SYSTEMATIC TESTING OF A NOVEL BREAKWATER ARMOUR TOE SOLUTION: THE ACCROBERM™ I

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The ACCROBERM™ I unit has been conceived as a substitute of the first row and the rock buttress of a traditional ACCROPODE™ toe. The use of this unit allows to reduce the breakwater footprint while simplifying the construction process, thanks to its systematic placing and lack of need of a rock toe mound. In this regard, the present study aims to qualify the hydraulic stability of the ACCROBERM™ I unit as well as to define its domain of application by performing a series of systematic testing. The study concludes that the ACCROBERM™ I unit is a hydraulically stable toe solution for an ACCROPODE™ II armoured revetment under a wide range of foreshore slope and relative water depth values. It also suggests two conservative applicability criterions as a preliminary design tool and marks the way forward to deepen the understanding on its domain of application by proposing several lines of potential research.

Keywords: rubble-mound breakwater; single-layer; concrete armour unit; toe; ACCROPODE™; ACCROBERM™

CONTEXT

The toe region can certainly be considered to be one of the most critical components of a sloped breakwater. With the twofold purpose of i) providing support to the armour layer placed above it; and ii) protecting the structure from scouring damages, it becomes of major importance to ensure a robust design as well as an adequate construction of this part of the structure.

Extensive laboratory research has been carried out in the last decades to better understand the different factors involved in toe stability as well as to provide design formulae for rock toes, However, both the testing methodologies and governing parameters considered on different studies vary widely, which has resulted in formulae that are not always directly comparable. In this regard, (Etemad-Shahidi et al. 2021) presents a comprehensive review of previous literature on the matter, with the double aim of analysing the differences in existing formulae and developing a new one with a wider range of applicability and the consideration of all governing parameters.

Such knowledge improvement on the design of rock toe mounds, together with an extensive experience on its construction, has led to a generalized application of this type of toe for different kinds of breakwater structures. This is also the case of breakwaters based on single-layer artificial armour units technologies, where the vast majority of designs applied until date have considered a rockfill toe berm to stabilize the armour and avoid overturning of the units located in the first row (Giraudel et al. 2014).

However, within construction projects, the sourcing of large-sized rock material to form the toe is usually limited and thus, expensive. Moreover, its later manipulation and positioning in contact with the first armour row, without breaking the units, are difficult and time consuming. Likewise, the execution of a trench which permits lowering the toe, thus reducing the rock size, or even blocking the first row of armour units (the so-called V-shaped toe) is generally complex. In this context, an alternative option consists of the use of concrete armour units on the toe of the structure, the shape of which can be modified in order to maximize the stabilizing factors (e.g., friction) and minimize the de-stabilizing ones (e.g., relative toe depth).

Several studies including physical model tests have been carried out on the use of concrete units as a toe of marine structures; mostly for specific projects. In (Van den Berge et al. 2009), the Xbase®, a flat-bottomed specific concrete element, was successfully implemented on the toe of a single-layer rubble-mound breakwater exposed to depth-limited wave conditions. Later on, (Van Gent & Van der Werf 2014-A) and (Van Gent & Van der Werf 2014-B), systematically analysed the hydraulic stability of a breakwater toe berm made of V-shaped flat concrete units, for both the case of a rock armour and a cube armour. It was concluded that this type of element is a suitable alternative to the use of rock in the toe, although it presents a more brittle mechanism of damage progression. After a certain value of wave height is reached, the units are uplifted and do not fall back into their original position.

To cope with such challenge to flat-bottomed toe units, (Coutos & Hong 2016) proposed the use of rectangular concrete elements with holes as a toe berm for a single-layer ACCROPODE™ II breakwater,

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permanently exposed to severe wave attack. An opening ratio of roughly 10% contributed to the reduction of uplifting pressures and a positive result on the toe stability. A similar solution was more recently applied by (Berté & Galmés 2024) as a toe protection for a stepped caisson subject to cyclonic wave conditions. In this case, the versatility of the concrete unit permitted to iterate a solution by modifying its geometry until a stable solution was found.

Within this framework CLI has developed the ACCROBERM™ I unit (Figure 1) to provide an easy-to-place toe solution which eliminates the need of sourcing large-sized rocks and provides stability to the armour (CLI, 2020).

THE ACCROBERM™ I

The ACCROBERM™ I, has been conceived as a substitute of the first units' row and the rock buttress of a traditional ACCROPODE™ toe. It has a conical-circular shape with a low gravity centre to avoid overturning and a vertical vent hole to allow for better evacuation of the sub-pressures (Giraudel & Galante 2023). The use of this unit allows to reduce the breakwater footprint while simplifying the construction process, thanks to its systematic placing and lack of need of a rock toe mound. A lower complexity of the construction process leads to a higher quality of execution, when the same material means and human expertise are considered. Therefore, the application of the ACCROBERM™ I technique to the toe of an ACCROPODE™ armoured structure generally contributes to achieve a higher-quality final result of the structure as a whole.

