THE PERFORMANCE OF A NEWLY DESIGNED CONCRETE ARMOUR UNIT FOR RUBBLE MOUND BREAKWATERS

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THE PERFORMANCE OF A NEWLY DESIGNED CONCRETE ARMOUR UNIT FOR RUBBLE MOUND BREAKWATERS

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Δ	Buoyant Density
Δ_x, Δ_y	Horizontal and Upslope Centre to Centre Distance Between Units (m)
A	Total Surface Area (m^2) of Armour Layer Panel Parallel to Slope
A_a	Area Covered by One Armour Unit (m^2), Equal to nA/ N_a
A_e	Erosion Area from the Profile
C_t	Coefficient of Transmission
D	Characteristic Armour Unit Length
D_n	Nominal Diameter
D_{n50}	Nominal Median Value
D_{sieve}	Sieve Opening
g	Gravitational Acceleration
h	Water Depth at the Structure's Toe
H	Wave Height at Structure's Toe
H_i	Incident Wave Height
H_s	Specific Wave Height
H_t	Wave Height Transmitted
K_c	Modified Layer Coefficient
K_D	Stability Coefficient
K_s	Shape Coefficient
K_t	Layer Coefficient
M	Mass of Armour Unit

M_{50}	Median Value of Mass Armour Unit
N	Number of Armour Units Per Unit Area ($1/m^2$)
n	Number of Layers
N_a	Total Number of Armour Units Placed on the Surface Area
n_v	Armour Layer Porosity
N_z	The Number of Zero-Crossing Waves in the Design
P	Permeability Factor
Q	Overtopping
R_u, R	Run-Up
s	Wave Steepness
S_d	Design Damage Number
S_r	Specific Gravity of Armour Unit Relative to the Density of Water at the Structure
T	Wave's Time Period
t_a	Armour Layer Thickness
T_M	Mean Time Period
T_P	Peak Time Period
V	Armour Unit Volume (m^3)
V_c	Concrete Volume Per Unit Area (m^3/m^2)
W	Weight of Individual Armour Unit in the Primary Layer
X, Xc	Dimensionless Horizontal Distance
Y, Yc	Dimensionless Upslope Distance
α	Angle of Structure's Slope

β	Angle of Wave Attack
ξ_{mcr}	Critical Value of the Surf Similarity Factor
ξ	Iraberren's Number
P_c	Density of Concrete
ρ_r	Density of Armour Layer
ρ_w	Water Density
ρ	Density of Armour Unit (m^3)
Φ	Packing Density Coefficient

PRESTASI UNIT PERISAI KONKRIT REKAAN BARU UNTUK TIMBUNAN BATU PEMECAH OMBAK

ABSTRAK

Hakisan dan banjir akibat rempuhan ombak merupakan cabaran utama bagi lokasi berhampiran laut. Cabaran-cabaran ini kian meningkat dari segi intensiti ombak dan kekerapannya akibat fenomena terkenal Pemanasan Global. Oleh yang demikian, keperluan untuk struktur yang lebih stabil dan lebih kuat amat diperlukan. Kajian ini bertujuan membangunkan satu unit perisai tiruan baru untuk menahan rempuhan ombak di pesisiran pantai. Reka bentuk perisai dijelaskan di dalam kajian ini. Keliangan lapisan (layer's porosity) dan ketumpatan susunan (packing density) ditentukan hasil daripada pengiraan pekali lapisan (layer coefficient). Ciri-ciri ini dibandingkan dengan unit perisai tiruan lain yang sedia ada. Beberapa ujian dilakukan bagi menguji prestasi hidraulik unit perisai tiruan yang telah direka. Ujian tersebut merupakan ujian dua dimensi yang merangkumi kestabilan, overtopping dan run-up hidraulik. Ujian ini dilakukan dalam flum hidraulik 10 m panjang, 0.3 m lebar dan 0.45 tinggi. Ia dijalankan pada tiga lapisan perisai iaitu: lapisan perisai batu; lapisan perisai yang terdiri daripada unit perisai yang direka, yang diletakkan dalam keadaan rawak; dan lapisan perisai yang terdiri daripada unit perisai yang direka, yang diletakkan dalam keadaan seragam. Dapatan yang diperoleh bagi ketiga-tiga lapisan perisai ini dibandingkan dan dianalisis. Sebagai kesimpulan, unit perisai yang ditonjolkan dalam kajian ini menunjukkan prestasi hidraulik yang tinggi dibandingkan dengan unit perisai batu. Di samping itu, ia

juga didapati lebih berliang serta lebih ekonomik jika dibandingkan dengan perisai lain yang sedia ada.

