Evolution of damage on roundheads protected with Cubes and Cubipod armour units

Pedro Lomonaco, IH-Cantabria, Santander, Spain
Cesar Vidal, IH-Cantabria, Santander, Spain
Josep R. Medina, Universidad Politecnica de Valencia, Valencia, Spain
M. Esther Gomez-Martin, Universidad de Alicante, Alicante, Spain

Introduction

Stability and hydraulic performance of roundheads in rubble-mound breakwaters are still of major concern to scientists, coastal engineers, contractors and port managers, partly because current formulations and procedures of roundhead design are far from being as studied as those developed for standard trunk sections.

Roundheads are typically exposed to the most stringent incident wave conditions, located at deeper water depths and subject to the full three-dimensional character of open waters, e.g. short-crested waves and/or a wider range of incoming wave directions, as well as in the vicinity of navigation channels, which has been proven a source of wave focusing (Misra *et al*., 2008). Moreover, its construction is in general the most difficult section of the breakwater since the roundhead is typically at the deepest location, is the last part of the breakwater so its access is limited, and it includes a complicated transition from the trunk section.

Rubble mound head sections diffract, shoal and refract the waves, which may induce the waves to focus over the submerged cone and break, forming very high cone-overflow velocities (Vidal *et al*., 1995; CEM, 2006). Physical models of roundheads have shown that under similar conditions the roundhead of a non-overtopping rubble mound structure is more susceptible to failure than their corresponding trunk sections. Further, the reduced support from neighbouring units produces a very sharp progression of damage, since the dislodged units does not contribute to the stability of the roundhead, thus once the damage starts, failure of the structure is just a matter of time. Therefore, design criteria of roundheads are commonly more stringent than trunk sections. In terms of conceptual design, and as a rule of thumb, the weight of the armour units at the roundhead is about 1.5 times the trunk armour weight, which implies that even if the trunk is made of quarry stone, roundheads may require artificial armour units.

Since the behaviour and response of the armour units at the roundhead portray a clear difference in comparison to the corresponding section at the trunk section, performance of newly developed armour units, tested in 2D physical model tests, require further investigation under the three-dimensionalities of a roundhead. Thus, confirmation and optimisation three-dimensional model tests are commonly executed at wave basins for those sections where the layout of the breakwater portray a roundhead, or even a change of alignment.

As part of the research and development project of the new armour unit named Cubipod, a series of physical model tests of a non-overtopping rubble mound structure with a simple semicircular (conic) roundhead, protected with two-layers of Cubipods, were conducted at the 8.6 x 28 m wave basin of the Environmental Hydraulics Institute (IH Cantabria) at the University of Cantabria, Spain.

A series of regular and irregular, long-crested and normally-incident (head-on) tests were performed for progressively increasing wave height conditions and constant Iribarren's number ($Ir = \tan \alpha / \sqrt{H/L}$), as well as one series with increasing wave height and constant wave period. The water depth as well as the structure's geometry remained constant. Along each test series, the initially undamaged structure is subject to a series of increasing wave height action. At the end of each wave height step, the roundhead damage is assessed by means of accurate laser profiling as well as from fixed remotely operated digital cameras. Without rebuilding, the following wave height step is executed until the "initiation of destruction" damage level is reached (*IDe*), defined when an armour unit is extracted from the bottom layer, exposing the filter. Then, the structure is rebuilt for the next series.

By this means, a full description on the evolution of the damage to the structure is obtained, identifying the relative effect of the incident wave conditions on the roundhead response, including the exact dimensions and location of the eroded sector.

For comparison and benchmark purposes, the irregular tests for increasing wave height conditions were repeated under exactly the same conditions, except that the rubble mound roundhead was protected with standard cubes. Equivalent detailed description of the damage evolution and geometry was also obtained.

This paper describes firstly the physical model tests executed; including the layout of the model, structure geometry and measurement devices. Estimated incident wave conditions and assessed damage are presented, emphasising on the geometrical description of the damage and, moreover, on the evolution of the damage as the wave height increases. A comparison is also made between the measured damage and the computed damage according to the formula given by Maciñeira & Burcharth, 2007.

Model layout and instrumentation

The experiments were carried out at IH-Cantabria's wave basin, facility located at the Ocean & Coastal Laboratory of the University of Cantabria, in Spain. The basin is 28 m long, 8.6 m wide and 1.2 m deep, equipped with a multi-board electric-drive piston wave maker. The wave basin included a flat 7.45 m long foreshore bathymetry enabling generation of higher waves. The platform is 23 cm high and is connected to the basin floor by a 4.9 m long concrete slope.

The structure installed was formed by a 2.94 m long rubble mound breakwater, oriented parallel to the incident wave crests, ended with a simple conic semicircular roundhead, thus the structure occupied half of the basin width. The seaward toe of the breakwater was placed ~4 m from the end of the transition slope, over the flat portion of the sturdy platform. Consequently, the landward toe was located as close as possible to the main passive wave absorbers, situated at the end of the basin. In order to minimise parasitic wave reflection and scattering, lateral wave absorbers, made of porous steel plates filled with polyurethane fibre, were placed near the basin sidewall opposite to the roundhead. A spending gravel beach was also prepared on the leeside of the structure for damping diffracted waves. In Figure 1, the breakwater layout in the wave basin is shown and, in Figure 2, a photograph of the basin with a roundhead Cubipod model in place is included where the wave machine is also seen at the background.

