

REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

**THE USE OF HIGH DENSITY CONCRETE CUBE IN THE ARMOUR
LAYER OF BREAKWATERS**

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MASTER OF SCIENCE THESIS

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Hasan Alper KAYA

Signature



*Dedicated to my family,
and to those who inspired me.*

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To accomplish the Master of Science programme in Civil Engineering, at Yıldız Technical University, the influence of the high-density concrete cubes were investigated as armor material for conventional breakwaters and berm breakwaters applying regular and irregular placement methods. The experimental study has been carried out in the Coastal and Port Engineering Laboratory at Yıldız Technical University.

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LIST OF SYMBOLS

M_a	Armor Material Mass
$H_{\%2}$	Average of the Highest 2% Wave Heights
$H_{1/3}$	Average of the Highest 1/3 Wave Heights
$H_{1/10}$	Average of the Highest 1/10 Wave Heights
B	Berm Width
v	Characteristic Flow Velocity
K_n	Coefficient Containing External and Internal Effects
σ	Cohesion Force
r	Correlation Coefficient
R_c	Crest Relative Freeboard
D_c	Crest Width
ξ_{cr}	Critical Breaker Parameter
S	Damage Level
S_d	Damage Percent of Eroded Area
ρ_{cube}	Density of Cube
ρ	Density of Unit
ρ_s	Density of Stone
ρ_w	Density of Water
d_b	Dept of Berm
C_D	Drag Coefficient
F_D	Drag Force
D	Diameter of Unit
A_e	Erosion Area

γ_{rec}	Factor Number
$\dot{u}(t)$	Flow Acceleration
μ	Friction Coefficient
F_r	Froude Number
g	Gravitational Acceleration
F_G	Gravitational Force
K_D	Hudson Stability Coefficient
β	Incident Wave Angle
F_I	Inertial Force
C_M	Inertia Coefficient
γ_{BB}	Influence Factor for Berm
γ_β	Influence Factor for Oblique Wave Attack
ξ	Iribarren Parameter
m_i	i^{th} Moment of Wave Spectrum
L	Length of the Calculation Area
F_L	Lift Force
M_{armor}	Mass of Armor Layer Material
$M_{50, \text{lowerlayer}}$	Mass of Armor Lower Layer Material
M	Mass of Unit
N_{PBL}	Maximum Quantity of Units that can be Placed in BxL Area
H_{max}	Maximum Wave Height
T_E	Mean Energy Period
T_m	Mean Wave Period
D_n, D_{n50}	Nominal Diameter
$D_{n, \text{armor}}$	Nominal Diameter of Armor Layer Material

$D_{n50,lowerlayer}$	Nominal Diameter of Concrete Cube
$D_{n50,upper}$	Nominal Diameter of Upper Layer Material
N_d	Number of Displaced Units
N_r	Number of Rocking Units
N_{sl}	Number of Sliding Units
N	Number of Waves
q	Overtopping Discharge
T_p	Peak Wave Period
P	Permeability
ψ_s	Packing Density
n	Porosity
D_1	Primary Damage
M_1	Primary Movement
N_{BL}	Quantity of Units Placed to BxL Area
Rec	Recession
γ_{berm}	Reduction Factor
N_0, N_{0d}	Relative Damage
Δ	Relative Density
C_r	Reflection Coefficient
Re	Reynolds Number
D_2	Secondary Damage
M_2	Secondary Movement
N	Shape Dependent Coefficient on Hudson Formulae
α	Slope Angle Relative to Flume Bottom
H_{m0}	Spectral Significant Wave Height

H_s	Spectral Significant Wave Height
S_r	Specific Gravity of Armor Unit
N_s	Stability Number
K_{DH}	Stability Coefficient for Damage Initiation
K_{D0}	Stability Coefficient for 0% Damage
$K_{D<5\%}$	Stability Coefficient for 5% Damage
σ	Standard Deviation
D_T	Total Damage
M_T	Total Movement
M_u	Underlayer Material Mass
V	Volume of Unit
H	Water Depth
h_{toe}	Water Depth at Toe
ξ	Wave Kinematics
H	Wave Height
T	Wave Period
s_m	Wave Steepness Obtained from Mean Period
s_p	Wave Steepness Obtained from Peak Period
L_m	Wavelength Obtained from Mean Period
L_p	Wavelength Obtained from Peak Period
We	Weber Number
W	Weight of Unit
B	Width of Calculation Area
L	Width of Wave Flume

LIST OF ABBREVIATIONS

ARC	Active Reflection Compensation
BID	Berm-Irregular-Double
CCS	Carbon Capture and Storage
CID	Conventional-Irregular-Double
CRS	Conventional-Regular-Single
CEM	Costal Engineering Manual
FR	France
FR	Fully-Reshaping
HR	Hardly-Reshaping
HD	High-Density
IC	Icelandic-Type
JONSWAP	Joint North Sea Wave Project
MA	Mass-Armored
ND	Normal-Density
NRT	Near Room Temperature
NL	Netherlands
OECD	Organization for Economic Co-operation and Development
PR	Partly-Reshaping
PM	Pierson-Moskowitz Spectrum
PIANC	World Association for Waterborne Transport Infrastructure
QTY	Quantity
RI	Regularity Index
RMSE	Root Mean Square Error
SI	Scatter Index

SWL	Still Water Level
UK	United Kingdom
USGS	United States Geological Survey
USA	United States of America



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The Use of High Density Concrete Cube in the Armour Layer of Breakwaters

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Master of Science Thesis

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In coastal regions, breakwaters have been used for many years for different purposes. Important coastal areas such as harbors and marinas can be made more sheltered and functional by building breakwaters. However, considering important parameters such as climate change, aesthetic of coastal areas, accessibility to construction materials, carbon emissions and construction cost, these structures must be developed day by day.

Berm and conventional breakwaters are very costly and require appropriate engineering services. Research conducted for many years, have contributed to improve these structures, but there are very few studies in the literature on the use of high-density (HD) concrete blocks. This study aims to contribute to this gap.

Experiments were performed in the Hydraulic and Coastal&Harbour Engineering Laboratory at the Yıldız Technical University. Conventional and berm breakwater models were used. HD blocks had a density of 3.15 gr/cm^3 , while normal density (ND) blocks had a density of 2.40 gr/cm^3 . For conventional breakwaters 1/1.5

slope was used, for berm breakwaters $1/1.5$ lower slope and $1/2$ upper slope was used.

Waves used in the experiments were generated with the JONSWAP spectrum (each individual wave series contained 1000 waves). Wave parameters were measured with 5 probes. Design wave height was determined as 20 cm. Damage to the armor layer has been analyzed with videos and photographs.

In conclusion, HD blocks were found more stable than ND blocks. For berm breakwaters, the highest damage occurred on the armor layer was observed when the berm level was at still water level. No damage was observed for conventional breakwaters with single layer regular placement method. Comparison of two conventional breakwaters with HD cubes showed that the laying-roughness is a significant parameter for armor layer stability. K_D values were found lower than the studies retrieved from the literature due to higher relative density of the HD cubes.

Keywords: Berm breakwater, conventional breakwater, high-density concrete, cube block, climate change.

Dalgakıranların Koruma Tabakalarında Yüksek Yoğunluklu Beton Küp Kullanılması

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Kıyı alanlarında, dalgakıranlar farklı amaçlar için uzun yıllardan beri kullanılmaktadır. Liman, marina gibi önemli kıyı alanları, dalgakıranlar inşa edilerek daha korunaklı ve işlevsel hale getirilebilmektedir. Ancak iklim değişikliği, kıyı alanlarının estetiği, inşaat materyallerine erişilebilirlik, karbon emisyonu ve inşaa maliyeti gibi önemli parametreler dikkate alınarak bu yapıların her geçen gün geliştirilmesi gerekmektedir.

Basamaklı ve geleneksel dalgakıranlar çok maliyetli olup uygun mühendislik hizmeti alması gereken yapılardır. Uzun yıllardan beri yapılan araştırmalar bu yapıları iyileştirme konusunda literatüre katkı sağlamıştır ancak yüksek yoğunluklu beton blokların kullanımı ile ilgili literatürde çok az sayıda çalışma bulunmaktadır. Bu çalışma, bu eksikliğe katkıda bulunmayı amaçlamaktadır.

Deneyler Yıldız Teknik Üniversitesi bünyesinde bulunan Hidrolik ve Kıyı&Liman Mühendisliği Laboratuvarında gerçekleştirilmiştir. Geleneksel ve basamaklı dalgakıran modelleri kullanılmıştır. Yüksek yoğunluklu bloklar 3.15 gr/cm^3 , normal yoğunluklu bloklar ise 2.40 gr/cm^3 , yoğunluğa sahiptir. Geleneksel

dalgakıranlar için 1/1.5 şev eğimi, basamaklı dalgakıranlar için ise alt şevde 1/1.5 üst şevde ise eğim 1/2 olarak alınmıştır.

Deneylerde kullanılan dalgalar JONSWAP spektrumu (her bir dalga serisi 1000 dalga içermektedir) ile oluşturulmuştur. Dalga parametreleri 5 adet prob ile ölçülmüştür. Tasarım dalga yüksekliği 20 cm olarak belirlenmiştir. Koruma tabakasında meydana gelen hasar videolar ve fotoğraflar yardımı ile analiz edilmiştir.

Sonuç olarak, yüksek yoğunluklu bloklar normal yoğunluklu bloklara göre daha stabil bulunmuştur. Basamaklı dalgakıranlar için koruma tabakasında hasar en çok basamak sahin su seviyesindeyken meydana gelmiştir. Geleneksel dalgakıranlar için tek sıra ve düzenli dizilimin kullanıldığı dalgakıran modellerinde hasar gözlenmemiştir. Yüksek yoğunluklu beton bloklara sahip iki geleneksel dalgakıranın karşılaştırılması sonucunda, yüzey pürüzlülüğünün koruma tabakası stabilitesi için önemli bir parametre olduğu görülmüştür. HD küplerin göreceli yoğunluğunun daha yüksek olması nedeniyle K_D değerleri literatürden alınan çalışmalardan daha düşük bulunmuştur.

Anahtar kelimeler: Basamaklı dalgakıran, geleneksel dalgakıran, yüksek yoğunluklu beton, küp blok, iklim değışikliğı.

1.1 Motivation

The motivation for this research covers various topics. It contributes not only to economic concerns, but also to solving problems that are maybe beyond economic reasons. For instance, climate change has effects on our planet in many areas such as coastal regions. An example can be given from Patil and Deo (2020), for coastal areas in India, they demonstrated that sea-level rise has a significant impact on shoreline change. Because of climate change, many components affect each other like a chain reaction. So, any solution whether a small one or a great one will result beneficial in terms of adaptation to climate change. In the following sections, motivational topics are going to be discussed deeply.

1.1.1 Climate Change and Sea-Level Rise

A significant portion of the world's population lives in coastal areas and most of the economic activities are carried out in these regions. With the increasing human population around the world, the stress in coastal areas increase as well as because of attractiveness of these areas. For example, according to Neumann *et al.* (2015), 73% of Netherlands' population lives in coastal areas. Another example is that coastal population in low-elevated regions in Bangladesh and China was almost doubled from 1990 to 2000. In the lights of these information, protection and management of coastal areas is extremely important. Neumann *et al.* (2015), studied 4 different scenarios for human population in coastal areas considering sea-level rise, coastal migration etc. for 2030 and 2060. Figure 1.1 shows their findings from two different scenarios, and depicts how low-elevated coastal areas are under population stress.

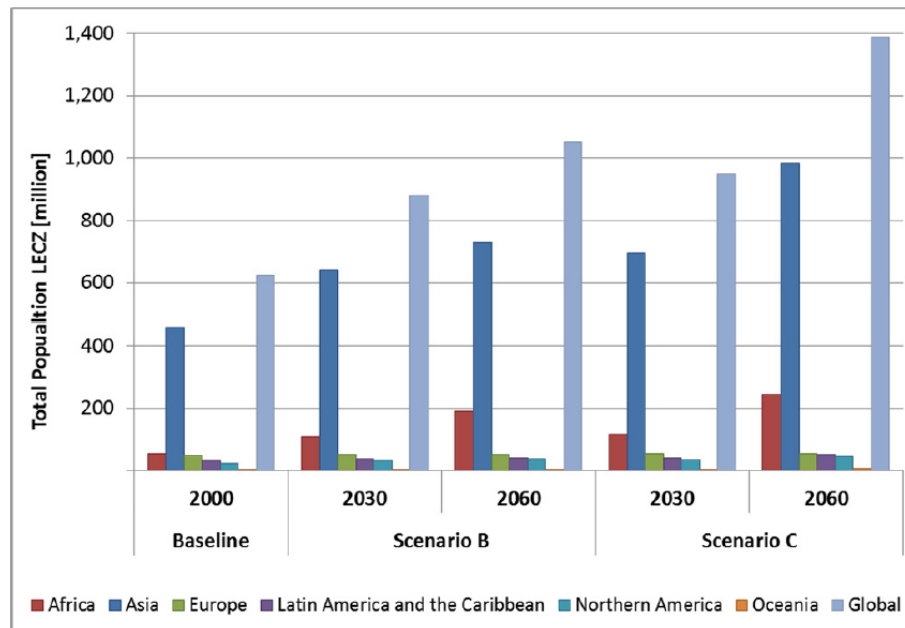


Figure 1.1 Population projections in low-elevated coastal zones (Neumann *et al.* 2015)

Sea-level rise is one of the most harming effects of changing climate. For example, general loss of life quality and coastal flooding are some important examples to sea-level rise. As mentioned earlier, human population in coastal zones is increasing, and management of these areas requires complex solutions because of changing climate and sea-level rise. Many researchers projected future sea-level by using climate scenarios, models and confidence levels. Figure 1.2 shows various sea-level rise projections from different studies.

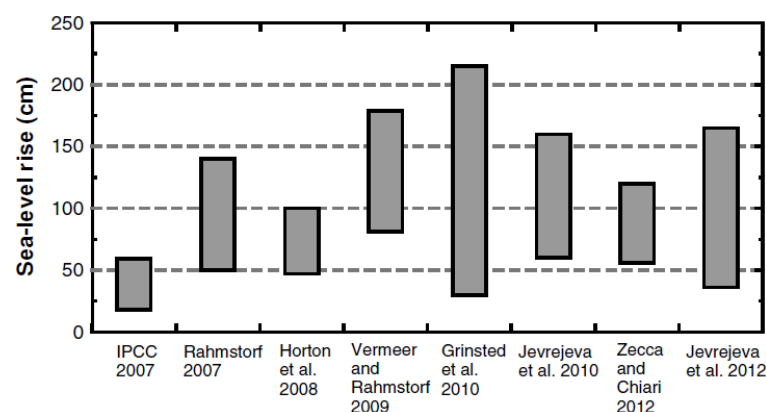


Figure 1.2 Sea-level rise projections from various studies (Chang *et al.* 2015)

A detailed research conducted by Houston (2013) to predict sea-level rise. Most importantly, he also focused on contributions of Antarctica and Greenland. By

using satellite measurements, he found that ice melting has significant influence on sea-level rise. He used different confidence levels for predictions. Table 1.1 shows results of his study. Note that, sea-level rise is not same in every region in world because of different coastal processes such as tidal activities.

Table 1.1 Predictions between 1990 and 2100 (Houston 2013)

Contributor	Low scenario		Mid scenario	High scenario	
	Uncertainty levels				
	5%	50%	50%	50%	95%
Greenland	0.01	0.06	0.095	0.11	0.21
Antarctica	-0.10	-0.04	0.035	0.09	0.16
Thermal expansion	0.08	0.16	0.210	0.27	0.44
Glaciers and ice caps	0.09	0.12	0.140	0.13	0.19
Totals	0.18	0.30	0.480	0.60	0.82

As aforementioned, effects of sea-level rise and changing climate cannot be overlooked because of their huge impacts on coastal regions. An important example can be given from the Netherlands. The Netherlands is the most densely populated country in Europe, and also one of the countries that will be affected by sea-level rise significantly. But the Afsluitdijk project, which was constructed between 1927 and 1932, is going to be elevated and strengthened due to sea-level rise to protect the country from flooding and possible other effects. The Afsluitdijk also separates and protects the largest freshwater deposit of the Netherlands from Wadden Sea. Figure 1.3 shows the Afsluitdijk and its location. As armor material, concrete blocks are going to be used in order to increase the stability of the dike.

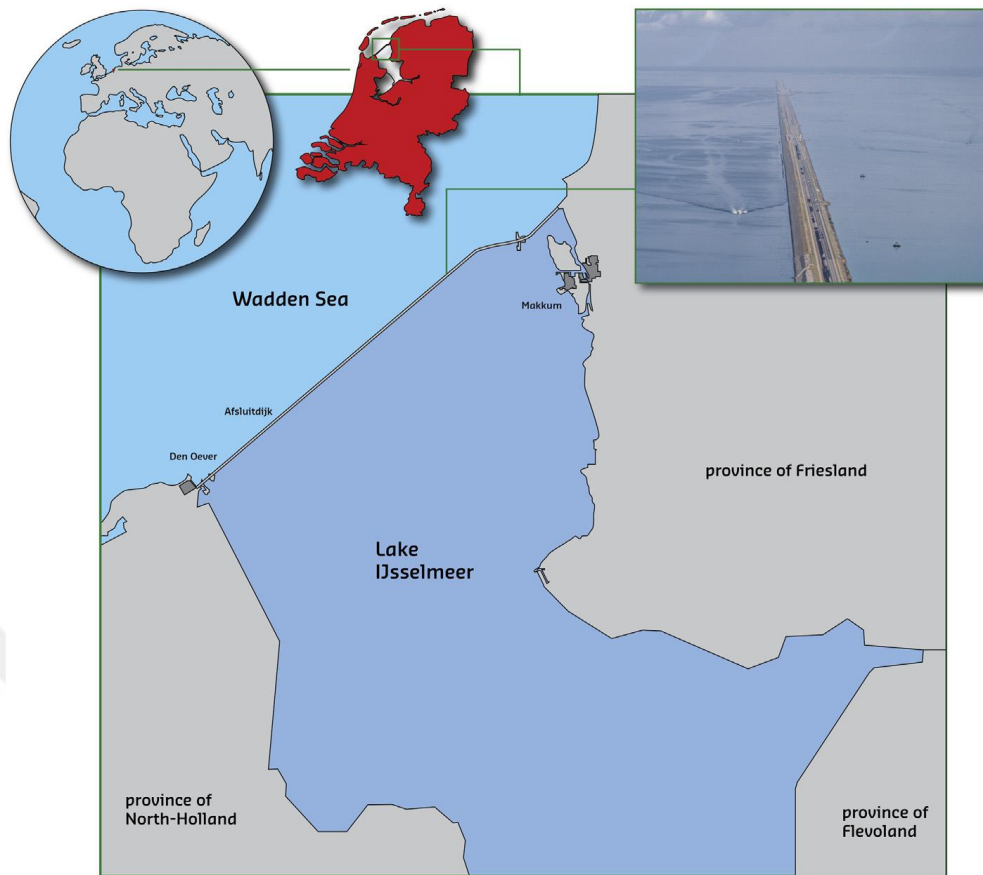


Figure 1.3 The Afsluitdijk and its location (Janssen *et al.* 2014)

According to Van Oord (2018), in the reinforcement of the Afsluitdijk 75,000 concrete Level Blocks will be used in the seaward side with 6,500 kg weight. In the construction phase, pontoon crane will be used to place all armor elements. Figure 1.4 shows scaled flume tests of the Afsluitdijk.



Figure 1.4 Flume tests of the Afsluitdijk at Deltares (Breteler *et al.* 2019)

In the light of given information, it can be concluded that shore protection structures such as breakwaters will have important roles in the future under

changing climate and sea-level in order to adapt new coastal zone dynamics. For instance, with the use of high-density cubes as armor layer material, increasing stability requirements can be compensated in an innovative way.

1.1.2 Increasing Wave Heights and Wave Power

Behavior of a coastal zone depends various parameters such as wave climate and geomorphological aspects. The wave climate of the coastal zones may change due to climate change and rising sea level. Thus, behavior of the coastal zones changes in time. These challenging circumstances require new adaptation techniques to the new conditions.

On the other part, for instance, storm surges are expected to change according to future projections (Mori *et al.* 2010). Therefore, it is important to consider influences of new future coastal conditions in order to reduce and restrain coastal hazards.

An important aspect was mentioned in the research article of Mori *et al.* (2010). They addressed design of coastal structures highlighting a coastal breakwater. As is known, in the design of breakwaters, several components are considered such as water depth and wave height. With changing climatic conditions, sea-level and wave dynamics, these design parameters are expected to change considerably and should be accounted for the construction of these type structures.

Instead of focusing only wave height like most studies in the literature, Reguero *et al.* (2019) investigated global wave power. Their findings showed significant results in terms of global wave power change. Figure 1.5 demonstrates critical results from their study showing that global wave power has increased by approximately 0.4% per year globally from 1948 to 2010 (Reguero *et al.* 2019). As known, waves are mostly generated by wind (see also Figure 1.6 for different wave types and their frequencies) with shear stress between wind and water surface, which refers that, energy increase is also an outcome of increased energy transfer between wind and sea-surface.

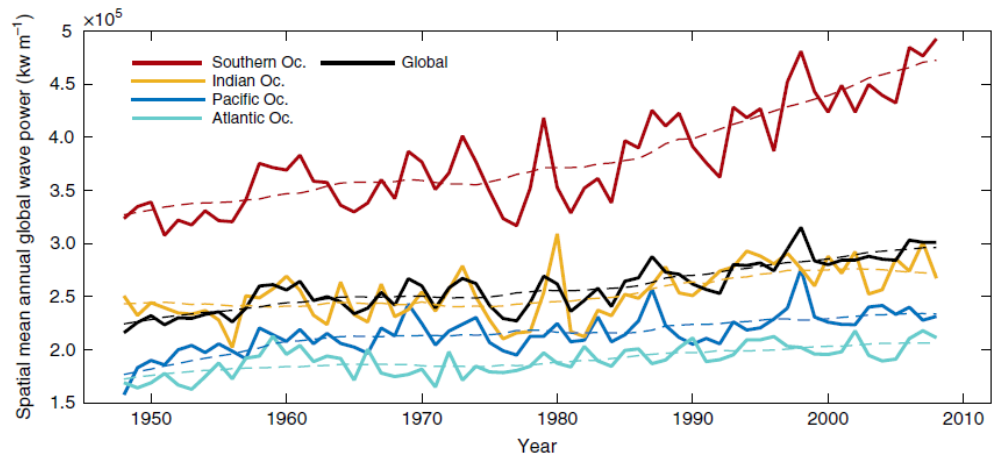


Figure 1.5 Mean annual global wave power increase from 1948 to 2010 (Reguero *et al.* 2019)

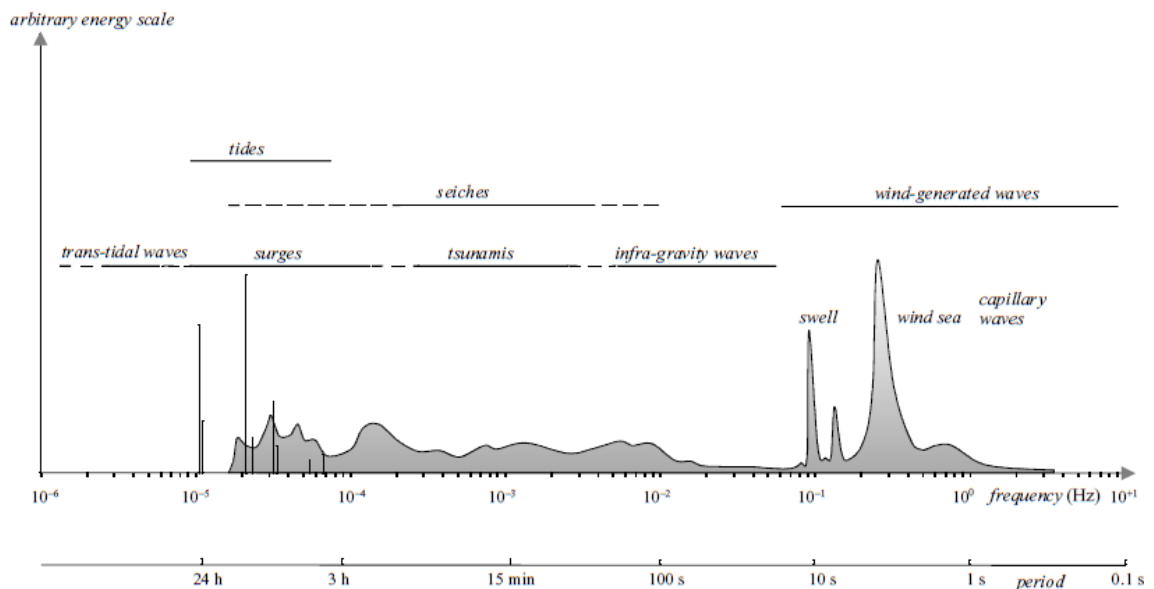


Figure 1.6 Periods and frequencies of different wave types (Holthuijsen 2010)

In conclusion, it is clear that adaptation to the changing environmental dynamics in coastal areas is crucial. For example, increasing wave heights and wave powers will require more stable armor elements than before for coastal protection structures. Thus, high-density concrete cubes may have important role to adapt the changing dynamics.

1.1.3 Cement Consumption and CO₂ Emission

In terms of compelling impacts of climate change, reducing CO₂ emissions and applying efficient energy procedures are compulsory. It is certain that energy

consumption and CO₂ emission in cement industry should be managed appropriately. In accordance with Benhelal *et al.* 2012 and Taylor *et al.* 2006, both research demonstrated that cement industry has been one of the largest CO₂ emission sources. It is predicted that cement consumption will increase with the increasing population and demand and will continue to increase dramatically. In addition, the cement production process consumes a significant amount of energy which is derived from fuel and electricity. Figure 1.7 and Figure 1.8 show global cement demand and CO₂ emissions from cement production, respectively.

