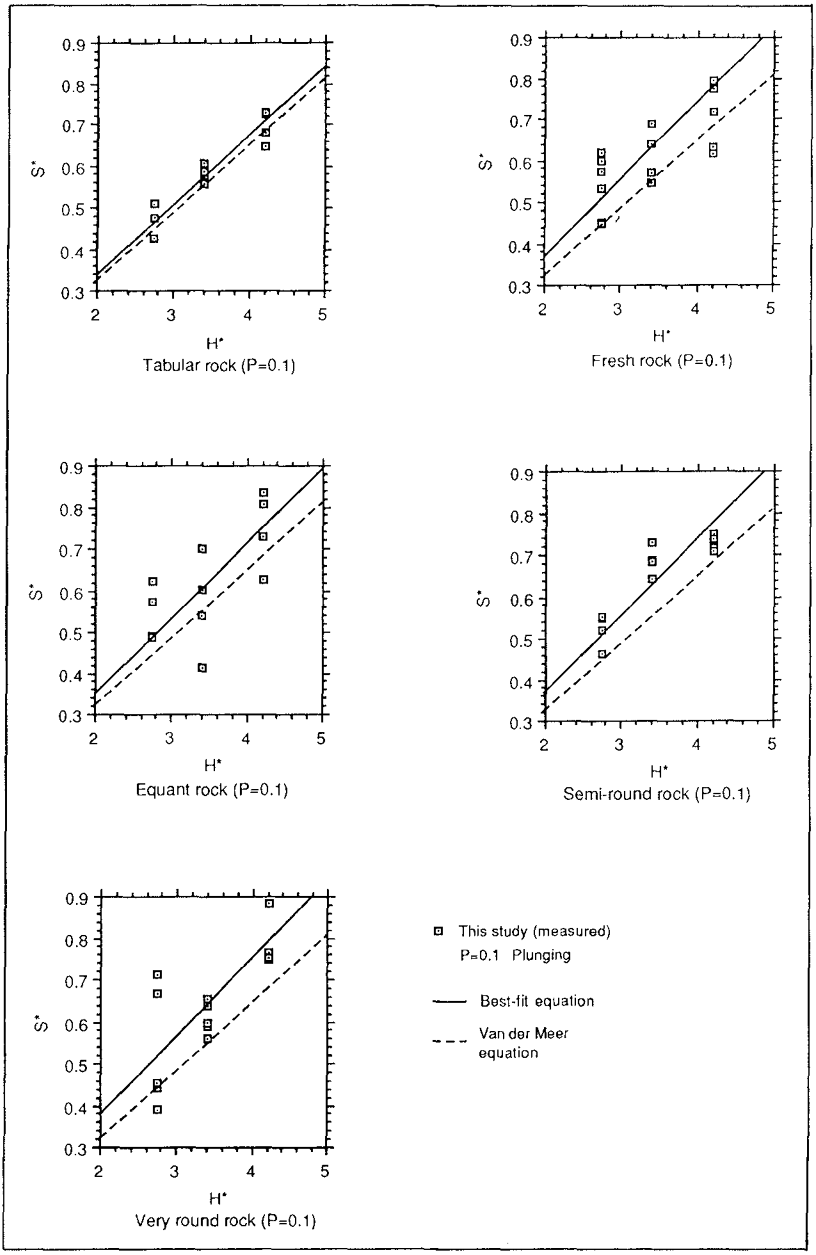

Figure 1 Van der Meer's predictions for plunging waves and curve fitting regression results for C_{pl}

was also noticeable scatter outside of Van der Meers 90% confidence bands, mostly at higher damage levels.

Table 1 Curve fitting regression results for C_{pl} and C_{su} in eqs. (2) and (3) for P = 0.1

Shape classes	Plunging C_{pl}	Surging C_{su}
Tabular	5.93	0.999
Fresh	5.63	0.711
Equant	5.61	0.894
Semi-round	5.39	0.830
Very round	5.35	0.713
Van der Meer	6.20	1.000

Initially it was felt that the consistently higher damage observed in this study could have resulted from the lower layer thickness, perhaps giving a lower value of P than the 0.1 limit given by Van der Meer. Subsequent analysis of this variable in the equations given by van der Meer indicated that substitution of a lower value of P cannot give satisfactory results for both surging and plunging formulae. A more reasonable explanation of this anomaly was derived after more detailed analysis and comparison of the results of this study with previous work. Samples of material from the previous studies were analysed using Latham's shape descriptor techniques.