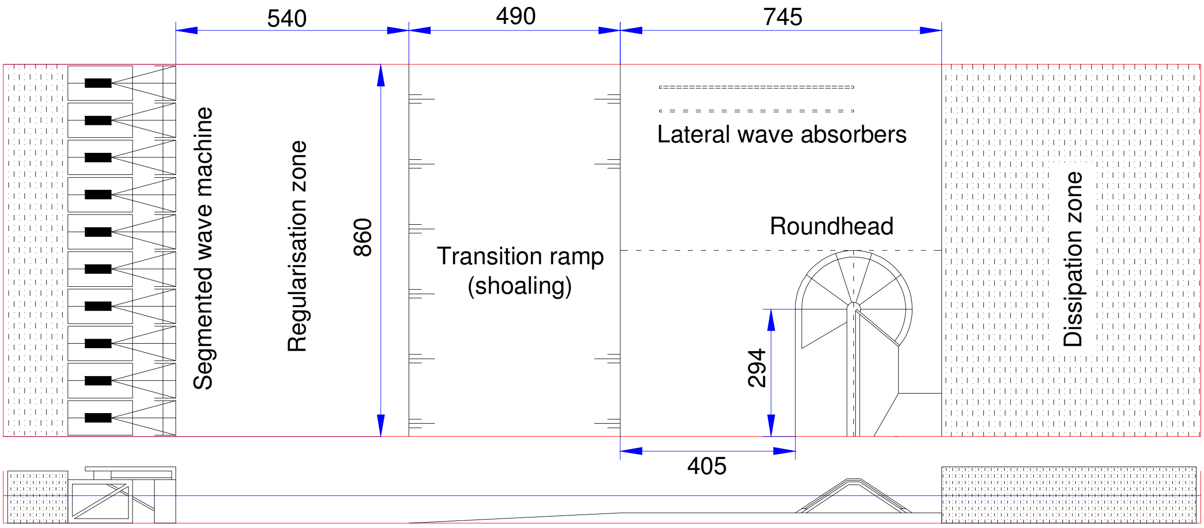

Figure 1: Layout of the roundhead model in the wave basin (dimensions in centimetres).

Figure 2: Photograph of the wave basin and the roundhead Cubipod model during testing.

The trunk section depicts a 1:1.5 seaward slope and 1:1.25 on the leeside. The roundhead portrays a constant 1:1.5 slope and was designed to be tested with a constant depth of 40 cm.

The total structure height is 80 cm, to avoid overtopping. The rubble mound is formed by a core (D_{n50}=0.88 cm), a filter layer (D_{n50}=1.81 cm) and the roundhead was protected by two layers of 128.4 grams resin Cubipods (D_{n50}=3.82 cm, ρ=2300 kg/m^3), or two layers of 144.5 grams resin Cubes (D_{n50}=3.98 cm, ρ=2300 kg/m^3). All armour units were placed with a ~46% packing density. The roundhead cross-section is shown in Figure 3.

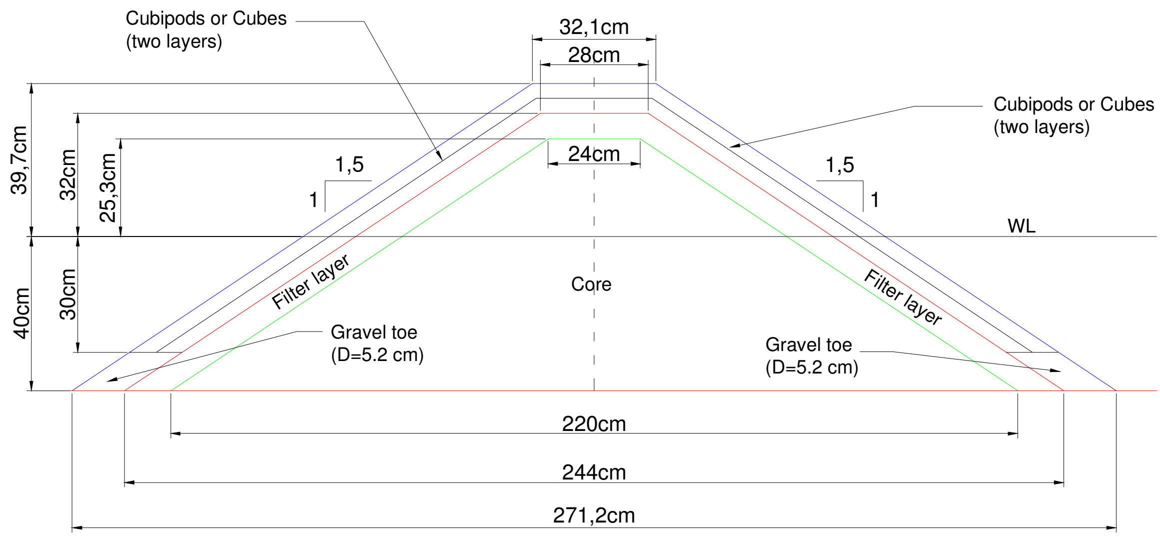

Figure 3: Typical cross-section of the roundhead.