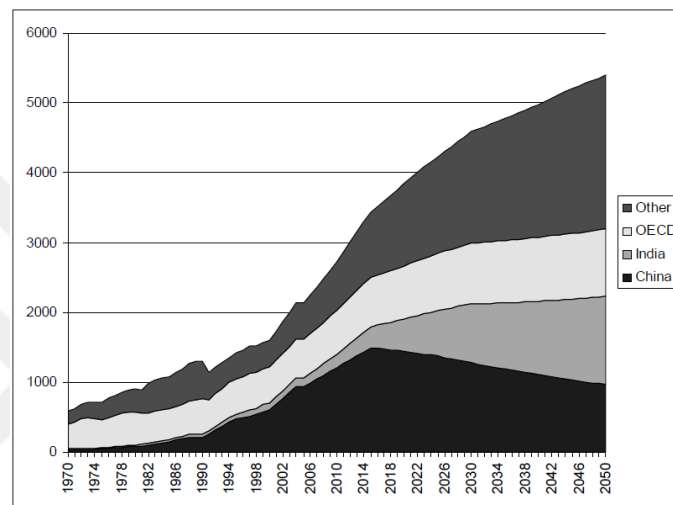


Figure 1.7 Global cement demand forecast from 1970 to 2050 (Taylor *et al.* 2006)

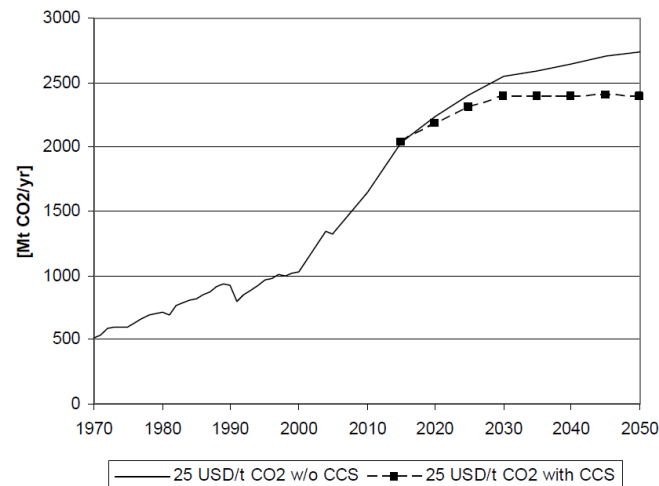


Figure 1.8 CO₂ emissions projection from cement production without CCS and with CCS (Taylor *et al.* 2006)

According to Triemstra (2000), using high-density concrete can reduce volume of the concrete cube armor units. Therefore, consumption of cement decreases. As a

result of this, with decreasing cement consumption, demand to the cement decreases. It can be concluded that high-density concrete may have significant and innovative role in the production of concrete armor cubes which contributes adaptation to climate change innovatively. Since freshwater resources are extremely important, it can also contribute lowering the amount of water used in concrete production.

1.1.4 Environmental Impacts of Stone Quarries

In the armor layer of breakwaters, rock can be used according to the design aspects but with increasing technology and opportunities, innovative concrete armor units can be used rather than using the rock. As is known, rock armor units are extracted from stone quarries but, there are two major issues about stone quarries. Firstly, it is not easy to find a stone quarry that is close to the construction site. Since all breakwaters are constructed in coastal regions, rocks should be transported to those regions and this process is uneconomic if the quarry stone is far from the construction site. Secondly, environmental impacts of stone quarries cannot be overlooked.

An extensive study was published by Langer (2001)(USGS), to investigate effects of stone quarries. According to this research, stone quarries have considerable environmental effects. The examples of negative effects of quarries are noise, dust, sinkhole collapse, water quality reduction, change in the natural groundwater behavior and threats against natural habitat. In Figure 1.9, some harmful effects of quarry stones can be seen.

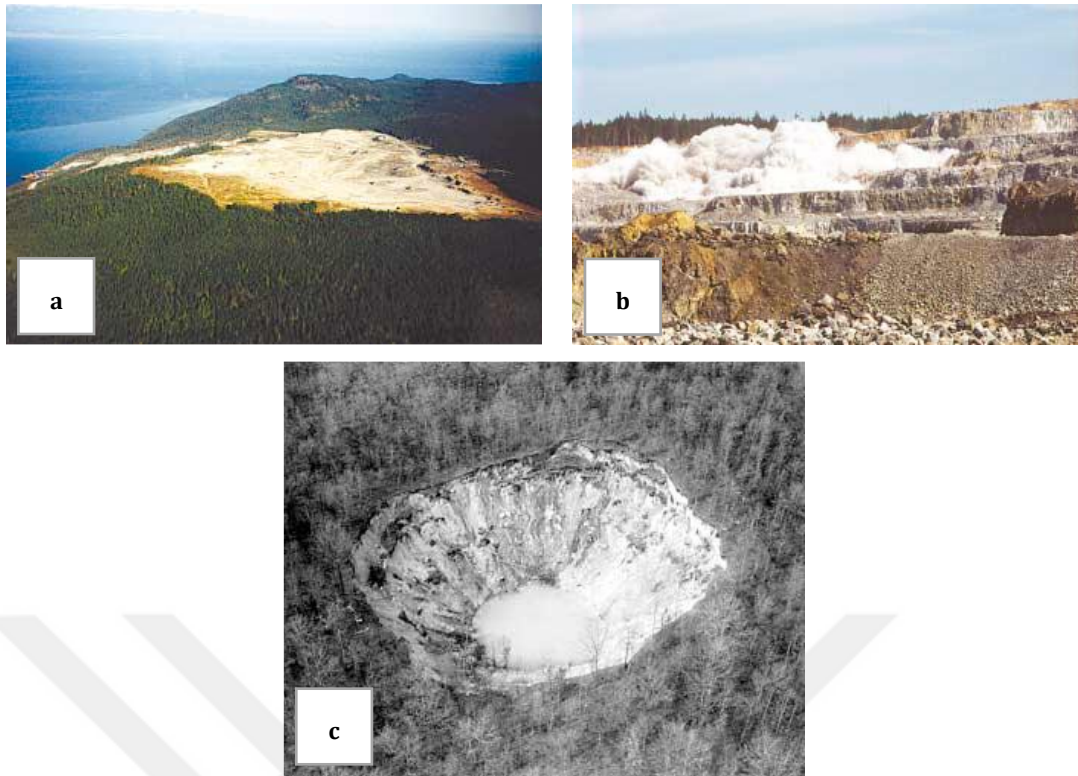


Figure 1.9 Harmful effects of stone quarrying (a: deforestation, b: dust, c: sink collapse) (Langer 2001)

Figure 1.10 shows the worst scenario for a quarrying operation. In the figure, number 1 shows the water table and its change, number 2 shows a discharge, number 3 demonstrates the destruction of a wetland, number 4 indicates a perennial stream and its destruction, number 5 expresses destruction of a woodland, number 6 shows irregularity of bedrock and underground cavities, number 7 and 8 express formations of sinkholes.

As a conclusion, environmental impacts of quarry stones cannot be omitted. For rubble-mound breakwaters, the use of high-density concrete cubes may have an important role on decreasing environmental impacts of quarry stones.

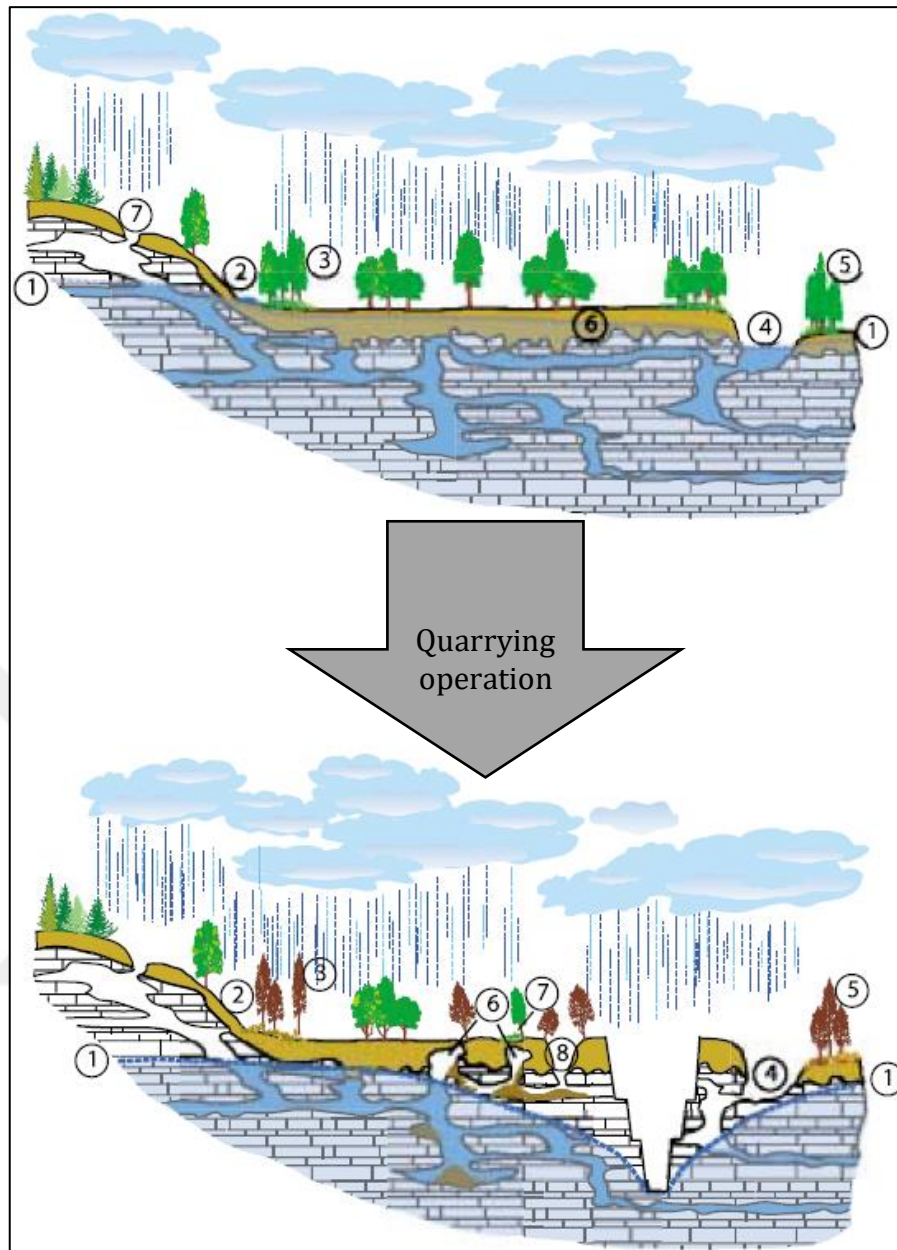


Figure 1.10 The worst scenario for negative effects of quarrying (Langer 2001)

1.1.5 Geotechnical Issues

In civil engineering applications, structure and behavior of the soil at construction site is one of the key aspects. Since most of the construction project are constructed to the soil, the engineering in this area is also important because regardless of the durability of the structure any mistake in geotechnical application may lead the collapse of the structure entirely. Depending on the self-weight of the structure and engineering properties of the soil, construction costs may increase.

At this point, reducing the self-weight of the structure might be reasonable in terms of geotechnical applications because the heavier the structure, the more stress applied to the soil. Additionally, since all breakwaters are constructed in the water, pore water pressure also should be considered because the pore water pressure decreases the bearing capacity of the soil during an earthquake.

In Triemstra (2000) and Zelfde *et al.* (1998), breakwaters at the Maasvlakte in Rotterdam were mentioned. If high-density concrete was used, it would change many engineering properties of the armor units. Concrete elements with 2.2 tons/m³ bulk density weigh 42.5 tons. Under the same loading conditions, concrete armor units with 4.0 tons/m³ only weigh 5 tons. Also, the concrete cubes were used in the experiments of Triemstra (2000) can be seen from Table 1.2 in order to comprehend effect of the density change.

Table 1.2 Comparison between normal-density and high-density cubes (Triemstra 2000)

	$\rho=2200 \text{ kg/m}^3$	$\rho=4000 \text{ kg/m}^3$
W (Weight)	100%	12%
V (Volume)	100%	16%
D_n (Nominal diameter)	100%	40%
Layer thickness (2 layer)	100%	40%
Units/m³ (Porosity 35%)	100%	1560%

It can be seen from Table 1.2, high-density concrete significantly decreases the weight of the cube armor unit. By reducing the weight of the cube armor unit, the self-weight of the breakwater can be decreased easily. Thus, the weight transferred to the soil decreases. Also, safety factor increases in terms of slip failures. In this way, in geotechnical design and construction phase, the cost reduces and maybe construction techniques might be more flexible. Additionally, Figure 1.11 expresses various types of rubble-mound breakwater failure including slip failures, core settlement and subsoil settlement.

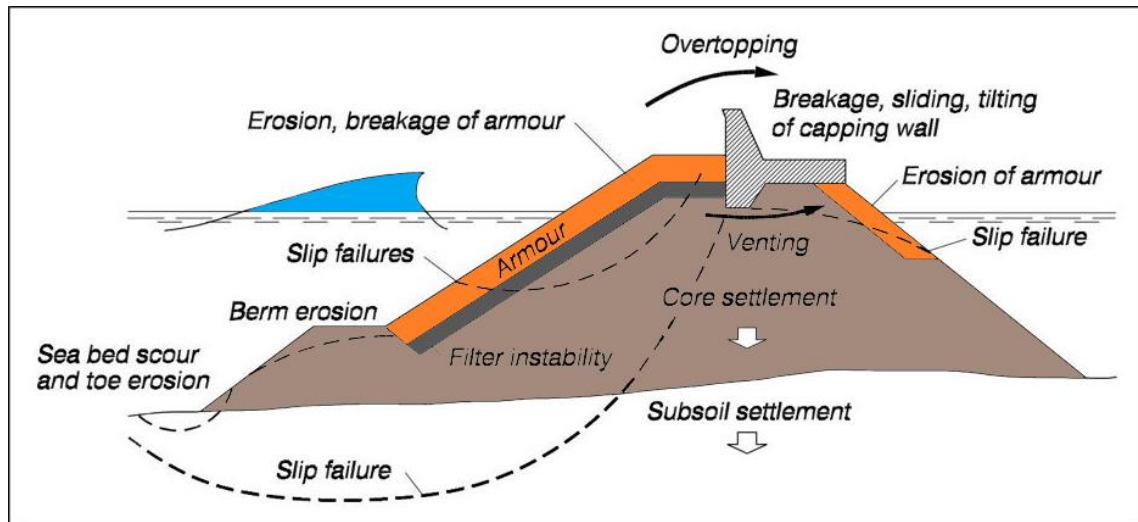


Figure 1.11 Some potential rubble-mound breakwater failures (CEM 2006)

A field application example from Belgium to the slope stability of a rubble-mound breakwater can be given from De Rouck *et al.* 2010. According to the research, they used HARO blocks with 2.30 t/m^3 density in the armor layer. They found the factor of safety lower than the allowed factor of safety in a thick soft layer part of the construction site after proper hydraulic cross section design. They came up with some solutions which are provided below. They applied combination of placing heavier toe and applying geotextile.

- Placing a heavy toe (little impact on settlement).
- Strengthening the soil with geotextile.
- Replacing soft soil with sand.
- Implementing soil improvement.

It can be understood from their solutions that hydraulic design of the structure has influence in slope stability and additional solutions may be required in some circumstances. For instance, instead of using heavy rock material or normal-density concrete cubes in the armor layer, using high density concrete cubes decreases the weight of the armor layer and the pressure on the soil layer below the structure significantly, as mentioned before. Thus, it may contribute slope stability of the seaward slope and can be cost effective. Figure 1.12 demonstrates slip surfaces of a breakwater at seaward.

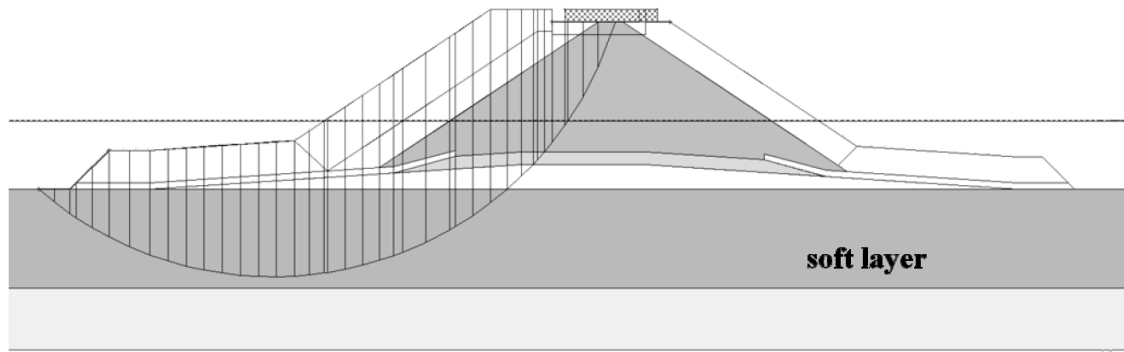


Figure 1.12 Slip surface of a breakwater at seaward (De Rouck *et al.* 2010)

1.2 Literature Review

Concrete cube armor units have a wide range of application field as armor layer material on shore protection structures such as conventional breakwaters and breakwaters with berm. Many researchers demonstrated that concrete cubes can be used as armor material (Van der Meer 1988, Van Gent *et al.* 1999, Triemstra 2000, Van Gent *et al.* 2001, Van Gent *et al.* 2003, Vieira *et al.* 2020, Yüksel *et al.* 2020). However, very few of these researchers have studied importance and influence of density. As known, concrete cubes can be placed regularly and irregularly, and also can be placed on a single layer and on a double layer.

Cube stability as an armor layer material is a complex problem and needs to be investigated in detail. In Van Gent *et al.* (1999), Van Gent *et al.* (2001), and Van Gent (2003) different breakwater concepts including single layer and double layer concepts were discussed. Additionally, normal-density and high-density cubes also were explained thoroughly. In the conceptual design phase of rubble mound breakwaters, generally, empirical formula are used, and those formula do not involve all related components (Van Gent 2003, Vieira *et al.* 2020). Therefore, design formula need further investigations in order to obtain more reliable results.

As stated by Van Gent (2003), cube armor layer units are practical elements and have many advantages. It is easy to produce cube armor units compared to other interlocking units like Coreloc and Accropode. According to Van Gent (2003), another important advantage of the cube armor unit is that it is easy to position them below water especially in locations where the visual range is low. Because operators usually need clear vision to place interlocking units, but it is not as

important as for concrete cube units. They can be placed easily compared to interlocking units.

As aforementioned by Van Gent (2001), breakwater stability depends on various parameters and design formula do not contain every parameter affecting the stability. He compared various parameters in order to clarify cube behavior in a single layer and double layer and considered breakwater as an integrated system rather than focusing only on cube units. Van Gent (2003) studied also the effect of filter layer material, wave steepness, packing density, crest elevation, and toe water depth.

For example, filter material selection is crucial. In single-layer systems, the diameter of the filter material is important. Even though single-layer systems provide a smooth top layer, smaller filter materials may wash out (Van Gent 2003). Although the difference in Figure 1.13 is not large, mid and large materials are recommended. Large material has the priority.

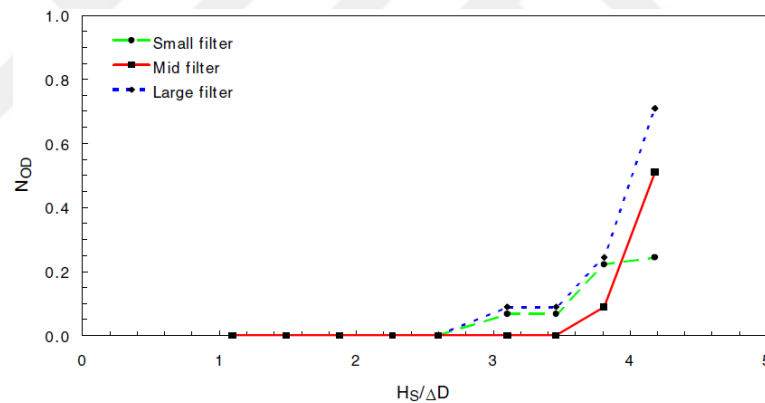


Figure 1.13 Effect of filter material on stability with $n=0.25$ and $h_{toe}=0.5$ m (Van Gent 2003)

Also, studies demonstrated that packing density is important for single layer armoring. For both high-density and normal-density armoring, packing densities with 0.25 and 0.3 open spaces (porosities) were found applicable. 0.25 packing density has the priority. However, Vieira *et al.* (2020) emphasized the influence of porosity on wave overtopping, because wave overtopping changes significantly with changing porosity. Figure 1.14, Figure 1.15, and Figure 1.16 show examples

with changing wave steepness for single layer armoring with high-density cubes (Van Gent 2003).

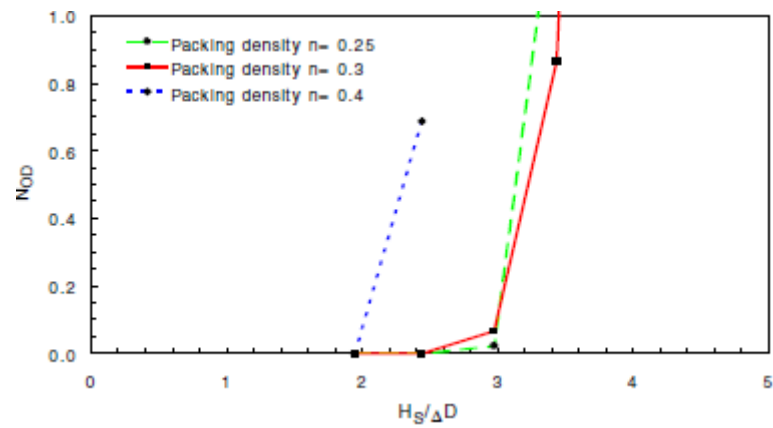


Figure 1.14 Effect of packing density for 0.02 wave steepness (Van Gent 2003)

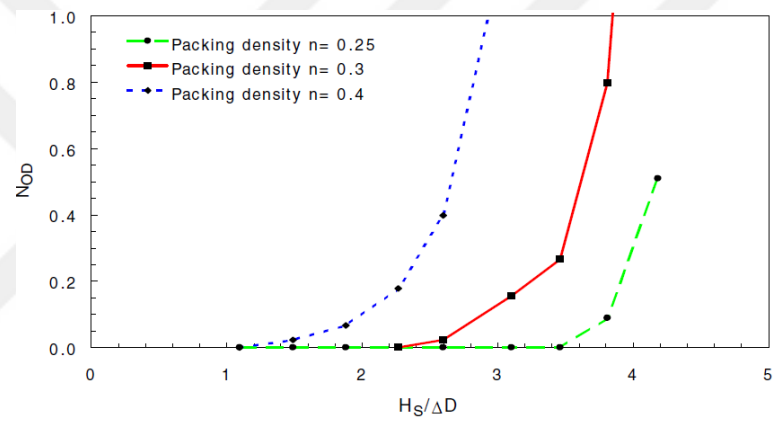


Figure 1.15 Effect of packing density for 0.04 wave steepness (Van Gent 2003)

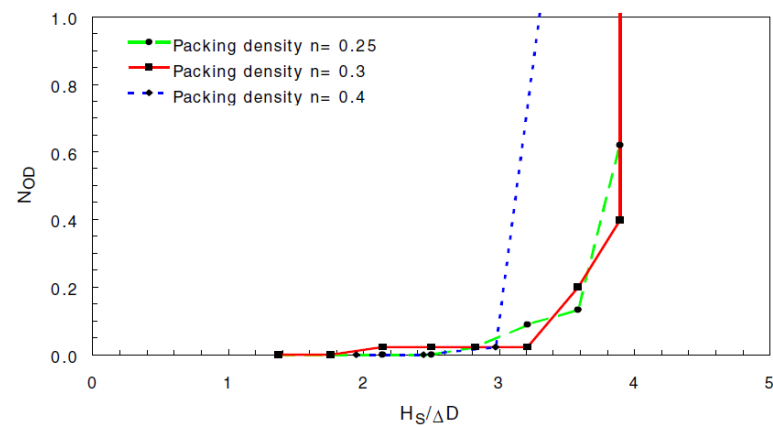


Figure 1.16 Effect of packing density for 0.06 wave steepness (Van Gent 2003)

Van Gent *et al.* (1999) investigated normal density cubes in a single layer, and they compared results with double layer normal density cubes. Figure 1.17 and Figure 1.18 show the stability of normal-density cubes and high-density cubes respectively. In Van Gent *et al.* (1999), the density of cube is 2433 kg/m³ and, in Van Gent *et al.* (2001), 4000 kg/m³.

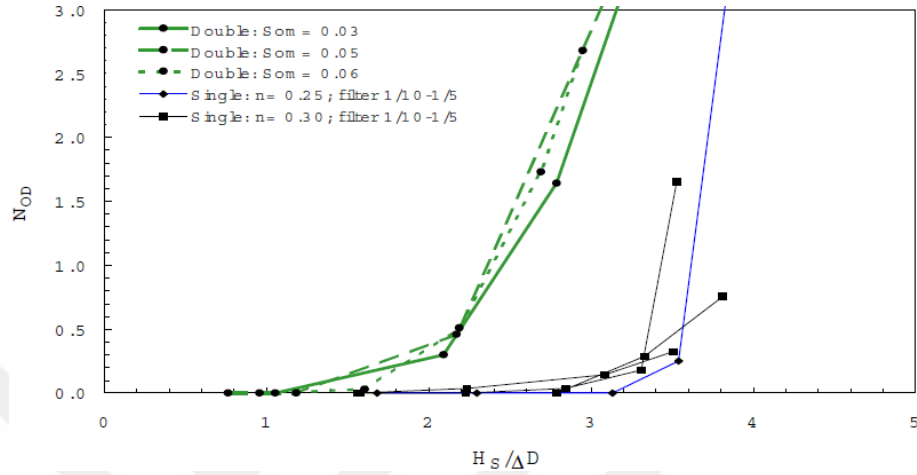


Figure 1.17 Double layer and single layer comparison for normal-density cubes (Van Gent *et al.* 1999)

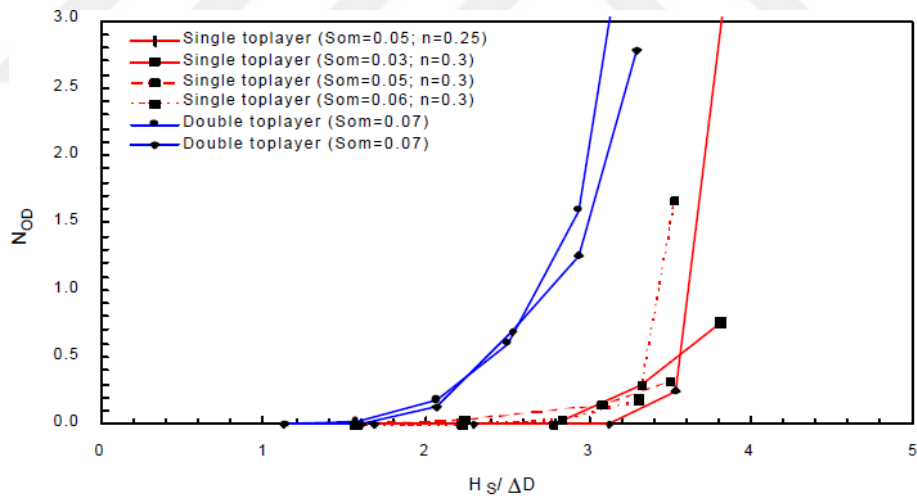


Figure 1.18 Double layer and single layer comparison for high-density cubes (Van Gent *et al.* 2001)

Figure 1.19a and Figure 1.19b show the damage process for normal-density cubes with 0.3 packing density and 1/20-1/10 filter gradation from Van Gent *et al.* (1999). In Figure 1.19b, the filter washout is pointed out with circles.

