## Packing and Voids for Rock Armour in Breakwaters

T P Stewart S D Newberry J-P Latham J D Simm

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### Summary

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This report describes a study conducted by HR Wallingford and funded by the Department of the Environment, Transport and the Regions (DETR). The study was concerned with rock armouring, as widely used on coastal defence structures and breakwaters throughout the UK. Although there are well-established procedures in place for designing such armouring, they have been based largely on observations made of bulk-placed rocks. In practice, rocks can be individually placed and packed together to a greater or lesser degree. The current design procedures do not fully take account of such placement methods.

The intention of the study was to investigate the effects of rock placement on the properties of armour layers and to develop methods of predicting those properties. The specific objectives of the study were as follows:

- To investigate the geometry of armour layers formed by individually placed stones.
- To investigate the hydraulic performance of armour layers formed by individually placed stones.

The armour layer geometry was investigated by the construction of test panels at full scale in the field and at scales of between 1:12 and 1:30 in the laboratory. The rocks that formed the test panels were carefully quantified in terms of shape and size. The panels were used to measure armour layer void porosity and thickness. A comparison of the results of the field and model test showed that scale models could accurately represent full-scale armour layers, provided that the rock shape characteristics were accurately modelled.

The scale models were used to investigate the influence of rock shape and placement method on the layer geometry. Several methods of quantifying rock shape were investigated. The degree of blockiness of the individual rocks was shown to have a significant effect on the layer. Rocks that are blocky in nature tend to form denser layers than those that are round. A simple method of predicting armour layer geometry, based on the shape of the rocks that form the layer, was developed using regression analysis.

The hydraulic performance of the armour layers was investigated by physical hydraulic model tests conducted in a 2-D flume. Two aspects of hydraulic performance were considered:

### Summary continued

- The stability of the layers under wave attack.
- The ability of the layers to dissipate wave energy.

The layers were subjected to sequences of random waves and the resulting damage was measured. Overtopping discharges were also measured as a method of quantifying the wave energy dissipation properties of the layers.

Armour layers were constructed using various shapes of rocks and placement methods. Single layers were investigated along with double layers. It was shown that the stability of individually placed layers is, in most cases, at least as good as that of bulk-placed layers. When particular care is taken to pack the individual rocks tightly, the stability of the layer can far exceed the stability of a bulk placed layer, in some cases withstanding twice the wave height for a given level of damage. The performance of such layers is, however, very sensitive to the degree of workmanship involved in their construction. For this reason the findings of this phase of the study should be applied with caution.

The stability of single layers was also investigated. Their performance was found to be extremely variable. This was due to the fact that a single layer can fail by the extraction of a single rock. The performance of the entire layer can thus depend upon the stability of a single rock.

Tighter packing of the armour rocks was not found to have a significantly deleterious effect on the ability of the layer to restrict overtopping discharges. Performance indicators were determined for double and single layers separately.

The results of the study are presented in such a way that they can be readily incorporated into current design methods.



### Notation

| A <sub>e</sub>       | Cross sectional area of armour layer eroded by waves (m <sup>2</sup> ).   |
|----------------------|---|
| BL <sub>c</sub>      | Blockiness coefficient of a rock, = $100 \text{ x rock volume / (XYZ)}$ .   |
| BL <sub>c mean</sub> | Mean blockiness coefficient of a rock batch.  |
| $BL_{c \; sdev}$     | Standard deviation of the blockiness coefficients of a rock batch.  |
| $C_{pl}$             | Plunging wave stability coefficient (Van der Meer equations).   |
| $C_{pl \; sdev}$     | Standard deviation of plunging wave stability coefficient   |
| C' <sub>pl</sub>     | Plunging wave stability coefficient (Bradbury et al's equations).   |
| C <sub>su</sub>      | Surging wave stability coefficient (Van der Meer equations).  |
| $C_{susdev}$         | Standard deviation of surging wave stability coefficient  |
| C' <sub>su</sub>     | Surging wave stability coefficient (Bradbury et al's equations).  |
| d                    | Minimum axial breadth of a rock, i.e., the minimum distance<br>between two parallel straight lines between which the rock can<br>just pass (m). |
| D <sub>n50</sub>     | Nominal diameter of a rock = $(M_{50}/\rho_a)^{1/3}$ (m).   |
| $F_1$                | Stability parameter (Pilarczyk equation)  |
| g                    | Gravitational acceleration (m/s <sup>2</sup> )  |
| ${ m H}_{1/10}$      | Average of the highest $1/10^{\text{th}}$ of the waves (m).   |
| H*                   | Dimensionless coefficient (Bradbury et al)<br>( $U_{1} \neq D_{2} \rightarrow D^{-0.18} = 0.5$  |
| H**                  | $= (H_s / \Delta D_{n50}) P^{arro} \zeta_m$<br>Dimensionless coefficient (Bradbury et al)   |
|                      | = (H <sub>s</sub> / $\Delta D_{n50}$ ) P <sup>0.13</sup> $\sqrt{\tan \alpha \zeta_m}^{-P}$  |
| H <sub>s</sub>       | Significant wave height (m).  |
| K <sub>D</sub>       | Stability coefficient (Hudson equation).  |
| k <sub>t</sub>       | Layer coefficient.  |
| 1                    | Maximum axial length of a rock, i.e., the maximum distance between any two points on the rock (m).  |
| l/d                  | Aspect ratio of a rock.   |
| l/d mean             | Mean aspect ratio of a rock batch.  |
| $l/d_{sdev}$         | Standard deviation of the aspect ratios of a rock batch.  |
| М                    | Mass of a rock (t).   |
| M <sub>15</sub>      | Mass not exceeded by by 15% (by weight) of rocks in a batch (t).  |
| M <sub>50</sub>      | Median mass of a rock batch, i.e., the mass not exceeded by 50% (by weight) of rocks in a batch (t).  |
| M <sub>85</sub>      | Mass not exceeded by 85% (by weight) of rocks in a batch (t).   |
| M <sub>c</sub>       | Dimensionless mass coefficient = $M/M_{50}$   |
| Ν                    | Number of waves in a storm.   |

### Notation continued

| N <sub>R</sub>       | Number of rocks extracted from armour layer.  |
|----------------------|---|
| n                    | Number of rock layers in an armour layer.   |
| n <sub>v</sub>       | Armour layer porosity, i.e., the proportion of the armour layer that consists of voids.                                   |
| Р                    | Notional structure permeability.  |
| P <sub>R</sub>       | Fourier Asperity Roughness parameter.   |
| q                    | Mean overtopping discharge per unit length of a structure $(m^3\!/\!s.m)$   |
| Q*                   | Dimensionless mean overtopping discharge (Owen equation)  |
|                      | $= q / T_m g H_s$   |
| $Q_{b}$              | Dimensionless mean overtopping discharge in plunging waves (Van der Meer equation) = $q/(gH_s^3) (s_p/\tan \alpha)^{0.5}$ |
| Qn                   | Dimensionless mean overtopping discharge in surging waves (Van der Meer equation) = $q/(gH_s^3)$                          |
| r                    | Slope roughness coefficient (Owen equation)   |
| R                    | Number of rocks in batch  |
| R*                   | Dimensionless structure freeboard (Owen equation)   |
|                      | $= R_c / (T_m \sqrt{(gH_s)})$   |
| R <sub>b</sub>       | Dimensionless structure freeboard in plunging waves (Van der Meer equation) = $R_c/H_s (s_p)^{0.5}/tan \alpha$            |
| R <sub>n</sub>       | Dimensionless structure freeboard in surging waves (Van der Meer equation) = $R_c/H_s$                                    |
| R <sub>c</sub>       | Structure freeboard (m)   |
| S*<br>S <sub>d</sub> | Dimensionless coefficient (Bradbury et al) = $(S_d / \sqrt{N})^{0.2}$<br>Damage number = $A_e/D_{n50}^2$                  |
| s <sub>m</sub>       | Wave steepness calculated from the mean wave period   |
|                      | $=2\pi H_{s}/g T_{m}^{2}$   |
| Sp                   | Wave steepness calculated from the peak wave period = $2\pi H_s/g T_p^2$  |
| t                    | Total armour layer thickness (m).   |
| T <sub>m</sub>       | Mean wave period (s).   |
| T <sub>p</sub>       | Spectral peak wave period (s).  |
| Ve                   | Bulk volume of armour layer eroded by waves (m <sup>3</sup> ).  |
| W                    | Test structure width (m).   |
| Z                    | Sieve size, i.e., the smallest square hole through which the rock can pass through with optimum orientation (m).          |

## Notation continued

| X,Y and Z          | The dimensions of the smallest box that can enclose a rock (m).  |
|--------------------|--|
| α                  | Slope angle of the armour face (measured from the horizontal).   |
| $\Delta$           | Buoyant density of the armour rock = $\rho_a/\rho_w - 1$ .   |
| $\Delta n_{\rm v}$ | The change in armour layer porosity caused by dense packing.   |
| $\Delta k_t$       | The change in layer coefficient caused by dense packing.   |
| $\gamma_{\rm f}$   | Roughness factor (Van der Meer equations)  |
| $ ho_a$            | Density of the armour rock (t/m <sup>3</sup> ).  |
| $ ho_b$            | Bulk (or 'as-placed') density of the armour layer $(t/m^3)$ .  |
| $ ho_{w}$          | Density of water $(t/m^3)$ .   |
| $\zeta_{\rm m}$    | Iribarren number (or 'surf similarity parameter') calculated from the mean wave period = tan $\alpha$ / $\sqrt{s_m}$ |
| $\zeta_{mc}$       | Critical Irribarren number = (6.2 P <sup>0.31</sup> $\sqrt{\tan \alpha}$ ) <sup>1/(P+0.5)</sup>                      |
|                    |  |



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Appendix Appendix A Statistical Methods



#### 1. INTRODUCTION

Empirical formulae (such as those of Hudson and Van der Meer) have been developed for the design of rock armour, and have gained widespread acceptance throughout the coastal engineering industry. These formulae are generally expressed in terms of the block weight required to withstand a design wave condition. Complementary formulae are available to determine the dimensional properties of rock armour layers. These are important for determining, for example, the quantity of rock required to form an armour layer of a particular thickness.

Despite the fact that the design procedures for rock armour layers are long established, there still remain areas of considerable uncertainty, particularly in estimating their dimensions and bulk densities. As an illustration of the problem it is worthwhile to consider, for example, the differences in suggested values of the thickness coefficient,  $k_t$ , used to estimate the thickness of a layer of rock armour. An accurate knowledge of the armour layer thickness is vital for design of the crest level of a breakwater or revetment. For irregular rocks, suggested values of  $k_t$  range from 0.75 to 1.15. Such discrepancies present a dilemma for designers and contractors and have serious implications for both the cost and the performance of rock-armoured structures, often leading to legal disputes. Much of the uncertainty arises from issues relating to rock shape and, in particular, packing density.

The extent to which rock armour needs to be tightly packed together is a serious area of concern at present. Clients prefer tight packing as it looks neat and allays public concerns about risks to people being trapped in voids. Designers perceive tight packing as increasing stability and reducing potential storm damage and consequent maintenance. However, they often neglect the reduction in energy dissipating capacity that such structures offer. Perhaps more importantly, contractors note the high costs of the necessary rehandling involved in tight placement (increasing unit costs per tonne for as-placed rock by 10%) and the high costs of the 10% to 20% additional (potentially wasted) material for which either the client or contractor has to pay.

In confined spaces, however, tight packing may offer significant advantages in reducing the total thickness of armour layers or in being able to use the available rocks where they are of insufficient individual weight. For such reasons, single tightly packed layers of armour have been used widely in overseas countries in which UK consulting engineers operate and are now being considered within the UK.

The DETR-sponsored project "Packing & Voids in Rock Armour" investigated the effect which parameters such as rock shape and packing density have on the properties of the armour layer, in terms of its dimensional properties and its hydraulic performance. It attempted to mitigate some of the areas of uncertainty that the current guidelines allow. In addition, it examined the relatively unexplored area of single layer rock armour. The output of the project will provide guidance to the industry that will remove some of the ambiguities from the design and construction process.

The specific objectives of the project were:

- To investigate the influence of rock shape and packing density on the thickness and as-placed density of armour layers.
- To investigate the influence of rock shape and packing density on the hydraulic performance of armour layers, as regards stability and wave energy dissipation.

The effect of the following variables were investigated:

- The size and grading of the rock.
- The rock shape.
- The method of placement, including the type of placement equipment, human factors and time considerations.



The project was conducted in three phases, as follows:

#### Phase 1 ~ Full-Scale Tests

A number of full-scale test panels were constructed at quarries and coastal sites between July and October 1999. Sets of carefully graded and measured armourstone, of different shape and size distributions, were used to determine the variability in the armour layer thickness and void porosity resulting from different approaches to placement. Rock suppliers Larvik Armourstone, Bardon Aggregates and Forster Yeoman Ltd provided rock for these tests. The test panels were constructed by Dean & Dyball Ltd.

#### Phase 2 ~ Dry Model Tests

This phase of the project involved construction of model rock-armoured structures at HR Wallingford's laboratory facilities, in some cases precisely replicating the full-scale test panels constructed in Phase 1. This replication allowed an investigation of scale effects on the dimensional properties of armour layers. Other tests involved the use of models intended to represent generic rock structures, and concentrated on investigating particular dimensional rock properties, such as shape or grade width. The dry model tests therefore allowed the range of parameters studied in the full-scale tests to be expanded upon.

#### Phase 3 ~ Hydraulic Model Tests

Phase 3 involved conducting hydraulic model tests to investigate the effect of rock shape and packing on the hydraulic performance of the armour. A comprehensive series of hydraulic studies were conducted in one of the flumes at HR Wallingford. Phases 2 and 3 together allowed the interdependency of packing density and hydraulic performance to be investigated.

### 2. REVIEW OF CURRENT GUIDELINES

#### 2.1 Introduction

This chapter presents a review of the guidance currently available to designers who are concerned with the influence of rock shape and packing density on the properties of armour layers. The chapter is arranged as follows: following this introduction, Section 2.2 provides an overview of the recommended methods of classifying individual rock shape. Section 2.3 reviews the guidelines concerning the geometric properties of the armour layer, i.e. its void porosity and thickness. Section 2.4 examines the hydraulic properties of the layer, i.e., its stability under wave attack and its ability to dissipate wave energy. Finally, Section 2.5 discusses the limitations of the current guidelines and proposes a programme of research to address them.

This review concentrates on the most widely used sources of design guidance. These are the Shore Protection Manual published by the US Army Corps of Engineers (Refs. 2.1 and 2.2), the British Standard BS6349 on maritime structures (Ref. 2.3) and the CIRIA/CUR manual on the use of rock in coastal engineering (Refs. 2.4 and 2.5).

#### 2.2 Rock shape classification

#### 2.2.1 Introduction

The classification of rock shape is vital to the design of armour layers, since the shape of the individual rocks that constitute the layer can have a significant influence on its geometric and hydraulic properties. Numerous methods of classifying the shapes of rock particulates (of which armour rocks are only one example) have been developed across a broad range of disciplines. An overview of these methods can be found in Ref. 2.6. This review, however, will concentrate on those methods that have been applied specifically to heavy armour rocks.

#### 2.2.2 Existing guidelines

The 1977 and 1984 issues of the Shore Protection Manual and the 1991 British Standard on maritime structures distinguish only between "smooth" and "rough" rocks in their design methods, but suggest no quantitative methods of classifying these different rock shapes. The most detailed information on rock shape classification is found in the 1991 issue of the CIRIA/CUR manual on the use of rock in coastal engineering. The most basic form of shape classification is the measurement of the rock's axial dimensions, as follows:

1 - the maximum axial length, i.e., the maximum distance between any two points on the rock.

d - the minimum axial breadth, i.e., the minimum distance between two parallel straight lines between which the rock can just pass.

z - the sieve size, i.e., the smallest square hole through which the rock can pass through with optimum orientation.

The ratio l/d is known as the aspect ratio of the rock and describes the degree to which it is elongate. Due to its simplicity and objectivity, it is one of the most commonly used measurement-based shape descriptors. It cannot, however, distinguish between tabular and simple elongate rocks. To do this, the z/d ratio is necessary. However, the objective measurement of z is not practical for heavy armour rocks, and the l/d ratio is usually used in isolation. In practise, according to the CIRIA/CUR manual, this is not a significant problem, since the most important factor is the divergence of the rock shape from the equant form. Equant rocks (i.e., those whose axial dimensions are approximately equal) are easier to handle, and, more importantly, less likely to break than elongate rocks. Elongate rocks will result in more variability in layer thickness, since their long axes can be placed with a variety of orientations (see Section 2.3). Research has also suggested that the stability characteristics of equant and elongate rocks are different (see



Section 2.4). For these reasons it is usual to impose a limit, typically 5%, on the number of rocks in the layer with aspect ratios of greater than 3.

Whilst axial measurement can provide an adequate description of the gross dimensions of the rocks, it provides no information on whether the rocks are angular or rounded. Angularity and roundness describe how well the faces of the rock are defined. On angular rocks, the faces are bounded by sharp edges and corners, whilst on rounded rocks the edges and corners are less acute. The CIRIA/CUR manual recommends that armour rocks should be "predominantly angular" and that rocks that are "too rounded or spherical for stability" should be excluded from armour layers. Axial measurement is therefore often supplemented by visual comparison with archetypal shape categories. Figure 2.1 reproduces the shape categories given in the 1991 edition of the CIRIA/CUR manual. These classifications describe the angularity of the rocks as well as their aspect ratios. The first three categories in Figure 2.1, ET, IR and EQ, describe rocks of simultaneously decreasing angularity and aspect ratio. Most heavy armour rock falls into one of these three categories. The two remaining categories, SR and VR, describe only the angularity of the rocks and do not set limits on their aspect ratios. Rocks in these categories have worn or crushed edges, smooth surfaces and are less likely to be used as heavy armour.

Each shape category in Figure 2.1 has an associated Fourier Asperity Roughness parameter,  $P_R$ . This parameter is based upon a Fourier analysis of the outline of a random projection of the rock, as described in Latham and Poole (Ref. 2.7). It ranges from 0.005 for the VR category to 0.017 for the ET category, as follows:

ET 0.017 IR 0.014 EQ 0.012 SR 0.010 VR 0.005

The value of  $P_R$  is usually determined by visual comparison with the shape categories given in Figure 2.1. In 1996, the CIRIA/CUR manual was updated and incorporated in the CUR/RWS manual (Ref. 2.5). It reproduced most of the information on rock shape contained in the 1991 issue.

Another commonly used shape categorisation method is Powers' scale of roundness (Ref. 2.8), reproduced in Figure 2.2. This method describes only the angularity of the rocks and does not consider their aspect ratios. The two most round categories in Powers' scale, Rounded and Well Rounded, correspond approximately to the SR and VR categories of the CIRIA/CUR method. Similarly, Powers' intermediate categories of Sub-angular and Sub-rounded correspond approximately to the EQ category from CIRIA/CUR, whilst Powers' Angular corresponds to IR in the CIRIA/CUR system. There is no equivalent to the ET category in Powers' system.

#### 2.3 Armour porosity and layer thickness

#### 2.3.1 Introduction

The relationship between the total armour layer thickness and the dimensions of the rocks that form it is generally expressed in terms of a layer coefficient,  $k_t$ , thus:

 $t = n \ k_t \ D_{n50}$ 

Where t is the total layer thickness (m) n is the number of layers  $k_t$  is the layer coefficient  $D_{n50}$  is the nominal rock diameter (m) (2.1)



The nominal rock diameter,  $D_{n50}$ , is given by:

$$D_{n50} = (M_{50}/\rho_a)^{1/3}$$
(2.2)

Where  $M_{50}$  is the mass not exceeded by 50% (by weight) of the batch (t)  $\rho_a$  is the density of the armour rock (t/m<sup>3</sup>)

The armour void porosity,  $n_v$ , describes the proportion of voids in the armour layer, and is given by:

$$n_v = 1 - \rho_b / \rho_a \tag{2.3}$$

Where  $\rho_b$  is the bulk (or "as placed") density of the armour layer (t/m<sup>3</sup>)

#### 2.3.2 Existing guidelines

#### **Shore Protection Manual**

The 1977 Shore Protection Manual provides the following guidelines for  $k_t$  and  $n_v$ , both of which were assumed to be primarily a function of rock shape:

| Rock shape | n | Placement | k <sub>t</sub> | n <sub>v</sub> |
|------------|---|-----------|----------------|----------------|
| smooth     | 2 | random    | 1.02           | 0.38           |
| rough      | 2 | random    | 1.15           | 0.37           |

(from Table 7-11 of 1977 SPM)

These values were determined experimentally. The terms "rough" and "smooth" can be assumed to correspond to the more commonly used terms "angular" and "rounded", as defined in Figure 2.1. The placement in each case was described as "random", meaning that the orientation of the rocks was not controlled.

The most significant inference to be drawn from these guidelines was that rough / angular rocks formed relatively thicker layers than smooth / rounded rocks. The relationship between rock shape and armour void porosity appeared to be insignificant.

In the 1984 issue of the Shore Protection Manual, the following revised values were presented:

| Rock shape     | n | Placement | k <sub>t</sub>  | n <sub>v</sub> |
|----------------|---|-----------|-----------------|----------------|
| smooth         | 2 | random    | 1.02            | 0.38           |
| rough          | 2 | random    | 1.00            | 0.37           |
| parallelepiped | 2 | special   | $t > 2 D_{n50}$ | 0.27           |

(from Table 7-13 of 1984 SPM)

The layer thickness coefficients for "rough" rocks were revised downwards to be almost equal to those for "smooth" rocks, although the porosity values remained unchanged. A new shape category, described as "parallelepiped", i.e., a six-sided shape on which all opposite sides are similar and parallel, had also been added. No specific value of  $k_t$  was recommended for such rocks. Instead, the layer thickness was said to be twice the average long dimension of the stones. The placement method was given as "special", which, considering the description of layer thickness, presumably meant that the rocks should be placed so that their long axes were normal to the plane of the slope. This would obviously result in each layer having a thickness of greater than  $D_{n50}$ , i.e.,  $k_t > 1$ . The resulting layer porosity, at only 0.27, was very low.

The Shore Protection Manual is due to be superseded in 2003 by the Coastal Engineering Manual (Ref. 2.19). A draft copy of the new manual reproduces the advice given in the 1984 issue of the Shore Protection Manual.

#### **British Standard 6349**

The 1991 British Standard 6349 for maritime structures made the following recommendations:

| n | k <sub>t</sub> | n <sub>v</sub> |
|---|----------------|----------------|
| 2 | 1.00*          | 0.37**         |
| 1 | 1.15*          | -              |
|   | (0)            |                |

(\*from Section 4.3.5 of BS 6349)

(\*\*from Table 5 of BS 6349)

The rock shape was given as "rough angular" and the placement method as "random". For a double layer, the data are therefore identical to those given by the 1984 version of the Shore Protection Manual for "rough" rocks. For the first time a specification was given for single layers, i.e., n = 1, suggesting that single layers should have higher  $k_t$  values than double layers.

#### The CIRIA/CUR Rock Manual

The 1991 issue of the CIRIA/CUR manual provided the following detailed guidelines for layer thickness and porosity:

| Rock shap<br>classificat | pe<br>tion | Placement<br>type | Above/below<br>water | k <sub>t</sub> | n <sub>v</sub> |
|--------------------------|------------|-------------------|----------------------|----------------|----------------|
| angular                  | IR         | (b) + (d)         | Above                | 1.20           | 0.39           |
| -                        |            | (b) + (e)         | Above                | 1.05           | 0.39           |
|                          |            | (c) + (f)         | Above or below       | 0.75           | 0.40           |
|                          | EQ         | (b) + (d)         | Above                | 1.15           | 0.37           |
|                          |            | (b) + (e)         | Above                | 1.00           | 0.37           |
|                          |            | (c) + (f)         | Above or below       | 0.80           | 0.38           |
| rounded                  | SR         | (b) + (d)         | Above                | 1.25           | 0.36           |
|                          |            | (b) + (e)         | Above                | 1.10           | 0.36           |
|                          |            | (c) + (f)         | Above or below       | 0.75           | 0.37           |
|                          | VR         | (b) + (d)         | Above                | 1.20           | 0.35           |
|                          |            | (b) + (e)         | Above                | 1.05           | 0.35           |
|                          |            | (c) + (f)         | Above or below       | 0.80           | 0.36           |

(from Table 20 of 1991 CIRIA/CUR manual)

The placement types referred to in the above table are as follows:

(b) Standard method from Appendix 1 of the CIRIA/CUR manual.

(c) Random placement to achieve a high porosity for wave energy dissipation.

(d) Long axes of elongate, tabular and irregular blocks to be placed normal to the slope.

(e) Long axes of elongate, tabular and irregular blocks to be placed up-slope with short axes along-slope.

(f) Long axes of elongate, tabular and irregular rocks may take any orientation.

The data in the above table suggest that angular rocks form more porous armour layers than rounded rocks, with values of  $n_v$  ranging from 40% for IR rocks to 35% for VR rocks. The results also suggest that, if the rocks are placed with the specific intention of achieving high wave energy dissipation, a 1% increase in porosity value can obtained.

The effect of rock shape on the layer thickness seems to be inconsistent, since "irregular" and "very round" rocks have almost identical  $k_t$  values, whilst the intermediate rock shapes have either higher or lower values. The most significant influence on layer thickness coefficient appears to be the placement method. The placement methods are each defined by two variables. The first of these variables (either (b) or (c)) appears to refer to whether the rock is placed with or without control of its orientation. For (b) to apply, the orientation of the rocks must be controlled, using a grab for example. This should allow a relatively tight pack to be obtained. Appendix 1 of the manual, as referred to by method (b), specifies that each rock should be placed so that it has a minimum of three points of support in its layer. For (c) to apply, the rocks should be placed more randomly, using a crane for example. This method produces a looser and more porous pack. Another situation where (c) may apply is where the rocks are placed underwater and control over placement is less rigorous.

The second descriptor refers to the actual orientation of the rocks. In type (d) the rocks are placed so that their long axes are normal to the plane of the slope. This equates to the "special" placement method specified by the 1984 Shore Protection Manual. The resulting  $k_t$  factors are high, ranging from 1.15 to 1.25. When type (e) is applied, both the long and the short axes of the rocks will be in the plane of the slope. The intermediate axes are normal to the slope and thus effectively control the layer thickness. The resulting  $k_t$  values range from 1.00 to 1.10, and are therefore equal to or slightly higher than the 1984 Shore Protection Manual and the BS 6349 values.

Orientation type (f) is completely random, and must therefore apply when placement method (c) is used. The resulting  $k_t$  values are low, ranging from 0.75 to 0.80. These low values result from the natural tendency of rocks to lie with their short axes normal to the slope when no orientation control is applied. They might also have been intended to account for the lower placement density that could result from the overall lack of control when placing.

It was noted in the CIRIA/CUR manual that there were many areas of uncertainty in the specification of layer thickness and porosity, and in particular that the layer thickness was often over-predicted by the 1984 Shore Protection Manual method. It is interesting to note, therefore, that of all the data given, only the more random placement method produces values of  $k_t$  lower than those given by the Shore Protection Manual. It is also worth noting that when the CIRIA/CUR manual was compiled there were no published studies of layer thickness and porosity of full-scale structures. However, some hydraulic model tests (Ref. 2.20) had produced lower than expected  $k_t$  values (typically  $k_t = 0.8$ ) when no effort was made to prevent the rocks from lying with their short axes normal to the slope. This effect was particularly marked when using rocks that were non-equant. The observations prompted the advice concerning orientation type (f), as discussed above. Recognising the potential for errors to arise, the CIRIA/CUR manual recommended the use a test panel to assist in the design process. It also called for further research into the area of armour thickness and porosity to provide improved guidance.

The 1996 issue of the CIRIA/CUR manual reprinted some of the data from Table 20 of the previous manual, although it was less prescriptive on porosity and layer thickness, and again recommended the use of test panels.

#### **Other sources**

Gauss & Latham (Ref. 2.9) measured armour void porosity and layer thickness on a full-scale revetment constructed at Beesands in South Devon. (Although published in 1995 this work was too late to be incorporated in the 1996 edition of the CIRIA/CUR manual). The armour layer was formed by a double layer of rocks weighing between 3t and 7t. The authors concluded that the materials and construction methods used at Beesands were not untypical of those used on rock armoured revetments. On the basis of the measurements, Gauss & Latham recommended that a layer thickness coefficient of 0.85 and a void porosity of 0.31 would provide realistic targets for the design of similar rock armour layers. This value of void porosity is significantly lower than those quoted in the widely accepted design guides. The layer thickness coefficient is also significantly lower than those quoted in the Shore Protection Manual or BS



6349, but is approximately in the centre of the wide range quoted in the CIRIA/CUR manual. Gauss & Latham recommended that further research should be carried out on the subject, and that the collation of data from test panels would be particularly useful.

The study also highlighted the importance of standardising the survey techniques used to measure armour surface profiles. The CIRIA/CUR manual recommends that the upper surface of the armour layer should be defined by the base of hemispherical probe with a diameter equal to  $0.5D_{n50}$ . Gauss & Latham showed that any divergence from this method could cause significant differences in the measurement of the layer.

Newberry (Ref. 2.10) conducted a similar study on a revetment at Reculver. The revetment was armoured with a double layer of 1-3t rocks and had a smaller cross section than that examined by Gauss & Latham. A layer thickness coefficient of 0.94 and a void porosity of 0.34 were measured using the  $0.5D_{n50}$  diameter probe survey method . Again, the porosity is lower than the values quoted in the guidelines and the layer coefficient is within the quoted ranges. Manion (Ref. 2.11) presented a review of data collected at various rock-armoured structures on the UK coastline. On a total of 18 structures the void porosity varied between 0.29 and 0.38, with an average of 0.33, again suggesting that the design guides overestimate the porosity of armour layers. No information was provided on layer thickness or the survey methods used.

#### 2.4 Hydraulic performance

#### 2.4.1 Introduction

This section is not intended to be a complete review of rock armour hydraulics, a subject on which a great deal of research effort has been expended in the past. Instead it focuses only on those sources that have specifically addressed the issue of rock shape, packing and placement and their influence on hydraulic performance.

#### 2.4.2 Existing guidelines on armour stability

#### **Shore Protection Manual**

Some guidance on the effect of rock packing on stability comes from the 1977 Shore Protection Manual. The recommended design method is based upon the well-known Hudson formula, as follows:

$$H_s / \Delta D_{n50} = (K_D \cot \alpha)^{1/3}$$

(2.4)

Where  $H_s$  is the design significant wave height (m)  $\Delta$  is the buoyant density of the armour rock =  $\rho_a/\rho_w - 1$   $\rho_a$  is the density of the armour rock (t/m<sup>3</sup>)  $\rho_w$  is the density of the water (t/m<sup>3</sup>)  $D_{n50}$  is the nominal diameter of the rock (m)  $K_D$  is a stability coefficient that varies with the rock shape and placement method  $\alpha$  is the slope angle of the armour face

The recommended values of  $K_D$  for double layers of armour are given in the following table, for breaking and non-breaking waves:

| Rock shape     | Placement | n | K <sub>D</sub> breaking | K <sub>D</sub> non-breaking |
|----------------|-----------|---|-------------------------|-----------------------------|
|                |           |   | waves                   | waves                       |
| smooth rounded | random    | 2 | 2.1                     | 2.4                         |
| rough angular  | random    | 2 | 3.5                     | 4.0                         |
| rough angular  | special   | 2 | 4.8                     | 5.5                         |
| rough angular  | random    | 1 | -                       | 2.9                         |

(from Table 7-7 of 1977 SPM)



As can be seen, the change from smooth rounded rocks to rough angular rocks increases  $K_D$  for both breaking and non-breaking waves by 66%, which equates to an increase of approximately 20% in the design wave height. "Special" placement of the rough angular rocks increases  $K_D$  by 37%, and therefore the design wave height by approximately 10%. In this case the special placement meant that the rocks were placed with their long axes perpendicular to the face of the structure. This presumably increases the degree of interlocking between the rocks.

A value of  $K_D$  was given for single layers in non-breaking conditions only. The use of single layers in breaking conditions was not recommended. It was also specified that the single layer rocks should be carefully fitted together. The value of  $K_D$  given for rough angular rocks in a single layer is less than for a double layer.

| Rock shape     | Placement | n | K <sub>D</sub> breaking | K <sub>D</sub> non-breaking |
|----------------|-----------|---|-------------------------|-----------------------------|
|                |           |   | waves                   | waves                       |
| smooth rounded | random    | 2 | 1.2                     | 2.4                         |
| rough angular  | random    | 2 | 2.0                     | 4.0                         |
| rough angular  | special   | 2 | 5.8                     | 7.0                         |
| parallelepiped | special   | 2 | 7.0-20.0                | 8.5-24.0                    |
| rough angular  | random    | 1 | -                       | 2.9                         |

In the 1984 issue of the Shore Protection Manual, the following revised values of K<sub>D</sub> were presented:

(from Table 7-8 of 1984 SPM)

It was also recommended that, in the Hudson formula, the significant wave height,  $H_s$ , should be replaced by  $H_{1/10}$ , i.e., the average height of the highest 10% of the waves. This latter value is usually approximately 30% higher than  $H_s$ . Although, for random placement, some of the values of  $K_D$  had changed, the relative difference between rough angular and smooth rounded rocks remained, giving a 20% increase in design wave height. The difference between random and special placement, however, became more marked, suggesting increases in design wave height of 20% for breaking waves and 40% for non-breaking waves.

Results for the parallelepiped category had also been added, based on the work of Markle and Davidson (Ref. 2.12). Very high values of  $K_D$  were quoted for such rocks, provided that the special placement was observed. These values of  $K_D$  imply that an armour layer constructed in this way may withstand waves of twice the height of those that may be withstood by a conventional one. The data given for single layers in the 1977 manual was repeated in the 1984 issue.