This showed that the bulk of van der Meer's tests were performed with material similar in roughness and degree of rounding to the semi-round rock of this study, but with more equant gross shape. The material used by Thompson & Shuttler had characteristics similar to the equant rock of this study. It was concluded therefore that van der Meer's equations represent the stability of equant and semi-round rock.

6. Effects of Layer Thickness and Particle Shape

For armour with a narrow grading, the procedure most often adopted is to build a two layer system with random block orientation and individual placement of armour. A layer thickness of less than $2D_{n50}$ may therefore be common. Differences in the layer thickness achieved in this study and those in van der Meer's study represent a 30% reduction in layer thickness. It was suspected that this comparative reduction in layer thickness alone gave the increase in damage from that predicted by van der Meer for equant and semi-round materials.

This increase can be explained by replacing some coefficients in the van der Meer equations by variables. Analysis of the results by least squares non-linear regression gave acceptable explanations for the influence of both shape and layer thickness. The shape effects were best described by using the coefficients

C_{pl} and C_{su}. To fix these values at 6.2 and 1.0 for equant and semi-round materials required either that:

(i) the power coefficients of P, 0.18 and 0.13 must be adjusted to be functions of layer thickness; or
(ii) the power coefficient of $S/\sqrt{N}$, must be adjusted.

Both (i) and (ii) were tested, but the most satisfactory results were achieved by adjustment of the power coefficents of $S/\sqrt{N}$. Conveniently a single adjustment of this coefficient can account for both surging and plunging results as shown in Table 2.

These revised equations may be given:

Plunging waves: $S^{*'} = H^{*}/C'_{pl}$ (4)

Surging waves: $S^{*'} = H^{**}/C'_{su}$ (5)

$S^{*'} = (S/\sqrt{N})^{x(1)}$ for plunging (4a)

$S^{*'} = (S/\sqrt{N})^{x(2)}$ for surging (5a)

Table 2. Derivation of curve fitting power coefficients for $S/\sqrt{N}$ by least squares non linear regression

	Plunging	Surging
	$C'_{pl} = 6.2$	$C'_{su} = 1.0$
Equant	x(1)=0.236	x(2)=0.249
Round	x(1)=0.269	x(2)=0.260
Equant & semi-round	x(1)=0.252	x(2)=0.254

The coefficients x(i) and x(ii) may therefore be reasonably assigned the same value of 0.25. The only difference in the formulae needed to describe the effects of layer thickness on damage for equant and semi-round rock was therefore a change in the power coefficient from 0.2 to 0.25. Thus S in eqn.(4a) and eqn.(5a) can be replaced by:

$$S^{*'} = (S/\sqrt{N})^{0.25} \quad (6)$$

Further curve fitting to establish best fit values of C'_{pl} and C'_{su} in equations (4) and (5), assuming equation (6), was then carried out to quantify the effects of armour shape on stability. The regression results for C'_{pl} and C'_{su} for each armour shape are presented in Figures 2 and 3, and Table 3.

It is important to emphasise that this analysis is only valid for the range of conditions used in this study [i.e 1:2 slope, impermeable core, layer thickness t_a = 1.5-1.7 D_{n50}].