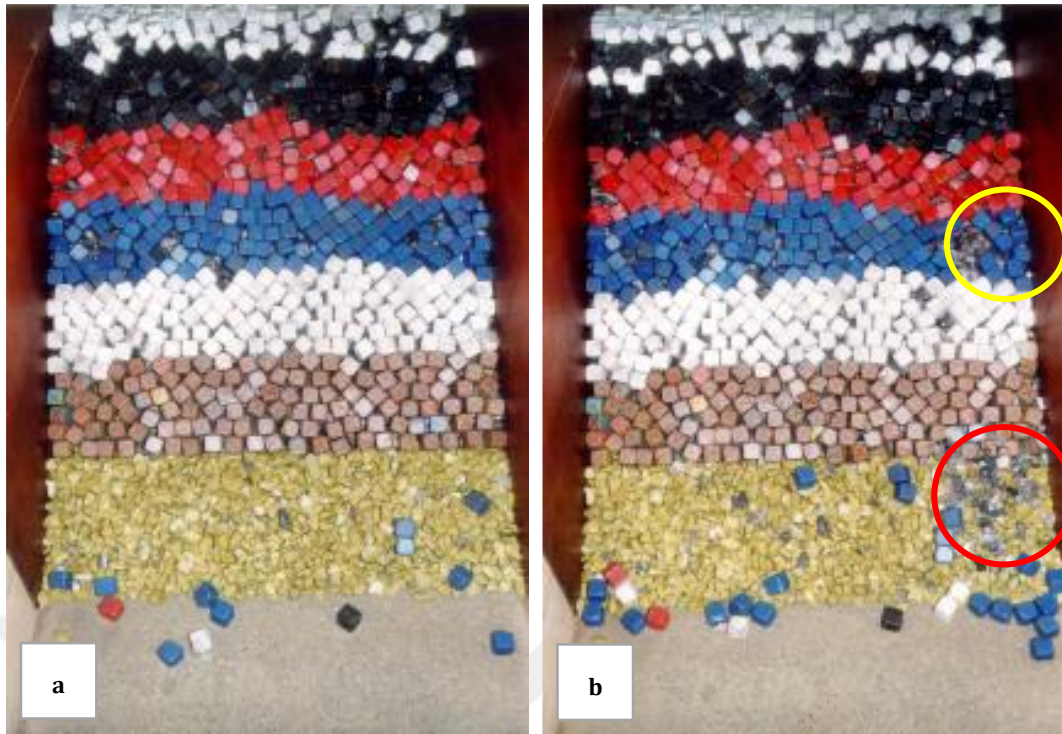


Figure 1.19 Single layer armoring damage process for normal-density cubes (Van Gent *et al.* 1999)

In the review study of Vieira *et al.* (2020), they discussed cube concrete armor units in a single layer. In accordance with the study, Figure 1.20 was derived for breakwaters with single layer armoring, and stability numbers were compared for $N_{od}=0.2$ and $N_{od}=0.05$. Since some results obtained from laboratory tests, which are not applicable, they excluded these experimental results such as the armor layer with high porosity and filter layer with the light material. The filtered results show breakwaters with the following dimensional and material properties: 1:1.5 slope, 0.25-0.30 porosity, emerged structure, and filter material mass larger than 1/20 of the armor material. Figure 1.20 describes a wide range of stability numbers from different studies.

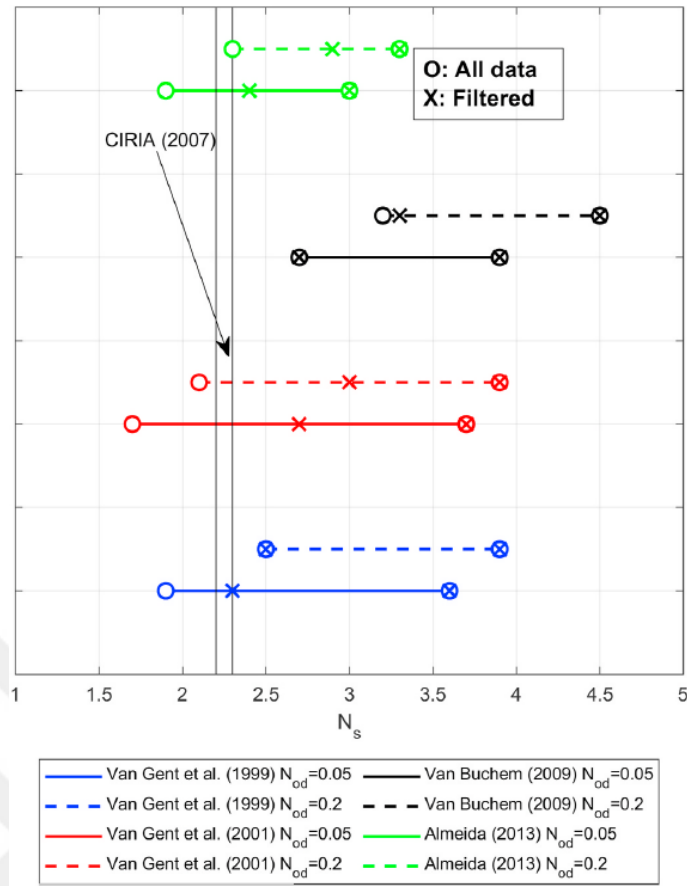


Figure 1.20 Range of stability numbers derived from different studies (Vieira *et al.* 2020)

It is important to highlight that pattern of cubes in a single layer is critical in terms of the durability of the structure. For regular placement style, lack of overlay may damage the armor layer. If overlay between cube units in the lower and upper rows is low, the settlement occurs which leads to possible failure or damage to the breakwater (Almeida 2013, Drouen 2018, Vieira *et al.* 2020). Figure 1.21 shows the result of the lack of overlapping between two rows (marked red).

Since it is not proper to apply damage criteria for double layer cubes to single layer cubes, a new damage classification was proposed by Vieira *et al.* (2020). The proposed classification can be seen in Figure 1.22. In this figure, IDa and IDe represent the initiation of damage and initiation of destruction respectively. Also, RI represents the regularity index.

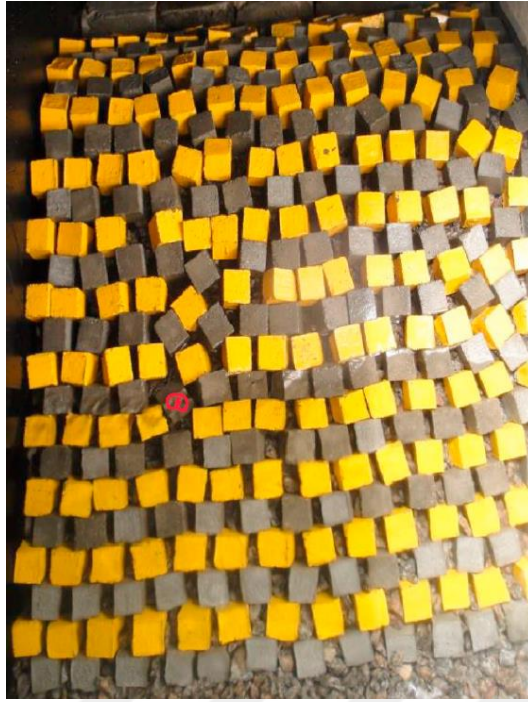


Figure 1.21 An example for lack of overlapping (Almeida 2013)

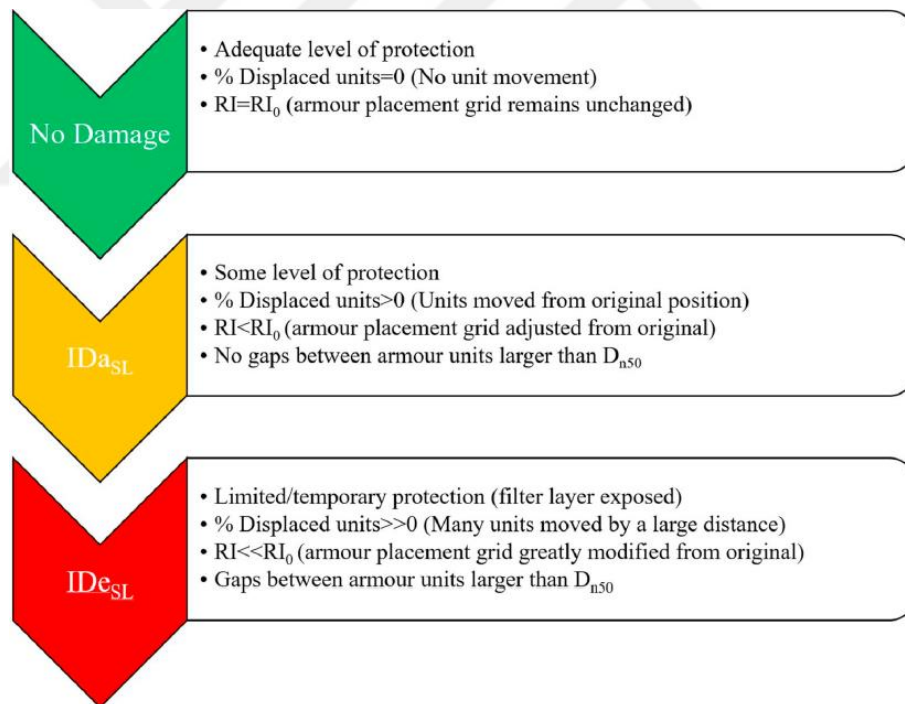


Figure 1.22 An alternative damage classification flowchart for single layer armoring (Vieira *et al.* 2020)

According to Van Gent *et al.* (1999), Van Gent *et al.* (2001), Van Gent (2003), and Vieira *et al.* (2020) the use of concrete armor cubes in a single layer is a feasible

solution and cost-effective. The single-layer placement also decreases the amount of material needed to produce cube units. In a similar way, the use of high-density cube as an armor layer material in a single top layer or on a double layer is also applicable and effective in decreasing cost (Triemstra 2000, Van Gent *et al.* 2001 and Van Gent 2003).

Another research maintained by Van Gent and Luis (2013) by using concrete cubes on a single layer. According to the previous research since 1988, cubes in a single layer is applicable and is also competitive with other one-layer armor units such as Xbloccs, Core-loc and Accropode, in terms of economic concerns. Obviously, single layer cubes are also economically competitive with two-layer armor units such as Tetrapod and Antifer.

In their laboratory experiments, Van Gent and Luis (2013) strengthened their idea by using high-density cubes and normal-density cubes as armor layer in breakwaters. They found that both normal-density and high-density cubes are applicable in a single armor layer. Also, in single layer application, they observed higher $H_s/\Delta D_n$ values when damage occurred. They also used field data from Punta Langostera (Spain) and Boa Vista (Cape Verde) to increase the reliability of the comparison. Their laboratory experiments can be seen from Figure 1.23.



Figure 1.23 Model tests of single layer cubes for Punta Langosteira at left (a) and Boa Vista at right (b) (Van Gent and Luis 2013)

Van Gent and Luis (2013) also propounded some significant parameters to compare one-layer armor units, design, laboratory tests, construction and maintenance. Their key parameters are depicted in Figure 1.24.

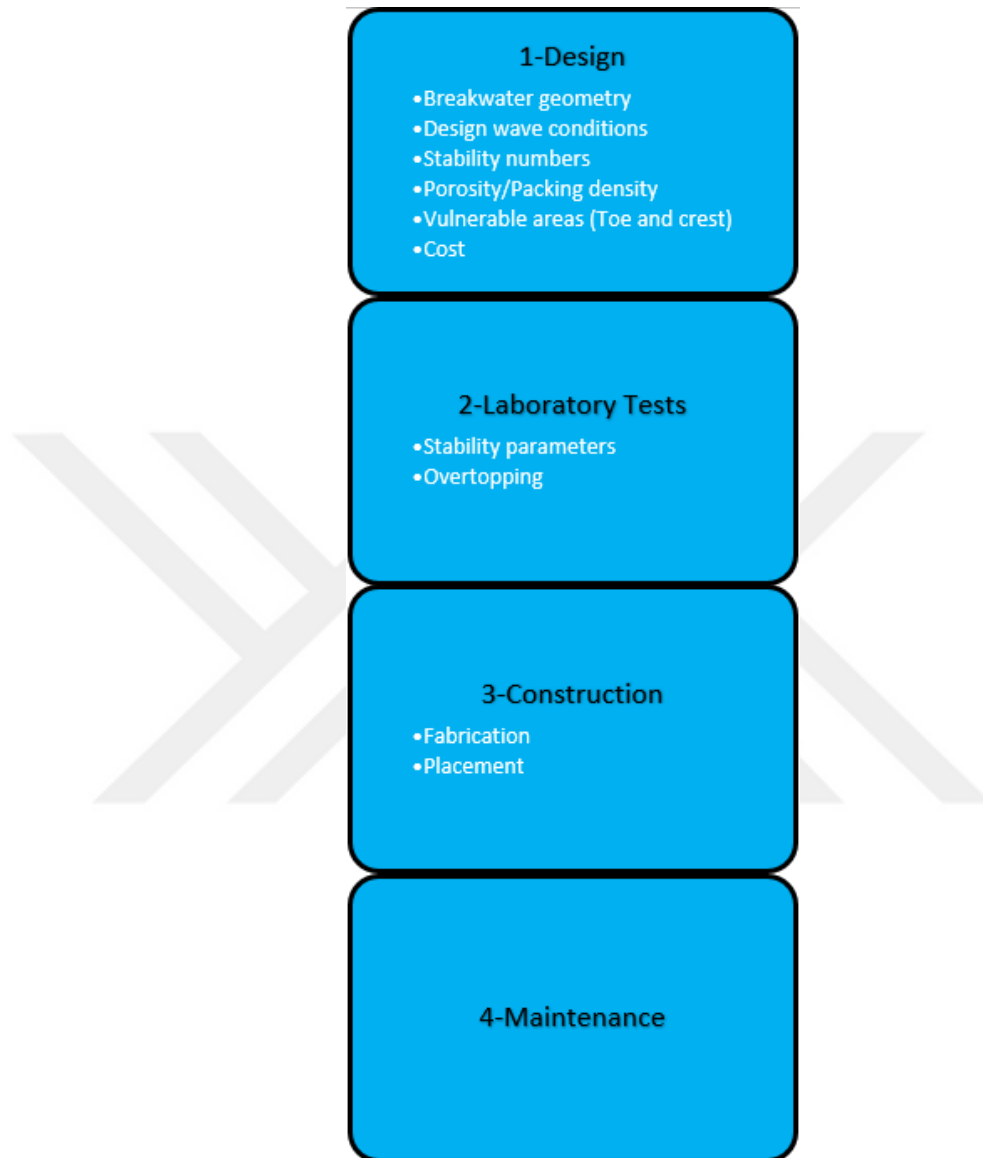


Figure 1.24 Key parameters to compare single layer armor units (adopted from Van Gent and Luis 2013)

As aforementioned, density of the concrete cubes can be changed to increase the stability of the armor layer. A comprehensive study was conducted by Triemstra (2000) on the use of high-density concrete armor units in the armor section of rubble-mound breakwaters. The study is one of the leading studies in the literature about high-density cubes.

For concrete cubes, there is a linear relationship between H_s/D_n and Δ . According to Triemstra (2000), by implementing today's technological improvements, it is possible to produce concrete cube armor units with 4000 kg/m^3 density by using magnetite. However, in accordance with the literature, in order to test the validity of the linear relationship between H_s/D_n and Δ for cubes with 4000 kg/m^3 density, flume tests are required. Also, in order to understand armor layer stability, a wide range of variables should be taken into account besides cube density. Figure 1.25 shows some important components affecting armor layer stability (Triemstra 2000).

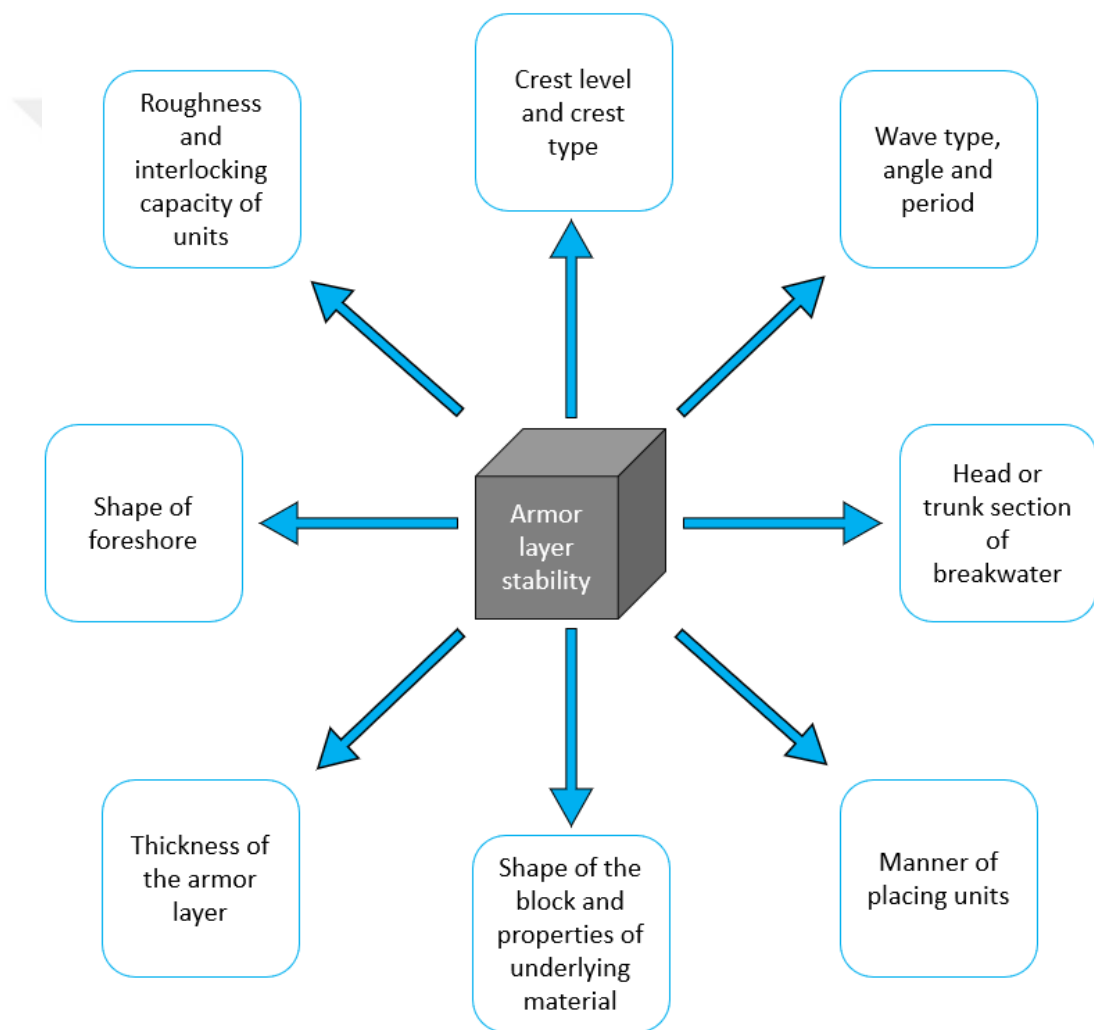


Figure 1.25 Some important parameters affecting armor layer stability (adopted from Triemstra 2000)

It can be seen from Figure 1.25, there are many parameters affecting stability. Laboratory experiments are recommended to clarify their impacts on the stability of armor layer. A general stability formula can be derived by considering affecting parameters.

$$\frac{H_s}{D_n} = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \dots K_n \cdot \Delta^x \quad (1.1)$$

In the given equation, H_s is the significant wave height at the toe of the structure, D_n is the nominal diameter of the armor unit and coefficients $K_{1,2,3,4,\dots,n}$ are the external and internal effects such as wave angle and wave period. Also, Δ^x is the relative density ($x=1$).

By considering same conditions in order to compare two distinct armor units, reduced stability equations are provided below.

$$\frac{H_s}{\Delta_1 D_1} = \frac{H_s}{\Delta_2 D_2} \quad (1.2)$$

$$\frac{D_1}{D_2} = \frac{\Delta_2}{\Delta_1} \quad (1.3)$$

It can be clearly seen from given equations, if the density of the armor unit increases, the required armor unit size decreases. In accordance with Triemstra (2000), comparison of 4000 kg/m³ density concrete cube and 2200 kg/m³ density concrete cube is given below ($\rho_w=1025$ kg/m³).

$$\Delta_1 = \frac{2200 - 1025}{1025} = 1.15$$

$$\Delta_2 = \frac{4000 - 1025}{1025} = 2.90$$

The nominal diameter and weight of the unit will decrease by a factor of 2.5 and 8.9 respectively. Calculations are given as follows.

$$\frac{D_1}{D_2} = \frac{2.90}{1.15} = 2.5$$

$$\frac{W_1}{W_2} = \frac{D_1^3 \rho_1}{D_2^3 \rho_2} = \frac{2.5^3 \cdot 2200}{1^3 \cdot 4000} = 8.6$$

According to Ito *et al.* (1995), by using stability formula of Hudson (1959), a relationship between the armor unit density and the damage causing wave height can be drawn. Figure 1.26 expresses how density of the material increases resistance of the material against damage-causing wave height. Hudson's (1959) stability formula for armor units is provided below.

$$N_s = \frac{H_s}{\Delta D_n} = (K_D \cot \alpha)^{\frac{1}{3}} \quad (1.4)$$

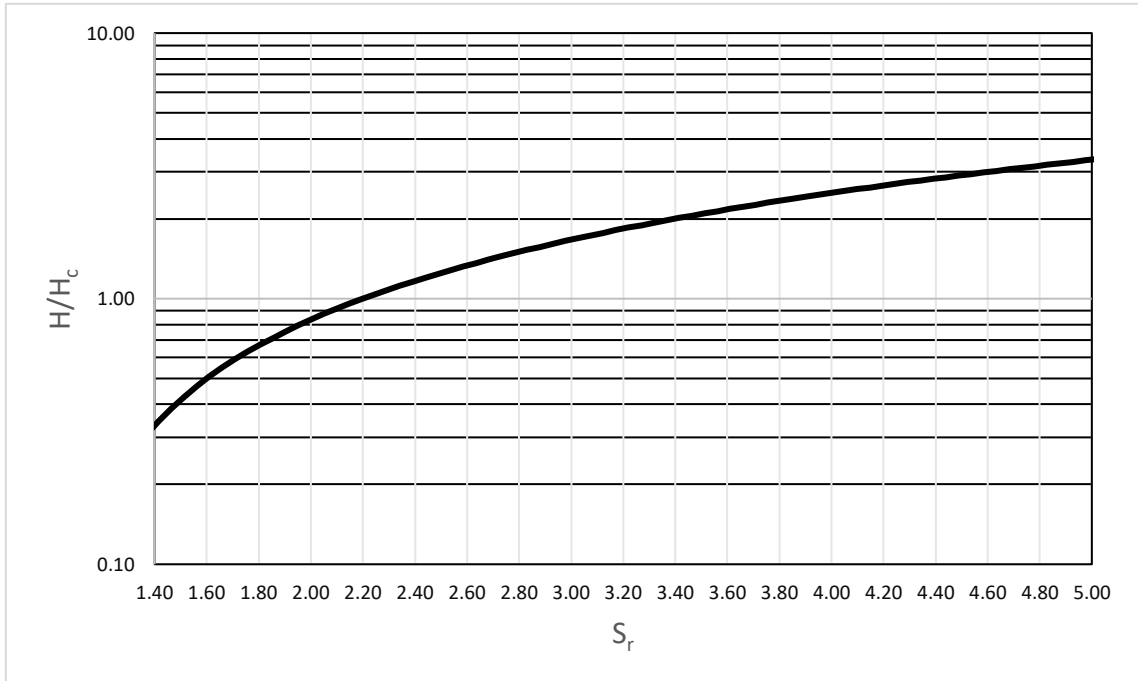


Figure 1.26 Resistance of the armor unit against damage-causing wave height depending on its density

Stability of armor units depends on some parameters according to the specific shape of the unit. For instance, Dolos made with normal-density concrete, obtains its stability 31% from weight, and 69% from interlocking. Increase of the density has slight influence on stability for Dolos, around 27%. For concrete cube armor units, the circumstance is very different compared other interlocking units. The contribution of the interlocking to the stability is 0%. However, the increase of the density has tremendous effect on stability approximately 88%. A comprehensive

bar chart was provided by Triemstra (2000) in order to describe contributions on stability (see Figure 1.27).

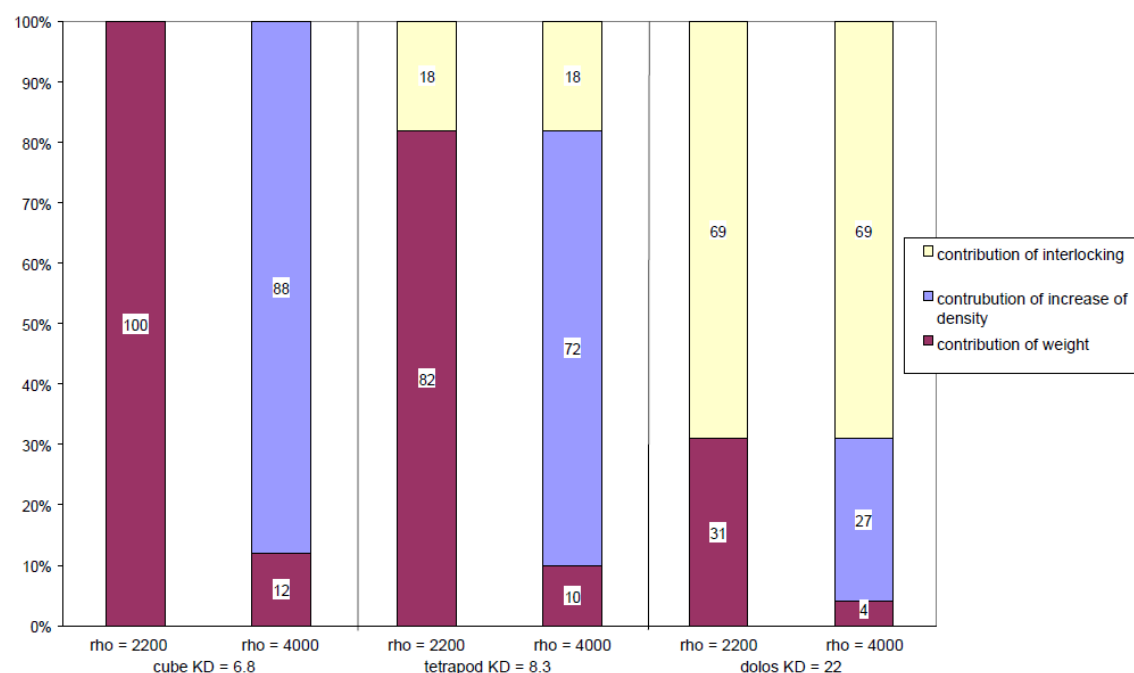


Figure 1.27 Contributions on stability for Dolos, Tetrapod and Cube (Triemstra 2000)

In order to evaluate the performance of high-density cubes, Triemstra (2000) used normal-density cubes as well. As filter layer, different nominal diameters were used depending on the armor unit. For the tests, all slope angles were 1:1.5. To prevent overtopping, high level crest was used. Double armor layer was applied for both high-density cube tests and normal density cube tests with approximately 35% porosity. Triemstra (2000) applied two different cube placement methods, placing by hand and dumping with a bucket. In 8 separate experiment series, consisting of 5 or 6 runs, different wave heights were used with an increasing order with same wave steepness. Damage determination was performed by using test photos with visualization technique. Irregular waves (1000 waves) were generated using JONSWAP spectrum for each run.