The Cubipod is similar to a cube except that it features protrusions on each face to prevent excessive packing as well as to increase the friction with the filter layer (Gomez-Martin & Medina, 2007). The purpose of this armour unit design is not only to maintain most of the cube's advantages, such as high structural strength, easy casting and placement, as well as low progressive failure risk, but also to avoid certain disadvantages of the cube itself, such as low hydraulic stability and heterogeneous packing. Cubipod armour units have been tested extensively in wave flumes and have shown an outstanding performance with equivalent stability coefficients (K_D) in excess of 30. Further details on Cubipod hydraulic performance can also be found in Gomez-Martin & Medina, 2006.

Nine resistive-type wave probes were located seaward of the roundhead to estimate incident wave conditions. The wave probes were aligned in three groups parallel to the incident wave direction, to identify variations around the rubble mound head.

Damage on the roundhead was assessed applying four different techniques, i.e. by visual counting of dislodged and/or extracted units, by laser profiling, comparison of photographs taken by remotely-operated fixed digital cameras (also known as the flickering technique, Phelp *et al*., 1999) and, finally, applying the virtual net technique. Each technique is applicable under different conditions and damage levels. The flickering technique is suitable to measure very small displacements and assess damage levels up to 20%, allowing the tracing of displacements and settling. Accurate profiling would describe in detail the deformation of the structure, able to assess any damage larger than 3% to 5%. The virtual net technique is similar to the flickering technique, but is particularly suitable to assess changes in porosity and settling. Visual counting was only used to determine during the test series the damage level as defined by Vidal *et al*., 1991, particularly when the first unit is dislodged, situation known as "initiation of damage" (*IDa*). In this paper, the evolution of damage will be analysed with data obtained from the laser profiler, sequences of digital images and visual counting in terms of the damage level ($D_{\%}$).

The laser profiler measure the distance from the instrument to any reflecting solid object, spanning an arch of 100° with an angular resolution of 0.25° and an accuracy of 1 mm over the range of the laser (8 m). Although the instrument is non-intrusive, it cannot measure properly underwater, so filling and draining the basin was required every time a profile was taken. The cross-section profile obtained each time is the result of an average over 250 measurements, performed automatically in approximately 10 s. The laser profiler (seen in Figure 2) is mounted on a carriage guided by a precision screw and driven by a computer controlled step motor, which is also fixed to a steel frame positioned over the roundhead. A total of 70 cross-sections parallel to the wave direction were taken each time, one every 1 cm, embracing a 70 cm sector approximately centred over the waterline.

Comparison of two profiles, one taken before the test and the second taken after the test, allows the evaluation of the damage quantitatively and, further, provides an accurate geometrical description of the dislodgement area.

Performed stability tests

The stability and performance of the roundhead was studied by a series of progressively increasing wave conditions with constant deep-water Iribarren's number (*Ir*). Cubipod armour units were tested for up to four different *Ir* conditions and for irregular (JONSWAP, γ=3.0) and monochromatic waves. Cubes were also tested under the same irregular wave conditions used for the Cubipods. Overall, a total of 65 tests were conducted for Cubipods and 37 tests for Cubes.

Basically, the testing procedure consisted in, first, establish the Iribarren's number, and an initial wave height was selected such no damage was expected. Hence, the wave period could be defined:

$$T = \frac{Ir\sqrt{2\pi H / g}}{\tan\alpha} \quad \text{for monochromatic waves (300 waves), and} \qquad (1)$$

$$Tp = 1.2\,T_{01} = 1.2\left[\frac{Ir\sqrt{2\pi H_{50} / g}}{\tan\alpha}\right] \quad \text{for irregular waves (1000 waves).} \qquad (2)$$

In Eq. (1), T stands for the wave period, H is the wave height, g is the acceleration of gravity and α is the structure's slope angle. In Eq. (2) Tp is the peak period, T_{01} is the mean spectral period ($T_{01}=m_0/m_1$), and H_{50} is the average of the 50 highest waves of the series ($H_{50}\approx 1.4\ Hs$). In a 1000 waves sea state, H_{50} is equivalent to $H_{1/20}$, which has been identified previously as an improved descriptor for stability of rubble mound breakwaters (Vidal *et al*., 2006), and would produce an equivalent damage as a monochromatic wave with the same height. The wave height and wave period pair (*H, T* or *Hs, Tp*), defined the conditions for a wave height step test.

At the end of each wave height step, damage was assessed by visual counting of dislodged units, capturing digital pictures remotely and, when the damage produced was noticeable in comparison to the previous step, draining of the basin and laser profiling was also performed. Without rebuilding, the procedure was repeated by increasing the wave height (1 cm in monochromatic waves, and 1.5 cm in irregular waves) and re-computing the wave period keeping constant the Iribarren's number by applying Eqs. (1) or (2) accordingly. A test series, formed by a progressively increasing wave height and wave period, was executed until an armour unit of the second layer has been dislodged, exposing the filter, situation known as "initiation of destruction", *IDe*, (Vidal *et al.*, 1991). In Table 1, the general characteristics of performed tests have been summarised for reference.