In the draft version of the new Coastal Engineering Manual (Ref. 2.19), the advice given in the previous versions of the Shore Protection Manual is essentially repeated, although no  $K_D$  values are given for parallelepiped rocks.

#### **British Standard 6349**

The 1991 British Standard 6349 for maritime structures makes no specific recommendations on how to take account of rock packing, but cautions that stability may be reduced if the rocks are packed loosely. It does not contain any recommendations regarding the stability of single armour layers.

#### The CIRIA/CUR Rock manual

The 1991 issue of the CIRIA/CUR manual concentrates on Van der Meer's equations for the design of armour stability. These equations provide an estimate of the wave conditions that a structure may be subjected to before it sustains a particular level of damage, and are as follows:

| $H_s / \Delta D_{n50} = 6.2 P^{0.18} (S_d / \sqrt{N})^{0.2} \zeta_m^{-0.5}$  | for plunging waves   | (2.5) |
|--|--|-------|
| $\mathrm{H_s}/\Delta D_{\mathrm{n50}} = 1.0~\mathrm{P^{-0.13}}~(\mathrm{S_d}/\sqrt{N})^{0.2}~\sqrt{\mathrm{cot}}~\alpha~\zeta_{\mathrm{m}}^{\mathrm{P}}$   | for surging waves  | (2.6) |
| Where $H_s$ is the significant wave height (m)<br>$\Delta$ is the buoyant density of the armour rock = $\rho_a$<br>$\rho_a$ is the density of the armour rock (t/m <sup>3</sup> )<br>$\rho_w$ is the density of the water (t/m <sup>3</sup> )<br>$D_{n50}$ is the nominal diameter of the rock (m)<br>P is the notional permeability factor<br>$S_d$ is the damage number<br>N is the number of waves<br>$\alpha$ is the slope angle of the armour face<br>$\zeta_m$ is the Iribarren number calculated from the mean<br>$S_m$ is the wave steepness calculated from the mean<br>$T_m$ is the mean wave period (s) | $/\rho_{\rm w} - 1$<br>hean wave period = tan $\alpha / \sqrt{s_{\rm m}}$<br>an wave period = $2\pi H_{\rm s} / g T_{\rm m}^{2}$ |       |

Plunging and surging are different forms of wave attack. The transition between plunging and surging waves occurs at a critical value of  $\zeta_m$ , designated  $\zeta_{mc}$  and given by:

$$\zeta_{\rm mc} = (6.2 \ {\rm P}^{0.31} \ \sqrt{\tan \alpha} \ )^{1/({\rm P}+0.5)}$$
(2.7)

where  $\zeta_m < \zeta_{mc}$  for plunging waves

 $\zeta_{\rm m} > \zeta_{\rm mc}$  for surging waves

Van der Meer's equations are discussed in greater detail in Chapter 5 of this report. Although Van der Meer did not explicitly consider rock shape as a variable, it was noted that rounding of the rocks caused by repeated handling during the test programme may have resulted in a reduction in stability. Neither did Van der Meer's work did not allow for variations in the construction technique applied to the layer and how they might result in varying degrees of interlock between rocks or varying layer thickness.

These issues were partly addressed by Bradbury et al (Refs. 2.13 and 2.21) and Latham et al (Ref. 2.20), who recommended that Van der Meer's equations could be modified to take account of rock shape and layer thickness. Bradbury et al used individually placed rocks to form their armour layers, as opposed to the bulk placed rocks used by Van der Meer. The resulting armour layers were, surprisingly, less stable than Van der Meer's. The first modification suggested by Bradbury et al was that the term  $(S_d / \sqrt{N})^{0.2}$  in Van der Meer's equation should be changed to  $(S_d / \sqrt{N})^{0.25}$ . This was attributed to differences in the armour layer thickness; they used double layers with a typical thickness of  $1.6D_{n50}$  compared to  $2.3D_{n50}$  used by Van der Meer. Bradbury et al then determined variable coefficients in place of the values of 6.2 and 1.0 in Van der Meer's equations. These coefficients, called  $C_{pl}$  and  $C_{su}$  for the plunging and surging wave equations respectively, were found to vary with rock shape as follows:

| $C_{pl} = 5.4 + 70P_R$ | for plunging waves | (2.8) |
|------------------------|--------------------|-------|
|------------------------|--------------------|-------|

 $C_{su} = 0.6 + 40 P_R$  for surging waves (2.9)

 $P_R$  is the Fourier Asperity Roughness parameter (see Section 2.2). It describes the degree of roundness of the rocks, with low values of  $P_R$  indicating more rounded rocks. According to Bradbury et al,  $P_R$  varies with rock shape as follows:

| Elongate/tabular | $P_{R} = 0.017$ |
|------------------|-----------------|
| Irregular        | $P_{R} = 0.014$ |
| Equant           | $P_{R} = 0.012$ |
| Semi-round       | $P_{R} = 0.010$ |
| Very-round       | $P_{R} = 0.005$ |

Bradbury et al's results confirmed the suggestion that rounded rocks have lower stability levels than angular rocks. The design wave height for rocks with  $P_R = 0.017$  can be between 20% (for plunging waves) and 56% (for surging waves) higher than for rocks with  $P_R = 0.05$ . A less expected conclusion to be drawn from this work was that elongate or tabular rocks are more stable than equant ones. It was speculated that this additional stability might have arisen because tabular rocks lying with their long axis in the plane of the slope present a greater resisting moment to overturning by wave action than do equant rocks. The range of structures tested was, however, limited to low porosity structures, with P=0.1. The authors cautioned that the findings would not necessarily apply to all types of structures.

The CIRIA/CUR manual also reproduces the work of Pilarczyk (Ref. 2.14), who provides suggested modifications to the stability formulae for irregularly placed rock armour. Pilarczyk produces a stability equation in the following form:

 $H_{s}/\Delta D_{n50} = F_1 2.25 (\cos \alpha) \zeta_m^{-0.5}$ 

Where  $H_s$  is the design significant wave height  $\Delta$  is the relative density of the rock  $D_{n50}$  is the rock diameter  $F_1$  is a parameter dependent on the packing type  $\alpha$  is the structure slope  $\zeta_m$  is the surf similarity parameter based upon mean period

The intention of Pilarczyk's work was to give guidance for various types of composite armour, such as open stone asphalt, grouted stone and gabions. However, included are results for pitched stones, which are regularly shaped, very tightly packed rocks. Pilarczyk gave values of  $F_1$  of 1.33-1.5 for good quality pitching, effectively concluding that pitched rock can be up to 50% more stable, in terms of the design wave height for a given damage level, than randomly placed irregular rock.

In 1996, version of the manual contained essentially the same information on the relationships between shape, packing and stability.

#### **Other sources**

Sollitt and DeBok (Ref. 2.15) tested a single layer of parallelepiped shaped rocks, placed with their long axes normal to the armour slope. The armour layer was thus very similar to that described in the 1984 Shore Protection Manual, although the latter used a double layer. The results were very similar, in that it was reported that this method of construction produced a very densely packed and stable armour layer, with  $K_D$  values of between 23 and 29. This represents an approximate doubling of the design wave height compared to conventional armour layers.

Pilarczyk and den Boer (Ref. 2.16) reviewed measures for increasing the stability of rock armour. One suggested method was to place the rocks with their long axes perpendicular to the slope, or to place just the largest stones perpendicularly as binders. In either case the stability could be estimated by replacing  $D_{n50}$  in the stability formulae by the average of the lengths of the longest side of the stones. This may result in an increase of 50-100% in the design wave height, depending on the shape of the stones.

(2.10)

#### 2.4.3 Existing guidelines on wave energy dissipation

The effect of rock-packing on the wave energy dissipation characteristics of a rock-armoured slope is best examined in terms of run-up and overtopping. To calculate run-up on an armoured slope the roughness coefficient, r, is used. It can also be incorporated directly into the overtopping prediction methods. The roughness coefficient is the ratio of the run-up on an armoured slope to that on an equivalent smooth and impermeable slope. It takes account of both the surface roughness and the porosity of the armour layer. The 1977 and 1984 issues of the Shore Protection Manual provide the following advice on roughness coefficients for various types of armoured slopes, based on the work of Battjes (Ref. 2.17):

| Slope characteristics    | Placement | r           |  |
|--------------------------|-----------|-------------|--|
| smooth, impermeable      | -         | 1.00        |  |
| Basalt blocks            | fitted    | 0.85 - 0.90 |  |
| One layer quarrystone    | random    | 0.80        |  |
| (impermeable foundation) |           |             |  |
| Quarrystone              | fitted    | 0.75 - 0.80 |  |
| Rounded quarrystone      | random    | 0.60 - 0.65 |  |
| quarrystone              | random    | 0.50 - 0.55 |  |
|                          |           |             |  |

(from Table 7-2 of 1977 and 1984 SPM)

A slightly higher value, indicating higher run-up and hence overtopping, is given for rounded rocks than for standard rocks. This may be due to the different surface roughness rather than porosity, since armour layers formed of rounded rocks are generally considered to be more porous than those formed by angular rocks. Of more interest is the value for "fitted" quarrystone which, at 0.75 - 0.80, is considerably higher than that given for randomly placed stones. This probably represents the upper limit of the roughness coefficient for tightly packed conventional armourstone. The value given for fitted Basalt blocks is higher again. These blocks, which are columnar in shape, can be placed to provide a much denser surface than conventional rocks.

Part 1 of British Standard 6349 (Ref. 2.18) provides a method of estimating run-up on rock armoured structures but does not distinguish between different types of rock armour. The 1991 and 1996 issues of the CIRIA/CUR rock manual provided the following values for roughness coefficient.

| Type of slope  | r           |
|--|-------------|
| smooth, impermeable  | 1.00        |
| stone blocks, pitched  | 0.95        |
| stone blocks, granite sets                                   | 0.85 - 0.90 |
| one layer of stones on impermeable base                      | 0.80        |
| dumped round stones  | 0.60 - 0.65 |
| rock with total layer thickness $> 2D_{n50}$                 | 0.50-0.60   |
| (from pp 249 of 1991 and Table 5.2 of 1996 CIRIA/CUR manual) |             |

(from pp 249 of 1991 and Table 5.2 of 1996 CIRIA/CUR manual)

The information is much the same as that given in the Shore Protection Manual, since it derives mainly from the same source (Ref. 2.17). The one notable omission is that of a value for fitted quarrystone. The CIRIA/CUR manual suggests that these roughness factors can be incorporated directly in the overtopping prediction equations of Owen (see Ref. 5.3).

Van der Meer & Janssen (Ref. 5.4) provide the following updated values of roughness coefficient,  $\gamma_f$ , which can also be incorporated into overtopping prediction methods:



| Construction                    | $\gamma_{ m f}$ |
|---------------------------------|-----------------|
| smooth, concrete, asphalt       | 1.0             |
| closed, smooth, block revetment | 1.0             |
| grass (3cm)                     | 0.90-1.0        |
| one rubble layer                | 0.55-0.60       |
| two or more rubble layers       | 0.50-0.55       |
|                                 |                 |

(from Van der Meer & Jenssen)

The principal difference between these coefficients and those already given is the value for a single layer of rocks (rubble). Van der Meer & Janssen recommend a value of between 0.55 and 0.60, as opposed to 0.8. The use of roughness coefficients in the prediction of overtopping is dealt with in detail in Chapter 5 of this report.

All of the roughness coefficients quoted above were determined on armour layers that were themselves porous but that were placed on effectively impermeable structures, such as clay dikes. The have, on occasion, been applied to armour layers placed on permeable structures. This has probably produced a conservative estimate of overtopping.

#### 2.5 Discussion

#### 2.5.1 Armour layer geometry

The Shore Protection Manual and BS6349 are in reasonable agreement that the layer coefficient for a double layer of rock armour should be between 1.00 and 1.02. They also agree that the armour layer porosity should be between 37% and 38%.

The CIRIA/CUR manual gives more complex advice; layer porosity ranges from 40% to 35%, depending on the roundness of the rocks. Rounder rocks are said to produce less porous layers. The CIRIA/CUR manual quotes high values of  $k_t$  (up to 1.25) for rocks that are placed with their long axis normal to the slope of the structure. Such layers must be similar to those formed by 'specially placed' parallelepiped rocks, as described in the Shore Protection Manual. It is very unusual to place rocks in such a manner in the UK and Europe, so the quoted values of little interest to the current study. The CIRIA/CUR manual's advice on more conventional types of placement suggests that rocks that are placed in such a way that their short axes are prevented from lying normal to the slope produce layers with  $k_t$  values of between 1.00 and 1.10. This requires a reasonable degree of orientation control during placement. Rocks that are more randomly placed tend to lie naturally with their short axes normal to the slope and form layers with  $k_t$ values of between 0.75 and 0.80. The quoted differences in porosity resulting from the two methods of placement are however, only 1%. Such information is difficult for a designer to interpret and apply.

The field data that has become available since 1995 suggest that most of the sources overestimate the porosity and the layer coefficients. Measured layer porosity on real structures is typically between 30% and 35% rather than between 35% and 40%. Measured layer coefficients are generally less than 1.0. These discrepancies probably arise because the recommendations do not properly take account of variations in rock shape and placement method. It was therefore proposed that the current study should conduct a series of trial constructions (at both model and full-scale) with carefully controlled rock shapes and placement methods. The tests should cover all the variations in these parameters that are likely to be encountered on real structures. It was hoped that systematic variations in armour porosity and layer thickness could be related to the rock shapes and placement methods.

#### 2.5.2 Armour layer stability

The Shore Protection Manual recommends the use of Hudson's equation to design armour layers for stability under wave attack. The only reference to rock shape is the quotation of different values of stability coefficient  $K_D$  for 'rough angular' and 'smooth rounded' rocks. The individual placement of

rocks (as opposed to bulk placement) is not addressed, other than the case of the rarely used 'special' placement method. The vast majority of designs that use Hudson's equations will therefore simply use the  $K_D$  values recommended for 'rough angular' rocks, with little consideration given to rock shape or placement method.

Neither does the method of Van der Meer consider individual rock placement. This issue was examined by Bradbury et al, who, rather surprisingly, found that individually placed layers under-performed compared to Van der Meer's equations. This counter-intuitive result was attributed to the fact that the individually placed layers were thinner than the bulk-placed layers. Other researchers, such as Pilarczyk and den Boer, found that careful placement of certain rocks to act as binders in the layer could substantially increase armour stability.

There is clearly a lack of information on the stability of individually placed armour layers. Since this is how the majority of heavy grade armour layers are constructed, further research was considered to be imperative. A series of tests was therefore proposed to investigate the stability of such layers with careful control of rock shape and placement method.

The only guidance available on single armour layers, was a  $K_D$  coefficient for non-breaking waves and a recommendation that single layers are not used in breaking wave conditions. This limits the use of single layers considerably. It was therefore decided that the test programme should include single layers and that they be tested in a wide range of conditions.

#### 2.5.3 Wave energy dissipation

It is suspected that increasing armour stability by tightly packing the rocks may also cause the layer to be less effective at dissipating wave energy, causing increased run-up and overtopping. These quantities are generally accounted for by a roughness coefficient. Although different values are given for rounded and angular rocks, no account is taken of packing density. The hydraulic model tests were therefore designed to allow overtopping discharges to be measured and, from these, to infer roughness coefficients for densely packed armour layers.

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# 3. ARMOUR LAYER GEOMETRY – FULL SCALE TESTS

## 3.1 Introduction

This chapter describes the results of Phase 1 of the project, the full-scale construction tests. The full-scale tests were completed between July and October of 1999. The scope of the work described in the original Project Implementation Plan (Ref. 3.1) was exceeded, as four trial constructions were carried out, rather than the three that were originally proposed. In addition, a further set of results was made available from similar tests that had been conducted by Newberry (Ref. 2.10), then of Queen Mary & Westfield College, at Reculver, Kent in 1999. Newberry's work provided the template for the current study by defining the important parameters involved in the interdependency of rock shape, placement method and armour layer geometry, as well as developing the experimental and analysis techniques.

# 3.2 Objectives of Phase 1

The objective of Phase 1 of the project was to investigate the dimensional properties of rock armour layers at full-scale. Specifically, it was intended that the following parameters should be measured:

- Armour layer thickness coefficient, k<sub>t</sub>
- Armour layer bulk density,  $\rho_b$
- Armour layer porosity, n<sub>v</sub>

The influence of the following parameters were investigated:

- Rock shape
- Rock size
- Rock placement method
- Number of layers

The results of Phase 1 were used in conjunction with the results of Phase 2, i.e., the geometric model scale tests, to provide improved guidance for designers who are required to estimate the dimensional properties of armour layers.

# 3.3 Construction schedule

Four trial constructions were carried out by Dean & Dyball Ltd. specifically for this project; two were on coastal sites and two were in the source quarries. Each trial construction was completed in a single day. The schedule was as follows:

| • | Coastal site at Shoreham, Sussex        | 21 <sup>st</sup> July, 1999     |
|---|---|---------------------------------|
| • | Bardon Hill quarry, Leicestershire      | 2 <sup>nd</sup> September, 1999 |
| • | Coastal site at Immingham, Lincolnshire | 15 <sup>th</sup> October, 1999  |
| • | Torr Works quarry, Somerset             | 21 <sup>st</sup> October, 1999  |

In addition, data were made available from an earlier study carried out by Queen Mary and Westfield College:

• Coastal site at Reculver, Kent

January - February 1999

The Reculver tests were carried out on a revetment that eventually formed a permanent part of a coastal defence structure.

The principal features of the trial constructions are summarised in Table 3.1. At each of the trials conducted specifically for the project, both single and double layer revetments were constructed. The

slope of the revetments was 1:2. This slope was chosen as being typical of the structures that are commonly constructed in the UK and was maintained as a constant throughout the field tests. Three types of placement plant were used, a three-point grab, a bucket and an orange-peel grab. The three-point grab was used on the trials with the 3-6t and 8-12t rocks (i.e., the Shoreham, Bardon Hill and Torr Works trials) whilst the bucket was used on the single trial at Immingham with the 500kg rocks. The orange-peel grab was used at Reculver only, with the 1-3t rocks. These methods are consistent with the way in which the variously sized rocks would be placed on real structures. When investigating double layer structures, two packing approaches were used. Further details are given in Section 3.5, which describes the construction of the armour layers. Single layer structures were built to a single packing density only, again to reflect standard construction practice.

The first trial was carried out at Shoreham, where Dean & Dyball were in the process of constructing a series of rock groynes as part of ongoing coastal defence work. A batch of the 8-12t rocks that were to be used in the groynes was set aside and individually weighed on a portable weighbridge. The plant that was present on site (a 75t excavator equipped with a three-point grab) was used to build the test panels. The rock was syenite, from Larvik Armourstone's quarry in Norway. This rock is characterised by the tendency of individual blocks to have a rectangular (or 'blocky') shape (see Plate 3.1). Single and double layers were constructed. On the double layer revetment, both placement methods were used in an attempt to achieve variation in the packing density. Plate 3.5 shows the surface of the finished double layer revetment (dense pack).

The second trial was carried out at the Bardon Hill quarry of Bardon Aggregates, using a batch of individually weighed 3-6t granite rocks (Plates 3.2 and 3.6). These were more irregular in shape than the Larvik rocks used in the first trial. Again, placement was by three-point grab, this time with a 35t excavator, and two packing approaches were investigated in the double layer revetment.

The third trial was carried out at Immingham, where 500kg Larvik Armourstone rocks were being used to construct a new revetment. As at Shoreham, a selection of rocks was set aside and individually weighed for use in our project. The rocks (Plate 3.3) were more irregular in shape than those used at Shoreham. Being considerably smaller, they were placed using a bucket rather than a grab, again using the 35t excavator (Plate 3.7). Only one packing density was attempted, since a bucket cannot manipulate rocks as easily as a grab.

The final trial was conducted at the Torr Works quarry of Foster Yeoman Ltd. Limestone rocks of 3-6t were used (Plates 3.4 and 3.8). Placement was by three-point grab on the 35t excavator and two packing densities were attempted on the double layer revetment.

The earlier trial at Reculver was slightly different from the other four, in that the test panel was part of a permanent structure and could therefore be built to one specification only. It was a double layer of 1-3t rocks, placed by an orange-peel grab (Plate 3.9).

# 3.4 Rock specifications

Specifications of the batches of rock used in each trial are given in Table 3.2. The following information is provided for each batch:

| Total mass      | The total mass of rocks in the batch (t)   |
|-----------------|--|
| $\rho_a$        | The density of the rocks $(t/m^3)$   |
| M <sub>50</sub> | The mass not exceeded by 50% (by weight) of the batch (t)                              |
| M <sub>85</sub> | The mass not exceeded by 85% (by weight) of the batch (t)                              |
| M <sub>15</sub> | The mass not exceeded by 15% (by weight) of the batch (t)                              |
| $M_{85}/M_{15}$ | The ratio of $M_{85}$ to $M_{15}$ for the batch  |
| l/d             | The average (by number) l/d ratio of all the rocks in the batch, where l and d are the |
|                 | longest and shortest dimensions of each rock respectively                              |

| l/d>3            | The proportion (by number) of rocks which have I/d ratios of greater than 3                 |
|------------------|---|
| D <sub>n50</sub> | The nominal diameter of the batch = $(M_{50}/\rho_a)^{1/3}$ (m)                             |
| Block shape      | The typical block shape estimated by visual inspection of the batch, according to the shape |
| -                | classifications given in the CIRIA/CUR Rock Manual (Ref 3.3) and reproduced as              |
|                  | Figure 2.1.   |

The values of  $M_{50}$ ,  $D_{n50}$  etc. given in Table 3.2, refer to the entire batch of rock provided for each trial. However, where sub-sets of the batch were used, then the values of  $M_{50}$ ,  $D_{n50}$  etc used in all the subsequent calculations are those of the sub-set only. The values of  $M_{85}/M_{15}$  given in Table 3.2 indicate that all the rock batches used fell within the definition of narrow or 'single sized' graded armour stone given in the CIRIA/CUR Rock Manual (Ref. 2.4), i.e.,  $M_{85}/M_{15} < 2.7$ .

The shape classification methods described in Chapter 2 of this report were applied to the rocks. On site, with heavy armour rocks, the only practicable methods of shape classification are visual inspection and measurement of the principal dimensions. The average l/d ratio for each batch is given in Table 3.2. These are typical of armour grade rocks, in that they are between 2.0 and 2.5. The rock used for the Shoreham trials had the highest average l/d ratio, at 2.30, and the greatest proportion, at 10.1%, of rocks with l/d ratios of greater than 3. The Torr Works rocks had the lowest average l/d ratio, at 2.01, with no l/d values of greater than 3.

Chapter 4 of this report, which describes the scale model tests, contains more detailed information on the shape and size distributions of the batches of rocks used in the field trials. The chapter also provides some information concerning the 'blockiness' characteristics of the rocks used in the field trials. Blockiness, as described by Newberry (Ref. 2.10), is a quantitative measure of the degree of roundness of the rocks and was discovered, during the model tests, to have a significant influence on the characteristics of armour layers. Further details are given in Section 4.4.5.

The rocks were compared with the shape classifications given in Figure 2.1. All were judged to belong to the 'angular' group of categories. Within this group, the Shoreham and Reculver rocks were classified as 'equant' in shape. The Bardon Hill and Torr Works rocks were classified as 'irregular' in shape. The Immingham rocks were judged to be a combination of both shape categories. These classifications were attributed on the basis of visual inspection only, before any measurements were taken. There are some contradictions between the visual judgement and the axial measurements. For example, the l/d data show that the Shoreham rocks were clearly the most elongate, yet they were visually classified as 'equant'. This highlights the problems inherent in block shape classifications that involve subjective judgements.

# 3.5 Test procedures and measurements

# 3.5.1 Underlayer construction

The first stage of each trial was the construction of a plane 1:2 slope to represent the underlayer on which the armour layer would be placed. A horizontal area was also prepared at the toe of the slope.

# 3.5.2 Rock armour weighing and measurement

Each rock was weighed individually and marked with a reference number so that it could be identified during the construction process. A sample of the rocks was measured using a steel tape to determine the average l/d ratio of the batch.

## 3.5.3 Rock armour placement

The approach to rock placement at each trial was dependent upon the plant used and the number of layers in the structure. When placing with a grab, the plant operator has a greater degree of control over the packing density than when placing with a bucket. The tests that used a grab to place the rocks therefore provided the opportunity for two types of packing to be investigated. In the least stringent method,

referred to as *standard* packing, the rocks were placed with a minimum of orientation control. Each rock was placed with the orientation that it had naturally adopted in the stockpile. The only placement criterion that had to be satisfied was that the rock should have a minimum of three points of contact in the layer in which it was placed. Only if three points of contact could not be achieved with the rock's natural orientation, was the rock rotated. It thus equated to the placement type (b) recommended by the CIRIA/CUR manual as discussed in Section 2.3.2 of this report. In the more stringent method, referred to as *dense* packing, full orientation control was applied. The rocks were rotated until the orientation that was likely to produce the maximum number of points of contact in the layer, and the minimum volume of voids, was achieved. The rock was removed and replaced several times if necessary. This packing approach thus exceeded the standards specified by the CIRIA/CUR manual. It was intended to replicate construction situations in which a particular effort is made to minimise voids, such as on the crest of structures. In both types of packing care was taken to ensure that no individual rock projected excessively from the armour layer. The test that used a bucket to place the rocks used standard packing only.

Single armour layers must, in general, be packed tighter than double armour layers, since particular care must be taken to protect the filter layer and core. The single layers were therefore, with the exception of the Immingham test, built using the dense packing method only. The Immingham test panel was placed by bucket and could not therefore use the dense packing method.

Rock placement during the Shoreham and Bardon Hill tests was supervised by engineers from High Point Rendel and Posford Duvivier respectively, along with Dean & Dyball staff. At the remaining two trials, placement was supervised by a Dean & Dyball engineer. In all cases the placement plant was operated by the same Dean & Dyball operator, who was extremely experienced in coastal construction work. The packing methods were intended to replicate those typically used on revetment structures in the UK.

As mentioned in Section 3.5.2, each rock was assigned a reference number when it was weighed. The reference number of each rock was noted as it was placed, allowing the total mass of rock that went into each layer of the structure to be calculated. This also allowed precise values of  $M_{50}$  and  $D_{n50}$  to be calculated for each layer of the structure.

At either end of each panel a series of 'shuttering rocks' were placed to provide support against which the first and last rocks in the panel could be placed. These shuttering rocks were not considered as part of the revetment in the determination of the panel weight or volume, but provided a method of eliminating edge effects from the calculation of as-placed density and porosity. The revetment could therefore be considered as part of a longer run of structure.

## 3.5.4 Surveying

All surveying was carried by using a total station EDM. The underlayer was first surveyed using a standard survey staff on a 2m x 2m grid. The underlayer was always re-surveyed after the test panel was dismantled to determine if any compaction had occurred during rock placement.

The surfaces of the armour layers were surveyed using a survey staff fitted with a hemispherical probe with a diameter of  $0.5D_{n50}$ . Traverses of the armour layer were generally taken at 2m intervals along the crest of the revetment. 1m intervals were used in the case of the smaller Immingham test panel. The distance between points in the traverse was 1m measured horizontally, as shown in Figure 3.1. In addition, as Figure 3.1 shows, care was taken to ensure that the first and last high points in the traverse were included in the survey. After surveying the surface of the armour layer with the hemispherical probe, additional points were surveyed at the toe and crest of the revetment using the standard survey staff. These measures ensured that the volume and cross sectional area of the armour layer was accurately described by the survey results.

# 3.6 Data analysis

## 3.6.1 Rock specifications

For each batch of rock, grading curves were determined from the individual rock weight data and values of  $M_{50}$ ,  $D_{n50}$  etc calculated. Full details of the rock batches can be found in Section 4.7. The record of rock reference numbers also allowed the calculation of these parameters for the subset of rocks that went into each layer of the structure. The total mass of rock in each layer was also determined.

## 3.6.2 Armour layer properties

The survey data were converted into 3-dimensional models of the test panels using the digital surface mapping software 'Surfer' (Ref. 3.2). Surfer was used to fit 3-D surfaces to the co-ordinate data acquired during the surveys of the underlayer and armour layers. Figures 3.2 and 3.3 show examples of the 3-D surfaces generated to represent the underlayers and armour surfaces respectively.

Surfer includes routines for the calculation of volumes described by 3-D surfaces. These were used to estimate the as-placed volume of each test panel. The bulk density,  $\rho_b$ , of the armour layer could then be readily calculated, given that the total mass of rock in the layer was known. Also calculated was the porosity,  $n_v$ , of the armour layer, given by:

$$n_v = 1 - \rho_b / \rho_a$$

The porosity describes the proportion of the bulk volume of the armour layer that is taken up by the voids. The intact rock density,  $\rho_a$ , was obtained from the quarry records.

Surfer can also be used to determine cross sections of the 3-D surfaces that it generates, such as that shown in Figure 3.4. This facility was used to determine sections of the armour layers from which the layer thickness, t, could be measured. Up to six sections were taken for each test panel. For each section, a layer thickness was calculated by converting the Surfer section data to 'Excel' spreadsheet format and applying a purpose-written macro. The layer thickness was measured normal to the slope of the revetment, and over the main part of the slope only, so that end effects would be ignored, as shown in Figure 3.5. The layer thickness of the revetment was taken to be the average of those measured at each section.

The relationship between layer thickness and rock dimensions is generally expressed in terms of a layer coefficient,  $k_t$ , thus:

 $t = n k_t D_{n50}$ 

Where t is the layer thickness (m) n is the number of layers

An average layer coefficient was thus calculated for each structure.

# 3.7 Results

Tables 3.3, 3.4 and 3.5 summarise the results in terms of layer coefficient, as placed density and porosity, for the single layer, double layer (standard pack) and double layer (dense pack) respectively.

Significant variations in porosity, and hence in as-placed density, were observed. The heavy, grab-placed rock consistently produced denser and less porous armour layers than the lighter, bucket- placed rock. Using a standard pack, the former produced armour layers with porosities of between 30.0% and 34.8%, compared with 39.2% to 40.0% produced by the latter. This tendency was observed in both the single and double layer revetments.

(3.2)

(3.1)

Amongst the heavy, grab-placed rock, the 8-12t Larvik armourstone used in the Shoreham trial produced the least porous structures. Here, a minimum porosity of 27.6% was achieved. The lowest density achieved at the other heavy grab-placed rock trials was 30.9%. The porosity produced by the grab-placed rocks, using a standard approach to packing, averaged approximately 34% for single and double layer structures. The equivalent result at Shoreham was 30%. These differences are believed to be due to the rectangular shape of the Shoreham rocks. The Bardon Hill, Torr Works and Reculver rocks were more irregular in shape. There was no marked relationship between rock size and resultant porosity amongst the heavy, grab-placed rock.

The two approaches to packing produced relatively small changes in armour layer density. In the Shoreham and Bardon Hill trials, when a dense pack was attempted, the porosities reduced from 30.1% to 27.6% and from 32.8% to 30.9% respectively. These changes represent reductions of less than 10% in the volume of voids in the armour layer. In the Torr Works test, no significant reduction in porosity was achieved by the dense packing approach.

The layer coefficient tended to vary in accordance with the porosity, with the highest values occurring for small bucket-placed rock and the lowest for the large grab-placed rock. The highest layer coefficients were measured at the Immingham trial (up to 1.03). The lowest layer coefficients (0.71 to 0.77) were obtained during the Shoreham trials. The other large, grab-placed rock produced layer coefficients of between 0.80 and 0.94, with averages of 0.81 for single layer and 0.89 for double layer structures. Again, these differences are believed to be a function of the rock shape. It may also be significant that the Shoreham rocks were the most elongate of the three batches (see Table 1). The Bardon Hill, Torr Works and Reculver results should be regarded as more typical of large grab-placed rock armour generally.

## 3.8 Conclusions

It was not the intention of Phase 1 of the project to provide definitive values of layer thickness, density or porosity. Phase 2, i.e., the dry scale model tests described in the following chapter, will investigate the important parameters over a wider range and in more detail. Comparisons with results of Phase 1 will provide information on scale effects. Some preliminary conclusions can, however, be made.

The CIRIA/CUR Rock Manual provides limited guidance on porosity,  $n_v$ , suggesting that typical values of between 35% and 42% should be used for narrow graded armour layers. The results of Phase 1 of this project suggest average values of  $n_v$  of 34% for large, grab-placed rock and 40% for lighter bucket-placed rock. These results apply to single and double armour layers made up of irregular shaped armour rocks. When the rocks are of an unusually rectangular nature, such as those used at Shoreham, and placement is by grab, then a lower porosity armour layer, of say 30%, can result. If a special effort is made to achieve a dense pack for aesthetic or safety reasons then the porosity may be reduced by a further 2%.

The latest version of the Rock Manual makes no definitive recommendation of values of layer coefficient,  $k_t$ . The results of Phase 1 of this project suggest that for large, grab-placed, irregular rock, values of between 0.82 and 0.92 can be expected for single and double layers. Values as low as 0.71, however, were obtained with particularly rectangular shaped rock. Lighter, bucket-placed rock produced values of between 0.92 and 1.03.

# 3.9 References for Chapter 3

- **3.1** Packing and Voids in Rock Armour for Breakwaters, Project Implementation Plan, DETR Partners in Innovation Scheme : Contract Reference 39/126 cc1831, HR Wallingford, 1999.
- **3.2** Surfer Version 7, Contouring and 3-D surface mapping for scientists and engineers, Golden Software Inc., 1999.



# 4. ARMOUR LAYOUR GEOMETRY - MODEL SCALE TESTS

## 4.1 Introduction

This chapter describes Phase 2 of the study, the dry model tests. The tests were intended to investigate the geometric properties of rock armour layers. They involved the construction of model rock armour panels at HR Wallingford's laboratory facilities. In some cases the models replicated the full-scale test panels constructed during Phase 1, thus permitting an investigation of model scale effects. Other tests used models that represented generic rock structures, and concentrated on investigating particular rock properties, such as shape or size distribution. The dry model tests therefore allowed the range of parameters studied in the full-scale tests to be expanded upon. Boskalis Zinkcon Ltd gave permission for batches of rocks prepared for a previous study to be used in the tests.