THE PERFORMANCE OF A NEWLY DESIGNED CONCRETE ARMOUR UNIT FOR RUBBLE MOUND BREAKWATERS

ABSTRACT

Erosion and inundation, resulting from wave impacts, are challenges synonymous with the near sea location. These challenges have grown in intensity and event due to the well known phenomenon of Global Warming. Therefore, the need for stronger and more stable structures has increased. The intention of this study is to develop a new artificial armour unit used for armouring offshore rubble mound breakwaters. A design of the intended armour has been given in this study. A number of calculations for determining the layer coefficients were conducted, hence, obtaining the layer's porosity and packing density. These characteristics were compared to other well known artificial armour units. In order to test the newly designed artificial armour unit for its hydraulic performance a number of tests were conducted. These tests are two dimensional tests that include hydraulic stability, overtopping and run-up. These tests were conducted in a hydraulic flume of a 10 m length, 0.3 m width and 0.45m height. The tests were conducted on three armour layers a rock armour layer, an armour layer composed of randomly placed newly designed armour units and the third is an armour layer made up of uniformly placed newly designed armour units. The results of the three armour layers are compared and analyzed. In conclusion, the armour unit that was presented in this study showed higher hydraulic performance than the rock armour unit. Also, the presented armour unit is more porous than some well known armour units and more economical.

CHAPTER ONE

INTRODUCTION

1.1 Background

Throughout human history it is realized that great civilizations such as the Greek, Roman and Egyptian civilizations were located near the sea. A near sea location was a sign of wealth, prosperity and strength due to the sustainable source of food, easy access to trade that increases the technology of the civilization through the generation of new weapons and goods, the interaction with other cultures by exchanging knowledge and ideas and also the sea can be seen as a natural defence line that reduces the possibility of foreign invasion.

Although having a near sea location has many benefits it also has its shortcomings. Seas are not always calm. They can go rogue because of the action of storms and the effects of high waves can be destructive on coastal areas. So in order to maintain the outcome of the near sea location, people began to think of ways to protect their coastal areas and water ways to reduce human and property loss to the erosion and flooding caused by the sea.

Coastal defence is a natural response to the challenges presented by the near sea location. French (2001) classified the approaches of applying coastal defence into two approaches, the soft and hard approach. The soft approach for coastal defence uses the surrounding sediment in order to reduce wave action.

According to Dean and Dalrymple (2004) beach nourishment, which is one of the most common methods of the soft approach, is defined as the placement of sand from onshore or offshore sources to restore eroded beaches. Although this approach avoids constructing a physical barrier but it also has its drawbacks such as the reduced clarity of the water around the dredged area, short life of the refills where repeating the nourishment is needed and the state of knowledge for this approach is insufficient in explaining the reason of variance in performance of different refills (French, 2001).

On the other hand, the hard approach involves the construction of physical barriers to reduce the effect of waves. It has been a common practice to place a physical barrier between the cause and the problem. The hard approach is called to be the traditional way in applying coastal defence (French, 2001). These hard structures are designed and constructed to prevent further erosion of a beach or to protect the hinterland from wave attacks. This approach is popular when faced with a coastal problem due to the vast knowledge gained throughout the years, people tend to feel much more secure when seeing a physical barrier to protect them and industrial and resort areas located near the sea need a strong structure for protection because of their high value.

Dean and Dalrymple (2004) classified these structures into three categories onshore, shore detached and offshore structures. Onshore structures, such as sea walls and revetments are constructed parallel to the coast line. Sea walls according to Fleming (1998) are nearly straight faced structures designed to protect a coast from a high range of waves during its service life. Revetments are defined as structures constructed parallel to the shore line for the purpose of limiting the erosion of the coast (Dean and Dalrymple, 2004). The materials chosen for these structures are stone, concrete or a mixture of them both. These structures are chosen when the land behind the structure (hinterland) is much valuable than the beach in front. In other words, erosion is allowed to happen to the beach fronting the structure.

Shore detached structures, such as groins and jetties; differ from the onshore structures by their place of construction. These structures are constructed perpendicular to the coast line. The shore protection manual (USACE, 2001) defines a groin as a narrow structure that stretches from a point onshore to a point offshore. Groins and jetties differ in scale and number. Groins tend to be smaller in scale than jetties but they are built in groups. Jetties are larger, single structures and they extend offshore further than the groins. These structures are chosen when the intention is to prevent sediment from entering harbours and to building up beaches when the area has a high long shore sediment movement. But they have some problems when constructing this type of structures such as down drift erosion and the interruption of the long shore sediment movement (French, 2001).