Table 1: General characteristics of performed tests

Test No	Wave type	Units	Iribarren	Wave heights (H or Hs)	Wave periods (T or T_{01})
01	Monochromatic	Cubipods	3.5	10 - 17 cm	1.32 – 1.73 s
02	Irregular	Cubipods	3.5	5 - 10 cm	1.18 – 1.78 s
03	Monochromatic	Cubipods	3.0	9 - 17 cm	1.08 – 1.48 s
04	Monochromatic	Cubipods	3.0	9 - 18 cm	1.08 – 1.52 s
05	Irregular	Cubipods	3.0	6 - 12 cm	1.14 – 1.70 s
06	Irregular	Cubipods	2.5	5 - 13 cm	0.95 – 1.47 s
07	Irregular	Cubipods	2.0	6 - 12 cm	0.76 – 1.22 s
08	Irregular	Cubipods	2.3 – 3.4	7 – 13 cm	1.17 s
09	Irregular	Cubes	2.3 – 3.4	7 – 13 cm	1.17 s
10	Irregular	Cubes	2.0	7 – 15 cm	0.76 – 1.27 s
11	Irregular	Cubes	2.5	5 – 12 cm	0.95 – 1.40 s
12	Irregular	Cubes	3.0	6 – 13 cm	1.14 – 1.61 s
13	Irregular	Cubes	3.5	4 – 12 cm	1.18 – 1.78 s

Damage Assessment and Analysis

Damage caused to a rubble mound structure has been quantified historically in several ways, and nowadays it is commonly accepted to measure it in dimensionless form by the so-called damage parameter, S, as well as a percentage of displaced units, $D_{\%}$. Further, there has been a number of attempts to correlate a given damage level to the corresponding stability formulas (e.g. through the K_D value) and to a qualitative (visual) assessment of the damage (e.g. Vidal *et al.,* 1991).

The damage parameter, S, is commonly applied to a bi-dimensional damage of a (reshaping) breakwater, and it has been defined in dimensionless form by the ratio between the eroded area in the profile and the square of the armour stone nominal diameter. It is a measure of the average number of stones dislodged per unit length. The disadvantage of this parameter is that it does not provide information on the three-dimensionalities of local damage or scour, which may obscure possible structural failure. Further, it does not provide clear information in changes of porosity (due to settlement). Since the classical damage observed at the roundhead has an inherent three-dimensional character, which is observed as the progressive dislodgement of armour units at a single location, the damage parameter S as defined before seems not to be the correct choice for assessing damage of a roundhead. However, mechanical and laser profiling of damaged structures provide in fact an accurate and unambiguous assessment of the eroded areas on each measured cross-section.

The damage, $D_{\%}$, expressed in percentage of displaced units is, in the literature, the preferred form of expressing damage in roundheads. Basically it consists in providing the number of dislodged armour units relative to the total number of units in a given sector. The disadvantage of this parameter is that it requires the definition, beforehand, of the sector in consideration, and the final result depends largely on it. Selection of an area that is too large may yield very small damage and vice versa. Further, the definition of dislodgement or, equivalently, the distance a unit should be displaced to be accounted for, is also subject to subjective criteria. For those reasons, the damage observed and measured during the physical model tests will be reported and analysed unambiguously in absolute values, and compared in terms of $D_{\%}$ with the formulations available from the literature. Hence, it will be necessary to describe accurately the geometry of the damage, so the reference sector can be defined.

Evolution of Damage

During the tests, as the wave height and wave period increased to keep the Iribarren's number constant, the wave-induced flow around the head went from refraction and surge, to plunge of an overflowing jet from seaside to leeside. Finally, regardless of the Iribarren's number or whether the waves were monochromatic or irregular, the first dislodgement at the roundhead was observed on the leeside, slightly below the SWL, approximately at an angle of 15° measured from the breakwater axis (which is perpendicular to the wave direction). The dislodged unit(s) fell down slope rolling in the same direction of the overflow, away from the damage area, thus the structure reshaping does not contribute anymore to the stability and, further, the void created no longer supported the adjacent units. As the test continued or the waves increased, the unsupported units could be dislodged more easily, enlarging the damaged area, exposing the bottom armour layer. The process continued until the damage area is large enough so a unit from the bottom armour layer was dislodged, exposing the filter.

In Figure 4, an example sequence of photographs of the roundhead taken at the end of different wave height steps of Test 02 is shown to illustrate the evolution of the damage. The test shown corresponds to an *Ir* of 3.5 and irregular waves (see Table 1). The first unit was dislodged (*IDa*) for an incident wave height *Hs*=0.096 m and peak period *Tp*=2.02 s. Initiation of destruction (*IDe*) was observed for *Hs*=0.103 m and *Tp*=2.14 s. In Figure 4 a three dimensional digital reconstruction of the roundhead is also shown based on the profiles measured at the end of the test series.