# 4.2 Packing density of rock particulates

The packing density of rock armour is closely related to the more general problem of the packing of particulates. A considerable amount of research work has been carried out in this area, examining particulates that ranged in size from powder, through sand and gravel, to boulder sized rocks. A review of this work can be found in Newberry (Ref. 2.6). The factors that influence the packing density of a particulate are generally taken to be as follows:

- Absolute particle size
- Particle size distribution
- Particle shape distribution
- Surface roughness of material
- Strength of material
- Durability of material
- Deposition history
- Loading history
- Boundary effects

Most of the experimental work that investigated the influence of these parameters involved the measurement of the bulk densities of particulates in the laboratory or in the field. The standard methods for measuring the bulk density of particulates generally involve weighing the material contained within a known volume, for example within a cylinder of standard dimensions. When the dimensions of the particles are small compared to the size of the container, the boundary effects, i.e., the influence of the zone where the particles are in contact with the wall of the container, are small. Where the particles have a significant size compared to the container, however, boundary effects are significant. The information arising from such tests is therefore of little value when considering rock armour layers, which are only one or two rocks thick and where boundary effects are important. Furthermore, these methods do not consider the possibility of individual particle placement, as opposed to bulk placement.

Particulate packing prediction models have been developed using analytical and semi-analytical methods, with varying degrees of success (Ref. 2.6). Such models do not generally consider either boundary effects or the effect of individual particle placement. More recent work has concentrated on discrete element numerical models, i.e., models that consider the properties and behaviour of individual particles rather than of the bulk material. These methods show potential for modelling particle packs with boundary effects and individual placement. They do however, assume relatively simple particle shapes, such as spheres or ellipsoids. Although recent advances using 3D scanning of rock particles may ultimately allow realistic armour layers to be modelled, these techniques have not reached an advanced state of development. Physical modelling still offers the most appropriate way of providing accurate information on the geometric properties of rock armour layers.



# 4.3 Potential sources of geometric scale effects in model armour layers

The usefulness of the output of this project, as with any that is based upon physical model tests, depends to a large extent on the minimisation of scale effects. One obvious potential source of scaling error is the crushing of material at points of contact between rocks, since the contact stresses are greater in the prototype layer than in the model layer, whilst the compressive strength of the rock is the same in both. If this occurs, it is likely to make full-scale layers more dense that model ones. Since it is impractical to construct model layers from materials with a reduced compressive strength, this scale effect is unavoidable. However, observations of the construction of the full-scale test panels suggest that the amount of material lost due to local crushing is extremely limited, and would appear to have very little effect on the geometry of the layer. A difference in friction coefficient between the model and prototype rock surfaces is another scale effect that cannot realistically be avoided. However, surface friction is likely to be a significant factor only if the model rocks are excessively smooth. No such rocks were used in the models.

The other potential sources of error may be regarded as model effects rather than scale effects, since they are not inherent to the modelling method, but rather are a result of the way in which it is applied. One of these is the degree to which rocks can be manipulated as they are placed in the layer. When constructing a model layer it would be possible, for example, to manipulate several rocks simultaneously or to apply unrealistic levels of pressure to achieve a very dense pack. To avoid this, the methods of placement were carefully specified and controlled, as outlined in Section 4.7 of this chapter. The aim of the specifications was to try to replicate the placement methods used on the prototypes as closely as possible.

It was suspected that the most likely model effect would be the shape of the individual rocks, since small rock fragments tend to have different shapes than large rock fragments. The large rock fragments (with masses of between 1t and 15t) used in armour layers tend to be formed by breaks along the natural joint planes which occur during the blasting process. Small rock fragments used in laboratory studies (generally less than 1kg in mass) are the result of rocks that have been passed through crushing machines. These latter rocks tend to be more irregular in shape. To minimise this effect, a great deal of care was taken in classifying the shapes of the individual rocks, and in ensuring that the shapes of the model and prototype rocks were as closely matched as possible. This procedure is described in Sections 4.4 and 4.7 of this chapter.

# 4.4 Assembly and categorisation of rocks for model tests

# 4.4.1 Introduction

The first stage in the modelling process was the assembly and categorisation of a collection of rocks. Approximately 1300 limestone rocks were collected from crushed and graded sources. The rocks were categorised according to mass (Section 4.4.2) and shape (Sections 4.4.3 to 4.4.5). The shapes of the rocks were classified by visual comparison with archetypal shape categories and by direct measurement of their axial dimensions. The former method has the disadvantage of involving a subjective judgement on the part of the tester. It can however help to distinguish between rocks of very different shapes in circumstances where axial measurement cannot. A third method of categorisation, blockiness estimation, was developed during the course of the study. This is a shape descriptor based on measurement, as described in Section 4.4.5.

It was important that the rock collection was sufficiently comprehensive to allow the batches of rocks used in the field tests to be properly reproduced (in terms of rock shape and relative size) at model scale. Furthermore, it was our intention to use a wider range of rock characteristics in the models than were used in the prototype, in order that trends could be determined. To assist in the process of rock selection, each rock was given an identifying code number, against which its important characteristics were recorded. This allowed batches of rocks with precisely defined masses and shape parameters to be selected for constructing the models.



# 4.4.2 Mass distribution of the model rocks

Each rock was individually weighed to the nearest 0.5g. The rocks ranged in mass from 100g to 550g, with a mean of 290g. Figure 4.1 shows the mass distribution of the model rock collection. The absolute mass of the rocks was not important, since the scale of the structure-specific models could be adjusted to suit the materials available. Furthermore, it was not necessary to use the same geometric scale for each model. The grade width of the rock collection, i.e., the variability of mass, was of greater interest. The grade with of the rock collection, defined in terms of  $M_{85}/M_{15}$ , was 1.60. Given the size of the collection, and the flexibility allowed in setting a geometric scale, this proved adequate to accurately model the rock batches used in the field.

## 4.4.3 Visual shape comparison

Two visual comparison systems were used, the shape classifications given in the CIRIA/CUR manual (see Figure 2.1) and Powers' scale of roundness (see Figure 2.2). The results of the analysis are given in Figures 4.2 and 4.3. The shape classifications given in the CIRIA/CUR manual describe the angularity of the rocks (i.e., the degree to which their surfaces are bounded by sharp edges) as well as their aspect ratio (i.e., their degree of elongation). The first three categories in Figure 2.1, ET, IR and EQ, describe rocks of simultaneously decreasing angularity and aspect ratio. Most heavy armour rock falls into one of these three categories. The two remaining categories, SR and VR, describe only the angularity of the rocks and do not set limits on their aspect ratio. Rocks in these categories have worn or crushed edges, smooth surfaces and are less likely to be used as heavy armour. In fact, the CIRIA/CUR manual recommends that armour rocks should be "predominantly angular" and that rocks that are "too rounded or spherical for stability" should be excluded from armour layers. As can be seen from Figure 2.2, Power's scale of roundness describes only the angularity of the rocks and does not set limits on their aspect ratio. The two most round categories in Power's scale, Rounded and Well Rounded, correspond approximately to the SR and VR categories of the CIRIA/CUR method.

From Figure 4.2 we can see that almost the entire rock collection falls into the three most angular categories of the CIRIA/CUR method. Also given on Figure 4.2 are the average aspect ratios of all of the rocks in each shape category (see Section 4.4.4 for the definition of aspect ratio). As might be expected, the average aspect ratio falls sequentially in each category. Figure 4.3 shows the distribution of rocks according to Power's scale of roundness. There are no rocks in the two most "round" categories. Although the visual shape comparison was, as previously explained, a subjective exercise, it broadly confirmed that the rocks used in the model tests were, in terms of these simple shape categories, typical of those used in heavy armour layers.

## 4.4.4 Axial measurement

As a method of shape characterisation, axial measurement has the advantage over visual comparison of absolute objectivity. Each of the rocks was measured using a calliper gauge to an accuracy of 1mm. The measurements taken were as follows:

1 - the maximum axial length, i.e., the maximum distance between any two points on the rock.

d - the minimum axial breadth, i.e., the minimum distance between two parallel straight lines between which the rock could just pass.

The ratio l/d is known as the aspect ratio of the rock and describes the degree to which it is elongated. Due to its simplicity, it is one of the most commonly used measurement-based shape descriptors. The distribution of the aspect ratios of the model rocks is shown in Figure 4.4. The mean aspect ratio was 2.35, with approximately 10% of the rocks having aspect ratios of greater than 3.0. The mean aspect ratio of the rocks used in the field trials was 2.15, with only 4% having aspect ratios of greater than 3.0. Thus, although the model rocks had, on average, slightly greater aspect ratios than the rocks used in the field trials.

## 4.4.5 A new shape descriptor - blockiness

The blockiness coefficient,  $BL_c$ , is a shape descriptor that has been developed during the course of this study. It was first proposed by Newberry during the Reculver study (Ref. 2.10), where it was used to estimate rock weights. It is based upon a measurement of the smallest possible imaginary rectangular box that can enclose the rock, as shown in Figure 4.5. The blockiness coefficient is the proportion of the box, expressed as a percentage, that is taken up by the rock, given by:

$$BL_c = 100 \text{ x Volume of rock} / XYZ$$

(4.1)

where X, Y and Z are the dimensions of the enclosing box, as defined in Figure 4.5. The volume of the rock is determined from it mass, assuming that its density is know. Although it is based on dimensional measurement, there is some subjectivity in the calculation of BL<sub>c</sub>, since the tester must envisage the enclosing box. Newberry (Ref. 2.6) gives details of the consistency of blockiness measurements taken during field trials that involved a number of testers.

Figure 4.6 shows the distribution of blockiness coefficients for the rocks used in the model tests. The blockiness coefficients ranged from 30% to 95%, with a mean of 58%. The mean blockiness of the rocks used in the field trials (when measured) was 57%, with minimum and maximum values of 22% and 97% respectively. Figure 4.7 shows a scatter table of l/d against  $BL_c$  for the model rock collection. Each data point on Figure 4.7 represents an individual rock. It is noticeable that there is a weak dependency between the two parameters; rocks with low values of  $BL_c$  tend not to have high aspect ratios. Figure 4.8 shows the field test rock data presented in the same format. There are some differences in the model and field joint distributions of  $BL_c$  and l/d, particularly as the field data displays little dependency between the two parameters. However, as with the other rock characteristics, the size of the model collection was sufficient to ensure that the rock batches could be adequately modelled.

# 4.5 Dry model facilities

The models were constructed on a specially designed test rig at HR Wallingford. The rig consisted of a level concrete platform measuring 2.4m x 1.7m, enclosed on two sides by retaining walls, one of which contained a Perspex window. Two levelled horizontal rails were constructed at the open ends of the platform to support the profiling apparatus (see Figure 4.9). The models were constructed so that the revetment crest was normal to the retaining walls and therefore parallel to the rails.

The model structures were surveyed using a computer-controlled profiler that was designed and constructed by HR Wallingford. The profiler has a pivoted arm that is driven by an electric motor along a beam that spans the two horizontal rails. This pivoted arm is terminated by a spherical probe. The arm is free to rotate, and weighted so that the probe remains in contact with the surface of the armour layer as it is dragged over it. The angle of inclination of the arm is measured by an electronic inclinometer. During profiling, the angle of inclination of the beam and the location of the pivot point are scanned by the computer's A/D board. This data, when calibrated, provides a continuous record of the location of the spherical probe, in the form of horizontal and vertical co-ordinates. Before any model structures were surveyed, the profiling apparatus was calibrated by running the profiler over a series of wooden templates with known dimensions. These tests showed that the profiler could resolve horizontal and vertical measurements to within +/- 1mm.

The profiling arm was always driven normally up the armour slope, from the toe of the revetment to the crest, to help ensure that the probe remained in contact with the armour surface at all times. The profiler thus measured a normal cross section of the armour layer. The interval between these sections varied from model to model, as explained in Section 4.7, but generally between seven and ten sections were measured on each model.

The armour layers were all constructed on a mound of 4-8mm aggregate, which could be easily levelled and graded to form a plane slope at the required angles of inclination. The mound of aggregate was placed using wooden templates as guides and surveyed by the profiling arm before each model build.

## 4.6 Test programme

The test programme was conducted in two phases, as follows:

#### Phase 2(a) - structure-specific models.

The objective of these tests was to model the full-scale test panels that had been built during Phase 1 of the study. The tests included models of the Reculver revetment (see Chapter 3). Phase 2(a) was intended to investigate scale and model effects in the dimensional modelling of rock armour layers. The test programme for Phase 2(a) is summarised in Tables 4.1 and 4.2. Two types of tests were conducted; aspect ratio-matched and blockiness coefficient-matched. The differences between the two test types are explained in Section 4.7.

#### Phase 2(b) - generic models.

The objective of these tests was to model a series of generic test panels, intended to represent a wider range of structures. This phase generated the majority of the data that was ultimately used to formulate the recommendations for the dimensional design of armour layers. The test programme for Phase 2(b) is summarised in Tables 4.3 and 4.4.

## 4.7 Phase 2(a) - structure-specific models

## 4.7.1 Modelling method

The structure-specific models were designed to replicate as closely as possible the full-scale trial panels, not just in terms of the overall layer properties but also in terms of the individual rocks that formed them. During the field trials, the mass and shape of every rock in each test panel had been recorded. Individual rocks could therefore be selected from the model collection to reproduce these characteristics in the models.

The first stage in designing each model was the selection of a geometric scale factor that would allow optimum use to be made of the model rock collection. The scale selected for each model is given in Tables 4.1 and 4.2. The scales ranged from 12, in the case of the Immmingham trial, to 29 in the case of the Shoreham trial.

On most of the double layer structures (Shoreham, Bardon and Torr Works) two armour placement methods were adopted, designated as *standard* and *dense*. The differences between the two methods were as follows:

- In the *standard* placement approach the rocks were placed with a minimum of orientation control. Each rock was placed with the orientation that it had naturally adopted in the stockpile. The only placement criterion that had to be satisfied was that the rock should have a minimum of three points of contact in the layer in which it was placed. Only if three points of contact could not be achieved with the rock's natural orientation, was the rock rotated.
- In the *dense* packing approach, greater orientation control was applied. The rocks were rotated until the orientation that was likely to produce the maximum number of points of contact in the layer (and the minimum volume of voids) was achieved. Individual rocks were removed and replaced several times if necessary.

These methods were intended to reproduce those used in the field trials.

The Immingham and Reculver models like their full-scale equivalents, were constructed with the "standard" packing method only. In addition, single armour layers offer little scope for variation in packing density and were therefore constructed using the "dense" method only.

The structures were surveyed using the profiling arm described in Section 4.5. The locations of the armour profiles were chosen to match those used on the full-scale test panels, i.e., at 1m intervals (full-scale equivalent) on the Immingham model and 2m intervals in the others. The filter layer was also surveyed at 2m intervals, again to maintain consistency with the full-scale panels. On each model the size of the spherical probe was adjusted to match the size of the rocks, i.e. the probe diameter was equal to  $0.5D_{n50}$ . Although the profiler provides a continuous record of the armour surface profile, the saved co-ordinates were filtered to replicate the 1m horizontal intervals between survey points, as shown in Figure 3.6. Additionally, the crest and toe points were surveyed separately using a point probe (see Figure 3.6). In this way it was ensured that the full-scale and model armour layers were surveyed using consistent methods.

After conversion to survey format, the profiler data was analysed by Surfer using the same algorithms applied to the full-scale structures (see Chapter 3). Values of armour void porosity and layer thickness coefficient were calculated. These dimensionless parameters were calculated directly from the measured model quantities of total layer volume, total rock mass, layer thickness and  $D_{n50}$ . The bulk density of the armour layers,  $\rho_b$ , was not calculated, since it is a function of the rock density,  $\rho_a$ , which varied between model and prototype. The comparisons between model and field tests are thus independent of the density of the model rocks.

## 4.7.2 Aspect ratio-matched models

In order that the model test panels should represent the full-scale test panels as closely as possible, model rocks were individually selected to represent each prototype rock. The basis of the selection was, firstly, rock mass and, secondly, rock shape. At this stage in the study, the aspect ratio, l/d, was being used as the primary shape descriptor. These tests are therefore referred to as the 'aspect ratio-matched' models. The results of the rock selection process for each test panel are summarised in Figures 4.10 to 4.21. Each figure is a scatter table showing the joint distribution of the aspect ratios and masses of the individual rocks used in the field trial and their model equivalents. The masses of the rocks have been non-dimensionalised as a mass coefficient,  $M_c$ , as follows:

$$M_{c} = M/M_{50}$$

(4.2)

where M is the individual rock mass.  $M_{50}$  is the median mass of the rocks in the batch.

As can be seen, each model exhibited a slightly different distribution of  $M_c$  and l/d. It was obviously not possible to achieve precise matches of  $M_c$  and l/d for every rock used. An attempt was made, however, to achieve as accurate a representation as possible of the distributions of both parameters. Figures 4.22 to 4.33 show the model and full-scale distributions of l/d alone for each test panel. The distributions were calculated in terms of the percentage of non-exceedance, based upon the total number of rocks in the panel. As can be seen, the match between the model and prototype l/d distributions was generally achieved with a high level of accuracy. Figures 4.34 to 4.45 show the equivalent distributions of  $M_c$ . The latter distributions provide the closer match, since mass was the primary parameter upon which rock selection was based. The model that presented the greatest difficulty was the Reculver revetment, which contained a relatively high number of small rocks that could not be represented by the model rock collection. This resulted in some divergence between the model and prototype distributions of  $M_c$  at low values of  $M_c$ (Figure 4.45). No attempt was made to match the blockiness coefficients of the rocks during these tests. Figures 4.46 to 4.52 show the distributions of BL<sub>c</sub> for those tests in which blockiness was measured during the field trials, i.e., Bardon, Torr Works and Reculver. As can be seen, there were considerable differences between the model and prototype distributions. In particular, there was a consistent deficiency of rocks with high BL<sub>c</sub> values in the models.

The important properties of each rock batch are summarised in Table 4.5, which gives the following quantities:

- The number of rocks in the batch, R
- The mean aspect ratio of the batch, l/d mean
- The standard deviation of the aspect ratios of the batch, 1/d sdev
- The mass grade width of the batch,  $M_{85}/M_{15}$
- The mean blockiness coefficient of the batch, BL<sub>c mean</sub>
- The standard deviation of the blockiness coefficient of the batch, BL<sub>c sdev</sub>

In each case the equivalent field data are given alongside the model data. Table 4.6 shows the discrepancies between the model and field batch data. The grade width parameter,  $M_{85}/M_{15}$  is generally the closest match, followed by the aspect ratio parameters. As might be expected, the blockiness parameters are poorly matched, particularly in the case of  $BL_{c sdev}$ , showing that as well as a deficiency of rocks with high  $BL_c$  values, there was a deficiency of variation of blockiness.

The test results are summarised in Table 4.7, along with the equivalent results from the full-scale test panels. The model and field results are compared in Figures 4.53 and 4.54, which plot the measured armour porosity and layer thickness coefficients respectively. The values shown between each pair of data points are the differences between the measured field and model parameters, i.e., the error in the model prediction. Negative error values indicate that the model prediction was low. From Figure 4.53 it can be seen that porosity errors of between -4.6% and +8.1% were observed. The direction and magnitude of the error varied from model to model. The Shoreham models all overestimated the porosity, by between 5.5% and 8.1%. The Torr Works, Bardon Hill and Reculver models displayed similar, although slightly less consistent, trends; all but one (Bardon Hill single layer) significantly overestimated the porosity. The Immingham models underestimated the porosity by between 3.2% and 4.6%. It is probably significant that the Immingham field build used a less well-controlled placement method (see Chapter 3).

Using the statistical methods outlined in Appendix A, the 90% confidence limits of the model prediction of void porosity were estimated to be +5.4% and -8.6%. The limits are asymmetrical because the model tended to over-predict porosity. Using the aspect ratio-matched modelling approach, the field result can thus be expected (with a probability of 90%) to be within the range:

Model result +5.4% -8.6%

The errors in modelling the layer thickness were less consistent. In the double layer models the thickness coefficient was generally under-predicted, by as much as 0.13. The exception was the Reculver model, which over-predicted the thickness coefficient by 0.10. The single layer models both under and over predicted the thickness. Errors in the prediction of layer coefficient for all types of structures were between +0.18 and -0.13. The 90% confidence limits of the model prediction of layer coefficient were estimated to be +0.19 and -0.13. These limits are asymmetrical because of the models tendency to under-predict the coefficient. In general, the accuracy of the aspect ratio-matched models was poor.



# 4.7.3 Blockiness coefficient-matched models

At this point of the study it was decided that the blockiness coefficient,  $BL_c$ , should be investigated as an alternative shape descriptor. Intuitively it can be argued that rocks with a high value of  $BL_c$  will form less porous armour layers than those with a low value of  $BL_c$ . It was therefore decided to conduct a second series of model tests in which the  $BL_c$  distribution of the rocks used in the field would be matched in the model. Unfortunately, at only three of the field trials, Bardon Hill, Torr Works and Reculver, had the  $BL_c$  values of the rocks been measured. The blockiness coefficient-matched model tests were therefore restricted to these three trials (see Table 4.2).

New batches of rocks were selected for the blockiness-matched models. Their parameter distributions are summarised in Figures 4.55 to 4.82. In these models the blockiness coefficient was the primary parameter upon which selection was based, followed by mass and aspect ratio. As can be seen, this resulted in very close reproduction of the blockiness and mass characteristics, but significant divergence between the aspect ratio distributions. It thus proved impossible to match both shape characteristics. Tables 4.8 and 4.9 summarise the parameters of the rocks used in the blockiness-matched tests. Both  $BL_{c mean}$  and  $BL_{c sdev}$  correspond closely in the model and prototype. Values of  $l/d_{mean}$  and  $l/d_{sdev}$ , however, diverge considerably.

The test results are summarised in Table 4.10, and are plotted in Figures 4.83 and 4.84. As can be seen, these models produced closer reproductions of the field build layer properties than the aspect ratio-matched models did. The void porosity was modelled to within -1.6% and +1.7%. The estimated 90% confidence limits of the model predictions were +1.9% and -2.7%. It should be noted that the differences between the measured range of error and the estimated 90% confidence limits are greater for the blockiness-matched tests than for the aspect ratio-matched tests (Section 4.7.2) because of the smaller sample size (i.e., number of tests) used in former. The layer thickness coefficients were modelled to within +/-0.01. The 90% confidence limits on the layer coefficient prediction were estimated to be +/-0.01.

The limits on the equivalent models in the aspect ratio-matched tests were -3.0% and +2.5% on porosity (90% confidence limits of +3.2% and -5.2%) and -0.13 and +0.10 on thickness coefficient (90% limits of +0.22 and -0.12). The blockiness-matched models would therefore appear to provide considerably better predictions of the full-scale armour properties than the aspect ratio-matched models.

Because of the relatively small sample size, it is worth checking the apparent increase in accuracy for statistical significance. Since the object of the modelling was to produce an accurate model, the absolute values of the errors were treated as a test sample. The absolute errors in the models are given in Tables 4.11 and 4.12. A paired type (or non-independent) t-test was carried out as explained in Appendix A. The hypothesis of the significance test was as follows:

• The mean error produced by the blockiness-matched models was less than that produced by the aspect ratio-matched models.

The hypothesis was proven with a significance level of 99.5% on porosity and 99.95% on layer thickness.

# 4.7.4 Conclusions of the structure-specific model tests

In general, the results of the structure-specific tests suggest that reasonably accurate models of armour layers can be constructed using laboratory scale rocks, provided that model effects are minimised by ensuring that the rock shapes are similar in model and prototype. The results suggest that, in this respect, rock blockiness is a more important parameter than aspect ratio. When the blockiness coefficients of the model rocks were matched to the prototype values, the errors in the model's void porosity were between -1.6% and +1.7%. The errors in layer coefficient were between -0.01 and +0.01. These conclusions are based on a relatively small number of test structures. In Phase 2(b), the generic model tests, the effect of rock properties will be investigated in greater detail (Section 4.8).

# 4.8 Phase 2(b) - Generic models

## 4.8.1 Introduction

The objective of these tests was to investigate as wide a range of the governing parameters as possible. These were as follows:

- Armour slope
- Armour mass and mass grade width
- Rock shape (aspect ratio and blockiness)
- Method of placement
- Number of layers

Tables 4.3 and 4.4 summarise the test programme, along with the properties of the rocks that made up each test panel. More details are given in Tables 4.13, 4.14 and 4.15. As can be seen, 25 single-layer and 25 double-layer panels were constructed. In the case of the double-layer panels, most were built twice, once using the standard placement technique and once using the dense placement technique. A total of 68 models were thus tested. The methods of construction, surveying and measurement were the same as those used on the structure-specific models, as described in Section 4.7.

The tests were conducted in series, as indicated in the tables, each designed to investigate the influence of a particular parameter. Whilst the parameter under consideration was varied, other parameters were maintained at levels that were reasonably constant and typical of their distributions. Thus during Series D1, S1, D2 and S2 which were intended to examine the effect of the rock mass, the median armour mass and grade width were varied throughout the series. The rock shape parameters were, however, maintained at typical values, i.e., mean aspect ratio between 2.0 and 2.5 and mean blockiness coefficient between 50% and 60%. The standard deviations of these shape parameters were in the Medium range. For the same reason the armour slope was maintained at 1:2.

In Tables 4.3 and 4.4 the ranges of the variables are designated as Narrow, Medium or Wide. These ranges were defined as follows:

| • | Grade width  | Narrow<br>Medium<br>Wide | $\begin{split} M_{85} / M_{15} &\leq 1.2 \\ 1.2 &< M_{85} / M_{15} &\leq 1.4 \\ 1.4 &> M_{85} / M_{15} \end{split}$           |
|---|--------------|--------------------------|---|
| • | Aspect ratio | Narrow<br>Medium<br>Wide | $\label{eq:sdev} \begin{split} l/d_{sdev} &\leq 0.2\\ 0.2 < l/d_{sdev} \leq 1.0\\ 2.0 < l/d_{sdev} \end{split}$               |
| • | Blockiness   | Narrow<br>Medium<br>Wide | $\begin{split} BL_{c \text{ sdev}} \leq 5\% \\ 5\% < BL_{c \text{ sdev}} \leq 10\% \\ 10\% < BL_{c \text{ sdev}} \end{split}$ |

Series D3, S3, D4 and S4 were designed to investigate the effect of rock shape. In each of these series the limits of the shape parameters were closely controlled. As can be seen, the aspect ratio and blockiness were simultaneously varied within well-defined limits. Since each sub-set of rocks was used on slopes of 1:1.5, 1:2 and 1:3 the effect of slope was also investigated.

It should be noted that when a structure was built using both packing methods, almost exactly the same rocks were used each time. The very small differences between the values in Tables 4.13 and 4.14 for Series D3 and D4 were caused by the addition of one or two rocks when building the dense layer.

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When determining the final predictive equations the results of the structure specific model tests from Phase 2(a) were incorporated into the data set. The range of the rock batch variables cover by the combined data set was as follows:

| • | range of l/d <sub>mean</sub>  | Model $(1.79 - 3.23)$ | Field (1.90 – 2.31)   |
|---|-------------------------------|-----------------------|-----------------------|
| • | range of $l/d_{sdev}$         | Model $(0.14 - 1.21)$ | Field (0.31 – 0.52)   |
| • | range of BL <sub>c mean</sub> | Model (46.4 – 75.7)   | Field (53.8 – 63.5)   |
| • | range of $BL_{c sdev}$        | Model (2.23 – 12.4)   | Field (11.1 – 12.4)   |
| • | range of $M_{85}/M_{15}$      | Model $(1.05 - 2.21)$ | Field $(1.48 - 2.06)$ |

As can be seen, the ranges covered by the model rocks are wider than those used in the field.

## 4.8.2 Test results

The generic test results are summarised in Tables 4.16 and 4.17 and plotted in Figure 4.85. The data in Figure 4.85 are categorised according to whether they were single layers, double layers constructed with the standard packing approach or double layers constructed with the dense packing approach. As can be seen, a considerable range of porosity and layer thickness values were measured. The averages and ranges for each type of construction were as follows:

| • | Single layers          | Mean $n_v = 32.3\%$ , Range of $n_v = 23.2\%$ to $38.1\%$<br>Mean $k_t = 0.88$ , Range of $k_t = 0.67$ to $1.05$ |
|---|------------------------|--|
| • | Standard double layers | Mean $n_v = 35.9\%$ , Range of $n_v = 32.0\%$ to 40.0%<br>Mean $k_t = 0.88$ , Range of $k_t = 0.68$ to 1.05      |
| • | Dense double layers    | Mean $n_v = 34.5\%$ , Range of $n_v = 30.2\%$ to 37.9%<br>Mean $k_t = 0.87$ , Range of $k_t = 0.66$ to 1.01      |

It can be immediately deduced that single layers have, in general, lower porosity than double layers. The dense packing method appears to result in lower porosity than the standard packing method. Trends in layer thickness are not so obvious, as all the type of models produced similar results. These assertions are tested in the following sections.

# 4.8.3 The effect of placement method

Table 4.16 presents the result of the generic model double layer tests, giving results for both packing methods, along with the change induced by switching from the standard to the dense packing approach. It can be see that in all but one case (Test D17) the change of packing approach reduced the porosity. The maximum difference occurred during Test D24, in which a change of 4.2% was recorded. To this data can be added the results of the structure-specific model tests in which the packing method was varied. These are presented in Table 4.20 and display a similar trend. The mean change in armour layer porosity caused by the change in packing approach (considering the generic and structure-specific models as a single data set) was 1.8%. Figures 4.86 and 4.87 plot the armour porosity and layer thickness of all these models respectively.

A one-tailed t-test of statistical significance can be applied, based on the hypothesis:

• The mean porosity of the layers constructed using the dense packing approach is lower than the mean porosity of the structures constructed using the standard packing approach.

The data can be treated as a paired (or non-independent) distribution since essentially the same batches of rock were placed in each model (see Appendix A). The hypothesis is proved with a significance of 99.999%.

The influence of the packing approach on the layer thickness coefficient is less clear. In 15 of the 23 tests  $k_t$  was reduced by the denser packing approach, in the remaining 8 it was increased (Figure 4.87). Testing the hypothesis that the means are different, i.e., a two-tailed test, does not produce a level of statistical significance.

This analysis shows that the dense packing approach reduces the porosity by an average of 1.8% but does not affect the layer thickness. This is understandable since although dense packing involves controlling the orientation of the rocks as they are placed, there should be no systematic bias towards placing the long axis either in the plane of the slope or normal to the plane of the slope.

## 4.8.4 The influence of the governing variables

The influence of rock characteristics and placement methods on the geometry of the armour layer is complex. It is reasonable to assume that the layer geometry is influenced by more than one variable. The structure-specific model tests show, for example, that more than one rock shape descriptor is required to accurately predict the properties of the armour layer. A series of multivariate regressions was therefore carried out, treating layer porosity and thickness coefficient as the dependent variables. Linear regression routines from Excel spreadsheets were used. The first stage in the process was the selection of the independent variables. For meaningful multivariate regression analysis it is important that these variables be genuinely independent. From inspection of the results, it was decided that a blockiness descriptor and an aspect ratio descriptor were required. As well as using the means of these values, a measure of their range within the rock batches was required. The standard deviation was selected as the most appropriate measure of range. The grade width of the rock batch was also considered as an independent variable, in the form of  $M_{85}/M_{15}$ . The variables used in the regression analysis were thus as follows:

| • | Dependent variables   | Armour layer porosity, $n_v$<br>Armour layer thickness coefficient, $k_t$   |
|---|-----------------------|---|
| • | Independent variables | Mean blockiness coefficient<br>Standard deviation of the blockiness coefficient<br>Mean aspect ratio<br>Standard deviation of aspect ratio<br>Mass range M <sub>85</sub> /M <sub>15</sub> |

To prepare the data for the multiple regression analysis certain modifications were made. It is advisable that the independent variables be normally distributed. To assist in the interpretation of the relative importance of each variable, it is also helpful if all have similar magnitudes. The following conversions were therefore carried out:

- The l/d values of the rocks were converted to d/l values, leading to the parameters  $d/l_{mean}$  and  $d/l_{sdev}$ . These parameters are more normally distributed than their l/d equivalents.
- The blockiness values were recalculated as proportions rather than percentages. These revised valued were designated  $bl_c = BL_c/100$ . This led to the parameters  $bl_{c mean}$  and  $bl_{c sdev}$ .
- The grade width parameter was converted from  $M_{85}/M_{15}$  to  $M_{15}/M_{85}$ .

The independent variables were thus:

- $bl_{c mean}$  (Model range 0.46 to 0.76)
- $d/l_{mean}$  (Model range 0.31 to 0.56)
- $bl_{c sdev}$  (Model range 0.02 to 0.13)
- $d/l_{sdev}$  (Model range 0.01 to 0.15)
- $M_{15}/M_{85}$  (Model range 0.42 to 0.95)



Tables 18 and 19 give the values of the independent variables used in the regressions. Figures 4.88 to 4.97 show scatter plots of the dependent variables, porosity and layer coefficient, against each of the independent variables. All of the independent variables have values of between 0 and 1. It is clear that no single independent variable can adequately describe the dependent variables.

Figures 4.98 and 4.99 plot the dependent variables against the armour slope. The results suggest that the armour properties are influenced by the slope at which the layer is placed. There is, however, insufficient variation in the armour slope to use it as an independent variable in the multiple regressions. For this reason, armour slope was dealt with using a correction factor after the regressions had been carried out. For the regressions, a forward stepwise process was adopted, as follows:

- The significance of the relationship between the dependent variable and the independent variables was determined separately for each independent variable.
- A minimum acceptable level of statistical significance was specified (in this case 95%).
- The independent variable that had the highest level of significance was added to the multivariate model, provided its significance level was greater than the minimum acceptable level.
- The remaining independent variables were added to the model separately. The variable which displayed the highest level of significance (over the minimum level) was added to the model.
- If adding a new variable to the model causes the significance of a variable already in the model to fall below the critical level, that variable was removed from the model.
- This process was repeated until no further variables could be found to meet the minimum level of significance.

