Influence of wave conditions in damages at scale model tests of rubble-mound breakwaters under sea level rising

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Abstract: Usually, physical model tests support the design of breakwaters considering different incident wave conditions, including extreme events. This paper describes two-dimensional physical model tests of a rock armour breakwater, performed at LNEC´s experimental facilities, under the framework of the HYDRALAB+ project. The goal of the present work is to evaluate damage evolution under wave conditions resulting from future climate change scenarios. Test results are presented in terms of the non-dimensional damage parameter (S) and of the percentage of displaced armour units (D). The data analysis is focused on the cumulative damage progression related with wave parameters as H_{max} and $H_{2\%}$, for the imposed storm sequences. The use of the stability number (Ns), considering both $H=H_s$ and $H=H_{2\%}$ revealed a good agreement in order to characterize its relationship with damage evolution. On the other hand, the use of H_{max} revealed a decrease of the linearity on damage evolution.

Key words: Physical model, Damage evolution, Climate change, Storm sequences

1. INTRODUCTION

In the presence of climate change predictions, a large number of structures will need upgrading, in order to reduce the risk of future damages. Understanding damage progression under future climate change scenarios is of utmost importance for effective management of coastal defences.

Cumulative effects due to storm sequences could lead to progressive failures, due to, for instance, armour instability and related overtopping of the structures. Therefore, a correct description of storm evolution is deemed fundamental for analysing damage progression as well as its impact on wave overtopping, HYDRALAB+ (2017).

The aim of this work is to evaluate, on two-dimensional (2D) physical model tests, the damage evolution of a cross-section of a rubble-mound breakwater, under three different approaches of storm sequences. Measuring equipment was deployed in the flume to evaluate the free-surface elevation in different positions, the wave run-up and the overtopping over the structure.

Concerning damage evaluation, two techniques were used: visual observation (counting) of displaced units and a stereo-photogrammetric technique. With the results of these techniques, it was possible to evaluate the percentage of displaced armour units (D) and the non-dimensional damage parameter $S=Ae/(Dn_{50})^2$, where Ae is the eroded cross-sectional area around the still water level and Dn_{50} is the nominal diameter of the armour units. The present work aimed to analyse the relationship between the stability number, Ns, and the wave steepness, S_{0p}. Furthermore, the relationship between damage parameters (D and S) and the stability number, Ns was also evaluated. $Ns=H/(\Delta.Dn_{50})$ is normally used to characterize hydraulic stability, where $\Delta=(\rho_r-\rho_w)/\rho_w$ is the relative submerged mass density, ρ_r is the mass density of the rock, ρ_w is the mass density of the sea water and H is a characteristic wave height. To infer on the best wave parameter to establish this relationship, Ns was estimated considering three different wave heights: the significant height $H=H_s$ ($Ns_{,Hs}$), the maximum height $H=H_{max}$ ($Ns_{,Hmax}$) and the height exceeded by only 2% of the waves in a record $H=H_{2\%}$ ($Ns_{,H2\%}$).

2. METHODOLOGY

2.1 Physical Model Tests

2D physical model tests were conducted at the Ports and Maritime Structures Unit (NPE) of the Hydraulics and Environment Department, in a wave flume (COI 1) approximately 50 m long, with an operating width and an operating water depth of 80 cm each. The flume is equipped with a piston-type wavemaker embedding an active wave absorption system, AWASYS (Troch, 2005) for the dynamic absorption of reflected waves. The tested model was a double-layer, randomly placed rubble-mound breakwater with a porosity of ~37% and a 1:2 slope. The armour unit nominal diameter (Dn_{50}) was 4.45 cm, with a mass density of 2.6 g/cm^3.

The physical model was built and operated according to Froude's similarity law, with a geometrical scale of 1:30, as to ensure reduced scale effects (wave heights should lead to values of the Reynolds number, Re > 3x10^4). The foreshore slope was 2% and the flume was equipped with twelve resistive-type wave gauges deployed along its length, to measure the free-surface elevation at different locations. The equipment used to collect the volume of water that overtopped the structure consisted on a tank that was located at the back of the structure. Figure 1 illustrates the breakwater cross-section and the setup of the experimental equipment nearby the structure.