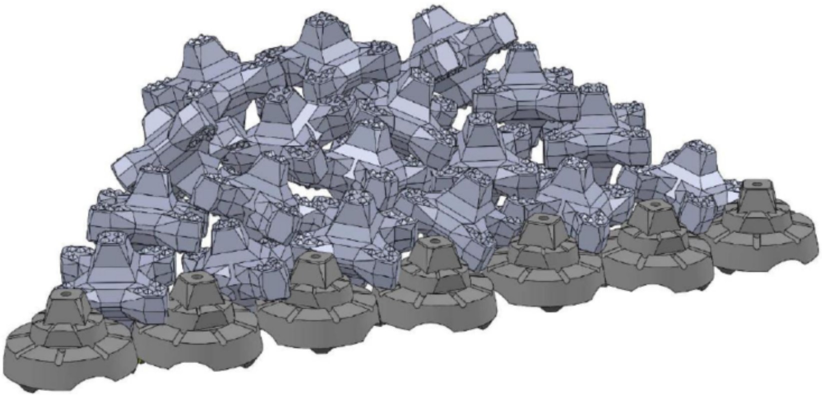

Figure 1. Application of the ACCROBERM™ I unit as a breakwater toe

In contrast with flat-bottomed concrete units, three prismatic protuberances (i.e., toes) located on the base of the ACCROBERM™ I (see Figure 2) allow for an imbrication with the underneath rock layer, and the subsequent development of a higher resistance to sliding. In the same way, three intersecting cylindric recesses permit placing the element on top of slightly irregular rock surfaces with a relatively big rock size, while contributing to the release of uplifting pressures.

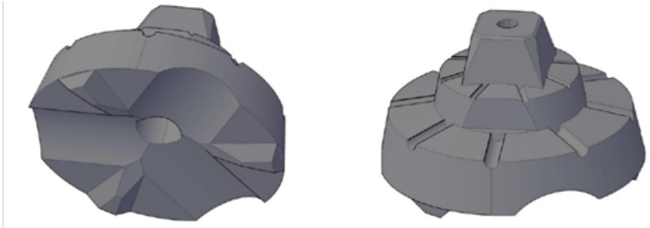

Figure 2. 3D view of ACCROBERM™ I unit

With regards to the weight and main dimensions of the unit, the ACCROBERM™ I has been geometrically defined to preserve the same volume and horizontal mesh than its associated ACCROPODE™ II unit. That is, for any given size of an ACCROPODE™ II armour unit, there is an ACCROBERM™ I toe unit with the same weight and mesh. The weight can however be increased, if required, by modifying the height of the crowns, thus adding additional stability while preserving the mesh. For extreme cases, the ACCROBERM™ I units can be anchored to the seabed by means of steel rebars introduced through its central hole and grouted to it.

In recent years, several 2D and 3D physical model tests have been carried out on the ACCROBERM™ I unit for specific projects to verify the feasibility of each design. In the same way, 3m^3 units were manufactured and installed in 2019 (Figure 3) on a 300 m long breakwater construction project in Dibba, United Arab Emirates, by the company SixConstruct (www.sixconstruct.com). However, to date limited systematic testing had been carried out on the ACCROBERM™ I to contribute to a better characterization of this novel toe unit and to establish a set of preliminary design guidelines.

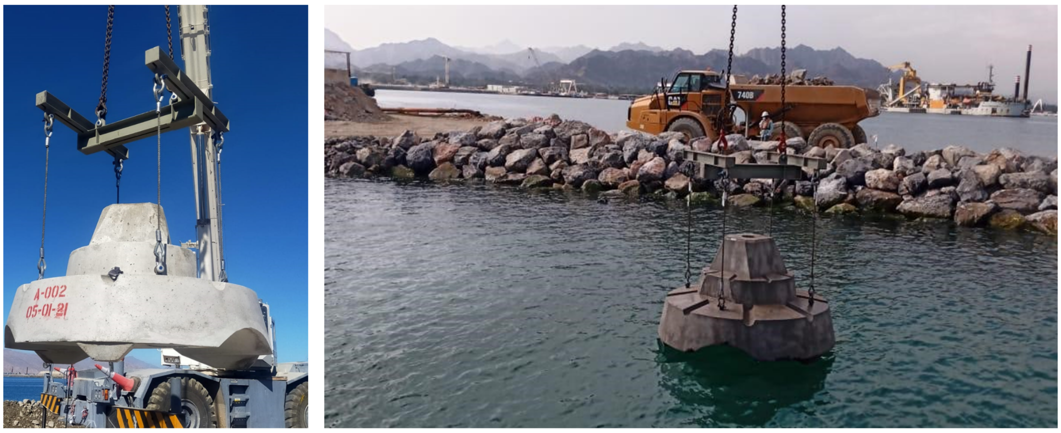

Figure 3. ACCROBERM™ I units installed on a project site in 2019

TEST SETUP AND PRGRAMME

By performing such systematic testing in an independent 3rd-party laboratory, the present study aims to qualify the hydraulic stability of the ACCROBERM™ I unit as well as to define its domain of application. In particular, the study will analyse the effect of the seabed slope (and thus, the wave steepness) and the relative depth at the toe of the structure.

The physical model tests have been executed at the wave flume of the Builders École d'Ingénieurs (former ESITC Caen) in Normandy, France. Their facilities include a 40m-long, 1m-wide and 1.5m-deep wave flume equipped with a state-of-the-art piston generator with active absorption of wave reflection. The flume presents glass side walls all along its length, which facilitates the observation of wave transformation and wave-structure interaction.

