CHAPTER 129

Durability of Rock Armour on Coastal Structures

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Abstract

This paper summarises many of the recent advances in the testing of rock quality for coastal structures. Advanced work on armour profile and armour unit shape descriptors is identified. A set of assessment methods for monitoring armoured slopes in the field are described, with examples drawn from recent monitoring exercises. The paper concludes by describing future directions of research in this field.

1 Introduction

Rock of mean unit weight within the range 2 to 20t is frequently used to protect or armour coastal structures such as breakwaters and sea walls. These structures are usually designed to dissipate much of the incident wave energy in flow over and through the rough and porous armour layer. Within such armour layers, each individual armour unit must therefore be capable of resisting the forces due to wave action, and must withstand mechanisms of chemical and physical deterioration operating in the marine environment. Historically the design of such armour layers required the use of rock judged to be "hard and durable", although few engineering tests were established to quantify the potential durability of the rock from any particular source. In this context durability may be defined as the capability of remaining useful for the original purpose. A more limiting definition, and that used in this paper, might require the material to remain at or above a defined level of usefulness, as given by armour layer performance and stability, over the full design life of the structure.

Recently a series of simple engineering tests have been developed to help quantify the potential durability of rock armour to be used on coastal structures, see Fookes & Poole (Ref 1). Appropriate acceptance values for each test have been advanced, based upon measurements of performance both in service and in the laboratory, see Poole et al, and Allsop et al (Refs 2, 3).

In most design work it has usually been assumed that the armour layer will remain at its original performance and stability levels throughout its design life, often about 30 to 50 years. However, it has been noted that rock armour on some structures has often not been as durable as had been hoped or anticipated. Many examples of early

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deterioration reducing the stability and effectiveness of the armour have been identified (Ref 1). At some sites the rock available may be of inferior quality and will therefore be more likely to deteriorate under the action of waves, tides and other environmental factors. Alternatively, the design of the armour layer may itself allow significant levels of armour movement, giving rise in turn to impact and abrasion damage. Such movement might be envisaged at the design stage, as on rock berm breakwaters, see Baird & Hall (Ref 4), or on dynamically stable rock slopes, see Van der Meer & Pilarczyk (Refs 5, 6). On more conventional structures these high levels of armour movement may not however be expected, and will consequently not have been allowed for in the design. This may occur if the wave climate has been under-estimated, or if the structure is otherwise under-designed. A few design methods do envisage some armour movement, and the extent and rate of armour unit removal may be calculated, see Allsop et al (Ref 7) and Thompson & Shuttler (Ref 8). None, however, allow the deterioration of the armour layer performance or stability to be predicted.

Similarly, all design methods for rock, or concrete, armouring assume implicitly that the armour unit size and shape will remain constant throughout the structure life. To compound the problem, the methods used for monitoring completed structures offer relatively little assistance in quantifying the performance in service of an armour layer, or of its constituent armour units.

A number of techniques are presently being developed in the UK to assist the designer of rock armoured coastal structures to predict the likely deterioration of the armour over the design life of the structure. These techniques include rock quality testing, hydraulic model studies, and field monitoring methods. It is hoped that these techniques will allow the designer to adopt either of two different strategies, depending upon the client's administrative and financial position.

In situations where little or no maintenance will be possible, the designer may choose to use an over-size armour calculated to remain within acceptable stability levels throughout the structure design life. The initial size of the armour will be specified allowing for a possible level of deterioration. Such a design approach will allow the benefits and costs of importing a hard and more durable rock to be compared with the alternative use of less durable local material. Long-term consequences of different construction and armour placement techniques might also be assessed.

Where low initial cost is required, but provision may be made either for maintenance or refurbishment, the designer may choose an alternative strategy. In this situation the structure may be armoured using the best material locally available. Measurements of the rock quality using engineering tests, together with estimates of the severity of local degradation processes, possibly derived from monitoring other local structures, will then allow predictions to be made of the rate of armour layer deterioration. From this, the designer may then estimate the frequency of maintenance or refurbishment requirements. Such estimates may be somewhat uncertain initially. Advanced monitoring techniques are therefore being developed to allow the degree, and hence rate, of deterioration to be quantified.