Offshore structures are structures constructed distant from the coastline. They are also called offshore breakwaters because they tend to break the waves offshore. There are many types of breakwaters but the main types are rubble mound breakwaters and caisson-type breakwaters (Allsop, 1998). French (2001) classified the main types of offshore breakwaters as submerged, emergent, segmented, non-segmented, solid and floating breakwaters. The type of offshore breakwater concerned in this study is the rubble mound breakwater. Rubble mound breakwaters are constructed from quarry rock for the core and large rocks or concrete armour units for the armour layers. These structures not only they reduce the wave action on a particular beach but they are also effective in building them up. The shore protection manual (USACE, 2001) states that rubble mound breakwaters can intercept the movement of sediment very effectively. Sediment is deposited on the shore behind the structure because the offshore breakwater is reducing the effect of wave forces that transport this sediment. Rubble mound breakwaters according to the CIRIA (1991) are numerous and popular because:

- Local quarries can supply the rock;
- A successfully built structure can be built even with limited skills, resources and equipment;
- The damage that happens to rubble mound breakwaters is gradual and it only occurs when the design limits are exceeded;
- Errors occurring in the design or construction phase can be mended before complete destruction happens;
- When repair works are needed, they are relatively easy and do not need specialised equipment;
- Due to their flexibility these structures are not sensitive to differential settlement.

1.2 Problem Statement

Although having a near sea location has many benefits but there are some drawbacks. Problems such as erosion and flooding are synonymous with such a location. Coastal countries are tackling these problems by applying one or both of the approaches of coastal defence. The threat of these problems has increased due to the well known phenomenon of Global Warming. Global Warming is believed to have a direct relationship with increasing the intensity of storms and sea level rise. Increasing storm intensity will lead to the higher risk of flooding for coastal areas. Waves are driven by winds and increasing wind speed will eventually make the waves more intense leading to the inundation of beaches and coastal areas. A study done by Aumann (2009) shows that storm intensity will increase as long as there is an increase in global warming. Global warming is also causing the melting of ice sheets and mountain glaciers leading to the expansion of the ocean waters. Titus (1990) found that seas will rise by a meter by the next hundred years. Such an increase will lead to the flooding of many low laying lands.

In addition, coastal countries have been rapidly developing the coastal areas. Furthermore, they did not stay on beaches but they extended their development further to the sea. Another issue arises for coastal countries which are lying on or near unstable earth plates. Moving earth plates can cause earthquakes and such an event happening near a coastal area or in the middle of the sea will increase the possibility of having a tsunami. Coastal areas that were hit by tsunamis suffered high losses both in property and people.

In addition, rock armour units are rare when it comes to heavy masses such as 10- 15 tons, hence, creating the need for an alternative. Furthermore, artificial armour units do have a number of problems. These problems are represented by their structural integrity issues such as slender armour units; or if their application is economical such as the issue of applying them in a double layer or a single layer

For the reasons mentioned the need for strong and stable structures has increased to reduce the effects of such threats. Also, the need for a unit that is more economical and possess higher structural integrity is more evident.

1.3 The Research Hypothesis

The newly designed artificial armour unit will be better in its hydraulic performance than the rock units. The new armour unit will be more stable than rock armour units, has less overtopping and less run-up. Also, this newly designed unit will be better from other artificial armour units in porosity of the armour layer and more economical.

1.4 Objectives

The aim of this study is to design a new armour unit that can achieve higher hydraulic performance than other units and more economical. The method that will be suggested for this study comes in three steps. The first step is to present a concept design that can be tested. The second step is to test the hydraulic performance of the newly designed armour unit. This is done by two dimensional tests conducted in a hydraulic flume. The third step is to compare the results with the performance of other armour units. This study will aim on achieving the following goals:

1. To develop a design that is better interlocking than rock;
2. To develop an armour layer composed of the newly designed armour unit that will perform better in hydraulic stability, overtopping and run-up than an armour layer composed of rock armour units;
3. To introduce a newly designed concrete unit that possesses structural integrity that can be compared to other armour units. In addition, an armour layer made out of the newly designed armour unit should posses higher porosity than a layer composed of an existing armour unit;

4. To present an armour layer made out of the newly designed armour unit that would have a lower packing density than an armour layer made out of an existing artificial armour unit.

1.5 Scope of Study

This study intends to present a concrete unit that can be used for armouring offshore breakwaters. The concrete unit will be designed to outperform the rock armour units. In addition, the newly designed concrete can be compared to other artificial armour units in performance as in porosity, packing density and economy.

1.6 The Importance of this Study

The purpose of any coastal defence system is to reduce the effect of wave action on the coastal area. Rubble mound breakwaters are structures designed and constructed to reduce the problems of flooding and erosion. These structures are situated in waters ranging from 5 to 50 meters in depth (Allsop, 1998) so they are meant to dissipate wave energy offshore. This causes the creation of a calm area between the structure and the shore where sediment can build up by that tackling the issue of erosion.

Since their location is offshore it is very important that these structures have the strength to take on the whole force of the wave. Stability of a rubble mound breakwater is the responsibility of the armour layers that cover their core. So it is very important to have a strong and durable armour layer that enables the structure to perform as meant to be in reducing the effects of wave action. This research intends to produce a concrete unit that enables the rubble mound breakwater to work more efficiently in providing the safety needed by the coastal areas.