Two model cross-sections have been considered for the tests (Figure 4), both consisting of 20 rows of ACCROPODE™ II armour units placed over a row of ACCROBERM™ I units on a 4/3 slope. The main difference between both sections is the presence of a toe berm under the ACCROBERM™ I row. Such berm allows the testing of lower values of the h_t/H_S ratio (where h_t is the toe depth and H_S is the significant wave height at the toe of the structure, $H_S \approx H_{1/3}$) without being bound to a depth limitation of the incident waves.

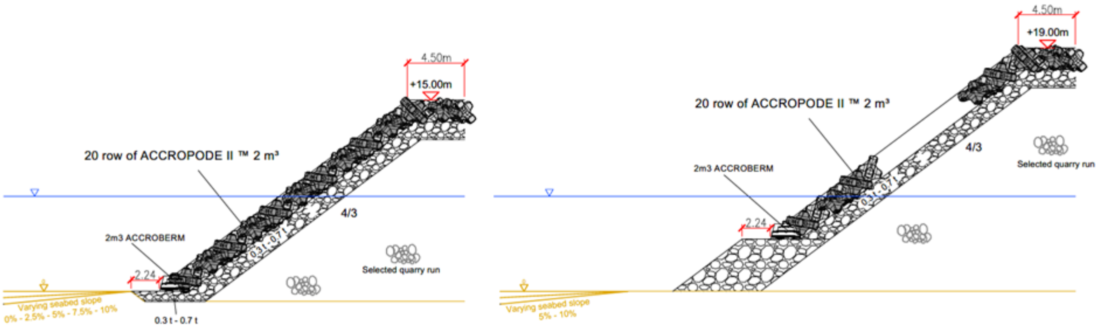

Figure 4. Model cross-section 1 (left) and 2 (right)

Model dimensions as well as the hydraulic conditions have been defined according to a Froude scaling of E = 1/31 (model to prototype). The equivalents of a 0.3 – 0.7 tonnes nature-size underlayer and a 1 – 300 kg quarry-run permeable core have been implemented in both models. The material of the toe berm is the same of the underlayer. In model cross-section nº2, a rigid wired mesh was installed on top of the rock berm to ensure that its geometry was not modified during the tests, which could impact the stability of the ACCROBEM™ I units on top of it. The opening size of the mesh (12 mm) has been chosen as to impede the extraction of berm rocks, while allowing for imbrication with an un-confined layer of rock placed between the berm and the ACCROBERM™ I units (Figure 5).

Figure 5. Rigid wire mesh applied to the rock berm supporting the ACCROBERM™ I units

The ACCROPODE™ II and ACCROBERM™ I model units are made of densified mortar (ρ_{mortar} = 2316 kg/m^3). They represent 2m^3 prototype units with a Hudson stability scaling and considering the densities of concrete and sea water to be $\rho_{concrete}$ = 2350 kg/m^3 and ρ_{sw} = 1025 kg/m^3. Following the indications given in (CLI 2023), the ACCROPODE™ II armour units were placed to a density of φ = 0.635 (Figure 6). The first row of armour units on the slope were installed regularly with the same orientation between ACCROBERM™ I units by ensuring three points of contact: one with each ACCROBERM™ I and one with the underlayer on the slope. Such positioning shall allow the first row of ACCROPODE™ II units to quickly reach an equilibrium position, with three points of contact, if an ACCROBERM™ I is extracted during the execution of the tests.

Figure 6. Detail of the ACCROPODE™ II armour placement

Five different foreshore slope values were tested between 0% and 10%, as well as a wide range of relative water depths for the ACCROBERM™ I, given by the ratio h_t/H_S. As a reference, the different wave height values to be tested have been defined in relation to the theoretical design wave height of the ACCROPODE™ II armour ($H_{S,design}$) and range between 40% to 145% of such value. On the other hand, the wave period has been kept constant for all the tests (T_P = 12.40s) in order to reduce the number of acting parameters in the analysis. However, further testing will be carried out in the future to include the wave period effect on the block stability. Table 1 presents an overall summary of the ranges considered for each parameter.

Table 1. Ranges considered for some of the main test parameters.

H_S	T_P	H_t/H_S	Foreshore Slope
40% to 145%$H_{S,design}$	12.40s	0.6 to 1.9	0%, 2.5%, 5%, 7.5% and 10%

A total of 7 test series with different combinations of the above parameters have been executed for this study; the las two series having three separate test sequences each (refer to Figure 7 for details). Within each particular sequence, 3 to 5 tests have been performed with an increasing value of the incident wave height. The duration of all the tests was 3h (prototype) which allowed for the number of waves to be always slightly over 1000.