In any review of the technical literature it may be noted that the terms "damage" and "armour layer damage" are used by various authors with somewhat different meanings. In particular "damage" has often been taken to mean the permanent extraction of an armour unit from its original position in the armour. Such a definition does not, however, permit the quantification of more gradual deterioration, such as the fracture or progressive abrasion of armour units in situ. For this paper, and it is hoped for subsequent work, two definitions of damage are suggested:

(a) armour unit degradation - deterioration/change of armour unit size and/or shape from an original or an idealised size/shape;

(b) armour layer damage - deterioration of an armour layer from an original or idealised state leading to changes in the hydraulic performance and/or stability of the armour layer.

2 Recent Developments

2.1 Rock quality assessment and engineering tests

A wide range of engineering tests are available to quantify material properties such as strength, hardness, abrasion, and chemical resistance. Of these, some tests have been developed by researchers at Queen Mary College (QMC) for the testing of rock, principally intended for use as roadstone or aggregates, but more recently also for use on coastal structures as rock armour. In such applications the rock will be subject to processes of mechanical and chemical deterioration. These processes include impact, abrasion, freeze/thaw, salt crystallisation and leaching, and have been discussed fully by Fookes & Poole, and Poole et al (Refs 1, 2). The use of standard engineering tests is however of little benefit to the designer unless the test results can be related to prototype performance.

In a recent study, a wide range of rock types and prototype structures was studied. Rock from sites in the UK, Arabian Gulf, and east coast of Australia was subjected to a range of engineering tests. The results of these tests were correlated with experience of performance, particularly of rounding, spalling or fracturing. This project yielded a suggested suite of tests with appropriate acceptance values. These studies have been reported fully by Allsop et al (Refs 3, 7). Some aspects of the tests, the acceptance values suggested, their limitations and use, are discussed further with examples in Section 3 below.

It may be noted, however, that the rock available in some circumstances may be of low potential durability. The use of simple accept or reject criteria only for the supply of rock armour may therefore not be particularly helpful. Techniques that allow the in service life of the available rock to be estimated will be more useful to the designer. A simple example of this approach has been presented recently by Fookes & Thomas (Ref 9). They describe the assessment of locally available rock in the course of a brief site visit. None of the rock easily available would pass the criteria suggested in References 2 and 3, and time was not available for a comprehensive test programme. A set of ad-hoc and qualitative assessment techniques was developed to allow the selection of the best material available. Engineering tests for point load strength, water absorption, and apparent specific gravity were used, together with a comprehensive understanding of the local geology, and of the processes of weathering and hardening. The potential useful life of the rock selected was estimated from the performance in service of various local coastal structures. In particular, assessments of armour stone rounding in service were made using a visually estimated score of relative roundness. In their brief appraisal, Fookes & Thomas demonstrated the potential use of engineering tests for rock quality assessment, together with in service performance monitoring of existing structures, as part of the design process for rock armouring. Since their appraisal, conducted in 1984, there have been further developments in monitoring techniques and in the quantification of the state of rock armour layers, and these are discussed in Sections 2.2 and 4 below.

2.2 Slope and shape monitoring techniques

Classic design methods for rock armouring envisage the construction of armour layers of fixed slope angle(s), thickness and layer porosity. The armour units within the layer are generally described only by the median unit weight, or by upper and lower limiting weights. Such simple descriptors do not, however, allow the hydraulic performance or stability levels of the armour layer to be fully quantified. Nor do they provide a particularly appropriate framework within which to monitor changes to the armour either in the field or in the laboratory.

Recently Latham & Poole (Ref 10) have advanced a set of more sophisticated techniques for the numerical description of the state of an armour layer. They have identified a range of descriptors intended to quantify the armour profile at both macro and micro levels. The descriptors have been tested using experimental profiles formed with glass balls or aggregate particles. Latham & Poole have described the use of high and low pass filters to the data. High pass filtering is clearly useful where particle shape and surface roughness are important. Conversely, low pass filtering may be used to reveal settlement or subsidence of the profile. It is however acknowledged that any relation between the properties of the armour layer profile and its hydraulic performance is as yet unquantified. The data rate required, at around 15-20 points per armour unit, also demands an automated measuring technique. This may be appropriate in the laboratory, but is not yet possible in the field. To accelerate data acquisition, researchers at both QMC and Hydraulics Research (HR) are actively pursuing video image processing techniques, some of which might be capable of digitising armour layer profiles directly.

