Influence of toe berm geometry on stability of reshaping berm breakwaters

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DOI
10.1016/j.coastaleng.2020.103636

Publication date
2020

Document Version
Accepted author manuscript

Published in
Coastal Engineering

Highlights

- Tests have been carried out to investigate the influence of toe berm on the recession of berm breakwaters.
- Model tests showed that toe berm width and thickness both have considerable influence on recession reduction.
- A design formula has been developed to account for the effects of toe configuration on berm recession.
- Results of the present research can be used as a guideline for the conceptual design of berm breakwaters including a wide toe berm.

Influence of toe berm geometry on stability of reshaping berm breakwaters

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Abstract

Reshaping berm breakwaters have been mainly designed and built for water depth less than 20m. In such conditions, a toe structure may be needed to reduce bottom settlements and increase geotechnical stability in the loose subsoil condition. Also, a toe berm can be deployed to reduce the berm recession and increase the stability of the Reshaping berm breakwater, especially in deep water. Although many studies have been conducted to study the effects of toe berms on stability of conventional breakwaters, investigations on the influence of a toe berm on stability of reshaping berm breakwaters are rare. This paper presents results of an experimental work that has been carried out to investigate the influence of a toe berm on the hydraulic stability of reshaping berm breakwaters. In a 2D physical test setup in a wave flume, a total of 207 tests were conducted to systematically examine the effects of toe berm configuration on the reshaping of berm breakwaters with three types of armor stones. The experimental program covers the influence of different geometrical parameters of the toe berm on the berm recession under various sea state conditions. Comparing results of berm recession of the cases having a toe structure with the cases without a toe berm shows that the amount of berm recession with toe berm is considerably less than the analogous amount for without toe structure. It is observed that an increasing toe berm width and thickness both have considerable influence on recession reduction. However, the toe depth has a relatively larger influence on recession than the toe width, and the influence is larger for higher stability numbers. It is concluded that a toe berm in front of reshaping berm breakwater not only does have influence on recession due to the depth influence and the changing wave conditions, but also the toe depth has a direct influence on the reshaped profile by preventing the displaced rocks to fall down to deeper parts. Using the test results, a new formula is developed for estimation of berm recession by taking into account the influence of the toe berm configuration. Given an acceptable stability number (Ho) as a design criterion for reshaping berm breakwaters, the present method predicts that the recession can be reduced up to 35% by the application of a toe berm. Thus, the main berm width can be shortened, resulting in reduction of the required armor stones volume. So, by using a smaller stone size for the toe berm, the stability of the structure is secured and also the total cost of the breakwater can be reduced.

Keywords: Reshaping berm breakwater; Toe berm; Armor stone; Recession; Physical modelling; Design formula

1. Introduction

1.1. Background

A reshaping berm breakwater is a rubble mound structure traditionally designed with a berm above the design water level at the seaward side. During wave attack, the berm will typically reshape into an S-shaped profile which has been proven to be more stable than the initially built profile. In fact the "as built profile" becomes dynamically stable under severe wave attack and re-shapes into a (more) statically stable profile, see Fig. 1. These protective structures are advantageous when it is not possible to quarry large armour stones or heavy construction equipment is not available.

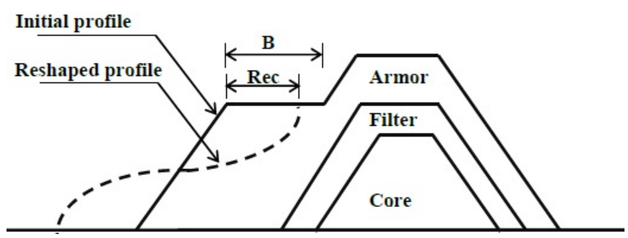

Fig. 1. Reshaped seaward profile of a mass armored reshaping berm breakwaters.

PIANC (2003) has produced a state of the art report on reshaping berm breakwaters in 2003, summarizing the research carried out till then, giving practical guidance for design and construction. This report also describes the behavior of different types of berm breakwaters by classifying them into statically stable non-reshaped, statically stable reshaped and dynamically stable reshaped berm breakwaters.
Sigurdarson and Van der Meer (2012) introduced a new classification of berm breakwaters, which is a modification of the classification proposed by PIANC. They distinguish between the mass armored berm breakwaters, with a homogeneous berm of mainly one stone class, and Icelandic-type berm breakwater, constructed with more rock classes. Then, based on the structural behavior of the two types of berm breakwaters which can be hardly reshaping, partly reshaping and fully reshaping, a classification with four typical types of berm breakwaters is introduced: hardly reshaping Icelandic-type berm breakwater, partly reshaping Icelandic-type, partly reshaping berm breakwater and fully reshaping berm breakwater. This paper focus on the mass armored reshaping berm breakwater, abbreviated hereafter as RBB.
The most important measure for the reshaping of a homogeneous berm breakwater is the recession of the berm (Rec) as ascertained by Burcharth and Frigaard (1988), cf. Fig. 1. Failure of a reshaping berm breakwater is consistently specified as Rec>B, where B is berm width. A number of researchers have proposed some methods and formulae for estimation of berm recession by considering various sea states and structural configurations, e.g., Hall and Kao (1991) and Tørum et al. (1999, 2003). Alikhani et al. (1996) conducted physical tests to analyze the influence of wave obliquity on the reshaping of berm breakwater exposed to head-on waves. Lamberti and Tomasicchio (1997) performed a laboratory investigation to quantitatively analyze the stone movements under head-on wave attacks at a reshaping breakwater. Tomasicchio et al. (2007) proposed a general model to determine stone mobility at reshaping or berm breakwaters under the attack of head on and oblique waves.

Afterwards Tomasicchio et al. (2013) developed a longshore transport (LT) model after a re-calibration of the model initially offered by Lamberti and Tomasicchio (1997) for a wide mobility range of units: from stones to sand.

Rao and Balakrishna (2002) carried out a series of tests with RBBs using homogeneous material in the Marine Structures laboratory of National Institute of Technology Karnataka and found that by increasing the berm width the recession will decrease, and it is possible to reduce armour stone size by a wider berm width, for the same sea state. Archetti et al. (2002) considered the loss of stone volume due to abrasion of armor stones at Icelandic berm breakwater which might occur owing to stone movements. Sigurdarson et al. (2008) developed a formula for the recession of the Icelandic-type berm breakwater.

Lykke Andersen and Burcharth (2009) carried out an extensive two dimensional experimental research on the reshaped seaward profile of mass armored berm breakwaters with a homogeneous berm and presented a formula for calculation of the berm recession, including a number of parameters. Shekari and Shafieefar (2013) performed a comprehensive experimental research and proposed a formula for the berm recession estimation including some structural configurations. Later, they extended the ranges of parameters covered in the previous tests, and presented formulae for prediction of key parameters for a reshaped profile (Shafieefar and Shekari, 2014). Lykke Andersen et al. (2014) have recently developed a formula for the berm recession estimation based on the database from several laboratories and revealed that the proposed formula has a very large application area and provides less uncertainty to appraise the stability for partly and fully reshaping structures than other approaches.

A toe structure is commonly used to provide support to the armor units of conventional rubble mound breakwaters and to prevent the occurrence of scour of the sediment bed directly beneath the lower side of the seaward armor layer. A number of rubble mound breakwaters have been damaged due to insufficient stability of the toe structure. When mound breakwaters are built in shallow waters, the highest waves start breaking on the sea bottom and impact the toe berm directly, so that in this case the stone size needed for the toe structure may exceed the armor unit size (Hovestad, 2005). Several studies have been conducted based on laboratory modeling, resulting in formulae for predicting the damage of toe structures, e.g., Gerding (1993), Muttray (2013), Van Gent et al. (2014). By carrying out a series of physical tests, Ebbens (2009) has worked on the influence of all governing parameters for toe stability of conventional breakwaters, leading to a new formula for estimation of the damage caused to the toe structures.

Herrera and Medina (2015) conducted physical model tests with a steep bottom slope (m=1/10) to ascertain the influence of shallow waters and steep seafloors on toe berm stability of conventional breakwaters and concluded that most damage arises when the still water level (SWL) is close to the crest of the toe. Afterwards, Herrera et al. (2016) developed a new design method to reduce the rock size by increasing the toe berm width, introducing two new concepts to better describe the hydraulic stability of wide toe berms: the most shoreward toe structure area which effectively protects the armor cover, referred to as the primary toe berm and, the most seaward toe structure area (secondary toe berm) which safeguards the primary toe berm. Van Gent and Van der Werf (2014) considered rock toe stability by means of a set of experimental modeling to predict the required rock size in the toe structure and observed that the wave height and the water level considerably affect the amount of damage to the toe. Recently Celli et al. (2018) have worked on effects of submerged berms on the stability of conventional rubble mound breakwaters and proposed a design criterion able to describe the influence of relative low and long berms on the stability of such structures.

condition.