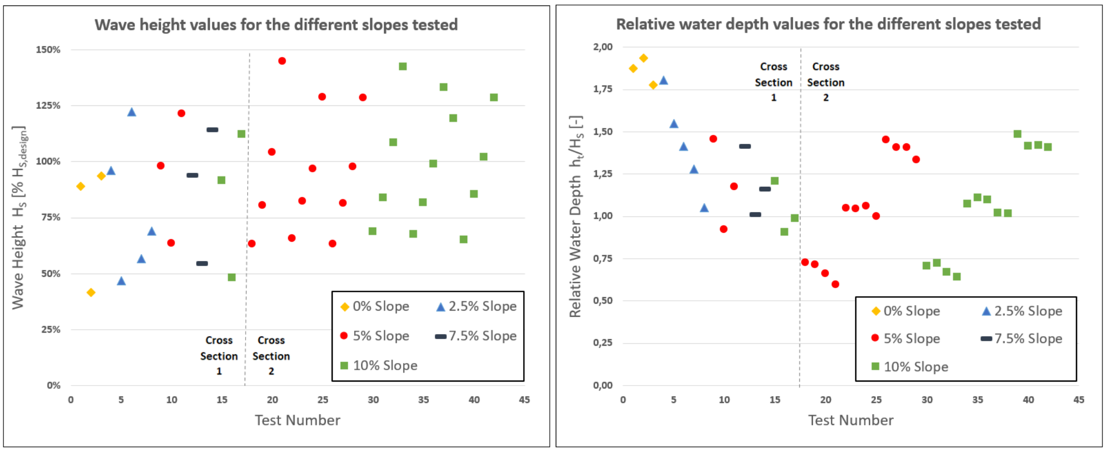

Figure 7. Ranges of values considered for the wave height (H_S) and the relative water height (h_t/H_S)

ANALYSIS METHODOLOGY

Since the peak wave period was kept constant for all tests, the Iribarren number ξ given by (1) varied due to changes in wave height and foreshore slope. This non-dimensional number has been used for the analysis of results in the next chapter, based on statistical wave parameters at the toe of the structure (i.e., ξ_{0P}). A similar approach has already been used in (Aliasgary et al. 2024) and (Safari et al. 2023) for the stability analysis of artificial armour units, using H_{m0} instead of $H_{1/3}$.

$$\xi = tan\alpha/\sqrt{H_S/L} \rightarrow \xi_{0p} = tan\alpha/\sqrt{H_{1/3}/L_0} \qquad (1)$$

Where tanα is the foreshore slope (i.e., 0 – 0.1); and $L_0 = gT_p^2/2\pi$. Both spilling and plunging breakers (according to the Iribarren number described above) have been considered along the different test series; with a predominance of the second type. Wave steepness $s_{0P} = 2\pi H_{1/3}/gT_p^2$ varied between 0.8% – 2.4%.

All tests were carried out with irregular waves on a JONSWAP spectrum with γ = 3.3 and a non-breaking limit condition for $H_S = H_{1/3}$ at the toe of the structure. The latter implies that a number of waves were breaking on and before reaching that point. For the calibration of input wave parameters at the generator, the below assumption has been made at the location of the structure's toe during the calibration test without structure:

$$H_{m0,tot}^2 = H_{m0,i}^2 + H_{m0,r}^2 \rightarrow H_{m0,tot} \approx H_{m0,i} \qquad (2)$$

Where $H_{m0,tot}$ is the total spectral significant wave height; $H_{m0,i}$ is the incident spectral significant wave height; and $H_{m0,r}$ is the incident spectral reflected significant wave height. The latter is a reasonable assumption when the reflection coefficient of the passive wave absorber (i.e., damping beach at the end of the flume) is low, which was the case.

In line with previous literature (e.g., (Etemad-Shahidi et al. 2021), (Safari, et al. 2018)), neither the armour nor the toe of the structure were repaired after the execution of each test within a particular sequence. This allowed to determine the cumulative damage along the sequence. Two photos (see example in Figure 8) were taken before and after the execution of each test: one general shot, perpendicular to the slope; and a second picture, vertical, focused on the ACCROBERM™ I units. The first permitted qualifying the settlement of the armour layer, while the latter allowed quantifying the displacements of toe units. This is made by superimposing the photos, which were always taken in the same way, and calculating the displacement of the centres of gravity. A fixed camera remained on the same support during the tests, with the same focal length setting.

Figure 8. Example of perpendicular photo of the armour layer (left) and vertical photo of the toe berm (right)

In order to avoid edge effects on the results, the data collected from the ACCROBERM™ I units placed in contact with the flume glass were removed from the analysis.

ANALYSIS OF RESULTS

The influence of two parameters has been mainly analysed within this study: i) The foreshore slope tanα; and ii) the relative water depth of the ACCROBERM™ I, measured as the ratio between the height of the water column on top of the unit and the significant wave height at the toe (h_t/H_S). To do so, and in line with (Van Gent & Van der Werf 2014-A) the test results are firstly presented by showing the damage number (N_{OD}) as function of the stability number (N_S). The first represent the number of displaced stones/units within a strip of width D_n, while the second is a non-dimensional factor commonly used on the stability analyses of structures under wave attack (CIRIA/CUR/CETMEF 2007), as shown in (3).

$$N_{OD} = \frac{N^{o}\ of\ displaced\ elements}{Width\ strip/D_{n50}}; \qquad N_S = \frac{H_S}{\Delta D_{n50}} \qquad (3)$$

Where $\Delta=(\rho_{rock}-\rho_{water})/\rho_{water}$; and $D_{n,50}$ is the median nominal stone diameter (e.g., of a rock armour or a toe). For the case of a structure with artificial armour or toe units, the density of concrete ($\rho_{concrete}$) and the nominal diameter ($D_n=V^{1/3}$) are used instead.