The above process was carried out for the results of the double (standard pack only) and single layers. The difference caused to porosity and layer thickness by dense packing was also investigated. No significant terms for the difference caused to layer thickness by packing could be determined, confirming the results of the analysis given in Section 4.8.3. The results of this process were a set of equations in the following form:

$$\begin{split} n_v &= A + B \ bl_{c \ mean} + C \ d/l_{mean} + D \ bl_{c \ sdev} + E \ d/l_{sdev} + F \ M_{15}/M_{85} \\ k_t &= A + B \ bl_{c \ mean} + C \ d/l_{mean} + D \ bl_{c \ sdev} + E \ d/l_{sdev} + F \ M_{15}/M_{85} \\ \Delta n_v &= A + B \ bl_{c \ mean} + C \ d/l_{mean} + D \ bl_{c \ sdev} + E \ d/l_{sdev} + F \ M_{15}/M_{85} \end{split}$$

The coefficients A to F are given in Table 4.21. The results of the porosity and layer coefficient and packing effect prediction equations are plotted in Figures 4.100, 4.101 and 4.102 respectively, each of which plots the predicted parameters against the measured parameters. The 90% confidence limits of the predictions, which can be inferred from the distributions of the prediction errors, are as follows:

Single layer  $n_v$ , +/-3.7% Single layer  $k_t$ , +/-0.106 Double layer  $n_v$ , +/-2.4% Double layer  $k_t$ , +/-0.097 Double layer  $\Delta n_v$ , +/-1.5%

It was clear from an examination of the errors in the prediction that the equations underestimated the void porosity and layer coefficients of the armour layers placed on a slope of 1:1.5. A refinement was therefore made to the model. For each of the three structure slopes, the average error in the prediction of void porosity and layer coefficient (for all models at that slope) was calculated. On the basis of this average error, a correction factor was applied as a multiplier to the coefficients A to E. The revised coefficients are given in Table 4.22 to 4.24. The revised predictions of void porosity and layer coefficient are plotted in

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Figures 4.103 and 4.104. The packing difference prediction was not modified. It can be seen that this correction has improved the accuracy of the model slightly, particularly in the prediction of the layer coefficient. This is confirmed by the lower values of the 90% confidence limits, which are as follows:

Single layer  $n_v$ , +/-3.6% Single layer  $k_t$ , +/-0.078 Double layer  $n_v$ , +/-2.4% Double layer  $k_t$ , +/-0.092 Double layer  $\Delta n_v$ , +/-1.5%

## 4.9 Discussion of regression model results

### 4.9.1 Influence of the rock characteristics

The regression model produced statistical relationships between the properties of the rock batches and the properties of the armour layers. It thus provides a tool for predicting the properties of the armour layer, given that the rock properties are known. The method is purely empirical, in that the causal relationships between the properties of the rocks and the armour layers are not considered. An examination of the regression model may, however, help to provide an understanding of the mechanisms by which rock properties influence the layer geometry. The following inferences, which necessarily involve some speculation, can be drawn from the values of coefficients in the regression equations:

The value of B in the porosity prediction equations is negative for both single and double layers. This implies that rocks with high blockiness coefficients form less porous layers. It is easy to understand the mechanism in this case, as the voids between blocky rocks will generally be smaller than those between rounded rocks.

The value of C in the porosity prediction equations is negative for both single and double layers, implying that rocks that have high aspect ratios (i.e., with low d/l values) form more porous layers. In double layers, at least, this may be a result of 'bridging' occurring when an elongate rock is placed over a gap between other rocks.

The value of B in the layer coefficient prediction equations is positive for both double and single layers, implying that rocks that have high blockiness coefficients form thicker layers. This may be a result of the way in which layer thickness is surveyed and defined (see Figure 3.6). Large gaps between rocks will result in a reduced measurement of average layer thickness. Such gaps will be reduced in size by the use of blocky rocks.

The value of C in the layer coefficient equations is positive for both double and single layers, implying that high aspect ratio rocks (i.e., with low d/l values) form thinner layers. This is almost certainly as result of the orientation that the rocks are placed with, i.e., with their long axes in the plane of the slope.

The mass grade width appears to have little influence on the armour layer geometry; it appears in only one of the equations (the porosity of single layers) and with a relatively weak effect. This is probably because the tests have been confined to relatively narrow grades, as appropriate to heavy armour rocks.

There are other factors in the equations that are less easy to explain. For example, the range of blockiness appears to have an influence on the porosity of double layers, but not on the porosity of single layers. It also appears to effect the thickness of single layers but not that of double layers. There is no obvious explanation for these effects.

In the equation that describes the effect of the dense packing, the B and C coefficients are both positive. This implies that the effect of dense packing is most pronounced when applied to rocks with low blockiness coefficients and high aspect ratios. The effect of aspect ratio is easy to understand, since rock with higher aspect ratios offer a greater scope for variable packing. The blockiness effect is less easy to account for. It is possible that, since blocky rocks tend to pack together well, there is less scope for improvement by optimising their orientation. It should also be noted that triangular or pyramidal rocks (which tend to have low blockiness coefficients) may respond well to packing.

## 4.9.2 Limits of applicability

The prediction equations derived by the multiple regression exercise will be strictly valid only for the range of independent variables covered by the model tests. These are summarised below.

- bl<sub>cmean</sub> (Model range 0.46 to 0.76)
- $d/l_{mean}$  (Model range 0.31 to 0.56)
- bl<sub>csdev</sub> (Model range 0.02 to 0.13)
- $d/l_{sdev}$  (Model range 0.01 to 0.15)
- $M_{15}/M_{85}$  (Model range 0.42 to 0.95)

These ranges were used as input to the prediction equations to produce the maximum and minimum possible predictions of void porosity and layer coefficient. The results were as follows:

Single layer porosity, range of predictions 22.9% to 41.9%

Single layer thickness coefficient, range of predictions 0.54 to 1.20

Double layer porosity, range of predictions 27.6% to 44.0%

Double layer thickness coefficient, range of predictions 0.66 to 1.07

Some of these results are well outside the range of measured values, since the equations have been used with combinations of rock parameters that were not covered by the model tests. For example, the very low porosity values result from the combinations of maximum blockiness ( $bl_{c mean} = 0.76$ ) and minimum aspect ratio ( $d/l_{mean} = 0.56$ ). These values are extremely unlikely to occur simultaneously in a batch of rocks, unless the batch has been specifically selected with this in mind. The parameters of the vast majority of rock batches used in armour layers will fall well within the ranges used in the tests. This subject is dealt with in Chapter 6 of this report, which outlines practical design guidance arising from the study.

## 4.9.3 Validation of the model

To validate the model, the prediction equations were applied to the three full-scale trial structures for which full records of the rock shape parameters were available, i.e., the Bardon Hill, Torr Works and Reculver structures. Validation was carried out for single and double layers. The results are plotted in Figures 4.105 and 4.106, which show the void porosity and layer coefficient results respectively. The figures plot the values measured in the field along with the 90% confidence intervals of the estimate made by the regression model. In all cases the measured value is within the intervals of the prediction.

# 4.10 Conclusions

The collection of model rocks assembled for the test programme was shown, in terms of shape classification, to be representative of heavy armour rocks used in full-scale structures (see Section 4.4). There was sufficient variety in the shapes of the model rocks to cover the full range of shapes likely to be encountered in batches of full-scale rocks.



It was found that the two packing approaches used in the study, standard and dense, could be consistently applied and resulted in measurable changes in the armour layer porosity. Typically the porosity could be reduced by 2% by applying the dense packing approach (see Section 4.8.3). The layer thickness, however, was not affected by the packing approach.

To produce accurate geometric models of armour layers at model scale it is important that the shapes of the model rocks are carefully controlled to match the shapes of the full-scale rocks. The rock blockiness proved to be particularly important in this respect, more so than the aspect ratio (see Section 4.8.3).

The effect of the rock properties on the geometry of the armour layer was investigated by a series of multivariate regressions, resulting in set of equations to predict armour layer porosity and thickness. These equations were validated by comparison with field results. In the case examined the field results fell within the 90% confidence limits of the model predictions (see Section 4.9).



# 5. ARMOUR LAYER HYDRAULICS - MODEL SCALE TESTS

# 5.1 Introduction

This chapter describes Phase 3 of the project, the investigation of the hydraulic performance of armour layers using physical model tests. Two elements of the hydraulic performance were considered:

- The stability of the layer under wave attack.
- The ability of the layer to dissipate wave energy.

Stability was investigated by subjecting the model armour layers to a series of random wave sequences in a flume and measuring the resulting damage. Relationships between wave conditions and damage were developed for various categories of rock armour and placement methods. The ability of the layers to dissipate wave energy was characterised by the overtopping discharges. The methods of categorising rock batches and placement methods developed in Chapter 4 were applied to the structures tested in the flume. This allowed very accurate control of the armour layer properties.

The analysis of armour layer performance presented in this chapter relies heavily on the methods developed by Van der Meer, which are among the most commonly used techniques for designing rock armour layers. This approach will allow the findings of the study to be incorporated readily into a widely accepted design procedure. The study also included a series of tests on single layer armour, as this is an area in which relatively little guidance is currently available.

# 5.2 Armour stability

## 5.2.1 Van der Meer's stability formulae

One of the most comprehensive of physical model investigations into the stability of rock armour layers was conducted by Van der Meer (Ref. 5.1), incorporating data from an earlier study by Thompson and Shuttler (Ref. 5.2). This work resulted in the widely known Van der Meer equations for the design of rock-armoured structures. These equations are recommended in guidelines such as the relevant British Standard (Reference 2.3) and the CIRIA/CUR manual (Reference 2.4).

The basic equations provide an estimate of the wave conditions that a structure may be subjected to before it sustains a particular level of damage, and are as follows:

| $H_{s} / \Delta D_{n50} = 6.2 \ P^{0.18} \ (S_{d} / \sqrt{N})^{0.2} \ \zeta_{m} \ ^{\text{-}0.5}$ | for plunging waves | (5.1) |
|---|--------------------|-------|
|---|--------------------|-------|

$$H_{s} / \Delta D_{n50} = 1.0 P^{-0.13} (S_{d} / \sqrt{N})^{0.2} (\cot \alpha)^{0.5} \zeta_{m}^{P} \text{ for surging waves}$$
(5.2)

where  $H_s$  is the significant wave height (m)  $\Delta$  is the buoyant density of the armour rock =  $\rho_a/\rho_w - 1$   $\rho_a$  is the density of the armour rock (t/m<sup>3</sup>)  $\rho_w$  is the density of the water (t/m<sup>3</sup>)  $D_{n50}$  is the nominal diameter of the rock (m) P is the notional permeability factor  $S_d$  is the damage number N is the number of waves  $\alpha$  is the slope angle of the armour face  $\zeta_m$  is the Iribarren number calculated from the mean wave period =  $\tan \alpha / \sqrt{s_m}$   $s_m$  is the wave steepness calculated from the mean wave period =  $2\pi H_s / g T_m^2$  $T_m$  is the mean wave period (s)



Plunging and surging are different forms of wave attack, as described later in this section. The transition between plunging and surging waves occurs at a critical value of  $\zeta_m$ , designated  $\zeta_{mc}$  and given by:

$$\zeta_{\rm mc} = (6.2 \ {\rm P}^{0.31} \ (\tan \alpha)^{0.5})^{1/({\rm P}+0.5)}$$
(5.3)

where  $\zeta_m < \zeta_{mc}$  for plunging waves  $\zeta_m > \zeta_{mc}$  for surging waves

Equations 5.1 and 5.2 apply in relatively deep water, where wave height is not limited by water depth. Alternative forms of the equations were developed for shallower water, where depth-limited wave breaking has an influence on the distribution of individual wave heights (see Ref. 5.1).

Van der Meer's equations are more complex than others used in the design of rock armour. They allow a number of variables to be considered, such as wave period, storm duration and structural permeability, which are neglected by other methods, e.g. that of Hudson (Ref. 2.2). Importantly, the equations also allow variable levels of damage to be accounted for in the design process since, in formulating the equations, Van der Meer developed a method of accurately quantifying damage. This is of particular interest to the current study, as we require a consistent and accurate method of comparing the damage suffered by different structures.

The following is a brief discussion of the important parameters in Van der Meer's equations:

#### • Stability number

The dimensionless variable  $H_s/\Delta D_{n50}$  is known as the stability number, and is of primary importance when considering the stability of rock armour under wave attack. It is common to most rock armour design formulae. A high stability number indicates that the rock is relatively unstable.

#### • Structure permeability

The notional permeability factor, P, describes the structures overall permeability to water flow. This figure has a major influence on the stability of the rock armour layer. Relatively impermeable structures, such as layers of rock armour placed over solid slopes or cores made up of very fine material, have much less stable armour layers than relatively open structures, such as homogenous mounds of rock armour. In the latter case, water penetrating the armour layer can percolate through the open core, thus relieving the pressure on the armour layer. Such a structure will have P value of 0.6, compared to a P value of 0.1 for the less permeable structure. Looking at the design equations it can be seen that this variation has a significant effect on the stability number of the structure.

#### • Damage number

The damage number,  $S_d$ , describes the degree of damage sustained, with  $S_d = 2$  equating to minimal damage and  $S_d = 12$  equating to serious damage or destruction.  $S_d$  is descriptor of the bulk volume of the armour layer eroded by the waves and is defined in the following way:

$$S_d = A_e / D_{n50}^{2}$$
 (5.4)

where  $A_e$  is the cross sectional area eroded by the waves.

The damage number is therefore equivalent to the number of idealised cubic rocks with a side length of  $D_{n50}$  eroded from a strip of width  $D_{n50}$ .

#### • Number of waves

The number of waves in the storm, N, is an important influence in random seas, as it can take a considerable amount of time for the largest individual waves in a sequence to occur, and it is these large waves which cause the most significant damage to the structure. It is generally agreed that the vast majority of damage is done within the first 1000 waves of the storm. The maximum number of waves that should be used in Equations 5.1 and 5.2 is 7,500.

#### • Iribarren number

The Iribarren number,  $\zeta_m$ , governs the form of wave breaking on the rock armour slope.  $\zeta_m$  is the ratio of the slope steepness to the wave steepness. There are a number of forms of wave breaking, but on typical rock armour slopes, which have slope angles,  $\alpha$ , of between 1:3 and 1:1.5, the surging and plunging forms are predominant. Plunging waves are those which break onto the surface of the rock armour slope and generally occur when  $\zeta_m$  is less than 3-4, although the precise value varies from structure to structure. Surging waves run up and down the armour slope without breaking and generally occur when  $\zeta_m$  is greater than 3-4. They are usually associated with sea states of relatively low steepness, such as swell conditions.

Neither the work of Thomson and Shuttler nor that of Van der Meer considered the effect of variations in construction method on the stability of the layer. In both cases the armour layers were constructed using bulk-placement. This is likely to result in layers that are relatively porous compared to the individually placed rock layers used in the present study.

## 5.2.2 Hudson's stability formula

During the testing, single layer structures were deemed to have failed whenever a single rock was removed from the layer. It was not therefore appropriate to analyse them in terms of a damage level. Instead, a stability coefficient at failure was derived from the Hudson equation, which is as follows:

$$H_{1/10} / \Delta D_{n50} = (K_D \cot \alpha)^{1/3}$$

(5.5)

where  $K_D$  is a stability coefficient

 $H_{1/10}$  is the average of the highest  $1/10^{th}$  of the individual waves at failure (m)

Note that this is the revised version of the Hudson equation (Ref. 2.2) which uses  $H_{1/10}$  in place of the original  $H_s$ . The recommended values of  $K_D$  for 'rough angular' rocks given in the Shore Protection Manual in a single layer, in non-breaking waves, is currently 2.9. No recommendation is given for breaking waves.

## 5.3 Overtopping discharges

### 5.3.1 Introduction

A further concern of the model tests was the effectiveness of the armour layers at dissipating wave energy. This was investigated by measuring the overtopping performance of the structures. Some of the most comprehensive studies of overtopping of sloped structures were those conducted by Owen (Ref. 5.3) and Van der Meer & Janssen (Ref. 5.4). Both took a similar approach in that they empirically derived a set of equations that predict the mean overtopping discharge as a function of structure geometry and sea-state.

## 5.3.2 Owen's method

The equations developed by Owen are as follows:

$$Q_* = A \exp(-BR_*/r)$$

where  $Q_*$  is the dimensionless mean overtopping discharge = q /  $T_m g H_s$ 

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(5.6)

q is mean overtopping discharge per unit length of the structure( $m^3/s.m$ ) R<sub>\*</sub> is the dimensionless freeboard = R<sub>c</sub> / (T<sub>m</sub>  $\sqrt{(gH_s)}$ ) R<sub>c</sub> is the structure's freeboard (m) r is the surface roughness factor A and B are coefficients which are a function of the slope angle Other terms are as previously defined

The roughness factor, r, describes the influence of the roughness of the armour layer on the overtopping discharge. It is the estimated ratio of the wave run-up on an armoured slope to the run-up on a smooth and impermeable slope of the same gradient. In Section 2.4.4 of this report, recommended values of roughness coefficient for various types of construction are given. As can be seen, the recommended values for a double layer of rock armour are between 0.50 and 0.60.

The Owen method was developed using waves of typical 'storm' steepness, i.e., between 0.035 and 0.055. Hawkes et al (Ref. 5.5) found that the Owen method could not be applied to swell waves, as it tended to significantly overestimate discharges in wave conditions of low steepness. A correction method based on the Iribarren number,  $\zeta_m$ , was developed. Owen's equation was found to be strictly applicable to plunging waves only, defined by Hawkes et al as those conditions with  $\zeta_m < 2.3$ . At higher vales of  $\zeta_m$  the prediction became increasingly inaccurate.

## 5.3.3 Van der Meer's method

The method of Van der Meer & Janssen distinguishes between plunging waves and surging waves. It is applicable to a wider range of wave conditions than the Owen method.

The equations are as follows:

| $Q_b = 0.06 \exp(-5.2 R_b/\gamma_f)$   | for plunging waves | (5.7) |
|--|--------------------|-------|
| $Q_n = 0.20 \exp(-2.6 R_n / \gamma_f)$ | for surging waves  | (5.8) |

 $Q_b$  and  $Q_n$  are the dimensionless mean overtopping discharges for plunging waves and surging waves respectively, given by:

| $Q_{b} = q/(gH_{s}^{3}) (s_{p}/\tan \alpha)^{0.5}$ | for plunging waves | (5.9)  |
|--|--------------------|--------|
| $Q_n = q/(gH_s^3)$                                 | for surging waves  | (5.10) |

R<sub>b</sub> and R<sub>n</sub> are the dimensionless crest freeboards for plunging and surging waves respectively, given by:

| $R_{\rm b} = R_{\rm c}/H_{\rm s} \left(s_{\rm p}\right)^{0.5}/\tan\alpha$ | for plunging waves | (5.11) |
|---|--------------------|--------|
| $R_n = R_c/H_s$   | for surging waves  | (5.12) |

where  $s_p$  is the wave steepness calculated from the peak wave period (= $2\pi H_s/g T_p^2$ )

 $\gamma_f$  is the armour layer roughness

Other terms are as previously defined

The coefficient  $\gamma_f$  performs the same function as the coefficient, r, in Owen's equation (Equation 5.6) in that it is the ratio of wave run-up on a rough slope to that on an equivalent smooth slope. It is therefore less than 1.0 for all non-smooth slopes. Section 2.4.4 gives recommended values of  $\gamma_f$  for various types of structure. As can be seen, the recommended value for a double layer of rock armour is, at 0.50-0.55, similar to that recommended for use in Owen's equation. Van der Meer & Janssen determined other reduction factors to account for berms, shallow foreshores and angled wave attack. These are not a concern of the present study.

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# 5.4 Selection of test parameters

## 5.4.1 Test structures

The primary intention of the hydraulic model tests was to investigate the effect of packing density on the performance of armour layers. The dry model tests (described in Chapter 4 of this report) provided information on the variation of packing density in armour layers. It was shown that porosity of the layers could be decreased if an effort was made by the constructor to achieve a tight pack. The packing density was also affected by the properties of the rocks that made up the layer. The most important parameters were found to be:

- The blockiness coefficient, BL<sub>c</sub>
- The aspect ratio, defined by the ratio l/d

Chapter 4 describes how these parameters are defined and how they influence the geometric properties of the armour layer.

Table 5.1 summarises the variable parameters of the structures that were tested during Phase 3. A total of 18 structures were tested, including single and double layers. The batches of rocks sorted and categorised for the dry model tests were re-used in the hydraulic tests. This allowed accurate control of the properties of the rock batches that made up the armour layers. As can be seen from Table 5.1, the sorted batches were used primarily to vary the rock shape characteristics.

The first fifteen structures tested consisted of an armour layer (either single or double) placed directly onto a core of rocks with a nominal diameter,  $D_{n50}$ , of 17mm, which is approximately 1/3 of that of the armour layer, which had a nominal diameter of 0.051m. According to Van der Meer's definitions of structure permeability (Ref. 5.1) such structures have a notional permeability coefficient, P, of 0.5.

Structures 1 to 9 investigated the effect of rock blockiness. Three different rock batches were used, with ranges of  $BL_c$  of 40-50%, 50-60% and 60-70%. Each was constructed with both the standard and dense packing methods (see Section 4.7 for the definitions of packing method) and in single and double layers. The rocks used in Structures 1 to 9 had aspect ratios, I/d, of between 1.5 and 3.0, which is typical of heavy grade armour. The aspect ratio of the rocks was varied in Structures 10 to 12, which used only rocks with I/d values of less than 2.0. Structures 13 to 15 were essentially repeats of Structures 1 to 3. They were also to investigate the effect of increasing the duration of the tests, i.e., the number of waves, N. Structures 1 to 12 were tested for 1000 waves, whereas the duration of testing of Structures 13 to 15 was extended to 3000 waves.

Structures 16 to 18 were used to investigate the effect of structure permeability, by constructing the armour layer over a filter layer that was itself placed on a solid mortar slope. According to the specification given in Ref. 5.1 the notional permeability, P, of this type of structure is 0.1.

The structural parameters that remained constant throughout the tests were as follows:

- Armour slope,  $\alpha$ , = 1:2
- Density of the armour rock,  $\rho_a = 2.73 \text{ t/m}^3$
- Nominal diameter of the rock,  $D_{n50} = 0.051m$
- Armour grading width,  $D_{85}/D_{15} = 1.2$  to 1.3
- Crest freeboard,  $R_c$ , = 0.35m

Figures 5.1 and 5.2 show sections of both types of structure in the flume.



## 5.4.2 Wave conditions

The wave conditions in which the structures were tested are summarised in Table 5.2. The table gives the wave heights and periods as defined by statistical and spectral analysis techniques. A JONSWAP spectrum was used in all cases. The water depth remained constant at 0.75m.

Two principal factors influenced the selection of wave conditions:

- Since the study was primarily concerned with damage, the wave conditions had to be sufficiently energetic to cause measurable damage to the structures.
- A sufficient range of wave conditions had to be covered to make the results generally applicable.

To ensure that the test conditions were severe enough to damage the structures, Van der Meer's equations were used to predict the likely damage that they would cause. Figure 5.3 shows the results of these calculations. The test conditions are superimposed on the damage curves predicted using Equations 5.1 and 5.2 with the following input parameters:

 $D_{n50} = 0.051 m$   $\alpha = 1:2$  P = 0.5N = 1000

These parameters represent the majority of the test structures. Figure 5.3 plots curves for damage levels,  $S_d$ , of between 2 (slight damage) to 17 (destruction). These calculations suggested that the wave flume would be capable of generating waves sufficient to destroy the test structures completely, even allowing for some increased stability due to dense armour packing. This broadly was confirmed by the results of the tests (see Section 5.7).

Table 5.3 also gives the steepness of each wave condition. Results are given for the statistically and spectrally derived wave conditions. The test conditions cover the steepness range of  $s_m = 0.007$  to  $s_m = 0.069$ , making them applicable to most realistic prototype sea states. Van der Meer's original test programme (Ref. 5.1) covered a slightly different steepness range of  $s_m = 0.004$  to  $s_m = 0.060$ . In addition, as can be seen from Figure 5.3, the conditions also cover a full range of Iribarren numbers and span the critical Irribarren value,  $\zeta_{mc}$ , which governs the transition between plunging and surging conditions.

# 5.5 Test Methodology

## 5.5.1 Test facilities

## Flume

The tests were conducted in the absorbing wave flume, which is 40m long, 1.5m wide and has a maximum working depth of 0.8m. For the present study, the flume bed was level and the water depth remained constant at 0.75m during all tests. The flume has an active wave-absorbing system that ensures that any waves reflected from the test structures are not re-reflected by the wave paddle. The paddle is controlled by a computer running HR Wallingford's purpose-written software WAVEGEN. The system can generate random waves to any required spectral shape and with very long repeat times. The flume is equipped with eight wave probes that are monitored by a PC using HR Wallingford's WAVES software. Their output is analysed using statistical and spectral analysis routines.

## Photographic equipment

Armour damage levels were assessed using a photographic technique. Images were recorded on a digital video system, which allowed individual frames to be captured. The camera was mounted at a fixed position covering the seaward slope of the structures, as shown in Figure 5.4. The camera was located so

as to be facing in a direction normal to the armour slope. The camera was triggered automatically to record 30s of footage every six minutes during the tests. An analysis of these pictures allowed individual displaced rocks to be identified. The number of rocks that had been extracted at any point during the test could thus be counted. This method of monitoring damage was favoured over the alternative method of profiling, as it was though to be more sensitive to low levels of damage.

### **Overtopping discharge measurement**

Water that overtopped the crest of the structures was collected in a storage tank via a chute fitted to the crest of the structure (see Figure 5.4). The tank was supported by a plate that was fitted with an electronic load cell. The load cell was monitored by the computer that also scanned the wave probes, allowing the weight of water in the tank to be continuously recorded. The average overtopping discharge could then be calculated from the change in weight of water in the tank over the course of the test.

## 5.5.2 Test procedures

## Wave calibration

The wave conditions were calibrated in the flume before construction of the test structures, and with a wave-absorbing beach at the downstream end of the flume to prevent reflections. The conditions were defined by a single wave probe, positioned at the eventual location of the toe of the test structures. Conditions were also monitored by a probe placed close to the paddle. The output of the wave probes were analysed spectrally and statistically, as follows:

- Spectral analysis allows the distribution of the energy content of the waves across the frequency spectrum to be determined via a Fast Fourier Transform Technique. The parameters determined by spectral analysis include the spectral significant wave height, H<sub>mo</sub> (an approximation of the significant wave height, H<sub>s</sub>,) determined from the area under the spectrum and the peak wave period, T<sub>p</sub> (the period at which the spectral energy density has its maximum value). Spectral analysis is carried out over relatively short sequences of repeating waves.
- Statistical analysis is carried out over longer durations, in this case 1000 waves. During such measurements the repeat time of the waves was always set to be longer than the test time to ensure that the distribution of individual waves was correctly modelled. Measurements of surface elevation were made relative to the mean value of the water level. A wave is defined as lasting between two successive down crossings of the mean water level. At the end of each sea state record, wave heights calculated from the sum of the maximum departure above and below the mean water level, are sorted in descending order from which statistical values of H<sub>s</sub> and H<sub>max</sub> etc. can be determined. The total length of the calibration period is divided by the number of waves recorded to give the mean zero-crossing wave period T<sub>m</sub>.

## 5.5.3 Structure testing

For each structure, the tests were divided into four groups, each of which used an almost constant wave period, of approximately 1.5, 2.0, 2.5 or 3.0s (see Table 5.2). Within each period group, tests were run in order of increasing wave height. Once a structure had failed, no higher wave heights were used in that period group. Failure of a double layer was deemed to have occurred if there was a substantial exposure of the filter layer. This typically corresponded to a damage level,  $S_d$ , of between 10 and 15, although it varied from test to test. If any damage occurred during a test, the structure was rebuilt before the following test. If no damage occurred, the next test proceeded without any change to the structure. If a structure failed before the completion of a test then the number of waves that caused the failure was noted. These results were incorporated in the analysis by non-dimensionalising them with the appropriate number of waves in Equations 5.15 and 5.16.



The definition of failure for a single layer was different to that of a double layer, because single layer structures cannot tolerate the extraction of any rocks. The structure was therefore deemed to have failed once a single rock was displaced from the layer.

During testing, the armour damage and the overtopping discharges were monitored using the techniques described in Section 5.5.1. The output of each test was therefore as follows:

- The number of rocks extracted over the course of the test.
- The mean overtopping discharge over the course of the test.

The duration of testing of most of the structures was limited to 1000 waves. The exceptions were Structures 13 to 15, which were tested for 3000 waves. During each test, as a quality control measure, the wave conditions at the paddle were monitored to ensure that they did not differ substantially from their calibrated values. Although this did not take account of the waves reflected from the test structure it would provide an indication of any paddle malfunction.

### 5.6 Results of the double layer armour stability analysis

### 5.6.1 Method of analysis

The initial step in analysing the results of the stability analysis was to convert the number of rocks extracted,  $N_R$ , to an equivalent damage number,  $S_d$ . Given that the porosity,  $n_v$ , of the armour layer was known, the average bulk volume of the armour layer eroded,  $V_e$ , was calculated from:

$$V_{e} = V_{r} / (1 - n_{v})$$
(5.13)

where  $V_r$  is the volume of the rocks eroded =  $N_R D_{n50}^{3}$ 

This produces a sufficiently accurate estimate of the eroded volume because the grade width of the rock batches was narrow. The average eroded area,  $V_e$ , was then calculated from:

$$A_e = V_e / w \tag{5.14}$$

where w is the test panel width

The damage number was then calculated from Equation 5.4.

In a study by Bradbury et al (Ref. 2.13) Van der Meer's equations were re-arranged as follows:

| $S^* = H^*/C_{pl}$    | for plunging waves | (5.15) |
|-----------------------|--------------------|--------|
| $S^* = H^{**}/C_{su}$ | for surging waves  | (5.16) |

where  $S * = (S_d / \sqrt{N})^{0.2}$   $H^* = (H_s / \Delta D_{n50}) P^{-0.18} \zeta_m^{-0.5}$  $H^{**} = (H_s / \Delta D_{n50}) P^{0.13} (\tan \alpha)^{0.5} \zeta_m^{-P}$ 

 $C_{pl}$  and  $C_{su}$  are variable coefficients to be used in place of the values of 6.2 and 1.0 in Equations 5.1 and 5.2. Bradbury at al determined values of  $C_{pl}$  and  $C_{su}$  for various rock shapes. The present study used a similar method, using linear regression to determine values of  $C_{pl}$  and  $C_{su}$  for each structure tested.

Figures 5.5 to 5.28 plot the results of the damage analysis for each structure after the 1000 wave tests. The results are divided into plunging and surging wave cases, as determined by the critical Iribarren number,  $\zeta_{mc}$ . In the case of the structures with P = 0.5,  $\zeta_{mc}$  was calculated from Equation 5.3 to be 3.56. The

estimated critical value for the structures with P = 0.1 was lightly higher, at 3.71. On each graph the dimensionless damage number S\* is plotted against either H\* or H\*\*, depending on whether the conditions are plunging or surging. The labels next to the data points show the wave condition number (see Table 5.2). On each of the figures a line is plotted representing the best fit of an equation of the form of either Equation 5.15 or Equation 5.16, as appropriate. From the gradients of these lines, values of  $C_{pl}$  and  $C_{su}$  were determined. The results are presented in Table 5.3. It should be noted that all results which recorded no damage, i.e.,  $S^* = 0$ , were omitted from the regression analysis. The standard deviation of  $C_{pl}$  and  $C_{su}$  was calculated for each structure (when sufficient data was available) by determining a stability coefficient for each individual test. These results are also presented in Table 5.3.

In the 1000 wave tests, damage levels,  $S_d$ , of 2 and 12 are equivalent to S\* values of 0.58 and 0.83 respectively. It can thus be seen that the data plotted in Figures 5.5 to 5.28 cover the full range of damage levels, from slight to near-destruction (see Section 5.2.1).

It is apparent from the graphs (and the standard deviations of the stability coefficients in Table 5.3) that there is a considerable amount of scatter in the stability results. This is inevitable in experiments of this type, since the layer stability is highly dependent on the random interlock of the rocks. The scatter displayed in Figures 5.5 to 5.28 is similar to that observed by Bradbury et al. It can also be seen that, in some cases, the regression analysis must rely on a small number of data points, largely as a result of the number of tests that either failed to cause any measurable damage or were so severe that they would have caused complete destruction. The former are plotted on the figures as causing zero damage, i.e., they lie of the H\* or H\*\* axis.

Also plotted on Figures 5.5 to 5.28 are lines representing  $C_{pl} = 6.2$  and  $C_{su} = 1.0$ , showing how the performance of each structure compared with that predicted by Van der Meer's equations. The 90% confidence limits of Van der Meer's equations are also presented, as determined from a standard deviation of 0.40 on  $C_{pl}$  and 0.08 on  $C_{su}$  (Ref. 5.1). The scatter in Van der Meer's results was thus much less than the scatter in our results; the average standard deviations of  $C_{pl}$  and  $C_{su}$  in our results were 1.76 and 0.15 respectively. This difference in scatter is almost certainly due to the different methods of layer construction used in the two studies; when individual placement is used the damage may be highly dependent on the way in which an individual rock interlocks with its immediate neighbours. With bulk placement, however, stability will be less dependent on interlock and therefore the displacement of an individual rock will have less consequence for the surrounding rocks.