1.2. Motivation for present study

Reshaping berm breakwaters have been mainly designed and built for water depths less than 20m. In such conditions, toe structure may be needed to: 1) to increase stability of the armor layer against sliding and reduce bottom settlements in the loose subsoil, 2) to reduce wave impact on the armor layer by changing wave conditions and inducing wave breaking and 3) to reduce the recession and contribute to a more stable structure when water depth is deep. A toe berm in front of a RBB not only does have some influence on recession due to depth influence and changing wave conditions, but also, the toe depth may have a direct influence on the reshaped profile, more or less regardless of the wave height (Van der Meer and Sigurdarson, 2016), as indicated in Fig. 2. The idea is that the displaced rock can fall down along the lower slope which has an influence on the recession of the berm. One needs more recession to get a similar "S-profile" if the rock can be displaced to deeper parts. So it is expected that a relatively small toe depth may significantly reduce the recession and contribute to a more stable structure (Van der Meer and Sigurdarson, 2016).

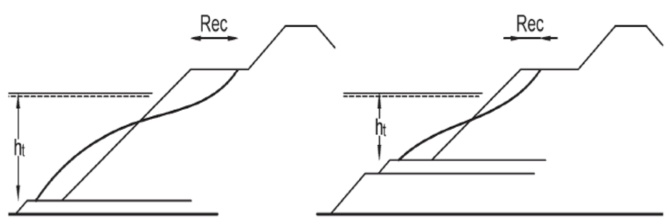

Fig. 2. The Influence of toe depth on recession for reshaping berm breakwaters, after Van der Meer and Sigurdarson (2016).

Although many studies have been conducted to study effects of toe berms on stability of conventional breakwaters, investigation on influence of toe berm on stability of RBBs is rare. To the best of the authors' knowledge only Moghim et al. (2009), have carried out a limited experimental test series for the cases with and without underwater berm section (secondary berm in addition to the main berm) to compare berm recession for these cases in deep water. They observed that the recession for the case with an underwater berm is lower than that without an underwater berm. They stated two reasons for the recession reduction. Firstly, it is due to wave breaking on underwater berm further away from the structure resulting berm dissipation and secondly, the displaced stones could be trapped on the underwater berm after reshaping.

Even though the stability number is the most significant parameter to describe the recession of RBBs, there are other parameters that influence berm recession. The geometrical parameters that may influence berm recession are: berm width (B_b), berm level (d_b), lower slope angle (cotα,), toe width (B_t) and toe depth (h_t). The influence of the main berm width and berm level, have been already investigated by several researchers, e.g., Lykke Andersen and Burcharth (2009), Shekari and Shafieefar (2013, 2014). The objective of present research is to examine the influence of the toe width (B_t) and toe depth (h_t) on the hydraulic stability of RBBs. The design of the berm itself is not considered herein. It should be noted that although sorting and porosity of the toe berm might have a certain influence on the stability of a RBB, the present study does not account for them.

1.3. Outline

The present paper presents results of an experimental work that has been carried out to investigate the influence of toe berm on stability of RBBs. Establishing a 2D physical tests in a wave flume, a total of 207 tests were conducted to systematically scrutinize the influence of toe berm width and height on the reshaping of berm breakwaters with three types of armor stones. The experimental program covers the influence of different geometrical parameters of the toe berm on berm recession under various sea state conditions. In this paper, the experimental setup is described in Section 2. Tests with different toe berm sizes and widths are analyzed in Section 3. A new formula is proposed to appraise the toe berm influence on hydraulic stability of RBBs in section 4. Section 5 describes the effectiveness of the toe berm on reduction of berm recession by comparing with calculated values using given formulas in the literature. Finally, conclusions are drawn in Section 6.

2. Laboratory set-up and model tests

Tests were carried out in a wave flume at the Hydraulic Engineering Laboratory of Tarbiat Modares University. The flume is 16 m long, 1 meter wide and 1 meter deep with glass panels all across the length for easier observations. The flume is equipped with a piston-type wavemaker that has the ability to generate regular and irregular waves. Fig. 3 exhibits a lateral view of the set-up with the position of the wave gauges employed in the present research while Fig. 4 presents the tested initial section of the RBB with toe berm which was built at the end of the flume; pink points correspond to the (secondary) toe berm. Irregular waves were generated in all tests with JONSWAP spectrum using a peak enhancement factor γ=3.3. The structure slope cot (α) =1.25 in all of the conducted tests.

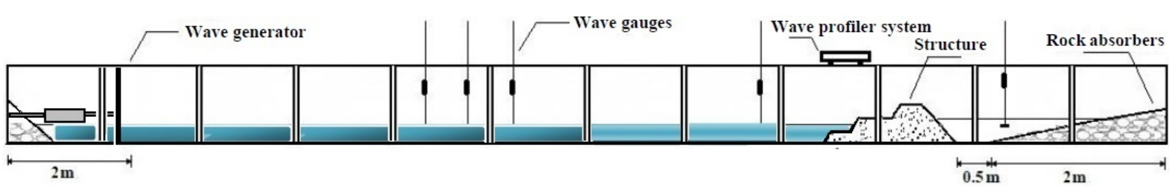

Fig. 3. Longitudinal cross section of the Laboratory set-up.

The water level fluctuations were recorded with four wave gauges located along the channel, between breakwater and wavemaker (Fig. 3). The recorded water level time series were separated to incident and reflected waves using Mansard and Funke method (1980). An active reflection absorption system is important in scale modeling especially when reflection from the structure is high. The range of reflection coefficient was 0.13 to 0.24 in the present research. Even though the reflection coefficient is smaller than for a traditional rubble mound breakwater, however, there still remains a re-reflected phenomena that can affect the results in the present paper.
Using the carriage of the structure profiler system by a trolley along the wave flume, the initial and reshaped profiles of the structure were recorded by a vertical point gauge in all experiments. To ensure the accuracy of profiling, initial and reshaped profiles were

measured along three lines, so that one profiling line was in the middle of the structure and the other crosswise lines were aligned with 20 cm distance from the central one. After each experiment, the reshaped profile was gauged in a spacing of 1 cm along the profiling line. To analyze the reshaped profile key points, the average of three profiles is used. Moreover, some conventional overlay photographs have been used for tracking the ultimate recessions and stereo photography for an instantaneous appraisement and confirmation of the obtained recession values.

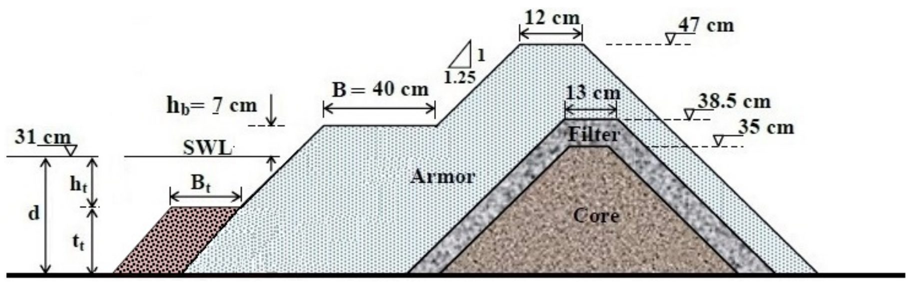

Fig. 4. Configuration of the berm breakwater model.

Three different stone sizes were used for the armor layer in order to obtain more insight on the toe structure influence on the amount of erosion and stability of the RBBs. However, the stone size of toe structure was constant in all tests, but the size was selected so that the toe structure did not reshape during all tests. Table 1 illustrates the properties of the materials related to different armor and toe berm layers, and Fig. 5 exposes their grain size distribution curves.

Table 1 Material properties

	Armor 1	Armor 2	Armor 3	Toe berm	Filter layer	Core
Mass density ρ_s (kg/m^3)	2670	2680	2700	2670	2800	2650
W_{n50} (kg)	0.012	0.029	0.049	0.012	0.0014	
D_{n50} (cm)	1.65	2.21	2.63	1.65	0.70	0.4
$f_g = D_{n85}/D_{n15}$	1.50	1.50	1.45	1.49	1.33	1.33

The governing parameters together with the possible range of usage are revealed in Table 2. The berm level h_b, and toe depth h_t are defined with respect to the still water level. The experimental model was reconstructed for each experiment.

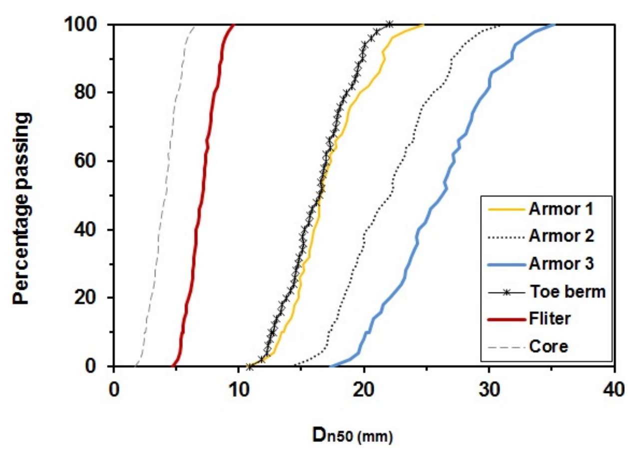

Fig. 5. Gradation curves of materials used in the experiment.

Table 2 Range of parameters considered in this study.