The definition and quantification of damage is a subject of debate (Etemad-Shahidi et al. 2021). Within toes made of natural rock armour and a width of at least $3*D_{n50}$, all individual aggregates which can be visually identified as having changed its original position can be counted. The first studies on the matter considered only the elements which are completely extracted from the toe, but more recent literature includes also stones that move within the structure. However, the characteristics of a toe made of a single row of artificial units, having a considerably larger size, demands a different approach. Artificial toe units such as the ACCROBERM™ I, but also armour units like the ACCROPODE™, are placed on top of a rock underlayer in an initial position that might not be that of equilibrium and can slightly re-adjust after the first solicitations. Moreover, a certain level of error in the quantification of unit displacement shall be also accounted for. Hence, it seems reasonable to consider a displacement threshold under which a movement of the unit is to be disregarded.

In this study, a threshold of 5% of the ACCROBERM™ I diameter has been chosen. Hence, all units which displacement after a particular test has been quantified under 5% of the unit diameter, have been considered as non-displaced units. Only displacements in the longitudinal direction (that of the flume's axis) were considered. On the other hand, in accordance with (CIRIA/CUR/CETMEF 2007), three levels of damage have been considered for the characterization of the toe stability:

- *Start of damage (SoD)*: This is the last test of a sequence for which no damage or significant movement of the units was detected.
- *Intermediate damage (ID)*: It corresponds to the first test of the sequence where significant movements (this is, >5%*DACCROBERM) were observed.
- *Failure (F)*: It has been considered that the toe of the structure was ruined either when:
    - At least, one ACCROBERM™ I was extracted (i.e., there was no contact anymore with the first row of ACCROPODE™ II units) even if its relative displacement was low; or
    - The displacement of, at least, one ACCROBERM™ I unit exceeded 50% its diameter (>50%*DACCROBERM)

The establishment of such thresholds remains conservative, when compared to those of a traditional rock toe, which contributes to a certain additional safety margin against a more brittle failure mechanism.

Hydraulic stability of the ACCROBERM™ toe unit

Hydraulic stability is one of the key design parameters to be considered when designing a breakwater toe. In this regard, the hydraulic stability of the ACCROBERM™ I unit can be analysed from Figure 9, where the stability number N_S is plotted against the Iribarren number for all the tests of the study. In the figure, the different foreshore slopes are identified by a change in colour. The fact that, for a given slope, H_S is the only variable parameter present in both N_S and ξ_{0p}, derives in a correlation of the points corresponding to tests done on the same foreshore slope.

The three levels of damage discussed before are indicated by means of a circle (Start of Damage), a triangle (Intermediate Damage) and a square (Failure) for the tests where these levels have been reached. It is to be noted that for the two gentler slopes (0% and 2.5%) no test led to damage on the toe.

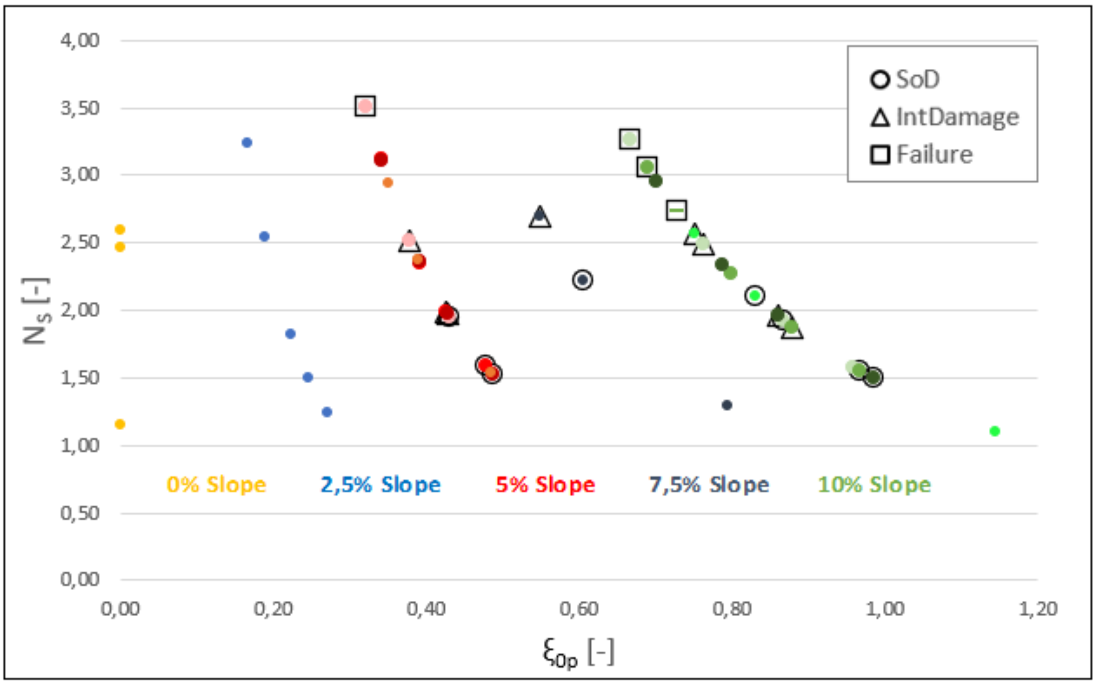

Figure 9. Stability number (N_S) versus the Iribarren number (ξ_{0p})

Start of Damage and Intermediate Damage were found in several tests on the slopes 5%, 7.5% and 10%; while Failure only happened in four cases; three on the 10% slope and one on the 5% slope. Failure was reached at values of N_S between 2.7 and 3.3 for the slope of 10%; while at $N_S = 3.5$ for the slope of 5%. It is worth to be noted that these values should not be directly compared to those of a rock toe berm, since in the levels of damage are defined differently, and the acceptable damage for rock toes is higher.