1.7 Thesis Organization

In this study six chapters are presented. In this section a summary for each chapter is given highlighting what has been achieved through each chapter.

1.7.1 Chapter One

In this chapter a general introduction was given. Also, the objectives, scope of study, importance of the study, the hypothesis of this study and the problem statement.

1.7.2 Chapter Two

The second chapter listed the idea behind choosing the offshore breakwater and the most fundamental principles for designing the mentioned structure. Also, the types of armour units and the history of the artificial units were also discussed. In addition, a number of studies conducted on the offshore breakwater for its stability and hydraulic performance were listed. Furthermore, the engineering measurements are mentioned in order to analyze the findings.

1.7.3 Chapter Three

This chapter discussed the design chosen for the new armour unit for this study. Furthermore, parameters for the new armour unit were mentioned. In addition, formulae were used to determine the layer coefficients for a layer composed of randomly placed units. The STAAD PRO software was used to determine the stresses produced in the newly designed armour unit when subjected to different types of loadings. In addition, this chapter discussed the steps for achieving a good implementation of the tests to prove the study's hypothesis. The steps from fabricating the armour units, designing the structure's cross-section, and the test implementation for the stability and hydraulic response are discussed. Also, the criteria of analyzing the results via the engineering measurement are listed in this chapter.

1.7.4 Chapter Four

This chapter lists the results of all the calculation and tests conducted in prior chapters. The results listed in this chapter are layer coefficients, maximum stresses, hydraulic stability, run-up and overtopping. The results were given as tables and figures.

1.7.5 Chapter Five

This chapter concludes the whole study. It summarizes the whole findings that were obtained through the tests and calculations conducted throughout the study. Furthermore, suggested future work will be listed.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In this chapter the researcher will list and discuss the studies that have been done by other researchers regarding rubble mound breakwaters. The studies will be divided according to the aspects that this study will focus on. These aspects are the stability of the rubble mound breakwater, its overtopping and run-up. Each aspect will discuss the effect of rock and concrete armouring on them. But at first a detailed description of a typical rubble mound breakwater will be given with a list of the requirements for each component of the structure that should posses. Finally, a method of analysis will be mentioned along with sub-types and their definitions.

2.2 Typical Rubble Mound Breakwater

A rubble mound breakwater is a structure that consists of rubble organised within a slope in order to dissipate wave energy. To be more specific a rubble mound breakwater is a structure that consists of a core from quarry-run rock covered by intermediate layers of rock separating the core from the armour layers that consist of larger armour units (Novák *et al.*, 2001). Constructing a rubble mound breakwater from single sized units will lead the structure to transmit higher levels of wave energy shoreward. Thus, it is preferable to grade the unit's sizes from the smaller in the core to the larger for the armour layers (Sorensen, 2006). The armour layers play a vital role in dissipating wave energy and protecting the core's finer materials. It is crucial that the armour units remain stable when attacked by the waves and disperse energy above and through the gaps between the armour and the under layers; by that limiting wave run-up, overtopping and reflection (Allsop, 1998).

The units comprising the armour layers are either from large rock or specially designed concrete units. The side slopes of rubble mound breakwaters are generally shallower than 1:1.33 or 1:1.5 (Allsop, 1998). Breakwaters armoured with concrete units tend to be steeper than breakwaters armoured with rock. Figure 2.1 shows a cross-section of a typical rubble mound breakwater.

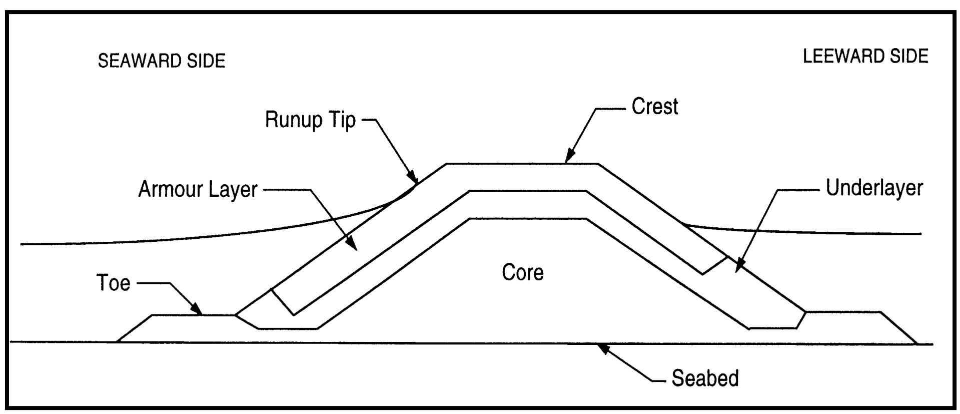


Figure 2.1: Cross Section of a Typical Rubble Mound Breakwater (Palmer and Christian, 1998)

2.3 Main Components of R.M.B.Ws and their Design Requirements

The main components of a typical rubble mound breakwater are listed below. It should be noted that there are other components that were not listed because not all breakwaters have them such as the scour apron and crown wall elements. With each component listed below are some basic design requirements.