## 5.6.2 Results of the analysis

## Effect of rock blockiness

The work of Bradbury et al showed that the stability of rocks under wave attack decreases with increasing rock roundness. It is intuitively easy to understand how this might be the case, since the more rounded a rock is, the less likely it is to interlock with its neighbours. Bradbury et al proposed values of  $C_{pl}$  and  $C_{su}$  that were a function of the Fourier Asperity Roughness, a measure of rock roundness and aspect ratio. Their findings are discussed in Section 2.4.2.3 of this report. Bradbury et al determined the following values of stability coefficient for various rock shapes:

|                  | $C_{pl}$ | C' <sub>pl</sub> | $C_{su}$ | C' <sub>su</sub> |
|------------------|----------|------------------|----------|------------------|
| Tabular/Elongate | 5.93     | 6.72             | 0.999    | 1.301            |
| Irregular        | 5.63     | 6.32             | 0.711    | 0.811            |
| Equant           | 5.61     | 6.24             | 0.894    | 1.087            |
| Semi-round       | 5.39     | 5.96             | 0.830    | 0.989            |
| Very round       | 5.35     | 5.88             | 0.713    | 0.810            |

Two values of plunging coefficient ( $C_{pl}$  and  $C'_{pl}$ ) and two values of surging coefficient ( $C_{su}$  and  $C'_{su}$ ) are given for each rock type.  $C_{pl}$  and  $C_{su}$  apply to the unmodified Van der Meer equation whilst  $C'_{pl}$  and  $C'_{su}$ 

apply to Bradbury et al's revised version, with the term  $(S_d / \sqrt{N})^{0.2}$  replaced by  $(S_d / \sqrt{N})^{0.25}$ . As can be seen from the coefficients presented above, Bradbury et al's structures tended to under-perform compared to Van der Meer's prediction, i.e.,  $C_{pl}$  was always less than 6.2 and  $C_{su}$  was always less than 1.0.

This was an unexpected result, since Bradbury et al used individual rocks placement, as opposed to Van der Meer's bulk placement. The difference was eventually attributed to the much thinner armour layers that resulted from individual placement  $(1.6D_{n50} \text{ compared to } 2.3D_{n50})$ . These conclusions were, however, restricted to structures with P = 0.1.

In the present study, rock roundness is characterised by the blockiness coefficient  $BL_c$ , as described in Section 4.4.5. Structures 2, 5 and 8 were built using the standard packing approach, and varied the blockiness range of the rock batches whilst keeping all the other rock parameters constant. These batches were then re-used to construct layers with the dense packing approach, as Structures 1, 4 and 7. The values of  $C_{pl}$  and  $C_{su}$  determined for these structures are given in Table 5.3 and plotted in Figure 5.29 and 5.30. Unfortunately the limited amount of damage caused by the surging waves did not allow  $C_{su}$  values to be calculated in some cases (see Table 5.3). The analysis will therefore concentrate on  $C_{pl}$ .

The  $C_{\text{pl}}$  values determined from these tests were as follows:

| BL <sub>c</sub> | C <sub>pl</sub> (standard) | C <sub>pl</sub> (dense) | C <sub>su</sub> (standard) | C <sub>su</sub> (dense) |
|-----------------|----------------------------|-------------------------|----------------------------|-------------------------|
| 40%-50%         | 6.33                       | 5.81                    | -                          | 1.67                    |
| 50%-60%         | 5.98                       | 6.77                    | 1.51                       | 2.08                    |
| 60%-70%         | 7.31                       | 10.25                   | 2.63                       | -                       |

As can be seen, there is a general increase in  $C_{pl}$  and  $C_{su}$  (and hence stability) as the blockiness of the rocks increases. The results are therefore in broad agreement with those of Bradbury et al, since blockiness can be regarded as the converse of roundness.

Bradbury et al examined a sample of the rocks used by van der Meer and concluded that their typical shape was between Equant and Semi-round according to the CIRIA/CUR definitions (see Section 2.2). As can be seen from Figure 4.2, very few of the rocks used in the current study fell into these shape categories. The rocks used by Van der Meer were therefore more rounded than the majority of the rocks used in the current study. This difference will be partly responsible for the differences in stability performance.

The data in Figure 5.29 also show the effect of packing approach on stability. The blockier rocks respond much more to placement method than the less blocky rocks do. The rocks with blockiness coefficients of between 60% and 70% produced a  $C_{pl}$  value of 10.25 when packed densely as opposed to a value of 7.31 when packed using the standard method. Equation 5.1 shows that the stability number,  $H_s/\Delta D_{n50}$ , is proportionate to  $C_{pl}^{4/3}$ . For any given level of damage, Structure 5 was thus capable of withstanding a wave height of 124% of that which could be withstood by a structure with a stability coefficient,  $C_{pl}$ , of 6.2. The effect of the dense pack was even more significant; Structure 4 was capable of withstanding a wave height of 195% of that which could be withstood by a  $C_{pl} = 6.2$  structure.

The response of the less blocky rocks to placement method was much less significant; in the case of the rocks with blockiness coefficients of between 40% and 50% the response to the dense packing was a slight decrease in stability.

As already explained, the lack of damage data in the surging wave zone inhibits the analysis of  $C_{su}$ . The results do not, however, contradict the results obtained in the plunging zone.

### Effect of rock aspect ratio

Tests 10 and 11 were carried out on structures made up of rocks with blockiness coefficients of between 50% and 60%. They differed from Structures 1 and 2, however, in that their aspect ratios, 1/d, were less than 2 rather than between 1.5 and 3.0 (see Table 5.1). The rocks with higher aspect ratios had thus been excluded from the batch. Previous to Bradbury et al's work it was generally assumed that rocks with high 1/d values were less stable than more equant rocks. It was therefore slightly unexpected that Bradbury et al determined higher stability coefficients for Elongate/Tabular rocks than for Equant rocks. Their method of shape classification did not, however, distinguish between aspect ratio and blockiness. The relatively high stability of their Elongate/Tabular rocks may have resulted from the fact that such rocks tend to have high blockiness coefficients, since they are often very slabby. The method of shape classification adopted by the current study makes this distinction, by using the blockiness coefficient, BL<sub>c</sub>.

In general, Structures 10 and 11 performed better than Structures 1 and 2, as can be seen by comparing the scatter plots shown in Figures 5.17 to 5.20 with those shown in Figures 5.5 to 5.8. The stability coefficients determined from linear regression were as follows:

| l/d        | C <sub>pl</sub> (standard) | C <sub>pl</sub> (dense) | C <sub>su</sub> (standard) | C <sub>su</sub> (dense) |
|------------|----------------------------|-------------------------|----------------------------|-------------------------|
| 1.5 to 3.0 | 5.98                       | 6.77                    | 1.51                       | 2.08                    |
| < 2.0      | 8.19                       | 8.45                    | 1.45                       | -                       |

The results show that rock batches were more stable when the rocks with high l/d values were excluded. This would appear to confirm the assumption that rocks with high aspect ratios are less stable than more equant rocks. This reduction in stability may arise from the fact that, since rocks with high l/d values tend to lie with their long axis in the plane of the slope, they form a thinner layer and have a relatively small area of interlock with their neighbours. Such rocks could be more easily plucked out of the layer by wave action. This hypothesis assumes a different failure mechanism to that assumed by Bradbury et al, who suggested that rocks lying with their long axis in the plane of the slope present a greater resisting moment to overturning by wave action.

### Low permeability structures

Tests 16 and 17 were carried out on structures with a notional permeability factor, P, of 0.1. They thus allow a direct comparison with the results of Bradbury et al's study. They used rocks with blockiness coefficients of between 50% and 60% and were constructed using the standard and dense packs respectively. The results are plotted on Figures 5.25 to 5.28. As can be seen, the structures out-performed the prediction of Van der Meer's equation, producing the following stability coefficients:

| Р   | C <sub>pl</sub> (standard) | C <sub>pl</sub> (dense) | C <sub>su</sub> (standard) | C <sub>su</sub> (dense) |
|-----|----------------------------|-------------------------|----------------------------|-------------------------|
| 0.1 | 7.91                       | 8.79                    | -                          | 2.63                    |

These findings are in contrast to the findings of Bradbury et al, who found that structures with P = 0.1 performed less well than the predictions of Van der Meer's equation, despite the individual placement of the rocks (see Section 5.6.2.1). This is difficult to reconcile with the results of the current study, since the standard layer should have been constructed in a very similar fashion to that of Bradbury et al, and the armour layer thicknesses were similar in both cases (1.6D<sub>n50</sub> for a double layer). In addition Bradbury et al covered a wide range of rock shapes, one of which should have corresponded to the rocks used on Structures 16 and 17.

Bradbury et al obtained a maximum  $C_{pl}$  value of 5.93, compared to a value of 7.91 obtained from the standard pack on Structure 17. The obvious conclusion to be drawn is that our standard pack was actually tighter than the pack used by Bradbury et al. It is possible that a minimum 3-point contact rule was not applied by Bardbury et al. This suggests that, when using individually placed armour layers, stability is extremely sensitive to the precise method of placement.

### Effect of test duration

Structures 13 and 14 were identical to Structures 1 and 2. They were, however, tested for a duration equivalent to 3000 waves rather than 1000 waves. Damage was also measured after 1000 waves. The results are summarised in Table 5.4. The measured stability coefficients were as follows:

| Waves | C <sub>pl</sub> (standard) | C <sub>pl</sub> (dense) | C <sub>su</sub> (standard) | C <sub>su</sub> (dense) |
|-------|----------------------------|-------------------------|----------------------------|-------------------------|
| 1000  | 6.76                       | 9.44                    | 1.50                       | 1.63                    |
| 3000  | 6.94                       | 9.59                    | 1.34                       | 1.68                    |

Figures 5.21 to 5.24 show the damage results recorded after 1000 waves. These may be used as a check on the repeatability of the results by comparing them with the results acquired from testing Structures 1 and 2. On Structure 14, constructed using the standard pack, a plunging stability coefficient,  $C_{pl}$ , of 6.76 was measured and a surging stability coefficient,  $C_{su}$ , of 1.50. The equivalent results from Structure 2 were 5.98 and 1.51. On Structure 13, which used the dense pack a  $C_{pl}$  value of 9.44 and a  $C_{su}$  value of 1.63 were measured. The equivalent results from Structure 1 were 6.77 and 2.08.

Although the standard pack stability was reproduced reasonably well, the dense pack was much more stable during its second test. The effect of dense packing was thus more significant in the latter tests. This could be due simply to random variation inherent in such tests. It is possible, however, that the quality of the layer construction might have improved over the course of the testing programme. In either case, it reinforces the proposition that the stability of individually placed layers is extremely sensitive to small changes in placement technique.

The results measured after 3000 waves are plotted in Figures 5.31 to 5.34. The stability coefficients determined from regression of the full data set (including the damage measured after 1000 waves) are given in Table 5.4. They are very similar to those determined after the 1000 wave tests. The trends displayed by the results of the 1000 wave tests are thus maintained over the remainder of the tests. This suggest that the term  $(S_d / \sqrt{N})^{0.2}$  adequately accounts for the time-dependency of damage.

It was speculated at the start of the project that, although a denser pack might delay the onset of damage, it might also make the structure more vulnerable to progressive failure and that any advantage of the denser pack might be lost after a small amount of damage had been done. However, the data plotted in Figures 5.31 to 5.34, along with the derived stability factors, show that the dense pack maintains its advantage over the standard pack over the longer term. For example, Test Conditions 9 and 14 caused considerable damage to Structure 14 during the 1000 wave tests (Figure 5.33) and more moderate damage to Structure 13 (Figure 5.31). During the following 2000 waves the damage proceeded at approximately the same rate on Structure 13 (Figure 5.31), long after Structure 14 had been destroyed. The dense pack does not therefore seem to encourage progressive failure.

### Effect of armour layer porosity

Figures 5.35 and 5.36 plot the plunging and surging stability coefficients (for all structures with P = 0.5) against the armour porosity, as defined using the methods developed in Chapter 4. Also plotted are lines representing Van der Meer's recommended values of 6.2 and 1.0 for  $C_{pl}$  and  $C_{su}$  respectively for bulk-placed layers. The majority of the stability coefficients determined for the individually placed layers are higher than the bulk-placed values. The surging wave coefficients are particularly high, although it should be remembered that they were based on very small data sets. It can also be seen that there is a general increase in stability coefficient as the armour porosity decreases. This is easy to understand intuitively, since lower porosity might be expected to be associated with greater interlock between individual blocks. The figures also plot formulae fitted to the data by least squares regression. They are as follows:

| $C_{pl} = 0.278 n_v^2 - 21.14 n_v + 406.8$ | (5.17) |
|--|--------|
|  |        |



The 90% confidence intervals of this formula, calculated from the standard deviation of the error in the best fit, are also plotted.

The porosity of the armour layers tested by Van der Meer is not know. However, if they were constructed using Equant to Semi-round stones, as claimed by Bradbury et al, using bulk-placement then it was probably relatively high. It is known that the bulk-placed armour layers built by Thompson and Shuttler had very high porosity values, since Ref. 5.2 quotes as-placed densities of up to 50%. It is therefore reasonable to assume thay Van der Meer's armour layers had porosity values of at least 40%. This accords well with the data in Figure 5.35, which shows that the plunging stability coefficients measured on the individually placed armour layers with porosities similar to bulk placed layers are no more stable than bulk-placed layers. Only when the layer porosity is decreased by careful placement and/or selection of rock shape does a measurable stability advantage exist.

# 5.7 Results of the single layer armour stability analysis

As explained in Section 5.5.2.2, the test procedures used for the single layers were different to those used for the double layers because of the different definition of failure. Like the double layer tests, the single layer tests were run in groups of constant period and increasing wave height. However, unlike the double layer tests, once a single rock had been displaced from the layer the structure was deemed to have failed and no more tests were carried out in that period group.

On failure, a stability coefficient,  $K_D$ , was then calculated using Equation 5.5 (a form of the Hudson equation) as follows:

$$K_{\rm D} = (H_{1/10} / \Delta D_{\rm n50})^3 / \cot \alpha$$
(5.19)

A value of  $K_D$  was determined for each wave period group. The value of  $H_{1/10}$  used to determine  $K_D$  for each period group was the highest wave condition that did not cause any damage. This is essential in a single layer, since the filter becomes vulnerable as soon as it is exposed. The stability results are presented in Table 5.5. In each case, the type of wave attack (plunging or surging) is also given. In most cases the stability coefficients determined for surging wave conditions are higher than those obtained for the plunging conditions. There is a great deal of variation in the  $K_D$  factors; they vary from 1.5 to 23.3. This is largely a result of the failure depending on the performance of a single rock out of many.

Camfield (Ref. 5.6) conducted experiments of 'selectively placed' single armour layers and determined  $K_D$  factors of between 4 and 23 for incipient failure, defined as the removal or displacement of a least one armour stone. No information was given concerning the shapes of the rocks used in Camfield's study, and no dependency on wave period was observed. The large variation in measured  $K_D$  values was attributed solely to variations in construction quality. Photographs of typical armour placement methods in the prepublication version of the new Coastal Engineering Manual (Ref. 2.19) suggest that 'selective' placement corresponds closely to the 'dense' placement method used in the current study and applied to all of the single layer structures.

It should be noted that Camfield determined  $K_D$  from the wave condition that caused the structure to fail, whereas the current study defined  $K_D$  from the highest wave condition which the structure could sustain without failing. Considering the fragility of single layer structures, which means that incipient failure can very quickly become progressive failure, the latter definition seems more appropriate for a conservative design. Given this proviso, Camfield's results were in broad agreement with those of the current study, both in their magnitude and their degree of variability.

The Hudson stability formula does not take any account of wave period. For design purposes the stability coefficient should therefore represent the case of the wave period that is most damaging to the structure. The lowest value of  $K_D$  was therefore selected from each structure. These values (designated  $K_{D min}$ ) are

given in Table 5.6. There was no obvious influence of layer characteristics on  $K_{D min}$ , so the variation in measured values is probably, as with Camfield's results, due to variable construction quality. The lowest measured values of  $K_{D min}$  was 1.5 for both plunging and surging conditions.

The current edition of the Shore Protection Manual recommends a  $K_D$  value of 2.9 for selectively placed single layer armour-stones in non-breaking wave conditions (Ref. 2.2). It cautions against the use of single layers in breaking wave conditions. The results of the current study suggest that a value of  $K_D$  of 1.5 should provide the basis of a reasonably conservative design for both breaking and non-breaking waves.

# 5.8 Results of the overtopping discharge analysis

## 5.8.1 Method of analysis

The output of the overtopping measurements was the discharge (or flow rate) per unit length of the structure crest, averaged over the course of the test. On sloped structures, differences in the overtopping performance of different types of surfaces are generally accounted for by a roughness coefficient. This coefficient is designated as  $\gamma_f$  in Van der Meer & Janssen's equations and as r in Owen's equation (see Section 5.3). The analysis presented here determines roughness coefficients for each of the armour layers tested. It concentrates on Van der Meer & Janssens's method since it is applicable to a wider range of wave conditions than is Owen's method.

Van der Meer's overtopping equations (Equations 5.7 and 5.8) can be re-written as follows:

$$\ln(Q_b) - \ln(0.06) = -5.2R_b/\gamma_f \qquad \qquad \text{for plunging waves} \qquad (5.20)$$

and

 $\ln(Q_n) - \ln(0.2) = -2.6R_n/\gamma_f \qquad \text{for surging waves} \qquad (5.21)$ 

Figures 5.37 to 5.42 plot, as an example, the results of the overtopping measurements taken on Structures 4, 5 and 6 using Van der Meer & Janssens's dimensionless variables. The results are divided into plunging and surging wave conditions according to the critical Irribarren Number,  $\zeta_{mc}$ . The figures plot [ln(Q<sub>b</sub>) - ln(0.06)] against R<sub>b</sub> for the plunging wave conditions and [ln(Q<sub>n</sub>) - ln(0.2)] against R<sub>n</sub> for the surging wave conditions. In each case a line was fitted to the data using linear regression. The gradients of these lines provide the roughness coefficients,  $\gamma_f$ , that make the experimental data conform to Equations 5.7 and 5.8. The same process was carried out for all the structures tested. The roughness coefficients are tabulated in Tables 5.7 and 5.8.

# 5.8.2 Results of the overtopping analysis

The results from the double layer structures are given in Table 5.7. The value of  $\gamma_f$  measured on the double layer structures varied from 0.40 to 0.48 in the plunging wave zone and from 0.65 to 0.90 in the surging wave zone. The effect of packing density appeared to be negligible; the average  $\gamma_f$  for the densely packed double layers was 0.44 compared to 0.43 for the double layers constructed with standard packing. The corresponding averages in the surging wave zone were 0.79 and 0.80. There was no obvious relation ship between armour layer porosity and roughness factor. The notional permeability, P, of the structure had no significant influence in the plunging zone; the roughness factors for Structures 16 and 17 were 0.42 and 0.40 respectively. In the surging zone, the permeability may have made difference; roughness factors of 0.90 and 0.85 were measured on Structures 16 and 17 respectively.

The single layer results have higher roughness coefficients;  $\gamma_f$  ranged from 0.45 to 0.53 in the plunging zone and from 0.76 to 0.96 in the surging zone. As with the double layer results, there appeared to be no obvious relationship between  $\gamma_f$  and the armour layer porosity.
Figures 5.43 and 5.44 plot the dimensionless overtopping results for all structures combined, divided into plunging and surging conditions. Best-fit lines are also plotted. The double and single armour layer results were analysed separately, giving the following roughness factors:

|                   | $\gamma_{\rm f}$ (plunging) | $\gamma_{\rm f}({\rm surging})$ |
|-------------------|-----------------------------|---------------------------------|
| All single layers | 0.50                        | 0.85                            |
| All double layers | 0.43                        | 0.79                            |

In Ref. 5.4, Van der Meer & Janssen make the following recommendations for  $\gamma_f$  in the plunging zone:

|               | $\gamma_{\rm f}$ (plunging) |
|---------------|-----------------------------|
| Single layers | 0.55-0.60                   |
| Double layers | 0.50-0.55                   |

These values are higher than those measured in the current study. Although Van der Meer & Janssen's recommended values were measured directly from run-up levels, rather than inferred from overtopping discharges as in the current study, they have been used successfully to predict overtopping discharges. The comparison with the values derived in the current study is therefore valid.

The difference in the roughness factors obtained in the current study and those given in Ref. 5.4 are primarily due to the fact that the latter are intended to be applied to rough surfaces on impermeable structures, such as clay dikes. The permeable structures used in the current study might be expected to dissipate some of the energy of the wave run-up by percolation through the armour layer and into the filter layer and core. The permeability of the structures probably also explains the high degree of scatter observed in the results.

Ref. 5.4 makes no specific recommendations of roughness coefficients for permeable structures. However, the CIRIA/CUR rock manual presents the results of model tests carried out by Delft Hydraulics (Ref. 5.7), which showed that run-up levels on armoured slopes were influenced by the structure's notional permeability factor, P. Separate prediction equations were developed for structures with P = 0.1 and for structures with P > 0.4, showing that structures with higher permeability generally imposed lower limits on run-up levels. The results were not, however, presented in the form of roughness coefficients, so cannot be readily used in the overtopping prediction equations. It is also apparent, from the results reproduced in the CIRIA/CUR manual, that the run-up data acquired on structures with high permeability displayed a greater degree of scatter than the data obtained from structures with low permeability.

It should also be remembered that the test structures included a narrow crest berm made up of two rocks (see Figures 5.1 and 5.2). This is a common characteristic of rock-armoured slopes as it improves the stability of the crest of the structure. This will account for a small part of the difference between Van der Meer & Jenssen's roughness coefficients and those obtained here. Its inclusion will, however, make our results more practically applicable.

For surging waves, the advice given in Ref. 5.4 is less specific. It recommends that when  $\zeta_m > 3-4$  then the roughness factors approach 1. This is in line with the findings of the current study, which recorded  $\gamma_f$  values of up to 0.96 in the surging wave zone.

### 5.8.3 Comparison with Owen's method

The comparison of the results with Owen's method was carried out in a similar way to the comparison with Van der Meer's method. Equation 5.6 was re-written as follows:

 $\ln(Q^*) - \ln(A) = -BR^*/r$ 

(5.22)



The A and B coefficients for a 1:2 slope were taken from Ref. 5.3 to be  $9.39 \times 10^{-3}$  and 21.6 respectively. Plotting [ln(Q\*) - ln(A)] against [-BR\*] and fitting a line by regression thus determined a value of the roughness coefficient, r. Figures 5.45 and 5.46 show the results. All of the double layer results were combined to produce Figure 5.45 and all of the single layer results were combined to produce Figure 5.45 and all of the single layer results were combined to produce Figure 5.46. As explained in Section 5.3.2, Owen's method is strictly applicable only to wave conditions with  $s_m \ge 0.035$ . The regression analysis was therefore restricted to such conditions. Figures 5.45 and 5.46, however, plot all of the test results, including those with  $s_m < 0.035$ . It can clearly be seen that the low steepness test results show excessive scatter and generally fall well below the regression line determined from the results with  $s_m \ge 0.035$ .

The roughness coefficients determined from the analysis of all the structures were as follows:

|                   | $r(s_m \ge 0.035)$ |
|-------------------|--------------------|
| All single layers | 0.54               |
| All double layers | 0.48               |

The r values obtained in this way are slightly higher than the  $\gamma_f$  values determined through the Van der Meer analysis of the plunging wave tests. The relationship between the single and double layer result is, however, very similar, i.e., the coefficient for a single layer is slightly higher than that for a double layer.

In the CIRIA/CUR rock manual it is recommended that a roughness coefficient of 0.50-0.60 be used in Owen's equation to represent a double layer of rock armour placed over an impermeable base. The lower values obtained here are, again, probably due to the fact that the armour layer was placed over a permeable structure. The relationship between the values obtained and the values recommended for impermeable structures is similar to that observed by the analysis in Section 5.8.2; the roughness coefficients of the permeable structures are lower than the minimum recommendation for the permeable structures.

The CIRAI/CUR manual recommends that a roughness coefficient of 0.80 should be applied to a single layer of armour stones placed over an impermeable base. This is considerably higher than the 0.55-0.60 recommended by Van der Meer & Janssen (see Section 5.8.2). Our results therefore suggest that, even allowing for the effect of structure permeability, Van der Meer & Janssen's estimate is the more realistic of the two.

### 5.9 Conclusions

### 5.9.1 Armour stability performance

The individually placed armour layers generally performed at least as well as predicted by Van der Meer's equations. Only in a few cases did the stability coefficients inferred from the results fall below the values derived by Van der Meer (see Figures 5.35 and 5.36).

Armour layers constructed using rocks with high blockiness coefficients were generally more stable than those constructed using rocks with low blockiness coefficients (see Figures 5.29 and 5.30). This is in accordance with the findings of previous researchers, who found that rock stability decreases with rock roundness.

The effect of changing the packing approach from 'standard' to 'dense' had a variable effect. It seems likely that, when an attempt is made to pack the rocks densely, the resulting stability is very sensitive to the level of workmanship applied to the build. This made repeatability of test results, even using the same personnel to construct all of the models, extremely difficult (see Section 5.6.2.4). The degree of scatter in the stability results of individual structures was also very high; Van der Meer's bulk-placed layers displayed standard deviations of 0.40 and 0.08 in  $C_{pl}$  and  $C_{su}$  respectively. The average standard deviation of  $C_{pl}$  for the individually placed layers was 1.76 (see Section 5.6.1). In most cases there was insufficient data to calculate a standard deviation of  $C_{su}$ .



Blockier rocks respond particularly well to denser packing (see Figures 5.29 and 5.30). The highest value of the plunging wave stability coefficient,  $C_{pl}$ , was 10.27. This was measured on an armour layer made up of relatively blocky rocks in a dense pack (Structure 4). The same batch of rocks produced an armour layer with a  $C_{pl}$  value of 7.31 when placed using the standard method (Structure 5).

Equant rocks were shown to be more stable under wave attack than rocks with high aspect ratios, provided that the blockiness coefficients of the rocks were equal (see Section 5.6.2.2). This refined the findings of Bradbury et al, who suggested that Elongate/Tabular rocks were more stable than Equant rocks, without considering blockiness as a parameter.

The low permeability structures (with P=0.1) performed considerable better than those tested by Bradbury et al in similar experiments. For a standard pack structure, the stability coefficient was 7.91 compared to a maximum of 5.93 determined by Bradbury et al (see Section 5.6.2.3). The fact that the dense pack was even more stable ( $C_{pl} = 8.79$ ), reinforces the idea that the stability of densely packed layers is very sensitive to the degree of workmanship involved in the construction.

Those densely packed structures which were tested for 3000 waves maintained the stability advantage which they had displayed at 1000 waves (see Section 5.6.2.4) over the longer term. There was no indication that increasing the density of the rock pack encouraged a progressive failure.

An approximate relationship exists between armour layer porosity and stability. The layers that had estimated porosities of 37% or greater displayed similar stability characteristics to Van der Meer's layers, which are estimated to have had porosities of at least 40% (see Figures 5.35 and 5.36). At lower porosity levels, the stability coefficients begin to increase rapidly.

The stability of single layer structures, analysed in terms of a Hudson  $K_D$  factor, is extremely variable, mainly because failure is dependent on the removal of a single rock (see Section 5.7).  $K_D$  factors, defined for a 'no-damage' situation, varied from 1.5 to 23.3. No obvious relationship between stability and either layer porosity or construction method was observed. For a conservative approach it will therefore be recommended that a  $K_D$  factor of 1.5 should be applied to all single layer designs.

### 5.9.2 Armour layer overtopping performance

Overtopping performance was quantified by determining new roughness factors that could be applied to Van der Meer & Janssen's and Owen's overtopping prediction equations (see Section 5.8). The roughness factors that had previously been used in these equations were intended for application to armour layers placed over impermeable structures. The roughness factors determined for the porous structures used in the current study were consistently lower, reflecting the ability of such structures to dissipate wave energy by percolation through the underlayer and core.

Changing the packing approach from standard to dense had no measurable effect on the overtopping performance of the armour layers. The number of layers did however, have a measurable effect; the slope roughness factors determined on single layers were consistently higher than those determined for double layers.

### 5.10 References for Chapter 5

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### 6. CONCLUSIONS AND APPLICATIONS OF THE RESEARCH

### 6.1 Introduction

The aims of this chapter are to summarise the findings of the research and to examine their implications for designers of rock-armoured structures. The intention is to produce practical design guidance that will encourage the take-up of the research findings by industry.

The majority of previous research into the characteristics of rock armour has focused on layers that were formed by bulk-placement. The objective of the current study was to provide an understanding of the characteristics of armour layers formed by individually placed rocks. Two main areas were considered; firstly the geometry of the layers, i.e., their porosity and thickness and secondly the hydraulic performance of the layers, i.e., their stability under wave attack and their ability to dissipate wave energy.

This chapter can be read alone to give an overview of the important findings. For readers wishing to explore aspects of the study in more detail, reference is made to the appropriate sections of the report.

### 6.2 Summary of the research findings

### 6.2.1 Rock characteristics

The first stage of the research programme was an identification of the important rock characteristics, with an emphasis on the classification of rock shape. It was felt that rock shape would be particularly significant where the interlocking of individually placed rocks was concerned. The following rock characteristics were investigated:

- Rock batch grade width,  $M_{85}/M_{15}$  (or  $M_{15}/M_{85}$ )
- Rock shape characteristics, in terms of -Rock blockiness coefficient, BL<sub>c</sub> (or bl<sub>c</sub>) Rock aspect ratio, l/d (or d/l) Comparison with archetypal shape categories

The batch grade width,  $M_{85}/M_{15}$ , describes the variation of rock size (or mass) within the batch of rocks. It is the ratio of the individual rock weight not exceeded by 85% (by weight) of the batch to the individual rock weight not exceeded by 15% (by weight) of the batch. For heavy grades of armour this ratio is typically between 1.5 and 2.5. The blockiness coefficient,  $BL_c$ , is a measure of rock roundness and is defined as the percentage of an imaginary enclosing box that is taken up by the rock (see Figure 4.5). The blockiness coefficients of heavy grade armour rocks can vary widely but are typically between 40% and 70%. The aspect ratio, 1/d is a measure of rock's aspect. It is the ratio of the longest to the shortest dimension of the rock, and in heavy grade armour is typically between 1.5 and 3.0. For the purposes of more convenient analysis, each of the parameters in the above list was given an alternative definition. These are the forms in which they are used in the prediction methods described in Section 6.2.2. They are as follows:

- $M_{15}/M_{85}$  is the inverse of  $M_{85}/M_{15}$
- bl<sub>c</sub> is the blockiness expressed as a proportion rather than as a percentage
- d/l is the inverse of l/d

It is useful to quantify these parameters from a sample of rocks if possible and determine the  $M_{15}/M_{85}$  ratio of the batch and the mean and standard deviations of the distributions of  $bl_c$  and d/l. Qualitative estimates of rock shape, such as the CIRIA/CUR shape categories (see Figure 2.1), are also a useful guide to the rock batch properties.



### 6.2.2 Armour layer geometry

The research programme involved a series of trial panel constructions, both in the field using heavy grades of armour rock, and in laboratory models using scales of between 1:12 and 1:29. It was found that the laboratory models could adequately represent the full-scale panels provided that the rock shape characteristics and the method of construction were carefully reproduced in the laboratory (see Section 4.7).

The rock shapes were found to influence armour layer geometry as follows:

- Rock with high blockiness coefficients tended to form denser layers.
- Rocks with high aspect ratios tended to form more porous layers
- Rocks with high blockiness coefficients tended to form thicker layers.
- Rocks with high aspect ratios tended to form thinner layers.

Although all of the trial panels were made up of individually placed rocks, some variations in placement approach were investigated. Two methods, designated *standard* and *dense*, were applied, as follows:

- In the *standard* placement approach the rocks were placed with a minimum of orientation control. Each rock was placed with the orientation that it had naturally adopted in the stockpile. The only placement criterion that had to be satisfied was that the rock should have a minimum of three points of contact in the layer in which it was placed. Only if three points of contact could not be achieved with the rock's natural orientation, was the rock rotated.
- In the *dense* placement approach, greater orientation control was applied. The rocks were rotated until the orientation that was likely to produce the maximum number of points of contact in the layer (and the minimum volume of voids) was achieved. Individual rocks were removed and replaced several times if necessary.

The variation in construction method was found to have a measurable effect on the armour layer porosity.

A series of equations were developed describing how rock shape, placement method and armour slope influence armour layer geometry (see Section 4.8). These were as follows:

$$n_{v} = 100 \text{ x} (A + B \text{ } bl_{c \text{ mean}} + C \text{ } d/l_{\text{mean}} + D \text{ } bl_{c \text{ sdev}} + E \text{ } d/l_{\text{sdev}} + F \text{ } M_{15}/M_{85})$$
(6.1)

$$k_{t} = A + B bl_{c mean} + C d/l_{mean} + D bl_{c sdev} + E d/l_{sdev} + F M_{15}/M_{85}$$
(6.2)

where  $n_v$  is the armour layer porosity (%)

k<sub>t</sub> is the layer thickness coefficient

bl<sub>c mean</sub> is the mean of the bl<sub>c</sub> values of the rocks

- $d/l_{mean}$  is the mean of the d/l values of the rocks
- $bl_{c sdev}$  is the standard deviation of the  $bl_c$  values of the rocks
- $d/l_{sdev}$  is the standard deviation of the d/l values of the rocks

The values of the coefficients A to F are given in Tables 6.1 to 6.3 for single and double layers and for various structure slopes. Equations 6.1 and 6.2 apply to single and double layers constructed using the standard placement method. The effect of changing from the standard to the dense placement method is described by the following equation:

$$\Delta n_{v} = 100 \text{ x} (A + B \text{ bl}_{c \text{ mean}} + C \text{ d/l}_{mean} + D \text{ bl}_{c \text{ sdev}} + E \text{ d/l}_{sdev} + F \text{ M}_{15}/\text{M}_{85})$$
(6.3)

where  $\Delta n_v$  is the change in porosity induced by changing from standard to dense placement method.

