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STABILITY OF HIGH DENSITY CUBE ARMOURED BREAKWATERS

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ABSTRACT

The performance of high-density cubes in the armor layer of a breakwater was investigated through an experimental study. For this purpose, two different cross-sections, one with a conventional cross-section and one with a berm, were modelled in a wave flume. A total of ten tests were performed for both cross-sections. Different concrete densities of cubes and different placement methods were applied. The dimensions of the cubes with two different densities were the same for all tests to avoid potential scale effects caused by the dimensions of HD cubes. The experimental study showed that HD cubes were more stable than ND cubes; the characteristic wave height for HD cubes was 1.5 times higher than that of the ND cubes. The use of HD cubes may provide economic efficiency and enables a significant reduction of the concrete volume, transportation of material,and reduction of required construction area for manufacturing, etc. HD cubes in a single layer turned out to be very stable. However, only using HD cubes in a part of the armor layer or only used on the second (upper) layer caused a decrease in the stability of the armor layer, especially in comparison to the armor layers that fully consist of HD cubes. The performance of HD cubes was also evaluated by comparing the experimental results with the Van der Meer (1988) formula and the suitability of the stability number for HD cubes was discussed.

Key Words: Breakwaters, Cube Blocks, High Density Concrete Armor Units, Single layer, Berm type breakwaters

1. INTRODUCTION

There might be some reasons and concerns leading the armor layer design to be constructed by high density concrete units. These might be drawn with the followings: 1- the difficulty of finding large rock materials; 2- Economical effects due to the increased concrete units' volume when normal density is considered; 3- Increasing waves caused by climate change requiring larger armor units; 4- Minimizing the manufacturing and construction site costs.

High density concrete armor units have been considered for variety type of armor units and one of them is cube armor unit which is the oldest and has a wide range of application on shore protection structures as being a conventional or a berm type breakwater depending on the design requirement and the conditions of the project area.

Many researchers demonstrated that concrete cubes can be used as armor unit (e.g., Van der Meer (1988), Van Gent et al*.* (1999), Triemstra (2000), Van Gent et al*.* (2001), Van Gent et al*.* (2003), Bueno Esposito et al. (2015), Van Gent and Van der Werf (2017), Sarfaraz and Pak, (2017), Howe and Cox (2018), Vieira et al*.* (2020,) Yuksel et al*.* (2020), Vieira et al. (2021)). However, few of these researchers have studied the importance and influence of density.

The main stability formula for concrete armor units was presented by Hudson (1953). Additionally, Van der Meer (1988) produced an empirical stability formula for cube units as follows,

$$N_s = \frac{H_s}{\Delta D_n} = \left[6.7 \frac{N_0^{0.4}}{N^{0.3}} + 1.0 \right] . s_{0m}^{-0.1} \qquad (1)$$

where H_s is the significant wave height, Δ is the relative density, D_n is the nominal diameter (which is the side length of the cube), N_0 is the relative damage number, N is the number of waves, s_{0m} is the wave steepness based on the mean wave period. The formula defines the stability number (N_s) in terms of the ratio of $H_s/\Delta D_n$ and the ratio contains the influence of the density of the concrete unit. Therefore, considering high density (HD) concrete unit rather than normal density (which is about 24 kN/m^3) would result in reduction on the required size of the armor unit.

The effect of changing the density of the armor units has been investigated by only few studies in the past (such as Hudson, 1959, Ito et al., 1994, Triemstra, 2000, Van Gent et al., 2001, Van Gent, 2003), although the densities of the materials in Hudson's tests were between 2146 kg /m^3 and 3076 kg/m^3.

Concrete cubes can be placed single or double layer with different placement methods of regular or irregular. According to Van Gent et al. (1999), Van Gent et al. (2001), Van Gent et al. (2003), and Vieira et al. (2020 and 2021), the use of concrete armor cubes in a single layer is a feasible and cost-effective solution specifically when it is compared to the other concrete units constructed with one-layer like xblocs, core-loc and accropode. In a similar way, the use of high-density cube as a single or double layer is also applicable and effective in decreasing the costs (Triemstra, 2000; Van Gent et al., 2001; and Van Gent, 2003). Obviously, single layer cubes are also economically competitive with two-layer armor units such as Tetrapod and Antifer.

By implementing today's technological improvements, it is possible to produce concrete cube armor units with 40 kN/m^3 density using magnetite or other high-density materials (Triemstra (2000) and Van Gent et al. (2001)). However, in accordance with the literature, in order to test the validity of the linear relationship between H_s/D_n and Δ in cubes with 40 kN/m^3 density, flume tests are required. Triemstra (2000) also studied other variables such as packing density, influence of filter layer and wave steepness.

Ito et al. (1994) conducted some experiments with high density Tetrapodes varying between 17.8 and 42.8 kN/m^3. The authors suggested a relationship between K_D and the specific gravity, where K_D decreases with increasing specific gravity. As it is known that K_D was proposed by Hudson (1959) to characterize the hydraulic performance of different armor units placed on conventional double-layer armors (Medina and Gomez-Martin, 2012). On the other hand, they concluded that the stability of high-density armor blocks was found to be significantly affected by scale effects due to the very small dimensions of the units. Because concrete armor unit sizes are usually limited in the model by the available sizes (often >3.0cm). A practical limitation can be that the detection of rocking becomes increasingly difficult for small concrete unit size. However, Ito et al. (1994) used very small concrete units in their experiments (Hydralab III, 2007).

Van Gent et al. (2001) conducted some tests with high density cubes (almost 40 kN/m^3) in a traditional double top layer and single top layer over a strait slope. They revealed that high density cubes were as stable as normal density cubes. They also noticed that an increase of the density by a factor of 1.5 would lead to a reduction in the weight by a factor of 5, a reduction in volume per unit by a factor of 8, would lead to a reduction in the volume of concrete in the top layer by a factor of 2.

Cube stability as an armor layer is a complex problem and still needs to be investigated in detail. The stability number is an empirical formula that is to be used for the conceptual design of rubble mound breakwaters and in fact it is a function of several parameters and depends on unit shape, placing method, slope angle, relative density, etc., and these parameters are not taken into account by the formula itself. Therefore, a design formula is needed in order to obtain more reliable results such as for high density cube blocks with different placement methods. This study therefore aims not only investigating the performance of HD cube units, but also the convenience of using the existing formula for high density cube units with different placements.

In this study, the impact of the using high-density cubes as armor units was investigated for conventional and berm type breakwaters. A 1/1.5 straight slope was used for conventional breakwater, and 1/1.5 lower and 1/2 upper slopes were used for berm type breakwaters. Both regular and irregular placement methods of units were used, and moreover high density (HD) cubes in a single layer were tested. These different placement techniques using HD cubes were discussed based on their stability. So, the idea about designing relatively more economical, environmental-friendly, and stable breakwaters with the use of HD concrete blocks would be revealed.

The remainder of the present paper is organized as follow: A description of the methodology for investigation of the stability of conventional and berm type breakwaters in terms of placement techniques and the density of the cubes used in the armor layer is provided in Section 2, with the test conditions detailed in Section 3. Results and discussions from the stability experiments are, provided in Sections 4 and 5 respectively. Conclusions are presented in Section 6.

2. METHODOLOGY

Two different conventional cross-sections were considered: (1) with a single layer using regular placement, (2) with a double layer using irregular placement. The second model was a berm type breakwater consisting of an irregularly placed double layer on the lower slope. For these model tests, normal-density (ND) and high-density (HD) cubes were utilized. For the berm type breakwater models, the water depth was varied between 0.45 m and 0.65 m, where the berm level was kept constant at 0.55 m similar to the study of Yuksel et al. (2020). Consequently, with the combination of these various circumstances, 10 different breakwater models were tested. Table 1 shows all tested breakwater models where ND and HD mean that the density of cubes are 24 kN/m^3 and 31.5 kN/m^3, respectively where d_{toe} is the depth of breakwater toe and pacing density (ψ_S) is ratio between the real and the maximum number of blocks per unit area.

The tested conventional cross-sections are elaborated below. Placement styles for these models can also be seen from Figures 1a, b.

Case 1-(CID) First (lower) layer ND cube – Second (upper) layer HD cube using irregular placement: In this experiment, ND cubes were placed in the first (lower) layer and HD cubes were placed in the second (top; upper) layer.

Table 1 Experimental conditions

Test Case	Breakwater type	Placement type	Layer	d_{toe} (m)	Used cubes	Packing density (ψ_S)
1-CID	Conventional	Irregular	Double	0.55	First Layer ND Second Layer HD	0.59
2-CID*	Conventional	Irregular	Double	0.55	First and Second Layer ND Second Layer HD in the reference area	0.59
3-CID	Conventional	Irregular	Double	0.55	First Layer HD Second Layer HD	0.59
4-CRS	Conventional	Regular	Single	0.55	ND	0.59
5-CRS	Conventional	Regular	Single	0.55	HD	0.59
6-BID	Berm	Irregular	Double	0.45	First Layer ND Second Layer HD	0.59
7-BID	Berm	Irregular	Double	0.55	First Layer ND Second Layer HD	0.59
8-BID	Berm	Irregular	Double	0.65	First Layer ND Second Layer HD	0.59
9-BID**	Berm	Irregular	Double	0.45	First and Second Layer ND Second Layer HD in the reference area	0.59
10-CID	Conventional	Irregular	Double	0.55	First Layer ND Second Layer ND	0.59

*2-CID; HD cubes was placed only over the reference area in the second (upper) layer including first row at the top layer of crest. Rest of the armor layers have ND cubes.

** 9-BID; HD cubes were placed only over the reference area both in the first (lower) and second (upper) layers including two rows in berm close the water side. Rest of the armor layers have ND cubes.

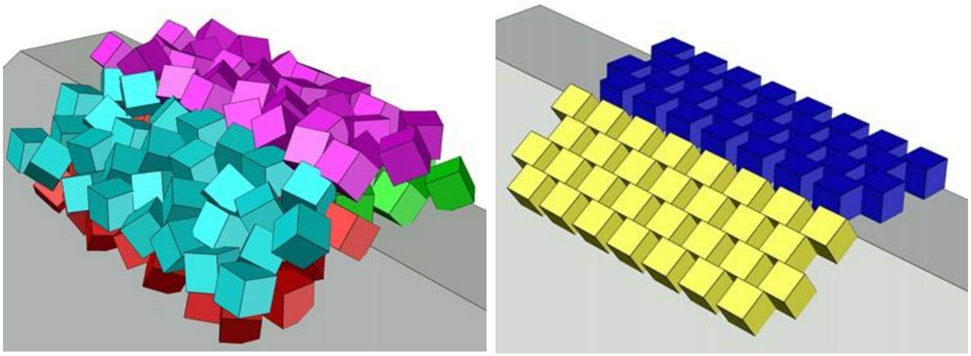
Case 2-(CID) Reference Area HD with irregular placement: HD cubes on the second (upper) layer considered only in the reference area and in the area from the upper boundary of the reference area to the top of the crest. The rest consisted of ND cubes. The placement method was irregular for both layers.

Case 3-(CID) Double Layer HD cubes using irregular placement: In this model, both first (lower) and second (upper) layers consisted of HD cubes only.

Case 4-(CRS) Single layer ND cubes with regular placement: ND cubes were placed regularly in a single layer over the slope.

Case 5-(CRS) Single layer HD cubes with regular placement: HD cubes were placed regularly in a single layer over the slope.

Tested conventional breakwater cross-sections for double layer and single layer can be seen in Figure 2 and 3, respectively. An additional test was conducted for a conventional breakwater with double layer ND cube over the slope as Case 10 to verify the test with Van der Meer (1988) formula and to discuss the results with the results obtained from HD tests.



(a) (b)

Figure 1 Irregular (a) and regular (b) placement styles.

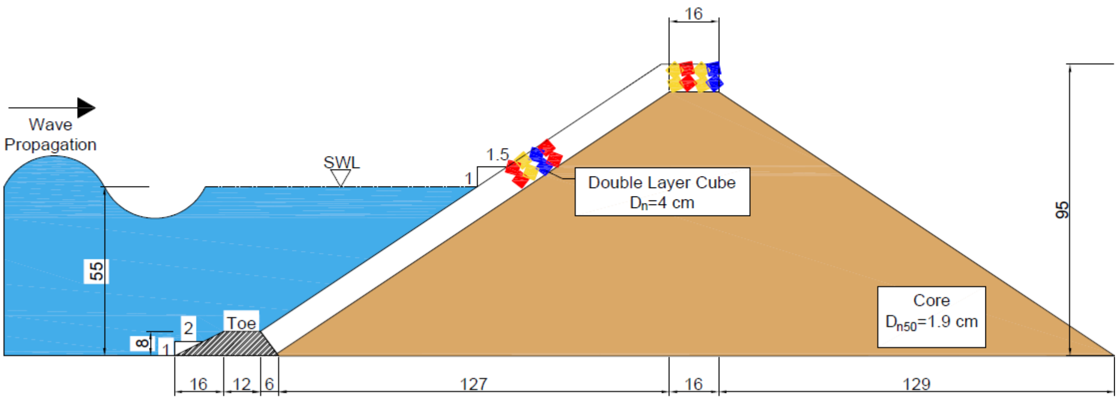


Figure 2 Cross-section for double layer models (units are in cm).

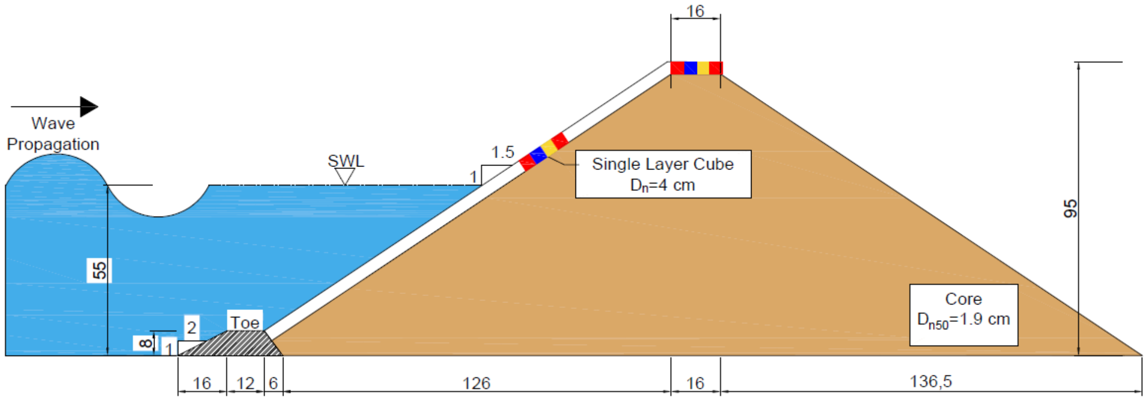


Figure 3 Cross-section for single layer models (units are in cm).