Moreover, the water depth ratios h_t/h generally applied to rock toes of sloped breakwaters ($h_t/h > 0.5$, see (CIRIA/CUR/CETMEF 2007)) are higher than those considered within this study (refer to Figure 12, chapter 5.3).

However, the Failure N_S values are low when compared with those of artificial units used on the design of the armour layer (e.g., $N_{S,DESIGN} \approx 2.8$ for ACCROPODE™ II, usually expected to reach a 120% $N_{S,DESIGN} \approx 3.4$ for ID values without suffering relevant damage). This is probably due to the influence of the chosen parameters (tanα and h_t/H_S) on the toe stability and the rather extreme values chosen for the tests.

At this point it is relevant to describe the particular sequence of waves that led to damage and/or failure of the toe in the phase 2 tests (cross-section 2 in Figure 4; slopes of 5% and 10%). The entire wave series of the second phase of the study was generated once from a Jonswap spectrum, and later reproduced for all the tests, with a certain amplitude gain on the generator according to the desired output (H_S) at the toe of the structure. Hence, the combination of waves shown in Figure 10 happened at the same time on all the tests of phase 2, with a different amplitude on each test.

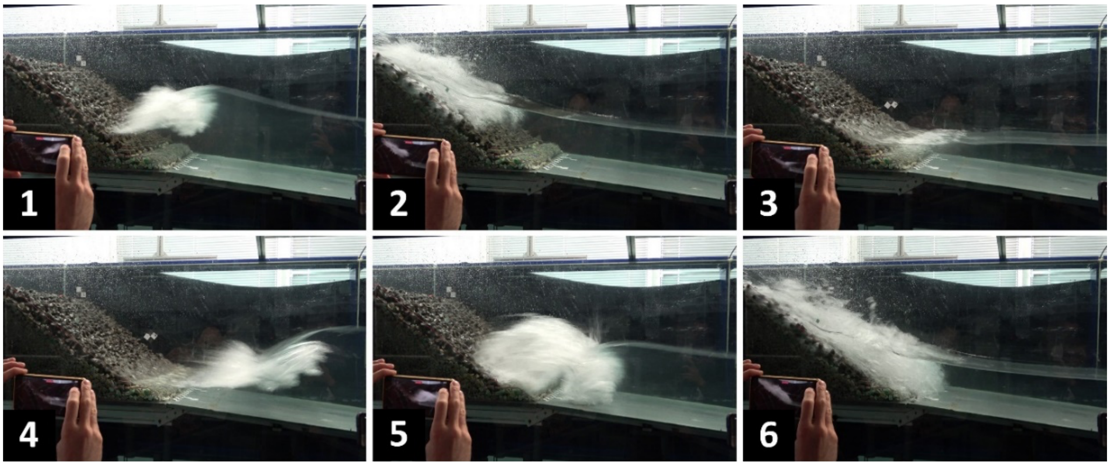

Figure 10. Specific sequence of waves which was originating damage and/or failure during the tests on cross-section 2

The sequence shown in Figure 10 presents a considerable run-down event almost exposing the toe units (photos 3 & 4), followed by a plunging wave which directly impacts on the toe (photos 5 & 6). The particular case shown in the figure corresponds to a foreshore slope of 10%, a value of $h_t/H_S \approx 0.64$, and a relative significant wave height of $H_S \approx 140\% H_{S,DESIGN}$; and led to the complete extraction of four ACCROBERM™ I units from the toe. Additionally, two other units lost contact with the ACCROPODE™ II slope armour units being supported by them and were therefore also considered extracted.

Such failure of the toe facilitated the extraction of one ACCROPODE™ II armour unit of the first row, as well as a general settlement of the armour towards the toe. It is to be remarked that the ensemble of the structure remained stable until the end of the series (the sequence happened around the end of the first quarter of test), although aerations were produced on the higher third of the armour. This might be due to the regular positioning of the first row of ACCROPODE™ II units, which allows them to reach a relatively more stable position (with three points of contact with the berm) if the ACCROBERM™ I unit below is extracted. The afore gives a sort of "backup" protection to the structure's toe, in case of an extraction.

The above example emphasizes the relevance of performing the testing of toe elements with irregular waves, even for the case of systematic testing, since it is not only the individual wave parameters but also certain combinations of them which lead to the most destructive events.

Evolution of damage

In order to analyse the evolution of damage on the ACCROBERM™ I toe, Figure 11 has been prepared by presenting the damage number N_{OD} against the stability number N_S, for the different tests performed. The left image of the figure presents all the executed tests, while the one in the right side shows only those corresponding to identified levels of damage (SoD, ID and Failure). Within each colour range, darker tones indicate larger values of the h_t/H_S ratio.