2.3.1 Core

A core is made from quarry-run or materials excavated locally, often with little sorting or processing (Allsop, 1998). The core is made permeable to ensure the minimum wave transmission through the cross section of the structure. The core of a rubble mound breakwater can be made of small rock or from geo-textile tubes filled with sand taken from the sea bed. Reedijk *et al*. (2008) found that the permeability of the core has a strong effect on the stability of armour layers. Low permeable cores, such as geo-textile tubes filled with dredged sand from the sea bed, tend to cause damage to the armour layer more than the permeable core that consists of quarry-run rock. It is also important to ensure that segregation would not occur when dumping the core's material. According to Rouault *et al.* (2005) preventing segregation is not possible and it should be accounted for when designing a rubble mound breakwater.

2.3.2 Toe Armour

In order to support the face of an armour layer from waves a toe protection is needed. The toe protection is only needed on the sea side of the structure and the units comprising this element are generally smaller than the armour units. Toe armour units are more stable if their dimensions were the same as the armour units (CIRIA, 1991). In depth studies were conducted by CIRIA (1991) established that toe protection having a height way above the sea bed are more prone to damage than when having a toe near the bottom.

2.3.3 Under-Layers

Palmer and Christian (1998) define an under layer as the foundation of the armour layer. Another function for the under layer is that it works as a filter in order to prevent the erosion of the core. The size of rock to be used in under layers is usually taken as a proportion from the weight of the armour units. CIRIA (1991) suggests that the units comprising the under layers should weigh from one tenth to one fifteenth of the armour units' weight. On the other hand, the USACE (2001) recommends that the under layer units should have one tenth or one fifth of the weight of the armour layer units depending on the type of armour layer and their stability coefficient (K_D). Other under layers that lay beneath the first under layer has a weight of one twentieth the weight of units making up the layer above. The USACE (2001) also suggests that the under layer beneath the armour layer should have a minimum thickness of two quarry stones and this thickness is used for all under layers if there were a number of layers. It is preferred to have a large under layer due to two reasons. The first is that the roughness of the under layers' surface increases the interlocking with the armour layer, this is seen when the armour layer is made out of concrete units.

Secondly, the larger the units of the under layer the higher permeability achieved resulting in a more stable armour layer (CIRIA, 1991).

2.3.4 Slope Angle

The sea side slope according to Allsop (1998) has slopes shallower than 1:1.33 or 1:1.5. The CIRIA (2007) suggests that the slope should be as steep as possible to minimise the structure's volume. Rock armour layers are placed with an angle not steeper than 1:1.5 contrasting with armour layers made up from concrete units; they can be arranged into steeper angles reaching 1:1.33. The rock manual also suggests that double layered bulky concrete armour units are arranged at slopes of 1:2.5 to 1:1.5. Highly interlocking armour units arranged in a single layer can be placed on slopes ranging from 1:1.5 to 1:1.33. For the shoreward face, the slope is taken as steep as possible but it is often preferable to take it 1:1.33.

2.3.5 Crest

The crest elevation of a rubble mound breakwater is dependent on the amount of overtopping acceptable which will not cause damaging waves in the structure's lee (USACE, 2001).The crest's width is also dependable on the amount of overtopping allowed. The CIRIA (1991) and the USACE (2001) agreed that the minimum width of a rubble mound breakwater's crest should allow three armour units to be placed. For rock armour units the three or four units on the crest is a minimum requirement. For concrete armour units it is preferred to have three rows of interlocking units to make up the width of the structure. The width of the crest should also allow the movement of equipment such as trucks and cranes for building up or maintaining the structure.

2.3.6 Armour Layer

The constituents of this layer are either rock or specially designed armour units. The size of these units is chosen to resist the direct attack of the waves and they are arranged to a constant slope and layer thickness (Allsop, 1998). These units may be placed in an arranged manner in order to gain better wedging and interlocking between individual armour units, or they may be placed randomly. The stability of this layer is an important factor that leads to the success of the structure or to its failure. Since the aim of this study is to design a concrete armour unit, the armour layer will be discussed in detail in the coming section.

2.4 Armour Layer Characteristics

Rubble mound breakwaters are protected by armour layers made out of rock or artificial armour units. In addition, wave energy is dissipated when waves clash with the armour layer reducing its strength and transmitted through the core. The stability of this layer is an important issue that engineers focus on when designing a rubble mound breakwater. The more stable the armour layer is, the more successful the structure will be.

