Céline TRMAL

MSc Coastal Engineering

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Brief Literature Review:
Displacements of rock armour on rubble mound breakwaters

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Contents

1 Introduction

Rubble mound breakwaters are maritime structures widely used to protect mainly harbours or navigable areas against wave action, especially during storms. Depending on the wave action on the breakwater, movement of armourstone pieces may occur. The present paper presents a brief literature review on the displacements of rock armour on rubble mound breakwaters. In the first section, background information about breakwaters is given. Then details about sizing of rock armour for breakwater stability and protection are provided to allow better understanding of stone motions in breakwater. And finally these motions and their consequences are exposed through analysis of recent publications.

2 Context

Rubble mound breakwaters are generally organised in two categories: conventional rubble mound breakwaters (see figure 1) and berm breakwaters (see figure 2).

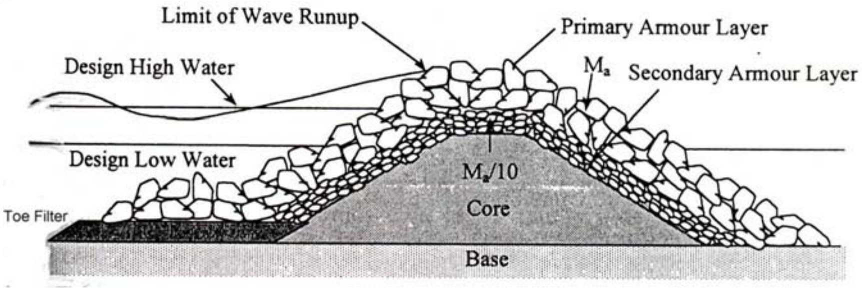

Figure 1: Conventional rubble mound breakwater (Kamphius 2000)

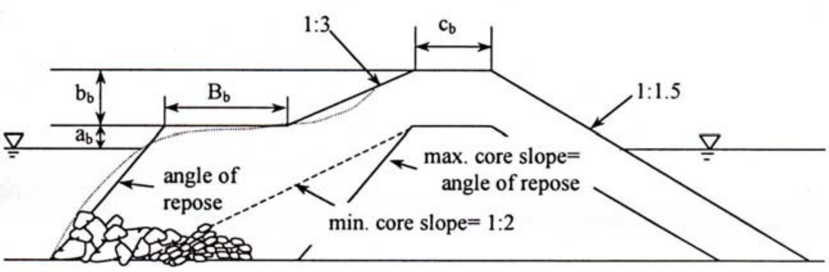

Figure 2: Berm breakwater (Kamphius 2000)

In both cases, they have an outer layer whose role is to provide an armour against wave action, which is generally called “armour layer”. It dissipates by its porosity the wave energy and protect the under layers from being washed up by waves. This armour layer can be built either with natural rock armour also called armourstone or concrete armour units. This choice between natural and concrete armour depends on the size of the armour units required to withstand the wave action, the rock quality, the availability of rock units around a reasonable distance from the construction site and their price.

In the case of berm breakwaters the armour layer is always built with rock armour units. The horizontal berm is built just above the Still Water Level. Sigurdarson, Gisli et al. (1996) explain the advantages of building a berm breakwater instead of a conventional rubble mound breakwater. In summary these advantages are: the reduction of overtopping and wave reflection by better absorption of waves due to the berm, the possibility of using smaller stones as explained below (section 3.3). Berm breakwaters are increasingly being used in Iceland and Norway (Sigurdarson et al. 1996; Torum and Krogh 2000).

Some technical references give details of the sizing of rock armour breakwaters and the use of rock material in such structures. The most relevant are:

- the French guidelines concerning materials “les enrochements” published in 1989 by the LCPC (Laboratoire Central des Ponts et Chaussées) (LCPC 1989)
- the “Manual on the Use of Rock in Coastal and Shoreline Engineering” published in 1991 (currently up-dated) by CIRIA (Construction Industry Research and Information Association, United Kingdom) and CUR (Centre for Civil Engineering Research and Codes, Netherlands) (CIRIA-CUR 1991),
- the “Coastal Engineering Manual” published in 2002 by the USACE (US Army Corps of Engineering, USA) (USACE 2002).

It is worth highlighting that these references can only be considered as guidelines; they give the best practices but are not standards. The only standards available are the European Standards EN 13 383-1 and –2, which have been drawn up in 2002 and which come into force in 2004 (CEN 2001a; CEN 2001b). They concern armourstone as a construction material and deal with both specification for end-uses and test methods.