Thus, the difference between the initial profile and the final profile is obtained from the measured profiles to assess and characterise the damage, particularly helpful for defining the active zone to be considered in the computation of the percentage of damage. Figures 5 and 6 presents a selected series of maps showing the measured areas of erosion (in red) and accretion (in blue) at the roundhead. Figure 5 portray the erosion-accretion maps for some of the tests made with Cubipods, while Figure 6 depicts selected tests made with Cubes. The erosion-accretion maps also show a polar grid of the head, where each radius is separated 15º. The waterline has been indicated in blue, while +/- 10 cm levels have been plotted in green and orange, respectively. In Figures 5 and 6, waves propagate in the positive y-axis direction.

As can be seen, the damage is concentrated in an area spanning different arches and located at different water depths, both depending on the wave period. It seems that the extension of the damaged area is function of the wave height and, finally, it appears that there is no influence of the type of units and whether monochromatic or irregular waves were used. For comparison purposes and percentage damage assessment, it can be said that the damage is observed in all tests at an arch of 60º, ranging from -15º (up-wave) to 45º (down.-wave), measured relative to the trunk axis. Hence, the active zone will be considered from –20 cm to +20 cm, which corresponds to the maximum wave height that produced the failure in almost all tests.

Table 2 summarises all major characteristics and results of the performed tests, including the wave conditions to dislodge the first armour unit (*IDa*), equivalent K_D value, wave conditions for initiation of destruction (*IDe*) and its corresponding *Ns* value, as well as the total number of units dislodged.

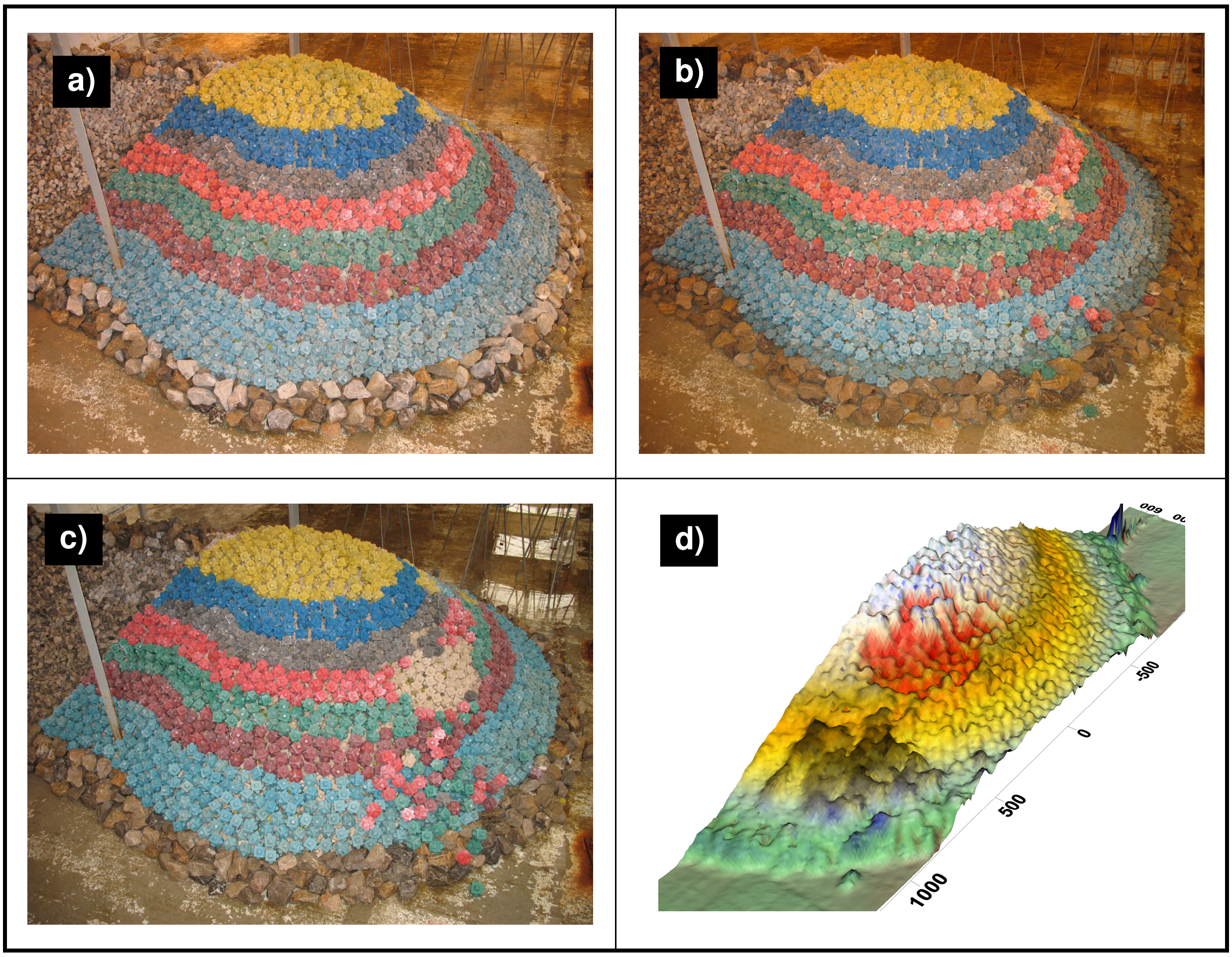

Figure 4: Progression of damage on the Cubipod roundhead during Test 02. a) No damage, b) *IDa*, c) *IDe* and d) Digital reconstruction of the roundhead at *IDe* measured with the laser profiler. Waves propagate in the pictures from top to bottom.