Parameter	Expression	Range
Wave height at toe of structure (m)	H_{m0}	0.06 to 0.12
Spectral peak wave period (s)	T_p	1 to 1.54
Berm width (m)	B_b	0.40
Number of waves per test	N	500-3000
berm elevation above still water level (m)	h_b	0.07
Water depth (m)	d	0.22 to 0.31
Toe width (m)	B_t	0.30 to 0.50
Toe height (m)	t_t	0.04 to 0.10
Toe depth (m)	$h_t = d - t_t$	0.14 to 0.20

Table 3. Range of non-dimensional wave parameters.

Parameter	Expression	Range of parameter
Mean wave steepness	$S_{om} = \frac{2\pi H_{m0}}{g T_p^2}$	0.017 to 0.076
Stability Number	$H_0 = \frac{H_{m0}}{\Delta D_{n50}}$	1.43 to 4.31
Wave period index	$T_0 = T_p \sqrt{\frac{g}{D_{n50}}}$	19.31 to 37.55
Period Stability Number	$H_0 T_0 = \frac{H_{mo}}{\Delta D_{n50}} \times T_p \sqrt{\frac{g}{D_{n50}}}$	27.86 to 162.16
Reynolds number ($\times 10^4$)	$Re_D = \frac{\sqrt{g.H_{mo}}}{\nu} .D_{n50}$	Armor 1: 1.26 to 1.79, Armor 2: 1.69 to 2.40, Armor 3: 2.02 to 2.85

where D_{n50} is armor material nominal diameter, g is ground acceleration and ν is the kinematic viscosity, $\Delta = \rho_s/\rho_w - 1$ relative density, ρ_s is mass density of armor unit, ρ_w is mass density of water, and T_p is a spectral peak wave period.

Table 4. Range of non-dimensional structural parameters.

Parameter	Expression	Range of parameter
Front slope	$cot\,(\alpha)$	1.25
Relative main berm width	B/H_{m0}	2.75 to 4.85
Relative toe width	B_t/L_{op}	0.08 to 0.32
Relative toe depth	h_t/H_{m0}	1.5 to 3.75
Relative toe depth	h_t/d	0.63 to 0.86

The Reynolds number for armor stones (Re_D) is used to assess viscous scale effects.

Scale effects related to armour stability have been studied experimentally by many researchers, i.e. Lykke Anderson (2006) and Van der Meer (1988). Lykke Anderson (2006) worked on viscous scale effect in model testing of berm breakwaters and recommended Re>30,000 to neglect scale effects. Lykke Andersen et al. (2014) have adopted $Re<10^4$ to disregard the test cases due to possible scale effects. According to the Van der Meer (1988), the Reynolds number should be larger than 1 to 4×10^4 to minimize the scale effect on armor stability. Therefore, if Reynolds number is larger than 10000 the viscous scale effect is small. The lowest Reynolds number value for the present tests with the lowest wave height is ($Re > 1.25 \times 10^4$), cf. Table 3. Thus, the viscous scale effect on results of present study is not significant.

3. Data analysis and discussion

To assess the influence of a toe berm on berm recession and to determine the sensitivity of reshaping process to such a structure, the following variables are examined:

- Wave height and period (H_{m0}, T_p),
- Toe Width (B_t),
- Toe depth (h_t),
- Water depth in front of the toe *(d)*,
- Armor stone size (D_{n50}) and number of waves (N).

Nevertheless, there are other important parameters that have influence on berm recession including the berm width B_b, the berm elevation due to still water level, h_b, front slope, $\cot(\alpha)$ well as the stone gradation factor (obtained via gradation curve), $f_g = D_{n85}/D_{n15}$.
The approach of Lykke-Anderson is used to evaluate the influence of various parameters on berm recession. This approach has already been used by Moghim et al. (2009) and Shafieefar and Shekari (2014). Based on this approach, the dimensionless recession is assumed to be function of a stability index (H_0, T_0), the main berm configuration (B_b and h_b), the toe berm configuration (B_t, h_t), number of waves (N), water depth and the stone gradation (f_g). Thus, a product of 8 functions could be used:

$$\frac{Rec}{D_{n50}} = f(H_0,T_0,B_b,h_b,B_t,h_t,N,d,f_g) = f_{H_0}(H_0,T_0).f(B_b).f(h_b).f_{B_t}(B_t).f_{h_t}(h_t).f_N(N).f_d(d).f_g \quad (1)$$

where f_{H0} accounts for the influence of the stability index (H_0,T_0), f_N accounts for the number of waves, f_g for the stone gradation factor, f_{Bt} for the toe Width, f_{ht} for the toe depth and water f_d for the water depth. Since parameters related to the main berm (B_b and h_b) and stone grading were not changed in the present tests, their influences are not considered in this paper. Therefore, a product of 5 parameters is studied:

$$\frac{Rec}{D_{n50}} = f(H_0,T_0,B_t,h_t,N,d) = f_{H_0}(H_0,T_0).f_{B_t}(B_t).f_{h_t}(h_t).f_N(N).f_d(d) \quad (2)$$

In this section, observations from the experiments are presented first by considering effects of different parameters on berm recession. Afterwards, it is assessed to quantify the function of each parameter on berm recession (*Rec*), as the main parameter for profile schematization.

3.1 Influence of wave height and wave period

Fig. 6 reveals the reshaped profile of the structure for five different wave heights (H_{m0} = 6.45, 7.45, 8.85, 10.45 and 11.85 cm) with a 1.0 second peak period and after 1500 waves.

Also, reshaped profiles of the structure with and without a toe berm are shown in Fig. 7 for three different stability numbers. The width and height of the toe berm was identical in these test cases. Comparing the reshaped profiles of the cases with and without toe berm shows that the recession is reduced considerably by applying the toe berm. The influence of the toe berm on reduction of recession is larger for higher stability numbers. Also, these figures reveal that the location intersection point, i.e. the point where the reshaped profile intersects the initial profile of intersection point is almost constant for all wave heights for tests with a toe berm; but moves up due to usage of toe berm. Comparing the depth of intersection for cases with and without toe berm indicates that the intersection point moves up by 6.3% for tests with Armor 1; 3.8% with Armor 2; and 12.1% with Armor 3. Also, comparative results show that the consecutive berm recessions are significantly reduced due to toe berm influence, especially under longer wave period and higher wave conditions, i.e., a reduction of about 51% is seen for berm recession value, H_{m0} = 11.85 cm and T_p = 1.54 s.

Results show that the recession of the main berm is reduced considerably by adding a relatively small toe berm; denoting that the toe structure increases the armor stability, see Fig 7. Comparing the eroded areas of the reshaped profiles for cases having a toe berm with ones without a toe berm indicates that the difference between the eroded areas is comparable to the toe berm area for H_0>3, i.e. for dynamically stable berm breakwaters.

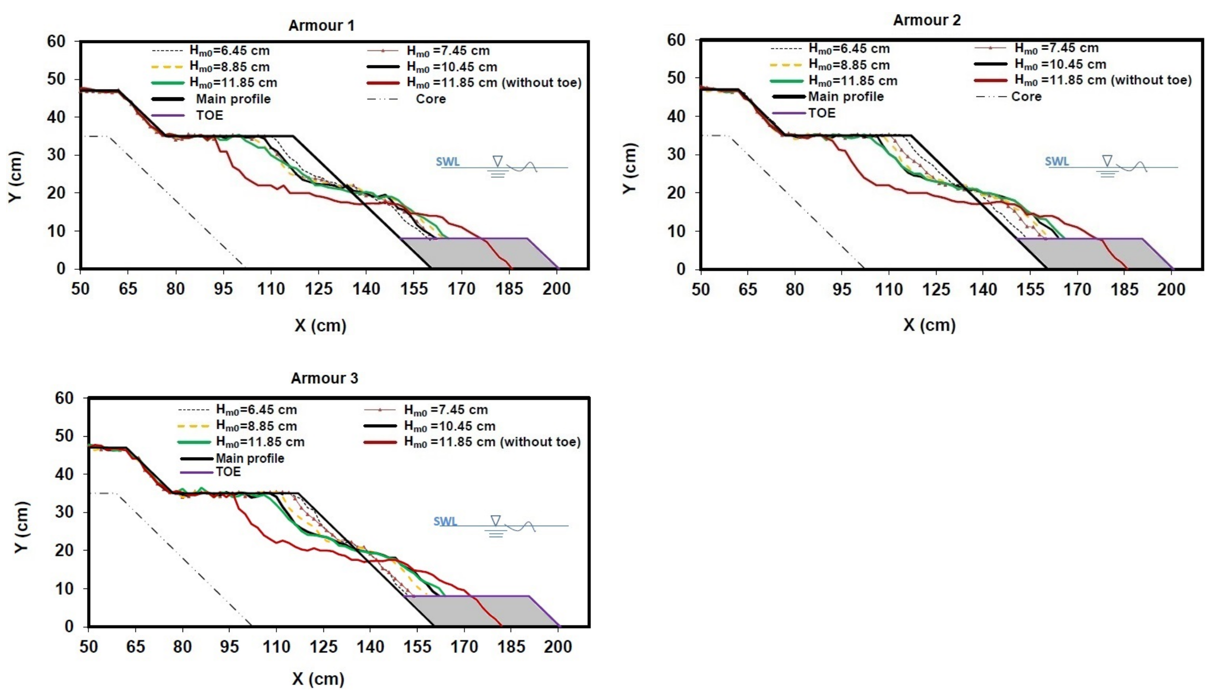

Fig. 6. Toe berm influence on berm recession for various wave heights (d=28cm, B_t=40 cm, t_t=8 cm).