The values of the coefficients A to F are given in Table 6.4. This adjustment applies to double layers only; single layers should always be constructed using the dense placement method.

The 90% confidence limits of predictions made using these equations are as follows:

Single layer  $n_v$ , +/-3.6% Single layer  $k_t$ , +/-0.078 Double layer  $n_v$ , +/-2.4% Double layer  $k_t$ , +/-0.092

These confidence limits describe the scatter observed in the model tests only; they do not take account of other factors (such as the workmanship involved in the construction process) that are beyond the control of the researchers. They were, however, applied successfully to a limited number of field tests.

### 6.2.3 Armour layer stability

The most widely used design tools for predicting the stability of rock armour layers under wave attack are Van der Meer's equations, which are as follows:

$$H_s / \Delta D_{n50} = 6.2 P^{0.18} (S_d / \sqrt{N})^{0.2} \zeta_m^{-0.5}$$
 for plunging waves (6.4)

$$H_{s} / \Delta D_{n50} = 1.0 P^{-0.13} (S_{d} / \sqrt{N})^{0.2} (\cot \alpha)^{0.5} \zeta_{m}^{P} \text{ for surging waves}$$
(6.5)

The terms of the equations are defined in the notation section of this report. Van der Meer's equations are generally taken to apply to armour layers made up of bulk-placed rocks. The current study subjected armour layers made up of individually placed rocks to random wave attack and measured the resulting damage. The stability of the individually placed layers was generally at least as good as that predicted by Van der Meer's equations (see Section 5.6). Van der Meer's method can therefore be applied conservatively to individually placed layers.

The stability of the individually placed layers was found to be influenced by:

- Rock placement method
- Rock shape characteristics, in terms of -Rock blockiness coefficient Rock aspect ratio

The tests showed that rocks with high blockiness coefficients were more stable than those with low blockiness coefficients and that equant rocks were more stable than elongate rocks. It was also shown that the stability of the layer could be increased by applying the dense placement method as opposed to the standard placement method (see Section 6.2.2 above for definitions of standard and dense placement methods).

The stability of each layer tested was quantified by the determination of alternative stability coefficients,  $C_{pl}$  and  $C_{su}$ , in place of the values of 6.2 and 1.0 in Equations 6.4 and 6.5. A higher value of stability coefficient indicates that an armour layer is capable of withstanding a greater wave-height for a given level of damage. Figures 6.1 and 6.2 plot the resulting stability coefficients against the armour layer void porosity. Although the data display a considerable amount of scatter, it can be seen that higher armour stability is generally associated with low void porosity.

The data plotted in Figures 6.1 and 6.2 were acquired from tests carried out on structures with notional permeability P = 0.5. Tests conducted on structures with P = 0.1 also showed that individually placed armour layers out-performed bulk-placed layers.

The interaction between rock shape, placement method, void porosity and armour stability was found to be extremely complex. There was a great deal of scatter in the experimental data and repeatability of test results was difficult to achieve. It was concluded that, when rocks are placed individually, their stability is particularly sensitive to the level of workmanship applied to the construction process. The degree of scatter in the stability results was much greater than had been observed in any of Van der Meer's original experiments. The results should therefore be applied very conservatively.

The research programme also investigated single armour layers (see Section 5.7). Their stability was analysed in terms of a stability factor,  $K_D$ , in Hudson's equation as follows:

$$H_{1/10} / \Delta D_{n50} = (K_D \cot \alpha)^{1/3}$$
(6.6)

The  $K_D$  factors of single layers, were defined at a no-damage situation and were found to vary widely, from 1.5 to 23.3. No obvious relationship between stability and rock shape was observed. This randomness of stability was attributed to the failure of the structures being sensitive to the behaviour of a single rock, since once one rock had been removed the structure was in danger of failing.

### 6.2.4 Armour layer wave dissipation

The tests also included an assessment of the overtopping performance of the armour layers (see Section 5.8). The test measurements were compared with estimates made using the standard overtopping prediction methods, i.e., the method of Owen:

$$Q_* = A \exp \left(-BR_*/r\right) \tag{6.7}$$

and the method of Van der Meer & Janssen:

| $Q_b = 0.06 \exp(-5.2 R_b / \gamma_f)$                 | for plunging waves | (6.8) |
|--|--------------------|-------|
| $Q_{\rm n} = 0.20 \exp(-2.6 R_{\rm n}/\gamma_{\rm f})$ | for surging waves  | (6.9) |

The terms of these equations are defined in the notation of this report. The results of the tests were used to infer alternative values of the roughness coefficients, r in Owen's equation and  $\gamma_f$  in Van der Meer & Janssen's equations, for the various types of structures tested. The results were as follows:

| Owen's equation                        |                                |
|--|--------------------------------|
| Current study                          | Previous recommendation        |
| Single layers, $r = 0.54$              | Single layers, $r = 0.80$      |
| Double layers, $r = 0.48$              | Double layers, $r = 0.50-0.60$ |
| Van der Meer & Janssen's equations – p | olunging waves                 |
| Current study                          | Previous recommendation        |
| Single layer, $\gamma_f = 0.50$        | Single layers, 0.55-0.60       |
| Double layer, $\gamma_f = 0.43$        | Double layers, 0.50-0.55       |
| Van der Meer & Janssen's equations – s | urging waves                   |
| Current study                          | Previous recommendation        |
| Single layer, $\gamma_f = 0.85$        | Single layers, $< 1.0$         |
| Double layer, $\gamma_f = 0.79$        | Double layers, $< 1.0$         |

The values of roughness coefficient thus determined were lower than those currently recommended. The principal reason for this difference is believed to be that the currently recommended values are applicable strictly to armour layers placed over impermeable structures. The structures tested in the current study had permeable cores that allowed water to percolate through the armour layers, thus limiting overtopping.

### 6.3 Practical application of the research findings

### 6.3.1 Determining rock shape characteristics

The application of the methods proposed in this report relies on obtaining an accurate description of the shapes of the rocks that will make up the armour layer. Ideally, a representative batch of rocks should be quantified in terms of mass and shape characteristics. During field trials conducted for this study, batches of between 70 and 240 rocks were measured. The data required for each rock (i.e., each piece of armourstone) in the batch are as follows:

- The mass
- The blockiness coefficient (as obtained from the mass, rock density and measured dimensions)
- The aspect ratio

From these data the parameters required by Equations 6.1, 6.2 and 6.3 can be determined. In most cases however, when preparing a design, such detailed information will not be available. It will therefore be necessary to assume values of the rock shape characteristics, as described in Section 6.3.2.

In estimating the typical blockiness for a rock source, several factors require consideration. These factors are primarily rock type, rock size in relation to typical discontinuity spacings and production methods.

The most common sedimentary rock types exploited for armourstone are limestones, dolostones and sandstones. Where they occur in-situ in the quarry, they will have a characteristic spacing between the bedding planes and between the various sets of joints which typically cut orthogonally across the bedding planes. Blocks that are extracted by being loosened along these naturally occurring discontinuities will often retain a high blockiness inherited by the orthogonality of the joints and bedding planes. However, it is possible that the blasting process will not just loosen but it will fragment the rocks, creating freshly intersecting irregular fractures that would reduce blockiness. The extent to which this happens is likely to depend on the thickness between bedding planes. So for example, in a bedded sequence of Carboniferous Limestone, if the mean bedding spacing is 2 metres, (~20 tonne in-situ blocks) a typical grading based on the smaller products of the blast pile e.g. 1 to 3 tonne blocks, is almost certainly derived of blocks bounded by new irregular blast induced fractures. In contrast, (provided a high energy blast is not used) for a limestone with a mean bedding spacing of, say, 0.9 metres, it is reasonable to expect relatively blocky pieces with natural bedding and joint surfaces to fall out of the blast in the 1 to 3 tonne size range.

Igneous rock types such as granite, syenite, andesite, gabbro, basalt and dolerite, are all popular sources of armourstone. The joint patterns and discontinuity spacings vary considerably, although with basalts and dolerites there is often a tendency to produce columnar jointing patterns (linked to cooling/shrinkage) where the width of columns may promote high blockiness values. Thus, higher blockiness values may be expected for armourstone gradings with mass ranges (and associated dimension ranges) that match the natural column spacing. In general, the high aspect ratio of the in-situ columnar blocks that can be seen in the quarry face is not well preserved after the blasting process. This is because fracturing normal to the column axes often occurs leaving reasonably equant blocks with a high blockiness in the blast pile. For the remaining igneous rock types and especially in granites, sub-horizontal sheeting joints (caused by unloading stress relief) may provide a dominant discontinuity set causing the rock mass to break up in a similar fashion to bedded sedimentary rocks. Again, this may give quite blocky armourstone. However, in igneous rocks that are being exploited for armourstone, it is more common for the joint patterns to produce irregular patterns of non-orthogonal, often widely spaced joints so that the bocks produced for gradings of



heavy armourstone are generally bounded by fresh blast-induced fractures and are therefore often, on average, of lower blockiness.

Metamorphic rocks exhibiting a natural banding (i.e. foliation produced by mineral alignment or mineral segregation) such as gneiss are sometimes used for armourstone. If the foliation is well developed and clearly visible, these sources of armourstone often yield rocks with a higher aspect ratio. Blockiness will be governed by the spacing between sets of natural joints and spacing between planes of weakness and how these compare with the average dimension of the armourstone grading.

Armourstone may also be obtained from dimension stone quarries (e.g. the syenite rocks from the Larvik quarries). These are typically pieces cut out (or pneumatically split using a row of closely spaced holes) and thus retain a very orthogonal blocky shape, but have later not been selected for further cutting and polishing. Natural blocks that are bounded by several angled joints are also not used and if very large, are further broken up e.g. by a breaker, to make them smaller for manoeuvrability into the waste piles. In most cases, these uneconomic waste blocks that are by-products of the dimension stone industry make excellent armourstone, and a large proportion of the blocks in any such consignment will retain the blocky characteristics resulting from the original cutting and splitting processes.

It may be possible to determine the mean blockiness of a batch based on the individual rock type, production methods and some details about the discontinuity spacings. However, this research has yet to be undertaken before any conclusive findings can be reported. For this reason, it is recommended that, when measurements of shape characteristics are not available, the values measured during the field trials carried out for the present study are assumed for design purposes. The use of the average shape characteristics is discussed in Section 6.3.2. (Note: in the rare case that the source rock, armour size and production methods are known to match or resemble any particular source of rock reported in the field trials, the shape characteristics from that specific field trial may be considered the most appropriate set of values to use for design purposes.)

### 6.3.2 Designing armour layer geometry

Equations 6.1 to 6.3 provide a method of estimating the geometric properties of the armour layer, using the rock shape and size distributions. The information required to use the equations is outlined in Section 6.2.2. As an illustration of how the properties of the layer can vary, Figures 6.3 to 6.6 plot Equations 6.1 and 6.2 over the full range of values of  $bl_{c mean}$  and  $d/l_{mean}$  used in the experimental work for single and double layers. The other independent variables in the equations were set to typical values for heavy grade armour rocks, as discussed below. The figures demonstrate how rock shape can influence the armour layer porosity and layer coefficient. Blocky rocks tend to form denser layers, whilst elongate rocks tend to form less dense layers. According to the equations, the predicted porosities range from 28% to 40%, whilst layer coefficients range from 0.60 to 1.00.

The information required to use Equations 6.1 to 6.3 is, however, highly unlikely to be available during the design stage of a project. One of the most important of the required parameters is rock blockiness. Section 6.3.1 explains how blockiness can vary depending on rock source, production method and handling method. There is currently, however, no reliable method of predicting rock blockiness without direct measurement of a rock batch. A method of estimating the armour properties for initial design purposes is therefore required.

The curves in Figures 6.3 to 6.6 represent the full range of model parameters that were tested, including batches of rock that were specially selected to produce extreme values to help identify trends. The majority of rock batches fall within a much narrower range. During the five field tests (which used rock batches intended for coastal protection works) the ranges of the independent variables in Equations 6.1 to 6.3 were as follows:

|                      | Minimum | Maximum | Mean  |
|----------------------|---------|---------|-------|
| bl <sub>c mean</sub> | 0.538   | 0.635   | 0.615 |
| d/l mean             | 0.480   | 0.554   | 0.508 |
| bl <sub>c sdev</sub> | 0.111   | 0.126   | 0.119 |
| d/l sdev             | 0.087   | 0.127   | 0.104 |
| $M_{15}/M_{85}$      | 0.485   | 0.676   | 0.558 |

The rock batches came from a variety of sources and there is no reason to believe that their shapes were untypical. The application of the mean values to Equations 6.1 to 6.3 produces the following porosity and layer coefficients for a 1:2 slope armour layer:

|               | Porosity | Layer coefficient |
|---------------|----------|-------------------|
| Double layers | 32.1     | 0.91              |
| Single layers | 32.3     | 0.83              |

Values for other slopes can be predicted using the coefficients given in Tables 6.1 and 6.3. These are the suggested values to use in the preliminary design of the armour layer if no information on rock shape is available. If confidence limits are required, then those given in Section 6.2.2 should be applied. If the special measures described in Section 6.2.2 are taken to produce a dense pack then, according to Equation 6.3 and the typical rock characteristics given above, the porosity of the double layer can be reduced by 1.5%.

The values given above apply to layers made up of individually placed rocks using plant which provides an adequate degree of control over the placement, and in particular the orientation, of the rocks. Typically, this would require placement by a grab. Rocks placed with little or no degree of control, such as those tipped from an excavator bucket, will not satisfy these criteria. Such layers should be regarded as bulk-placed layers and should be designed according to the existing criteria (see Chapter 2).

The porosity and thickness of a layer will also depend on the skill and attention of the plant operator and the quality control applied on site. Such variation is difficult to account for in these recommendations. It is therefore recommended that test panels are constructed, as specified in the CIRIA/CUR manual on the use of rock in coastal engineering (Refs. 2.4 and 2.5). These are probably more important for individually placed layers than for bulk-placed layers. They will provide by far the best method of estimating quantities and ensuring agreement between all the interested parties.

### 6.3.3 Designing armour layers for stability

Figures 6.1 and 6.2 plot the plunging and surging stability coefficients against armour void porosity. The data were measured on the structures with notional permeability factors, P, of 0.5. Each graph also plots a curve fitted to the data by regression, along with 90% confidence limits. Van der Meer's recommended values of  $C_{pl} = 6.2$  and  $C_{su} = 1.0$  for bulk-placed layers are plotted as horizontal lines on each figure. The figures suggest that the stability of layers with void porosities approaching 40% is similar to that of Van der Meer's bulk-placed layers. When the void porosity reduces below 35% then the stability begins to increase significantly.

If armour void porosity can be confidently predicted, then Figures 6.1 and 6.2 can be used to estimate stability coefficients. For the reasons discussed in Section 6.2.3, the scatter in the data is extremely wide. The same applies to the porosity predictions, as can be seen from the width of the 90% confidence intervals given in Section 6.2.2. It is therefore suggested that, to ensure a conservative estimate of armour layer stability, the upper limit of the porosity prediction is used in conjunction with the lower limit of the stability coefficient prediction. It should also be noted that the lowest armour porosity tested for stability was 34.4% (Figure 6.1). It is not recommended that the trend be extrapolated to lower porosity levels.



The data presented in Section 6.3.2 suggest that typical individually placed armour layers have void porosities of less than 35%. This implies that many individually placed layers that were designed on the basis of Van der Meer's equations have considerable reserve strength. The estimated void porosity for a typical, individually placed double armour layer, constructed using the standard placement method, was given in Section 6.3.2 as 32.1%. Applying the 90% confidence limits of +/-2.4% (see Section 6.2.2) gives a potential porosity range of 29.7% to 34.5%. It is worth noting that the measured range of porosity of the full-scale double layers constructed with the standard placement approach (described in Chapter 3) was 30.1% to 34.4%.

Therefore, assuming an armour layer porosity of 34.5%, the lower 90% interval from Figures 6.1 and 6.2 give the following values of  $C_{pl}$  and  $C_{su}$ :

$$C_{pl} = 7.8$$
  $C_{su} = 1.8$ 

These correspond to 35% and 60% increases in design wave height, compared to Van der Meer's equation, in the plunging and surging zones respectively.

To use these revised values the following criteria must be satisfied:

- The rocks should be individually placed with good orientation control and above water. In practise this means that the rocks should be placed by a grab, not dumped into position. A crane with a sling will not provide sufficient control.
- The constructor should be confident that a void porosity of less than 35% can be achieved.
- Rocks should not be excessively round. If blockiness measurements are available there should be few or no rocks with blockiness coefficients of less than 50%.

If tight rock packing is to be relied upon as a significant factor in the design of an armour layer then it is recommended that, as with all designs that diverge from standard procedures, physical model tests should be conducted to supplement the design.

### 6.3.4 Physical modelling of rock armoured structures

The test results show that the stability of a rock armour layer can be sensitive to the shapes of the rocks that form it. To provide the most useful model results, the model and prototype rock shapes should therefore be as consistent as possible. Since at the modelling stage, it is rare to have any detailed information on the shapes of the prototype rocks, a generic or typical rock shape must be assumed. It is already standard practise to exclude models any rocks that are excessively elongate. The results of this study show that it would be advisable to set additional controls on rock shape, in particular on rock blockiness.

The placement method also has a major influence on the stability of the layer. Care should be taken to ensure that the placement method used in the model replicates that used in the prototype. It may be advisable in some circumstances to monitor the porosity of the model layer and ensure that it is representative of the prototype layer.

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## Tables





|                   | Shoreham     | Bardon Hill  | Immingham  | Torr Works   | Reculver         |
|-------------------|--------------|--------------|------------|--------------|------------------|
| Structure Type    | revetment    | revetment    | revetment  | revetment    | revetment        |
| Slope             | 1:2          | 1:2          | 1:2        | 1:2          | 1:2              |
| Layers            | single and   | single and   | single and | single and   | double           |
|                   | double       | double       | double     | double       | only             |
| Rock source       | Larvik       | Bardon Hill  | Larvik     | Torr Works   | France           |
| Nominal size      | 8-12t        | 3-6t         | 500kg      | 3-6t         | 1-3t             |
| Placement plant   | 3-point grab | 3-point grab | bucket     | 3-point grab | orange-peel grab |
| Packing densities | standard     | standard     | standard   | standard     | standard         |
|                   | and dense    | and dense    | only       | and dense    | only             |

 Table 3.1
 Test panel specifications

### Table 3.2Rock specifications

|                     | Shoreham | Bardon Hill | Immingham            | Torr Works | Reculver  |
|---------------------|----------|-------------|----------------------|------------|-----------|
| Rock source         | Larvik   | Bardon Hill | Larvik               | Torr Works | France    |
| Nominal size        | 8-12t    | 3-6t        | 500kg                | 3-6t       | 1-3t      |
| Rock type           | syenite  | granite     | syenite              | limestone  | limestone |
| Number of rocks     | 68       | 80          | 100                  | 70         | 240       |
| Total               | 573.08   | 299.76      | 53.97                | 324.63     | 481.25    |
| mass (t)            |          |             |                      |            |           |
| $\rho_a (t/m^3)$    | 2.71     | 2.80        | 2.71                 | 2.75       | 2.70      |
| $M_{50}(t)$         | 9.37     | 3.68        | 0.55                 | 4.64       | 2.23      |
| M <sub>85</sub> (t) | 11.45    | 5.08        | 0.71                 | 6.85       | 3.13      |
| M <sub>15</sub> (t) | 6.82     | 2.98        | 0.43                 | 3.39       | 1.52      |
| $M_{85}/M_{15}$     | 1.68     | 1.70        | 1.65                 | 2.02       | 2.06      |
| Average l/d         | 2.30     | 2.10        | 2.18                 | 2.01       | 2.15      |
| 1/d > 3             | 10.1%    | 2.4%        | 2.5%                 | 0%         | 4.2%      |
| $D_{n50}(m)$        | 1.51     | 1.10        | 0.59                 | 1.19       | 0.90      |
| Block shape         | equant   | irregular   | equant/<br>irregular | irregular  | equant    |

### Table 3.3 Single layer results summary

|                        | Shoreham | Bardon Hill | Immingham | Torr Works | Reculver |
|------------------------|----------|-------------|-----------|------------|----------|
| kt                     | 0.71     | 0.80        | 1.03      | 0.82       | -        |
| $\rho_{\rm b} (t/m^3)$ | 1.90     | 1.84        | 1.63      | 1.79       | -        |
| n <sub>v</sub> (%)     | 30.0     | 34.3        | 40.0      | 34.8       | -        |

| Table 3.4 | <b>Double layer</b> | results summary | (standard | pack) |
|-----------|---------------------|-----------------|-----------|-------|
|-----------|---------------------|-----------------|-----------|-------|

|                           | Shoreham | Bardon Hill | Immingham | Torr Works | Reculver |
|---------------------------|----------|-------------|-----------|------------|----------|
| $\mathbf{k}_{\mathrm{t}}$ | 0.77     | 0.88        | 0.92      | 0.91       | 0.94     |
| $\rho_{\rm b} (t/m^3)$    | 1.89     | 1.89        | 1.65      | 1.85       | 1.77     |
| n <sub>v</sub> (%)        | 30.1     | 32.8        | 39.2      | 32.9       | 34.4     |

| Table 3.5 | Double | layer resu | lts summary | (dense pack) |
|-----------|--------|------------|-------------|--------------|
|-----------|--------|------------|-------------|--------------|

|                        | Shoreham | Bardon Hill | Immingham | Torr Works | Reculver |
|------------------------|----------|-------------|-----------|------------|----------|
| kt                     | 0.76     | 0.86        | -         | 0.92       | -        |
| $\rho_{\rm b} (t/m^3)$ | 1.96     | 1.93        | -         | 1.86       | -        |
| n <sub>v</sub> (%)     | 27.6     | 30.9        | -         | 32.5       | -        |



| Field test  | Geometric scale | Ту     | pe of layers model | led            |
|-------------|-----------------|--------|--------------------|----------------|
|             |                 | Single | Double             | Double (dense) |
|             |                 | _      | (standard)         |                |
| Shoreham    | 29              | √      | ✓<br>✓             | ✓              |
| Bardon Hill | 25              | √      | ✓                  | ✓              |
| Immingham   | 12              | √      | ✓                  |                |
| Torr Works  | 26              | ✓      | ✓                  | ✓              |
| Reculver    | 20              |        | 1                  |                |

### Table 4.1 Structure-specific test programme, aspect ratio-matched models

### Table 4.2 Structure-specific test programme, blockiness coefficient-matched models

| Field test             | Geometric scale | Ту     | pe of layers modell | led            |
|------------------------|-----------------|--------|---------------------|----------------|
|                        |                 | Single | Double              | Double (dense) |
|                        |                 |        | (standard)          |                |
| Shoreham*              | 29              |        |                     |                |
| Bardon Hill            | 25              | √      | √                   | ✓              |
| Immingham <sup>*</sup> | 12              |        |                     |                |
| Torr Works             | 26              | √      | √                   | 1              |
| Reculver               | 20              |        | ✓                   |                |

\* Blockiness coefficients were not recorded on the Shoreham and Immingham field tests



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| method                   | Dense       |               |              |    |    |                      |                |    | >               | >                | >             | >               | >               | >             | >               | >                | >             | >               | >                | >             | >               | >               | >               | >               | , |
|--------------------------|-------------|---------------|--------------|----|----|----------------------|----------------|----|-----------------|------------------|---------------|-----------------|-----------------|---------------|-----------------|------------------|---------------|-----------------|------------------|---------------|-----------------|-----------------|-----------------|-----------------|---|
| Placement                | Standard    | >             | >            | >  | >  | 1                    | >              | >  | >               | >                | >             | >               | >               | >             | >               | >                | >             | >               | >                | >             | >               | >               | >               | >               |   |
|                          | 1:3         |               |              |    |    |                      |                |    | >               |                  |               | >               |                 |               | >               |                  |               | >               |                  |               | >               |                 |                 |                 |   |
| our slope                | 1:2         | >             | >            | >  | >  | 1                    | >              | >  |                 | >                |               |                 | ~               |               |                 | >                |               |                 | >                |               |                 | >               |                 | >               | , |
| Arm                      | 1:1.5       |               |              |    |    |                      |                |    |                 |                  | >             |                 |                 | >             |                 |                  | >             |                 |                  | >             |                 |                 | >               |                 | ľ |
| BL <sub>c</sub><br>range |             | Μ             | Σ            | М  | М  | М                    | Μ              | Μ  | z               | z                | z             | Z               | Z               | z             | z               | z                | z             | z               | z                | z             | М               | Μ               | Μ               | Μ               |   |
| BL <sub>c</sub>          | 70-80       |               |              |    |    |                      |                |    |                 |                  |               |                 |                 |               |                 |                  |               | >               | >                | >             |                 |                 |                 |                 |   |
| oefficient,              | 60-70       |               |              |    |    |                      |                |    |                 |                  |               |                 |                 |               | >               | >                | >             |                 |                  |               |                 |                 |                 |                 |   |
| ockiness co<br>(%)       | 50-60       | >             | >            | >  | >  | 1                    | >              | >  |                 |                  |               | >               | >               | >             |                 |                  |               |                 |                  |               | >               | >               | >               | >               | , |
| Mean blc                 | 40-50       |               |              |    |    |                      |                |    | >               | >                | >             |                 |                 |               |                 |                  |               |                 |                  |               |                 |                 |                 |                 |   |
| l/d<br>range             |             | М             | М            | М  | М  | М                    | М              | М  | М               | М                | М             | М               | М               | М             | М               | M                | М             | М               | М                | М             | Z               | Z               | Z               | Z               |   |
|                          | .0-3.5      |               |              |    |    |                      |                |    |                 |                  |               |                 |                 |               |                 |                  |               |                 |                  |               |                 |                 |                 |                 |   |
| ratio, l/d               | .5-3.0 3    |               |              |    |    |                      |                |    |                 |                  |               |                 |                 |               | >               | >                | >             |                 |                  |               |                 |                 |                 |                 | , |
| an aspect                | .0-2.5 2    | >             | >            | >  | >  | <ul> <li></li> </ul> | >              | >  |                 |                  |               | >               | >               | >             |                 |                  |               | >               | >                | >             |                 |                 |                 | >               |   |
| Me                       | .5-2.0 2    |               |              |    |    |                      |                |    | >               | >                | >             |                 |                 |               |                 |                  |               |                 |                  |               | >               | >               | >               |                 |   |
| Mass<br>range            |             | z             | Z            | Z  | Z  | W                    | W              | W  | М               | М                | Μ             | Μ               | Μ               | М             | Μ               | Μ                | Μ             | Μ               | Μ                | М             | М               | Μ               | Μ               | М               |   |
| (g)                      | 350-<br>400 |               |              |    | >  |                      |                |    |                 |                  |               |                 |                 |               |                 |                  |               |                 |                  |               |                 |                 |                 |                 |   |
| nass, M <sub>50</sub>    | 300-<br>350 |               |              | >  |    |                      |                |    | >               | >                | >             | >               | >               | >             | >               | >                | >             | >               | >                | >             | >               | >               | >               | >               |   |
| n armour 1               | 250-<br>300 |               | >            |    |    | <ul> <li></li> </ul> | >              | >  |                 |                  |               |                 |                 |               |                 |                  |               |                 |                  |               |                 |                 |                 |                 |   |
| Media                    | 200-<br>250 | >             |              |    |    |                      |                |    |                 |                  |               |                 |                 |               |                 |                  |               |                 |                  |               |                 |                 |                 |                 |   |
| Test<br>code             | <u> </u>    | D1            | D2           | D3 | D4 | D5                   | D6             | D7 | D8              | D9               | D10           | D11             | D12             | D13           | D14             | D15              | D16           | D17             | D18              | D19           | D20             | D21             | D22             | D23             |   |
| omment                   |             | ss controlled | narrow range |    |    | ass controlled       | ith wide range | 1  | hape controlled | ith narrow range | of blockiness | hape controlled | th narrow range | of blockiness | hape controlled | ith narrow range | of blockiness | hape controlled | ith narrow range | of blockiness | hape controlled | th narrow range | of aspect ratio | hape controlled | - |
| 0                        |             | Лa            | ith          |    |    | L                    | $\sim$         |    |                 |                  |               |                 |                 |               |                 |                  |               |                 |                  |               |                 | •               | _               |                 |   |

Table 4.3 Test programme, generic double layer

Ranges N - narrow M - medium W - wide



| Test          | Comment           | Test | Medi        | an armour   | mass, M <sub>50</sub> | 0 (g)       | Mass     | Μ       | ean aspect ratio, l/c | - <del></del> | l/d   | Mean b | ockiness coeffic | ient, BL <sub>c</sub> | $\mathrm{BL}_{\mathrm{c}}$ | Ar    | mour slope |          | Placement | method |
|---------------|-------------------|------|-------------|-------------|-----------------------|-------------|----------|---------|-----------------------|---------------|-------|--------|------------------|-----------------------|----------------------------|-------|------------|----------|-----------|--------|
| Batch         |                   | code |             |             |                       |             | range    |         |                       |               | range |        | (0)              |                       | range                      |       |            |          |           |        |
|               |                   |      | 200-<br>250 | 250-<br>300 | 300-<br>350           | 350-<br>400 | <u> </u> | 1.5-2.0 | 2.0-2.5 2.5-3.0       | 3.0-3.5       |       | 40-50  | 50-60 60-70      | 70-80                 |                            | 1:1.5 | 1:2        | 1:3 5    | Standard  | Dense  |
|               | Mass controlled   | S1   | >           |             |                       |             | z        |         | <b>&gt;</b>           |               | Μ     |        | <b>`</b>         |                       | М                          |       | >          |          |           | >      |
| $\mathbf{S1}$ | with narrow range | S2   |             | >           |                       |             | Z        |         | >                     |               | Μ     |        | >                |                       | М                          |       | >          |          |           | >      |
|               |                   | S3   |             |             | >                     |             | Z        |         | >                     |               | Μ     |        | >                |                       | Μ                          |       | >          |          |           | >      |
|               |                   | S4   |             |             |                       | ~           | Ν        |         | ~                     |               | Μ     |        | <b>`</b>         |                       | Μ                          |       | 1          |          |           | ~      |
|               | Mass controlled   | S5   |             | 1           |                       |             | W        |         | >                     |               | Μ     |        | >                |                       | М                          |       | 1          |          |           | 1      |
| S2            | with wide range   | S6   |             | >           |                       |             | W        |         | ~                     |               | Μ     |        | ~                |                       | Μ                          |       | 1          |          |           | ~      |
|               |                   | S7   |             | >           |                       |             | W        |         | ~                     |               | Μ     |        | ~                |                       | М                          |       | 1          |          |           | ~      |
|               | Shape controlled  | S8   |             |             | ~                     |             | Μ        | ~       |                       |               | Μ     | ~      |                  |                       | Ν                          |       |            | ~        |           | ~      |
| S3(a)         | with narrow range | S9   |             |             | ~                     |             | Μ        | ~       |                       |               | Μ     | ~      |                  |                       | Ν                          |       | 1          |          |           | ~      |
|               | of blockiness     | S10  |             |             | >                     |             | Μ        | ~       |                       |               | Μ     | ~      |                  |                       | Ν                          | ノ     |            |          |           | ~      |
|               | Shape controlled  | S11  |             |             | ~                     |             | Μ        |         | ~                     |               | Μ     |        | ~                |                       | Ν                          |       |            | <i>۲</i> |           | ~      |
| S3(b)         | with narrow range | S12  |             |             | >                     |             | Μ        | ļ       | ~                     | <u> </u>      | Μ     |        | ~                |                       | Ν                          |       | <b>^</b>   |          |           | >      |
|               | of blockiness     | S13  |             |             | >                     |             | Μ        |         | ~                     |               | Μ     |        | ~                |                       | Ν                          | ノ     |            |          |           | ~      |
|               | Shape controlled  | S14  |             |             | >                     |             | Μ        |         | >                     |               | Μ     |        | >                |                       | Ν                          |       |            | >        |           | >      |
| S3(c)         | with narrow range | S15  |             |             | >                     |             | Μ        |         | ~                     |               | Μ     |        | >                |                       | Ν                          |       | 1          |          |           | 1      |
|               | of blockiness     | S16  |             |             | >                     |             | Μ        |         | ~                     |               | Μ     |        | >                |                       | Ν                          | 1     |            |          |           | <      |
|               | Shape controlled  | S17  |             |             | ~                     |             | Μ        |         | ~                     |               | Μ     |        |                  | >                     | Ν                          |       |            | ~        |           | ~      |
| S3(d)         | with narrow range | S18  |             |             | >                     |             | Μ        |         | ~                     |               | Μ     |        |                  | >                     | Ν                          |       | 1          |          |           | ~      |
|               | of blockiness     | S19  |             |             | >                     |             | Μ        |         | ~                     |               | Μ     |        |                  | >                     | Ν                          | 1     |            |          |           | ~      |
|               | Shape controlled  | S20  |             |             | >                     |             | Μ        | >       |                       |               | Z     |        | >                |                       | Μ                          |       |            | ~        |           | >      |
| S4(a)         | with narrow range | S21  |             |             | >                     |             | М        | >       |                       |               | z     |        | >                |                       | Μ                          |       | >          |          |           | >      |
|               | of aspect ratio   | S22  |             |             | >                     |             | Μ        | 1       |                       |               | Ν     |        | ~                |                       | М                          | 1     |            |          |           | ~      |
|               | Shape controlled  | S23  |             |             | ~                     |             | Μ        |         | ~                     |               | Ν     |        | ~                |                       | Μ                          |       | ~          |          |           | ~      |
| S4(b)         | with narrow range | S24  |             |             | >                     |             | Μ        |         | >                     |               | Z     |        | >                |                       | Μ                          |       | >          |          |           | >      |
|               | of aspect ratio   | S25  |             |             | >                     |             | М        |         |                       | >             | z     |        | >                |                       | М                          |       | >          |          |           | >      |