Tested cross-sections with berm, are given below in details. Placement styles and cross-sections with different water levels are depicted in Figure 4. Figure 5 shows the transition from the lower slope to the berm according to Yuksel et al. (2018).

Case 6-(BID) Emerged berm (Irregular): ND cubes were placed in the first (lower) layer and HD cubes were placed in the second (upper) layer. The berm was 10 cm above the SWL. The placement method was irregular for both layers.

Case 7-(BID) Berm at SWL (Irregular): ND cubes were placed in the first (lower) layer and HD cubes were placed in the second (upper) layer. The berm was at the still water level.

Case 8-(BID) Submerged berm (Irregular): ND cubes were placed in the first (lower) layer and HD cubes were placed in the second (upper) layer. The berm was 10 cm below the SWL. The placement method was irregular for both layers.

Case 9-(BID) Emerged berm with HD cubes over reference area (Irregular): HD cubes were placed over the reference area both in the first (lower) and second (upper) layers including first two rows of the berm. The rest was filled with ND cubes. The placement method was irregular for both layers.

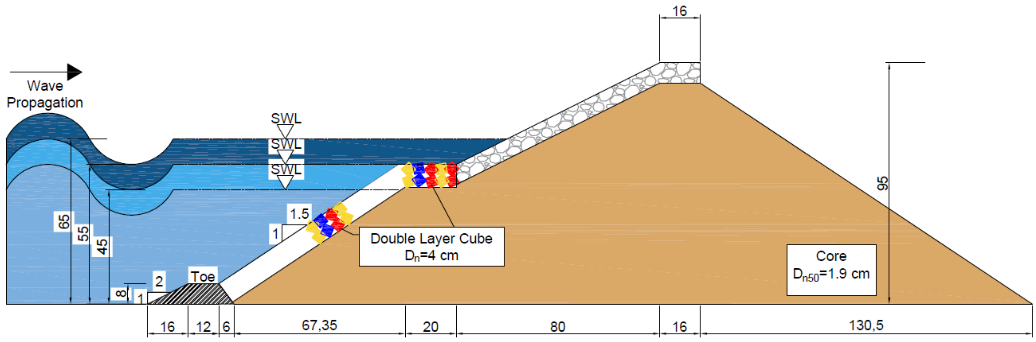


Figure 4 Cross-section for models with berm (units are in cm).

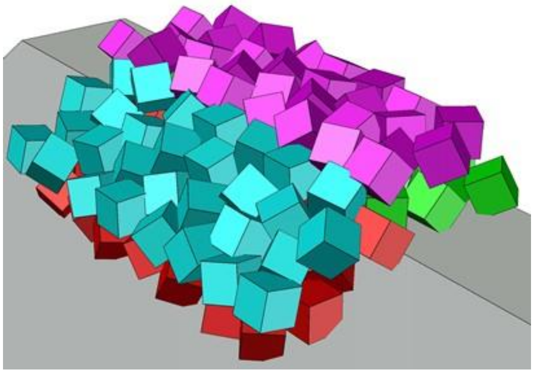


Figure 5 Irregular placement style for the transition section of the breakwaters with berm (Yuksel et al., 2018).

To determine the damage accurately, it is important to define the reference area because the displaced and moved units are not uniformly distributed over the slope due to wave action. The reference area was defined as the area between two levels of SWL $\pm$ H_s, which corresponds to SWL $\pm$ $5D_n$ for the selected design wave height of H_s=0.20 m and nominal cube diameter of 4 cm. By considering these issues, the reference area was kept constant as $10D_n$ below the crest for the conventional breakwater model and the area below the berm for berm type breakwater (Yuksel et al., 2020).

Unit displacement or movement is termed as damage; however their definitions are different. In this study damage is defined by displaced units in the following way (Frens, 2007 and Yuksel et al., 2020):

- No damage: No units are displaced.
- Initial damage: A few units are displaced.
- Failure: The under layer is exposed to direct wave attack.

According to above definitions, damage was calculated and evaluated as follow:

1-Displacement ratio was calculated with the equation given below:

$$\text{Displacement Ratio } (D_i) = \frac{\text{Number of displaced units}}{\text{Total number of units within reference area}} (\%) \qquad (2)$$

The displacement of units is defined as the movement of a block more than distance of D_n (Van der Meer, 1988) from their original position. The displacement ratio was classified as D_1, D_2, and D_T which represent the displacements between $1D_n$ and $2D_n$, above $2D_n$, and above $1D_n$, respectively. Hence, D_T indicates all (total) displaced cubes in the reference area (Frens, 2007).

On the other hand, movement can be considered as an action of mobility which can be defined as an amount of displacement less than D_n. Movement may be occurred before displacement and the units may lose support from their adjacent units. In a similar way using Equation (2), three different categories of movement are expressed in relation to the nominal diameter: <0.5D_n, 0.5-1.0D_n, and 0.0-1.0D_n which are indicated with M_1, M_2, and M_T (total movement), respectively (Frens, 2007).

Between each sea state, the damage was not repaired, so the displacement and movement ratio after each sea state is the cumulative damage.

2- Relative damage number: Damage to concrete units can be described by the relative damage number N_0 which is defined by the actual number of displaced units related to a width (along the longitudinal axis of the breakwater) of one nominal diameter, D_n. In this study, the damage number was found by counting the displaced units of one nominal diameter width in the reference area from the camera records.

$$N_0 = \frac{\text{Number of displaced units of one nominal diameter } D_n \text{ in reference area}}{L/D_n} \qquad (3)$$

where L is the width of the model structure excluded one nominal diameter from each side wall and D_n is the nominal diameter of the cube.

3. EXPERIMENTAL SETUP AND PROCEDURES

Experimental research was carried out in the wave flume of the Coastal and Harbor Engineering laboratory at Yildiz Technical University. The flume has a length of 26 m, a width of 1 m and a height of 1 m. The channel is equipped with a piston-type wave generator that has an active reflection system (Figure 6).

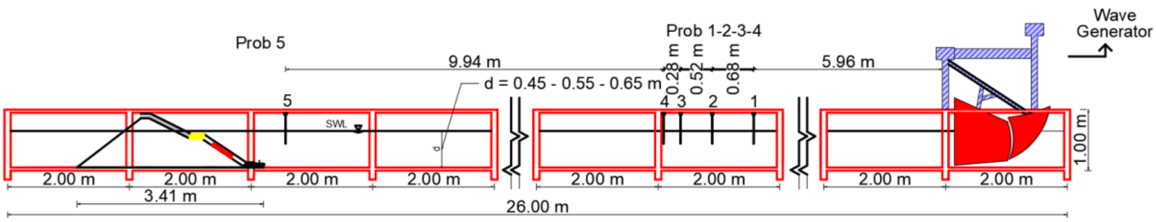


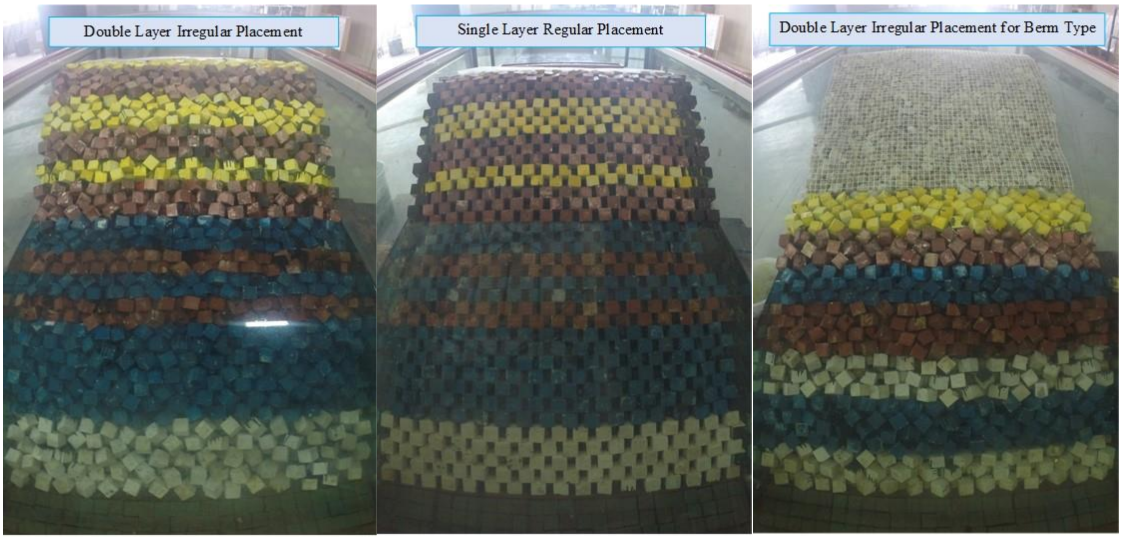
Figure 6 Longitudinal cross-sections of the wave channel

The nominal diameters for both normal and high-density cube models were 40 mm to avoid the scale effects as indicated by Ito et al. (1994). Densities were 24.0 kN/m^3 and 31.5 kN/m^3 for ND and HD cubes, respectively. The breakwater models were placed on a horizontal foreshore. All models have 1 m width and 0.95 m height consisting of a permeable core layer with quartz stone, a toe and the armor layer. The under layer consisted of stones with a nominal diameter of 19 mm for all cases. The packing density per layer of the blocks was kept 59% for both ND and HD cubes for all tests. The slope of the conventional breakwater was 1:1.5. For berm type breakwater, the lower slope was 1:1.5 with cube armor layer while the upper slope was 1:2 with rock armor layer with a nominal diameter of 32.5 mm and it was fixed with a wire mesh in order to focus on the investigation of the performance of the lower slope which this method is similar to the study of Yuksel et al. (2020).

The water level was varied with respect to the berm level. Three different water depths (d) of 0.45, 0.55 and 0.65 m were selected to investigate the effect of the berm position relative to the still water level. In other words, the still water levels (SWL) were 0.1 m below, at, and 0.1 m above the berm level (d_b/d=-0.222, 0 and 0.154 where d_b is the vertical distance between berm and SWL; d_b/D_n=-2.5, 0 and 2.5). The berm width on the other hand was kept constant as $5D_n$ according to the definition given by Yuksel et al. (2020).

Figure 7a, b and c show different breakwater models in the experimental study for double layer irregular placement, single layer regular placement for conventional breakwater and double layer irregular placement for berm type breakwater, respectively.

For the irregular placement, the blocks were placed by letting them fall free from a height of half a nominal diameter above and to increase the irregularity of the placement. In these experiments for irregular placements of the armor layers, special attention was given to reproduce a similar irregularity for both normal and high-density cubes, which was indicated by Van Gent et al. (2001). For regular single layer placement, blocks were placed one by one for each calculated location on the slope, and they were placed staggered over the slope (Figure 1b). For both placement methods, the units were placed in colored bands to improve the visualization of the displacement and so to measure the damage.



(a) (b) (c)

Figure 7 Tested breakwater models in the experimental study

The standard Froude scaling method for the under layer, which is the core material, is based on a relation between the armor block weight and the under-layer material weight, $M_{armour} / M_{50,underlayer}$. A relation based on the nominal diameter of the armor and under layers $D_{n,armour} / D_{n50,underlayer}$ is also commonly used. Van Gent (2003) recommended a ratio between 2 and 2.5. The ratio was considered as $D_{n,armour} / D_{n50,underlayer} = 40/19 = 2.1$ for both conventional and lower slope and berm, and $D_{n50,armour} / D_{n50,underlayer} = 34/19 = 1.8$ for upper slope of the berm type breakwater.

The viscous scale effects are negligible when the Reynolds number is larger than $2x10^3$ (Hughes, 1993; Lykke Andersen, and Burcharth, 2010; Wolters et al., 2010). The Reynolds number is calculated by $Re = U.D/\nu$ where D is the characteristic dimension of the armor material and ν is the kinematic viscosity, which for the water at 10^0 C is $1.33x10^{-6}$ m^2/s, U is the seepage velocity $U = (P.H_i.L_m)/(2.d.T_m)$, P is the volumetric porosity of the core material, H_i is the significant wave height at the toe, L_m is the mean wave length of the waves, and T_m is the mean wave period at the toe. The resulting Reynolds number is $5x10^3$ for the typical values used in this study, i.e., P=0.49, H_i=0.14 m, T_m=1.16 s, d=0.45 m, D_{n50}=0.019 m, which indicates that the experiments are not influenced by the scale effects. However, in a small-scale physical model, the friction forces between units may not be equal to those in the prototype because the armor unit surface can be relatively rougher in the model than for the large-scale units. Painting the unit provides somewhat a smoother surface, hence all units were painted (with different colors).

Toe stability of the structure was out of the scope of this research. The toe stability was ensured by fixed with steel frame for all cases not to affect the stability performance of the armor. The width and the thickness of the toe were $4D_n$ and $2D_n$=8 cm, respectively. The crest width of the structure was $G_c=4D_n$.

A total of 13 irregular wave conditions with a JONSWAP spectrum ($\gamma = 3.3$) in deep water were selected for all tests. Wave conditions were measured by wave probes at five different locations. One of them was located in front of the structure toe. The other four probes were in constant water depth with known spacing to separate incident and reflected waves from the measured surface elevations (Figure 6). The applied method for separating the incident and reflected waves was employed by using the Mansard and Funke (1980) method. The spectral significant wave height H_s (in this paper: $H_s=H_{m0}=4(m_0)^{0.5}$) and wave period $T_{m-1,0}$ ($T_{m-1,0=}m_{-1}/m_0$) were obtained from the measured wave energy spectrum. A number of additional experiments were performed to check the repeatability of the tests. The analysis was based on the time series of the incident waves at the toe. In addition, waves were also calibrated at the toe of the structure by comparing the incident waves for the experiments without structure (using a gravel beach instead of structure).