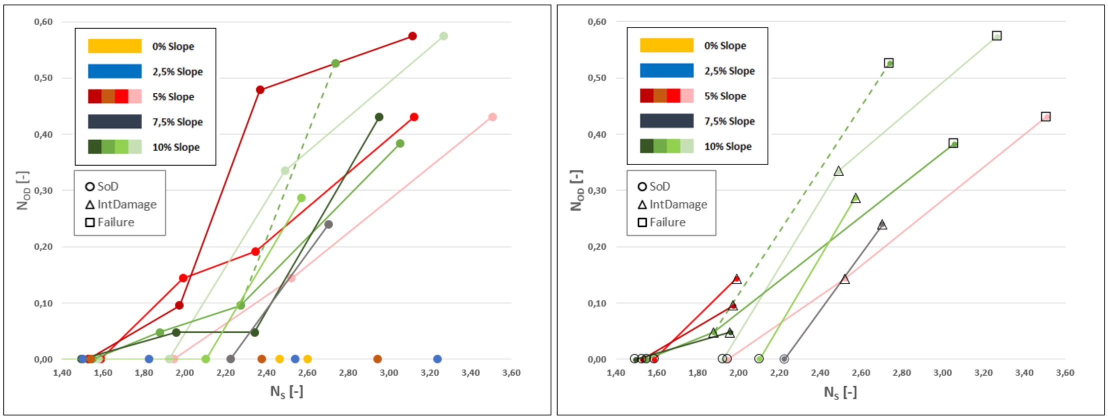

Figure 11. Relation between the number of damage N_{OD} and the stability number N_S for different slopes

As it can be seen in the figure, no damage was produced to the toe (N_{OD} = 0) during Phase 1 tests (cross-section 1) with foreshore slopes of 0%, 2.5% and 5%; represented by yellow, blue and orange points in the left chart. A common feature of those tests is that only medium to high values of the ACCROBERM™ I relative water depth (i.e., $1 \leq h_t/H_S \leq 2$) were applied (refer to Figure 7, right); which combined with the gentler foreshore slopes led to less aggressive conditions on the toe. The latter is true even for values of N_S for which there was damage and/or failure of the toe in tests with harsher conditions (i.e., steeper slopes and/or lower values of h_t/H_S).

In general terms, the evolution of damage observed for all tested conditions seems to be faster than expected for a similar toe berm made of rocks, which is in accordance with the findings of (Van Gent & Van der Werf 2014-B). As it happens with artificial units on the armour, damage on an ACCROBERM™ I toe does not happen gradually but rather abruptly after a certain wave height is exceeded, for a given combination of foreshore slope and h_t/H_S. However, the generalization of such conclusion is limited by the amount of toe failures reached during this study, since 3 out of 4 events of toe destruction were for the same foreshore slope (10%). Moreover, similar tests with the same geometry and hydraulic conditions but applied on a rock toe would be required to verify whether or not the damage evolution is indeed faster in the case of a concrete unit toe.

With regards to the identification of a damage threshold for the different damage levels, the Intermediate Damage is affected by a larger scatter $ID \in [0.05, 0.34]$ than the Failure $F \in [0.38, 0.57]$.

Influence of the foreshore slope tanα and the relative water depth h_t/H_S

Preliminary conclusions on the effect of the foreshore slope tanα on the hydrodynamic performance of the ACCROBERM™ I unit can be drawn from Figure 9 and Figure 11 already presented. Not only the slope of 10% cumulated most of the failure events, for different h_t/H_S ratios, but they also happened earlier (i.e., at a lower value of N_S) than for a gentler slope of 5%. The toe remained stable even if subject to some damage for all other combinations of slope and relative water depth, except for a case with a 5% slope and a low value of h_t/H_S. Therefore, it could be concluded for the ACCROBERM™ I, that an increase in the foreshore slope decreases the stability of the toe, which is in line with previous literature for other types of toe berms. Moreover, a 10% slope appears to induce instabilities for a wider range of values of h_t/H_S. Hence, a conservative design criterion could be stablished to limit the application of such technique to cases where the foreshore slope is milder than 10%. The afore shall not impede the proposal of particular designs exceeding such criterion which could be validated through detailed physical modelling.

With regards to the effect of the relative water depth on the stability of the ACCROBERM™ I, Figure 12 presents the stability number (N_S) versus the h_t/H_S value for all the executed tests. The same figure is also used to present the stability number versus the water depth ratio (h_t/h). Additionally, the three levels of damage are indicated by a circle (SoD), a triangle (ID) and a square (Failure).