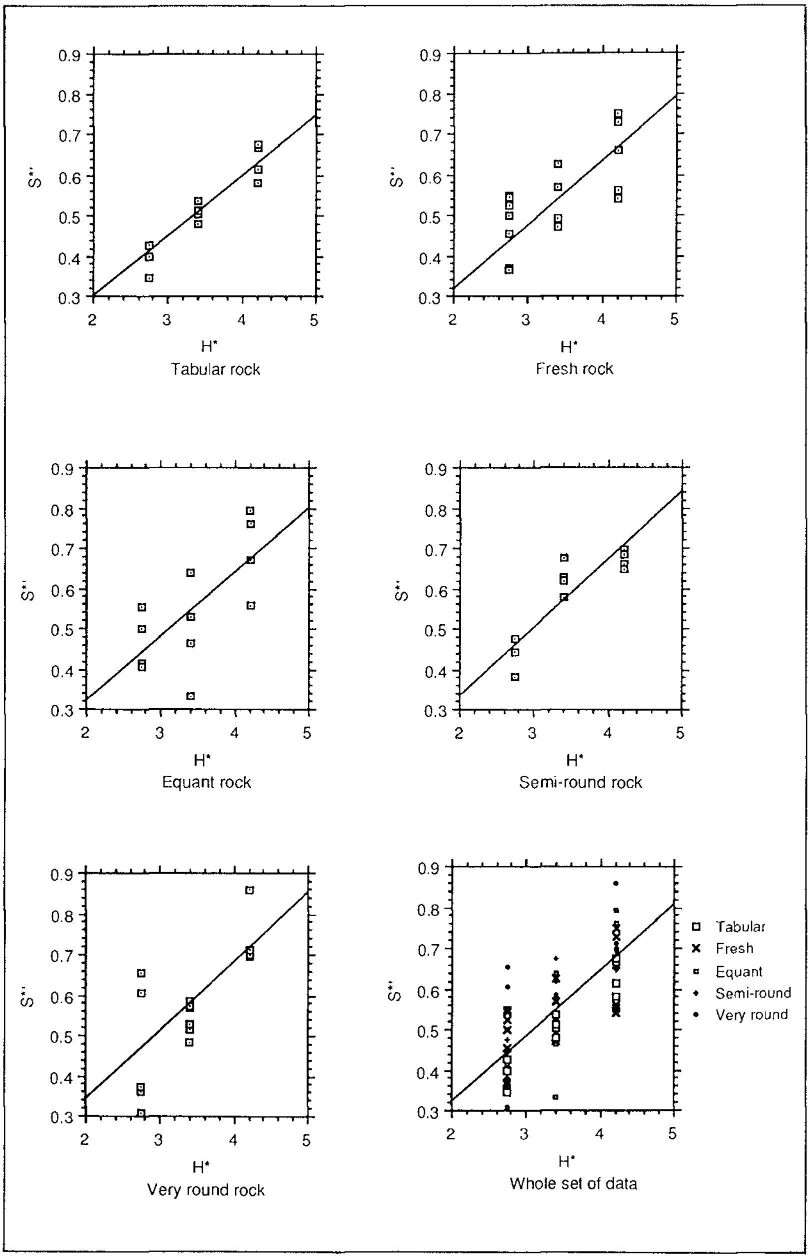

Figure 2 Curve fitting regression results for C'_{pl}, plunging wave formula

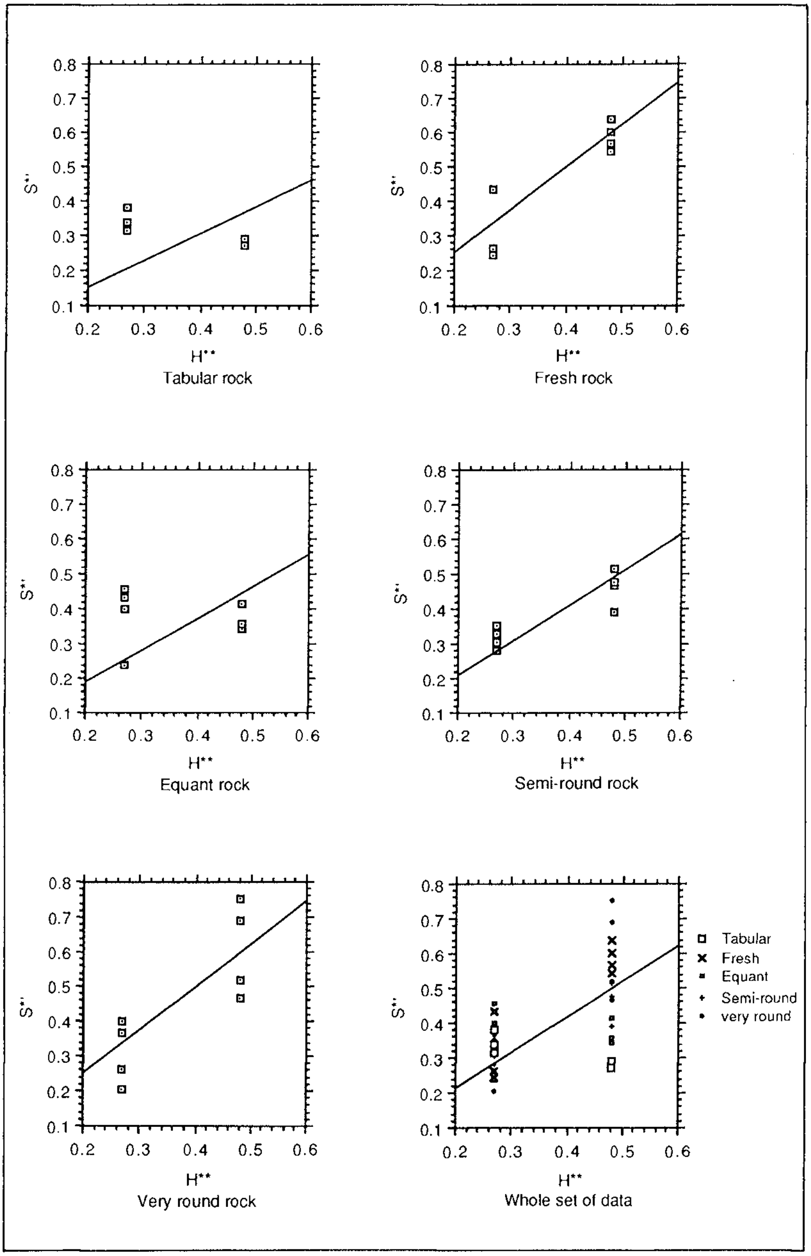

Figure 3 Curve fitting regression results for C'_{su}, surging wave formula

Table 3 Curve fitting regression results for C'_{pl} and C'_{su} in eqs. (9) and (10)

Shape classes	Plunging C'_{pl}	Surging C'_{su}
Tabular	6.72	1.301
Fresh	6.32	0.811
Equant	6.24	1.087
Semi-round	5.96	0.989
Very round	5.88	0.810

The results of shape analysis of the armour determined during the test programme can be compared with the stability coefficients C'_{pl} and C'_{su}. From a simple regression of C'_{pl} and C'_{su} on P_R, the following summary equations were derived:

$$C'_{pl} = 5.4 + 70.0\ P_R \tag{7}$$

$$C'_{su} = 0.6 + 40.0\ P_R \tag{8}$$

Figures 4 and 5 show the results of this analysis including data derived from the original tests carried out by van der Meer, for which values of 6.2 and 1.0 can be assumed for C'_{pl} and C'_{su}.

Van der Meer's equations can now be modified to account for different shaped armour and layer thicknesses. Substituting the new coefficients for 2 layers of armour on an impermeable core at a slope of 1:2, the proposed modifications to van der Meer's equations are given by:

$$H_s/\Delta D_{n50}\sqrt{\xi_m} = C'_{pl}\ P^{0.18}\ (S/\sqrt{N})^{0.25} \tag{9}$$

$$H_s/\Delta D_{n50} = C'_{su}\ P^{-0.13}\ (S/\sqrt{N})^{0.25}\ \sqrt{\cot\alpha}\ \xi_m^P \tag{10}$$

where C'_{pl} and C'_{su} are shape coefficients given in equations (7) and (8) by the Fourier asperity roughness parameter P_R.

C'_{pl} and C'_{su} have been set to be coincident with C_{pl} and C_{su} respectively for flume tests results from all studies using Equant and Semi-round type test material. However C_{pl} and C_{su} in the general equations (2) and (3) may not have the same influence on stability as eqns. (7) and (8) since, for example permeability in the core may greatly influence the effect of shape on damage.

The implications of these equations are now summarized. The change in damage S as a result of using tabular or very round rock by comparison with equant rock has the following influence.