For each test, the incoming significant wave height in front of the toe was gradually increased to define the wave height leading to failure. The characteristic wave height was determined as H_s=0.20 m based on ND cubes. Moreover, beyond characteristic wave height was considered when the related model did not reach to failure. The characteristic wave was only increased by around 10% due to limitations of larger waves associated with the model dimensions chosen, the wave generator capacity and water depth at the structure toe.

The damage was repaired after each series of test run, but not after each individual test run. Each placement method was tested for the wave steepness of around $s_p = 2\pi H_s / gT_p^2 = 0.033$.

Each test run consisted of about 1000 waves. The damage was cumulative for each test series and detected using a visualization technique by taking digital photos before and after each run from a fixed location perpendicular to the slope. The damage was determined by counting the moved armor units and measuring the movement distance in terms of displaced units related to a width (along the longitudinal axis of the breakwater) of nominal diameter (D_n). To avoid potential side wall effects that could affect the results, $1D_n$ widths from both sides of the wall were not considered for the calculation of the damage (Frens (2007), Van Gent, (2013), Yuksel et al. (2020)).

In this study, heavy concrete production with a targeted density of 31.5 kN/m^3 was obtained by using barite aggregate. Castings in different mixing ratios designed to achieve the desired density were realized and the density criterion, which is the main target, was achieved. The optimum mixing ratio was chosen in this way and in heavy concrete production a barite aggregate with 0-5 mm of grain size, CEM II 42.5 R type cement and the super plasticizer were used. In the mixture design, the water/cement ratio was determined as 0.55, and the super plasticizer ratio was determined as 0.44%.

Table 2 provides an overview of the applied values of the most important parameters for both type of breakwaters (conventional and berm type). Wave series with wave heights and corresponding Ns values for ND and HD cubes in the experiments were given in the appendix.

Table 2 Ranges of the parameters for the experimental data set

Parameter	Symbol	Value
Slope angle for conventional type	$\cot\alpha$	1.5
Upper and lower slope angle for berm type	$\cot\alpha$	2 and 1.5 respectively
Relative density for ND cubes, HD cubes and rocks	Δ	1.4 and 2.15 respectively
Rock size upper slope for berm type (m)	$D_{n50\text{-}upper}$	0.034
Cube size for both of ND and HD cubes (m)	D_n	0.040
Grading armor material	D_{n85}/D_{n15}	1.4
Grading underlayer material (core)	D_{n85}/D_{n15}	1.38
Berm width (m)	B	0.20
Berm level w.r.t. SWL (m)	d_b	–0.1 - 0.1
Berm level ratio (positive: submerged; note $H_s=H_{m0}$)	d_b/H_s	0.5 - 2.0
Berm level ratio for submerged, at SWL and emerged	d_b/d_{toe}	0.22-0.0-(-0.15) respectively
Wave steepness ($s_{m-1,0}=2\pi H_s/gT^2_{m-1,0}$ note $H_s=H_{m0}$)	$s_{m-1,0}$	0.026 - 0.050
Wave steepness ($s_p=2\pi H_s/gT_p^2$ note $H_s=H_{m0}$)	s_p	0.021 - 0.045
Deep water wave height over depth (note $H_s=H_{m0}$)	H_s/d_{toe}	$\leq$ 0.4
Wave height ratio (note $H_s=H_{m0}$)	$H_{2\%}/H_s$	1.4
Number of waves	N	1000
Stability number (note $H_s=H_{m0}$)	$N_s=H_s/\Delta D_n$	0.58 - 3.93

4. Results and Discussion

4.1 Conventional Cube Armored Breakwaters

The tests were conducted only for 55 cm water depth. Double layer irregular placement and single layer regular placement techniques were used.

(i) Case 1: (CID) First (Lower) layer ND – Second (Upper) layer HD with irregular placement

Positions of both high density and normal density cubes and considered reference area can be observed in Figure 8.

The wave heights were low at the start of the experiment, such as H_{m0}=0.05 m (at wave series 1; W1) and H_{m0}=0.08 m (at wave series 2; W2). Thus, armor layer was stable, yet movements were observed (10%). For wave series 3 (W3) and 4 (W4), significant wave heights were relatively higher than the previous waves, H_{m0}=0.10 and 0.11 m, total movement ratios increased and reached to 14% and 23%, respectively under these wave conditions (Figure 9). The wave series 4 (W4) was the last series without displacements and, the stability number (N_s) was 1.28.

The first displacement was observed at W5 (H_{m0}=0.14 m and N_s=1.63) and total displacement ratio was 2% (Figure 9). From W5 (H_{m0}=0.14 m) to W7 (H_{m0}=0.16 m), movements reached their maximum ratio of 37%. At W7, total displacement ratio reached to 6%. W8 (H_{m0}=0.17 m and N_s=1.98) possessed notable wave conditions due to wave-structure interaction under highly energetic waves when compared to the previous wave series. Total displacement ratio became 20%, while total movement ratio decreased to 29%. Beyond this condition, the variations of movement and displacement ratios were quite low regarding to clamping strength between adjacent cubes. From W9 (H_{m0}=0.18 m) to W13 (H_{m0}=0.21 m), displacement ratio increased slightly. At W13, the stability number was N_s=2.44. Total movement and total displacement ratios were found to be 26% and 24%, respectively. At W13, wave height was considerably energetic (H_{m0}=0.21 m; which is bigger than the characteristic wave height of 0.20 m), and wave forces were quite strong on the armor units. Filter layer of the model breakwater was never visible, and there was no displacement, yet movements were observed at the first layer of ND (lower layer).

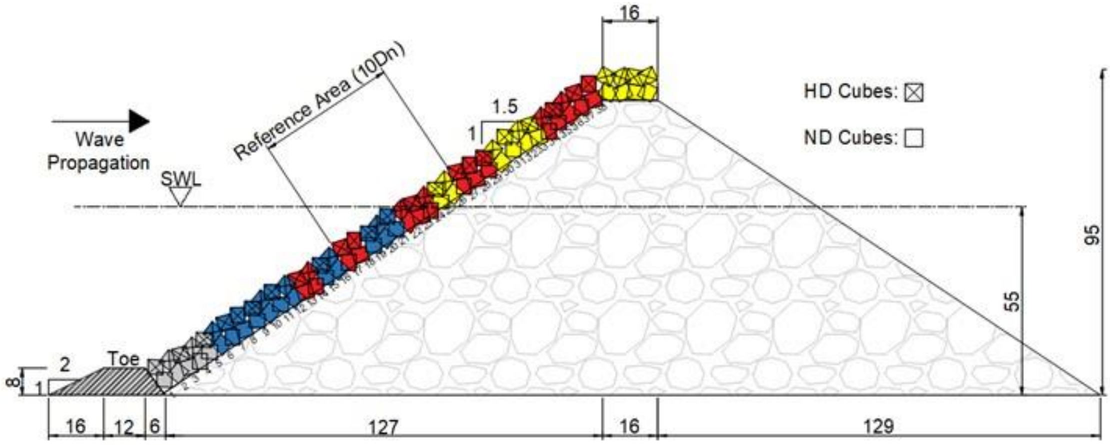


Figure 8 Positions of the HD and ND cubes for the case1 (CID); First Layer (lower layer) ND and Second Layer (upper layer) HD (units are in cm).

The movement of cubes in the first layer (lower layer) directly affected the stability of the second layer (upper layer) for this case. Visual observations showed that the first (lower) armor layer (ND) behaved quite different when compared to the second (upper) armor layer (HD). W8 was defined as a critical test series in relation to wave-structure interaction, this claim can be justified with the movement of ND cubes at the first (lower) layer triggered the HD cubes at the second (upper) layer and then caused to increase the displacement capability of the HD blocks. This resulted that the HD cubes at the reference area lost their connection with the ND cubes, and movements at the first layer considerably increased the instability of the HD cubes (Figure 9). However, after clamping adjacent armor units, the stability of the HD cubes increased again. Consequently, the HD cubes at the second (upper) layer did not show more displacements and the filter layer never became visible, even for beyond the characteristic wave condition (W13, H_{m0}=0.21 m). These HD cubes contributed to the stability of the ND cubes, even for significant wave loading.

In order to reveal the advantage of using HD cubes (Case 1) on the second layer, the results were compared with the results of two-layer ND cubes (Case 10) by considering the measured relative damage (N_0) versus the ratio of H_{m0}/D (Figure 10a). The relative damage (N_0) increases gradually for both cases, except for Case 1 where a sudden increment occurs due to the movement of ND units on the first layer triggered the HD units on the second layer at W8 and then continued slightly. On the other hand, at the end of the wave series, the relative damage is smaller for Case1 where N_0 corresponding to the ratio of H_{m0}/D of 5.0 is 2.7 and 5.6 for Case1 and Case10, respectively. Therefore, this outcome supports the idea that using HD cubes on the second layer provides more stability than that of the case using ND cubes, as it can be expected. On the other hand, when the stability number (N_s) versus the relative damage (N_0) is drawn in Figure 10b including the measurement results obtained from Case 1 (filled triangles), Case 2 (crosses), and Case 10 (open triangles) together with the calculation result of Van der Meer (1988) formula for normal density units (ND), the calculated stability numbers obtained for HD cube cases (Case 1 and 2) are found to be lower than that of ND cube case (Case 10). Figure 10b suggests that if only the upper layer consists of HD units (Case 1, filled triangles) or if only in the reference area HD units are used in the upper layer (Case 2, crosses), the stability is less than for a double layer of normal density units (Case 10, open triangles). However, this is partly because in Figure 10b the relative density Δ on the horizontal axis for Case 1 and Case 2 is the relative density of the high-density units while for Case 10 the relative density is for normal-density units. Nevertheless, the stability of the armor layers where a part of the armor layer consists of HD units, is less than the stability parameter would suggest. Figure 10 clearly shows that if HD units are used only in the upper layer of a reference area (Case 2: crosses) leads to more damage than if the entire upper layer consists of HD units (Case 1: filled triangles). Comparison between the Van der Meer (1988) formula and measurement results of two-layer ND units (Case 10) gave good agreement. If the stability parameter on the horizontal axis correctly accounts for the effects of high-density, the curve would be valid also for an armor layer of which both layers consist of HD units. Figure 10 indicates that applying only HD in the upper layer (Case 1) or a part of the upper layer (Case 2) leads to more damage than if HD units are placed over the entire armor layer (curve).

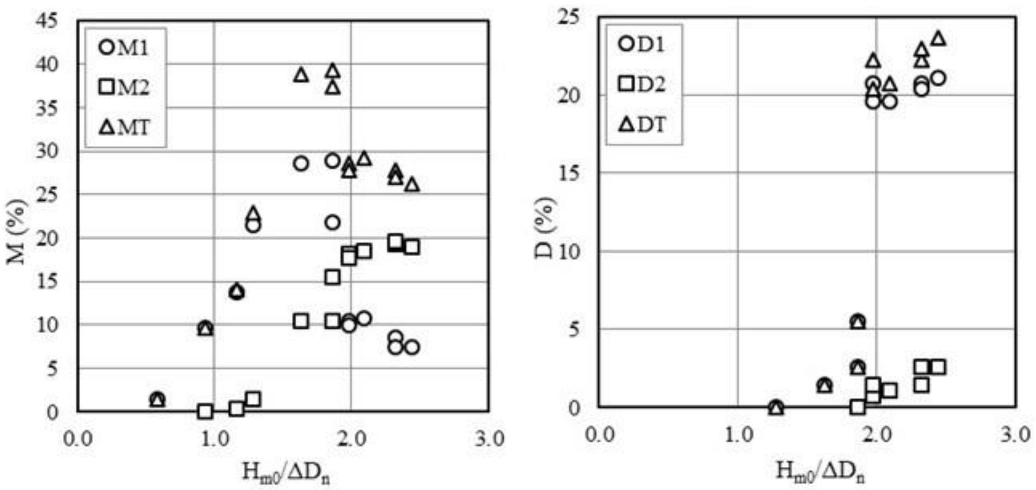
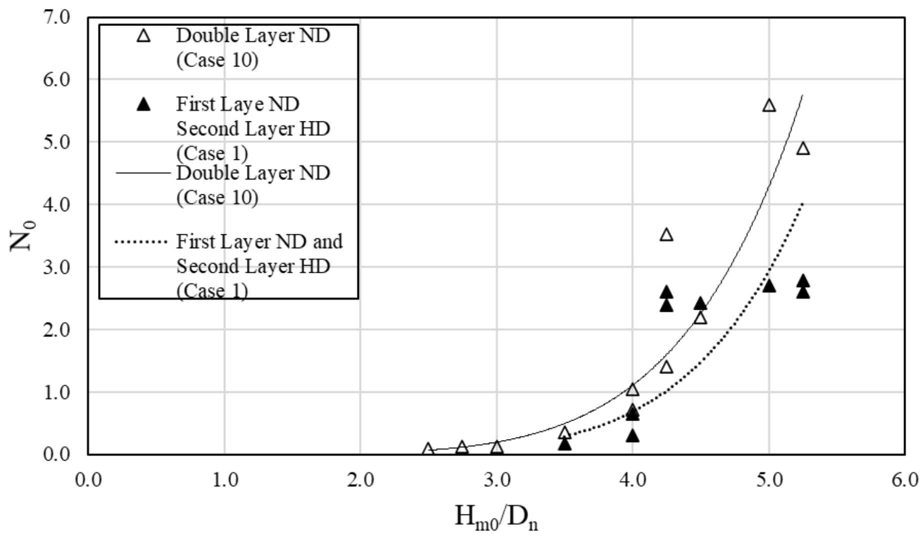
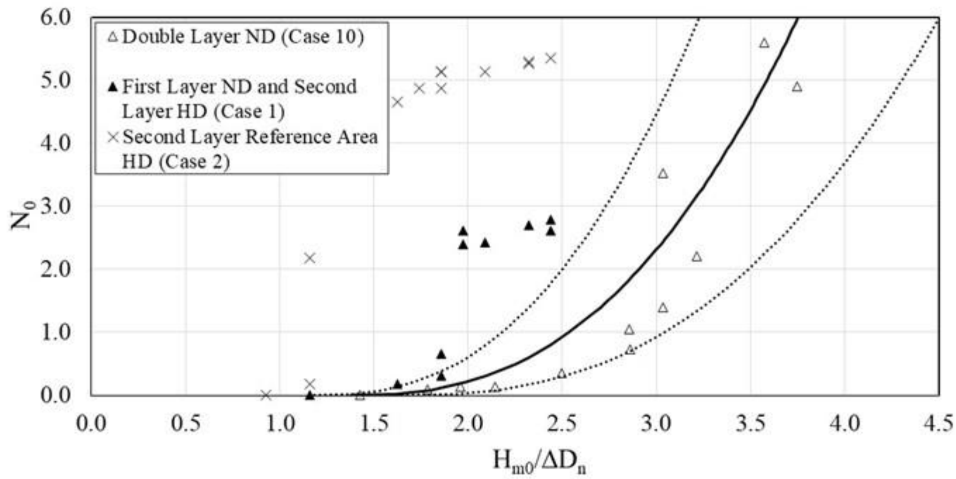


Figure 9 Movement (left: M) and displacement (right: D) in the reference area for the (CID) First Layer ND Cubes and the Second (upper) Layer HD Cubes (the stability number based on HD).