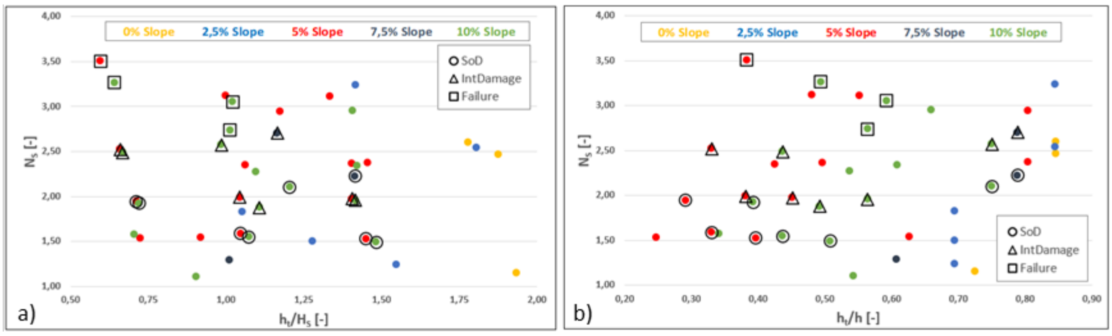

Figure 12. Stability number (N_S) versus a) left, relative water depth of the ACCROBERM™ I (h_t/H_S); and b) right, water depth ratio (h_t/h) for the different tests

All toe failure events occurred for relative water depths lower than or around $h_t/H_S \leq 1$ and water depths ratios lower than $h_t/t < 0.6$. The toe remained stable or sustained minor damage during tests with an equivalent wave height (same level of N_S) and foreshore slope (i.e., 5% and 10%), but higher values of h_t/H_S and h_t/h ratios. On the other hand, the first relevant damages to the toe (ID level) were reported for rather low values of N_S (between 2.0 and 2.7) during tests with a variety of slopes and relative water depths lower than or around $h_t/H_S \leq 1.5$. Hence, a conservative design criterion could be stablished to limit the application of the ACCROBERM™ I technique to cases where its relative water depth is higher than such value ($h_t/H_S > 1.5$). As with the foreshore slope, the afore shall not impede the proposal of particular designs exceeding such criterion which could be validated through detailed physical modelling.

The considerable scatter presented in Figure 12 (a and b) allow to identify certain thresholds (particularly for the case of the relative water depth of the ACCROBERM™), but do not permit to detect trends that can be transformed into design formulae. More research, with an increase of the parameter ranges is recommended in this regard.

CONCLUSIONS AND RECOMENDATIONS

Based on this study of the hydraulic stability of the ACCROBERM™ I toe unit, and considering the tested combinations of tanα and h_t/H_S, the following main conclusions can be drawn:

- The ACCROBERM™ I technique provides a hydraulically stable toe solution for an ACCROPODE™ II armoured revetment under a wide range of foreshore slope and relative water depth values. It simplifies the placement of the first row of armour units and reduces the structure's footprint, since it does not require the implementation of a rock toe mound in front of them.
- The evolution of damage on a toe made of one row of artificial concrete units such as the ACCROBERM™ I unit, seems to be faster than that of a rock toe. This shall lead to the consideration of stricter criteria to establish the different levels of damage. This paper includes a conservative recommendation for establishing the levels of damage in future studies of the ACCROBERM™ I, listed below. Large scatter in the results does not allow to provide a reference value of N_{OD} until more research is carried out on the subject.
    - *Intermediate Damage*: First test of the sequence where significant movements (i.e., displacement > 5%*$D_{ACCROBERM}$) are observed.
    - *Failure*: First test of the sequence where the ACCROBERM™ I units' displacement exceeds 50% of its diameter, or if there is a lack of contact between the armour and the toe units.
- An increase in the foreshore slope decreases the stability of the ACCROBERM™ I toe, which is in line with previous literature for other types of toe berms. Moreover, a 10% slope appears to induce instabilities for a wider range of values of h_t/H_S. Hence, a conservative design criterion is suggested to limit the application of the technique to cases where the foreshore slope is milder than 10%. However, particular designs exceeding such criterion could be validated through detailed physical modelling.
- With regards to relative water depth h_t/H_S, a conservative design criterion is suggested to limit the application of the ACCROBERM™ I technique to cases where this value is higher than 1.5. As with the foreshore slope, the afore shall not impede the proposal of particular designs exceeding such criterion to be validated through detailed physical modelling.

- A single adverse sequence of a few waves might be responsible of more toe damage than the rest of the entire series. Testing with irregular waves is of key importance for any future study on the ACCROBERM™ I toe stability and its domain of application.

FUTURE LINES OF RESEARCH

It is recommended to deepen on the analysis of the influence of the foreshore slope (tanα) and the relative water depth (h_t/H_S) by performing further testing which brings the toe to failure under cases of mild slopes and large relative depths. In this regard, tests with higher values of N_S could be performed while keeping the combinations of tanα and h_t/H_S that did not produce significant damage within this study, up to the eventual destruction of the toe or the armour layer (whatever comes earlier). This would help to reaffirm the stability of the ACCROBERM™ I solution within its domain of application.

Previous literature has found an effect of the wave steepness or wave period on the stability of a rock toe. In this study, the wave steepness was varied but the wave period (T_P) was kept constant. Hence, it is also suggested to assess the specific influence of the wave period on the ACCROBERM™ toe stability by performing a series of tests with varying values of T_P.

It is also recommended to study the influence of other elements such as the size of berm or anti-scouring rock placed under the ACCROBERM™ I units. Since these rocks are the element of the structure to which the drag forces of the toe units are being transferred, its stability is of utmost importance to ensure the expected performance of the ACCROBERM™ I units.

Finally, the execution of 3-dymensional physical model tests is highly recommended to analyse the effect of oblique waves on the ACCROBERM™ I stability. Such type of testing is frequently carried out for the validation of specific project designs including ACCROBERM™ I toe units, but systematic testing has not yet been performed.

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