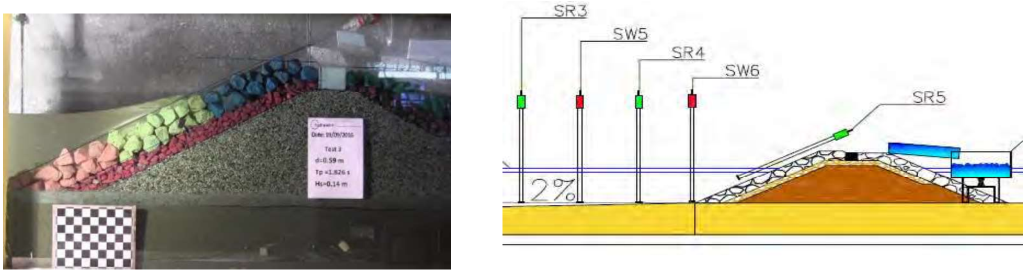

Fig. 1. Model of the breakwater cross-section and experimental equipment setup nearby the structure.

Table I summarizes the test characteristics for the three test approaches: Approach A simulates increasing significant wave heights (H_s) with increasing peak periods (T_p) and water depths; Approach B simulates a constant wave period, alternating water depths and increasing wave heights; Approach C simulates, for two water depths, a standard storm build-up, with a constant peak period. In all approaches, irregular wave tests were conducted for water levels and significant wave heights corresponding to extreme events, associated to climate change scenarios, represented by a severe sea level rise (SLR), with a cumulative effect of meteorological adverse conditions.

Table I. Test conditions at the structure toe (model scale).

Approach A				Approach B				Approach C			
Test	Water depth (m)	T_p (s)	H_s (m)	Test	Water depth (m)	T_p (s)	H_s (m)	Test	Water depth (m)	T_p (s)	H_s (m)
1	0.30	1.83	0.11	8	0.37	2.19	0.12	9	0.27	2.19	0.12
2	0.30	1.83	0.12	9	0.27	2.19	0.12	11	0.27	2.19	0.14
3	0.30	1.83	0.14	10	0.37	2.19	0.14	13	0.27	2.19	0.16
4	0.34	2.01	0.12	11	0.27	2.19	0.14	15	0.27	2.19	0.17
5	0.34	2.01	0.14	12	0.37	2.19	0.16	8	0.37	2.19	0.12
6	0.34	2.01	0.16	13	0.27	2.19	0.16	10	0.37	2.19	0.14
7	0.34	2.01	0.17	14	0.37	2.19	0.17	12	0.37	2.19	0.16
				15	0.27	2.19	0.17	14	0.37	2.19	0.17

2.2 Damage Analysis

Damage was characterized by two methods: counting the number of displaced units (D) over the total number of blocks on the active zone; and measuring the eroded area at the active zone of the armour (approximately, $7Dn_{50}$ around the still water level) by dividing the eroded volume by the length of the cross-section. Broderick (1983) and Van der Meer (1988) defined a dimensionless damage parameter, $S=Ae/(Dn_{50})^2$, where Ae is the eroded cross-sectional area around the still water level and Dn_{50} is the nominal diameter of the armour units.

Results are presented in terms of the evolution of the non-dimensional damage parameter (S) and of the percentage of displaced armour units (D) with the stability number, $Ns_{,H=}H/\Delta Dn_{50}$, considering $H=H_s$, $H=H_{2\%}$ and $H=H_{max}$. Only approaches B and C, comprising a representative sample of increasing wave heights, were considered to relate S with Ns.

Table II and Table III show the percentage of displaced armour units (D) and the non-dimensional damage parameter (S) computed for each storm sequence, respectively. Due to problems related with photograph acquisition (it was not possible to determine Ae), results from test T1, for storm sequence A, and T13, for storm sequence B, are not presented. Storm C, under sea level rise conditions with increasing significant wave heights, presented the highest values of cumulative damage for both D and S parameters.

The non-dimensional damage parameter (S) at the end of storm sequences A, B and C, according to the damage classification proposed by Van de Meer (1988) for a 1:2 rock slope, corresponds to intermediate damage at the end of all sequences.

Since damage is a function of the stability number, Ns, which is a function of the wave steepness, $S0_p=2\pi H/(gT_p^2)$, the trend of Ns related with $S0_p$ was also estimated considering H equal to H_s and $H_{2\%}$. These values were calculated based upon the data collected at the wave gauge located at the toe of the structure (SW6), at a seaward distance of 0.15 m from the structure toe.

Figure 2 illustrates, for test sequences A, B and C, the stability number, Ns, obtained in the scale model tests (including both initial and intermediate damage stages), as a function of S_{0p} when considering $H=H_s$ and $H=H_{2\%}$. The obtained values of Ns, respectively $Ns_{,Hs}=1.75$ and $Ns_{,H2\%}=2.50$, are in accordance with the presented in Herrera *et al*. (2017).

Table II. Percentage of displaced armour units (D) for each storm sequence.