(a)



(b)

Figure 10 (a) Relative damage for Case 1 and Case 10 versus the ratio of H_{m0}/D_n (b) Relative damage for case 1 based on HD (filled triangles), case 2 based on HD (crosses) and case 10 based on ND (open triangles) together with the formula of Van der Meer (1988) for conventional cube armored breakwaters, where the solid line represents the result of formula itself and dashed lines show the confidence bands.

(ii) Case 2: (CID) Reference area HD with irregular placement

The cube arrangement together with the reference area is shown in Figure 11. The HD cubes were placed over the first (lower) layer of the ND cubes only from the 17th row which corresponds to "SWL-H_s equals to $5D_n$" to the second-row crest (i.e., only including first row). The ND cubes constituted the first (lower) layer and the second layer as they were from the 16th row (below SWL-$5D_n$) to the toe.

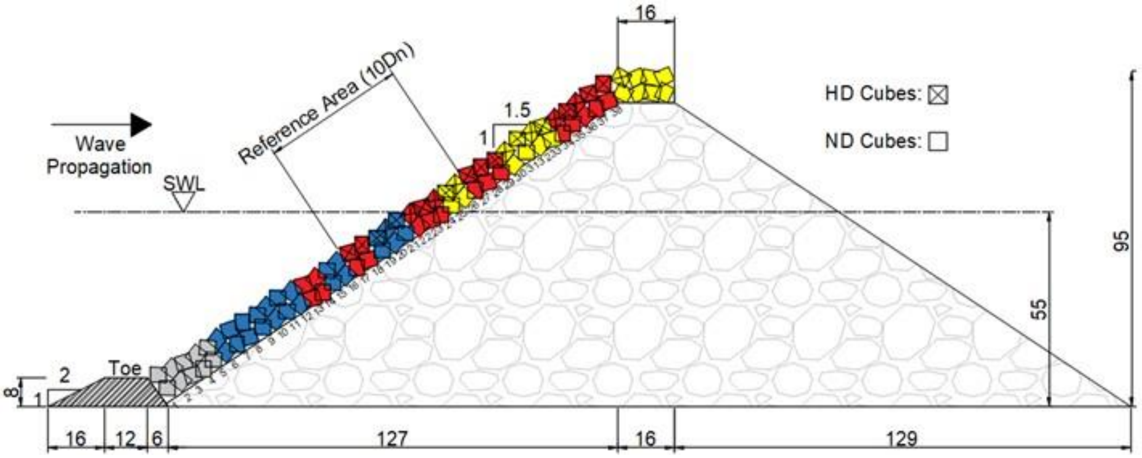


Figure 11 Positions of HD and ND cubes for the case; Reference Area HD Cubes (units are in cm).

In this experiment, although wave heights were low at W1 (H_{m0}=0.05 m and N_s=0.58) and at W2 (H_{m0}=0.08 m and N_s=0.93), movement ratio M_1 (D_n<0.5) reached to 31% due to the rocking behavior of HD cubes. The number of the rocking cubes increased and reached to their maximum ratio of 38% (H_{m0}=0.10 m and N_s=1.16) and the first displacement was also observed at W3 (Figure 12). Total movement ratio and displacement ratio reached to 31%, and 18%, respectively with a sudden increase of W4 (H_{m0}=0.10 m and N_s=1.16). On the other hand, total movement ratio suddenly decreased to 10% at W5 (H_{m0}=0.14 m and N_s=1.63) and total displacement almost doubled and reached to 40%. Displacement ratio increased in a small amount from W6 (H_{m0}=0.15 m) to W13 (H_{m0}=0.21 m) because sliding occurred, and clamping strength increased over the lower slope. Filter layer became visible (close to the crest) through the armor layer at W13 (H_{m0}=0.21 m and N_s=2.44) because segregation occurred in the armor layer above the reference area due to sliding damage. Maximum displacement ratio was reached to 46% at W13. In this case, very large amount of movements occurred even for the lower stability numbers (M<30%) which was unacceptable.

It is necessary to elaborate the behavior of the model at W4 (H_{m0}=0.10 m) and at W5 (H_{m0}=0.14 m). Starting from W4 to the end of W5, “Sliding” behavior was observed. This behavior was also referred in CEM (2003). The high-density cubes in the second layer pushed the normal density cubes downwards due to their movements. Mostly normal density cubes lost their positions and dislocated to the toe of the structure.

26 (4 HD and 22 ND) dislocated cubes were observed at the toe of the structure after W13. Sliding damage also caused the packing density to increase below the reference area while the packing density above the lower limit of the reference area decreased.

As indicated before, Figure 10 shows the relative damage (N_0) obtained from the tests against the results calculated by the Van der Meer (1988) formula. The stability number (N_s) was calculated using the relative density of the HD cubes for Case 2. The stability number predicted by Van der Meer (1988) formula was much higher than that of Case 2 because it does not consider the damage due to sliding.

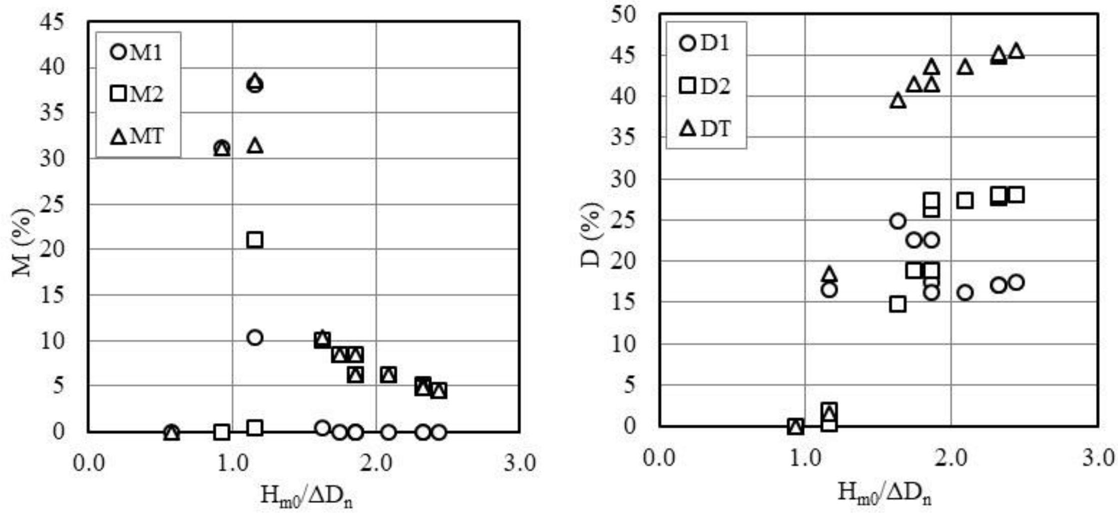


Figure 12 Movement (left: M) and displacement (right; D) in the reference area for the Reference Area HD Cubes (the stability number based on HD).

(iii) Case 3: (CRS) Double layer HD with irregular placement

HD cubes were used in both of the first and second armor layers. Positioning of the HD cubes can be seen in Figure 13.

HD cubes were found to be stable, and displacement did not occur. However, the first movement started at W3 (H_{m0}=0.09 m) with the movement ratio of 0.4% and became 6% at W4 (H_{m0}=0.11 m). For W5 (H_{m0}=0.14 m) and W6 (H_{m0}=0.16 m), the movement ratios almost doubled and reached to 13% and 24%, respectively. From W7 (H_{m0}=0.18 m) to W11 (H_{m0}=0.23 m, which is beyond the characteristic wave height), movement ratio increased slightly and reached to 30% at W11. Only movement was observed under this test condition and there were no displacements (Figure 14). Using the applied high density in the stability number, the results indicate that the stability of the HD armor layer is more stable than the stability formula by Van der Meer (1988) suggests.

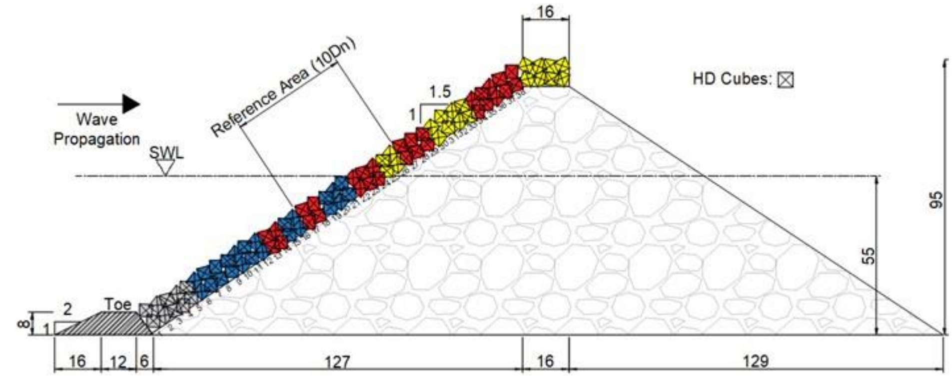


Figure 13 Positions of the HD cubes for the case of Double Layer HD Cubes

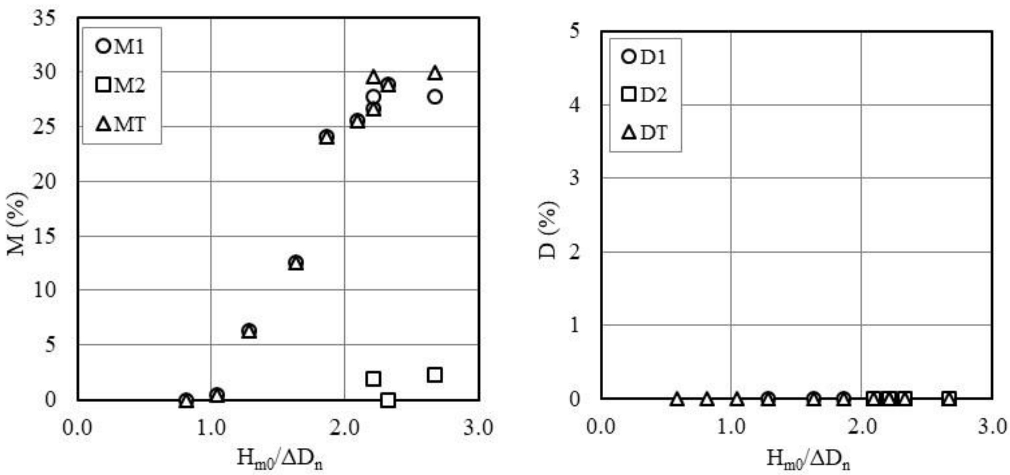


Figure 14 Movement (left: M) and displacement (right: D) in the reference area for the case of Double Layer HD Cubes (the stability number based on HD).

(iv) Case 4: (CRS) Single layer ND cubes with regular placement

Figure 15 shows the reference area and cube arrangement of the ND cubes over the slope.

Displacement was not observed in the armor layer for this case (Figure 16). Only movements occurred due to friction between adjacent armor units. Movement started at W1 (H_{m0}=0.05 m) and the movement ratio was 3% at W8 (H_{m0}=0.18 m). Then, movement gradually increased, and the ratio reached to 9% at W13 (H_{m0}=0.21 m and N_s=3.75) which was the last wave. Only 23 cubes (9%) performed movement behavior (Figure 16). These cubes moved lower than 0.5D_n which means that "0.5D_n-1.0D_n" movement (M_2) was not observed.