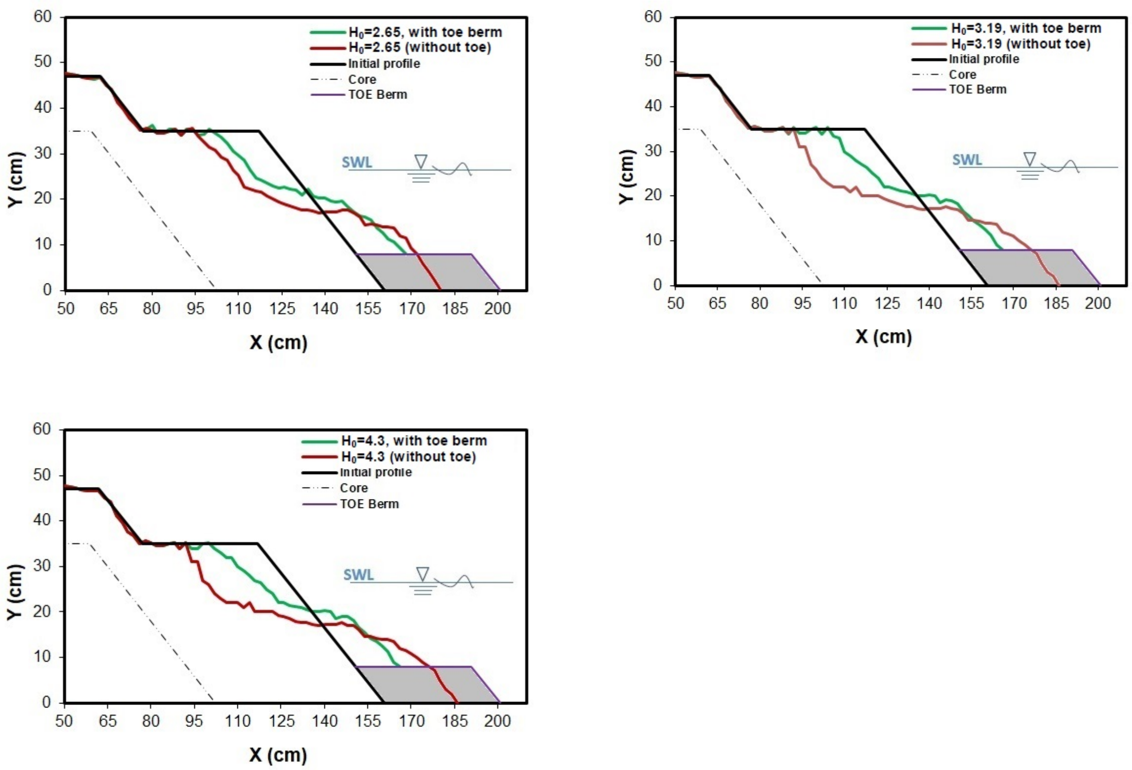

Fig. 7. Reshaped profiles of the structure with and without a toe berm for different stability numbers; d=28cm, B_t=40 cm, t_t=8 cm.

Fig. 8 exhibits the evolution of the observed berm recession depending on the wave height and wave period for tests with d = 28 cm and N=3000. According to this figure, the berm recession is increased by increasing wave period for a constant wave height for both cases with and without toe berm. Therefore, it seems a stability number which includes non-dimensional wave period is more appropriate for describing berm recession; e.g. H_0T_0 or $H_0\sqrt{T_0}$.

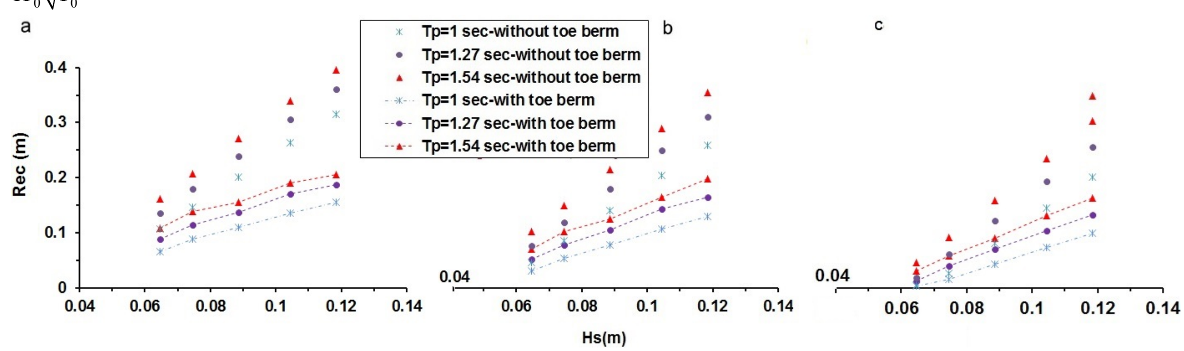

Fig. 8. Variation of berm recession versus wave height considering different armors. a) Armor 1 b) Armor 2 c) Armor 3.

Fig. 9 reveals the trend analysis of the observed dimensionless berm recession for a wide interval of stability numbers ranging from stable to dynamically stable structures. Even though the scatter between data for the stability number irrespective of wave period influence, i.e. H_0, is not too much, there is some great scatter and bias remaining. It can be noticed that, for different wave height and armor stone size combinations with the same T_0 value, the amount of recession is higher for a higher wave height.

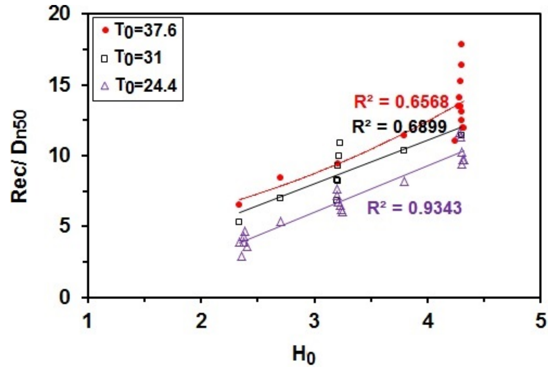

Fig. 9. Influence of H_0 on dimensionless berm recession.

Variations of berm recession of toed berm breakwater versus different stability numbers for all tests are illustrated in Fig. 10, regardless of considering influences of other parameters. One can see that stability numbers including wave period show better correlations.

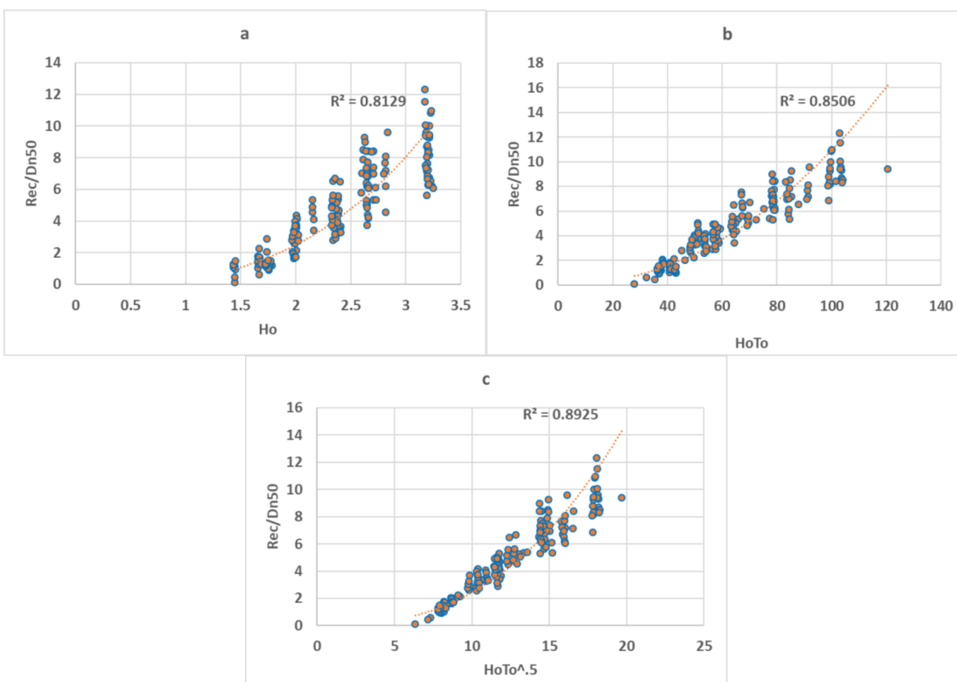

Fig. 10. Variation of berm recssion versus various stability indices for all tests.

