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Influence of armour porosity on the hydraulic stability of cube armour layers

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ABSTRACT

Armour placement and packing density directly affect construction costs and hydraulic performance of mound breakwaters. In this paper, the literature concerning the influence of armour porosity on the hydraulic stability of single- and double-layer armours is discussed. Qualitative and quantitative estimations for the influence of armour porosity and packing density on the hydraulic stability are given for the most common concrete armour units. The analysis focuses on specific 2D hydraulic stability tests of double-layer randomly-placed cube armours with different armour porosities and permeable core. The stability number showed a 1.2-power relationship with the packing density for double-layer randomly-placed cube armours considering armour unit extraction and Heterogeneous Packing. The literature review and experimental results with small-scale breakwater models protected with a variety of armour units clearly indicate that a significant increase in armour porosity above the recommended values substantially decreases armour hydraulic stability. To avoid uncontrolled model effects, packing density should be routinely measured in small-scale tests, and armour placement techniques should be monitored at prototype scale. The actual packing density obtained in small-scale models and prototypes has to be explicitly reported, because packing density significantly affects hydraulic stability during service time.

1. Introduction

Rock armoured mound breakwaters have been built for centuries. When breakwaters had to be constructed in harsher environmental conditions, larger stones were needed for armour layers. In the 19th century, when local quarries were not able to provide stones of the appropriate size and price, precast concrete cubes and parallelepiped blocks were introduced and numerous precast concrete armour units were designed later to optimize the armour layer of mound breakwaters. The overall breakwater construction cost depends on numerous factors, these being associated to design and logistic factors, including the type of armour material (unreinforced concrete, granite rock, sandstone rock, etc.), armour unit mass, personnel and material unit costs, total concrete consumption, placement equipment, casting, handling and stacking procedures, etc. This paper focuses on armour porosity and the associated packing density, because these two parameters significantly affect breakwater hydraulic performance, construction costs and payments.

Hudson's formula published by Hudson (1959), popularized later by USACE (1984), focused the attention of the engineering community on the stability coefficients (K_D) associated with different armour units, randomly placed in double-layer armours with a prescribed nominal porosity, P, and a layer coefficient, k_Δ. Using the equivalence $H=H_s$ in the original Hudson formula, Eq. (1) is known as the generalized Hudson formula, still widely used by practitioners to compare different breakwater designs at the preliminary stage, including double- and single-layer armours,

$$M=\frac{H_s^3\rho_r}{K_D[(\rho_r/\rho_w)-1]^3\cot\alpha}=\frac{H_s^3\rho_r}{\Delta^3K_D\cot\alpha} \tag{1}$$

where K_D is the stability coefficient; M is the armour unit mass; H_s is the incident significant wave height; α is the slope angle: $\Delta=(\rho_r/\rho_w-1)$ is the relative submerged mass density; and ρ_r and ρ_w are the armour unit and water mass densities, respectively. The equivalent cube size or nominal diameter of the armour units is defined as $D_n=(M/\rho_r)^{1/3}$; and Eq. (1) can be re-written as a function of the stability number, $N_s=H_s/(\Delta D_n)=(K_D\cot\alpha)^{1/3}$.

If Eq. (1) is used to compare different armour units in similar storm conditions, the higher the K_D is, the lower armour unit mass and concrete consumption. Since the invention of the Tetrapod in 1950, numerous armour units have been developed in the search

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for high values of K_D and the corresponding economic savings. Usually, high values of K_D are associated with complex armour unit shapes (e.g., Dolos), reducing concrete consumption and requiring smaller rocks in the filter layer and lighter placement cranes. These savings should exceed the additional costs associated with more expensive concrete and complex formworks, production, handling, stacking and placement compared to the simple and easy to handle conventional cubes and parallelepiped blocks.

The invention of Accropode™ in 1980 and other interlocking units later, designed for single-layer armouring, significantly reduced concrete consumption and cost (see Vincent et al., 1989; Holtzhausen, 1998). Structural integrity is a key issue when using these bulky units as are adequate placement and packing density to guarantee interlocking of units during service time (see Jensen, 2014; Latham et al., 2013). In the preliminary design phase, armour porosity and placement technique are usually considered as secondary factors, which are either explicitly prescribed (see Mouquet, 2009; Paulsen and Wareing, 2009) for single-layer armours or implicitly defined by engineering manuals (e.g., USACE, 1984; CIRIA, 2007) for double-layer randomly-placed armours. There are other environmental and structural characteristics not included in Eq. (1) which may also have a significant influence on the armour stability, such as packing density, Iribarren's number, core permeability and relative crest-freeboard; this paper focuses attention on packing density because it is frequently a key factor affecting construction cost, concrete consumption and breakwater safety.