As mentioned before, Triemstra (2000) used two different placement methods, dumping with a bucket and placing by hand. According to their observations, normal-density and high-density cubes were behaved differently during placement. For both placement styles, while observing settlement and constant

placing pattern for the normal-density cubes, the behavior for high-density cubes was exactly opposite. High-density cubes preserved their first placed or dumped location without settling. For this reason, after placement, high-density cubes laid more random. Also, the placement methods affected the laying of cubes and thus, influenced the mobility of cubes which affected the stability of the armor layer. This circumstance was named as “laying-roughness”. Figure 1.28 and Figure 1.29 represent how normal-density and high-density cubes position on the breakwater slope (a and b) depending on the placement style, their irregularity (c and d) and their laying-roughness (e and f).

From Figure 1.28c, Figure 1.28d, Figure 1.29c and Figure 1.29d, irregularity of both concrete cube units can be seen. Figure 1.29d represents the most irregular placement among 5 different situations. Also, from Figure 1.29e and Figure 1.29f, abundance of rough laying cubes can be seen compared to Figure 1.28e and Figure 1.28f. As a result, placement style and density of the unit affects laying-roughness.

For all experiments conducted with normal-density cubes, cubes placed by hand were found more stable than cubes dumped on the breakwater slope. Same results were observed for high-density cube units (Triemstra 2000). In order to compare normal-density cubes and high-density cubes, laying roughness should be considered in order to equally evaluate experiments. The closest laying roughness patterns were observed between dumped normal-density cubes and hand-placed high-density cubes. Therefore, these experiments were compared among all experimental results. Figure 1.30 demonstrates comparison of normal-density cubes and high-density cubes. Additionally, according to Triemstra (2000), Van der Meer’s (1986) curve is only valid for hand-placed high-density cubes, not for dumped high-density cubes. Figure 1.31 shows linearity relationship between H_s/D_n and Δ .

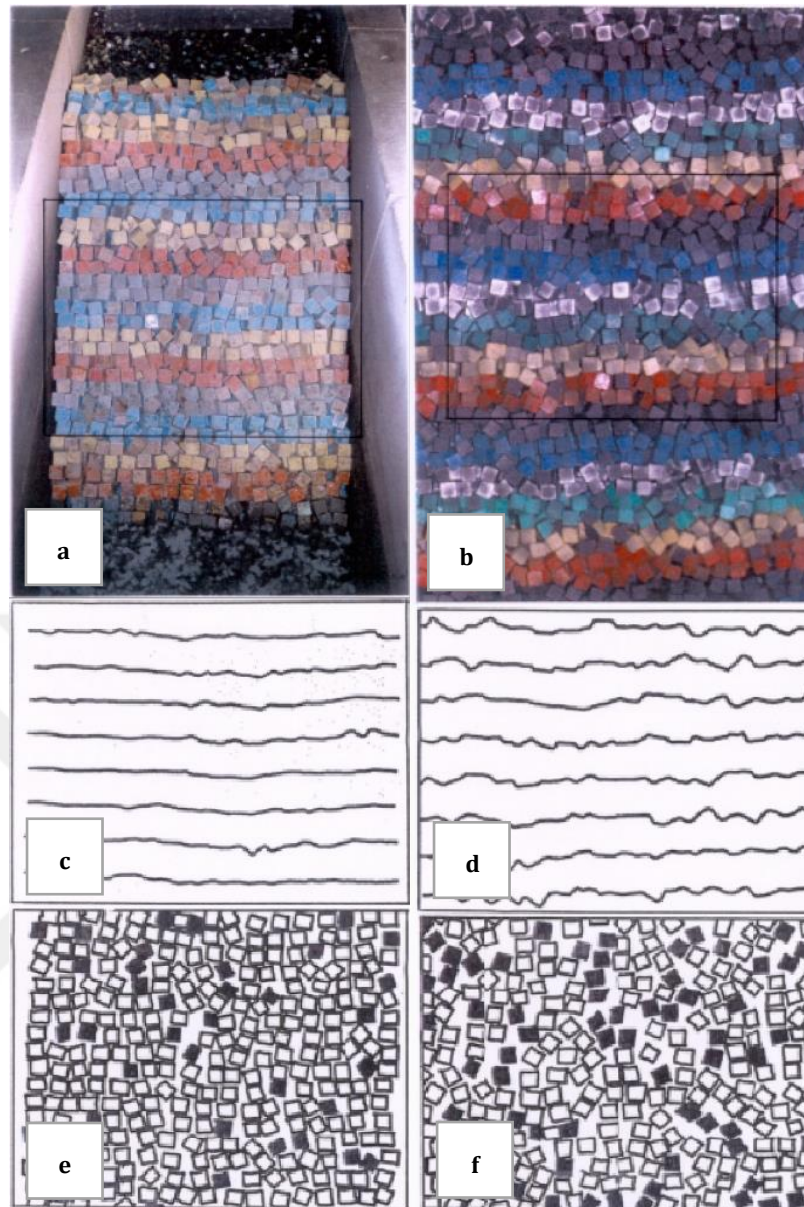


Figure 1.28 Figures at left represent normal-density cubes, figures at right represent high-density cubes for “hand-placing” placement style (Triemstra 2000)

Figure 1.31 establishes validity of concrete cubes with 4000 kg/m^3 density because there are linear relationships between H_s/D_n and Δ values for all 4 experiments. The lines drawn from origin to the points representing high-density cubes, directly passes through points representing normal-density cubes. It is also can be seen from Figure 1.30, the 4000 kg/m^3 density is also valid for Van der Meer’s (1986) stability formula.

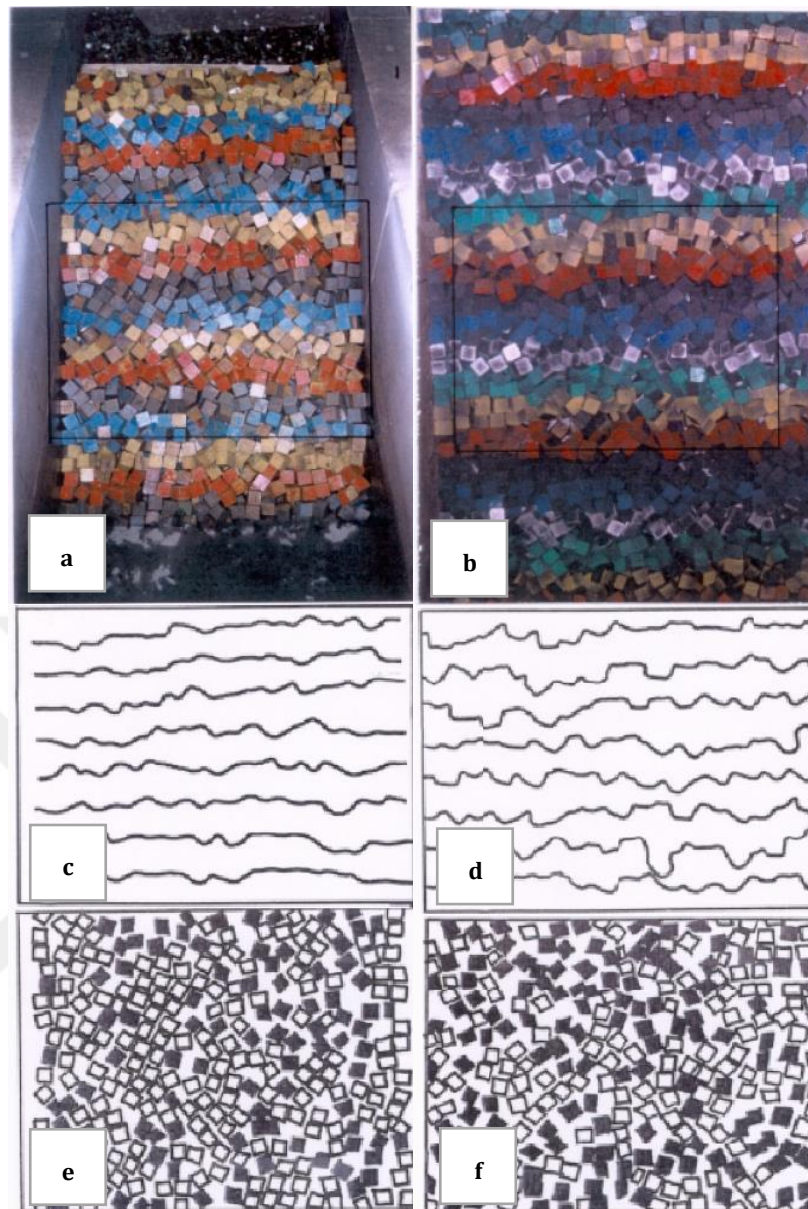


Figure 1.29 Figures at left represent normal-density cubes, figures at right represent high-density cubes for “dumping” placement style (Triemstra 2000)

Triemstra (2000) concluded that, it is not proper to compare experiments with same placement styles. It is more accurate and more convenient to compare results of experiments with the same laying-roughness to each other. As it can be seen from Figure 1.30, different cubes with different placement methods can be compared. Finally, in accordance with flume test results, high-density concrete armor cubes are as stable as normal-density concrete armor cubes, and feasible for armor layer applications.

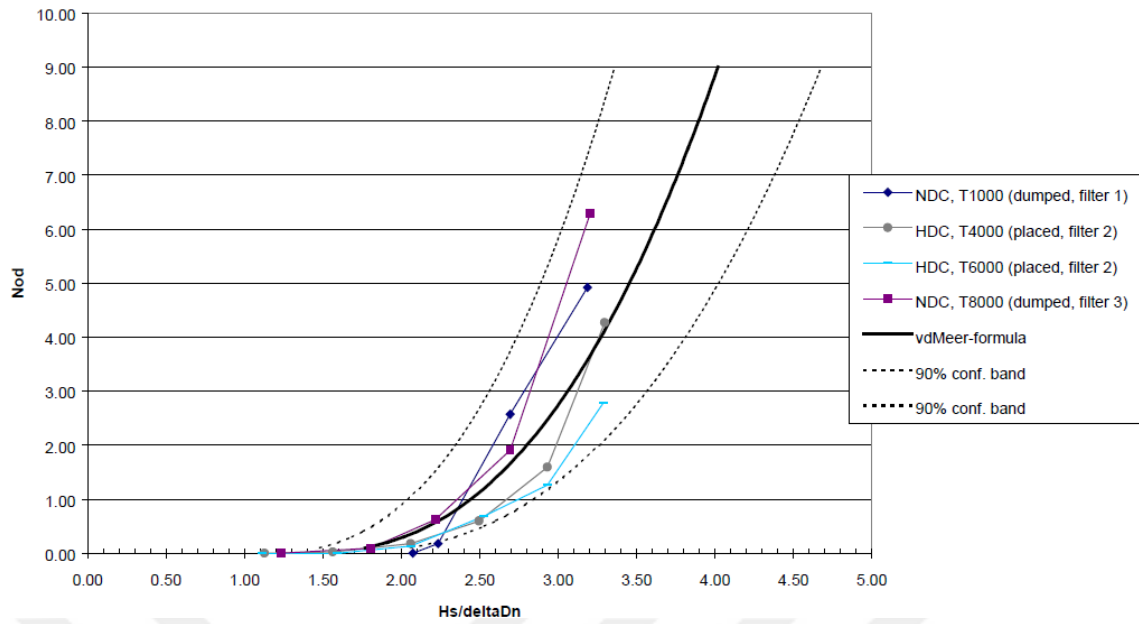


Figure 1.30 Comparison of high-density and normal-density cubes (Triemstra 2000)

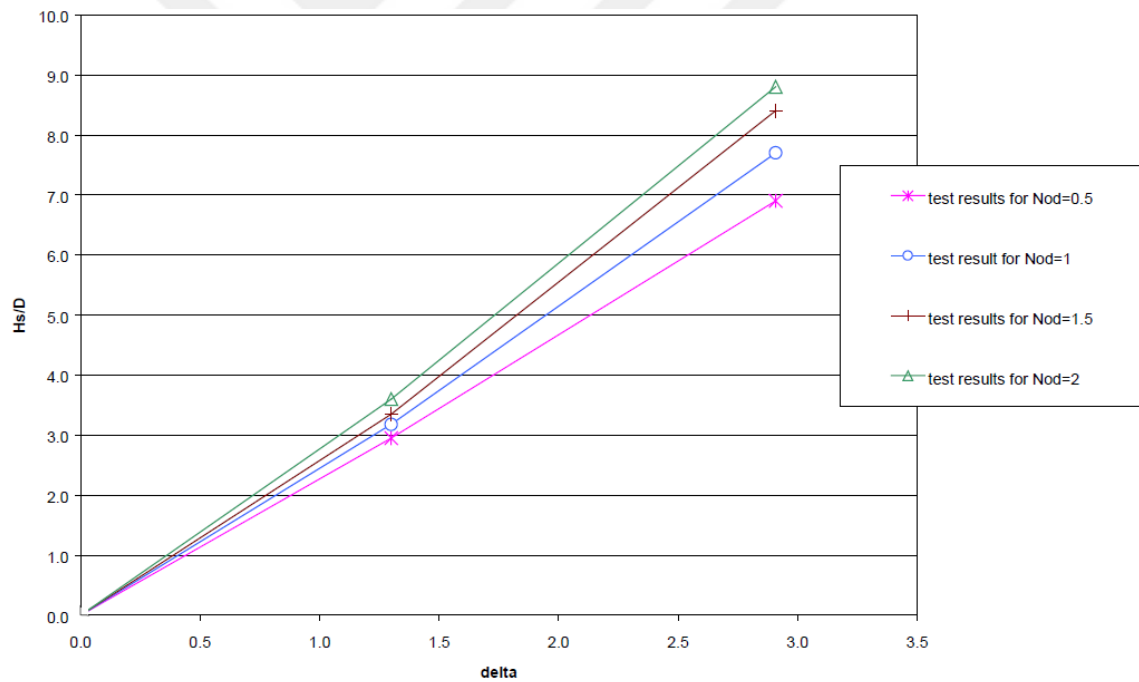


Figure 1.31 Relationship between H_s/D_n and Δ according to test results (Triemstra 2000)

In 2018, a study performed on Hanbar armor units by Howe and Cox (2018). The main idea derived from this study was that density increase has a positive influence on the stability of these types of armor elements.

According to Howe and Cox (2018), in many parts of the world, typically, coastal structures are designed by considering breaking wave conditions. Many studies have recently showed that, global sea level rise will increase. Studies of Church *et al.* (2013) demonstrated that sea level is going to increase up to 90 cm until 2100. Therefore, to accommodate new conditions, all constructed breakwaters will require important armor enhancements.

Howe and Cox (2018) studied various types of breakwaters in their laboratory. Main purpose of the study was to investigate retrofitting of existing structures by using rock armor units and Hanbar armor units. This study also investigated the effect of density change for Hanbar armor units. Figure 1.32 shows examples for both high-density Hanbar and conventional Hanbar. It is also obviously can be seen from Figure 1.32, increase in density, directly affects volume of the armor unit.

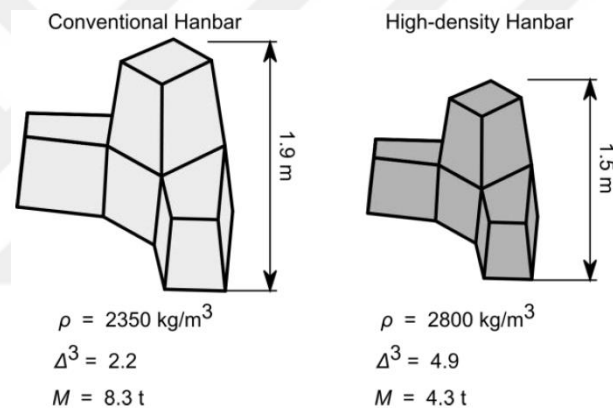


Figure 1.32 Conventional Hanbar and high-density Hanbar (Howe and Cox 2018)

As it can be seen from Figure 1.32, density of the Hanbar unit was increased from 2350 kg/m³ to 2800 kg/m³. To obtain high-density, Howe and Cox (2018) used steel furnace slag. But importantly, chemical reactions between steel furnace slag and Portland cement makes concrete prone to cracking. Thus, Portland cement was replaced with geopolymer cement to avoid chemical reactions between steel furnace slag and Portland cement.

Howe and Cox (2018) discussed the results of their retrofitting strategies in two main titles. Additionally, it is sometimes hard to find larger rock armor units, which explains the recent situation in Australia. Thus, they focused on effects of Hanbar armor units. Results of their physical model tests indicated that when

conventional Hanbar armor units placed in single layer, they perform very poorly and not applicable to upgrade existing breakwaters. It was also found that conventional Hanbar units very poorly interlock with the rock armor. But, when the Hanbar units placed in two layers, they performed well. As it was expected, according to the research, high-density Hanbar performed well. High-density Hanbar units were applied to the existing two-layer conventional Hanbar armor units. Interlocking of two different Hanbar units performed well and applicable for the recent and future breakwater upgrades.

As mentioned before, concrete cubes have wide range of application fields. An example can be given from Yüksel *et al.* (2020) for berm breakwaters. In the last decades, the importance of breakwater with berm increased significantly due to its good performance. These breakwaters are successful in terms of reducing overtopping. Rather than increasing the crest of the breakwater, it is better to construct a berm in seaward. In this way, the breakwater becomes cost effective. Yüksel *et al.* (2020) investigated behavior of berm type breakwaters with cube blocks with 1.4 relative density. Their investigation included that different water levels and different placing methods, also they changed the width of the berm. In the study, irregular and regular placed cubes were tested at three different water depths. Figure 1.33 and Figure 1.34 show different placing styles from their experiments.

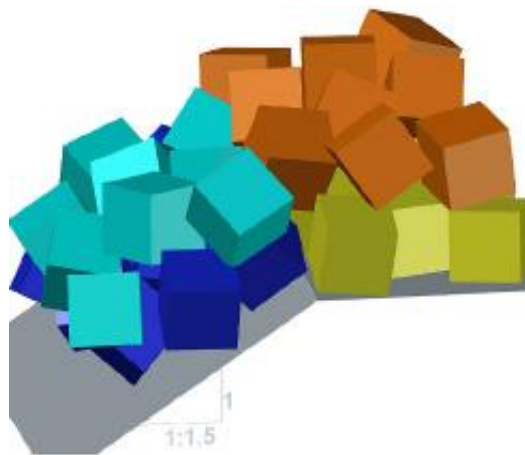


Figure 1.33 Irregular placement (Yüksel *et al.* 2020)

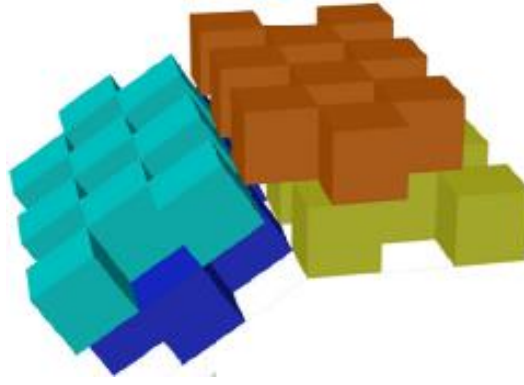


Figure 1.34 Regular placement (double pyramid)(Yüksel *et al.* 2020)

Yüksel *et al.* (2020) found that wider berms decrease the damage importantly for both irregular placement and regular placement. Additionally, for both placement styles, it was also suggested that at least 4 concrete cubes should be placed to the berm of the structure. Because waves were highly effective on transition line, Berm at SWL (Still Water Level) was exposed the greatest damage for both placement styles. Lastly and importantly, double pyramid placement style was found superior against irregular placement but damage initiation for the double pyramid placement triggers a chain reaction which makes structure brittle.

Figure 1.35, Figure 1.36 and Figure 1.37 show damage curves of lower layers for all experiments for emerged berm, berm at SWL and submerged berm, respectively. It can be seen from all figures, double pyramid placement is superior, but behavior of the system is mostly different than irregular placement.

For the recession, Yüksel *et al.* (2020) have found important results. The width of the berm and the elevation of the berm is effective on recession. Because berm at SWL interacts directly with incident waves, it has the greatest recession compared with submerged berm and emerged berm. The emerged berm was also found superior against other berm levels in terms of recession.

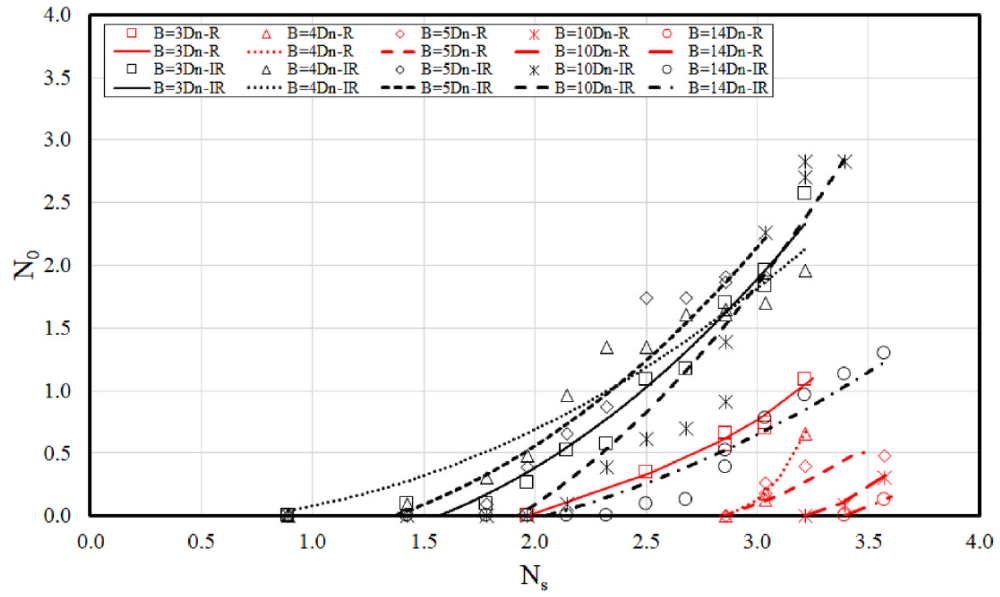


Figure 1.35 Lower slope damage comparison for emerged berm (regular: red, irregular: black)(Yüksel *et al.* 2020)

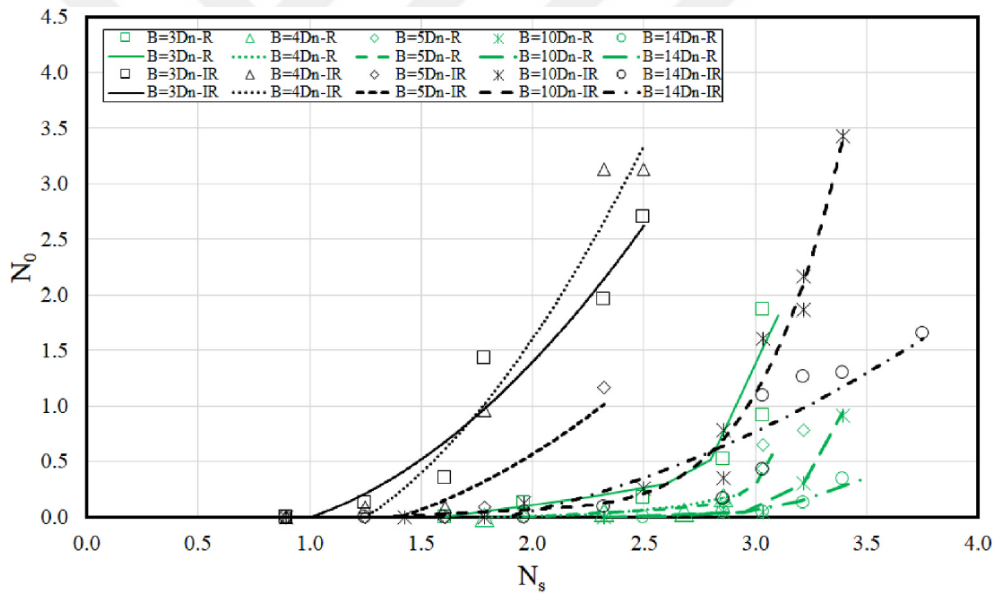


Figure 1.36 Lower slope damage comparison for berm at SWL (regular: green, irregular: black)(Yüksel *et al.* 2020)

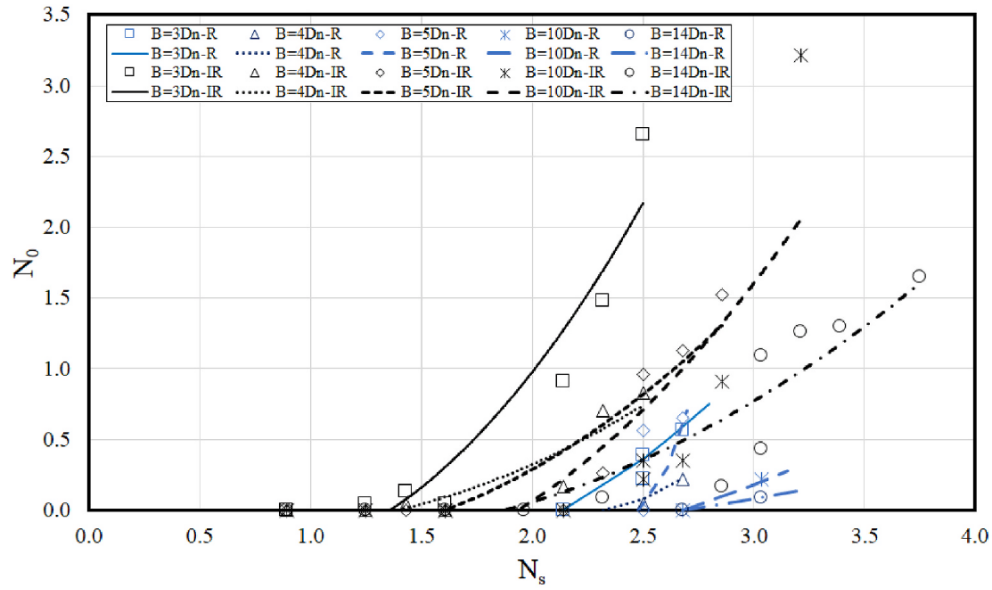


Figure 1.37 Lower slope damage comparison for submerged berm (regular: blue, irregular: black)(Yüksel *et al.* 2020)

Another study was conducted by Van Gent and Van der Werf (2017) by placing concrete armor cubes in a berm. As mentioned before, presence of a seaward berm reduces overtopping effectively (Van Gent and Van der Werf 2017, Yüksel *et al.* 2020). They also mentioned that berm is a great geometrical component for a breakwater to reduce required armor material in the upper slope compared to conventional rubble mound breakwaters.