3 Stability of the armour layer

3.1 Governing parameters

The main governing parameter of the armour layer stability is the stability number and defined by: $N_s=H_s/((\rho_s/\rho_w-1).D_{n50})$ where H_s is the significant wave height, ρ_s the rock density, ρ_w the water density and D_{n50} the nominal median diameter. The nominal median diameter is related to the median mass M_{50} by $(M_{50}/\rho s)$^1/3.
The amount of movements displayed by the block is related to the value of N_s. Stone motions are not expected on conventional rubble mound breakwaters whereas on berm breakwaters motions are allowed (see below in section 3.3).

Values of Ns	**Types of structure**
Ns = 1-4	Stable breakwaters
Ns = 3-6	S-shape and berm breakwaters
Ns = 6-20	Rock slopes / beaches
Ns = 15-500	Gravel beaches
Ns > 500	Sand beaches (during storm surges)

Table 1: Stability number for different structures (CIRIA-CUR 1991)

3.2 Sizing of armourstone on conventional rubble mound breakwaters

As it has been already said few standards are available about the design of armour units. However this has been studied for several years by field observations and physical models. Some empirical formulae have been developed from experimental work to find the suitable size of block which allows the block to withstand the wave-induced forces.

For the first attempt of block sizing two formulae are commonly used:

- the Hudson's formula can be expressed as (Hudson 1958)

  N_s= $(K_D.\cot \alpha)$^1/3 where α is the slope angle and K_D is a stability coefficient, originally established from physical model using regular waves and no overtopping but later other values of K_D were determined to take account of the other variables, for example wave breaking, rock shape... These values are given in function of the damage. For the design of a conventional rubble mound breakwater a damage percentage of 0-5 % is preferable to have no motion of stones. Values of this coefficient determined by physical models can be found for instance in the Coastal Engineering Manual (USACE 2002).

- the Van der Meer's formula (Van der Meer 1988):

$N_S = 6{,}2\,P^{0{,}18}\,S^{0{,}2}\,N^{-0{,}1}\xi_m^{-0{,}5}$ for plunging wave: $\xi_m < \xi_C$

$N_S = 1{,}0\,P^{-0{,}13}\,S^{0{,}2}\,N^{0{,}1}\,\sqrt{\cot\mathrm{an}\,\alpha}\;\xi_m^P$ for surging wave: $\xi_m > \xi_C$

$$\text{where } \xi_C = \left(6{,}2\,P^{0{,}31}\sqrt{\tan\alpha}\right)^{\frac{1}{P+0{,}5}} \text{ and } \xi_m = \frac{\tan\alpha}{\sqrt{\dfrac{2\pi H_S}{g T_m^2}}}$$

T_m : mean period

P : notional permeability

S : relative eroded area

N : number of waves.

More details can be found in the Coastal Engineering Manual (USACE 2002).

The van der Meer's formula introduces more parameters than the Hudson's formula and so more difficult to apply, but seems to be used more often for the first attempt of block size. However they differ only in extreme wave condition.

The condition of "no damage" introduced by K_D in the Hudson's formula or S in the van der Meer's formula leads to a value of N_s fairly closed to 1 or 2. However the use of these formulas does not prevent from assessing the stability by physical model before construction.

3.3 Berm breakwaters

The functioning of berm breakwaters is different from the conventional breakwaters presented above. The stability number varies between 2 and 6. Thus, in similar wave conditions, berm breakwaters use smaller rocks than conventional rubble mound breakwaters but motion of the armourstone pieces consequently occurs.

The horizontal berm is reshaped by wave action. Indeed the profile changes to an S-shape after the first storms, this phase is called the reshaping stage. Extensive studies on physical models have been carried out to determine the profile change (Juhl et al. 1996; Torum and

Krogh 2000) and equally numerical models have been elaborated to predict the profile after reshaping (Norton and Holmes 1992).

Two types of berm breakwaters are generally distinguished according to the value of Ns:

- static stable berm breakwater, i.e. the berm is allowed to reshape into a static stable S-shape, after the reshaping stage no additional motion is expected;
- dynamical stable berm breakwater, i.e. the berm is allowed to reshape into a stable S-profile, but the individual stones are allowed to roll up and down the slope.

The transition between the both types has been found by physical modelling to be closed to Ns=2.7 (Torum and Krogh 2000).

4 Movement of rock armour units

During the life time of the breakwater the armourstone are subjected to two kinds of forces: the wave-induced forces which can lead to motion of armourstone pieces and the mechanical forces due to collision happening during armourstone motion.

4.1 Different types of displacement

The possibility of motion of armourstone pieces depends on the satisfactory damage level chosen for the sizing of armourstone pieces and the interlocking due to the armoustone shape.