At prototype scale, armour units are usually placed using crawler cranes; armour porosity and placement below mean water level (MWL) are not easy to control due to poor visibility, waves and wind (see Medina et al., 2010). Because armour porosity and packing density are not explicitly included in most of the hydraulic stability formulae used by practitioners, such as Eq. (1), short-term cost optimization tends to increase armour porosity of prototypes above tested and recommended values. Unfortunately, a significant increase in the armour porosity usually leads to a significant reduction in hydraulic stability. This paper analyses the influence of packing density on the hydraulic stability with special attention to double-layer randomly-placed cube armours. The aim is to estimate the model effect associated to armour porosity, which can differ substantially between the prototype and the corresponding small-scale model tested in laboratory.

Section 2 includes a literature review concerning the effects of armour porosity on the hydraulic stability of different armour units. Section 3 focuses on porosity changes within cube armours due to Heterogeneous Packing (HeP) and explains the Virtual Net method used to measure armour damage in the small-scale tests reported in this research. Section 4 describes the 2D hydraulic stability tests of cube models with different armour porosities carried out for this study including the analysis of the experimental results. Finally, the most relevant conclusions of this research are provided in Section 5.

2. Literature on the influence of armour porosity on hydraulic stability

Porosity is widely used to refer to the volume of voids in a granular system. Nevertheless, armour porosity is not always easy to determine; armour thickness must be defined first, which may be an easy task for orderly-placed armour units but not so straightforward for randomly-placed units. Armour thickness of randomly-placed units is usually referred to as $n=1$ (single-layer) or $n=2$ (double-layer) times the equivalent cube size, $nD_n=n(M/\rho_r)^{1/3}$. However, most engineering manuals (e.g., USACE, 1984; CIRIA, 2007) recommend, for each unit, a specific layer coefficient or layer thickness factor, k_Δ, and a specific nominal porosity, P, called "fictitious porosity" by Zwamborn (1978). Placing density (φ [units/m^2]) is a real physical variable which is controlled by the placement grid and is related to k_Δ and P according to

$$\varphi = n(k_\Delta)(1-P)\left(\frac{\rho_r}{M}\right)^{2/3} \quad (2)$$

where n is the number of layers in the armour; k_Δ is the layer coefficient; P is the nominal porosity; and $M/\rho_r=D_n^3$ is the volume of the armour unit. Different pairs of k_Δ and P lead to the same placing density, φ; thus, Frens (2007) drew attention to misinterpretations caused by the use of different criteria regarding the layer coefficient and the porosity concept. In order to prevent misunderstandings, this paper will refer to the number of layers n, the packing density $\phi=\varphi D_n^2$, and armour porosity $p=1-\phi/n$. Using this definition, the packing density can be used to assess the relative consumption of concrete in the armour layer, which may be considered the dimensionless placing density

$$\phi = \varphi D_n^2 = n(k_\Delta)(1-P) = n(1-p) \quad (3)$$

Armour porosity p is equal to nominal porosity P only when considering a layer coefficient of $k_\Delta=1.00$. Therefore, this study uses a two-parameter armour characterization (n and p or ϕ), instead of the conventional three-parameter characterization (n, P and k_Δ). For instance, USACE (1984) recommended $n=2$, $P=50\%$ and $k_\Delta=1.04$ for double-layer Tetrapod armours, which is equivalent to $n=2$ and $p=48\%$ ($\phi=1.04$). Using different notations for the same concepts, CIRIA (2007) recommends $n=2$, $P=50\%$ and $k_\Delta=1.02$ for Tetrapod armours which is equivalent to $n=2$ and $p=49\%$ ($\phi=1.02$).

Armour porosity and placement can be very well controlled in small-scale tests; dry construction, perfect view of the armour layer and placement by hand are ideal laboratory construction conditions which do not exist at prototype scale. On the contrary, prototype conditions usually involve placement grids, crawler cranes, blind underwater placement and other restrictions that generate uncertain armour porosities and these may significantly change in space and time (see Medina et al., 2010; Latham et al., 2013). In this paper, the literature review is focused on armour porosity and its influence on hydraulic stability. The analysis of the literature reveals that a significant reduction in the packing density ϕ below the recommended value results in a significant decrease in the hydraulic stability of the armour. Table 1 shows the armour unit and number of layers, the placement technique and packing density of different experiments discussed in the literature.

Hald et al. (1998) carried out small-scale tests of single-layer rock armours with $\cot\alpha=1.5$ and different placement techniques, which may be used to describe the hydraulic performance of hundreds of single-layer rock armours in rubble-mound breakwaters built in Norway since 1886. Packing density $\phi=0.60$ was assumed, and results were compared with conventional double-layer rock armours. Single-layer orderly-placed rock armours were more stable than double-layer randomly-placed rock armours, which were much more stable than single-layer randomly-placed rock armours. Vandenbosch et al. (2002) conducted small-scale tests of single-layer rock armours with $1.5 \le \cot\alpha \le 3.0$; different placing densities were analyzed. Packing density $\phi=0.70$ was considered "normal" and a decrease in packing density resulted in decreased armour stability. USACE (1984) recommended $p=37\%$ ($\phi=1.26$) for double-layer rough and smooth quarrystone armours; however, armour porosity is not easy to measure. Latham et al. (2002) provided a rapid survey method to estimate packing densities and analysed in detail six real breakwaters with $1.08 \le \phi \le 1.29$.