Further advanced work is also continuing at QMC on the description of particle shape and roughness. Both of these factors considerably influence the hydraulic performance and the stability of the armour layer. Historically relatively little attention has been paid to particle shape. Qualitative terms such as cubic, angular, flat, and rounded, have often been used to describe shape. In some instances ratios of maximum and minimum perpendicular dimensions have been measured, or limiting values suggested. In few instances have the effects of particle shape been quantified. In no example known to the authors has armour unit shape or roughness been quantified and related numerically to armour performance or stability. In an effort to help overcome these problems, Latham and Poole have developed a number of sophisticated descriptors for particle shape and roughness. Preliminary work suggests that a single total roughness parameter might be used to assess many of the effects of armour unit shape on hydraulic performance and stability. A surface texture factor has also been derived for use in quantifying changes in armour unit texture and roughness. Again, automated data collection methods, such as video image analysis, have been investigated.

3 Rock Quality Tests

A suite of engineering tests have been used to assess the durability of the rock fabric, in rock armouring, on coastal structures. The tests have been adapted to analyse the effects of the physical and chemical degradation mechanisms operating in the marine environment; in particular the mechanisms causing abrasion, fracturing and spalling of the armour. The tests selected and the recommended acceptance value for each test are given below.

Recommended Acceptance Values for Quality Control Tests

Test	Recommended Acceptance Value
Aggregate impact value	25 maximum
Franklin point load index	$4MN/m^3$ minimum
Water absorption	2.5% maximum
Specific gravity	2.6 minimum
Magnesium sulphate soundness loss	12% maximum
Fracture toughness	$0.7MN/m^{3/2}$ minimum

The sulphate soundness and water absorption tests are used to assess the effects of salt water on the degradation of the armour. This is particularly important in situations where the rock has a high clay mineral content, such as in clay cemented sandstones or in weathered igneous rocks. Absorption and soundness tests have proved to be particularly useful in assessing the relative performance of various low strength rocks (Ref 9). The sulphate soundness tests induce swelling pressures within the rock fabric, causing accelerated disaggregation of the minerals. The specific test used in this study is a modified version of the ASTM soundness test. Magnesium sulphate is used in preference to sodium sulphate, as it produces more repeatable results, due to the single form into which magnesium sulphate crystallises.

The specific gravity of the rock is also of particular importance, in its stability against wave induced movement. Empirical design formulae for rock armoured structures indicate that more dense rock will be more stable than less dense rock of otherwise similar characteristics (Ref 7).

The Franklin point load test is used as a measure of tensile strength of the rock fabric. This test is particularly useful, since it requires no specimen preparation and can be carried out with portable test apparatus. It should, however, be noted that a fairly wide scatter of results may be obtained from this test. A sufficiently large sample of specimens should therefore be tested, to ensure that the results are statistically valid. Other tests have been considered as a measure of tensile strength; in particular the test for fracture toughness using the single edge notched beam method. This test provides results which correlate well with breakwater armour performance, and with the other engineering tests. Accurate specimen preparation and expensive testing equipment are, however, required for this particular test. Additionally, some difficulties have been experienced in preparing test specimens of coarse grained rocks (such as granites), where the test provides less reliable results. Whilst it is felt that this test does provide useful additional information on the rock quality, the additional costs and time taken tend to mitigate against its use.

The aggregate impact test is used as a measure of the potential for the disaggregation of the rock fabric by rock impact. This type of degradation typically occurs where armour is allowed to rock under wave action, or is subject to impact by suspended materials. Other tests have also been used to examine the wear resistance of the rock, including the Los Angeles abrasion test, an especially developed roller mill test, and the aggregate abrasion test. Whilst none of the tests have yet been fully calibrated against structure performance, general guidelines for the aggregate abrasion test have been drawn from the standards used in roadstone selection and experience drawn from a number of coastal structures.

The acceptance values tabulated above have been suggested on the basis of the in service performance of a range of rock types. In instances where the rock does not meet the specifications, in one or more of the tests, the full range of results should be considered carefully. Additionally, large scale inherent weaknesses in the rock, such as natural joints and bedding planes, which may affect armour unit size should also be considered. Only after careful analysis of the implications of any deficiencies in the rock should a decision be made to accept or reject the material.