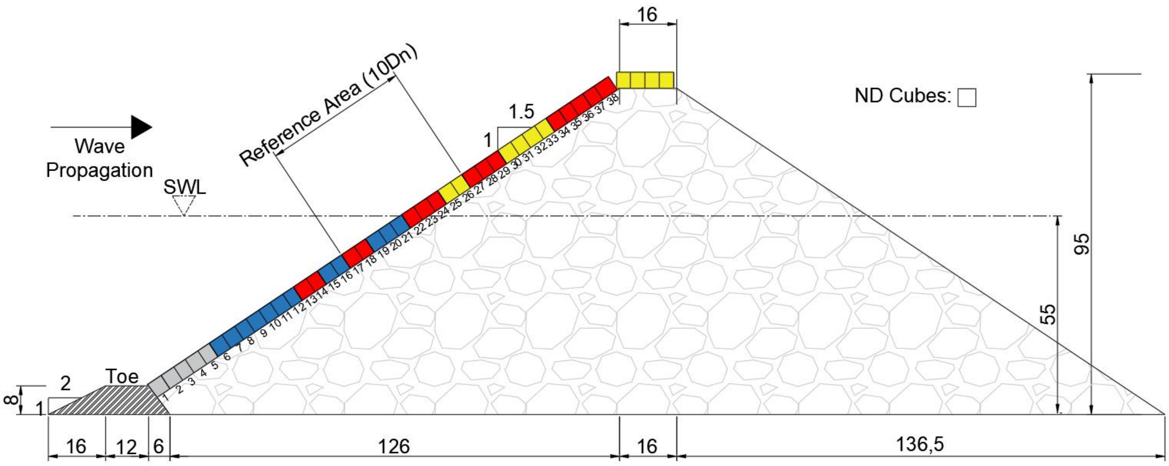


Figure 15 Positions of the ND cubes for the experiment Single Layer ND Cubes with Regular Placement

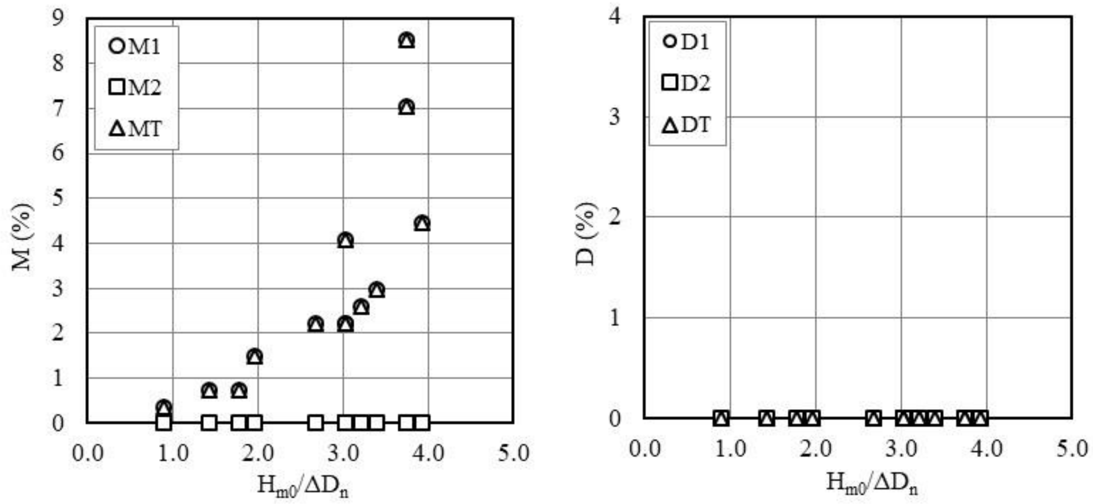


Figure 16 Movement (left: M) and displacement (right: D) in the Single Layer ND Cubes with Regular Placement (the stability number based on ND).

(v) Case 5: (CRS) Single layer HD cubes with regular placement

Figure 17 shows the reference area and cube arrangement of the HD cubes over the slope.

Displacement was not observed in this experiment. Only movements occurred due to friction between adjacent armor units (Figure 18). The movement started at W1 (H_{m0}=0.05 m), and the ratio became 2% at W5 (H_{m0}=0.14 m). Then, movement reached its maximum ratio of 4% at W9 (H_{m0}=0.19 m). From W9 (H_{m0}=0.19 m) to W13 (H_{m0}=0.21 m), neither movement nor displacement occurred. At the end, only 10 cubes (4%) performed movement behavior and these cubes moved lower than 0.5D_n. Therefore, M_2 was not observed throughout the experiment.

Total movement ratio was found to be lower for the HD cubes than for the ND cubes (more than half) for the same wave conditions. It was 9% for ND at W13, H_{m0}=0.21 m while total movement ratio was 4% for HD at W13, H_{m0}=0.21 m.

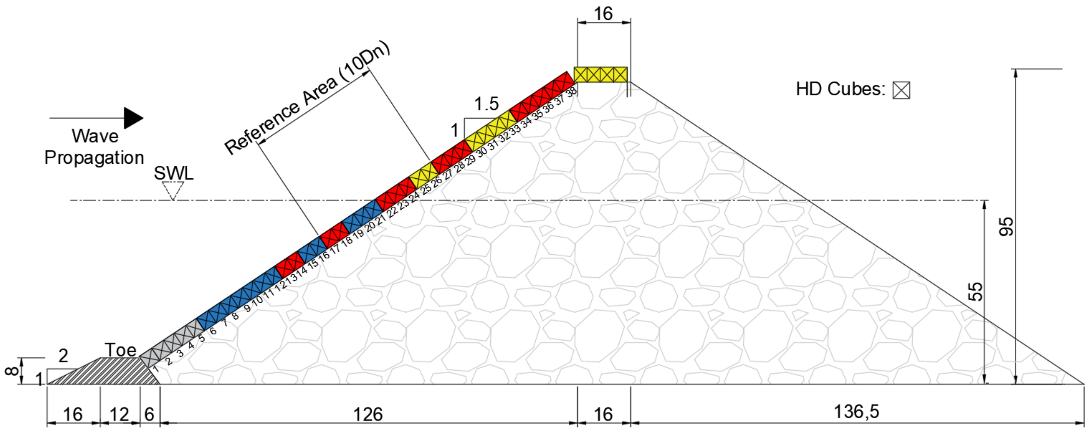


Figure 17 Positions of the HD cubes for the experiment Single Layer HD Cubes with Regular Placement

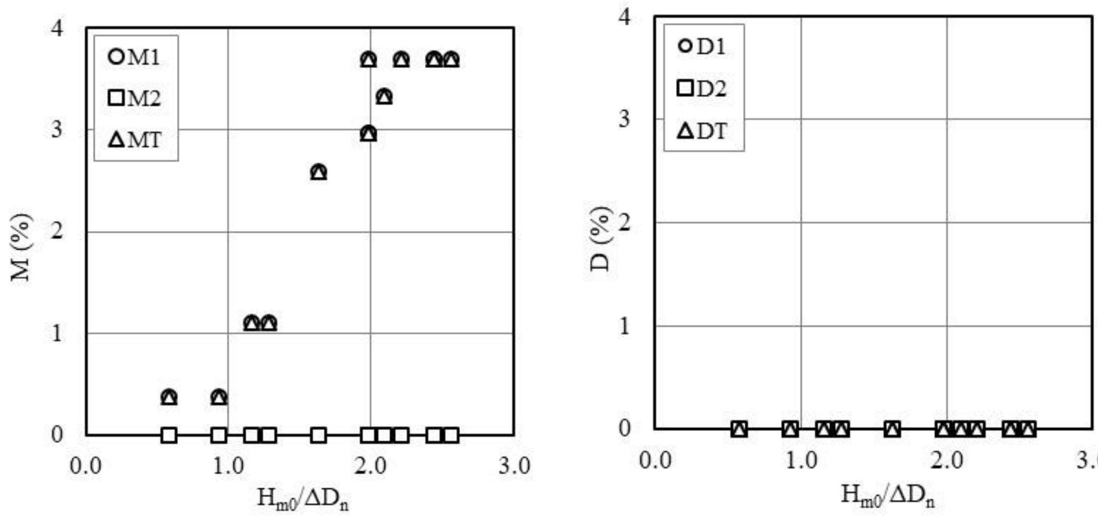


Figure 18 Movement (left: M) and displacement (right: D) in the Single Layer HD Cubes with Regular Placement (the stability number based on HD).

4.2 BERM TYPE BREAKWATER with CUBE BLOCKS in the LOWER SLOPE and BERM

The high-density cubes (HD) in the second (upper) layer and the normal density cubes (ND) in the first (lower) layer were used in the lower slope and berm of the armor layer. The berm was emerged (d=45cm), at SWL (d=55cm) and submerged (d=65cm) for the first three different cases and difference of these berm levels was provided by keeping the berm level constant at d=55 cm and changing only SWL, this method was also followed in Yuksel et al. (2020) and Van Gent (2013). The last case was carried out for emerged berm where HD cube units in this case did not cover entire second layer but used only on the first and second layer of the reference area and on the first two rows of the berm. For all experiments, the upper slope was fixed as mentioned in Section 2. Arrangements of both ND and HD cubes are given in Figure 7 for the berm type breakwater.

(i) Case 6: (BID) Emerged berm with irregular placement

The reference area and cube arrangements can be seen in Figure 19 for this case. For low wave height at W1 (H_{m0}=0.05 m), only M_1 (<0.5Dn) movement was observed. At W2 (H_{m0}=0.08 m), rocking movements were dominant, and the movement ratio was 16%. From H_{m0}=0.11 (W3) m to H_{m0}=0.12 m (W4), M_2 type movements started, and M_T reached to 42%. This wave was the last wave condition without displacement (Figure 20). At W5 (H_{m0}=0.14 m and N_s=1.63) the first displacements occurred (Figure 20). The displacement ratio was 1% for this wave condition. Until the end of the wave series of W6 (H_{m0}=0.15 m), the displacement ratio was constant, but total movement ratio changed and reached to its maximum value of 49%. At W7 (H_{m0}=0.15 m) displacements started again and the ratio reached to 2%. At W9 (H_{m0}=0.16 m) displacements kept increased to the end of the series and the displacement ratio became 3% and reached to 6% at W11 (H_{m0}=0.18 m).

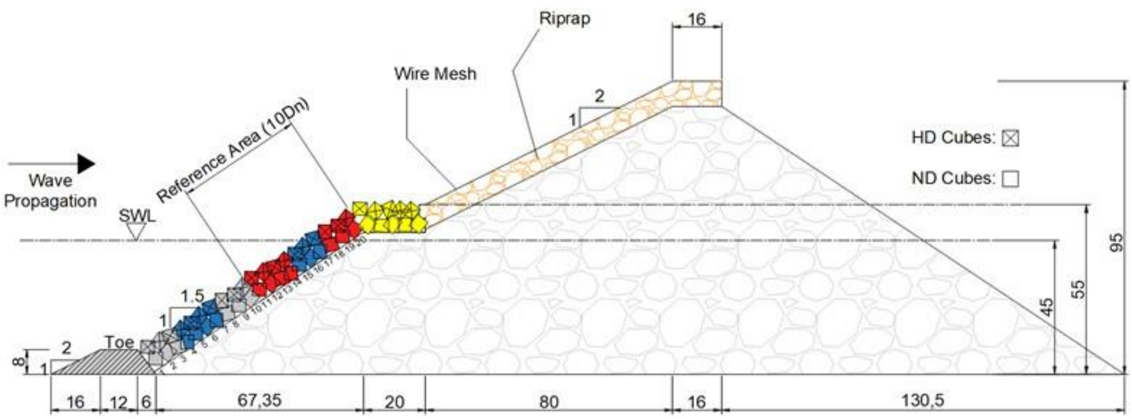


Figure 19 Positions of the HD and ND cubes for the experiment Emerged Berm

One of the most important observations in this experiment was that no sudden damage was declared. Most of the damage was observed in the upper rows of the reference area. Lower rows behaved more stable when compared to upper rows in the reference area. At the end of the experiment, the lower slope preserved its stability and core layer never became visible through the armor layer, and no cubes dislocated to the toe of the structure.

Stability number (N_s) versus relative damage (N_0) values were drawn and they are presented in Figure 21 including the results of the first three cases (emerged, at SWL, and submerged berm) with the Van der Meer (1988) formula for conventional breakwater cross-section consisted of ND cube units. The results for this case where the berm was emerged seemed to be compatible with the lower confidence band of the Van der Meer (1988) formula.

Figure 22 represents the results of dimensionless recession including the first three cases. For this case, from W1 (H_{m0}=0.05 m) to W7 (H_{m0}=0.15 m), there were no displacements in the berm. At W7 (H_{m0}=0.15 and N_s=1.74), the first displacement was observed in the 1st row of the berm, close to water side. In other words, recession started at the 1st row of the berm. At W9 (H_{m0}=0.16 m), there was no additional displaced cube observed. Only, 5 cubes dislocated from berm to lower slope.

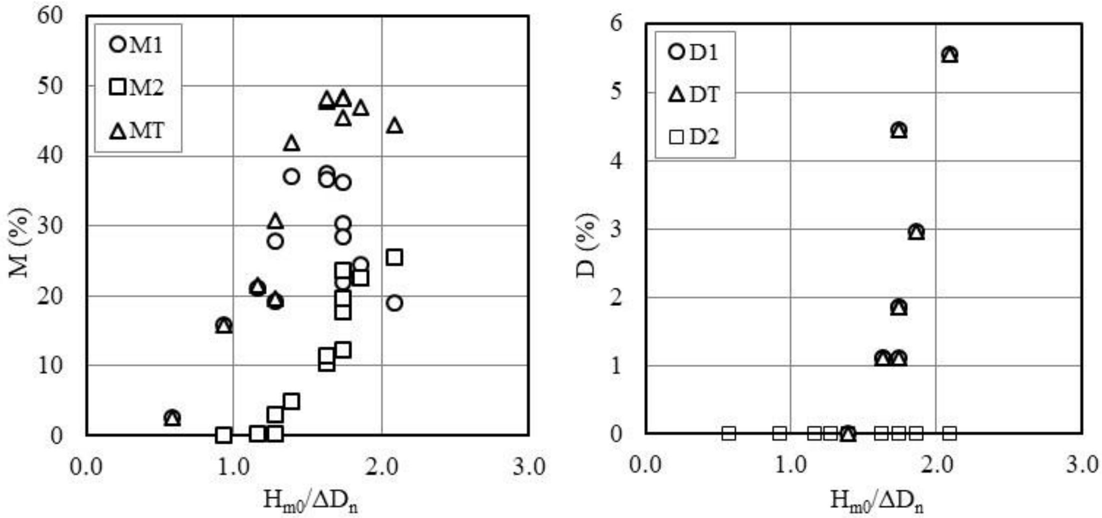


Figure 20 Movement (left: M) and displacement (right: D) in the lower layer HD Cubes with irregular placement for emerged berm case (the stability number based on HD).

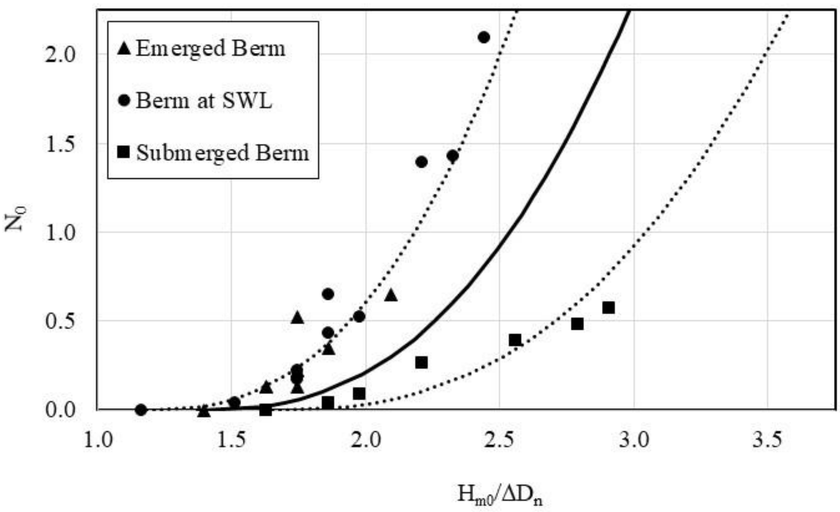


Figure 21 Relative damage for the emerged berm (Case 6), berm at SWL (Case 7) and submerged berm (Case 8) with the formula by the Van der Meer (1988) for conventional cube armored breakwaters using ND cubes where solid line indicates the Van der Meer (1988) formula and dashed lines show the confidence bands.