Finally, Table 2 also includes the measured percentage of damage, $D_{\%}$, computed at the end of the test series and at the aforementioned 60º sector. In Table 2, the relative fragility of the structure is noticed, since for most of the cases a slight wave height increase was required from the initiation of damage to destruction. It appeared that the minimum stability coefficient for Cubipods was almost twice the one found for Cubes, supporting the previous findings on the behaviour of the units in the trunk section. However, under some conditions, the stability of Cubipods was practically the same as the one observed for Cubes. This is not surprising, since the features incorporated in the Cubipod design (meant to avoid heterogeneous packing and to increase friction with the filter layer) are not properties contributing to the stability under the flow conditions at the roundhead. In terms of minimum stability, it can be said that the Cubipod have shown a significant improvement in the stability performance at the roundhead, in comparison to a Cube, although cubes have also shown a surprisingly outstanding behaviour for relative low Iribarren numbers.

In Table 2, Ns is the stability number and has been computed as $Ns=H/(\Delta D_{n50})$ for monochromatic waves, and as $Ns=Hs/(\Delta D_{n50})$ for irregular waves. Δ is the relative density, defined by the ratio of the armour unit density, ρ_s , and the water density, ρ: $\Delta=(\rho_s/\rho-1)$.

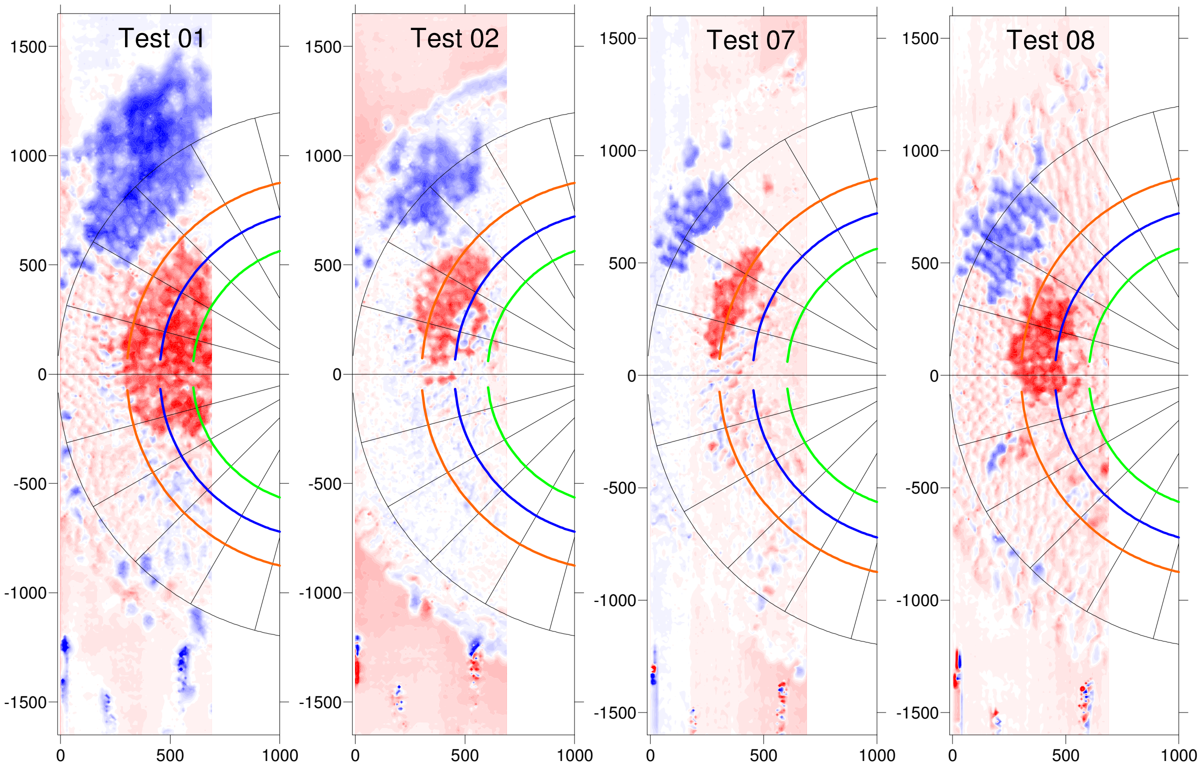

Figure 5: Erosion-Accretion maps of the roundhead protected with Cubipods. Red indicates erosion and blue accretion. Blue line indicates SWL, while orange and green lines depict -10 cm and +10 cm levels, respectively.