In many instances, where the only rock available is of marginal or inferior quality, the tests may be used as a guideline to the performance of such material. Modifications to the design may sometimes be made to allow for the use of inferior quality of materials in the design. Further calibration data is, however, still required to allow the performance of substandard rock to be predicted with any degree of confidence.

The case studies outlined below illustrate some limitations of the durability tests and discuss the implications of results, suggesting appropriate modifications to the designs wherever necessary. A range of test results achieved in recent studies is shown in Table 1.

Two coarse granites from Spain have been examined, both of which exhibit good results in all but the Aggregate Impact Value test (AIV), where values of 30 and 41 were achieved - both above the recommended maximum of 25. These high values are clearly a function of the extremely coarse crystals of which these rocks are composed, and the angular nature of the aggregate size samples tested. The high impact values imply that the rock is less resistant to impact than might be desirable and suggest that abrasion, caused by movement of armour, or attrition by suspended sediment might cause fairly rapid rounding of the rock.

Rock type 4, (Table 1), exhibited an AIV of 41. Whilst the other test results were within acceptable limits, they were not so high as to imply a high level of durability. The shape characteristics of the armour, which was virtually cubic, and the absence of inherent planes of weakness in the armour did, however, allow a tight placement of the armour, thus reducing the likelihood of impacts from rocking movements. Hydraulic model tests conducted previously for a specific use had shown the rock armour to be very stable. The rock could therefore be expected to remain reasonably immobile under most wave conditions, and should therefore only suffer abrasion damage due to attrition by suspended sediments. By allowing a minimal over-design of rock weight, and ensuring that the armour is tightly packed, such rock of otherwise marginal quality should perform to an acceptable level.

The use of rock quality testing, together with hydraulic model tests may be illustrated by an example of a recent study for the rehabilitation of a vertical sea wall using rock armour. Two sources of rock were considered, the properties of which are given in Table 1 (rock types 1 and 2). Both rock types exhibited good results in all of the rock fabric tests. However, the large inherent weaknesses due to jointing in the carboniferous limestone indicated that the rock armour might break into smaller pieces if subjected to movements under wave action. The proposed construction method was considered carefully in the placement of rock in the hydraulic model. During testing, noticeable levels of armour rocking were recorded. The client was advised both on the hydraulic consequences of the design and the proposed construction method, and also on the implications of the anticipated armour movement on the selected rock armour type. As a result of the hydraulic model studies and the rock durability tests, it was possible to give advice on a suitable method of construction, to increase the packing density of the armour and thus reduce potential movement of the inferior quality rock.

4 Monitoring Techniques

Most conventional damage assessment techniques have been concerned solely with the evaluation of the proportion of armour units extracted permanently from the armour, resulting in cavities or voids. This is

Table 1: Rock properties

Rock Type	Location	Apparent Relative Density t/m^3	Water Absorption %	Magnesium Sulphate Soundness %	Franklin Point Load Index	Aggregate Impact Value	Aggregate Abrasion Value
1 Carboniferous Limestone	Westleigh UK	2.70	0.6	0.1	7.4	20	10.2
2 Gritstone (greywacke)	Triscombe UK	2.66	0.1	9.5	13.8	10	4
3 Granite Coarse Biotite	Pico D'Ouro Spain	2.64	0.6	0.2	10.4	30	3.5
4 Granite Coarse Biotite	Porrino Spain	2.64	0.5	0.6	5.9	41	5.4
5 Fine Grained Greywacke	Belfast N Ireland	2.67	0.7	2.1	8.1	11	6.7
6 Kentish Limestone	Offham UK	2.53	2.4	40.0	-	28	19.6
7 Granite	Gothenburg Sweden	2.70	1.0	0.6	-	-	-
8 Granodiorite	Gothenburg Sweden	2.85	0.3	4.1	8.0	19	3.9

perhaps an over simplification of armour layer damage, since a number of significant, but more gradual degradation processes are not considered. The type of damage or degradation may vary according to a number of controlling factors.

(a) Environmental factors; such as waves, tidal range, temperature, salinity.
(b) Armour shape and size.
(c) Armour interlock.
(d) Rock quality.