Existing shore protection structures like breakwaters with berm or without berm will confront sea level rise (Houston 2013, Church *et al.* 2013, Chang *et al.* 2015). These shore protection structures can be adapted to the changing environmental effects by constructing a berm or changing the geometry of the existing berm for the new conditions (Van Gent and Lim 2016, Van Gent and Van der Werf 2017).

According to Van Gent and Van der Werf (2017), single layer systems with interlocking armor units are cost effective and applicable. However, this armoring style generally require difficult techniques and most of these complex armor units are patented. Thus, a fee must be paid to the owner of the patent. Alternatively, concrete cube can be applied on a single layer effectively and also is a non-patented armor unit (Van Gent *et al.* 1999, Van Gent *et al.* 2001, Van Gent 2003, CEM 2006, Rock Manual 2007, Van Gent and Luis 2013, Van Gent and Van der Werf

2017, Vieira *et al.* 2020). Figure 1.38 shows an example for a single layer armored breakwater.



Figure 1.38 Rubble mound breakwater with cubes on a single layer (Van Gent and Van der Werf 2017)

Physical model tests can be seen from Figure 1.39 and 1.40. In lower slope and berm, concrete cubes were used. In upper slope, rock material was used since wave loadings are relatively low compared to lower slope. Experiments were conducted in the Scheldt Flume of Deltares at Delft on a flume that has a 1 m width and 110 m length. In this study, half of the flume was used, 55 m. Tests were performed for different berm levels, emerged berm, berm on SWL and submerged berm.



Figure 1.39 Physical model of the berm breakwater with single layer cubes (Van Gent and Van der Werf 2017)

Van Gent and Van der Werf (2017) obtained valuable results for three relative berm levels. The damage curves can be seen from Figure 1.41. The lower the berm position, the higher damage observed on the upper slope. Also note that, they used a rounded berm (see Figure 1.40) instead of using a sharp edge berm. In

accordance with Van Gent and Van der Werf (2017), no damage occurred in the berm and in the lower slope.

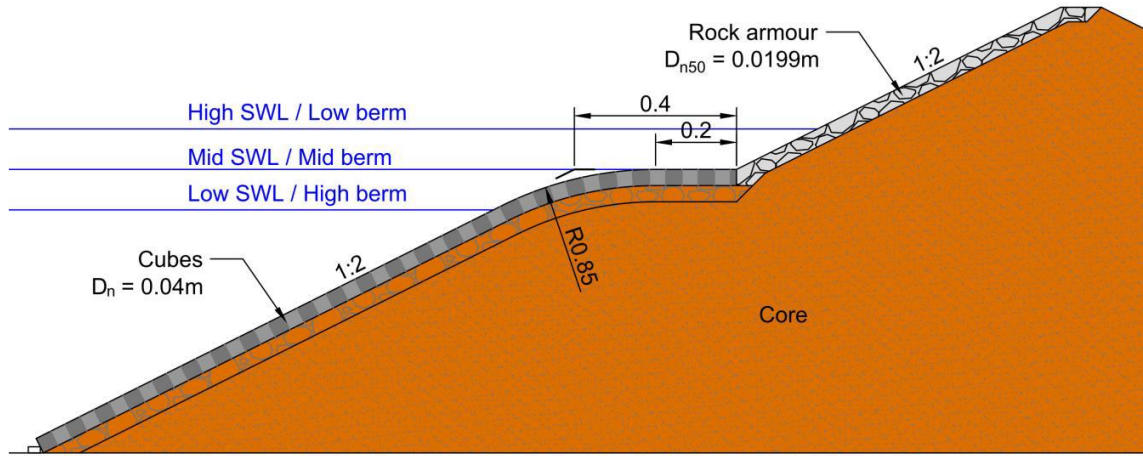


Figure 1.40 Cross-section of the physical model (Van Gent and Van der Werf 2017)

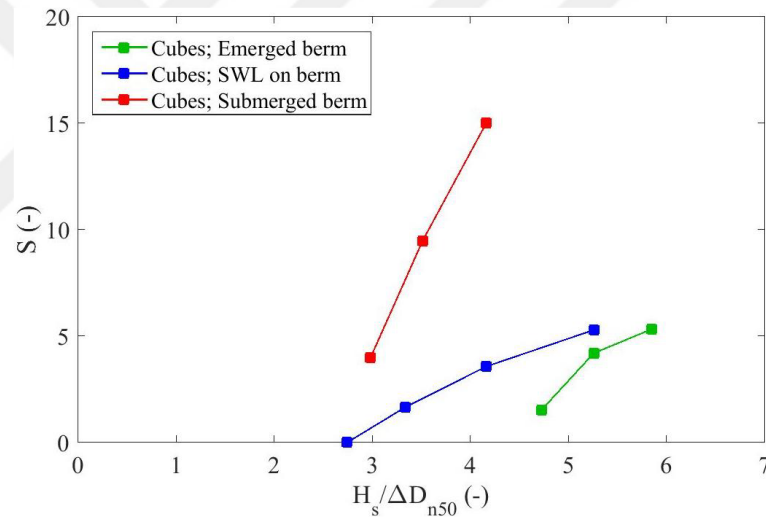


Figure 1.41 Damage curves for the upper slope of the model breakwater for changing berm levels (Van Gent and Van der Werf 2017)

1.3 Objective of the Thesis

In this study, the impact of the high-density cubes were investigated as armor material in the armor layer of conventional and berm breakwaters. 1/1.5 slope was used for conventional breakwaters, and 1/1.5 lower 1/2 upper slope was used for berm breakwaters. In the study, both regular and irregular placement methods were used, and all cubes were placed by hand dropping them from a few centimeters above the slope. 55 cm water depth was used for conventional

breakwaters. For berm breakwaters, 45 cm, 55 cm and 65 cm water depths were used. Therefore, three different relative berm elevations were investigated: emerged berm, berm at SWL, and submerged berm.

1.4 Hypothesis

In coastal areas, breakwaters, groins, seawalls, and many other coastal protection structures have been used for many years for different purposes. Important coastal areas such as harbors, beaches and marinas can be made more sheltered and functional by building breakwaters. However, these structures must be developed in order to adapt changing environmental and economic conditions. Hence, many studies are carried out around the world to develop engineering properties of these structures.

In this study, conventional breakwaters and berm breakwaters have been investigated. These two breakwater types are very flexible and can be modified such as changing cross-section, placement method and material. Thus, stability of these structures can be enhanced. The study covers impact of high-density cubes as armor layer material using regular and irregular placement methods. The main idea is that relatively more economical, environmentally friendly and stable breakwaters can be designed with the use of high-density concrete blocks. This experimental study is expected to support other experimental studies and field applications in the future.

STABILITY OF CONVENTIONAL BREAKWATERS AND BERM BREAKWATERS

2.1 Derivation of Stability Number and Development of Stability Formulae

To understand the stability of an armor unit, it is essential to focus on the derivation of the stability number N_s and development of stability formulae proposed by researchers.

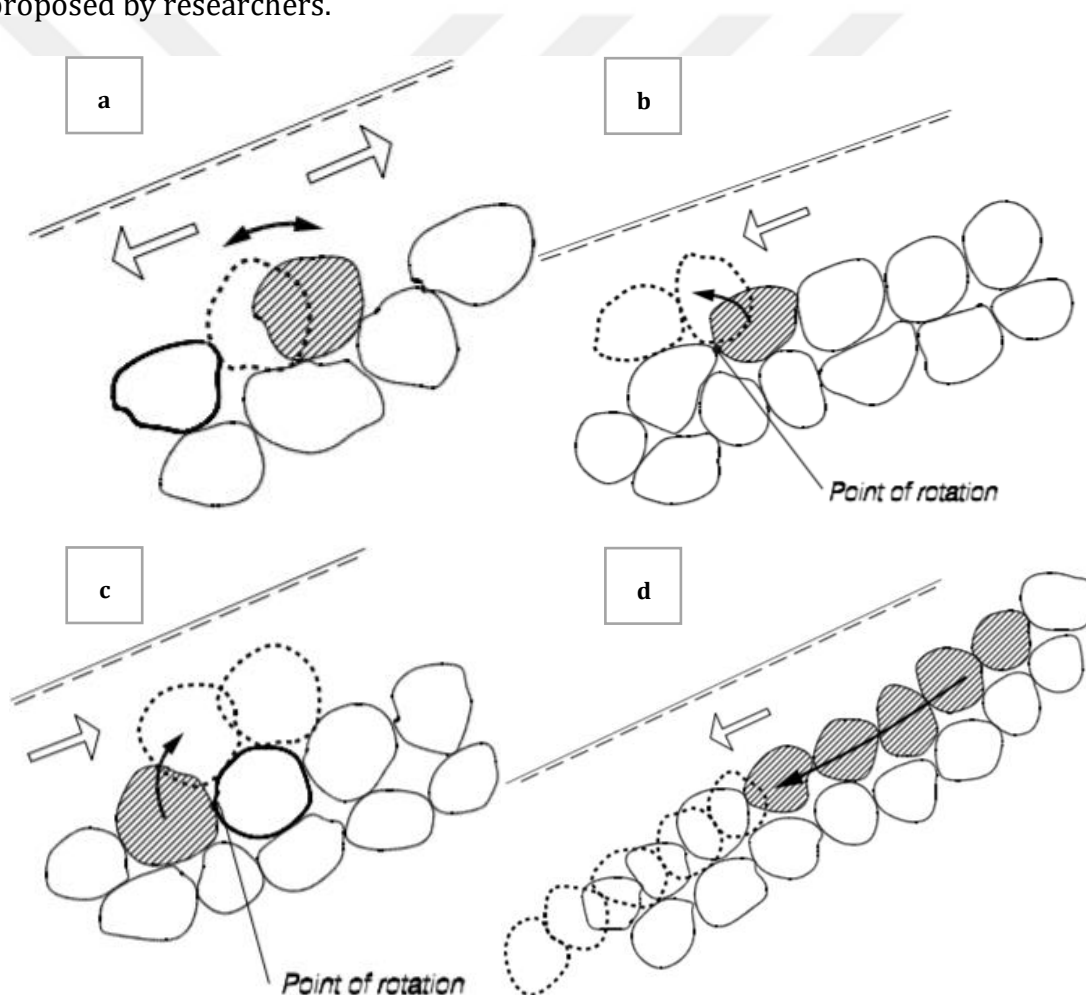


Figure 2.1 Armor unit movements (a: rocking, b: down-slope displacement, c: up-slope displacement, d: sliding) (CEM 2006)

Wave loadings can be effective on a rubble-mound breakwater in many ways such as the movement of the armor units. As mentioned by CEM (2006), there are 4 types of armor unit movement. These 4 movement types are settlement, sliding, displacement and rocking. In Figure 2.1 above, different types of armor movements are visualized (CEM 2006).

In CEM (2006) wave generated forces are explained in detail. Since it is hard to formulate the stability of armor units theoretically, their design is mostly based on hydraulic experiments. Also, empirical formulae involve strict assumptions in terms of boundary conditions. By employing the Morison equation, a qualitative stability ratio can be obtained. Since ocean waves perform chaotic motions on armor units, and the armor units also have numerous shapes and sizes, some assumptions must be considered. Acting forces on an armor unit can be summarized as follows.

- F_D : Drag force
- F_L : Lift force
- F_I : Inertial force
- F_G : Gravitational force

The acting forces on an armor unit are depicted in Figure 2.2 and Figure 2.3 for a run-up and a run-down condition, respectively. In the Figure 2.2 and Figure 2.3, red arrow is the F_L , blue arrow is the $F_I + F_D$ and, green arrow is the F_G . Also surrounding armor materials have interacting forces as well.

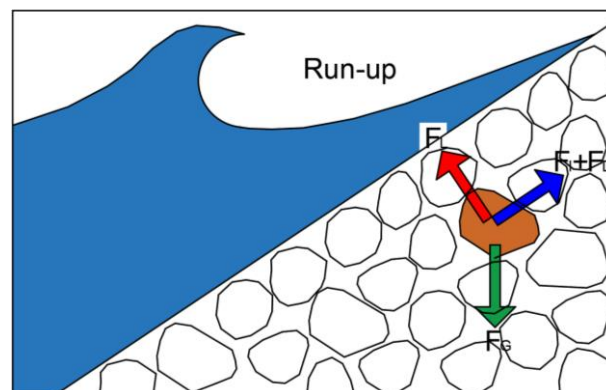


Figure 2.2 Acting forces on an armor unit in a run-up

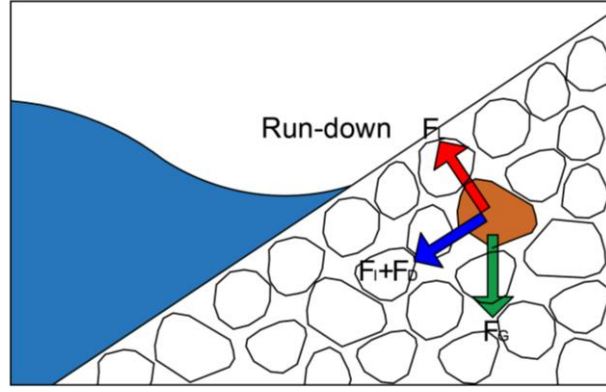


Figure 2.3 Acting forces on an armor unit in a run-down

The Morison equation, which is given below, is the sum of the drag force and the inertia force. By using the equation, for oscillatory flows, the inline force effecting on a body is calculated.

$$F(t) = F_I + F_D \quad (2.1)$$

$$F_I = \frac{\pi}{4} \rho C_M D^2 \cdot \dot{u}(t) \quad (2.2)$$

$$F_D = \frac{1}{2} \rho C_D D \cdot u(t) |u(t)| \quad (2.3)$$

$$F(t) = \frac{\pi}{4} \rho C_M D^2 \cdot \dot{u}(t) + \frac{1}{2} \rho C_D D \cdot u(t) |u(t)| \quad (2.4)$$

In the Morison equation, $\dot{u}(t)$ is the flow acceleration.

$$\dot{u}(t) = \frac{du}{dt} \quad (2.5)$$

Considering the instability phase for an armor unit, where the lift and drag force dominate the inertia force, the following equation can be obtained by reducing the inertial force from the Morison equation.

$$\frac{F_D + F_L}{F_G} \cong \frac{\rho_w D_n^2 v^2}{g(\rho_s - \rho_w) D_n^3} = \frac{v^2}{g \Delta D_n} \quad (2.6)$$

Also, the characteristic flow velocity for a breaking wave on a breakwater slope can be written as follows.

$$v = (gH)^{1/2} \quad (2.7)$$

By reorganizing these two equations for a breaking wave height of H, the stability parameter N_s is obtained.

$$N_s = \frac{H}{\Delta D_n} \quad (2.8)$$

For the non-exceedance of instability condition, the stability number can be generalized as follows. By excluding H, D_n , and Δ , the other parameters influencing stability of the armor layer can be expressed by using the functions of K.

$$N_s = \frac{H}{\Delta D_n} \leq K_1^a K_2^b K_3^c K_4^d \dots K_n^z \quad (2.9)$$

There are many armour unit types, as mentioned in CEM (2006). Some of them have complex shape, which provides them ability to interlock. Dolosse and tetrapod are great examples for these units which have interlocking ability. But note that, these armor units have disadvantages as well. For instance, slope angle is a very important parameter for these armor units and might be disadvantageous in some conditions. See Figure 2.4 for the influence of slope angle on stability of different categorized armor units, interlocking types (a) and bulk types (b).

CEM 2006 mentioned several parameters affecting hydraulic stability of armor layers. These parameters are categorized in 3 titles. These are sea state parameters, structural parameters and combined parameters. Since the combined parameters were derived from the sea state and structural parameters, they are going to be excluded from this part. The affecting parameters are provided below in Table 2.1.

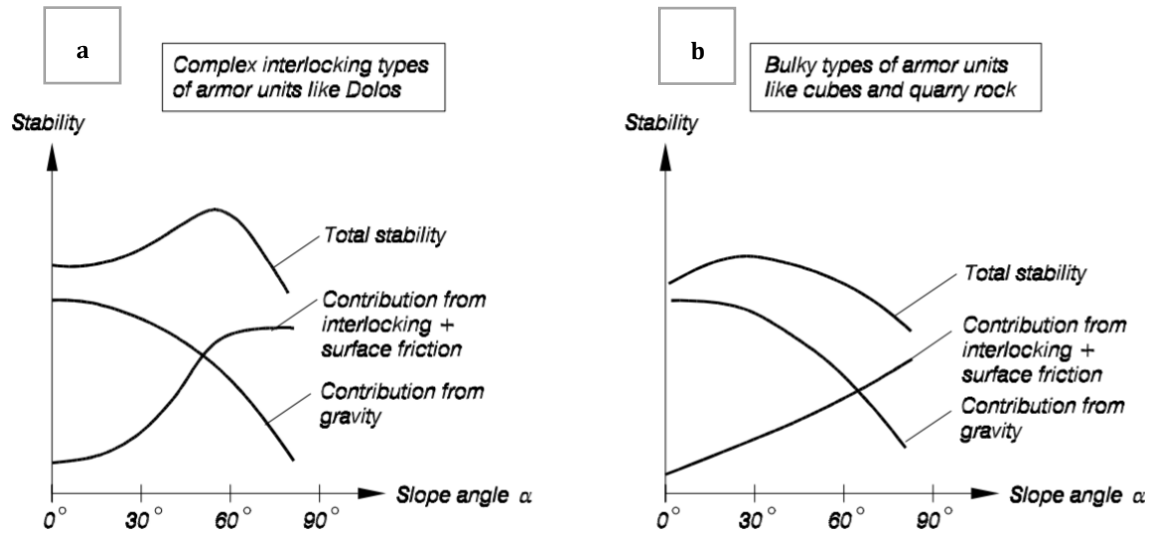


Figure 2.4 Impact of slope angle on different type of armor units (CEM 2006)

Table 2.1 Parameters affecting armor layer stability (CEM 2006)

Sea state parameters	Structural parameters
• Characteristic wave heights: H_s, $H_{1/3}$, H_{m0}, $H_{1/10}$, etc. • Characteristic wavelength: L_m, L_{0m}, L_p, etc. • Characteristic wave steepness: s_m, s_{0m}, s_p, etc. • Wave asymmetry • Shape of the spectrum: JONSWAP, PM, TMA, etc. • Wave grouping • Water depth, d • Incident wave angle, β • Number of waves, N_z • Mass density of water, ρ_w	• Seaward profile of the structure such as armor layer slope, freeboard, etc. • Mass density of armor units, ρ_s • Grading of rock armor, d_{n50}, d_{n15}, d_{n85} • Mass of armor units • Shape of armor units • Packing density of armor layer • Placement pattern of armor layer • Layer thickness of armor layer • Porosity and permeability of underlayers, filter layer(s) and core

2.1.1 Iribarren

Iribarren (1938) assumed that following parameters affect stability of an armor unit on a breakwater slope: wave height at the toe of the structure, area of the armor unit, density of the water, frictional resistance. These parameters can be gathered in an equilibrium. Iribarren's (1938) formula is given below.

$$N_s = \frac{H_s}{\Delta D_n} = N^{-\frac{1}{3}}(\mu \cos \alpha \mp \sin \alpha) \quad (2.10)$$

In this formula, N is a coefficient which depends on the shape of the unit, α is the angle of the slope and μ is the coefficient of friction. The coefficient N can be obtained by performing experiments on the desired armor unit. Iribarren's (1938) formula is not sufficient to determine the stability of the armor layer due to the lack of affecting parameters. Also, it is hard to determine both N and μ .

2.1.2 Hudson

Yüksel (2011) mentioned that Hudson (1959) started his own research first by referring Iribarren's (1938) formula because Hudson (1959) wanted to develop a new and a more general stability formula for armor units. In order to do that, Hudson (1959) started with analytical study and expanded it to an experimental study. He improved the stability formula provided by Iribarren's (1938), but he also overlooked some crucial parameters. For instance, the wave climate that he used in his experiments included regular wave attack emphasizing that the irregular waves were overlooked in his experimental study. After the study, Hudson (1959) recommended the following equilibrium for the design of armor units.

$$N_s = \frac{H_s}{\Delta D_n} = (K_D \cot \alpha)^{\frac{1}{3}} \quad (2.11)$$

In this stability formula, K_D is a coefficient which varies depending on the geometrical properties of the armor unit and also, is a damage level function. Note that, this formula can be used on slopes between 1:1.5 and 1:5 interval.

2.1.3 Van der Meer

Since Hudson's (1959) formula has various shortcomings, Van der Meer (1988) performed experiments on rubble mound breakwaters for various armor units. He derived specific stability formulae for varying conditions such as wave breaking type and armor unit type. Van der Meer (1988) performed these experiments on a 1:1.5 slope and used stones, cubes, accropodes, doloses and tetrapods. The cubes used in the experimental study were normal density cubes (2340 kg/m^3) and were placed irregularly by using a bucket.

According to the study an important parameter was found as an influential parameter affecting stability of the armor layer, the storm duration. The longer the storm duration, the more damage occurs on structure. Van der Meer (1988) performed his study with an irregular wave climate, including 1000 waves in each individual test run.

Van der Meer (1988) performed experiments on rock armor units and presented the following empirical formula.

$$N_s = \frac{H_s}{\Delta D_n} = f(S^{n1} \cdot \xi^{n2} \cdot N^{n3} \cdot \alpha^{n4} \cdot P^{n5}) \quad (2.12)$$

In the given formula, ξ is the wave kinematics, N is the number of waves, S is the damage level, α is the slope angle of the breakwater, P is the permeability of the slope derived from experiments. As aforementioned, Van der Meer (1988) considered the breaking type of the incident waves as an influential parameter. Thus, he used Iribarren parameter, which is given below.

$$\xi = \frac{\tan \alpha}{\sqrt{\frac{H}{L}}} \quad (2.13)$$

In the given formula above, H/L is the wave steepness derived from the incident wave. It can also be expressed as follows.

$$s = \frac{H}{L} = \frac{2\pi}{g} \frac{H}{T^2} \quad (2.14)$$

Van der Meer (1988, 1998) used the following damage categories to calculate the damage level on a breakwater slope for cubes. Since most of the cube movement occurs in the range between SWL+ H_s and SWL- H_s , he considered this area as the reference area.

1) No movement

2) Number of blocks displaced less than $0.5D_n$ (rocking)

$$N_{0<0.5} = \frac{\text{Number of rocking units } (N_r)}{L/D_n} \quad (2.15)$$

3) Number of blocks displaced more than $0.5D_n$ (sliding)

$$N_{0>0.5} = \frac{\text{Number of sliding units } (N_{sl})}{L/D_n} \quad (2.16)$$

4) Number of blocks displaced out of the layer ($>2.0D_n$) (displacement)

$$N_{0d} = \frac{\text{Number of displaced units } (N_d)}{L/D_n} \quad (2.17)$$

Another damage definition was also presented by Van der Meer (1998) that includes sliding and displacement because these two major parameters mainly cause damage on breakwater armor.

$$N_{0,mov} = N_{0d} + N_{0>0.5} \quad (2.18)$$

Van der Meer (1988) found the following stability equations for concrete cubes for two different stability categories, N_{0d} and $N_{0,mov}$.

$$N_s = \frac{H_s}{\Delta D_n} = \left(6.7 \frac{N_{0d}^{0.4}}{N^{0.3}} + 1 \right) s_{0m}^{-0.1} \quad (2.19)$$

$$N_s = \frac{H_s}{\Delta D_n} = \left(6.7 \frac{N_{0,mov}^{0.4}}{N^{0.3}} + 1 \right) s_{0m}^{-0.1} - 0.5 \quad (2.20)$$

In these equations, N is the number of waves, s_{0m} , which is given below, is the wave steepness based on the mean wave period.

$$s_{0m} = \frac{2\pi H_s}{g T_m^2} \quad (2.21)$$

Table 2.2 demonstrates different damage levels, N_{0d} , starting from no damage to failure of the armor layer (Van der Meer 1988).

Table 2.2 Damage levels (Van der Meer 1988)

	Star of damage	Initial damage (no repair needed)	Intermediate damage (needs repair)	Failure (under layer exposed to wave attack)
N_{0d}	0	0-0.5	0.5-1.5	>2

2.2 Stability of Conventional Breakwaters with Concrete Armor Units

In accordance with Rock Manual (2007), there are two principal reasons that can be considered which armor unit is going to be used for armor layer for a rubble-mound breakwater. First one is the wave conditions in the construction area. Second one is the amount, quality and size of the rock units at construction site. In a construction site where wave conditions are moderate and quantity, size, and quality of armor stone are enough, in most cases rock will be used in the armor layer due to aesthetic and economic considerations. For more rough design conditions or at construction sites in which armor stone of adequate quantity, size and quality is not existing, artificial armor units may be used.

According to Rock Manual (2007), in order to provide hydraulically stable armor layers, several approaches have been developed. These approaches emphasize three main components weight, interlocking and friction:

- The first approach is based upon artificial armor units is that these components gain their stability principally by their **weight**.
- The second approach is about artificial armor units is that these artificial units use important **interlocking** between adjacent units.
- The third approach is about uniformly placed concrete armor units. These units obtain their resistance mostly by **friction** between each single unit.

An explanatory table was provided in Rock Manual (2007) for some artificial armor units. It can be seen from the Table 2.3, considering placement style, cube armor units obtain their stability from their own weight and friction between units. Thus, it is obvious to deduce that contribution of interlocking is zero for concrete cubes.