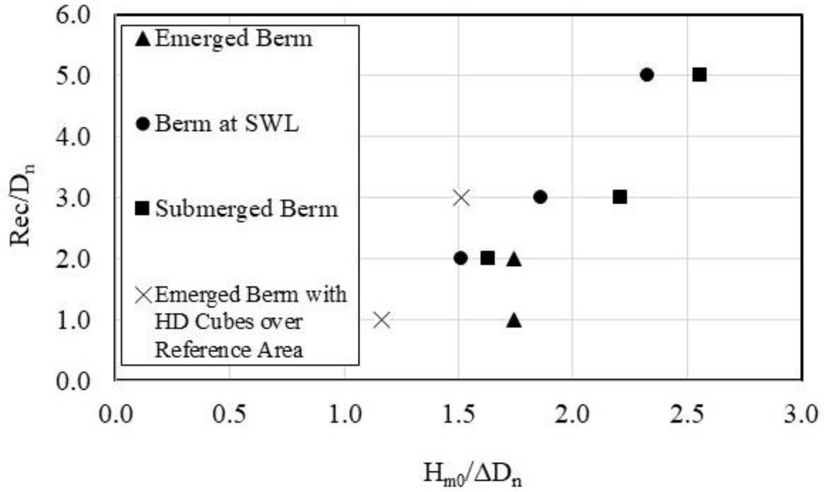


Figure 22 Stability number (N_s) and dimensionless recession (Rec) for berm (case 6-7-8) with the HD cubes (the stability number based on HD).

(ii) Case 7: (BID) Berm at SWL with irregular placement

The reference area and cube arrangements can be seen in Figure 23 for this case. There was no movement at W1 (H_{m0}=0.05 m) in the lower slope. The first movements were observed at W2 (H_{m0}=0.08 m). After that, no additional movements occurred at W3 (H_{m0}=0.09 m). At W4 (H_{m0}=0.10 m and N_s=1.16), the total movement ratio became 8%, and both M_1 and M_2 type movements were observed (Figure 24). W5 (H_{m0}=0.13 m and N_s=1.51) was one of the most important wave series because the first displacement occurred in this wave condition (Figure 24). From W6 (H_{m0}=0.15 m) to W10 (H_{m0}=0.16

m), total movement and displacement ratios increased gradually. At W10 (H_{m0}=0.17 m and N_s=1.98) total movement and displacement ratios became 42% and 5%, respectively. In addition, 42% was the highest total movement ratio for this experiment. After this wave, the movement ratio decreased gradually. At W11 (H_{m0}=0.19 m and N_s=2.21) the displacement ratio almost doubled and reached to 12%. After W11, total displacement ratio increased and reached to its maximum ratio of 18%, at W13 (H_{m0}=0.21 m and N_s=2.44 which is beyond the characteristic wave).

Flume observations showed that lower slope stability was affected by the berm recession. Wave run-down forces were substantially influential on some displaced cubes in the first row of the berm. Thereby, some cubes in the lower slope lost their stability due to these displaced cubes at the berm, while HD cubes kept ND cubes as stable as possible and only one dislocated HD cube was observed at the toe of the structure.

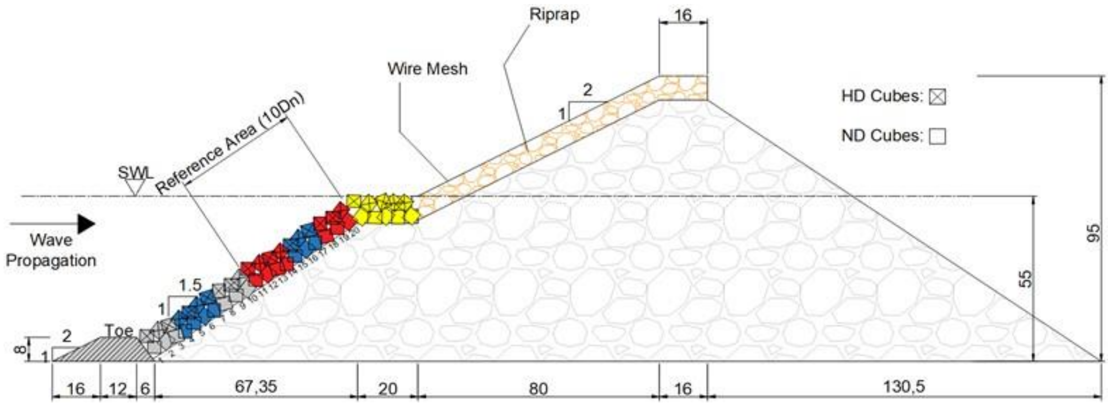


Figure 23 Positions of the HD and ND cubes for the experiment Berm at SWL

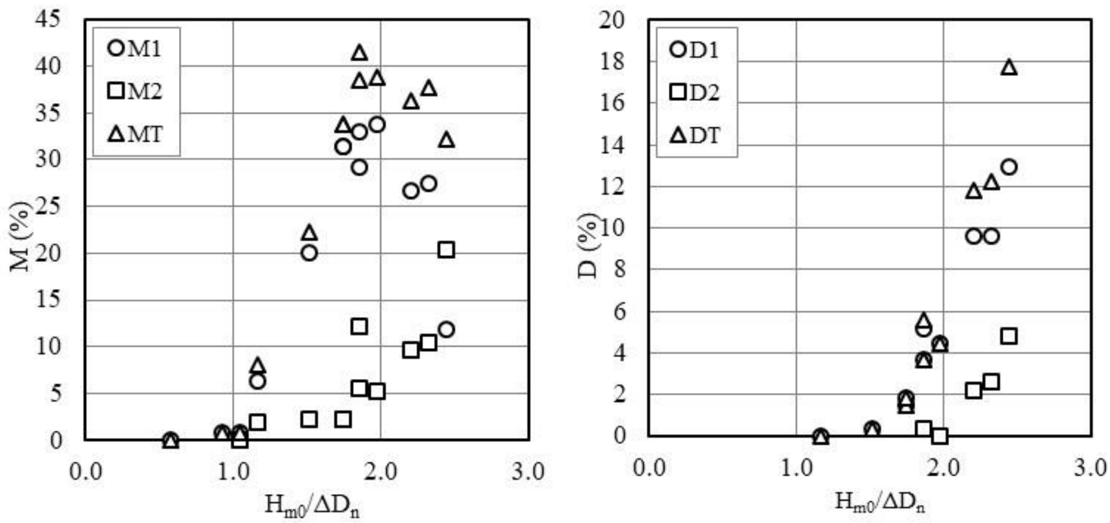


Figure 24 Movement (left: M) and displacement (right: D) in the lower layer HD Cubes with irregular placement for berm at SWL (the stability number based on HD).

The results of the dimensionless recession number for this case were given in Figure 22. From W1 (H_{m0}=0.05 m) to W4 (H_{m0}=0.10 m), there was no displacement at the berm. At W5 (H_{m0}=0.13 m and N_s=1.51), first displacement occurred at the 2nd row and movements were observed for other cubes close to the water side. From W6 (H_{m0}=0.15 m) to W10 (H_{m0}=0.16 m), displacements occurred at both 1st row and 2nd row of the berm, but recession was still at the 2nd row. At W10 (H_{m0}=0.17 m and N_s=1.98), recession started at 3rd row of the second layer of berm. At W11 (H_{m0}=0.19 m and N_s=2.21), new displacements were observed but these displaced cubes were at the first three rows. Thus, recession was still in the 3rd row. W12 (H_{m0}=0.20 m and N_s=2.33) was the first wave series that recession reached to the 5th row at the second layer, total number of displaced cubes reached to 18. At the last wave series of this case, W13 (H_{m0}=0.21 m and N_s=2.44, beyond characteristic wave), 12 more cubes displaced, and the total displacements reached to 30. Since the berm level was at SWL, it was strongly affected by the wave forces.

(iii) Case 8: (BID) Submerged berm with irregular placement

The reference area and cube arrangements can be seen in Figure 25 for this case. Water depth was 65 cm. The stability number versus the movement and displacement ratios are given in Figure 26. There was no movement for the first two wave series, at W1 (H_{m0}=0.05 m) and at W2 (H_{m0}=0.07 m). Movements started at W3 (H_{m0}=0.09 m) with the ratio of 3%. From W4 (H_{m0}=0.08 m) to W7 (H_{m0}=0.14 m), displacement was not observed, but total movement ratio reached to 37%. Visual observations showed that wave forces acting on lower slope was relatively low at waves from W1 (H_{m0}=0.05 m) to W7 (H_{m0}=0.14 m). However, at W8 (H_{m0}=0.16 m and N_s=1.86), wave forces were slightly greater than the previous wave. The first displacement occurred in this wave series (Figure 26). Displacement ratio increased to 0.7% at W9 (H_{m0}=0.17 m).

Starting from W3 (H_{m0}=0.09 m), rocking (M_1) was observed significantly in the lower slope. It reached to its maximum ratio at W11 (H_{m0}=0.22 m which is beyond the characteristic wave) with 39%. Also, total movement M_T reached to its maximum ratio at W12 (H_{m0}=0.24 m) with 46%. From W10 (H_{m0}=0.19 m and N_s=2.21) to W13 (H_{m0}=0.25 m and N_s=2.91), the displacement ratio increased as well, but this increment was gradual. At W13 (H_{m0}=0.25 m), total displacement at lower slope was 5%. Therefore, movements were dominant in the lower slope. Most of the wave forces were found to be more effective on the upper slope of the breakwater. However, run-down forces were effective in the lower slope significantly for the high energetic waves.

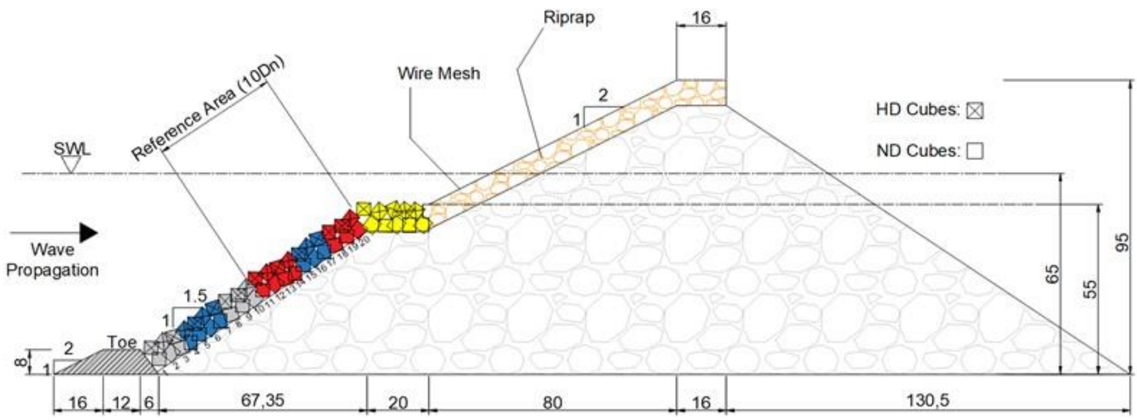


Figure 25 Positions of the HD and ND cubes for the Submerged Berm case

The relative damage (N_0) results against to the stability number (N_s) values obtained for this case can be seen in Figure 21. The comparison between the case results and the Van der Meer (1988) formula showed that the experimental results were mostly consistent with the upper confidence band of the formula. This indicates that applying the formula for the tested case with the berm at the still water level provides an underestimate of the actual damage.

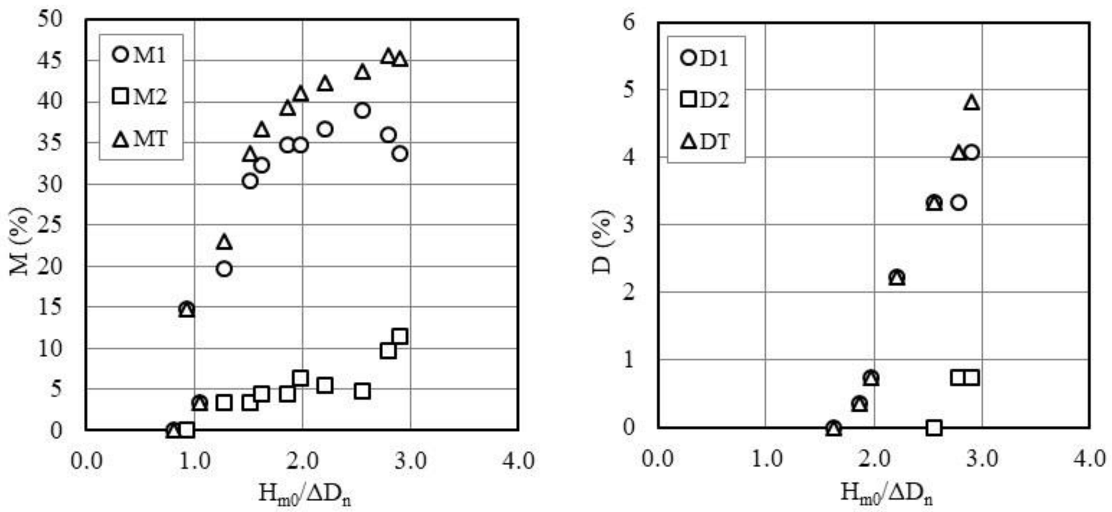


Figure 26 Movement (left: M) and displacement (right: D) in the lower layer HD Cubes with irregular placement for submerged berm (the stability number based on HD).