An inspection method has been developed that allows the simultaneous appraisal of the effects of each of these elements. The methods used in this study are based closely on those developed by researchers at QMC and described by Allsop et al (Ref 3). A number of categories of armour layer damage have been identified, allowing the principle mechanisms of damage to be clearly defined on each structure. A brief description of each of the damage categories is given below.

The most obvious form of armour layer damage is the void or cavity, as considered by more conventional damage assessment methods. Fractures in armourstones may occur when the armour is permitted to move freely under wave action and/or where there are large inherent planes of weakness in the rock. Subsize armour may be defined as armour which is below specification size. This may occur as a result of poor quality control during construction, or may result from fracturing whilst in service. The final damage category used in this method of damage description is unstable armour. This is loosely defined as armour which is visibly mobile under wave action. Unstable armour is often characterised by rounded or abraded edges resulting from rocking movements, and is frequently observed on newly constructed structures, where initial placement may allow the armour to move freely. Such a condition is, however, usually temporary, as unstable armour tends to stabilise or is removed completely from the armour layers by wave action.

These armour layer degradation descriptors have been used in a monitoring method which aims to give a fuller description of armour layer damage than methods used previously. No sophisticated equipment is required to carry out surveys, but the method is, at present, limited to the sections of the structure that are surface emergent. Data is collected within carefully selected, delineated areas, each of which must be of sufficient size to provide a statistically valid sample of the armouring. The size of sample areas is dependent upon armour size and the freeboard of the structure. As a guideline, sample areas should contain a minimum of 100 armourstones. Similarly, the number and location of sample areas needed depends upon the size and exposure of the structure. Where possible, separate sets of measurements should be made for the intertidal and supratidal zones of the structure. Sample areas should be referenced to local fixed points, to allow relocation on subsequent surveys.

Surveys are conducted by counting the number of armour units in each of the damage categories. The most useful expression of damage is given by the total number of armour units in each category, expressed as a percentage of the total number of armour rocks in the study area.

A number of other damage assessment methods have also been considered (Ref 11). Expression of the degree of armour unit interlock may be a useful indicator of the integrity of the armour layers. A descriptor known as co-ordination number has been used to evaluate block interlock. This is simply defined as the average number of armourstones in contact with each individual armourstone in the sample.

Comprehensive monitoring programmes have been instigated using these measurement techniques. Several structures have been surveyed, covering a range of degrees of exposure to wave conditions and structure types. Some important aspects and conclusions drawn from the inspections are given below.

Port Talbot breakwater main arm was chosen for study, as a structure of typical rubble mound construction, exposed to a fairly severe wave climate. The main breakwater is approximately 2km long, changing alignment twice along its length, and is subject to a particularly large tidal range of approximately 8 metres. Sample areas were selected at locations of varying exposure - according to water depth and breakwater alignment, and separate sets of measurements were recorded in the intertidal and supratidal zones. The results of the first survey are shown in Table 2. A marked contrast in armour layer damage occurs between the intertidal and supratidal zones. Certain sections of the structure have degraded more rapidly than others, particularly in the intertidal zone. Sample area 3 (Table 2) has suffered far greater damage than other sections of the structure. This area is in a more exposed location, in deeper water and facing the predominant wave direction. The predominant category of armour layer damage on this structure is cavities. This is largely due to the severe wave conditions to which the structure is exposed. The rock armour is of relatively good quality, as is evidenced by the relatively low proportion of fracture damage. However, degradation by fracturing is significantly greater on the more exposed section of the structure, where more movements are likely to occur.

The revetment at Herne Bay, Eastcliff III is a recently constructed (1986) riprap armoured structure. Armour has a W_{50} of 850kg and the rock armour type is a granodiorite from Sweden. The properties of the rock are given in Table 1. An extremely low level of armour layer damage was measured on the first survey (Table 3). Good quality control during construction is evidenced by the absence of subsize armour. The quality of the rock appears to be very good, with little evidence of abraded or fractured armour. It should, however, be noted that the structure had not been subjected to a winter storm season at the time of the survey. Whilst overall armour layer damage was low, unstable armour figured prominently as a damage type. This might reasonably be expected on a newly constructed structure. Initial