 Table 4.4
 Test programme, generic single layer structures

Ranges N - narrow M - medium W - wide



| Test series | Test | Layer    | R     | Aspec               | t ratio             | Grading         | Block               | ciness              |
|-------------|------|----------|-------|---------------------|---------------------|-----------------|---------------------|---------------------|
|             | Code | type     |       | l/d <sub>mean</sub> | l/d <sub>sdev</sub> | $M_{85}/M_{15}$ | BL <sub>cmean</sub> | BL <sub>csdev</sub> |
|             | SH1  | Single   | 37    | 2.25                | 0.47                | 2.19            | 57.2                | 9.3                 |
|             |      | _        | (37)  | (2.27)              | (0.51)              | (2.06)          | (-)                 | (-)                 |
| Shoreham    | SH2  | Double   | 62    | 2.29                | 0.52                | 1.81            | 57.8                | 8.6                 |
|             |      | standard | (62)  | (2.31)              | (0.52)              | (1.75)          | (-)                 | (-)                 |
|             | SH3  | Double   | 66    | 2.26                | 0.49                | 1.81            | 58.0                | 8.4                 |
|             |      | dense    | (66)  | (2.28)              | (0.49)              | (1.75)          | (-)                 | (-)                 |
|             | BA1  | Single   | 39    | 2.16                | 0.42                | 1.49            | 56.6                | 8.5                 |
|             |      |          | (39)  | (2.15)              | (0.37)              | (1.48)          | (62.4)              | (12.0)              |
| Bardon      | BA2  | Double   | 73    | 2.17                | 0.42                | 1.60            | 56.5                | 8.1                 |
|             |      | standard | (73)  | (2.13)              | (0.38)              | (1.58)          | (62.3)              | (12.2)              |
|             | BA3  | Double   | 75    | 2.17                | 0.42                | 1.66            | 57.0                | 8.3                 |
|             |      | dense    | (75)  | (2.14)              | (0.38)              | (1.66)          | (62.2)              | (12.1)              |
|             | IM1  | Single   | 37    | 2.14                | 0.31                | 1.53            | 59.8                | 7.5                 |
| Immingham   |      |          | (37)  | (2.13)              | (0.31)              | (1.51)          | (-)                 | (-)                 |
|             | IM2  | Double   | 69    | 2.17                | 0.40                | 1.61            | 59.1                | 7.3                 |
|             |      | standard | (69)  | (2.14)              | (0.38)              | (1.61)          | (-)                 | (-)                 |
|             | TW1  | Single   | 34    | 2.02                | 0.36                | 1.90            | 56.7                | 7.6                 |
|             |      |          | (34)  | (1.96)              | (0.40)              | (1.93)          | (62.7)              | (12.4)              |
| Torr Works  | TW2  | Double   | 65    | 2.02                | 0.42                | 1.99            | 55.6                | 7.9                 |
|             |      | standard | (65)  | (1.90)              | (0.45)              | (1.99)          | (63.4)              | (11.3)              |
|             | TW3  | Double   | 65    | 2.02                | 0.42                | 2.05            | 56.1                | 7.8                 |
|             |      | dense    | (65)  | (1.96)              | (0.46)              | (2.04)          | (63.5)              | (11.7)              |
| Reculver    | RE1  | Double   | 240   | 2.16                | 0.45                | 2.06            | 56.9                | 6.9                 |
|             |      | standard | (240) | (2.16)              | (0.43)              | (2.06)          | (53.8)              | (11.1)              |

 Table 4.5
 Parameters of rock batches used in structure-specific model tests, aspect ratio-matched models (field test data in brackets)



| Test series | Test | Layer              | R  | Aspec               | t ratio             | Grading         | Block               | kiness              |
|-------------|------|--------------------|----|---------------------|---------------------|-----------------|---------------------|---------------------|
|             | Code | type               |    | 1/d <sub>mean</sub> | l/d <sub>sdev</sub> | $M_{85}/M_{50}$ | BL <sub>cmean</sub> | BL <sub>csdev</sub> |
|             | SH1  | Single             | 0% | -1%                 | -8%                 | 6%              | _                   | _                   |
| Shoreham    | SH2  | Double<br>standard | 0% | -1%                 | 0%                  | 3%              | _                   | _                   |
|             | SH3  | Double<br>dense    | 0% | -1%                 | 0%                  | 3%              | -                   | _                   |
|             | BA1  | Single             | 0% | 0%                  | 14%                 | 1%              | -9%                 | -29%                |
| Bardon      | BA2  | Double<br>standard | 0% | 2%                  | 11%                 | 1%              | -9%                 | -34%                |
|             | BA3  | Double<br>dense    | 0% | 1%                  | 11%                 | 0%              | -8%                 | -31%                |
| Immingham   | IM1  | Single             | 0% | 0%                  | 0%                  | 1%              | _                   | _                   |
| -           | IM2  | Double<br>standard | 0% | 1%                  | 5%                  | 0%              | _                   | _                   |
|             | TW1  | Single             | 0% | 3%                  | -10%                | -2%             | -10%                | -39%                |
| Torr Works  | TW2  | Double<br>standard | 0% | 6%                  | -7%                 | 0%              | -12%                | -30%                |
|             | TW3  | Double<br>dense    | 0% | 3%                  | -9%                 | 0%              | -12%                | -33%                |
| Reculver    | RE1  | Double standard    | 0% | 0%                  | 5%                  | 0%              | 6%                  | -38%                |

# Table 4.6 Discrepancies in parameters of rock batches used in structure-specific model tests, aspect ratio-matched models (negative values indicate that model parameter is lower)

# Table 4.7 Results of structure-specific model tests, aspect ratio-matched models (field results in brackets)

| Test series | Test code | Armour void porosity, $n_v$ (%) | Layer thickness coefficient, kt |
|-------------|-----------|---------------------------------|---------------------------------|
|             | SH1       | 38.1 (30.0)                     | 0.89 (0.71)                     |
| Shoreham    | SH2       | 35.6 (30.1)                     | 0.73 (0.77)                     |
|             | SH3       | 33.6 (27.6)                     | 0.73 (0.76)                     |
|             | BA1       | 31.3 (34.3)                     | 0.75 (0.80)                     |
| Bardon      | BA2       | 35.3 (32.8)                     | 0.77 (0.88)                     |
|             | BA3       | 33.4 (30.9)                     | 0.79 (0.86)                     |
| Immingham   | IM1       | 35.4 (40.0)                     | 0.95 (1.03)                     |
|             | IM2       | 36.0 (39.2)                     | 0.91 (0.92)                     |
|             | TW1       | 34.0 (34.8)                     | 0.85 (0.82)                     |
| Torr Works  | TW2       | 35.2 (32.9)                     | 0.81 (0.91)                     |
|             | TW3       | 34.1 (32.5)                     | 0.79 (0.92)                     |
| Reculver    | RE1       | 36.1 (34.4)                     | 1.04 (0.94)                     |

| Test batch | Test | Layer    | R     | Aspec               | et ratio            | Grading         | Block               | kiness              |
|------------|------|----------|-------|---------------------|---------------------|-----------------|---------------------|---------------------|
|            | Code | type     |       | l/d <sub>mean</sub> | l/d <sub>sdev</sub> | $M_{85}/M_{15}$ | BL <sub>cmean</sub> | BL <sub>csdev</sub> |
|            | BA4  | Single   | 39    | 2.34                | 0.92                | 1.61            | 62.5                | 12.4                |
|            |      |          | (39)  | (2.15)              | (0.37)              | (1.48)          | (62.4)              | (12.0)              |
| Bardon     | BA5  | Double   | 73    | 2.49                | 1.01                | 1.63            | 62.3                | 12.3                |
|            |      | standard | (73)  | (2.13)              | (0.38)              | (1.58)          | (62.3)              | (12.2)              |
|            | BA6  | Double   | 75    | 2.27                | 0.74                | 1.65            | 62.3                | 12.2                |
|            |      | dense    | (75)  | (2.14)              | (0.38)              | (1.66)          | (62.2)              | (12.1)              |
|            | TW4  | Single   | 34    | 2.53                | 1.03                | 1.66            | 62.7                | 12.4                |
|            |      |          | (34)  | (1.96)              | (0.40)              | (1.93)          | (62.7)              | (12.4)              |
| Torr Works | TW5  | Double   | 65    | 2.75                | 1.20                | 1.83            | 63.4                | 11.3                |
|            |      | standard | (65)  | (1.90)              | (0.45)              | (1.99)          | (63.4)              | (11.3)              |
|            | TW6  | Double   | 65    | 2.77                | 1.21                | 1.69            | 63.6                | 11.7                |
|            |      | dense    | (65)  | (1.96)              | (0.46)              | (2.04)          | (63.5)              | (11.7)              |
| Reculver   | RE2  | Double   | 240   | 2.21                | 0.84                | 1.73            | 53.9                | 10.5                |
|            |      | standard | (240) | (2.16)              | (0.43)              | (2.06)          | (53.8)              | (11.1)              |

 Table 4.8
 Parameters of rock batches used in structure-specific model tests, blockiness-matched models (field test data in brackets)

| Table 4.9 | Discrepancies in parameters of rock batches used in structure-specific model tests, |
|-----------|---|
|           | blockiness-matched models (negative values indicate that model parameter is lower)  |

| Test batch | Test | Layer    | R  | Aspec               | et ratio            | Grading         | Blockiness          |                     |
|------------|------|----------|----|---------------------|---------------------|-----------------|---------------------|---------------------|
|            | Code | type     |    | l/d <sub>mean</sub> | l/d <sub>sdev</sub> | $M_{85}/M_{15}$ | BL <sub>cmean</sub> | BL <sub>csdev</sub> |
|            | BA4  | Single   | 0% | 9%                  | 149%                | 9%              | 0%                  | 3%                  |
|            |      |          |    |                     |                     |                 |                     |                     |
| Bardon     | BA5  | Double   | 0% | 17%                 | 166%                | 3%              | 0%                  | 1%                  |
|            |      | standard |    |                     |                     |                 |                     |                     |
|            | BA6  | Double   | 0% | 6%                  | 95%                 | -1%             | 0%                  | 1%                  |
|            |      | dense    |    |                     |                     |                 |                     |                     |
|            | TW4  | Single   | 0% | 29%                 | 158%                | -14%            | 0%                  | 0%                  |
|            |      |          |    |                     |                     |                 |                     |                     |
| Torr Works | TW5  | Double   | 0% | 45%                 | 167%                | -8%             | 0%                  | 0%                  |
|            |      | standard |    |                     |                     |                 |                     |                     |
|            | TW6  | Double   | 0% | 41%                 | 163%                | -17%            | 0%                  | 0%                  |
|            |      | dense    |    |                     |                     |                 |                     |                     |
| Reculver   | RE2  | Double   | 0% | 2%                  | 95%                 | -16%            | 0%                  | -5%                 |
|            |      | standard |    |                     |                     |                 |                     |                     |

| <b>Table 4.10</b> | Results of structure-specific model tests, | blockiness-matched | models (field | l results in |
|-------------------|--|--------------------|---------------|--------------|
|                   | brackets)                                  |                    |               |              |

| Test series | Test code | Armour void porosity, n <sub>v</sub> (%) | Layer thickness coefficient, kt |
|-------------|-----------|--|---------------------------------|
|             | BA4       | 32.7 (34.3)                              | 0.80 (0.80)                     |
| Bardon      | BA5       | 32.2 (32.8)                              | 0.87 (0.88)                     |
|             | BA6       | 31.7 (30.9)                              | 0.86 (0.86)                     |
|             | TW4       | 35.7 (34.8)                              | 0.82 (0.82)                     |
| Torr Works  | TW5       | 34.6 (32.9)                              | 0.90 (0.91)                     |
|             | TW6       | 33.6 (32.5)                              | 0.92 (0.92)                     |
| Reculver    | RE2       | 35.0 (34.4)                              | 0.95 (0.94)                     |

| Test series | Test | Armour l | ayer porosi | ty, $n_v$ (%) | Layer thickness coefficient, kt |       |       |  |
|-------------|------|----------|-------------|---------------|---------------------------------|-------|-------|--|
|             | code | Field    | Model       | error         | Field                           | Model | error |  |
| Bardon      | BA1  | 34.3     | 31.3        | 3.0           | 0.80                            | 0.75  | 0.05  |  |
| Bardon      | BA2  | 32.8     | 35.3        | 2.5           | 0.88                            | 0.77  | 0.11  |  |
| Bardon      | BA3  | 30.9     | 33.4        | 2.5           | 0.86                            | 0.79  | 0.07  |  |
| Torr Works  | TW1  | 34.8     | 34.0        | 0.8           | 0.82                            | 0.85  | 0.03  |  |
| Torr Works  | TW2  | 32.9     | 35.2        | 2.3           | 0.91                            | 0.81  | 0.10  |  |
| Torr Works  | TW3  | 32.5     | 34.1        | 1.6           | 0.92                            | 0.79  | 0.13  |  |
| Reculver    | RE1  | 34.4     | 36.1        | 1.7           | 0.94                            | 1.04  | 0.10  |  |

 Table 4.11 Errors in model prediction, aspect ratio-matched models

| Table 4.12 | Errors in | model | prediction, | blockiness | -matched | models |
|------------|-----------|-------|-------------|------------|----------|--------|
|------------|-----------|-------|-------------|------------|----------|--------|

| Test series | Test | Armour l | ayer porosit | ty, $n_v$ (%) | Layer thickness coefficient, kt |       |       |  |
|-------------|------|----------|--------------|---------------|---------------------------------|-------|-------|--|
|             | code | Field    | Model        | error         | Field                           | Model | error |  |
| Bardon      | BA4  | 34.3     | 32.7         | 1.6           | 0.80                            | 0.80  | 0.00  |  |
| Bardon      | BA5  | 32.8     | 32.2         | 0.6           | 0.88                            | 0.87  | 0.01  |  |
| Bardon      | BA6  | 30.9     | 31.7         | 0.8           | 0.86                            | 0.86  | 0.00  |  |
| Torr Works  | TW4  | 34.8     | 35.7         | 0.9           | 0.82                            | 0.82  | 0.00  |  |
| Torr Works  | TW5  | 32.9     | 34.6         | 1.7           | 0.91                            | 0.90  | 0.01  |  |
| Torr Works  | TW6  | 32.5     | 33.6         | 1.1           | 0.92                            | 0.92  | 0.00  |  |
| Reculver    | RE2  | 34.4     | 35.0         | 0.6           | 0.94                            | 0.95  | 0.01  |  |

| Table 4.13 | Parameters of rock batches used in generic model tests, double layers constructed with |
|------------|--|
|            | standard packing approach  |

| Test series | Test code | Slope | Aspec               | et ratio            | Grading         | Blockiness          |                     |
|-------------|-----------|-------|---------------------|---------------------|-----------------|---------------------|---------------------|
|             |           |       | l/d <sub>mean</sub> | l/d <sub>sdev</sub> | $M_{85}/M_{15}$ | BL <sub>cmean</sub> | BL <sub>csdev</sub> |
|             | D1        | 1:2   | 2.46                | 0.82                | 1.15            | 56.9                | 8.15                |
| D1          | D2        | 1:2   | 2.17                | 0.55                | 1.12            | 53.6                | 6.60                |
|             | D3        | 1:2   | 2.19                | 0.40                | 1.10            | 56.8                | 7.42                |
|             | D4        | 1:2   | 2.24                | 0.58                | 1.05            | 55.8                | 7.62                |
|             | D5        | 1:2   | 2.15                | 0.41                | 1.86            | 52.9                | 7.91                |
| D2          | D6        | 1:2   | 2.16                | 0.44                | 1.79            | 53.8                | 9.30                |
|             | D7        | 1:2   | 2.19                | 0.44                | 1.47            | 55.0                | 9.14                |
|             | D8        | 1:3   | 1.96                | 0.39                | 1.24            | 46.4                | 2.52                |
| D3(a)       | D9        | 1:2   | 1.96                | 0.38                | 1.24            | 46.5                | 2.53                |
|             | D10       | 1:1.5 | 1.96                | 0.39                | 1.24            | 46.4                | 2.52                |
|             | D11       | 1:3   | 2.14                | 0.33                | 1.27            | 55.2                | 2.90                |
| D3(b)       | D12       | 1:2   | 2.15                | 0.33                | 1.26            | 55.2                | 2.94                |
|             | D13       | 1:1.5 | 2.16                | 0.32                | 1.27            | 55.3                | 2.96                |
|             | D14       | 1:3   | 2.57                | 0.79                | 1.21            | 63.6                | 3.01                |
| D3(c)       | D15       | 1:2   | 2.58                | 0.75                | 1.22            | 63.7                | 3.00                |
|             | D16       | 1:1.5 | 2.51                | 0.78                | 1.20            | 63.7                | 3.04                |
|             | D17       | 1:3   | 2.28                | 0.65                | 1.31            | 74.7                | 4.35                |
| D3(d)       | D18       | 1:2   | 2.35                | 0.68                | 1.30            | 74.6                | 3.86                |
|             | D19       | 1:1.5 | 2.34                | 0.69                | 1.30            | 74.6                | 4.02                |
|             | D20       | 1:3   | 1.80                | 0.14                | 1.25            | 54.8                | 7.19                |
| D4(a)       | D21       | 1:2   | 1.80                | 0.14                | 1.25            | 54.8                | 7.04                |
|             | D22       | 1:1.5 | 1.79                | 0.14                | 1.25            | 54.6                | 7.11                |
|             | D23       | 1:2   | 2.23                | 0.14                | 1.23            | 57.3                | 6.43                |
| D4(b)       | D24       | 1:2   | 2.73                | 0.15                | 1.23            | 60.1                | 8.10                |
|             | D25       | 1:2   | 3.23                | 0.14                | 1.31            | 58.6                | 7.26                |



| Test series | Test code | Slope | Aspec               | t ratio             | Grading         | Block               | Blockiness          |  |
|-------------|-----------|-------|---------------------|---------------------|-----------------|---------------------|---------------------|--|
|             |           |       | l/d <sub>mean</sub> | l/d <sub>sdev</sub> | $M_{85}/M_{15}$ | BL <sub>cmean</sub> | BL <sub>csdev</sub> |  |
|             | D8        | 1:3   | 1.95                | 0.39                | 1.25            | 46.5                | 2.52                |  |
| D3(a)       | D9        | 1:2   | 1.95                | 0.39                | 1.25            | 46.5                | 2.52                |  |
|             | D10       | 1:1.5 | 1.95                | 0.39                | 1.25            | 46.5                | 2.52                |  |
|             | D11       | 1:3   | 2.14                | 0.33                | 1.27            | 55.3                | 2.92                |  |
| D3(b)       | D12       | 1:2   | 2.15                | 0.33                | 1.26            | 55.2                | 2.94                |  |
|             | D13       | 1:1.5 | 2.16                | 0.32                | 1.27            | 55.3                | 2.96                |  |
|             | D14       | 1:3   | 2.57                | 0.79                | 1.21            | 63.6                | 3.01                |  |
| D3(c)       | D15       | 1:2   | 2.61                | 0.78                | 1.22            | 63.7                | 2.98                |  |
|             | D16       | 1:1.5 | 2.53                | 0.79                | 1.19            | 63.7                | 3.03                |  |
|             | D17       | 1:3   | 2.31                | 0.68                | 1.30            | 74.7                | 4.32                |  |
| D3(d)       | D18       | 1:2   | 2.31                | 0.68                | 1.30            | 74.7                | 4.32                |  |
|             | D19       | 1:1.5 | 2.31                | 0.68                | 1.30            | 74.7                | 4.32                |  |
|             | D20       | 1:3   | 1.80                | 0.14                | 1.25            | 54.6                | 7.22                |  |
| D4(a)       | D21       | 1:2   | 1.80                | 0.14                | 1.25            | 54.6                | 7.22                |  |
|             | D22       | 1:1.5 | 1.79                | 0.14                | 1.25            | 54.8                | 7.17                |  |
|             | D23       | 1:2   | 2.23                | 0.14                | 1.23            | 57.3                | 6.43                |  |
| D4(b)       | D24       | 1:2   | 2.73                | 0.15                | 1.23            | 60.1                | 8.10                |  |
|             | D25       | 1:2   | 3.23                | 0.14                | 1.30            | 58.7                | 7.22                |  |

 Table 4.14 Parameters of rock batches used in generic model tests, double layers constructed with dense packing approach

| Table 4.15  | <b>Parameters</b> | of rock | batches | used in | generic | model | tests. | single | lavers |
|-------------|-------------------|---------|---------|---------|---------|-------|--------|--------|--------|
| 1 abic 4.15 | 1 al ameter 5     | OTTOCK  | Datenes | uscu m  | Scheric | mouti |        | Single | ayus   |

| Test series | Test code  | Slope | Aspec               | t ratio             | Grading         | Block               | kiness              |
|-------------|------------|-------|---------------------|---------------------|-----------------|---------------------|---------------------|
|             |            | _     | l/d <sub>mean</sub> | l/d <sub>sdev</sub> | $M_{85}/M_{15}$ | BL <sub>cmean</sub> | BL <sub>csdev</sub> |
|             | S1         | 1:2   | 2.60                | 0.94                | 1.16            | 59.8                | 8.16                |
| S1          | S2         | 1:2   | 2.14                | 0.36                | 1.12            | 54.4                | 6.04                |
|             | S3         | 1:2   | 2.19                | 0.44                | 1.11            | 59.4                | 7.50                |
|             | S4         | 1:2   | 1.84                | 0.37                | 1.05            | 50.5                | 8.01                |
|             | S5         | 1:2   | 2.17                | 0.35                | 1.91            | 53.8                | 7.51                |
| S2          | S6         | 1:2   | 2.24                | 0.45                | 2.21            | 57.1                | 8.37                |
|             | S7         | 1:2   | 2.30                | 0.50                | 1.46            | 58.4                | 9.61                |
|             | <b>S</b> 8 | 1:3   | 2.08                | 0.40                | 1.25            | 46.5                | 2.23                |
| S3(a)       | S9         | 1:2   | 2.13                | 0.39                | 1.24            | 46.7                | 2.33                |
|             | S10        | 1:1.5 | 2.18                | 0.37                | 1.24            | 47.0                | 2.27                |
|             | S11        | 1:3   | 2.14                | 0.35                | 1.25            | 55.4                | 3.01                |
| S3(b)       | S12        | 1:2   | 2.17                | 0.34                | 1.27            | 56.1                | 3.12                |
|             | S13        | 1:1.5 | 2.18                | 0.34                | 1.28            | 55.8                | 3.12                |
|             | S14        | 1:3   | 2.60                | 0.72                | 1.17            | 63.6                | 2.81                |
| S3(c)       | S15        | 1:2   | 2.76                | 0.86                | 1.24            | 64.1                | 3.23                |
|             | S16        | 1:1.5 | 2.83                | 0.82                | 1.23            | 64.1                | 3.03                |
|             | S17        | 1:3   | 2.39                | 0.61                | 1.40            | 74.0                | 3.31                |
| S3(d)       | S18        | 1:2   | 2.31                | 0.64                | 1.23            | 75.0                | 3.65                |
|             | S19        | 1:1.5 | 2.62                | 0.74                | 1.36            | 75.7                | 4.43                |
|             | S20        | 1:3   | 1.80                | 0.14                | 1.26            | 55.8                | 7.25                |
| S4(a)       | S21        | 1:2   | 1.81                | 0.14                | 1.27            | 55.3                | 7.39                |
|             | S22        | 1:1.5 | 1.81                | 0.14                | 1.25            | 55.7                | 7.98                |
|             | S23        | 1:2   | 2.22                | 0.14                | 1.16            | 58.1                | 6.05                |
| S4(b)       | S24        | 1:2   | 2.72                | 0.17                | 1.19            | 59.6                | 9.12                |
|             | S25        | 1:2   | 3.22                | 0.14                | 1.33            | 57.2                | 5.82                |



| Test series | Test | Stan               | dard | De                 | nse  | Cha                | Change       |  |
|-------------|------|--------------------|------|--------------------|------|--------------------|--------------|--|
|             | code | n <sub>v</sub> (%) | kt   | n <sub>v</sub> (%) | kt   | $\Delta n_{v}$ (%) | $\Delta k_t$ |  |
|             | D1   | 37.8               | 0.87 | -                  | -    | -                  | -            |  |
| D1          | D2   | 36.3               | 0.87 | -                  | -    | -                  | -            |  |
|             | D3   | 33.9               | 0.84 | -                  | -    | -                  | -            |  |
|             | D4   | 32.9               | 0.90 | -                  | -    | -                  | -            |  |
|             | D5   | 35.2               | 0.80 | -                  | -    | -                  | -            |  |
| D2          | D6   | 34.0               | 0.85 | -                  | -    |                    | -            |  |
|             | D7   | 33.1               | 0.86 | -                  | -    | -                  | -            |  |
|             | D8   | 39.8               | 0.89 | 37.8               | 0.89 | -2.0               | 0.00         |  |
| D3(a)       | D9   | 39.0               | 0.85 | 36.8               | 0.84 | -2.2               | -0.01        |  |
|             | D10  | 39.8               | 0.92 | 36.2               | 0.90 | -3.7               | -0.01        |  |
|             | D11  | 37.0               | 0.92 | 35.6               | 0.92 | -1.4               | 0.00         |  |
| D3(b)       | D12  | 36.5               | 0.89 | 34.7               | 0.85 | -1.8               | -0.03        |  |
|             | D13  | 34.8               | 0.91 | 32.7               | 0.90 | -2.1               | -0.02        |  |
|             | D14  | 38.5               | 0.86 | 36.1               | 0.83 | -2.5               | -0.03        |  |
| D3(c)       | D15  | 40.0               | 0.85 | 37.9               | 0.83 | -2.1               | -0.02        |  |
|             | D16  | 37.0               | 0.94 | 36.3               | 0.94 | -0.7               | 0.00         |  |
|             | D17  | 32.0               | 0.90 | 33.6               | 0.94 | 1.6                | 0.04         |  |
| D3(d)       | D18  | 33.9               | 0.87 | 32.7               | 0.91 | -1.2               | 0.04         |  |
|             | D19  | 32.1               | 0.91 | 30.2               | 0.92 | -1.9               | 0.01         |  |
|             | D20  | 36.5               | 1.02 | 34.3               | 1.00 | -2.2               | -0.02        |  |
| D4(a)       | D21  | 34.8               | 0.94 | 33.7               | 0.95 | -1.2               | 0.01         |  |
|             | D22  | 35.7               | 1.05 | 32.8               | 1.01 | -2.9               | -0.04        |  |
|             | D23  | 36.1               | 0.89 | 34.4               | 0.87 | -1.7               | -0.03        |  |
| D4(b)       | D24  | 39.2               | 0.84 | 35.0               | 0.79 | -4.2               | -0.05        |  |
|             | D25  | 38.3               | 0.68 | 35.4               | 0.66 | -2.9               | -0.02        |  |

 Table 4.16 Generic model test results, double layers



| Test series | Test code  | Armour porosity, n <sub>v</sub> , (%) | Layer thickness coefficient, |
|-------------|------------|---------------------------------------|------------------------------|
|             |            |                                       | k <sub>t</sub>               |
|             | S1         | 29.6                                  | 0.73                         |
| S1          | S2         | 32.7                                  | 0.85                         |
|             | S3         | 32.0                                  | 0.81                         |
|             | S4         | 32.1                                  | 0.84                         |
|             | S5         | 34.9                                  | 0.76                         |
| S2          | S6         | 32.3                                  | 0.83                         |
|             | S7         | 31.7                                  | 0.79                         |
|             | <b>S</b> 8 | 31.0                                  | 0.82                         |
| S3(a)       | S9         | 35.6                                  | 0.76                         |
|             | S10        | 33.8                                  | 0.93                         |
|             | S11        | 33.1                                  | 0.89                         |
| S3(b)       | S12        | 31.0                                  | 0.83                         |
|             | S13        | 32.8                                  | 1.00                         |
|             | S14        | 33.7                                  | 0.86                         |
| S3(c)       | S15        | 35.9                                  | 0.80                         |
|             | S16        | 34.5                                  | 0.98                         |
|             | S17        | 28.8                                  | 0.92                         |
| S3(d)       | S18        | 29.5                                  | 0.88                         |
|             | S19        | 23.2                                  | 0.90                         |
|             | S20        | 31.6                                  | 1.00                         |
| S4(a)       | S21        | 28.2                                  | 0.89                         |
|             | S22        | 29.1                                  | 1.04                         |
|             | S23        | 29.8                                  | 0.83                         |
| S4(b)       | S24        | 30.9                                  | 0.75                         |
|             | S25        | 35.3                                  | 0.67                         |

### Table 4.17 Generic model test results, single layers



| Test series | Test code | Aspec               | t ratio             | Grading         | Block               | kiness              |
|-------------|-----------|---------------------|---------------------|-----------------|---------------------|---------------------|
|             |           | d/l <sub>mean</sub> | d/l <sub>sdev</sub> | $M_{15}/M_{85}$ | bl <sub>cmean</sub> | bl <sub>csdev</sub> |
|             | D1        | 0.444               | 0.129               | 0.870           | 0.569               | 0.081               |
| D1          | D2        | 0.481               | 0.087               | 0.895           | 0.536               | 0.066               |
|             | D3        | 0.473               | 0.091               | 0.908           | 0.568               | 0.074               |
|             | D4        | 0.472               | 0.109               | 0.950           | 0.558               | 0.076               |
|             | D5        | 0.481               | 0.082               | 0.538           | 0.529               | 0.079               |
| D2          | D6        | 0.480               | 0.091               | 0.559           | 0.538               | 0.093               |
|             | D7        | 0.473               | 0.086               | 0.682           | 0.550               | 0.091               |
|             | D8        | 0.528               | 0.095               | 0.805           | 0.464               | 0.025               |
| D3(a)       | D9        | 0.527               | 0.094               | 0.804           | 0.465               | 0.025               |
|             | D10       | 0.528               | 0.095               | 0.805           | 0.464               | 0.025               |
|             | D11       | 0.479               | 0.075               | 0.790           | 0.552               | 0.029               |
| D3(b)       | D12       | 0.477               | 0.074               | 0.791           | 0.552               | 0.029               |
|             | D13       | 0.474               | 0.072               | 0.786           | 0.553               | 0.030               |
|             | D14       | 0.422               | 0.115               | 0.825           | 0.636               | 0.030               |
| D3(c)       | D15       | 0.418               | 0.110               | 0.821           | 0.637               | 0.030               |
|             | D16       | 0.433               | 0.117               | 0.833           | 0.637               | 0.030               |
|             | D17       | 0.467               | 0.110               | 0.764           | 0.747               | 0.043               |
| D3(d)       | D18       | 0.457               | 0.111               | 0.771           | 0.746               | 0.039               |
|             | D19       | 0.458               | 0.112               | 0.767           | 0.746               | 0.040               |
|             | D20       | 0.560               | 0.045               | 0.802           | 0.548               | 0.072               |
| D4(a)       | D21       | 0.559               | 0.044               | 0.797           | 0.548               | 0.070               |
|             | D22       | 0.562               | 0.044               | 0.801           | 0.546               | 0.071               |
|             | D23       | 0.451               | 0.028               | 0.810           | 0.573               | 0.064               |
| D4(b)       | D24       | 0.367               | 0.020               | 0.811           | 0.601               | 0.081               |
|             | D25       | 0.310               | 0.013               | 0.766           | 0.586               | 0.073               |
| Shoreham    | SH2       | 0.460               | 0.105               | 0.552           | 0.578               | 0.086               |
| Bardon      | BA2       | 0.480               | 0.094               | 0.625           | 0.565               | 0.082               |
|             | BA5       | 0.455               | 0.141               | 0.613           | 0.623               | 0.124               |
| Immingham   | IM2       | 0.476               | 0.088               | 0.621           | 0.591               | 0.073               |
| Torr Works  | TW2       | 0.515               | 0.105               | 0.503           | 0.556               | 0.079               |
|             | TW5       | 0.485               | 0.141               | 0.546           | 0.634               | 0.113               |
| Reculver    | RE1       | 0.480               | 0.093               | 0.485           | 0.569               | 0.069               |
|             | RE2       | 0.499               | 0.133               | 0.578           | 0.539               | 0.106               |