The dimensionless recession number results for this case are given in Figure 22. From W1 (H_{m0}=0.05 m) to W6 (H_{m0}=0.13 m), there was no displacement in the berm, but movements were detected at the berm as M_1 and M_2. At W7 (H_{m0}=0.14 m and N_s=1.63) recession started at the 2nd row of the berm with one cube. At W8 (H_{m0}=0.16 m) and W9 (H_{m0}=0.17 m) additional displacements were observed but these displaced cubes were at the 1st and 2nd row of the berm. Thus, recession was still at the 2nd row. Also, at W8 (H_{m0}=0.16 m) and W9 (H_{m0}=0.17 m), wave interaction between the berm and the lower slope increased because run-down wave forces started to be influential on the berm. At W10 (H_{m0}= 0.19 m and N_s=2.21), additional displacements occurred at the berm, and recession reached to the 3rd row. W11 (H_{m0}=0.22 m and N_s=2.56) was the first wave series that recession reached to the 5th row of the berm. Additional displacements occurred at the 4th row as well. Run-down forces were effective on the berm. For W12 (H_{m0}=0.24 m) and W13 (H_{m0}=0.25 m), additional displacements were detected at the berm. At W13 (H_{m0}=0.25 m and N_s=2.91), total number of displaced cubes in the berm were 30 which corresponds to the ratio of 22%. All displaced cubes were from the second (upper) layer of the berm, yet the berm shape was not deformed throughout the experiment. Eight of those total displaced cubes dislocated from the berm to the lower slope.

(iv) Case 9: (BID) Emerged berm with HD cubes over reference area with irregular placement

Arrangements of the HD and ND cubes are shown in Figure 27. Figure 28 depicts that there were no movements against the first wave, W1 (H_{m0}=0.05 m). Rocking started at W2 (H_{m0}=0.08 m), and the movement ratio was 5%, and then increased to its maximum value of 35% at W3 (H_{m0}=0.10 m). It should be noted that, only rocking (M_1) occurred in these wave series. After W3 (H_{m0}=0.10 m and N_s=1.16), rocking ratio decreased, but M_2 movement started to initiate, and the ratio reached to 17%. After W4 (H_{m0}=0.11 m), total movement ratio was 50%, which was half of the considered cubes in the reference area. After W4 (H_{m0}=0.11 m) M_1 ratio (rocking ratio) decreased and M_2 ratio increased, but total movement ratio M_T was constant at 50% (maximum M_T). At W5 (H_{m0}=0.13 m and N_s=1.51), M_T suddenly decreased to 6% and first displacement occurred in this wave condition with the ratio of 37% (Figure 28), because "Sliding" behavior was detected in the lower slope of the model breakwater. This behavior changed the packing density of the breakwater. Packing density decreased at the top of the reference area, while it increased significantly at the lower part of the reference area. Hence, neither displacement nor movement was observed remarkably on underside of the lower slope after the W5 wave series (H_{m0}=0.13 m).

In this case, a very large amount of movement occurred even for the lower stability numbers (M>30%), which was unacceptable. The amount of displacements was also very large for N_s>1.5. The behavior of the HD cubes in the reference area is very similar to Case 2 for the conventional breakwater.

Remarkable movements and then sliding behavior in the lower slope were observed, that were affected by the recession on the berm. The lower slope armor layer showed significant damage, but the core layer was never visible.

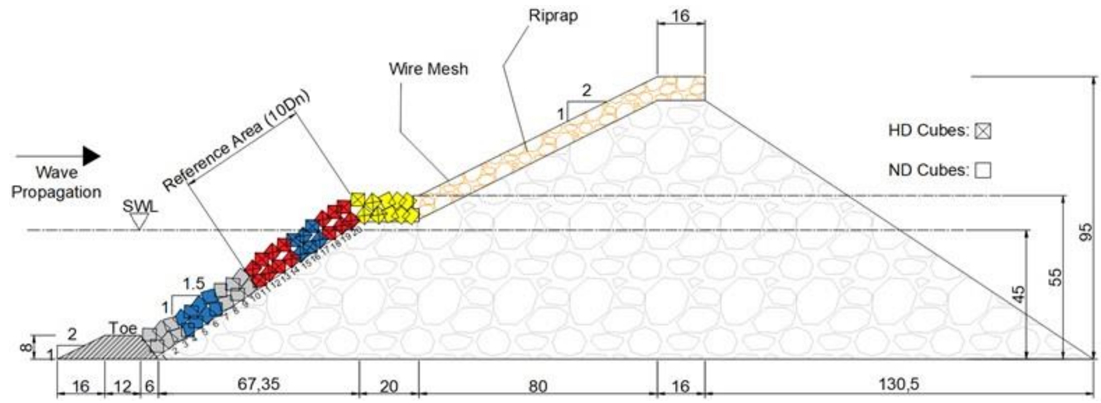


Figure 27 Positions of the HD and ND cubes for the case of Emerged Berm with HD Cubes over Reference Area

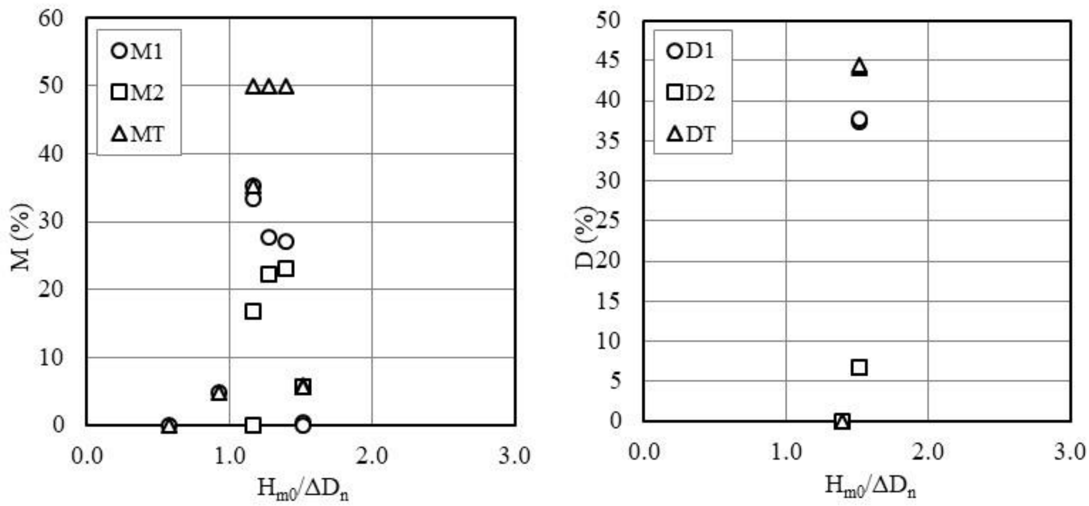


Figure 28 Movement (left: M) and displacement (right: D) in the lower layer HD Cubes over the reference area with irregular placement for emerged berm (the stability number based on HD).

The dimensionless recession number results of this case are presented in Figure 22. Recession was not observed for waves W1 (H_{m0}=0.05 m), W2 (H_{m0}=0.08 m) and W3 (H_{m0}=0.10 m). Only M_1 (rocking) movements were observed at W3. Displacements at berm started at W4 (H_{m0}=0.11 m and N_s=1.28) at the 1st row and then remained constant until the end of W5 (H_{m0}=0.13 m). At W5 (H_{m0}=0.13 m and N_s=1.51), another 10 displacements occurred on the berm ("Sliding" behavior occurred in the lower slope at this wave) and recession began at the 3rd row. Fourteen cubes were displaced from the berm to the lower slope.

5. DISCUSSION

The detailed discussion was made separately for conventional and berm type breakwaters given in the followings.

(i) Conventional Breakwaters

The damage initiation parameters are presented in Table 3 for all cases conducted for conventional breakwaters. To reveal the advantage of using HD units can be made by a comparison between Case 3 (double layer HD) and Case 10 (double layer (ND). Double layer HD cubes of Case 3 has a stability number larger than 2.67 obtained at W11 with H_s=0.23m, while it was 1.79 at W3 with H_s=0.10m for Case 10.

As for single layer cases of HD (Case 5) and ND cubes (Case 4), the stability number of ND cubes were larger than for HD cubes at the same wave condition of W3. However, when the amount of the movement ratios was checked for each case, they were 4% and 9% for HD and ND cubes, respectively. It should be noted that there was no displacement observed for the Case 3, 4 and 5.

Similarly, the comparison between “Case 1 and Case 10” and “Case 2 and Case 10” can be made through the results presented in Table 3 and Figure 10. The damage initiation was started at W5 for Case 1, while it was at W3 for Case 10, although the stability number Ns was 9% lower for HD cubes than for the ND cubes. On the other hand, the observations showed that the first (lower) layer of ND cubes triggered the second armor layer (HD) and increased the displacement capability of the HD units. This is also why the damage was larger for the Case 1 than for the Case 3 where the armor layers entirely consisted of HD cubes. Besides, the stability number N_s corresponding to the damage initiation in the Case 3 was more than 1.5 times of the Case 1.

When the Case 2 and Case 10 are compared, both has the damage initiation at the same wave condition of W3 with H_s=0.10m and the stability number of HD cubes is lower than that of ND cubes. Case 2 found to be less stable can be observed in Figure 10 that the results shifted more to the left comparing to the Case 1 due to the involvement of sliding behavior and so the relative damage of the Case 2 was about twice as much of the Case 1.

Table 3 Properties of the damage initiation of cube armored conventional breakwaters

Experiment	**Case**	**Wave series**	**H_{m0} (m)**	**N_s**
First Layer ND Cubes and Second Layer HD Cubes	1	W5	0.14	1.63
Reference Area Double Layer HD Cubes	2	W3	0.10	1.16
Double Layer HD Cubes	3	W11	0.23	>2.67
Single Layer ND Cubes	4	W13	0.21	>3.75
Single Layer HD Cubes	5	W13	0.21	>2.44
Double Layer ND Cubes	10	W3	0.10	1.79

When all the results were evaluated through observations, HD cubes in general showed more stable behavior than ND cubes except for the Case 2 due to the sliding event. Comparing Case 3 (HD) with Case 10 (ND) showed that the HD cubes are clearly more stable than the ND cubes (damage starts at Ns>2.67 versus 1.79). If the stability number Ns would account for the effects of the relative density, these values should have been similar. Since they are not the same, the stability number Ns does not seem to account for all effects of the density. That is also why the experimental results of HD cubes did not match with the Van der Meer (1988) formula which gave good agreement with the ND cubes results.

Van Gent et al. (2001) indicated that criteria for "failure of the top layer" cannot be taken equal for single and double top layers since for double top layers reserve much more stability. They suggested that N_0=2.0 was used to indicate the failure of double top layers, while it was 0.2 for single top layers. Moreover, Vieira et al. (2021) on the other hand proposed a threshold relative damage of N_0=0.1 for single top layers due to taking the direct wave attack on the filter through the leaving gap into consideration. For this study there were no displacements occurred for both single layer of HD and ND cubes and for double layer of HD cubes and it was not possible to reach to the threshold stability that corresponds to the displaced units of one diameter width owing to the limitations of the model dimensions, wave generation capacity and water depth at the toe of the structure preventing of larger waves. However, the obtained results showed that single layers (case 4 and 5) were more stable than that of double layers when HD (single/double layer) and ND (single/double layer) cube cases were compared to each other. As it can be seen from Table 3, the damage initiation started at an earlier wave series for double layer cases (Case 3 and 10). This can be explained by the strength of single layers that is a combination of the strength due to weight (also valid for double layers), the strength due to contact forces between the adjacent blocks (as for placed block revetments) and less wave attack on single units due to smoother surface of the entire slope. Triemstra (2000) also indicated that the stability of elements on the slope was largely influenced by the "laying roughness" of the elements and the "laying roughness" of the elements was affected by placing method as well as density. This statement also supports the reason why the single layer as being more stable than that of double layer.

(ii) Berm type breakwaters

Table 4 reveals the damage initiation parameters at the lower slope. The current experiments were tested at 0.45 m (emerged berm), 0.55 m (at SWL), and 0.65 m (submerged berm) water depths using irregular placement method for the berm width of $5D_n$. Results of the HD cubes experiments were also compared with results of berm type breakwaters consisted of ND cubes only conducted by Yuksel et al. (2020).

Figure 29 shows comparison of the HD between ND cubes for berm type breakwaters. It can be seen that displacements started early for berm at SWL similar to ND, but displacements started at higher stability numbers for the submerged berm. More displacements were observed in berms at SWL, and less displacements occurred for submerged berms. The initiation of the displacement found at the higher wave condition for all berm levels with HD cubes than the ND cubes.

Although the HD cubes were used at the second (upper) layer of the armor layer, the results of presented experiments for berm type breakwaters were found to be compatible with the Van der Meer formula (Figure 29). Figure 30 represents measured stability number versus predicted stability number for berm type breakwaters. The predicted stability number was calculated based on Yuksel et al. (2020). Based on the physical model tests in Yuksel et al. (2020), prediction method was derived for the stability of the lower slope for ND cubes and their prediction method offered a reduction in cube size. An empirical formula was described to determine the required cube size for each berm level where the berm emerged, at SWL and submerged in their study. In order to account for the influence of the berm on the lower slope with cubes, the reduction factors related to the width of the berm, the position of the berm and the wave steepness were considered. Good agreement between the measured and predicted stability parameters using Yuksel et al. (2020) formula was obtained for all berm levels in Figure 30.