Table 2.3 Classification of some concrete armor units according to placement, stability factor and shape (Rock Manual 2007)

Placement pattern	Number of layers	Shape	Stability factor (main contribution)		
			Own weight	Interlocking	Friction
Random	Double layer	Simple	Cube, Antifer Cube, Modified Cube		
			Tetrapod, Akmon, Tripod		
		Complex		Stabit, Dolos	
	Single layer	Simple	Cube		Cube
		Complex		Stabit, Accropode, Core-loc, Xbloc	
Uniform	Single layer	Simple	Haro		Seabee, Haro
		Complex			Cob, Shed, Tribar, Diode

The design of shore protection structures is a complex process. The design of armor layers basically same for rock armoring and concrete armor layers, except design formulae or/and parameters are different. According to Rock Manual (2007), especially for preliminary sizing, the most basic approach is by using Hudson's empirical equation considering certain K_D values. Alternatively, other empirical formulas can be used for only chosen concrete armor unit types. Also, physical model tests are essential in this area since there is not enough information about artificial concrete armor units.

Generally, for artificial concrete armor units, between 2200 kg/m^3 and 2600 kg/m^3 , which corresponds to $\Delta \cong 1.2-1.6$, standard mass density is implemented. For Cubes (involving Antifer cubes), much higher density values can be implemented reaching up to 3000 kg/m^3 ($\Delta \cong 3.0$) and 4000 kg/m^3 ($\Delta \cong 4.0$). For complex units like Tetrapod, this density augmentation has rarely been done. In

accordance with Rock Manual (2007), applying high density concrete cubes to the armor layer may be useful. The use of high-density concrete units in the armor layer decrease unit volume and also thickness of armor layer. Additionally, Van Gent *et al.* (2002) demonstrated that stability parameter $N_s = H_s / \Delta D_n$ can describe damage for high density cubes. On the contrary, there is insufficient information about high-density interlocking armor units whether damage can be described by using stability parameter $N_s = H_s / \Delta D_n$. Interlocking armor units with high-density need to be investigated in very detail.

Depending upon artificial armor unit type such as Cube, Dolos and Tetrapod, one or two-layer placing patterns are used. Rock Manual (2007) mentioned that for two-layer systems, depending on the shape of the armor unit, the units may have a superior or lesser interlocking degree. Generally, if damage begins, with the increasing wave height, damage increases as well because stability of the two-layer systems principally depend on individual units' stability. For this placing type, crucial failure happens only when both two layers are displaced and underlayers such as filter layer and core layer are washed.

For one-layer systems, armor units are placed to a given placement grid or density (Rock Manual 2007). Xbloc, Accropode and Core-loc are examples for these kinds of units. Behavior of these units is quite different from two-layer placed armor units. When single layer placement pattern is compared to the two-layer pattern, the underlayer of the breakwater will be exposed more to wave forces. Additionally, brittle or sudden failure progress is more likely for one-layer placement when compared to two-layer.

Generally, for one-layer interlocking systems, even low damage levels (<5%) are not acceptable for design. It is important to maintain its position of the armor layer even during a storm. Thus, for one-layer systems, safety tolerance is relatively large in terms of $H_s / \Delta D_n$ or K_D . In addition, the one-layer armor layer should be able to resist more hydraulic load compared to two-layer systems. The amount of the excess load is approximately 20%, which corresponds to design wave height exceeded by 20%. It can be also concluded that safety margins are higher and advantageous for single layer systems (Rock Manual 2007).

There are two main parameters to define damage for randomly placed systems. N_d and N_{0d} are the parameters to quantify damage for such systems.

- N_{0d} (Damage number): Amount of displaced concrete armor units in a strip of breakwater slope of width D_n .
- N_d (Damage number): Number of displaced armor units (as percentage) in a specific area according to the design water level. The range is $1.5 H_d$ above and below design water level.

According to Rock Manual (2007) and with the recommendations of Van der Meer (1988), Table 2.4 shows typical values for N_d and N_{0d} . Note that, using $N_{0d}=0$ is a very conservative design parameter which corresponds to $N_d=0$.

Table 2.4 Characteristic damage numbers for various armor units (Rock Manual 2007)

Armor type	Damage number	Damage level		
		Start of damage	Intermediate damage	Failure
Cube	N_{0d}	0.2-0.5	1	2
Tetrapod		0.2-0.5	1	1-5
Accropode		0	-	>0.5
Cube	N_d	-	4%	-
Dolos		0-2%	-	≥15%
Accropode		0%	1-5%	≥10%

2.2.1 Hudson's Formula for Randomly Placed Concrete Armor Units

In accordance with Hudson (1959), for double layer placed concrete armor units, required unit size can be expressed by a formula, which was also provided before. Below, Hudson's formula can be seen in a rewritten form using H_s . K_D values can be found in Rock Manual (2007) or in Coastal Engineering Manual (2006). K_D values vary depending on the type of the concrete armor unit.

$$N_s = \frac{H_s}{\Delta D_n} = (K_D \cot \alpha)^{\frac{1}{3}} \quad (2.22)$$

Table 2.5 shows double layer armor units, the countries and years in which they were invented, and their stability numbers with recommended slope.

Table 2.5 Properties of double layer armor units with K_D (Rock Manual 2007)

Armor unit	Country and year	K _D values in Hudson stability formula				Slope
		Trunk		Head		
		Breaking waves	Non-breaking waves	Breaking waves	Non-breaking waves	
Cube (double)	-	6.5	7.5	-	5	1:1.5 1:3
Tetrapod	FR (1950)	7	8	4.5	5.5	1:2
Tribar	USA (1958)	9	10	7.8	8.5	1:2
Stabit	UK (1961)	10	12	-	-	1:2
Akmon	NL (1962)	8	9	-	-	1:2
Antifer Cube	FR (1973)	7	8	-	-	1:2

2.2.2 Stability Formulae of Specific Types of Randomly Placed Units

Numerous research have been done in this area and various stability formulae have been developed including cubes in single layer and double layer, Tetrapods, Core-locs and more. Performance of the armor units depends on many aspects such as slope angle and porosity. The slope angle is an important parameter for breakwater stability. Steeper slope may have important role decreasing costs but generally, the angle of the slope should not be steeper than 1:2 (Rock Manual 2007). Some important stability formulae can be seen from Table 2.6.

Table 2.6 Stability formulae for some randomly placed armor units

Concrete armor unit		Formula
Cube	Double layer (Van der Meer 1988)	$\frac{H_s}{\Delta D_n} = \left(6.7 \frac{N_{0d}^{0.4}}{N^{0.3}} + 1 \right) s_{0m}^{-0.1}$
	Single layer (d'Angremond <i>et al.</i> 1999, Van Gent <i>et al.</i> 1999 and 2002)	$\frac{H_s}{\Delta D_n} = 2.9 - 3.0 \quad N_{0d} = 0$ $\frac{H_s}{\Delta D_n} = 3.5 - 3.75 \quad N_{0d} = 0.2$
Tetrapod (Van der Meer 1988)		$\frac{H_s}{\Delta D_n} = \left(3.75 \left(\frac{N_{0d}}{\sqrt{N}} \right)^{0.5} + 0.85 \right) s_{0m}^{-0.2}$
Accropode (Van der Meer 1988)		$\frac{H_s}{\Delta D_n} = 3.7 \quad N_{0d} = 0$ $\frac{H_s}{\Delta D_n} = 4.1 \quad N_{0d} > 0.5$

For cubes in a double layer, slope of the structure is 1:1.5 with $3 < \xi_m < 6$. The formula was derived by Van der Meer (1988) based on mean wave period, T_m . For cubes in single layer, design experience is very limited. Recommendation of Van Gent *et al.* (1999 and 2002) is to place concrete cubes to the underlayer one side flat. Single layer cube placement also requires special attention because of direct wave attack to the underlayer. Any failure in the armor layer for one-layer placement results greater hydraulic forces on the underlayer of the breakwater. This may also cause catastrophic results for the structure.

Since breakwater design is an important and crucial process, Rock Manual (2007) provided a well-structured and comprehensive figure to provide information about recommended range of stability numbers for conceptual design, see Figure 2.5. Also see Figure 2.6 for wave steepness versus stability number graph. But note that, this graph was not provided by Rock Manual (2007) to design a structure.

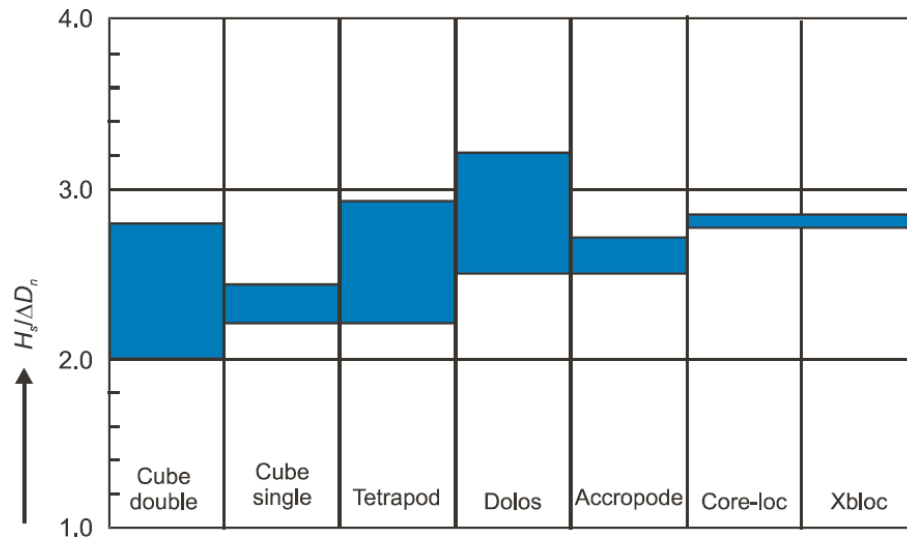


Figure 2.5 Suggested stability number ranges for conceptual design (Rock Manual 2007)

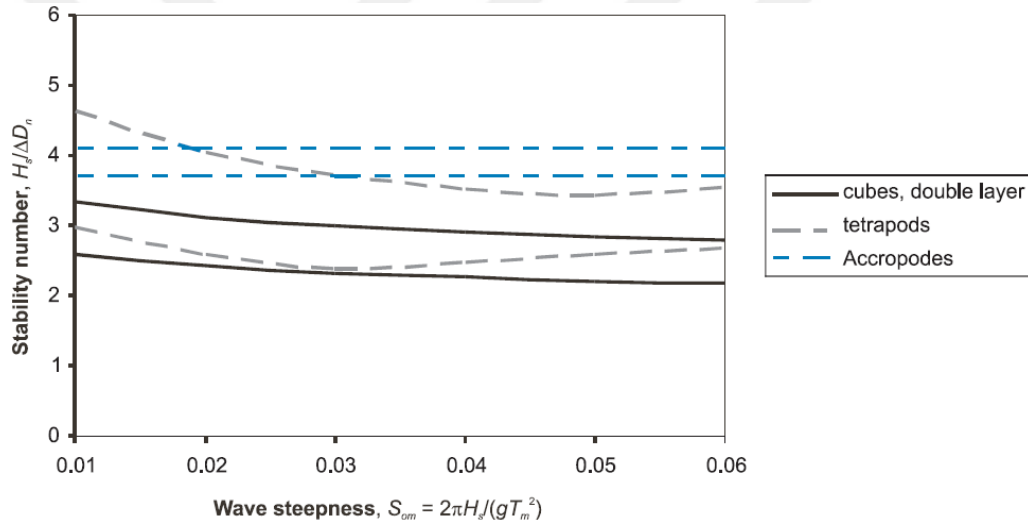


Figure 2.6 Wave steepness versus stability number graph (Rock Manual 2007)

Another important issue was also mentioned by Rock Manual (2007) about design and test results of accropode, tetrapod and cube. As it can be seen from Figure 2.7, evolution of the damage curves show important aspects. For example, in the design of single layer armoring, designers must be careful because the figure also implies that the single layer placement is a brittle placement pattern that damage occurs rapidly. For double layers, damage occurs gradually, almost linearly, and more controllably meaning that the layer can also be repaired easily compared to single layers. Additionally, suggested design value for double layers, overlaps at $N_{0d}=0.5$ (see dashed lines at Figure 2.7).

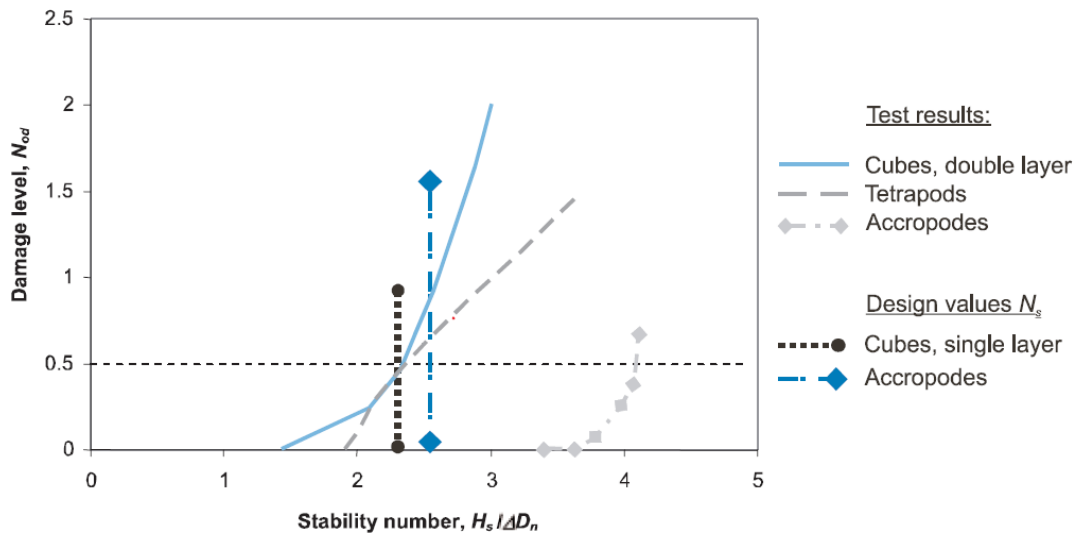


Figure 2.7 Damage curves for tetrapod, accropode and cube ($N=1000$ waves and $s_{0m}=0.03$) (Rock Manual 2007)

Rock Manual (2007) also provided a comprehensive table about the stability numbers of armor units using N_s . The table is given below including recommended slopes (Table 2.7).

Table 2.7 Stability of armor units using N_s (Rock Manual 2007)

Armor type	Damage level (%)	Stability number (N _s)				Slope
		Trunk		Head		
		Non-breaking waves	Breaking waves	Non-breaking waves	Breaking waves	
Cube (double)	0	1.8-2.0		-		1:1.5
	4	2.3-2.6		-		1:2
	0 (N0d=0)	1.5-1.7		-		1:1.5
	5 (N0d=0.5)	2.0-2.4		-		
	<5	2.2	2.1	1.95	-	1:1.5
		2.45	2.35	2.15	-	1:2
		2.8	2.7	2.5	-	1:3

Table 2.7 Stability of armor units using N_s (Rock Manual 2007) (cont.)

Cube (single)	0 (N0d=0)	2.2-2.3 (with 1.5 safety factor against sudden failure, 0.25 packing with under layer placed one side flat)		-		-
Tetrapod	0 (N0d=0)	1.7-2.0		-		1:1.5
	5 (N0d=0.5)	2.3		-		
	<5	2.3	2.2	2.1	1.95	1:1.5
	-	2.5	2.4	2.2	2.1	1:2
	-	2.9	2.75	2.3	2.2	1:3
Dolos (r=waist to height ratio)	2 (N0d=0.3)	2.7 (r=0.32)		-		1:1.5
	-	2.5 (r=0.34)		-		
	-	2.3 (r=0.36)		-		
	<5 (N0d=0.4)	3.2 (r=0.32)		-		-
Accropode*	0 (N0d=0)	2.7 (15.0)	2.5 (12.0)	2.5 (11.5)	2.3 (9.5)	1.33
Core-loc*	0 (N0d=0)	2.8 (16.0)		2.6 (13.0)		1.33
Xbloc*	0 (N0d=0)	2.8 (16.0)		2.6 (13.0)		1.33

* Corresponding Hudson stability numbers are given in brackets. Also, the stability of the armor layer does not increase slopes gentler than $\tan\alpha=1:2$.

2.2.3 Underlayers for Concrete Armoring

Rock Manual (2007) demonstrated that to transfer external loadings properly, underlayer materials such as core material and filter material must be in a specific size. In terms of permeability, a relatively narrow graded material should be used for the underlayer construction. The grain-size distribution of the lower layer material should not be too wide or too small due to the required permeability criteria. For instance, a low permeability leads to a low wave transmission which

also causes the increase of acting forces on the offshore side of the breakwater. A summary of recommendations on concrete armor units and armor stone size of underlayer material is given below on Table 2.8 (Rock Manual 2007).

Table 2.8 Recommendations on concrete armor units and armor stone size of underlayer material (Rock Manual 2007)

Armoring type	M_u^* and M_a^*		
Single-layer cubes	$M_{50,u}=0.07M_a$	$M_{min,u}\geq 0.05M_a$	$M_{max,u}\leq 0.10M_a$
Single-layer interlocking units	$M_{50,u}=0.10M_a$	$M_{min,u}\geq 0.07M_a$	$M_{max,u}\leq 0.14M_a$
Double-layer armoring	$M_{50,u}=0.10M_a$	$M_{min,u}\geq 0.05M_a$	$M_{max,u}\leq 0.15M_a$

2.3 Stability of Berm Breakwaters

A berm breakwater is a coastal structure having a berm on the seaward slope. According to the literature and history, berm breakwaters first gained major attention in the early 1980s as mass armored reshaping structures (Rock Manual 2007, Pillai *et al.* 2017, Yüksel *et al.* 2020). Construction and design of berm breakwaters require new considerations such as upper slope armor gradation and maintenance of the structure after construction phase.

Generally, rubble-mound breakwaters are constructed in a trapezoidal shape. However, berm breakwaters are constructed with a berm on seaward side due to their good performance. There are various considerations on the design on berm breakwaters and also different classifications which were introduced by Van der Meer and Sigurdarson (2016) and PIANC (2003). An example for a berm breakwater is given below from Helguvik, Iceland (Van der Meer and Sigurdarson 2016).



Figure 2.8 Berm breakwater at Helguvik, Iceland (Van der Meer and Sigurdarson 2016)

Berm breakwaters are great shore protection structures to dissipate wave energy and decrease wave overtopping compared to conventional breakwaters. Also, they decrease armor stone gradings significantly providing flexibility to the designer. If there is not enough rock size for conventional breakwater armoring, then berm breakwater can be selected (Rock Manual 2007).

2.3.1 Classification by PIANC (2003)

PIANC (2003) proposed following classification for berm breakwaters with $H_s/\Delta D_{n50}$ and $H_0 T_{m0}$ numbers (Table 2.9).

Table 2.9 Classification of berm breakwaters (PIANC 2003)

Type of breakwater	$H_s/\Delta D_{n50}$	$H_0 T_{m0}$
Statically stable non-reshaped	<1.5-2.0	<20-40
Statically stable reshaped	1.5-2.7	40-70
Dynamically stable reshaped	>2.7	>70

For statically stable non-reshaped cross-section, few stones are allowed to move, similar to conventional breakwater. This cross-section also may be economical compared to conventional cross-sections. But it still requires relatively heavy armor stones compared to other two berm cross-sections. Hence, enough armor

stone must be available which is dedicated to construction (PIANC 2003, Rock Manual 2007).

Statically stable reshape cross-section is more flexible than statically stable non-reshaped cross-section. This cross-section is allowed to have a new stable shape. In this new shape, no individual armor material is allowed to move. This type of berm breakwater is a good selection at regions where enough armor material is not available (PIANC 2003, Rock Manual 2007).

Dynamically stable reshaped cross-section is the most dynamic cross-section which is allowed to have a new shape and also armor materials can move along the armoring slope. If other two options are not possible, dynamically stable reshaped cross-section can be used (PIANC 2003, Rock Manual 2007).

2.3.2 Classification by Van der Meer and Sigurdarson (2016)

According to Van der Meer and Sigurdarson (2016), they updated the classification given by PIANC (2003). Their suggestions involve more components and criteria. Firstly, they mentioned following concepts, mass-armored berm breakwater (**MA**) and Icelandic-type berm breakwater (**IC**) (see Figure 2.9 and Figure 2.10).

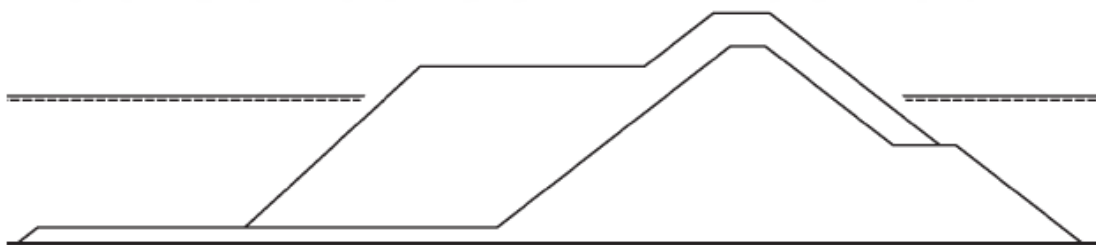


Figure 2.9 Mass-armored berm breakwater (Van der Meer and Sigurdarson 2016)

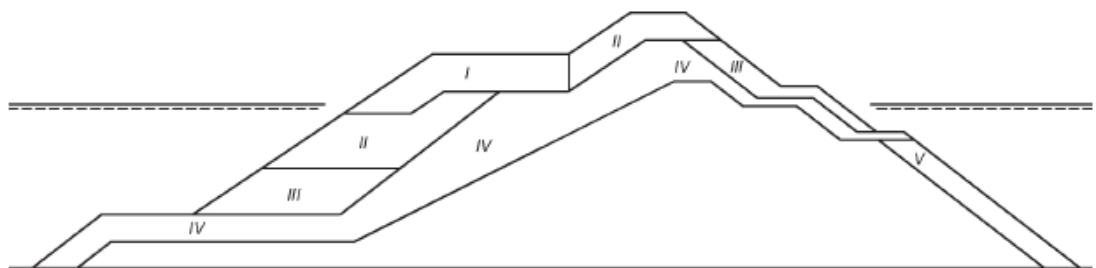


Figure 2.10 Icelandic-type breakwater with berm (Van der Meer and Sigurdarson 2016)

For mass-armored berm breakwater, the berm is constructed homogeneous with a wide gradation. However, in the Icelandic-type, the berm is heterogeneous including armor groups with narrow gradation (Van der Meer and Sigurdarson 2014). In the Figure 2.10, numbers ranging from I to V represent the rock classes on a descending order. So, I is the largest armor unit which is placed close to the wave attack region and V is the smallest armor unit which is placed to the leeside of the breakwater where wave forces are low (Van der Meer and Sigurdarson 2016).

In addition to these, they combined these concepts with following structural behavior concepts for berm breakwaters. These behavioral concepts are hardly reshaping (**HR**), partly reshaping (**PR**) and fully reshaping (**FR**) (Van der Meer and Sigurdarson 2016).

By combining the given concepts, Van der Meer and Sigurdarson (2016) concluded following classification types for berm breakwaters (see also Figure 2.11).

- Hardly reshaping Icelandic-type berm breakwater (**HR-IC**)
- Partly reshaping Icelandic-type berm breakwater (**PR-IC**)
- Partly reshaping mass-armored berm breakwater (**PR-MA**)
- Fully reshaping mass-armored berm breakwater (**FR-MA**)

For different wave climate conditions, Sigurdarson and Van der Meer (2012) proposed a descriptive table about above explained berm breakwaters (Table 2.10).