3.2 Influences of toe width

In order to investigate the effects of geometrical parameters of the toe berm, a number of tests were carried out by varying width and height of the toe berm. In this regard, five toe berm widths (B_t = 0.3, 0.35, 0.4, 0.45 and 0.5 m) were applied with different wave combinations. The range of relative berm width was $0.08 < Bt/Lp < 0.32$. The height of the toe berm was kept constant at 8 cm, and thus the relative toe depth was h_t/d=0.714 for this test series, cf. Table 4.

It is accepted that the water depth above the toe could be used as water depth if the toe is wide enough to support the entire reshaped profile. This procedure is probably valid unless the toe is very high. If the toe is not wide enough to support the entire profile, then one can use a value for h between the water depth above the toe and the water depth without the toe, according to Lykke Andersen and Burcharth (2009) and Sigurdarson and Van der Meer (2016). In the present study, the toe was wide enough to support the entire reshaped profile for all tests.

Fig. 11 exposes the process of berm erosion due to the toe width effect for three different stability numbers which are related to statically stable and dynamically stable reshaped berm breakwaters. Here berm erosion means the armor erosion; however owing to incident waves the toe berm partly reshapes. It is observed that an increasing toe berm width has an influence on the recession reduction. However, the influence is larger for higher stability numbers.

Fig. 12 reveals the dimensionless recession versus stability number for different berm widths with constant wave length L_{op}=1.56 m. It is observed that an increasing toe width has no considerable influence on berm recession for lower stability numbers, (H_0<2.7). However, decreasing the berm width from the mean value of B_t=0.4 m to B_t=0.3 m results in increasing the recession by 13%. A better assessment concerning toe berm influence can be attained from Fig. 13 where the variation of berm recession is plotted versus dimensionless toe berm width (B_t/H_{m0}) for different stability numbers. It is perceived that the berm recession is decreased by increasing B_t/H_{m0} for a constant stability number. However, the rate of decrease is larger for higher stability numbers. It can be concluded that beside the influence of toe berm by preventing the displaced rock to fall down along the lower slope, the toe width has an additional reducing influence as a result of changing wave conditions, especially for higher stability numbers (H_0>3).

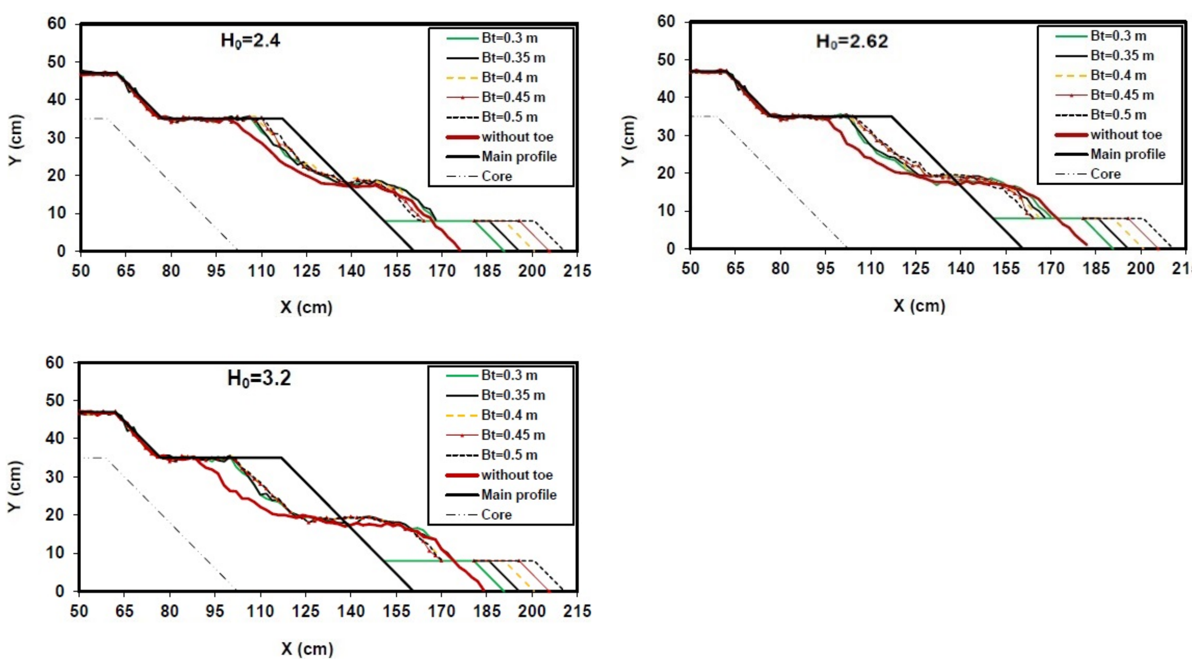

Fig. 11. Influence of toe width on berm recession for different stability numbers.

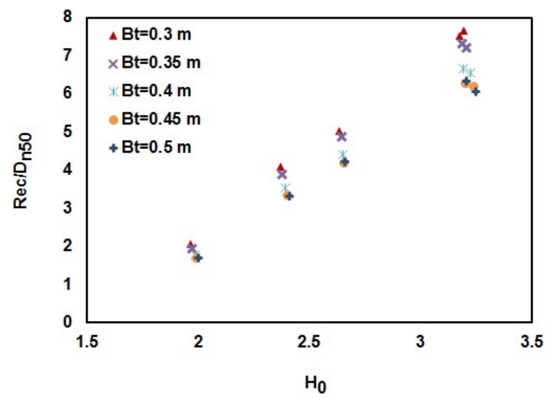

Fig. 12. Dimensionless armor recession versus stability number for different toe widths; L_{op}=1.56 m.

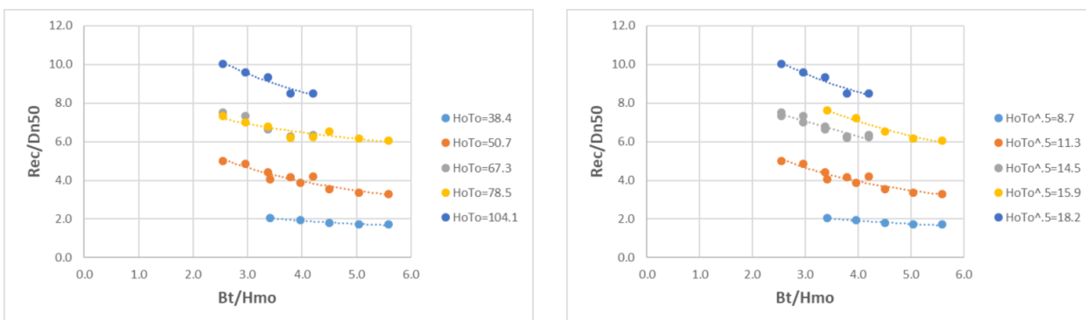

Fig. 13. Variation of berm recession versus B_t/H_{m0} for different stability numbers.

To formulate the influence of toe width on berm recession, several dimensionless parameters were scrutinized and different algebraic functions were examined. Results revealed that a power function is preferable as:

$$\frac{Rec}{D_{n50}} = a\,(1+\frac{B_t}{H_{mo}})^b \qquad (3)$$

Fig. 14 represents variation of coefficients *a* and *b* in Eq. (6) versus stability numbers H_0T_0 and $H_0\sqrt{T_0}$ according the present dataset. It is perceived from the figure that there are small differences in the coefficient *b* for different wave combinations; which may be related to the experimental scatter. In order to unify the values for this coefficient, the mean value is calculated, i.e. $b = -0.1$. The value of *a* is a function of the sea state conditions, i.e. wave characteristics. So, the influence of toe width can be appraised by inserting the value for *b* into Eq. (6), given by:

$$\frac{Rec}{D_{n50}} = a\,(1+\frac{B_t}{H_{mo}})^{-0.1} \qquad (4)$$

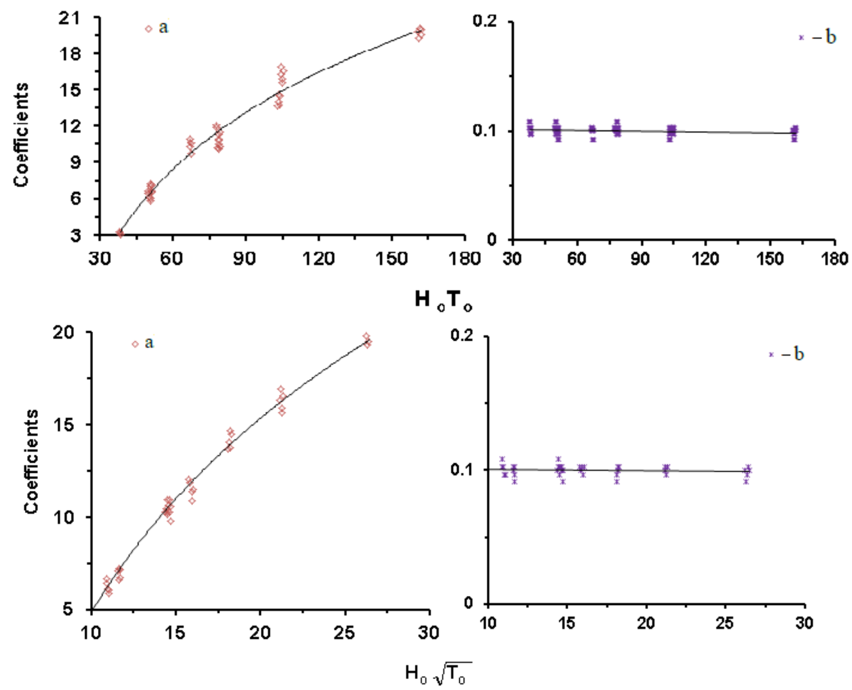

Fig. 14. Variation of coefficients a and b versus H_0T_0 and $H_0\sqrt{T_0}$.