Damage, S Plunging : Tabular = 0.81 Equant
Very round=1.40 Equant

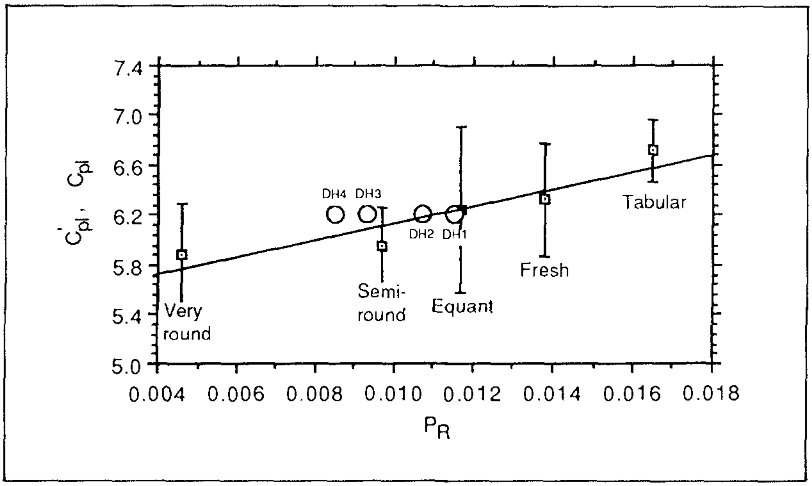

Figure 4 Best fit for shape coefficient C'_{pl} in Equation (7) versus block shape parameter P_R

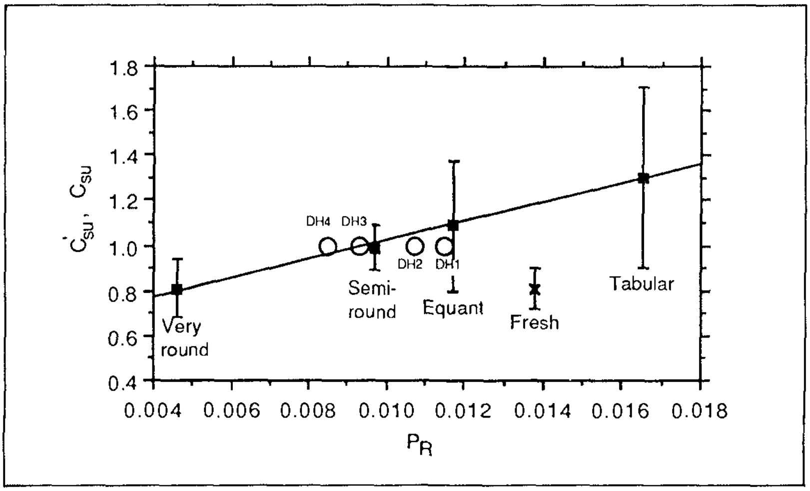

Figure 5 Best fit for shape effect coefficient C'_{su} in Equation (8) versus block shape parameter P_R

Surging : Tabular =0.52 Equant
Very round=3.44 Equant

This simple summary of the shape effects given by equations (7) and (8) may be an over-simplification of the complexity of shape effects but indicates the potential dangers of underdesign if the effects of shape are ignored.

The surging wave data gave more scatter than the plunging data and gave large standard errors for the curve fitting, whilst the fresh rock results did not conform to summary trends at all, casting some doubts on this simple interpretation of the surging waves results.

10. Conclusions

The results of the study gave consistently higher damage levels than predicted by van der Meers equations for shape classes of material of similar shape characteristics to those from which the formulae were derived.

These differences have been attributed to the lower layer thickness achieved by placing armour in a two layer thickness resulting in a total layer thickness of $t_a \approx 1.6\ D_{n50}$. Such increasd damage for thinner armour layers can be predicted by assuming that the power 0.2 for $(S/\sqrt{N})$ in both surging and plunging equations is replaced by 0.25.

For different armour shapes and conditions represented in the model test series van der Meer's equations can be simply modified, assuming the 0.25 power corection for double armour layers with the introduction of two shape coefficients.

$$C'_{pl} = 5.4 + 70.0\ P_R$$

$$C'_{su} = 0.6 + 40.0\ P_R$$

into the equations:

$$H_s/\Delta D_{n50} \sqrt{\xi_m} = C'_{pl}\ P^{0.18}\ (S/\sqrt{N})^{0.25}$$

$$H_s/\Delta D_{n50} = C'_{su}\ P^{-0.13}\ (S/\sqrt{N})^{0.25} \sqrt{\cot\alpha}\ \xi_m^P$$

11. Acknowledgements

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Summary of notation

ξ_m	Iribarren or surf similarity number
P	Notional Permeability factor
S	Dimensionless damage to a mean profile
N	Number of waves in a storm or test
H_s	Significant wave height
Δ	Relative density
D_n	Nominal particle diameter
C_{su}	Surging wave shape coefficient, defined in equation (2)
C_{pl}	Plunging wave shape coefficient, defined in equation (3)
C'_{su}	Surging wave shape coefficient defined in equation (4)
C'_{pl}	Plunging wave shape coefficient defined in equation (5)
A_e	Cross section area eroded