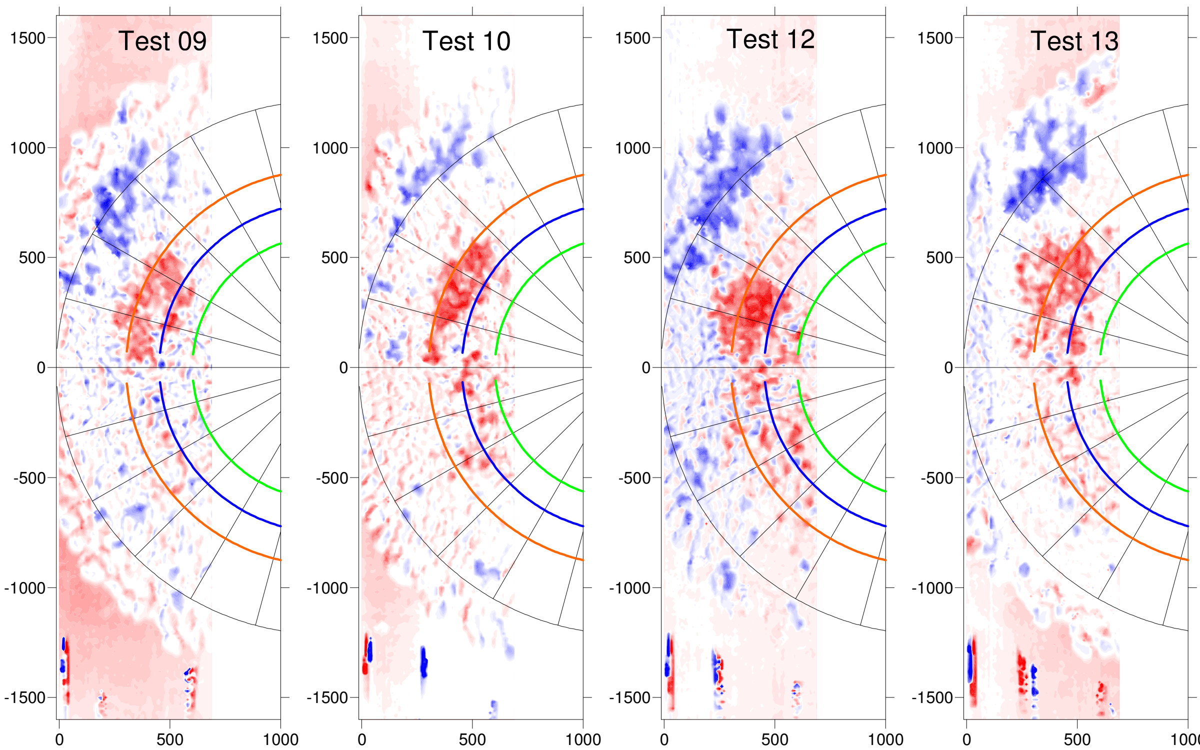

Figure 6: Erosion-Accretion maps of the roundhead protected with Cubes. Red indicates erosion and blue accretion. Maps are in millimetres and waves propagate in positive y-direction.

Table 2: Summary of the damage descriptors of the performed tests

Test No	H and T or Hs and Tp for IDa	Ns for IDa	H and T or Hs and Tp for IDe	Ns for IDe	Total dislodged units	D%
01	13.6 cm, 1.62 s	2.74	13.8 cm, 1.73 s	2.78	219	17.65
02	9.6 cm, 2.02 s	1.93	10.3 cm, 2.14 s	2.08	54	4.35
03	14.7 cm, 1.44 s	2.96	16.4 cm, 1.48 s	3.31	68	5.48
04	15.3 cm, 1.40 s	3.08	18.0 cm, 1.52 s	2.91	111	8.95
05	8.4 cm, 1.61 s	1.70	12.2 cm, 2.04 s	2.46	88	7.09
06	10.2 cm, 1.52 s	2.06	13.4 cm, 1.76 s	2.69	50	4.03
07	11.0 cm, 1.36 s	2.22	12.3 cm, 1.46 s	2.47	36	2.90
08	8.0 cm, 1.40 s	1.60	12.9 cm, 1.40 s	2.59	64	5.16
09	7.7 cm, 1.40 s	1.49	12.7 cm, 1.40 s	2.46	51	4.28
10	8.8 cm, 1.22 s	1.70	14.6 cm, 1.52 s	2.82	40	3.36
11	9.0 cm, 1.44 s	1.75	11.7 cm, 1.68 s	2.25	66	5.54
12	7.1 cm, 1.49 s	1.37	12.7 cm, 1.93 s	2.45	78	6.55
13	7.4 cm, 1.74 s	1.42	11.6 cm, 2.14 s	2.24	52	4.37

Finally, the percentage of damage has been computed applying Vidal *et al.*, 1995:

$$D_{\%} = \frac{N_c D_{n50}}{(1-P)A_l} \tag{3}$$

Where N_c is the number of dislodged units, P is the porosity of the armour layer and $A_l=0.862$ m, is the 60º arc-length of the active zone at SWL.

Damage comparison

The percentage of damage can be compared with formulations found in the literature developed for similar armour units. Guiducci *et al*., 2005 propose to compute the damage in terms of the ratio between the actual incident wave height and the wave height for initiation of damage. However, it has been found difficult to relate the active zone as suggested by Guiducci *et al*. and the current measurements, yielding a large dispersion in the comparison.