3.3 Influences of toe depth

The influence of toe depth, h_t, on berm recession was examined by conducting a number of tests with varying toe depth and wave conditions while the toe width was reserved constant. Fig. 15 presents the reshaped profiles of the structure for different berm thicknesses and 3 stability numbers. Fig. 16 reveals the dimensionless recession versus relative toe depth (h_t/d). It is observed that the recession is increased by decreasing h_t/d value for all stability numbers. However, the influence of toe depth is larger for higher stability numbers. The reason is that in higher toe thickness –analogue to lower h_t/d- the toe berm contributes to changing the wave condition and increasing energy dissipation.

Dependence of the berm recession on h_t/H_{m0} is shown in Fig. 17 for three different stability numbers. The figure reveals that the berm recession is decreased by decreasing h_t/H_{m0} for all stability numbers. Comparing the recession values for test cases with $h_t/H_{m0} \simeq 1.5$ and $h_t/H_{m0} \simeq 2.0$ shows that the recession is reduced by 32% for all stability numbers. This means that when $h_t=1.5H_{m0}$, the recession is 32% lower than when $h_t=2\ H_{m0}$.

Overall, a comparison between the influences of the toe berm and the toe depth indicates that the toe depth has relatively more influence on recession than the toe width. Here, the toe berm has an additional effect due to changing the wave condition and wave energy dissipation, besides the function of preventing the displaced rock to fall down along the lower slope. Therefore, it is noticed that the influence of the toe depends on the configuration of the toe (i.e. its width, B_t, and height, h_t), as well as on the water depth (d) and on the incident wave length (L_{op}):

$$F_B = F_{Bt} + F_{ht} = f(B_t, h_t, d, L_p) \qquad (5)$$

Since the influence of B_t is taken into account by Eq. 5, the influence of h_t can be related to other parameters as:

$$F_{ht} = f(h_t, d, L_p) \qquad (6)$$

Thus, two dimensionless parameters of h_t/d and ht/L_{op} should be considered to formulate the influence of toe depth.

$$F_{ht} = f(\frac{h_t}{d}, \frac{h_t}{L_p}) \tag{7}$$

Even though h_t/L_{op} could be a relevant dimensionless parameter, the range of this parameter is only 0.05 to 0.15 in the present work. Thus, it is not taken into account for the formulation of the toe depth influence herein.

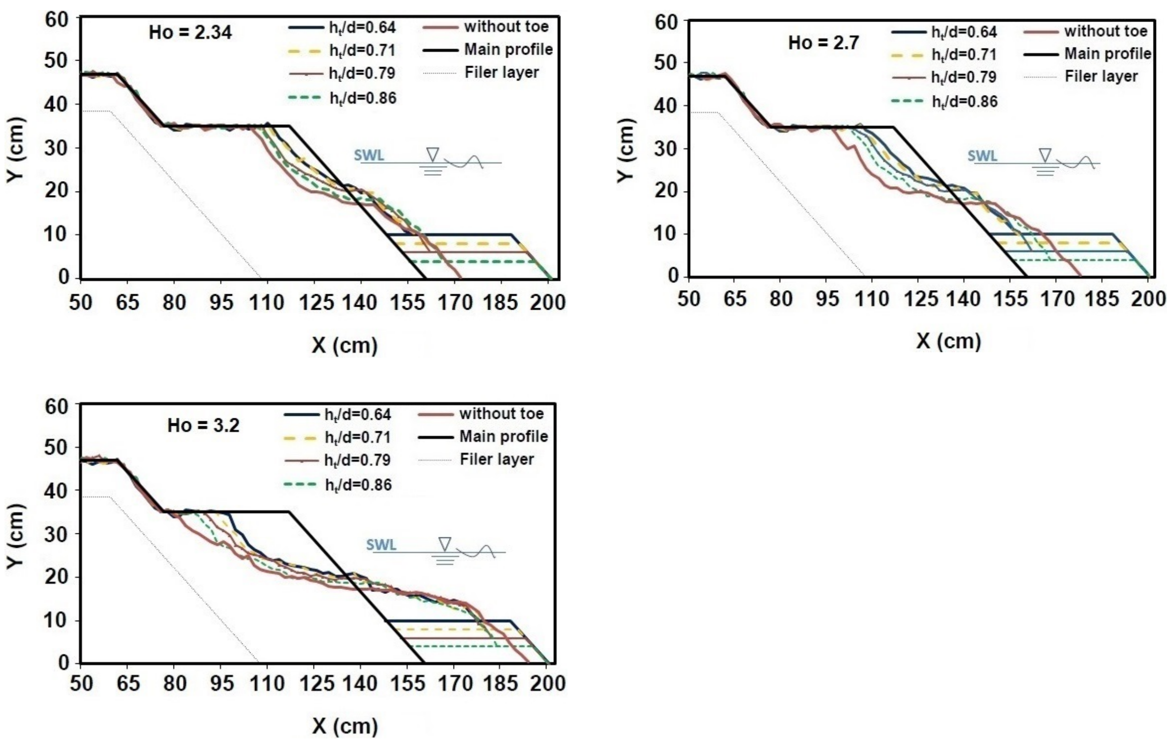

Fig. 15. Influence of toe depth on berm recession for different stability numbers.

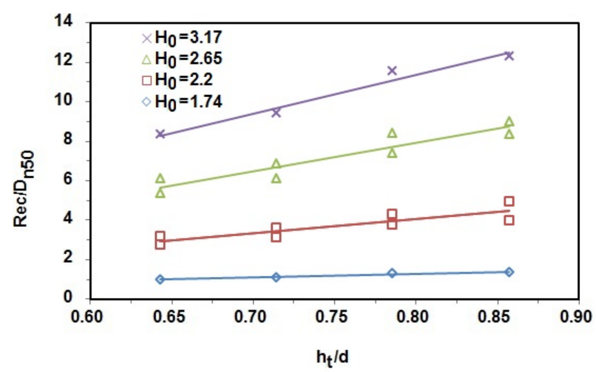

Fig. 16. Dimensionless recession versus relative toe depth (h_t/d) for different stability numbers.

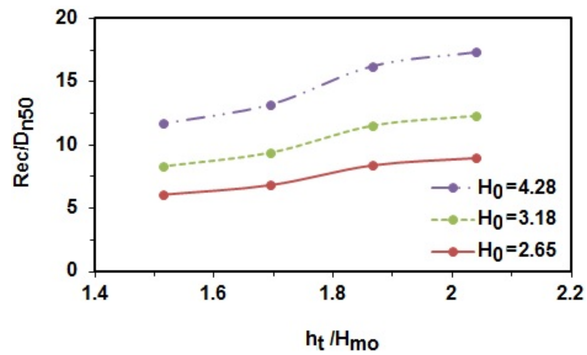

Fig. 17. Relative recession versus h_t/H_{m0} for different stability numbers; L_{op}=1.56 m.

According to the general trend of berm recession for different stability numbers, it is found that the relation between the relative recession and the relative toe depth is linear, i.e. the berm recession is reduced by decreasing the toe depth, see Fig. 16. This is due to the fact that when the toe depth is decreased (or the toe height increased), the S form reshaping profile is developed near the surface water level, and thus, the volume of displaced stones is decreased.

Results reveal that the influence function of toe depth can be written as:

$$F_{ht} = c\left(\frac{h_t}{d}\right) \qquad (8)$$

where c is a function of stability numbers. Its value will be determined in Section 4.

3.4 Number of waves (storm duration)

A series of tests were carried out to examine the storm duration influence on reshaping and berm recession development. Experimental observations indicate that more than 90% of ultimate reshaping profile takes place before N=1500, see Fig. 18. The variation of dimensionless berm recession (Rec/D_{n50}) versus number of waves (N/1500) is illustrated in Fig. 18 for different combinations of wave heights and periods.

The influence of the number of waves on profile development differs from statically stable slopes. Van der Meer (1988, 1992) found that the reshaped profile parameters are proportional to $F_N = N^b$, (where b varies from 0.05 to 0.15) in case of conventional rubble mound breakwaters. Shafieefar and Shekari (2014) worked RBBs and achieved that the influence of the number of waves (N) is relatively small for N larger than 3000, which could be expressed as:

$$F_N = 1.72 - \exp\left[-2.19\left(\frac{N}{3000}\right)\right] \qquad (9)$$

According to the trends in Fig. 19, it is distinguished that a power function is a good delineation of the reshaping of the structure during a storm for all combinations of conditions, which can be written as:

$$F_N = e\left(\frac{N}{1500}\right)^f \qquad (10)$$

According to equations of trend lines in Fig. 19, e is a function of various wave states, while the values of f is approximately independent of wave conditions having an average value of 0.264 and standard deviation of 0.005. So, the influence of N is evaluated by inserting the value for f into Eq. (10), given by:

$$F_N = e\left(\frac{N}{1500}\right)^{0.264} \tag{11}$$

where e is a dependent variable and is a function of $H_0\sqrt{T_0}$. Its value will be determined in Section 4.