Armour units have a direct relationship with the wave height. The higher the wave the largest armour unit is needed to protect the structure. Rock has been the main choice for armouring rubble mound breakwaters but it is hardly ever to get a 20 ton rock; 10 tons is rare; and the most common weight of rock used in armour layers around the world has a realistic yield below six tons (Allsop, 1998). Scarcity of heavy rocks lead to the searching of an alternative and the answer was artificial armour units made out of concrete.

In the coming sections this layer will be discussed in detail. The discussion will cover the types of armour units, their requirements, and an overview of the history of artificial units. Also the coming section will list and discuss the main studies that have been conducted on the stability of these units.

2.4.1 Rock Armour Units

Rock has been used abundantly as armour units on rubble mound breakwaters. The size of the rock is a main factor that can rule out local quarries from supplying a project. The CIRIA (2007) indicates that the need for rock sizing from 10-15 tons can be difficult for local quarries to supply also the means of transporting these stones can also cause economical problems. Thus it is advisable to have an alternative to rock armour when large stone is needed for the construction.

2.4.1.1 Properties of Rock Used as Armour Units

As mentioned above, it is common practise to use rock in different sizes, shapes and properties when constructing a rubble mound breakwater. So it is necessary for the rock to have properties that enables the structure to have a long service life. Rock for offshore structures should possess the characteristics of soundness, durability and hardness. It should also be free from weak cleavages, undesirable weathering and laminations. Rock having such specifications will not disintegrate under the action of sea water, air or in handling and placing (USACE, 2001).

Natural Properties

- **Mass:** densities of rock differ within the same source. The CIRIA (2007) recommends checking for quality variation when density variation is suspected. Low density materials should be tested for their durability before using them in constructing coastal structures. USACE (2001) desires the usage of high density rock when constructing coastal structures in order to decrease the volume of material needed in the structure.

- **Integrity of Rock and Breakage Resistance:** rough handling of rock can be expected leading to minor or major breakage of rock. Minor and major breakages are defined by the Rock Manual (CIRIA, 2007) . Minor breakage is defined as the breaking of rock corners during normal handling. This type occurs when the rock is bruised and crushed and produces rock fragments of small sizes. Minor breakage will cause the rounding of the rock's edges. On the other hand, major breakage can be defined as rock breaking along existing defects in its structure. If major breakage occurs on a large number of armour stones it can affect the design parameters of weight of individual armour rock and its nominal diameter. Armour rock integrity is the rock's resistance to extreme breakage during its life. The CIRIA (2007) distinguishes two types of rock integrity according to rock taken as individual or as a granular material. Individual rock integrity is the rock's resistance to breakage, while the integrity of granular material is the resistance of that material to extreme mass distribution.

- **Wearing Resistance:** considerable mutual shearing will be undergone by core and under-layer materials weighing less than 300 kg (CIRIA, 2007). This will lead to abrasive degradation along with higher mass losses in finer materials.

Production Induced Properties

- **Shape:** armour layer stability can be significantly affected by the shape of the armour units especially the units placed above sea level. Not only it affects the stability but also shape has an indirect effect on permeability, shear strength properties of filtering for the core and under-layer materials. Shape of armour units can influence the layer thickness, easiness of construction, packing density and hydraulic stability. The shape of a rock armour unit can be affected by the length to thickness ratio (LT), Blockiness (BLc), Cubicity and Roundness. All the mentioned aspects of rock armour shape are defined by the Rock Manual (CIRIA, 2007).

  The length to thickness ratio (LT) is defined as the maximum diagonal length, l (m), divided by the minimum distance, d (m), between parallel lines through which the particle would just pass. Blockiness (BLc) is defined as the ratio between the volume of the rock and the volume of the enclosing XYZ orthogonal with a minimum volume. The higher the Blockiness the higher the density, greater numbers of contact points leading to greater interlocking. The advantages of using Blockiness along with the length to thickness ratio are predicting the porosity and packing accurately, hydraulic performance and stability can be better predicted and the ability to match rock armour behaviour in a prototype with that in a hydraulic model. Figure 2.2 and 2.3 show the dimensions of rock for the (LT) ratio and examples for different blockiness ratios respectively.