 Table 4.18 Parameters used in multivariate regression analysis, double layers constructed with standard packing approach



| Test series | Test code | Aspec               | t ratio             | Grading         | Block               | kiness              |
|-------------|-----------|---------------------|---------------------|-----------------|---------------------|---------------------|
|             |           | d/l <sub>mean</sub> | d/l <sub>sdev</sub> | $M_{15}/M_{85}$ | bl <sub>cmean</sub> | bl <sub>csdev</sub> |
|             | S1        | 0.426               | 0.133               | 0.863           | 0.598               | 0.082               |
| S1          | S2        | 0.481               | 0.077               | 0.892           | 0.544               | 0.060               |
|             | S3        | 0.476               | 0.103               | 0.900           | 0.594               | 0.075               |
|             | S4        | 0.520               | 0.089               | 0.949           | 0.505               | 0.080               |
|             | S5        | 0.473               | 0.076               | 0.523           | 0.538               | 0.075               |
| S2          | S6        | 0.464               | 0.090               | 0.452           | 0.571               | 0.084               |
|             | S7        | 0.453               | 0.092               | 0.687           | 0.584               | 0.096               |
|             | S8        | 0.497               | 0.092               | 0.802           | 0.465               | 0.022               |
| S3(a)       | S9        | 0.485               | 0.092               | 0.810           | 0.467               | 0.023               |
|             | S10       | 0.472               | 0.079               | 0.809           | 0.470               | 0.023               |
|             | S11       | 0.479               | 0.081               | 0.799           | 0.554               | 0.030               |
| S3(b)       | S12       | 0.472               | 0.075               | 0.787           | 0.561               | 0.031               |
|             | S13       | 0.470               | 0.074               | 0.779           | 0.558               | 0.031               |
|             | S14       | 0.412               | 0.106               | 0.852           | 0.636               | 0.028               |
| S3(c)       | S15       | 0.397               | 0.120               | 0.806           | 0.641               | 0.032               |
|             | S16       | 0.383               | 0.107               | 0.816           | 0.641               | 0.030               |
|             | S17       | 0.442               | 0.101               | 0.717           | 0.740               | 0.033               |
| S3(d)       | S18       | 0.461               | 0.108               | 0.812           | 0.750               | 0.037               |
|             | S19       | 0.412               | 0.116               | 0.737           | 0.757               | 0.044               |
|             | S20       | 0.559               | 0.046               | 0.792           | 0.558               | 0.073               |
| S4(a)       | S21       | 0.555               | 0.045               | 0.786           | 0.553               | 0.074               |
|             | S22       | 0.555               | 0.046               | 0.803           | 0.557               | 0.080               |
|             | S23       | 0.452               | 0.028               | 0.860           | 0.581               | 0.061               |
| S4(b)       | S24       | 0.368               | 0.022               | 0.841           | 0.596               | 0.091               |
|             | S25       | 0.311               | 0.014               | 0.754           | 0.572               | 0.058               |
| Shoreham    | SH1       | 0.464               | 0.100               | 0.457           | 0.572               | 0.093               |
| Bardon      | BA1       | 0.480               | 0.092               | 0.671           | 0.566               | 0.086               |
|             | BA4       | 0.476               | 0.135               | 0.621           | 0.625               | 0.125               |
| Immingham   | IM1       | 0.478               | 0.072               | 0.654           | 0.598               | 0.075               |
| Torr Works  | TW1       | 0.512               | 0.093               | 0.526           | 0.567               | 0.077               |
|             | TW4       | 0.454               | 0.154               | 0.602           | 0.627               | 0.126               |

 Table 4.19 Parameters used in multivariate regression analysis, single layers



| Test series | Test codes | Standard    |                  | De          | nse                       | Change             |              |
|-------------|------------|-------------|------------------|-------------|---------------------------|--------------------|--------------|
|             |            | $n_{v}$ (%) | $\mathbf{k}_{t}$ | $n_{v}$ (%) | $\mathbf{k}_{\mathrm{t}}$ | $\Delta n_{v}$ (%) | $\Delta k_t$ |
| Bardon      | BA3/BA2    | 35.3        | 0.77             | 33.4        | 0.79                      | -1.9               | 0.02         |
|             | BA6/BA5    | 32.2        | 0.87             | 31.7        | 0.86                      | -0.5               | -0.01        |
| Torr Works  | TW3/TW2    | 35.2        | 0.81             | 34.1        | 0.79                      | -1.1               | -0.02        |
|             | TW6/TW5    | 34.6        | 0.90             | 33.6        | 0.92                      | -1.0               | 0.02         |
| Shoreham    | SH3/SH2    | 35.6        | 0.73             | 33.6        | 0.73                      | -2.0               | 0.00         |

 Table 4.20 Structure specific model test results with variable packing approach

| <b>Table 4.21</b> | <b>Results</b> of | multiple r | regression | analysis, | prior to | slope-correction | n |
|-------------------|-------------------|------------|------------|-----------|----------|------------------|---|
|                   |                   |            |            |           |          |                  |   |

| Layer  | Parameter                 | А      | В      | С      | D      | Е     | F      |
|--------|---------------------------|--------|--------|--------|--------|-------|--------|
| type   |                           |        |        |        |        |       |        |
| Single | n <sub>v</sub>            | 0.634  | -0.241 | -0.224 | 0.000  | 0.000 | -0.090 |
| Single | $\mathbf{k}_{\mathrm{t}}$ | 0.131  | 0.494  | 1.075  | -1.032 | 0.000 | 0.000  |
| Double | n <sub>v</sub>            | 0.603  | -0.214 | -0.200 | -0.402 | 0.000 | 0.000  |
| Double | $\mathbf{k}_{\mathrm{t}}$ | 0.210  | 0.302  | 1.049  | 0.000  | 0.000 | 0.000  |
| Double | $\Delta n_v$              | -0.114 | 0.097  | 0.081  | 0.000  | 0.000 | 0.000  |

| Table 4.22 | <b>Results</b> | of multiple i | egression  | analysis.  | after slope | e-correction. | $\cot \alpha = 1$ | 1.5 |
|------------|----------------|---------------|------------|------------|-------------|---------------|-------------------|-----|
|            | itesuites (    | f manupic i   | CSI COSION | anary 5159 | anter stop  | c correction, |                   |     |

| Layer  | Parameter      | А      | В      | С      | D      | Е     | F      |
|--------|----------------|--------|--------|--------|--------|-------|--------|
| type   |                |        |        |        |        |       |        |
| Single | n <sub>v</sub> | 0.604  | -0.229 | -0.213 | 0.000  | 0.000 | -0.086 |
| Single | kt             | 0.145  | 0.546  | 1.189  | -1.141 | 0.000 | 0.000  |
| Double | n <sub>v</sub> | 0.595  | -0.211 | -0.197 | -0.396 | 0.000 | 0.000  |
| Double | k <sub>t</sub> | 0.220  | 0.315  | 1.097  | 0.000  | 0.000 | 0.000  |
| Double | $\Delta n_v$   | -0.114 | 0.097  | 0.081  | 0.000  | 0.000 | 0.000  |

| Table 4.23  | <b>Results</b> of | ' multiple i | regression   | analysis.  | after slor | pe-correction. | $\cot \alpha = 2$ |
|-------------|-------------------|--------------|--------------|------------|------------|----------------|-------------------|
| 1 abic 4.25 | itesuites of      | munipici     | i egi ession | anary 515, | anter stop |                |                   |

| Layer  | Parameter        | А      | В      | С      | D      | Е     | F      |
|--------|------------------|--------|--------|--------|--------|-------|--------|
| type   |                  |        |        |        |        |       |        |
| Single | n <sub>v</sub>   | 0.635  | -0.241 | -0.224 | 0.000  | 0.000 | -0.090 |
| Single | $\mathbf{k}_{t}$ | 0.127  | 0.479  | 1.044  | -1.002 | 0.000 | 0.000  |
| Double | n <sub>v</sub>   | 0.602  | -0.213 | -0.200 | -0.401 | 0.000 | 0.000  |
| Double | $\mathbf{k}_{t}$ | 0.206  | 0.296  | 1.029  | 0.000  | 0.000 | 0.000  |
| Double | $\Delta n_v$     | -0.114 | 0.097  | 0.081  | 0.000  | 0.000 | 0.000  |

| <b>Table 4.24</b> | <b>Results of</b> | multiple r | egression | analysis, | after slope- | -correction, | $\cot \alpha = 3$ | 3 |
|-------------------|-------------------|------------|-----------|-----------|--------------|--------------|-------------------|---|
|-------------------|-------------------|------------|-----------|-----------|--------------|--------------|-------------------|---|

| Layer  | Parameter        | А      | В      | С      | D      | Е     | F      |
|--------|------------------|--------|--------|--------|--------|-------|--------|
| type   |                  |        |        |        |        |       |        |
| Single | n <sub>v</sub>   | 0.637  | -0.242 | -0.225 | 0.000  | 0.000 | -0.090 |
| Single | $\mathbf{k}_{t}$ | 0.131  | 0.493  | 1.072  | -1.029 | 0.000 | 0.000  |
| Double | n <sub>v</sub>   | 0.610  | -0.216 | -0.203 | -0.407 | 0.000 | 0.000  |
| Double | kt               | 0.213  | 0.306  | 1.065  | 0.000  | 0.000 | 0.000  |
| Double | $\Delta n_v$     | -0.114 | 0.097  | 0.081  | 0.000  | 0.000 | 0.000  |



| Structure | Layers | BL <sub>C</sub> (%) | l/d       | Packing  | Р   | n <sub>v</sub> (%) |
|-----------|--------|---------------------|-----------|----------|-----|--------------------|
| 1         | double | 50 - 60             | 1.5 - 3.0 | dense    | 0.5 | 35.2               |
| 2         | double | 50 - 60             | 1.5 - 3.0 | standard | 0.5 | 37.1               |
| 3         | single | 50 - 60             | 1.5 - 3.0 | dense    | 0.5 | 31.2               |
| 4         | double | 60 - 70             | 1.5 - 3.0 | dense    | 0.5 | 34.4               |
| 5         | double | 60 - 70             | 1.5 - 3.0 | standard | 0.5 | 35.5               |
| 6         | single | 60 - 70             | 1.5 - 3.0 | dense    | 0.5 | 29.7               |
| 7         | double | 40 - 50             | 1.5 - 3.0 | dense    | 0.5 | 36.1               |
| 8         | double | 40 - 50             | 1.5 - 3.0 | standard | 0.5 | 38.7               |
| 9         | single | 40 - 50             | 1.5 - 3.0 | dense    | 0.5 | 32.8               |
| 10        | double | 50 - 60             | < 2       | dense    | 0.5 | 34.6               |
| 11        | double | 50 - 60             | < 2       | standard | 0.5 | 36.1               |
| 12        | single | 50 - 60             | < 2       | dense    | 0.5 | 30.3               |
| 13*       | double | 50 - 60             | 1.5 - 3.0 | dense    | 0.5 | 35.2               |
| 14*       | double | 50 - 60             | 1.5 - 3.0 | standard | 0.5 | 37.1               |
| 15*       | single | 50 - 60             | 1.5 - 3.0 | dense    | 0.5 | 31.2               |
| 16        | double | 50 - 60             | 1.5 - 3.0 | dense    | 0.1 | 35.2               |
| 17        | double | 50 - 60             | 1.5 - 3.0 | standard | 0.1 | 37.1               |
| 18        | single | 50 - 60             | 1.5 - 3.0 | dense    | 0.1 | 31.2               |

 Table 5.1
 Test structures used in hydraulic model tests

\* Structures 13, 14 and 15 were identical to Structures 1, 2 and 3 respectively.

| Table 5.2 | Test conditions used in the hydraulic model tests |
|-----------|---|
|-----------|---|

| Test      | St         | tatistical resul | lts   | S           | Spectral result | S     |
|-----------|------------|------------------|-------|-------------|-----------------|-------|
| condition | $H_{s}(m)$ | $T_{m}(s)$       | Sm    | $H_{mo}(m)$ | $T_{p}(s)$      | Sp    |
| 1         | 0.10       | 1.5              | 0.030 | 0.10        | 1.7             | 0.023 |
| 2         | 0.14       | 1.5              | 0.040 | 0.14        | 1.7             | 0.032 |
| 3         | 0.18       | 1.5              | 0.049 | 0.17        | 1.7             | 0.039 |
| 4         | 0.22       | 1.6              | 0.052 | 0.22        | 1.7             | 0.050 |
| 5         | 0.25       | 1.5              | 0.069 | 0.26        | 1.7             | 0.060 |
| 6         | 0.10       | 2.1              | 0.015 | 0.10        | 2.2             | 0.013 |
| 7         | 0.15       | 2.1              | 0.022 | 0.15        | 2.2             | 0.019 |
| 8         | 0.18       | 2.1              | 0.027 | 0.19        | 2.2             | 0.024 |
| 9         | 0.22       | 2.1              | 0.032 | 0.22        | 2.2             | 0.028 |
| 10        | 0.25       | 2.1              | 0.037 | 0.26        | 2.2             | 0.033 |
| 11        | 0.10       | 2.6              | 0.010 | 0.10        | 3.0             | 0.007 |
| 12        | 0.14       | 2.5              | 0.014 | 0.14        | 3.0             | 0.010 |
| 13        | 0.19       | 2.5              | 0.020 | 0.19        | 3.0             | 0.014 |
| 14        | 0.22       | 2.5              | 0.023 | 0.22        | 3.0             | 0.016 |
| 15        | 0.27       | 2.5              | 0.027 | 0.27        | 3.0             | 0.020 |
| 16        | 0.10       | 3.0              | 0.007 | 0.10        | 3.6             | 0.005 |
| 17        | 0.14       | 2.9              | 0.011 | 0.15        | 3.6             | 0.008 |
| 18        | 0.19       | 2.9              | 0.015 | 0.18        | 3.6             | 0.009 |

| Structure | C <sub>pl</sub> | C <sub>pl sdev</sub> | C <sub>su</sub> | C <sub>su sdev</sub> |
|-----------|-----------------|----------------------|-----------------|----------------------|
| 1         | 6.77            | 1.73                 | 2.08            | -                    |
| 2         | 5.98            | 1.63                 | 1.51            | 0.08                 |
| 4         | 10.25           | 2.28                 | -               | -                    |
| 5         | 7.31            | 2.04                 | 2.63            | -                    |
| 7         | 5.81            | 0.60                 | 1.67            | -                    |
| 8         | 6.33            | 1.17                 | -               | -                    |
| 10        | 8.45            | 2.72                 | -               | -                    |
| 11        | 8.19            | 1.97                 | 1.45            | -                    |
| 13        | 9.44            | 2.01                 | 1.63            | 0.33                 |
| 14        | 6.76            | 2.24                 | 1.50            | 0.05                 |
| 16        | 8.79            | 2.09                 | 2.63            | -                    |
| 17        | 7.91            | 0.58                 | -               | -                    |

### Table 5.3 Results of double layer 1000 wave tests, stability coefficients

### Table 5.4 Results of double layer 3000 wave tests, stability coefficients

| Structure       | $C_{pl}$ | $C_{pl \ sdev}$ | $C_{su}$ | $C_{su \ sdev}$ |
|-----------------|----------|-----------------|----------|-----------------|
| 13 (3000 waves) | 9.59     | 1.95            | 1.68     | 0.26            |
| 14 (3000 waves) | 6.94     | 2.26            | 1.34     | 0.18            |

### Table 5.5 Results of single layer tests, stability coefficients

| Structure | Period Group     | Condition type | K <sub>D</sub> |
|-----------|------------------|----------------|----------------|
|           | $T_m(s)$ approx. |                |                |
|           | 1.5              | plunge         | 6.1            |
| 3         | 2.0              | plunge         | 5.0            |
|           | 2.5              | plunge         | 11.9           |
|           | 3.0              | surge          | 23.3           |
|           | 1.5              | plunge         | 6.1            |
| 6         | 2.0              | plunge         | 11.9           |
|           | 2.5              | plunge         | 11.9           |
|           | 3.0              | surge          | 10.2           |
|           | 1.5              | plunge         | 4.1            |
| 9         | 2.0              | surge          | 1.5            |
|           | 2.5              | surge          | 4.1            |
|           | 3.0              | surge          | 8.7            |
|           | 1.5              | plunge         | 4.1            |
| 12        | 2.0              | plunge         | 4.1            |
|           | 2.5              | surge          | 4.1            |
|           | 3.0              | surge          | 8.7            |
|           | 1.5              | plunge         | 1.5            |
| 15        | 2.0              | surge          | 1.5            |
|           | 2.5              | surge          | 1.5            |
|           | 3.0              | surge          | 1.5            |
|           | 1.5              | plunge         | 3.0            |
| 18        | 2.0              | plunge         | 8.2            |
|           | 2.5              | surge          | 8.2            |
|           | 3.0              | surge          | 17.4           |

| Structure | K <sub>D min</sub> (plunging waves) | K <sub>D min</sub> (surging waves) |
|-----------|-------------------------------------|------------------------------------|
| 3         | 5.0                                 | 23.3                               |
| 6         | 6.1                                 | 10.2                               |
| 9         | 4.1                                 | 1.5                                |
| 12        | 4.1                                 | 4.1                                |
| 15        | 1.5                                 | 1.5                                |
| 18        | 3.0                                 | 8.2                                |

### Table 5.6 Results of single layer tests, 'worst case' stability coefficients

### Table 5.7 Results of overtopping discharge tests, double layer structures

| Structure | $\gamma_{\rm f}$ (plunging) | $\gamma_{\rm f}$ (surging) |
|-----------|-----------------------------|----------------------------|
| 1         | 0.43                        | 0.65                       |
| 2         | 0.45                        | 0.74                       |
| 4         | 0.48                        | 0.75                       |
| 5         | 0.44                        | 0.76                       |
| 7         | 0.43                        | 0.83                       |
| 8         | 0.42                        | 0.80                       |
| 10        | 0.43                        | 0.76                       |
| 11        | 0.41                        | 0.76                       |
| 13        | 0.48                        | 0.86                       |
| 14        | 0.43                        | 0.82                       |
| 16        | 0.42                        | 0.90                       |
| 17        | 0.40                        | 0.85                       |

### Table 5.8 Results of overtopping discharge tests, single layer structures

| Structure | $\gamma_{\rm f}$ (plunging) | $\gamma_{\rm f}$ (surging) |
|-----------|-----------------------------|----------------------------|
| 3         | 0.53                        | 0.84                       |
| 6         | 0.52                        | 0.82                       |
| 9         | 0.47                        | 0.92                       |
| 12        | 0.50                        | 0.76                       |
| 15        | 0.50                        | 0.96                       |
| 18        | 0.45                        | 0.83                       |



| Layer  | Paramete       | А     | В      | С      | D      | Е     | F      |
|--------|----------------|-------|--------|--------|--------|-------|--------|
| type   | r              |       |        |        |        |       |        |
| Single | n <sub>v</sub> | 0.604 | -0.229 | -0.213 | 0.000  | 0.000 | -0.086 |
| Single | k <sub>t</sub> | 0.145 | 0.546  | 1.189  | -1.141 | 0.000 | 0.000  |
| Double | n <sub>v</sub> | 0.595 | -0.211 | -0.197 | -0.396 | 0.000 | 0.000  |
| Double | kt             | 0.220 | 0.315  | 1.097  | 0.000  | 0.000 | 0.000  |

 Table 6.1
 Coefficients for Equations 6.1 and 6.2, structure slope = 1:1.5

| Table 6.2 | <b>Coefficients for</b> | r Equations 6.1 | and 6.2, structure | slope = 1:2 |
|-----------|-------------------------|-----------------|--------------------|-------------|
|           |                         |                 |                    |             |

| Layer  | Paramete       | А     | В      | С      | D      | Е     | F      |
|--------|----------------|-------|--------|--------|--------|-------|--------|
| type   | r              |       |        |        |        |       |        |
| Single | n <sub>v</sub> | 0.635 | -0.241 | -0.224 | 0.000  | 0.000 | -0.090 |
| Single | k <sub>t</sub> | 0.127 | 0.479  | 1.044  | -1.002 | 0.000 | 0.000  |
| Double | n <sub>v</sub> | 0.602 | -0.213 | -0.200 | -0.401 | 0.000 | 0.000  |
| Double | k <sub>t</sub> | 0.206 | 0.296  | 1.029  | 0.000  | 0.000 | 0.000  |

| Table 6 2  | Coefficients for F | Caustions 6.1 sn | d 6.2. structure slov   | ne = 1.3 |
|------------|--------------------|------------------|-------------------------|----------|
| 1 abie 0.2 | Coefficients for E | quations 0.1 and | u 0.2, sti uttui e sioj | JC - 1.3 |

| Layer  | Paramete       | А     | В      | С      | D      | Е     | F      |
|--------|----------------|-------|--------|--------|--------|-------|--------|
| type   | r              |       |        |        |        |       |        |
| Single | n <sub>v</sub> | 0.637 | -0.242 | -0.225 | 0.000  | 0.000 | -0.090 |
| Single | k <sub>t</sub> | 0.131 | 0.493  | 1.072  | -1.029 | 0.000 | 0.000  |
| Double | n <sub>v</sub> | 0.610 | -0.216 | -0.203 | -0.407 | 0.000 | 0.000  |
| Double | kt             | 0.213 | 0.306  | 1.065  | 0.000  | 0.000 | 0.000  |

 Table 6.4
 Coefficients for Equation 6.3, all structure slopes

| Layer  | Paramete     | А      | В     | С     | D     | Е     | F     |
|--------|--------------|--------|-------|-------|-------|-------|-------|
| type   | r            |        |       |       |       |       |       |
| Double | $\Delta n_v$ | -0.114 | 0.097 | 0.081 | 0.000 | 0.000 | 0.000 |

### Figures






Figure 2.1 CIRIA/CUR rock manual shape categories



Figure 2.2 Power's scale of roundness



Figure 3.1 Armour layer survey technique



Figure 3.2 Digital model of Shoreham underlayer, from 'Surfer'



Figure 3.3 Digital model of Shoreham single layer revetment, from 'Surfer'



Figure 3.4 Definition of armour layer thickness from 'Surfer' cross section



Figure 4.1 Mass distribution of the model rock collection.



Figure 4.2 Shape distribution of the model rock collection, according to the CIRIA/CUR shape classifications



Figure 4.3 Shape distribution of the model rock collection, according to Powers' scale of roundness



Figure 4.4 Aspect ratio distribution of the model rock collection







Figure 4.6 Blockiness coefficient distribution of the model rock collection



Figure 4.7 Scatter table of aspect ratio against blockiness of the model rock collection



Figure 4.8 Scatter table of aspect ratio against blockiness of the rocks used in the field trials



Figure 4.9 Test apparatus





Figure 4.10 Scatter table of M/M<sub>50</sub> against I/d, Shoreham single layer, aspect ratio-matched model



Figure 4.11 Scatter table of M/M<sub>50</sub> against I/d, Shoreham double layer (standard pack), aspect ratio-matched model



Figure 4.12Scatter table of M/M50 against l/d, Shoreham doublelayer (dense pack), aspect ratio-matched model







Immingham single layer



Scatter table of M/M<sub>50</sub> against l/d, Immingham single

Figure 4.16

ayer, aspect ratio-matched model

Immingham double layer (standard)

2.5 -

2.0 -

6.0

5.0

4.0

3.0 Aspect ratio, I/d







⊲



6.0

5.0

4.0

Aspect ratio, I/d 3.0

2.0

1.0

0.0

0.0











Figure 4.20Scatter table of M/M50 against l/d, Torr Works doublelayer (dense pack), aspect ratio-matched model



Figure 4.21Scatter table of M/M50 against I/d, Reculver double<br/>layer (standard pack), aspect ratio-matched model











Figure 4.24Distribution of I/d, Shoreham double layer (dense pack), aspect ratio-matched model



Figure 4.25 Distribution of I/d, Bardon single layer, aspect ratiomatched model



Figure 4.26Distribution of I/d, Bardon double layer (standard<br/>pack), aspect ratio-matched model



Figure 4.27 Distribution of I/d, Bardon double layer (dense pack), aspect ratio-matched model



Figure 4.28Distribution of I/d, Immingham single layer, aspectratio-matched model



Figure 4.29Distribution of l/d, Immingham double layer (standard<br/>pack), aspect ratio-matched model













Figure 4.32 Distribution of I/d, Torr Works double layer (dense pack), aspect ratio-matched model



Figure 4.33Distribution of I/d, Reculver double layer (standard<br/>pack), aspect ratio-matched model



Figure 4.34Distribution of M/M50, Shoreham single layer,aspect ratio-matched model



Figure 4.35Distribution of M/Mso, Shoreham double layer(standard pack), aspect ratio-matched model



Figure 4.36Distribution of M/M<sub>50</sub>, Shoreham double layer (dense<br/>pack), aspect ratio-matched model



Figure 4.37Distribution of M/Ms0, Bardon single layer, aspect<br/>ratio-matched model













Figure 4.40Distribution of M/M50, Immingham single layer, aspectratio-matched model



Figure 4.41Distribution of M/M<sub>50</sub>, Immingham double layer(standard pack), aspect ratio-matched model





Figure 4.42 Distribution of M/M<sub>50</sub>, Torr Works single layer, aspect ratio-matched model



Figure 4.43Distribution of M/Mso, Torr Works double layer(standard pack), aspect ratio-matched model



Figure 4.44Distribution of M/M<sub>50</sub>, Torr Works double layer<br/>(dense pack), aspect ratio-matched model















Figure 4.48Distribution of BLc, Bardon double layer (dense pack),aspect ratio-matched model



Figure 4.49Distribution of BLc, Torr Works single layer, aspect<br/>ratio-matched model



Figure 4.50Distribution of BLc, Torr Works double layer(standard pack), aspect ratio-matched model



Figure 4.51Distribution of BLc, Torr Works double layer<br/>(dense pack), aspect ratio-matched model



Figure 4.52Distribution of BLc, Reculver double layer (standard<br/>pack), aspect ratio-matched model



Figure 4.53 Results of aspect ratio-matched models, armour void porosity



Figure 4.54 Results of aspect ratio-matched models, armour layer thickness









igure 4.57 Scatter table of M/M<sub>50</sub> against BL<sub>c</sub>, Bardon double layer (dense pack), blockiness-matched model









30

0.0













2.5 -

2.0

- 5-

Mass coefficient, M/M 50

0.1

0.5 -







6.0

5.0

4.0

Aspect ratio, Vd 3.0

2.0

1.0

0.0

6.0

5.0

4.0

Aspect ratio, I/d 3.0

2.0

1.0

0.0

6uib

ton %



6uib

% not exc



Distribution of I/d, Torr Works double layer (dense pack), blockiness-matched model Figure 4.67









Distribution of M/M<sub>50</sub>, Bardon single layer, blockinessmatched model Figure 4.69



Distribution of M/M<sub>50</sub>, Bardon double layer (standard pack), blockiness-matched model Figure 4.70









2.5

2.0

1.0 1.5 Mass coefficient M/M<sub>50</sub>

0.5

0.0

2.0

1.0 1.5 Mass coefficient M/M<sub>50</sub>

0.5

0.0

20 -

20







 $_{\rm F0}^{\rm f0}$  70 Blockiness coefficient, BL<sub>c</sub> (%)



















Figure 4.81Distribution of BL<sub>C</sub>, Torr Works double layer (densepack), blockiness-matched model







Figure 4.83 Results of blockiness coefficient-matched models, armour void porosity



Figure 4.84 Results of blockiness coefficient-matched models, armour layer thickness



Figure 4.85 Distribution of armour porosity and layer thickness results



Figure 4.86 The effect of placement method on armour void porosity



Figure 4.87 The effect of placement method on armour layer thickness













Figure 4.90Scatter table of nv and kt against d/lmean, double layermodels constructed with standard packing approach













Figure 4.94Scatter table of nv and kt against d/lsdev, double layermodels constructed with standard packing approach





Figure 4.93 Scatter table of n<sub>v</sub> and k<sub>t</sub> against bl<sub>csdev</sub>, single layer models











Scatter table of  $n_v$  and  $k_t$  against cot  $\alpha$ , double layer models constructed with standard packing approach Figure 4.98





models

0.45 -

0.40

0.30 -

0.25 -

0.50 -



Figure 4.100 Results of the porosity prediction equation (pre slope correction)



Figure 4.101 Results of the layer thickness prediction equation (pre slope correction)



Figure 4.102 Results of the packing prediction equation



Figure 4.103 Results of the porosity prediction equation (post slope correction)



Figure 4.104 Results of the layer thickness prediction equation (post slope correction)



Figure 4.105 90% confidence intervals of prediction of layer porosity


Figure 4.106 90% confidence intervals of prediction of layer porosity





Figure 5.1 Cross section of test structure with P = 0.5



Figure 5.2 Cross section of test structure with P = 0.1



Figure 5.3 Van der Meer's stability curves for test structure with P = 0.5



Figure 5.4 Arrangement of test structures in flume



Figure 5.5 Stability results for Structure 1, plunging waves only, 1000 wave test



Figure 5.6 Stability results for Structure 1, surging waves only, 1000 wave test



Figure 5.7 Stability results for Structure 2, plunging waves only, 1000 wave test



Figure 5.8 Stability results for Structure 2, surging waves only, 1000 wave test



Figure 5.9 Stability results for Structure 4, plunging waves only, 1000 wave test



Figure 5.10 Stability results for Structure 4, surging waves only, 1000 wave test



Figure 5.11 Stability results for Structure 5, plunging waves only, 1000 wave test



Figure 5.12 Stability results for Structure 5, surging waves only, 1000 wave test



Figure 5.13 Stability results for Structure 7, plunging waves only, 1000 wave test



Figure 5.14 Stability results for Structure 7, surging waves only, 1000 wave test



Figure 5.15 Stability results for Structure 8, plunging waves only, 1000 wave test



Figure 5.16 Stability results for Structure 8, surging waves only, 1000 wave test



Figure 5.17 Stability results for Structure 10, plunging waves only, 1000 wave test



Figure 5.18 Stability results for Structure 10, surging waves only, 1000 wave test



Figure 5.19 Stability results for Structure 11, plunging waves only, 1000 wave test



Figure 5.20 Stability results for Structure 11, surging waves only, 1000 wave test



Figure 5.21 Stability results for Structure 13, plunging waves only, 1000 wave test



Figure 5.22 Stability results for Structure 13, surging waves only, 1000 wave test



Figure 5.23 Stability results for Structure 14, plunging waves only, 1000 wave test



Figure 5.24 Stability results for Structure 14, surging waves only, 1000 wave test



Figure 5.25 Stability results for Structure 16, plunging waves only, 1000 wave test



Figure 5.26 Stability results for Structure 16, surging waves only, 1000 wave test



Figure 5.27 Stability results for Structure 17, plunging waves only, 1000 wave test



Figure 5.28 Stability results for Structure 17, surging waves only, 1000 wave test



Figure 5.29 Effect of rock blockiness on plunging wave stability coefficient, C<sub>pl</sub>



Figure 5.30 Effect of rock blockiness on plunging wave stability coefficient, C<sub>su</sub>



Figure 5.31 Stability results for Structure 13, plunging waves only, 3000 wave test



Figure 5.32 Stability results for Structure 13, surging waves only, 3000 wave test



Figure 5.33 Stability results for Structure 14, plunging waves only, 3000 wave test



Figure 5.34 Stability results for Structure 14, surging waves only, 3000 wave test



Figure 5.35 Effect of armour layer porosity on plunging wave stability coefficient, Structures with P = 0.5



Figure 5.36 Effect of armour layer porosity on surging wave stability coefficient, Structures with P = 0.5



Figure 5.37 Overtopping results for Structure 4, plunging waves onl



Figure 5.38 Overtopping results for Structure 4, surging waves onl



Figure 5.39 Overtopping results for Structure 5, plunging waves only



Figure 5.40 Overtopping results for Structure 5, surging waves only



Figure 5.41 Overtopping results for Structure 6, plunging waves only



Figure 5.42 Overtopping results for Structure 6, surging waves only



Figure 5.43 Overtopping results for all structures, plunging waves only



Figure 5.44 Overtopping results for all structures, surging waves only



Figure 5.45 Overtopping results for all double layer structures, Owen's dimensionless terms



Figure 5.46 Overtopping results for all single layer structures, Owen's dimensionless terms



Figure 6.1 Effect of armour layer void porosity on plunging wave stability coefficient, Structures with P = 0.5



Figure 6.2 Effect of armour layer void porosity on surging wave stability coefficient, Structures with P = 0.5



Figure 6.3 Effect of mean blockiness and aspect ratio on armour layer porosity, double layers in a standard pack



Figure 6.4 Effect of mean blockiness and aspect ratio on layer coefficient, double layers in a standard pack





Figure 6.5 Effect of mean blockiness and aspect ratio on armour layer porosity, single layers



Figure 6.6 Effect of mean blockiness and aspect ratio on layer coefficient, single layers





## Plates







Plate 3.1 8-12t Larvik rocks used in Shoreham trials



Plate 3.2 3-6t Bardon Hill rocks





Plate 3.3 500kg rocks used in Immingham trial



Plate 3.4 3-6t Torr Works rocks





Plate 3.5 Surface of double layer (dense pack) revetment at Shoreham



Plate 3.6 Double layer (standard pack) revetment at Bardon Hill





Plate 3.7 Placing 500kg rocks by bucket at Immingham



Plate 3.8 Surface of single layer revetment at Torr Works





Plate 3.9 Construction using the orange-peel grab at Reculver




Appendix A

Statistical Methods





## **Appendix A Statistical Methods**

Confidence limits on predictions of porosity and layer thickness.

The experimental results obtained during this study have been used to derive prediction methods for parameters such as armour layer void porosity and thickness. Confidence limits have been applied to these predictions to represent the degree of scatter in the experimental results. For this purpose the errors in the predictions (i.e., the difference between the measured and predicted value of a particular parameter) were treated as a sample, and the mean and standard deviations of the sample calculated.

The confidence limits of the prediction were then estimated from:

Confidence limits = predicted value + mean of errors  $\pm A\sigma$ 

Where  $\sigma =$  standard deviation of the errors

A = an appropriate multiplier based on the normal or t distrbution

Where the sample size was sufficiently large the multiplier A was taken from the normal distribution. In the case of 90% confidence limits A = 1.645. For smaller samples (n < 30) the equivalent value from the t-distribution was used. In such cases A is a function of the sample size (or degrees of freedom).

Significance tests

The significance tests used in the analysis were intended to determine how significant the difference between the means of two samples were. Such tests were used, for example, to determine if changing the placement method produced a significant difference in the void porosity or layer coefficient of an armour layer.

The significance tests were based on a t statistic, which is calculated from the standard deviations and means of the two samples. To determine whether there is a significance difference between the means of two independent samples the t statistic is calculated as follows:

$$t = \frac{\overline{x_1 - \overline{x}_2}}{\sqrt{\frac{\sigma^2}{n_1} + \frac{\sigma^2}{n_2}}}$$

where  $\overline{x}_1 = \text{mean of sample } 1$ 

 $\overline{x}_2$  = mean of sample 2

 $\sigma$  = standard deviation of combined sample =  $\sqrt{\sigma_1^2 + \sigma_2^2}$ 

 $\sigma_1$  = standard deviation of sample 1

 $\sigma_2$  = standard deviation of sample 2

 $n_1$  = number of results in sample 1

 $n_2$  = number of results in sample 2

The t statistic for paired (or non-independent) samples is calculated as follows:





where  $\overline{d}$  = mean of the differences between each pair in the sample

- $\sigma$  = standard deviation of the differences between each pair in the sample
- n = number of results in each sample

Levels of significance were then determined from the t-distribution.