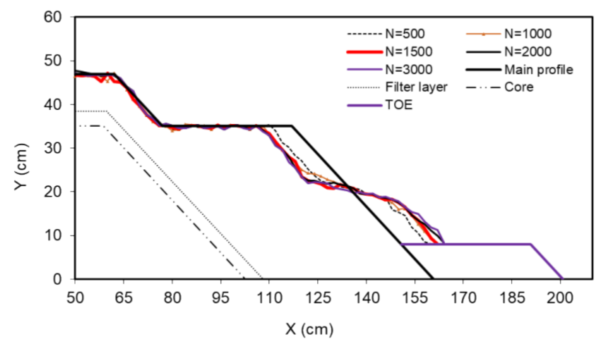

Fig. 18. Comparison of reshaped profiles due to number of waves

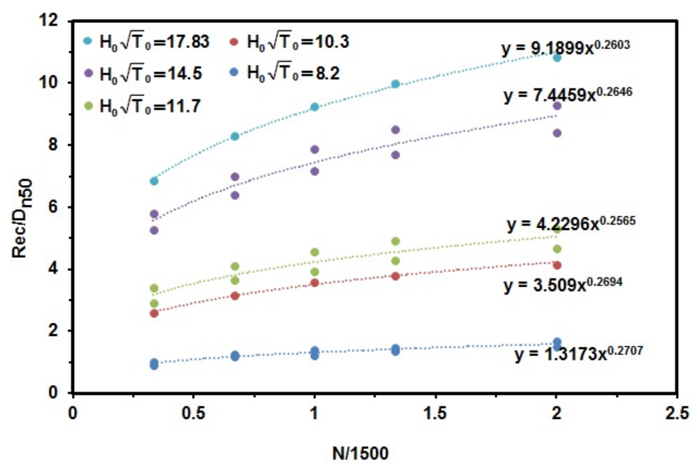

Fig. 19. Variation of dimensionless berm recession (Rec/D_{n50}) versus number of waves (N/1500).

3.5 Water depth in front of the toe

Tests with four different water levels in front of the toe structure (d = 22, 25, 28 and 31 cm) were conducted to examine water depth influence. It should be noted that the berm elevation above the bottom of the structure, i.e. $d+h_b$ was changed to maintain a constant berm elevation h_b. Fig. 20 reveals the change of erosion of a RBB having a toe berm due to water level variations, for a wave height H_{m0}=10.45 cm and peak period T_p=1.27 s (red indicates the low water depth and black the high water depth). It is noticeable that the water depth affects the erosion and berm recession. In fact, increasing water depth leads to higher wave momentum flux and less wave energy dissipation, thus resulting in more recession of the berm. However, it should be noted that the relative toe depth h_t/d varies by varying the water depth. So, both the water depth and toe depth have contribution in reshaping process in this series of tests. Since the influence of the relative toe berm depth is dominant, the influence of water depth is not taken into consideration separately in this paper.

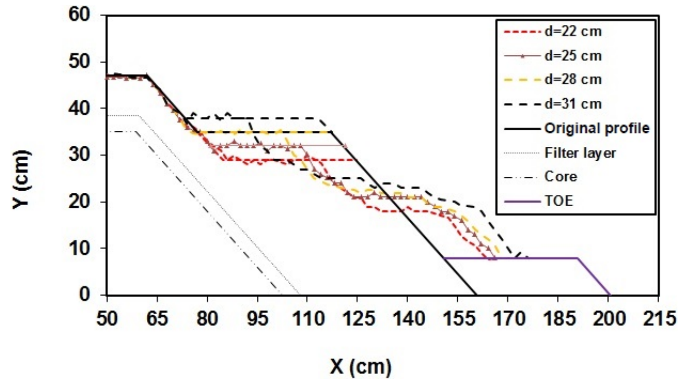

Fig. 20. Comparing of reshaped profiles due to various water depth (H_{m0} = 11.85 cm, T_p=1.54 s, D_{n50}=2.62 cm).

4. Proposed formula to appraise the toe berm role for the RBB stability

The approach of Lykke Andersen and Burcharth (2009) is used to gain a proper recession formula based on different wave combinations, armor stone sizes and toe berm configurations by combining the relevant functions given in the previous section as:

$$\frac{\mathrm{Re}c}{D_{n50}} = f(H_0,T_0).\left[\ \left(\frac{N}{1500}\right)^{0.264}.\left(1+\frac{B_t}{H_{so}}\right)^{-0.1}.\left(\frac{h_t}{d}\right)\ \right] \tag{12}$$

In fact, the coefficients a, c and e are substituted by the dimensionless function of $f\,(H_0, T_0)$. The value of this function is appraised by using Eq. (13):

$$f\,(H_0,T_0) = \left(\frac{\mathrm{Re}c}{D_{n50}}\right) \Big/ \left\{\left(\frac{N}{1500}\right)^{0.264}.\left(1+\frac{B_t}{H_{mo}}\right)^{-0.1}.\left(\frac{h_t}{d}\right)\right\} \tag{13}$$

Lykke Andersen and Burcharth (2009) observed that the period may have less influence than given by the H_0T_0 parameter for stability number H_0<3.5, and the berm recession is found to be proportional to $s_{om}^{-0.5}$ instead of applying the combined effect of sea state (i.e. wave height/period) and armor stone diameter.

In order to achieve an appropriate function for $f(H_0,T_0)$, right hand side of the above equation is computed for each data set and the obtained values are traced against the corresponding stability number $H_0\sqrt{T_0}$, as revealed in Fig. 21. Curve fitting to the present experimental data led to the following expression for estimating $f\,(H_0, T_0)$:

$$f\,(H_0,T_0) = -0.0173.(H_0\sqrt{T_0})^2 + 1.72.H_0\sqrt{T_0} - 10.5 \tag{14}$$

Ultimately, an accumulation of the achieved functions for the influence of parameters can be obtained as follows:

$$\frac{\mathrm{Re}c}{D_{n50}} = \left[-0.0173.(\mathrm{H}_0\sqrt{T_0})^2 + 1.72.\mathrm{H}_0\sqrt{T_0} - 10.5\right].\left(\frac{N}{1500}\right)^{0.265}.\left(1+\frac{B_t}{H_{mo}}\right)^{-0.1}.\left(\frac{h_t}{d}\right) \tag{15}$$

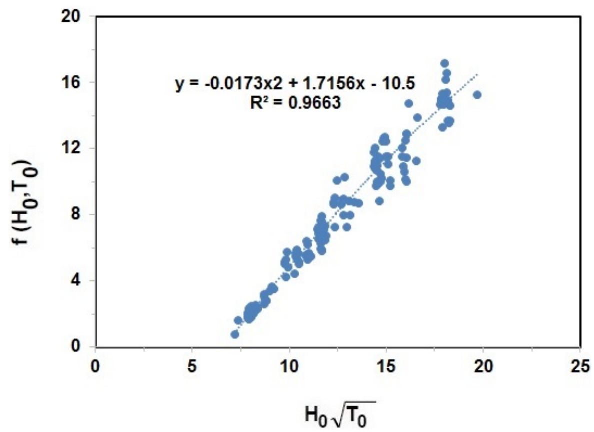

Fig. 21. Variation of $f\,(H_0, T_0)$ vs. $H_0\sqrt{T_0}$ using present experimental data.

Eq. (15) is valid for the toe berms with $2.54<B_t/H_{m0}<6.24$, $0.64<h_t/d<0.86$ exposed to sea state in the range $1.5<H_0<3.25$ and $6.33 < H_0\sqrt{T_0} < 19.7$.

Fig. 22 compares the measured dimensionless berm recessions and that estimated by Eq. (15). It is observed that there is a moderately good agreement between the predicted recession and the experimental data and deviations are somewhat minor.

The efficiency of the present estimation model is appraised using square of the correlation factor (R^2) and the average error (E) as:

$$R^2 = \left(\frac{N\sum XY - (\sum X)(\sum Y)}{\sqrt{[N\sum X^2 - (\sum X)^2][N\sum Y^2 - (\sum Y)^2]}} \right)^2 \qquad (16a)$$

$$E = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{Y-X}{Y}\right| \qquad (16b)$$

in which N is the total number of realizations, X is the calculated value and Y is the measured data. The square of the correlation factor between measured and corresponding predicted berm recession is R^2= 96.6%, and the average error is about 0.363, revealing a reliable regression.