Table 2.10 Classification of berm breakwaters and some guiding numbers (Sigurdarson and Van der Meer 2012)

Breakwater type	$H_s/\Delta D_{n50}$	$S_d=A_e/D_{n50}^2$	Rec/D_{n50}
HR-IC	1.7-2.0	2-8	0.5-2
PR-IC	2.0-2.5	10-20	1-5
PR-MA	2.0-2.5	10-20	1-5
FR-MA	2.5-3.0	-	3-10

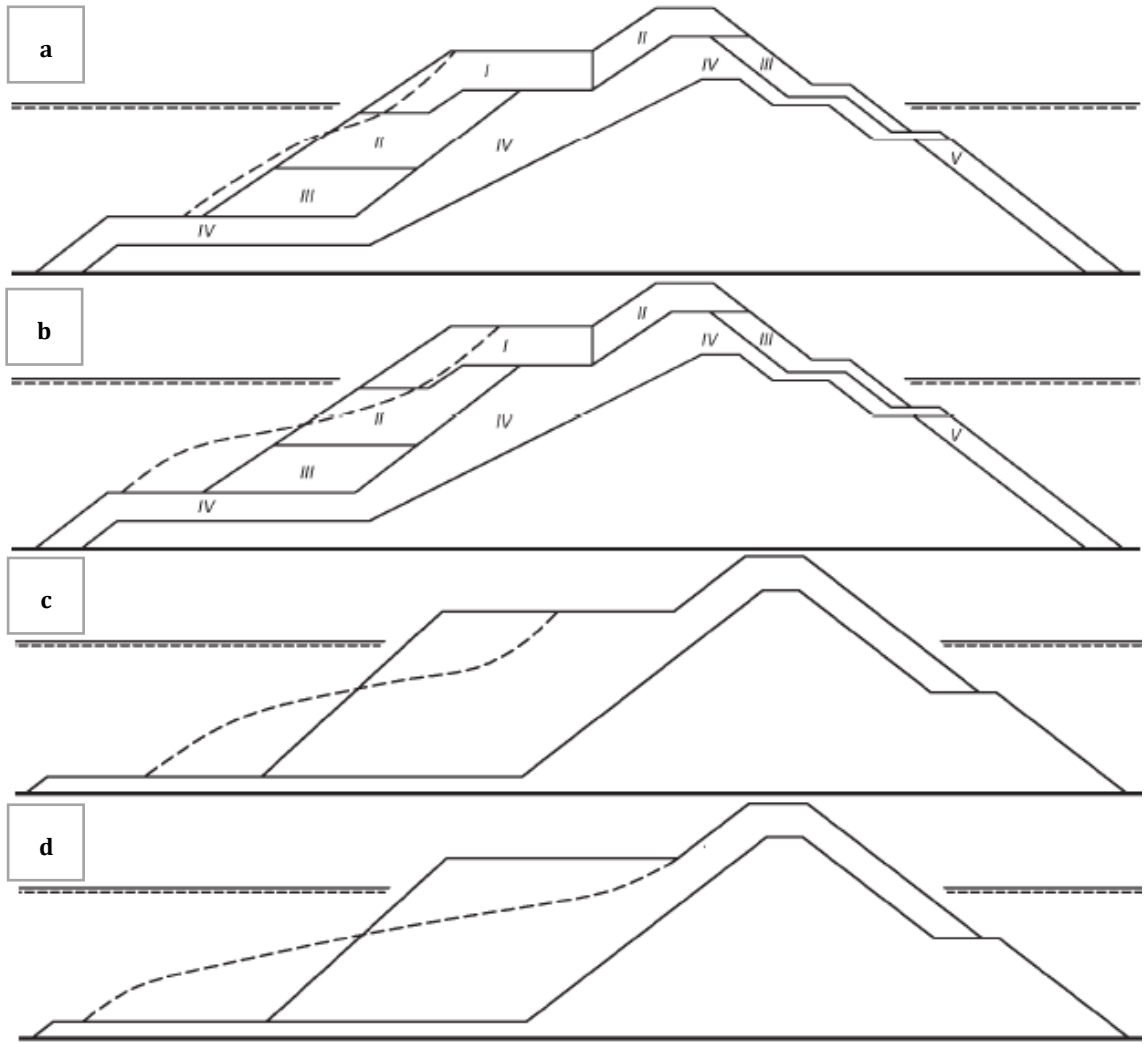


Figure 2.11 Berm breakwater classifications by Van der Meer and Sigurdarson (2016) (a: **HR-IC**, b: **PR-IC**, c: **PR-MA** and d: **FR-MA**)

Van der Meer and Sigurdarson (2014) expressed a graph including $H_s/\Delta D_{n50}$ on the x axis and Rec/D_{n50} on the y axis (see Figure 2.12). They used a large data set involving both constructed berm breakwaters and experimentally tested berm breakwaters. Van der Meer and Sigurdarson (2014) also suggested the following equations for breakwaters with berm. The equations give average results.

$$\frac{Rec}{D_{n50}} = 1.6 \left(\frac{H_s}{\Delta D_{n50}} - 1.0 \right)^{2.5} \quad (2.23)$$

$$\frac{Rec}{D_{n50}} = 0 \quad \text{for} \quad \frac{H_s}{\Delta D_{n50}} < 1.0 \quad (2.24)$$

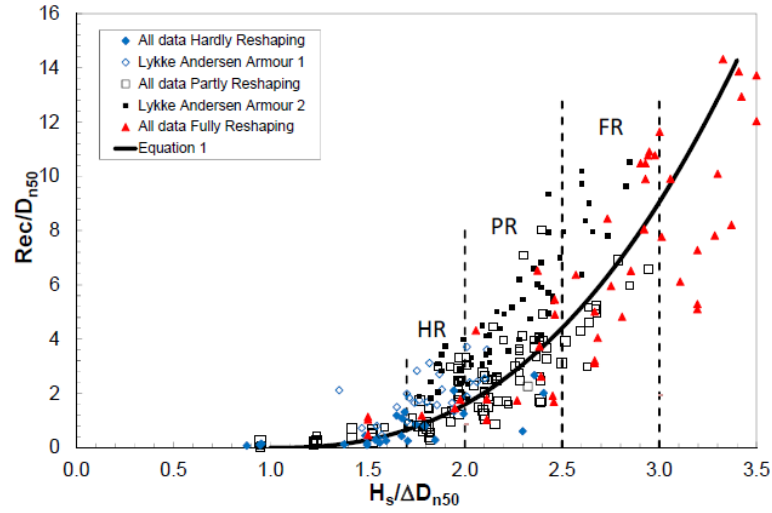


Figure 2.12 $H_s/\Delta D_{n50}$ versus Rec/D_{n50} (Van der Meer and Sigurdarson 2014)

As mentioned earlier, berm breakwaters are shaping structures after construction. However, shaping is acceptable if the following conditions are satisfied (Van der Meer and Sigurdarson 2016).

- The crest of the breakwater must be stable.
- Overtopping must not damage the leeside of the breakwater too much.
- The breakwater must stay statically stable after reshaping.
- There must be no significant amount of breaking of rock.

The formulae given by Van der Meer (1988) can be seen below for statically stable rock slopes for plunging waves and surging waves, respectively. These equations applicable in some specific conditions such as shallow water condition.

$$\frac{H_s}{\Delta D_{n50}} = 6.2P^{0.18}(S_d/\sqrt{N_w})^{0.2}\xi_m^{-0.5} \quad (2.25)$$

$$\frac{H_s}{\Delta D_{n50}} = 1.0P^{-0.13}(S_d/\sqrt{N_w})^{0.2}\sqrt{\cot \alpha} \xi_m^P \quad (2.26)$$

As known, Van der Meer (1988) defined the following formula to determine wave breaking type on breakwater slope.

$$\xi_{cr} = [6.2P^{0.31}\sqrt{\tan \alpha}]^{1/P+0.5} \quad (2.27)$$

In the above formulae, H_s is the significant wave height at the toe of the structure, ξ_{cr} is the critical breaker parameter, α is the slope angle, Δ is the relative density of the armor unit, D_{n50} is the nominal diameter of the armor unit, P is the permeability of the structure, S_d is the damage level and N_w is the storm duration of wave number.

2.3.3 Modified Stability Formula for Lower Slopes of Berm Breakwaters

2.3.3.1 Irregular Placement

As mentioned earlier, Van der Meer (1988) presented the following stability equation for concrete cubes for double layer irregular placement.

$$N_s = \frac{H_s}{\Delta D_n} = \left(6.7 \frac{N_{0d}^{0.4}}{N^{0.3}} + 1 \right) s_{0m}^{-0.1} \quad (2.28)$$

Yüksel *et al.* (2020) conducted experiments in a wave flume in Hydraulics and Coastal & Port Engineering Laboratory at Yıldız Technical University in order to upgrade the existing formula. They suggested the following formula for the stability of lower layer of berm breakwaters for irregular placement. They also accounted for following parameters as influential parameters in the lower slope, the position of the berm, the width of the berm and the wave steepness. Then, they included the parameter, γ_{berm} , to the stability equation.

$$N_s = \frac{H_s}{\Delta D_n} = \left(6.7 \frac{\left(\frac{N_{0d}}{\gamma_{berm}} \right)^{0.4}}{N^{0.3}} + 1 \right) s_{m-1,0}^{-0.1} \quad (2.29)$$

To find the reduction factor, γ_{berm} , they provided the following formulae for changing water levels, emerged berm ($d_b \leq 0$), submerged berm ($d_b \geq 0$) and berm at SWL ($d_b = 0$).

In the given formulae, B is the width of the berm, d_b is the level of the berm, $s_{m-1,0}$ is the wave steepness depending on the wave period $T_{m-1,0}$ and c_1 , c_2 , c_3 are the coefficients.

For the emerged berm ($d_b \leq 0$):

$$\gamma_{berm} = 1 - 0.07 \frac{B}{H_s} \left(1 - c_1 s_{m-1,0}^{c_3} \left| \frac{d_b}{H_s} \right|^{c_2} \right) \quad (2.30)$$

where $c_1 = 0.5$ $c_2 = 0.5$ $c_3 = 0.5$ with $0 \leq \gamma_{berm} \leq 1$

For the submerged berm ($d_b \geq 0$):

$$\gamma_{berm} = 1 - 0.07 \frac{B}{H_s} \left(1 - c_1 \left| \frac{d_b}{H_s} \right|^{c_2} \right) \quad (2.31)$$

where $c_1 = 0.5$ $c_2 = 0.7$ with $0 \leq \gamma_{berm} \leq 1$

For the berm at SWL ($d_b = 0$):

$$\gamma_{berm} = 1 - 0.07 \frac{B}{H_s} \quad (2.32)$$

It can be seen from the above given equations, Yüksel *et al.* (2020) did not observe any influence of the wave steepness on the submerged berm and on the berm at SWL.

2.3.3.2 Regular Placement

As mentioned before in the literature review part, in regular placed armor systems damage initiates suddenly compared to irregular placed systems (CEM 2006, Rock Manual 2007, Vieira *et al.* 2020). As a result of this, it is hard to create an equilibrium for these systems. So, Yüksel *et al.* (2020) calculated following stability number ranges for three different berm levels.

$$\text{Emerged berm} \rightarrow N_s = 2.9 - 3.4$$

$$\text{Berm at SWL} \rightarrow N_s = 1.8 - 2.5$$

$$\text{Submerged berm} \rightarrow N_s = 2.1 - 2.7$$

2.3.4 Derived Recession Formula for Berm Breakwaters

2.3.4.1 Irregular Placement

The following equation, which depends on the berm width and on the berm level, was derived by Yüksel *et al.* (2020).

$$\frac{Rec}{D_n} = (\gamma_{rec} N_0 + 1.8)^{1.15} \quad (2.33)$$

The factor number γ_{rec} can be calculated for changing water levels by using following equations.

For the emerged berm ($d_b/H_s < 0$) and for the submerged berm ($d_b/H_s > 0$):

$$\gamma_{rec} = \left(\left| \frac{d_b}{H_s} \right| \frac{B}{H_s} \right)^{0.5} \quad (2.34)$$

For the berm at SWL ($d_b/H_s = 0$):

$$\gamma_{rec} = \left(\frac{B}{H_s} \right)^{0.5} \quad (2.35)$$

2.3.4.2 Regular Placement

Yüksel *et al.* (2020) found that regular placement was performed better than irregular placement in terms of recession for concrete cube armor units. The stability of the berm for the regular placement was also found dependent on the width of the berm and level of the berm. Additionally, they mentioned that the berms with less than $4D_n$ length are not applicable.

2.3.5 Wave Overtopping Performance of Berm Breakwaters

Pillai *et al.* (2017) and Yüksel *et al.* (2020) mentioned that berm breakwaters have significant ability to decrease overtopping ratio compared to conventional breakwaters. As it is well known from CEM (2006) and Rock Manual (2007), if the desired overtopping discharge decreases on the leeside, then it is a must to increase the relative freeboard of the structure or new solutions are required such as placing a berm to the seaward side of the breakwater. Another example can be given for caisson breakwaters. A bullnose design with proper geometrical

dimensions significantly decreases the overtopping ratio (EurOtop 2007). As a result of these given examples, construction cost reduces importantly. There are many studies to determine the overtopping discharge on the leeside of the berm breakwaters. Below, the formula presented by Van der Meer and Sigurdarson (2014) for berm breakwaters is given.

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.2 \cdot \exp\left(-2.6 \frac{R_c}{H_{m0}\gamma_{BB}\gamma_\beta}\right) \quad (2.36)$$

$$\gamma_{BB} = \begin{cases} \mathbf{HR} \text{ and } \mathbf{PR} & 0.68 - 4.5S_{op} - 0.05\left(\frac{B}{H_{m0}}\right) \\ \mathbf{FR} & 0.70 - 9.0S_{op} \end{cases} \quad (2.37)$$

3.1 Experimental Setup and Procedures

3.1.1 Wave Flume

Experiments were carried out in the wave flume of the Hydraulics and Coastal & Harbour Engineering Laboratory at the Yıldız Technical University. The flume has adequate dimensions in order to maintain experimental study. The dimensions of the wave flume are 1 m height, 1 m width and 26 m length.

In this study, 8 different models were tested. These 8 models were tested in two different conventional cross-sections with a single layer regular placement and a double layer with irregular placement, and one cross-section with berm by placing irregularly on a double layer. Wave flume and physical models can be seen from Figure 3.1a, Figure 3.1b for the conventional cross-sections and Figure 3.1c for the berm cross-section, respectively. For conventional cross-sections, 0.55 m water depth was used. The water depth was only changed for the cross-sections with berm, 0.45 m, 0.55 m and 0.65 m. For the cross-sections with berm, by changing water level, three different cases were investigated, emerged berm, berm at SWL and submerged berm.

The wave flume has a wave generator with ARC (Active Reflection Compensation) system in order to generate irregular waves properly. The ARC system has ability to calculate reflections. Thus, the wave generator can generate following waves according to the calculated reflection values. In this way, it is possible to generate waves similar to nature. Figure 4 and Figure 5 show the wave flume and the wave generator respectively of the Coastal and Harbour Engineering Laboratory at the Yıldız Technical University. Additionally, to measure wave conditions in the wave flume, wave probes were used. Locations of these probes can be seen also from Figure 4.

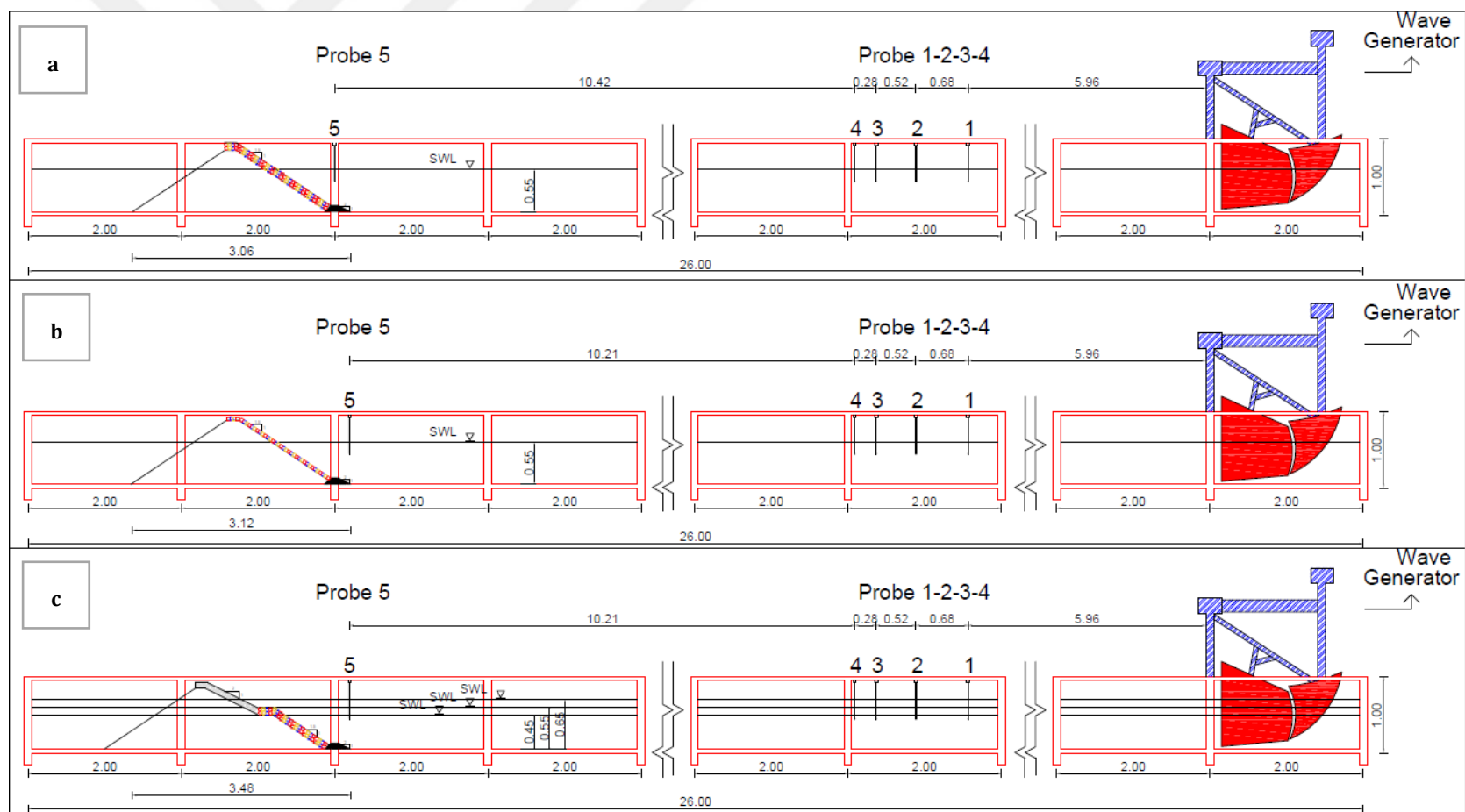


Figure 3.1 Wave flume and physical models (a: double layer irregular, b: single layer regular, c: double layer irregular with berm)

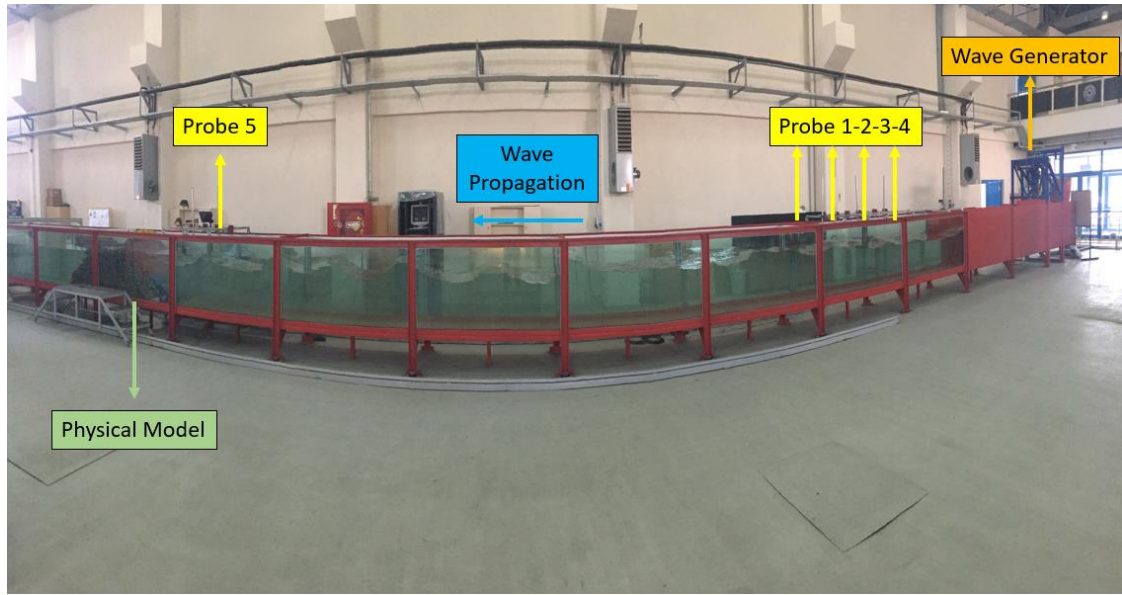


Figure 3.2 Wave flume of the Hydraulics and Coastal & Harbour Engineering Laboratory at the Yildiz Technical University



Figure 3.3 Wave generator with ARC

3.1.2 Cube Blocks and Placements

Cube blocks used in the armor layer were produced in the Hydraulics and Coastal & Harbor Engineering Laboratory. In the experimental research, normal-density and high-density cubes were used. All produced cubes have same dimensional properties, $4 \times 4 \times 4 \text{ cm}^3$. In order to reduce frictional scale effects, all sides of each cube were sanded. Table 3.1 shows properties of normal-density and high-density cubes.

Table 3.1 Properties of normal-density and high-density cubes

	Nominal diameter, D_n (cm)	Weight, W (gr)	Volume, V (cm ³)	Density, ρ_{cube} (gr/cm ³)
Normal-density cubes	4	155.7 (± 4.53)	64	2.4
High-density cubes	4	202 (± 4.53)	64	3.15

Today, high-density concrete is used in different fields such as in radioactive plants to reduce the effects of harmful rays. The selection of heavy aggregates used in the production of these kinds of concrete materials require special attention. Also, mixing ratio is important because investigations about such concretes are limited as well.

In the production phase of high-density concrete, there are several natural aggregates used such as Barite (BaSO_4), Limonite ($\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$) and Magnetite (Fe_3O_4). As we know Triemstra (2000) used Magnetite (Fe_3O_4) to produce high-density concrete cubes for his experimental research. In addition, industrial waste materials such as iron or lead can be used as artificial aggregate in order to increase the density of the material. By using natural or artificial aggregates, concrete can be produced with the density varying between 3000 kg/m³ and 9000 kg/m³ (Gümüşçü 2020). The density of the concrete is highly affected by the type of the used aggregate because of wide density range of the aggregates. Table 3.2 shows approximate densities of some special aggregates in NRT (Near Room Temperature).

Table 3.2 Densities of some special aggregates

	Barite	Limonite	Iron	Lead
Density, ρ (g/cm ³)	4.50	2.7-4.3	7.87	11.34

The optimum mixing ratio was chosen by trying different mixings in order to achieve the desired density for high-density cubes (3.15 gr/cm³). Natural Barite was used in concrete production as aggregate. Structure of it was completely crystal and pure Barite minerals. The grain-size distribution range of the aggregate

was between 0-5 mm. Also, CEM II 42.5 R type cement and super plasticizer were used. The water/cement ratio and the super plasticizer ratio were determined as 0.55 and 0.44% respectively.

All high-density and normal-density cubes were painted to white, red, yellow and blue in order to ease the analysis phase because eye visualization technique was used in that phase. Preparation phases for cubes can be seen from Figure 3.4a and Figure 3.4b.

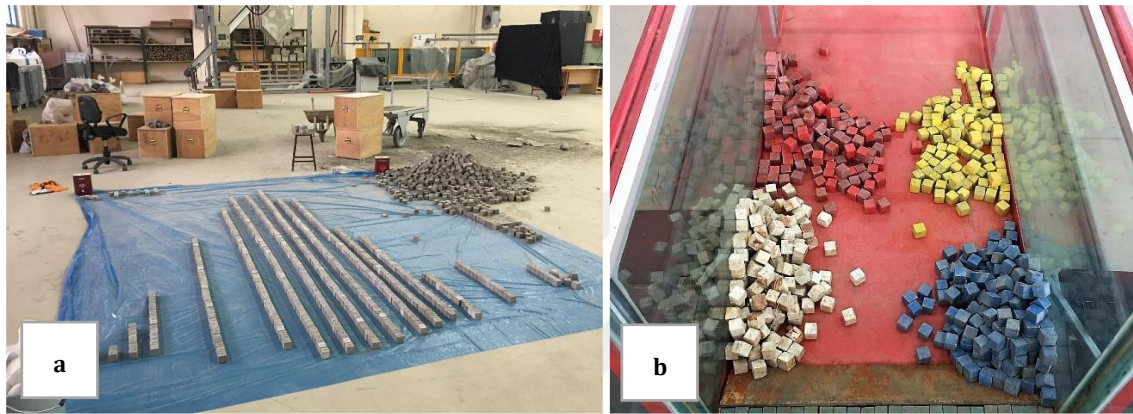


Figure 3.4 Preparation of cubes (Gülver 2019)

3.2 Breakwater Models

In this part, all investigated physical models are going to be explained. In total, two different conventional cross-sections with a single layer regular placement and a double layer with irregular placement, and one cross-section with berm by placing irregularly on a double layer were applied. Also patterns of normal-density and high-density cubes were changed in some experiments. In addition to these, water depth was also varied between 0.45 m and 0.65 m for cross-sections with berm. Consequently, with the combination of these various cases, 8 different breakwater models were tested. Table 3.3 shows all tested breakwater models. Note that, all cross-sections were firstly drawn to the glass of the wave flume and then constructed by referring the draw.

Table 3.3 Test programme

	Cross-section type	Placement style	Layer	Water level, h_{toe} (m)	Used cubes	Wave steepness (s_{0m})	Packing density (ψ_s)	Crest relative freeboard, R_c/D_c
1-CID	Conventional	Irregular	Double	0.55	ND-HD	0.04	0.59	2.50
2-CID	Conventional	Irregular	Double	0.55	ND-HD	0.04	0.59	2.50
3-CRS	Conventional	Regular	Single	0.55	HD	0.04	0.59	2.50
4-CRS	Conventional	Regular	Single	0.55	ND	0.04	0.59	2.50
5-BID	Berm	Irregular	Double	0.45	ND-HD	0.04	0.59	3.13
6-BID	Berm	Irregular	Double	0.55	ND-HD	0.04	0.59	2.50
7-BID	Berm	Irregular	Double	0.65	ND-HD	0.04	0.59	1.88
8-BID*	Berm	Irregular	Double	0.45	ND-HD	0.04	0.59	3.13

* 8-BID has a different pattern compared to 5-BID. In the experiment 8-BID, high-density cubes were placed over reference area and first two rows of the berm for both first layer and second layer. Rest of the armor layer was filled with normal-density cubes. For a detailed explanation, see chapters 3.2.1 and 3.2.2.

All conventional models have 1 m width and 0.95 m height consisting of a permeable core layer constructed with quartz stone, a toe and the armor layer. For cross-sections with berm, in addition to these, supplementary materials were used. In the upper slope, double layer riprap was used. Since the upper slope was out of the scope of this study, it was fixed with a wire mesh. Figure 3.5a, Figure 3.5b and Figure 4.5c show different breakwater models in the experimental study for double layer irregular placement, single layer regular placement and double layer irregular placement on berm, respectively.

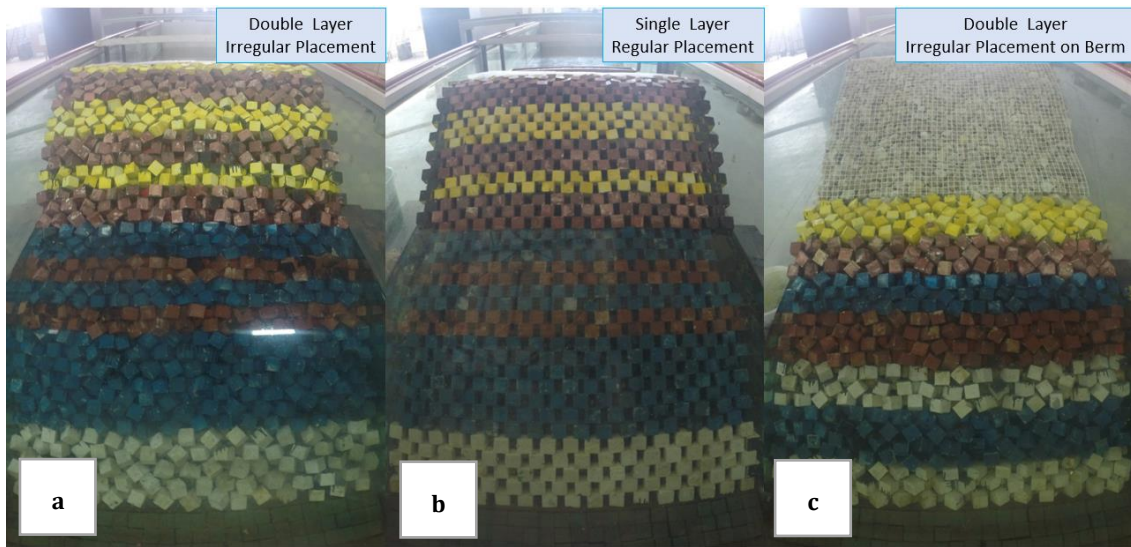


Figure 3.5 Tested breakwater models in experimental study

As mentioned, core layer was constructed by using quartz stone. The nominal diameter of the quartz stone is $D_{n50}=1.90$ cm having $M_{50}=18.25$ gr mass and $\rho_s=2.65$ tons/m³ of density. The weight relationship between core layer material and armor layer material was calculated according to equation presented by Van Gent and Spaan (1998). In addition, CEM (2006) recommends that this value should be around 10.

$$\frac{M_{armor}}{M_{50,lowerlayer}} \cong 10 - 20$$

Mass ratio for armor layer with high-density cubes:

$$\frac{M_{armor}}{M_{50,lowerlayer}} = \frac{202}{18.25} = 11.07$$

Mass ratio for armor layer with normal-density cubes:

$$\frac{M_{armor}}{M_{50,lowerlayer}} = \frac{155.73}{18.25} = 8.53$$

Nominal diameter ratio for cube armor layer:

$$\frac{D_{n,armor}}{D_{n50,lowerlayer}} = \frac{4.00}{1.90} = 2.11$$

In all parts of model breakwaters, concrete cubes were used with 4 cm nominal diameter. Incline of slope was determined according to Van der Meer (1988) and was chosen as 1/1.5. In order to test properly the whole system, all cubes should be touching each other including transition zone. We made sure that all cubes were touching each other before starting each test run. Also, in the upper slope of berm breakwaters riprap was used with $D_{n50}=3.40$ cm on 1/2 slope.