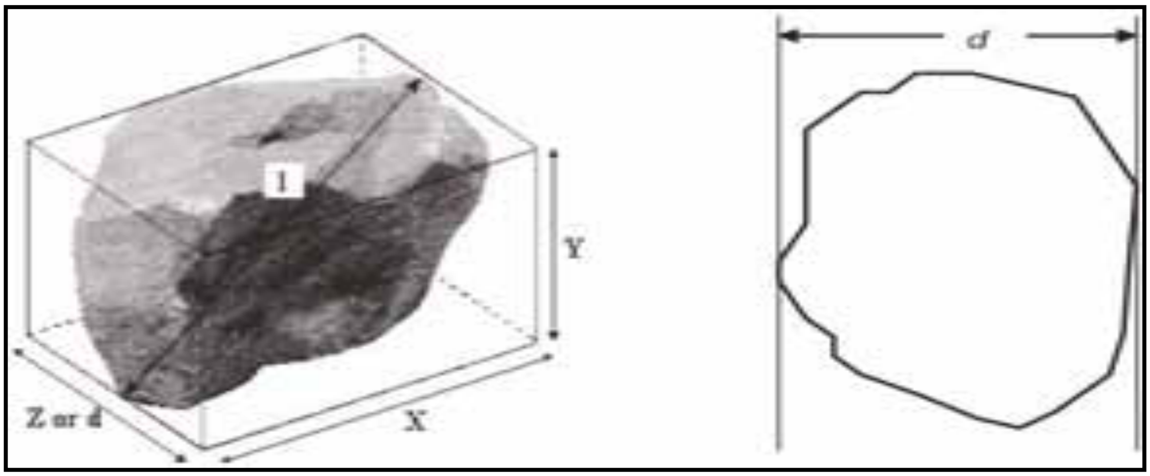
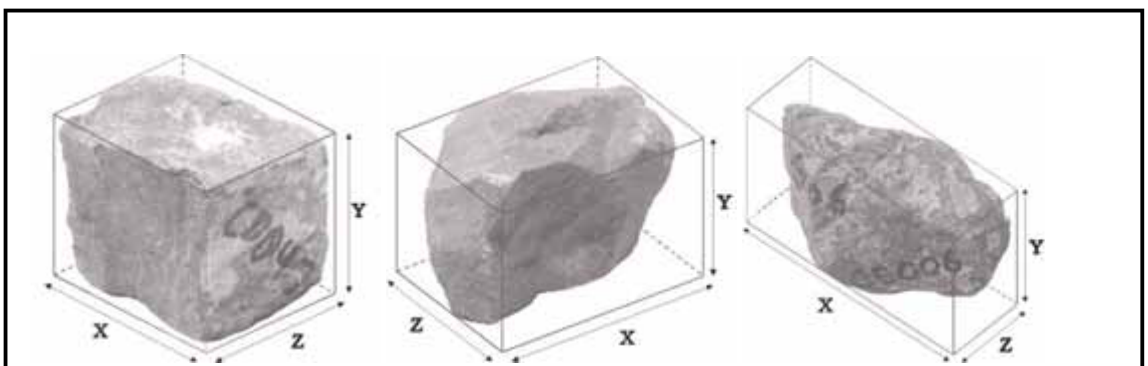


Figure 2.2: Dimensions of Rock Armour for the (LT) Ratio (CIRIA, 2007)



From Left to Right, BLc = 80%, 60% and 40%

Figure 2.3: Examples of Different Blockiness Values (CIRIA, 2007)

Cubicity is a relationship between the longest, intermediate and shortest orthogonal dimension of an individual armour stone. "It is given as (L+G)/(2E), where L,G and E are the longest, intermediate and shortest orthogonal dimensions starting by defining L and then taking the orthogonal G and E"(CIRIA, 2007).

Roundness is an aspect that can result from source or through the rock's service life. It can happen naturally from abraded boulder sources or from weathered igneous rocks. Rock armour units can also become rounded as result of the breaking of corners and edges.

According to the CIRIA (2007) it is recommended to limit the percentage of units having a (LT) of greater than 3:1 because smaller units tend to have larger value of (LT). In Europe the following limitations are desired:

- Heavy armour stone used in armour layers < 5 %
- Light armour stone in cover layers having a weight of less than 40 kg< 20%

Limiting the percentage of units having a (LT) less than three ensures that elongated units will permit acceptable interlocking. The removal of stones having cubicity values greater than three will have the same effect as reducing the proportion of units having a value of less than three.

- **Armour Stone Dimensions:** the fundamental measurement of rock armour units is their mass, M (kg), which can be measured by weighing the individual armour units. As a dimension used in the design, the nominal diameter, D_n (m) taken from the equivalent cube, is used. USACE (2001) and the CIRIA (2007) agreed on the relationship between the mass and the nominal diameter for a stone armour unit having a density of ρ (kg/m^3) is:

$$D_n = (M/\rho)^{1/3} \quad \text{or} \quad M = \rho D_n^3 \quad \text{..........(2.1)}$$

The relationship above can be used to determine any percentage of passing such as the median value:

$$D_{n50} = (M_{50}/\rho)^{1/3} \quad \text{or} \quad M_{50} = \rho D_{n50}^3 \quad \text{..........(2.2)}$$

The square opening of the sieve is referred to as D_{sieve} (m). Sighted by the Rock Manual (CIRIA, 2007), Lann (1981) described a relationship between the sieve size and the nominal diameter through a study of different rock and sieve analysis. He found that:

$$D_n = 0.84\ D_{sieve} \text{..........(2.3)}$$

2.4.2 Concrete Armour Units

When choosing a stone armour unit for a cover layer and the size is not available or not cost efficient, it is recommended to look for an alternative. Concrete armour units can be used as a replacement to stone armour units. The benefit from using concrete armour units is their higher stability coefficient value leading to placing them on steeper structure side slopes and also reducing the weight of the armour units intended to be used (USACE, 2001).