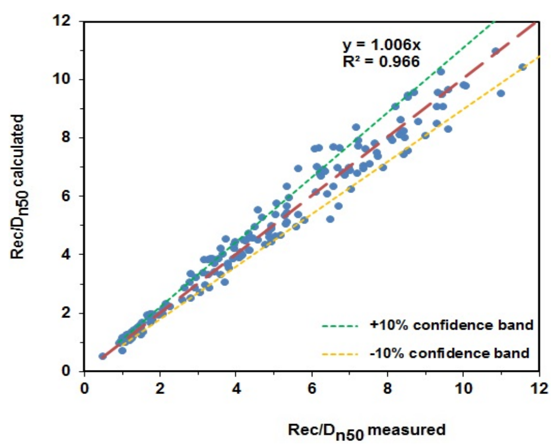

Fig. 22. Comparing the measured recession with that calculated by Eq. (15).

5. Evaluation of toe berm efficiency

The toe influence on berm recession is not included in the existing formulae proposed by Tørum et al. (1999), Lykke Andersen and Burcharth (2009), Moghim et al. (2011), Shafieefar and Shekari (2014), Hall and Kao (1991) and Lykke Andersen et al. (2014). Nevertheless, the recessions calculated by these formulae are compared with the measured recession of the database, see Fig. 23. Here, the black line exposes the general trend of whole data of other works while the red line belongs to present work. As discussed in previous section, the toe structure configuration has considerable influence on the reshaping profile of RBBs resulting from the product of the toe widths function (f_{bt}) and toe depth function (f_{ht}), i.e. $f_{toe} = f_{bt} \cdot f_{ht}$. Results show that 0.81< f_{bt} <0.92, 0.63< f_{ht} <0.86, and 0.54< f_{toe} <0.75 within the parameters range used in the present study.

The overall trends in Fig. 23 illustrate that the berm recession is reduced considerably due to toe berm influence especially for dynamically stable profiles. It is considered that the measured recessions are typically less than those predicted by formulas given by others. Even though, the other formulae give relatively similar results in many cases, however, a little discrepancy for the Tørum formula is comparatively observed which may be because of the typical limited ranges of parameters, i.e. only 30% of the data are within the intervals. A quantitative analysis according to these two trend lines shows that, toe structure reduces the berm recession up to 25% for *H0T0* =160 and it is about 22% for *H0T0*=90.

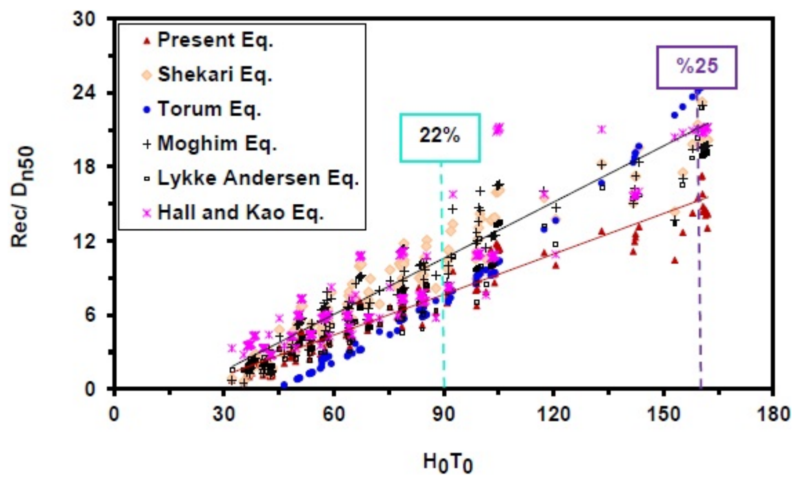

Fig. 23. Comparison of predicted berm recession and those obtained by other researchers' formulae in absence of toe berm.

Based on above-mentioned results, designers can consider implementing a toe berm with appropriate structural configuration to reduce the berm recession and improve the breakwater stability. Also, it will allow changing the armor stone diameter and/or breakwater geometry in order to accomplish an optimum design. An example for this process is schemed in Fig. 24, in which the required nominal diameter of armor rock has been plotted together with the recession computed by the method of Shafieefar and Shekari (2014) for toeless berm breakwater and the recession calculated by the present prediction formula; black hollow points correspond to a wider toe berm, green bold points to a narrow toe berm and red bold points to a toeless configuration. An example of such a plot is presented in Fig. 24 for two different toe berm configurations. In this analysis the wave

height is H_{m0}=10 cm, the wave period is T_p = 1.26s, the water depth at the toe berm is d = 37.5 cm, the toe berm widths are B_t = 30 and 40 cm, the toe berm thicknesses are t_t = 6 and 10 cm, and the relative mass density of stones is 1.68 g/cm3.
The figure illustrates that the effect of toe berm on the design of armor units is significant so that relatively smaller armor stones can be used to retain the stability of the trunk by deploying a toe berm comparing to the case without toe berm. The graph emphasizes that also considering a berm recession *Rec* = 15 cm, the required stone size for a berm breakwaters with a small toe berm and with a wide toe berm is respectively 11% and 18% less than that of the traditional structure; while for *Rec* = 20 cm the corresponding reduction is by 16% and 27%, respectively.

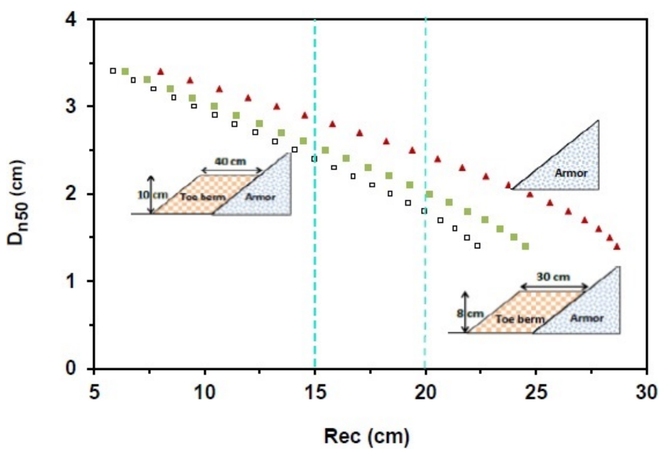

Fig. 24. Quantification of toe berm influence on berm recession.

6. Conclusions

This paper presents results of an experimental work that has been carried out to investigate the influence of toe berm on hydraulic stability of RBBs. The aim is to provide a new design criterion for reshaping mass toed berm breakwaters with a wide range of toe thicknesses and depths, i.e. $2.54<B_t/H_{m0}<6.24$ and $0.14<t_t/d<0.36$ compared to breakwater configurations. A comprehensive experimental study has been performed in a wave flume not equipped with a re-reflection absorption system. Experiments were conducted on a berm breakwater with and without toe berm leading to an empirical formula for evaluating the influence of such structures. Validity of the proposed formula is limited to the conditions adopted in the present model tests. The following conclusions can be drawn from the present study:

1. Within the intervals of parameters listed in Table 2, the results of the present research can be used as a guideline for the conceptual design of RBBs including a wide toe berm. The reliability is limited to toe berms that are within the range of 13% to 45% of the water depth in front of the structure, a trunk slope cot (α) =1.25, and a water depth in front of the toe structure between 8.36 and 18.79 times the armor stone size.
2. It is observed that increasing toe berm width, B_t, and thickness, t_t, both have considerable influence on recession reduction. However, the influence is larger for higher stability numbers. Comparison between the influences of toe berm and toe

depth indicates that the toe depth has relatively more influence on recession than the toe width in the ranges of parameters considered in this study.

3. Results revealed that besides the influence of the toe berm due to preventing the displaced rock to fall down along the lower slope, the toe configuration has additional reduction influence as a result of changing wave conditions and wave energy dissipation, especially for higher wave heights as they will break sooner by a (toe) berm.
4. Using the tests results, a new formula has been developed for the estimation of berm recession by taking into account the influence of toe berm configuration. The experimental comparison confirms the reliability of the proposed formula within the validity ranges of parameters.

5- Given an acceptable stability number (*Ho*) as a design criterion for RBBs, the recession can be reduced up to 35% by the application of a toe berm. Thus, the main berm width can be shortened, resulting in reduction of the required armor stones volume. So, by using a smaller stone size for the toe berm, the stability of the structure is secured and also the total cost of the breakwater can be decreased.

7. Nomenclature

B_b	berm width	B_t	toe width
D_{n50}	armor material nominal diameter	t_t	toe height
d	water depth	h_t	toe depth
N	number of waves	$\cot(\alpha)$	front slope
h_b	berm elevation above still water level	Re_D	Reynolds number for armor stones
H_{m0}	significant wave height	v	kinematic viscosity
T_p	spectral peak wave period	S_{om}	mean wave steepness
L_{op}	peak wave length	f_{H0}	Factor accounting for the influence of stability numbers
g	acceleration of gravity		
W_{n50}	weight exceeded by 50% of the stones	f_{Bt}	Factor accounting for the influence of toe width
f_g	gradation factor of armor stones		
ρ_s	mass density of stones	f_{ht}	Factor accounting for the influence of toe depth
ρ_w	mass density of water		
Δ	ρ_s/ρ_w-1 relative density	f_d	Factor accounting for the influence of water depth
H_0	stability number		
T_0	wave period index	f_N	Factor accounting for the influence of number of waves
H_0T_0	period stability number		
B_t	toe width		

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