Table 4 Properties of damage initiation parameters of the lower slope

Experiment	Wave	H_{m0} (m)	N_s (Measurement)	N_s (Yuksel et al., 2020)
Emerged Berm (▲)	W5	0.14	1.63	1.87
Berm at SWL (●)	W5	0.13	1.51	1.66
Submerged Berm (■)	W8	0.16	1.86	1.71
Emerged Berm with HD Cubes over Reference Area (✕)	W5	0.13	1.51	N.A.
Emerged Berm* (△)	W3	0.10	1.79	1.82
Berm at SWL* (o)	W4	0.10	1.79	1.91
Submerged Berm* (□)	W6	0.13	2.32	2.03

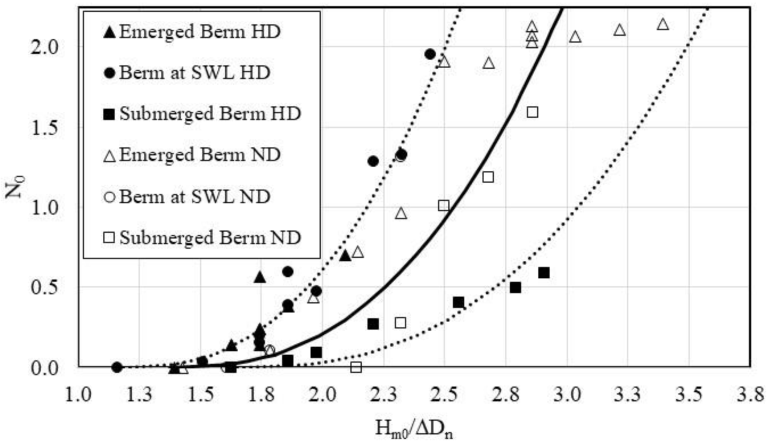


Figure 29 Comparison for experimental results of berm type breakwaters for HD and ND cubes with the Van der Meer (1988) formula for conventional cube armored breakwaters

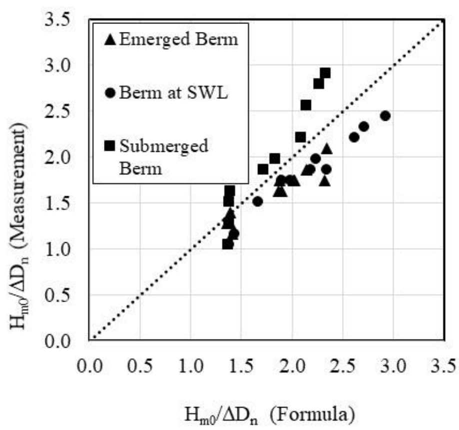


Figure 30 Measured stability number against predicted stability number using Yuksel et al., (2020) formula

7. CONCLUSIONS

The main purpose of this study was to provide insight into the performance of armor layers that consist of high-density cubes by analyzing effects of using different concrete densities of cubes and different placement methods. To determine the influence of different densities and different placement methods, conventional and berm type breakwater sections were modelled in a wave flume. Different configurations were considered for each type of breakwater cross-section by using normal (ND) and high-density cubes (HD) in single or double layers with regular or irregular placements.

The tests conducted for conventional breakwater cross-sections show that the armor layers with a first (lower) layer of ND cubes and a second (upper) layer of HD cubes (Case 1) are more stable than that of a traditional double layer of ND cubes (Case 10). On the other hand, the observations showed that the first (lower) layer of ND cubes triggered the second armor layer (HD) and increased the displacement capability of the HD units. This is also caused by the damage being larger for the case 1 than for the case 3 where the armor layers entirely consisted of HD cubes. Moreover, the stability number N_s corresponding to the relative damage initiation was more than 1.5 times higher for case 3 than for Case 1. This result meets the expectations that the stability of two layers of HD cubes is better than if HD cubes are only used in the upper layer.

The stability number for structures with only HD cubes in a reference area around the still water level were found to be lower compared to the other cases with HD cubes due to the sliding of HD cubes.

Only movement behavior was observed for the cases of the single layer with regularly placement of HD and ND cubes and there were no displacements or extractions occurred. Both breakwater models maintained their stability throughout the experiments. The amount of movements during the experiments with single layer of ND cubes (Case 4) was higher than that of the single layer of HD cubes (Case 5). The HD cubes in a single layer having relatively better performance and allowing for higher characteristic wave conditions might make it preferable due to the consideration of a potential increment of wave conditions in the future caused by the climate change.

All in all, HD cubes in general showed more stable behavior than ND cubes except for the case 2 due to the sliding. However, the stability numbers evaluated by the equation that is derived for ND cubes seemed not to represent the observed performance of HD cubes, not if HD cubes are only used in a part of the armour layer but also not if HD cubes are placed in the entire armour layer. The results show that using the current stability number N_s in a stability formula that has been derived for ND cubes, is not necessarily convenient for HD cubes.

The berm type breakwater cases were investigated for different berm levels and the cross-sections were created by ND cubes on the first layer and HD cubes on the second layer. These cases were compared with the previous study of Yuksel et al. (2020) where the same configurations were studied, but only with ND cubes. For all berm types it was found that the HD cubes used on the second layer of the lower slope and berm were more stable than that of the berm type breakwaters with the ND cubes.

In conclusion, HD concrete cubes were found to be more stable than ND cubes. HD cubes in a design would provide economic efficiency with a significant decrease of concrete volume compared to ND cubes. In the present test program, the characteristic wave height for the HD cubes was approximately a factor 1.5 higher than for normal density cubes.

Recommendations

The analysis was limited to the data obtained in the experiments carried out in this study. It is recommended to carry out additional testing for different densities and concrete block geometries.

Acknowledgement

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References

Brorsen, M, Burcharth, H. F. and Larsen, T. (1975). *Stability of dolos slopes*. In: B L Edge(ed), Proc 14th International Conference on Coastal Engineering, Copenhagen, 24–28 Jun 1974. ASCE, New York, vol 3, pp1691–1701.

Bueno Esposito, M., Díaz Vilarino, L.D., Martinez-Sanchez, J., Gonzalez Jorge, H., Arias, P. (2015). "3D reconstruction of cubic armoured rubble mound breakwaters from incomplete lidar data", International Journal of Remote Sensing 36(21):5485-5503.

Frens, A.B. (2007). “The impact of placement method on antifer-block stability”, Master of Science thesis, TU Delft.

Howe, D. And Cox, R., J., 2018, “Upgrading Breakwaters in Response to Sea Level Rise: Practical Insights from Physical Modelling”, 36. International Conference on Coastal Engineering, Baltimore, USA.

Hughes, S. A. (1993). *Physical Models and Laboratory Techniques in Coastal Engineering.* World Scientific.

Hudson, R. Y. (1959). Laboratory investigation of rubble-mound breakwaters. *Proceedings of ASCE Waterways and Harbours Division*, Vol. 85.

HydralabIII, (2007). “Guidelines for physical model testing of breakwaters: Rubble mound breakwaters”, Ver. 1.3 EC Contract no, 022441 (RII3).

Ito, M. Iwagaki, Y. Murakami, H. Nemoto, K. Yamamoto, M. and Hanzawa, M., 1994 “Stability of high-specific Gravity Armor Blocks”, 24. International Conference on Coastal Engineering, Kobe, Japan.

Lykke Andersen, T., and Burcharth, H.F., 2010. A new formula for front slope recession of berm breakwaters. Coastal Engineering 57, 359-374.

Mansard, E.P.D., and Funke, E.R., (1980). “The measurement of Incident and Reflected Spectra Using a Least Squares Method” In: Proceedings of the 17th Coastal Engineering Conference, pp. 154-172, Sdyney, Australia.

Medina, J. R. and Gomez-Martin, M. E., (2012). “K_D and safety factors of concrete armor units”, Int. Conference on Coastal Engineering 2012, Spain.

Rock Manual (2007). *The use of rock in hydraulic engineering*. CIRIA-CUR, Publication C683, London.

Sarfaraz, M. and Pak, A. (2017). "An integrated SPH-polyhedral DEM algorithm to investigate hydraulic stability of rock and concrete blocks: Application to cubic armours in breakwaters", Engineering Analysis with Boundary Elements 84, 1-18.

Triemstra, R. (2000). *The use of high density concrete in the armourlayer of breakwaters*. TU Delft Faculty of Civil and Environmental Engineering and Geosciences, Hydraulic Engineering. Delft, Netherlands.

Van der Meer, J. W. (1988). Stability of cubes, tetrapods and accropode. *Conference Breakwaters88,* (pp. 71-80).

Van Gent, M. R. A., Plate, S. E., Berendsen, E., Spaan, G. B. H., Van Der Meer, J. W., & d’Angremond, K. (1999). Single-layer rubble mound breakwaters. *Proc. Coastal Structures* (Vol. 99).

Van Gent, M. R. A., D'Angremond, K., & Triemstra, R. (2001). Rubble mound breakwaters: Single armour layers and high-density concrete units. *Breakwaters, coastal structures, and coastlines: Proceedings of the international conference organized by the Institution of Civil Engineers*. London, UK.

Van Gent, M. R. A. (2003). Recent developments in the conceptual design of rubble mound breakwaters. *COPEDEC VI*, Colombo, Sri Lanka.

Van Gent, M. R. A., & Luis, L. (2013). Application of Cubes in a single layer*. Proceedings of the 6th International Short Course/Conference on Applied Coastal Research (SCACR)*.

Van Gent, M.R. A., (2013). "Rock Stability of Rubble Mound Breakwaters with a Berm", Coastal Engineering, 78:35-45.

Van Gent, M. R. A., & Van der Werf, I. (2017). Single layer cubes in a berm. *International Short Course/Conference on Applied Coastal Research (SCACR)*

Vieira, F., Taveira-Pinto, F., & Rosa-Santos, P. (2020). Single-layer cube armoured breakwaters: Critical review and technical challenges. *Ocean Engineering*, 216, 108042.

Vieira, F., Taveira-Pinto, F., & Rosa-Santos, P. (2021). Damage evolution in single-layer cube armoured breakwaters with a regular placement pattern. *Coastal Engineering*, 169, 103943.

Wolters, G., & Van Gent, M. R. A. (2010). *Oblique Wave Attack on Cube and Rock Armoured*. Coastal Engineering, vol. 31, pp. 1–10, 2010.

Yuksel, Y., Cevik, E., Van Gent, M., Sahin, C., Gulver, M., Gultekin, C. (2018). "Stability effects of cube armor unit placement configurations in the berm of a breakwater" *36. International Coastal Engineering Conference (ICCE)*, Baltimore, USA

Yuksel, Y., Cevik, E., van Gent, M. R., Sahin, C., Altunsu, A., & Yuksel, Z. T. (2020). Stability of berm type breakwater with cube blocks in the lower slope and berm. *Ocean Engineering*, 217, 107985.

Appendix- Wave series with wave heights and corresponding Ns values for ND and HD cubes in the experiments.

Case 1: First Layer ND - Second Layer HD (Conventional Type)			Case 2: Reference Area HD with Irregular Placement (Conventional Type)			Case 3: Double Layer HD with Irregular Placement (Conventional Type)			Case 4: Single Layer ND with Regular Placement (Conventional Type)			Case 5: Single Layer HD with Regular Placement (Conventional Type)		
Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s
W1	0.05	0.58	W1	0.05	0.58	W1	0.05	0.58	W1	0.05	0.89	W1	0.05	0.58
W2	0.08	0.93	W2	0.08	0.93	W2	0.07	0.81	W2	0.08	1.43	W2	0.08	0.93
W3	0.10	1.16	W3	0.10	1.16	W3	0.09	1.05	W3	0.10	1.79	W3	0.10	1.16
W4	0.11	1.28	W4	0.10	1.16	W4	0.11	1.28	W4	0.11	1.96	W4	0.11	1.28
W5	0.14	1.63	W5	0.14	1.63	W5	0.14	1.63	W5	0.15	2.68	W5	0.14	1.63
W6	0.16	1.86	W6	0.15	1.74	W6	0.16	1.86	W6	0.17	3.04	W6	0.17	1.98
W7	0.16	1.86	W7	0.16	1.86	W7	0.18	2.09	W7	0.17	3.04	W7	0.17	1.98
W8	0.17	1.98	W8	0.16	1.86	W8	0.19	2.21	W8	0.18	3.21	W8	0.18	2.09
W9	0.18	2.09	W9	0.18	2.09	W9	0.20	2.33	W9	0.19	3.39	W9	0.19	2.21
W10	0.17	1.98	W10	0.16	1.86	W10	0.20	2.33	W10	0.17	3.04	W10	0.17	1.98
W11	0.20	2.33	W11	0.20	2.33	W11	0.23	2.67	W11	0.22	3.93	W11	0.22	2.56
W12	0.20	2.33	W12	0.20	2.33				W12	0.21	3.75	W12	0.21	2.44
W13	0.21	2.44	W13	0.21	2.44				W13	0.21	3.75	W13	0.21	2.44

Case 6: Emerged Berm with Irregular Placement (Berm Type)			Case 7: Berm at SWL with Irregular Placement (Berm Type)			Case 8: Submerged Berm with Irregular Placement (Berm Type)			Case 9: Emerged Berm with HD Cubes over Reference Area with Irregular Placement (Berm Type)			Case 10: Double Layer ND with Irregular Placement (Conventional Type)		
Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s	Wave	H_{m0} (m)	N_s
W1	0.05	0.58	W1	0.05	0.58	W1	0.05	0.58	W1	0.05	0.58	W1	0.05	0.89
W2	0.08	0.93	W2	0.08	0.93	W2	0.07	0.81	W2	0.08	0.93	W2	0.08	1.43
W3	0.11	1.28	W3	0.09	1.05	W3	0.09	1.05	W3	0.10	1.16	W3	0.10	1.79
W4	0.10	1.16	W4	0.10	1.16	W4	0.08	0.93	W4	0.10	1.16	W4	0.11	1.96
W4.1	0.11	1.28	W5	0.13	1.51	W5	0.11	1.28	W4.1	0.11	1.28	W4.1	0.12	2.14
W4.2	0.12	1.40	W6	0.15	1.74	W6	0.13	1.51	W4.2	0.12	1.40	W5	0.14	2.50
W5	0.14	1.63	W7	0.15	1.74	W7	0.14	1.63	W5	0.13	1.51	W6	0.16	2.86
W5.1	0.14	1.63	W8	0.16	1.86	W8	0.16	1.86	W5.1	0.13	1.51	W7	0.16	2.86
W6	0.15	1.74	W9	0.16	1.86	W9	0.17	1.98				W8	0.17	3.04
W7	0.15	1.74	W10	0.17	1.98	W10	0.19	2.21				W9	0.18	3.21
W8	0.15	1.74	W11	0.19	2.21	W11	0.22	2.56				W10	0.17	3.04
W9	0.16	1.86	W12	0.20	2.33	W12	0.24	2.79				W11	0.20	3.57
W10	0.15	1.74	W13	0.21	2.44	W13	0.25	2.91				W12	0.21	3.75
W11	0.18	2.09												