Maciñeira & Burcharth, 2007, also proposes a formulation relating percentage of damage, the stability number, wave steepness and the roundhead radius:

$$Ns = \frac{H_s}{\Delta D_{n50}} = 0.57 e^{0.07 R_n} (\cot\alpha)^{0.71} s_{op}^{0.4} D_{\%}^{0.2} + 2.08 s_{op}^{0.14} \tag{4}$$

Where R_n is the roundhead radius relative to the armour unit's diameter ($R_n=R/D_{n50}$), α is the structure's slope angle and $s_{op}=2\pi\, Hs/(gTp^2) = Hs/L_{op}$ is the wave steepness.

A comparison between the measured stability number for Cube and Cubipod irregular tests, and the stability number obtained with Eq. (4), is shown in Figure 7.

Figure 7 indicates that Cubipods (filled symbols) are more stable than Cubes (open symbols), supporting the initial observations and previous findings from Gomez-Martin & Medina, 2006. It is also noticed the close agreement between the predicted and measured stability numbers, particularly for those tests of minimum stability (i.e. for Iribarren's number of 3.5 and 3.0, as well as for the test of constant peak period), where Eq. (4) slightly over predicts the stability in comparison to the corresponding measured one. Finally, the disagreement of the monochromatic tests, where apparently the roundhead is more stable, can be explained by the definition of the stability number and its application in a formulation (Eq. 4) originally developed for irregular waves.

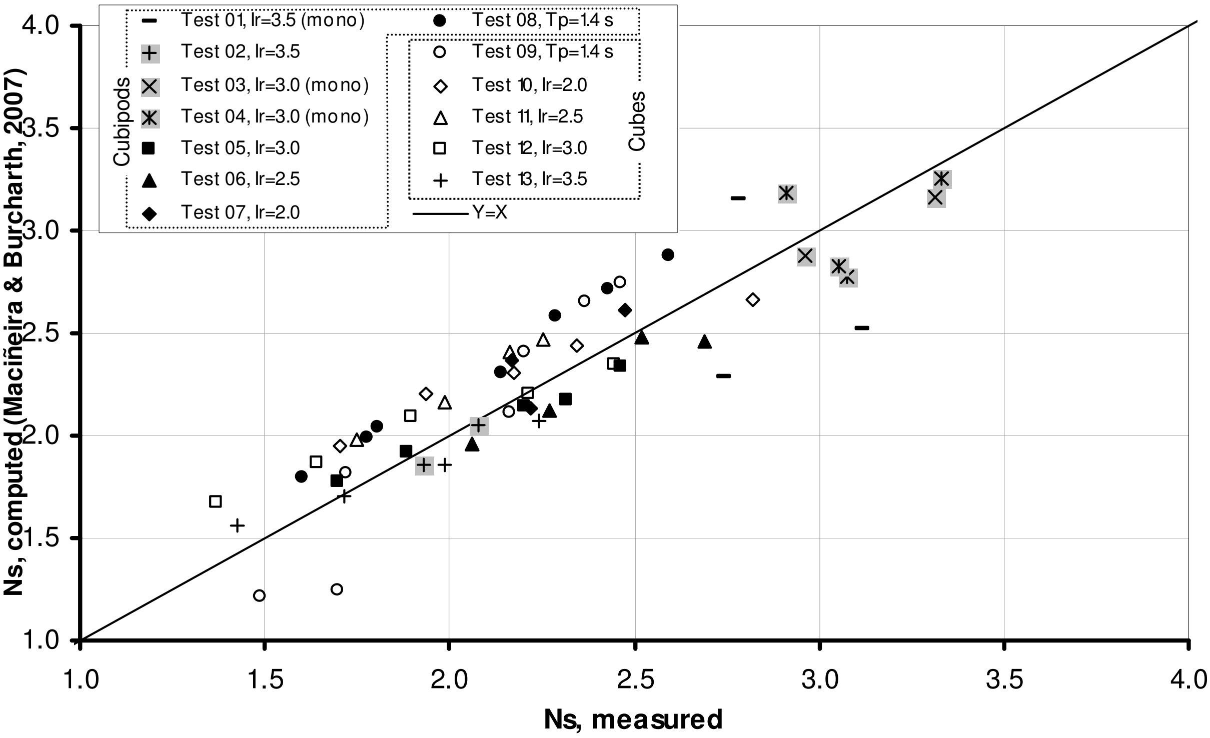

Figure 7: Comparison between the measured and computed (Eq. 4) stability number.

In this study, the stability of the roundhead protected with Cubipod armour units have been performed also for monochromatic waves to identify carefully the *IDa* and *IDe* damage levels. Thus, the corresponding wave height for irregular waves yielding an equivalent damage level could be established, following the same concept as indicated by Vidal *et al.*, 2006, showing that the wave height that best describes the damage on a rubble-mound structure would be an upper-bound percentile of the distribution, e.g. H_{50}. However, most common stability formulations available nowadays use the definition of the stability number in terms of the significant wave height. Further investigation is suggested to derive the corresponding predictive formulations to incorporate the most adequate wave height descriptor, and its equivalent response to monochromatic waves.

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