Table 2: Breakwater Damage Assessment - Port Talbot

Sample No	No of Rocks	Fractures (%)	Cavities (%)	Subsize Armour (%)	Unstable Armour (%)	Total (%)	Co-ordination No
1 Supratidal	492	0.4	4.1	0.2	0.4	5.1	4.4
Intertidal	368	0.8	10.6	0.3	5.4	17.1	4.1
2 Supratidal	468	0.9	7.1	0.2	1.3	9.4	4.8
Intertidal	408	1.2	14.0	2.2	0.7	18.1	4.2
3 Supratidal	223	3.6	9.9	0.4	0.9	14.8	3.7
Intertidal	177	4.0	33.3	4.0	2.8	44.1	4.0

Table 3: Breakwater Damage Assessment

Location	No of Rocks	Fractures (%)	Cavities (%)	Subsize Armour (%)	Unstable Armour (%)	Total (%)	Co-ordination No
Port Talbot	2712	1.1	9.4	1.5	0.8	12.8	4.2
Stornoway	693	1.4	1.7	2.2	3.0	8.3	4.6
Herne Bay Eastcliffe III	828	0.2	2.2	0	1.7	4.1	4.9

settlement and removal of any unstable blocks during the first winter may well result in a reduced proportion of damage, in this particular category, on the next survey. The relatively wide grading of rock armour made measurement of the co-ordination number difficult, and where the rock grading was reduced in median size, at the less exposed end of the structure, the rock was too small to make measurement of the co-ordination number practicable. A series of levels were also taken along profile lines running from toe to crest of the structure.

The structure monitored at Stornoway airport is also armoured with riprap. The median rock size is, however, larger than that at Herne Bay, with a W_{50} of 1 tonne. This structure had been in existence for some years prior to the first damage survey, but sections of the structure had been repaired only a few months before the survey took place. The rock type used on this structure is a Lewisean gneiss, which often includes large inherent planes of weakness in the armourstones. This is evidenced in the damage analysis (Table 3) by the proportion of fractured armourstones in the samples. Cavities were infrequent, since most of the damage to the structure had recently been repaired. A relatively high proportion of structure damage occurred either as subsize armour or as unstable armour. This may be explained, to some extent, by the fact that the structure was a little unusual, in that it had undergone recent rehabilitation. Prior to repair the structure had a large number of cavities, due to armour removal. When armourstones are extracted it is quite common for units surrounding the voids to move to new positions, often reducing the size of the voids, and also reducing interlock between armourstones. In some instances the voids are reduced to a size such that the replacement rock cannot be placed in a stable position during repair. Alternatively, armour below the original specification size must be used to fill the voids, thus maintaining a reasonable degree of interlock. Whilst this may explain the reasons for the presence of some subsize armour on the structure, some of the armour has clearly degraded in situ as a result of fracturing along the planes of weakness in the rock.

Data collected in this study can be used to provide a detailed analysis of armour layer damage. By identifying the proportions, quantities and locations of each of the damage types, scheduled maintenance can be planned. If surveys are carried out on a regular basis, problems of gradual degradation that might otherwise go undetected may be identified. As more data becomes available, it should provide a basis for the selection of appropriate materials and construction techniques at the design stage, or allow revised placement techniques or material standards to be adopted during the repair of existing structures.

5 Recommendations

The work described in this paper has identified a number of techniques of use to the designer or owner of rock armoured coastal structures. A set of engineering tests has been developed to allow the identification of durable rock, and to grade available material for potential durability. Field monitoring techniques using a minimum of equipment have been described that quantify changes both to the armoured slope and to individual armour units. A range of numerical descriptors have been defined and tested for armour profiles, and for armour unit shape and roughness.

Two further areas of research may now be identified. Armour unit shape and surface roughness clearly influence both the hydraulic performance and the stability of an armoured slope. Now that numerical descriptors are available for particle shape and roughness, it should be possible to conduct a series of hydraulic model tests to relate hydraulic performance and stability parameters directly to those for armour unit shape and roughness.

Also of importance to the prediction of armour layer performance is the quantification of changes to armour unit size and shape under the chemical and mechanical deterioration processes of the marine environment. This will require the quantification of rates of deterioration, such as rounding, in relation to the original rock material properties, wave climate and environmental parameters.

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