Three kind of movement can be observed:

- rocking, i.e. a block moves between its neighbours but stays inside the armour layer; it is very small displacement
- sliding/lifting, i.e. a rock armour can be lifted up from the armour layer by hydrodynamic action and then continue to slide on the breakwater slope
- rolling, i.e. a rock armour rolls on the slope after being lifted up.

It has been observed in physical model that the most common displacement mechanism for individual armourstone piece is of a rotational nature (80%) (Norton and Holmes 1992) and may occur during the reshaping of the berm and later for dynamically stable berm breakwater (Tomasicchio et al. 1994).

Rocking has not yet been observed in details for rock armour. But it has been measured for concrete armour units (Van der Meer and Heydra 1991) and was said to be a cause of breakage of concrete units.

4.2 Consequences of block motion

Motions of armourstone and particularly undergone impacts can lead degradation of the stones if their quality is not sufficient.

Three main types of rock damage have been observed:

- attrition, i.e. superficially damage of a rolling rock unit leading to reduce of unit size and rounding stones; it is due to a lack of mineral fabric strength and it is a slow action. Therefore the stability slowly decreases due to both the decrease of the stone diameter and the loss of interlocking of the rounded stones.
- minor breakage covers the corners and edges of blocks being knocked off. This is controlled by the strength of the mineral and grain fabric to resist new breakages (Latham 1998). The consequence is a loss of interlocking.
- major breakage into two or more pieces along geologically formed planes of weakness or blast-induced cracks (Latham 1998). This is due to a lack of integrity of armourstone. The consequences of having a broken block are not well researched in depth. They can go from a self-healing, when the broken block is locked by its neighbours or when neighbouring stones come to fill the void, to a massive failure when the underlayer is exposed and then washed away by waves or when the armour layer slumps (Ward 1992).

4.3 Measurements made on physical models

Over the last few years, a lot of studies have been done about armourstone displacements because of their implication in the rock degradation or breakage during service life of the breakwater. These studies were carried out mainly in berm breakwater since conventional rubble mound breakwaters are not expected to display motions of stones.

The most common way of study the armourstone motion is by filming the wave attack on a scaled structure in laboratory. After analysing the movies, different types of displacements and velocities can be obtained.

The displacement of stones has been fairly well investigated by intensive tests carried in wave flumes (Tomasicchio et al. 1994) and in a 3 dimensional physical model in 1996 (Archetti and Lamberti 1999; Juhl et al. 1996).

The main results were the determination of long shore transportation rates due to the obliquity of wave and the mean displacement of armourstone pieces (Archetti and Lamberti 1999).

The two measurements have been used to determine the total displacement of armourstone during storm to calculate the length of the total displacement of armourstone during the breakwater's lifetime under sea storms and then to quantify the volume loss of rock units due to abrasion (Archetti et al. 2002).

From the 3D test carried in 1996, stone velocities were calculated by using a grid superimposed to the image from the video recorder filming in plane, then by quoting the starting and final position of each movement (greater than 2 D_{n50}) and its duration. So the velocity calculated corresponds to the mean stone velocity between two frames of the video recording. A correction of 10 % was made to take account of the non-linear displacement of stones as well as a correction due to the slope (by dividing the velocity by $\cos(\alpha)$). This mean velocity was found to fit a log-normal distribution (Archetti and Lamberti 1999).

The "peak" velocities of rock armour units were observed in a wave flume by filming the profile of a berm breakwater (Torum and Krogh 2000). The "peak" velocity of significantly moving stones is calculated by measuring the displacement during one frame (0.04s) and dividing by that time, but the velocities are within ±25% due to the no-detection of the exact lateral location of armourstone pieces. The dimensionless velocity $(Vs/(gHs)^{0.5})$ was found to fit a two parameter Weibull distribution.

This "peak" velocity is obviously greater than the mean velocity observed by Archetti and Lamberti. The statistical distribution of the dimensionless "peak" velocity of stones and the statistical distribution of the crushing strength of stones were combined into a probability of failure, that is the crushing of stones (Torum and Krogh 2000).

5 Conclusion and perspectives

The ability of a breakwater to withstand hydraulic loads is based mainly on the wave condition, the rock density and the size of armourstone as a granular material. The size reduction of individual pieces due to abrasion or breakage may lead to damage of the structure and possibly even failure. It has been observed that the volume loss of armourstone due to abrasion during the life time of a breakwater can be quantified and that material properties can be related to the wave climate and the structure consideration into a damage model. However the problem of armourstone breakage due to in service motion is not yet tackled and the determination of stone movement, stone velocity and the probability of stones breakage still need further work.

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