Storm A	**Test**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
	D (%)	3.2	4.0	4.8	5.6	7.3	9.7	10.5	
Storm B	**Test**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	D (%)	4.0	4.8	6.5	6.5	7.3	8.9	10.5	11.3
Storm C	**Test**	**9**	**11**	**13**	**15**	**8**	**10**	**12**	**14**
	D (%)	3.2	3.2	4.0	9.7	11.3	14.5	14.5	16.1

Table III. Damage parameter (S) computed for each storm sequence

Storm A	**Test**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
	S	-	1.21	1.07	2.02	1.92	4.20	3.44	
Storm B	**Test**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	S	3.08	0.88	1.17	2.01	2.55	**-**	3.71	2.21
Storm C	**Test**	**9**	**11**	**13**	**15**	**8**	**10**	**12**	**14**
	S	2.22	1.57	1.62	3.81	3.49	3.85	3.98	5.16

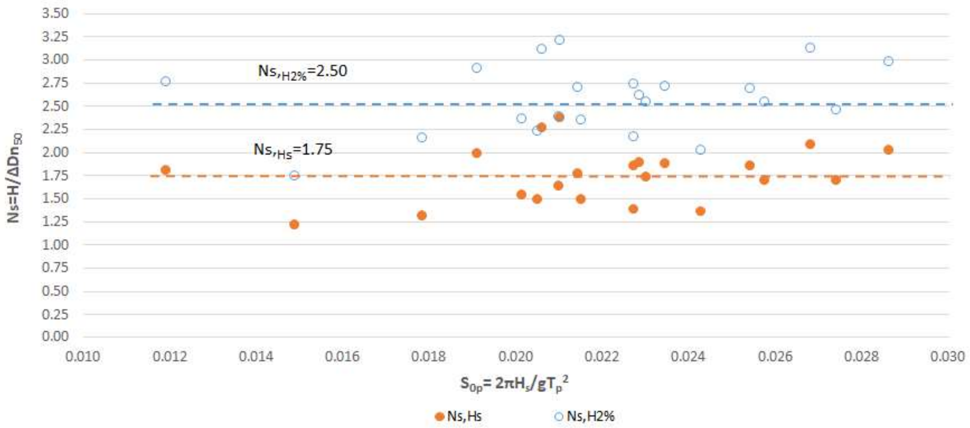

Fig.2. Stability number, Ns, obtained in the scale model tests for intermediate damage when considering $H=H_s$ and $H=H_{2\%}$.

Figure 3 depicts the percentage of displaced armour units, D, as a function of the stability number, Ns, for storm sequence B (increasing wave heights with alternating water depths, with SLR), considering $H=H_s$, $H=H_{2\%}$ and $H=H_{max}$. It shows that $Ns_{,Hs}$ exhibits a quasi-linear trend, whereas no linear trend is found for $Ns_{,Hmax}$. $Ns_{,H2\%}$ presents an intermediate case. The relationship between D and Ns can be defined as $D=aNs^b$, with $0.35 < a < 2.19$ and $2.5 < b < 3.3$. Also for storm sequence B, Figure 4 shows the non-dimensional damage parameter S as a function of $Ns_{,Hs}$ and of $Ns_{,H2\%}$. In this case, when using $Ns_{,H2\%}$, a 6-power relationship between S and Ns is found, in accordance with the results of Herrera *et al*. (2017).

Regarding storm sequence C, Figure 5 presents the relationship between S and Ns, for tests with two water depths (one of them considering SLR), each one comprising increasing wave heights. It shows that for LWL and SLR, S has a similar relationship with $Ns_{,Hs}$, $Ns_{,H2\%}$ and $Ns_{,Hmax}$. Storm sequence C presents higher values of cumulative damage S than the other sequences. Nevertheless, for the highest wave heights with SLR, damage decreases with increasing overtopping rates, Q, Figure 6. This decrease is also associated to accretion on the active zone, due to removed armour units from the crest zone.

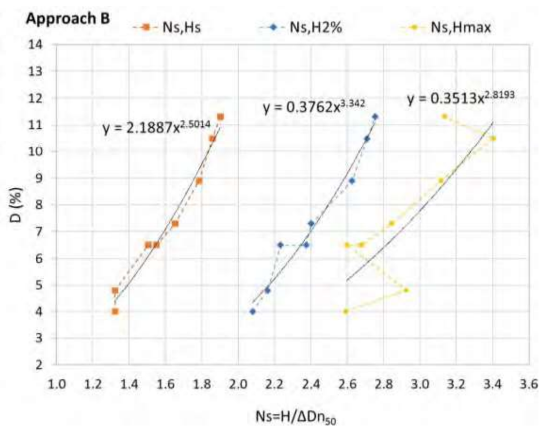

Fig.3. Approach B. Percentage of displaced armour units, D, versus the stability number, Ns.