A number of concrete armour units have been developed throughout the years. The coming sections will discuss the history of the concrete units alongside discussing the benefits and disadvantages of the commonly used artificial units.

2.4.2.1 The History of Concrete Armour Units

More than 50 years ago, the simplest artificial unit that can be found was the concrete cube. This unit was placed on the slopes of rubble mounds randomly to gain a permeable and rough armour layer. Since the cubes relied on their weight for stability this lead to a disadvantage, when placed on steep slopes (less than 1v: 2h) they tend to slide down forming a less permeable face leading to the increase in reflections, run-up and overtopping. Designers realised that depending on the armour units' weight caused problems thus interlocking along side with the weight was introduced. In 1950 Sogreah introduced the Tetrapod, the armour unit that used interlocking as an aspect of stability (Bakker *et al.*, 2003). The Tetrapod is "*an unreinforced concrete unit having a shape of four truncated conical legs projecting radially from a centre point*"(USACE, 2001). The advantage of the Tetrapod was the interlocking between individual units and the porosity of the armour layer was larger than an armour layer composed of cubes thus dissipating waves' energy and decreasing the wave run up. 11 and 20 ton Tetrapod armour units were used for the armour layer of Kertih's breakwater, Malaysia (Luger and van der Kolff, 1999). Figure 2.4 shows the terapod armour units.

Figure 2.4: Tetrapod Armour Units (Raunekk, 2009)

The Tribar was introduced by R. Q. Palmer in 1958. The shape of this unit consists of three cylinders connected by three arms connected by a centre point. Reinforcement of the Tribar depends on the method of placement and the unit's size. Tribar's reinforcement is discussed by the Shore Protection Manual (USACE, 2001), reinforcement is not needed when using land based equipment and the units weigh less than 20 tons. On the other hand, when using floating equipment reinforcement is desired due to the units bumping to each other due to wave action and the units weigh about 10 tons or more.

Resembling a ship anchor, the Dolos was designed in 1963 by E. M. Merrifield in South Africa. Reinforcement of this armour unit also depends on the weight of the unit. Dolos units weighing less than 20 tons do not require reinforcement, heavier than 20 tons reinforcement is required (USACE, 2001).

Three characteristics are shared by the armour units mentioned above. The first is that their placement can be either random or uniform. The second is that they are laid in double layers and thirdly, the stability of the three units is dependent on the weight of individual units and their interlocking with each other.

Palmer and Christian (1998) and Bakker *et al* (2003) agreed on, slender units provide inefficient stability and progressive failure of the whole structure that can be caused by the breakage of these units. In the late 60s, a new method of armouring was developed by using hallow blocks arranged uniformly in a single layer. Unlike the double layered armour units, these units depend for their hydraulic stability on friction. Examples of this type of armour units are the Cob, Shed and Seabee. Although these units are highly stable but they do have drawbacks. Problems such as uniform placement of these units in deep water can be difficult, thus friction type units are not applicable on exposed breakwaters (Bakker *et al.*, 2003).

Since the early 1980s, single layer armour units have replaced randomly double layered armour units due to the problems mentioned earlier. Single layer armour units have beneficial features such as the high interlocking between individual units and also the single layer random placement, thus making these units more economical than double layered armour units. The first unit to be presented as a single layer armour unit is the accropode designed by Sogreah in 1980 (CIRIA, 2007). According to Bakker *et al* (2003) the accropode has been used extensively on breakwaters around the world. This unit has a compact shape providing high structural stability and also a balance between interlocking and stability. Figure 2.5 illustrates the accropode armour unit.

Figure 2.5: Accropode Armour Units (CLI, 2009)

The Core-loc armour unit was introduced by Jeffry A. Melby and George F. Turk in 1995 and was patented by the US Army Corps of Engineers (Melby and Turk, 1995). The shape of this armour unit was intended to develop a highly stable armour layer having the minimum amount of stresses. Hence, using normal strength concrete with little or no armour unit breakage occurring during the structure's life (Melby and Turk, 1997). Core-loc armour units are similar with the accropode in the number of legs and their orientation; however, the legs of the core-loc have the dolos shape (Muttray *et al.*,