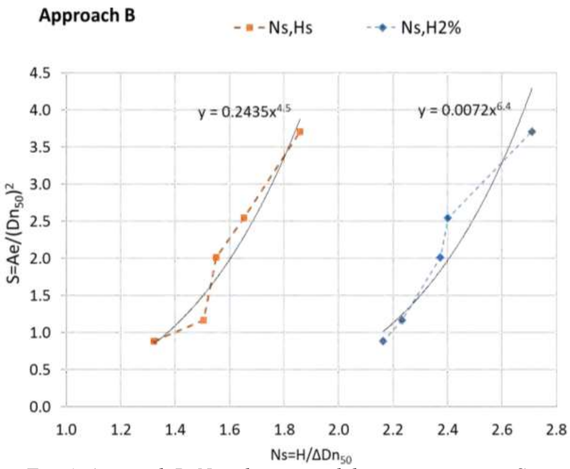

Fig. 4. Approach B. Non-dimensional damage parameter, S, versus $Ns,_{Hs}$ and $Ns,_{H2\%}$

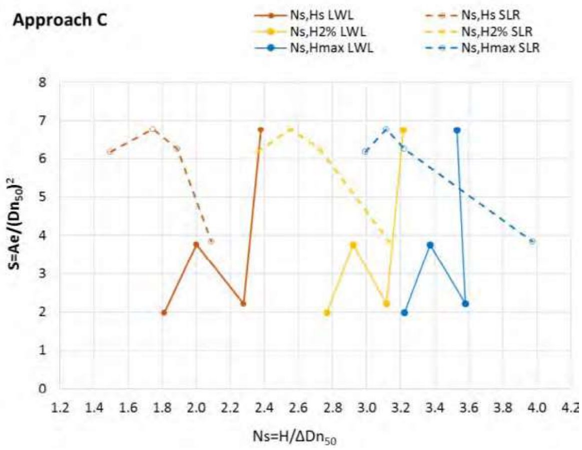

Fig. 5. Approach C. Non-dimensional damage parameter, S, versus $Ns,_{Hs}$, $Ns,_{H2\%}$ and $Ns,_{Hmax}$ for LWL and SLR.

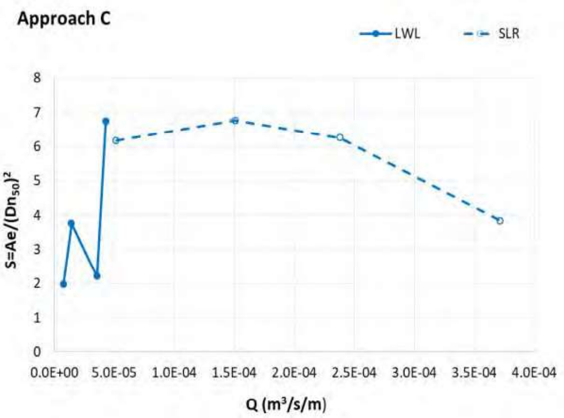

Fig. 6. Approach C. Non-dimensional damage parameter, S, versus overtopping rates, Q.

3. CONCLUSIONS

This study analyses the hydraulic stability of an armour layer composed of rock armours units, under three different storm sequences, two of them comprising sea level rise. It is based on physical model tests conducted in one of LNEC´s wave flumes, at a reference scale of 1:30. The tested armour layer has a 1/2 slope and a double layer with a porosity of ~37%. A 2% foreshore was used.

Wave conditions comprised three different storm sequences, A, B and C, with significant wave heights at the toe of the structure (H_s) between 0.11 m and 0.17 m and peak periods (T_p) of 1.83 s and 2.19 s. The wave steepness (S_{0p}) ranged between 0.012 and 0.029. The water depths at the toe of the structure were 0.27 m, 0.30 m, 0.34 m and 0.37 m.

Storm sequence C, under sea level rise conditions and with increasing significant wave heights, has shown the highest values of cumulative damage for both the percentage of displaced armour units (D) and the non-dimensional damage parameter (S). However, highest wave heights associated with SLR led to a decrease of damage, both for Approaches B and C, due to increase in wave overtopping.

The use of the stability number (Ns), considering both $H=H_s$ and $H=H_{2\%}$ at the toe of the model, revealed that damage increases with the stability number. On the other hand, with the use of H_{max} the relationship between damage evolution and Ns is not evident.

Concerning the alternated increase/decrease of S due to erosion/accretion phenomena, a larger test sample should be used in order to achieve a more accurate relationship between S and Ns.

Future works should also comprise the study of damage at the rear side of rubble-mound breakwaters under similar water levels and wave conditions, due to increase in overtopping rates.

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