Mass ratio for upper armor layer:

$$\frac{M_{armor}}{M_{50,lowerlayer}} = \frac{157.20}{18.25} = 8.61$$

Nominal diameter ratio for upper armor layer:

$$\frac{M_{armor}}{M_{50,lowerlayer}} = \frac{3.90}{1.90} = 2.05$$

Particle-size distribution curves can be seen from Figure 3.6 and Figure 3.7 for core layer material and upper layer material, respectively.

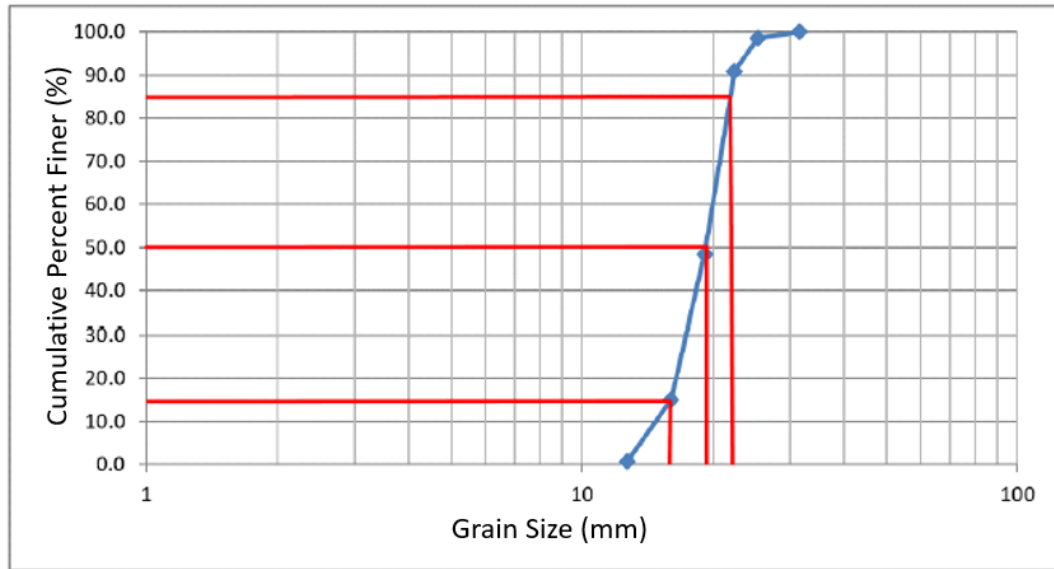


Figure 3.6 Particle-size distribution curve for core layer material

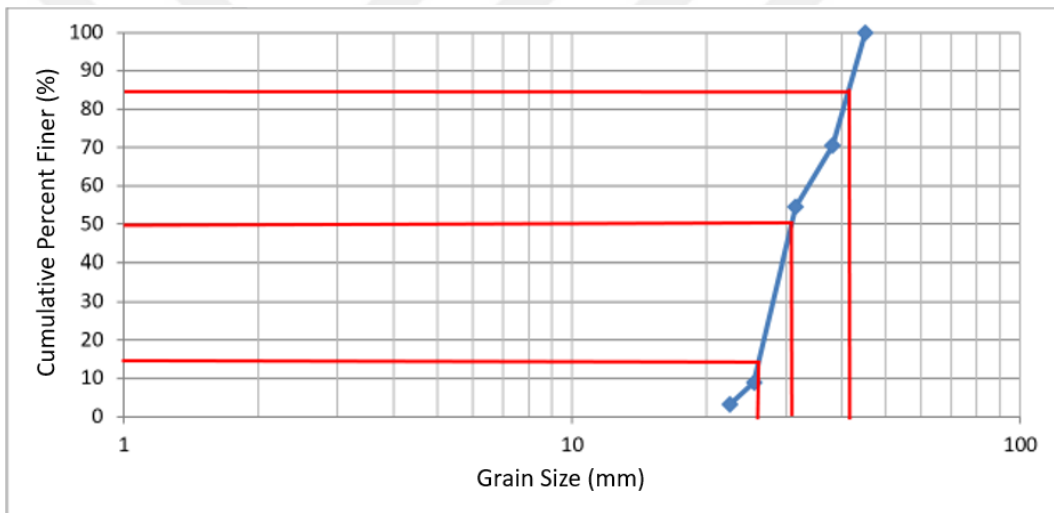


Figure 3.7 Particle-size distribution curve for upper slope armor layer

Since armor layer stability is the focus of this study, a strong toe was constructed in front of all model breakwaters and was welded to the floor of wave flume. Therefore, toe-based failures were prevented.

3.2.1 Conventional Cross-Sections

Conventional cross sections were investigated in various ways. The tested conventional cross-sections are elaborated and given below. Placement styles for these experiments also can be seen from Figure 3.8a and Figure 3.8b.

- **1-CID) First Layer ND Cubes– Second Layer HD Cubes (Irregular):** In this experiment, normal-density cubes were placed to the first layer and high-density cubes were placed to the second layer.
- **2-CID) Reference Area HD Cubes (Irregular):** In this model, first layer consisted only normal density cubes. But in the second layer, high-density cubes were placed starting from the bottom of the reference area to the first row of the crest (including first row) and rest of the second layer was filled with normal-density cubes.
- **3-CRS) Single Layer HD Cubes with Regular Placement (Regular):** High-density cubes were placed regularly in a single layer.
- **4-CRS) Single Layer ND Cubes with Regular Placement (Regular):** Normal-density cubes were placed regularly in a single layer.

Tested conventional cross-sections for double layer breakwaters and single layer breakwaters can be seen from Figure 3.9 and 3.10 respectively.

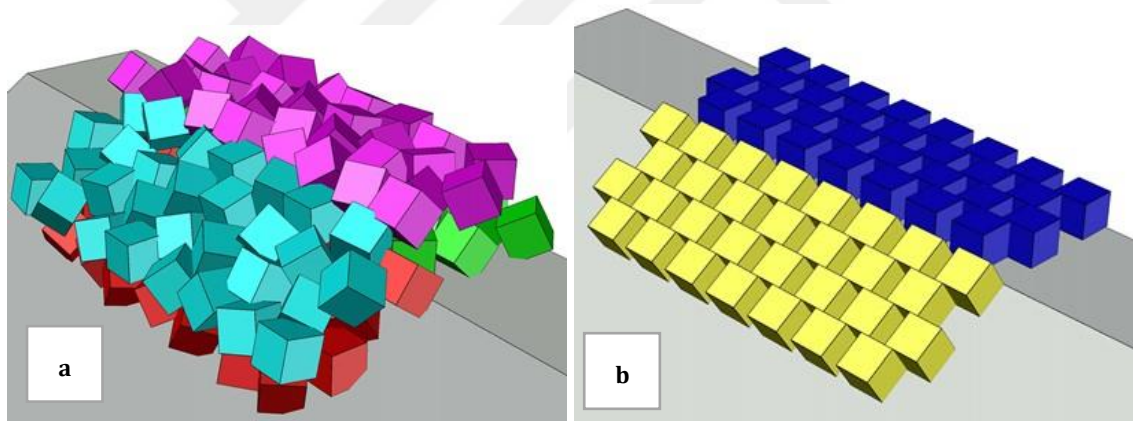


Figure 3.8 Irregular (a) and regular (b) placement styles

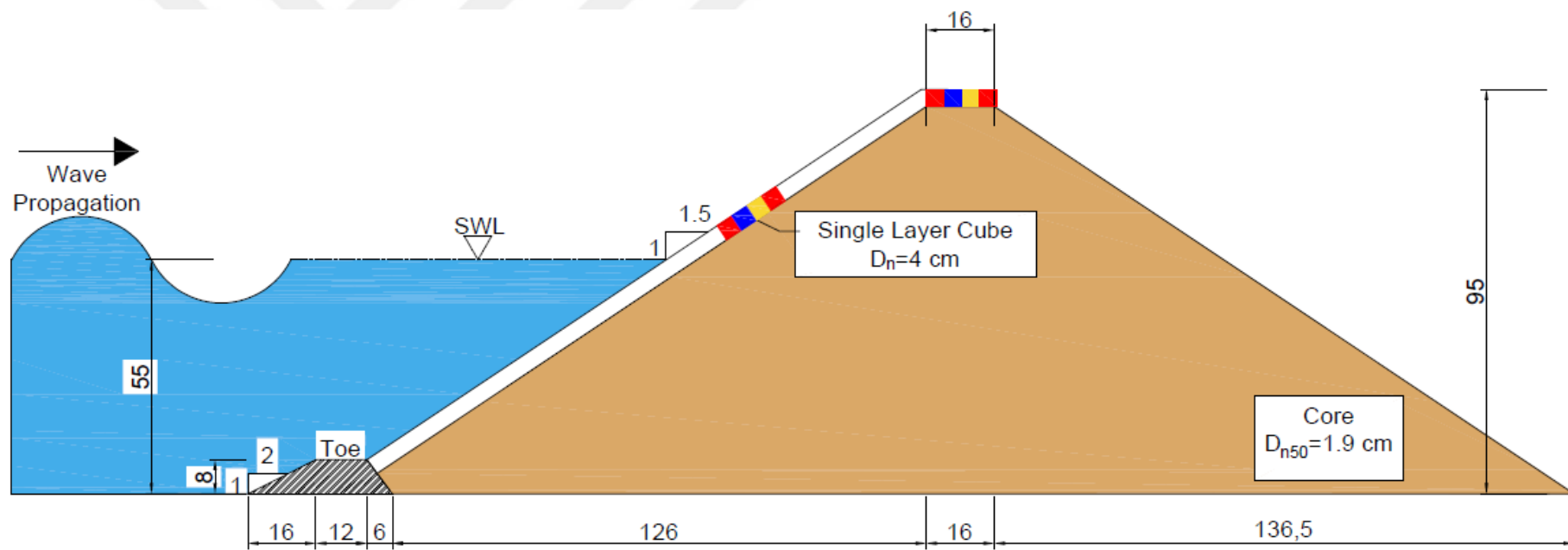


Figure 3.10 Cross-section for single layer models (units are in cm)

3.2.2 Cross-Sections with Berm

Tested cross-sections with berm, are given below with details. Placement style and used cross-section with different water levels can be seen from Figure 3.11 and Figure 3.12 respectively.

- **5-BID) Emerged Berm (Irregular):** In this experiment, normal-density cubes were placed to the first layer and high-density cubes were placed to the second layer. The berm was at 10 cm above the still water level.
- **6-BID) Berm at SWL (Irregular):** In this experiment, normal-density cubes were placed to the first layer and high-density cubes were placed to the second layer. The berm was at the still water level.
- **7-BID) Submerged Berm (Irregular):** In this model, normal-density cubes were placed to the first layer and high-density cubes were placed to the second layer. The berm was at 10 cm below the still water level.
- **8-BID) Emerged Berm with HD Cubes Over Reference Area (Irregular):** In this experiment high-density cubes were placed over reference area and first two rows of the berm for both first layer and second layer. Rest of the armor layer was filled with normal-density cubes.

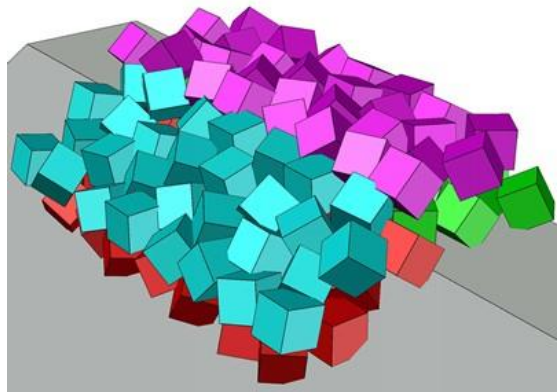


Figure 3.11 Irregular placement style for berm breakwaters

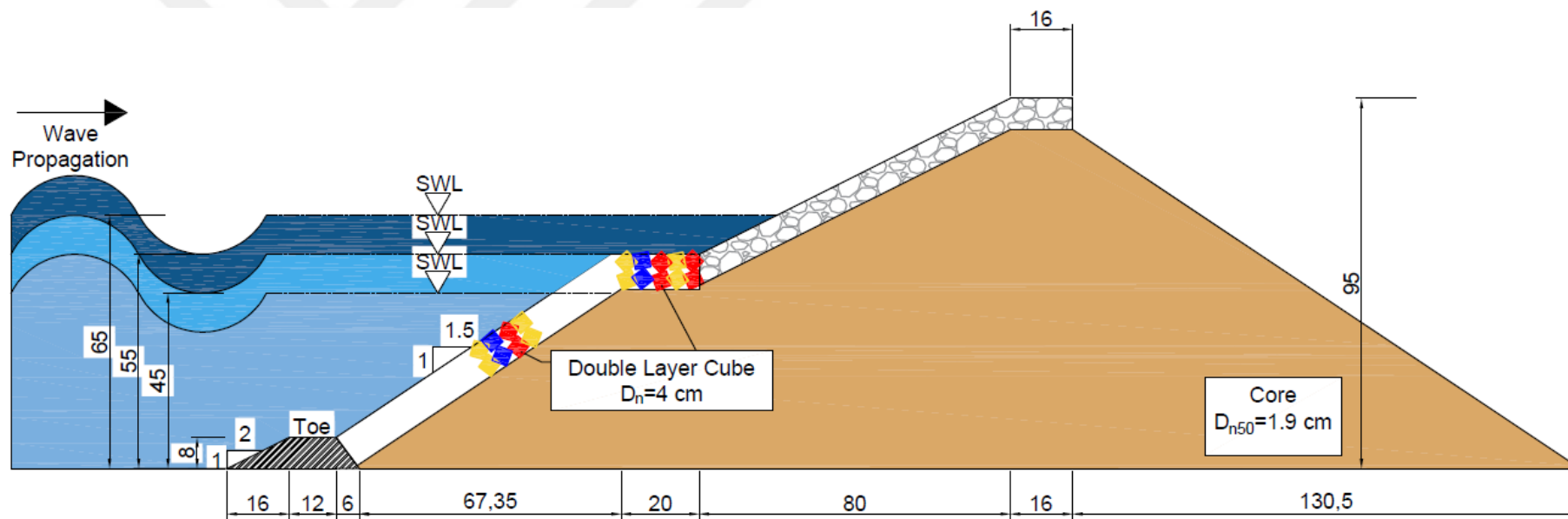


Figure 3.12 Cross-section for models with berm (units are in cm)

3.3 Placement Methods and Patterns

Two different placement methods were applied for this experimental study, irregular placement and regular placement. Each different method has its own advantages and disadvantages which are going to be discussed in the following chapters.

3.3.1 Irregular Placement Method

In this placement method, cube blocks were placed by hand dropping them from a few centimeters above the core layer. For the second armor layer, same method was applied, and the cubes were released from a few centimeters above the first armor layer. This placement method was used in conventional cross-section and berm cross section. Figure 3.13 shows pattern of first row of the first armor layer.

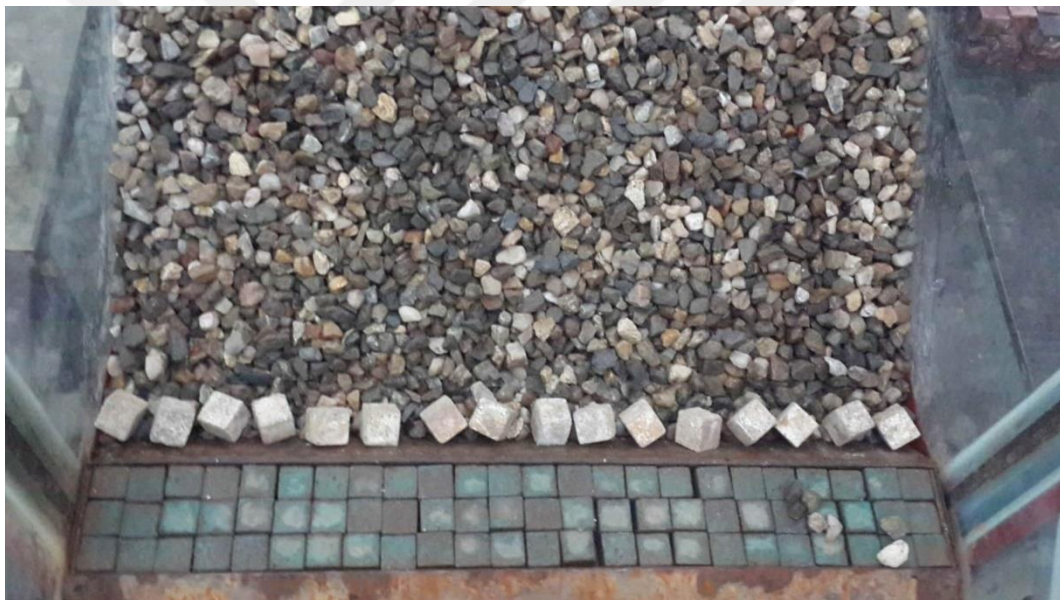


Figure 3.13 Placement of first row using irregular placement method

During the placement, same number of cubes were placed in each row in order to keep packing density same. For example, in the Figure 3.13, 16 cubes were placed to the first row of the first armor layer. To keep the packing density same, 15 cubes were placed to the first row of the top layer. These 15 cubes were placed nearly between cubes at the first armor layer. Then 15 cubes were placed to the second row of the first layer and 16 cubes were placed to the second row of the top layer. Figure 3.14a and Figure 3.14b show construction of the top layer.

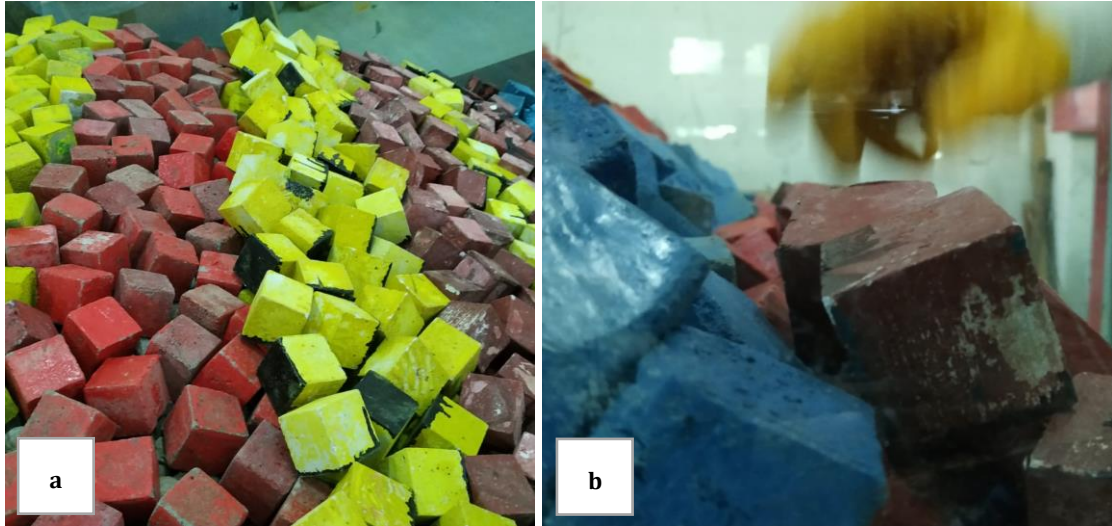


Figure 3.14 Construction of the second layer

Figure 3.15a and Figure 3.15b show core layer and quantity of cubes in each row, respectively.

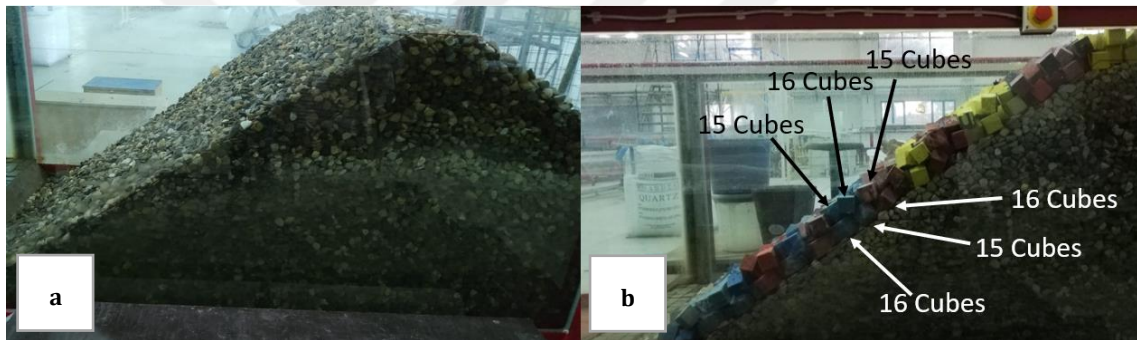


Figure 3.15 Core layer (a) and cube quantities (b)

3.3.2 Regular Placement Method

In regular placement method, cubes are placed differently compared to irregular placement method. Packing density was kept same in every area of the armor layer. To do that, cubes were placed approximately 2 cm space and, also 17 cubes were used in each row. This placement style was only applied to single layer conventional cross sections. Each cube, one by one, was placed into its predetermined location. Construction process of a single layer conventional cross-section can be seen from Figure 3.15.



Figure 3.16 Construction process of a single layer conventional cross-section

3.4 Packing Density (ψ_s) and Porosity (n)

Packing density and porosity are significant parameters that directly affect the stability of the breakwater. In this experimental study different packing densities and porosities were used and were calculated according to Frens *et al.* (2009). The packing density formula is presented below with definitions. Figure 3.17 shows an example calculation area for the packing density and porosity.

$$\psi_s = \frac{\text{Real number of placed blocks}}{\text{Max. possible number of block volumes per surface unit}} = \frac{N_{BL}}{N_{PBL}} = \frac{N_{BL} \cdot D_n^2}{B \cdot L} \quad (3.1)$$

N_{BL} : Quantity of units placed to $B \times L$ area

N_{PBL} : Maximum quantity of units that can be placed in $B \times L$ area

D_n : Nominal diameter of the unit

B : Width of the calculation area

L : Length of the calculation area

In order to calculate packing density, all cubes were counted in the reference area and divided by layer number. Thus, N_{BL} was calculated for the packing density calculations. Additionally, the openings in the reference area represent the porosity.

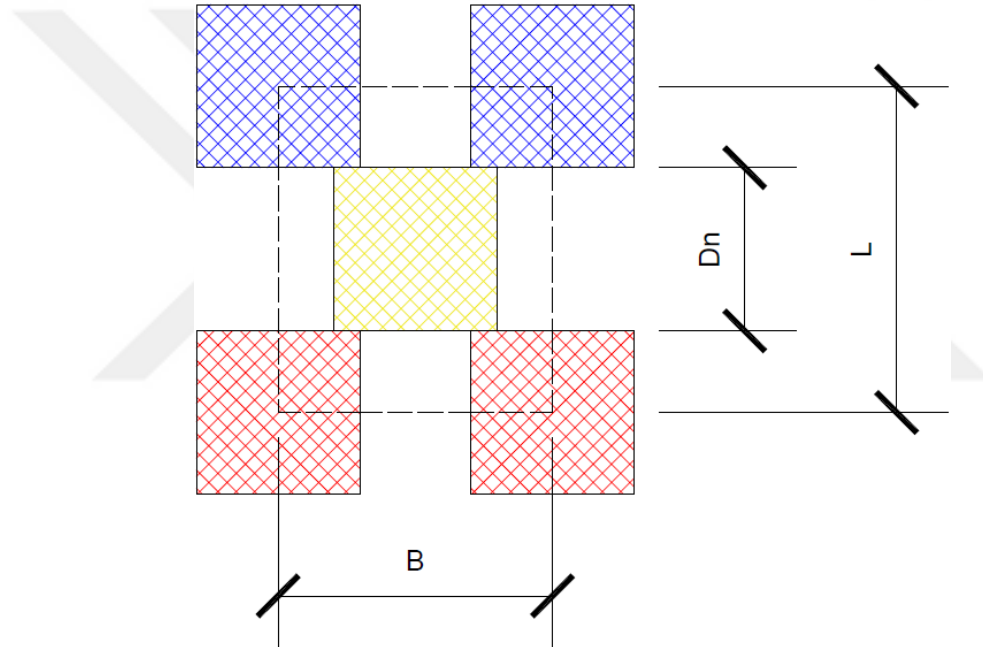


Figure 3.17 A unit section for packing density calculation

Packing density and porosity calculations for irregular placement:

$$\psi_s = \frac{N_{BL} \cdot D_n^2}{B \cdot L} = \frac{2 \times 4^2}{6.73 \times 8} = 0.59 \quad \text{and} \quad n = 1.0 - 0.59 = 0.41$$

3.5 Reference Area

Damage and movement of cubes were determined by using eye visualization technique. In order to do that the reference area was designated for each cross section taking into account $1H_s$ above and $1H_s$ below the SWL. Note that, for berm

cross-sections at 0.55 m and 0.65 m water depths, reference area was not changed, and same reference area was considered which was used in 0.45 m water depth ($10D_n$ below berm). The boundary of the reference area was determined according to the highest wave height which is $H_{m0}=0.20$ m. Note that, since the boundary conditions are different for cubes touching to the flume glass, these cubes were excluded from the reference area and analysis phase. Thus, width of the reference area was decreased to 92 cm. An example reference area can be seen from Figure 3.18. Red cubes were excluded.

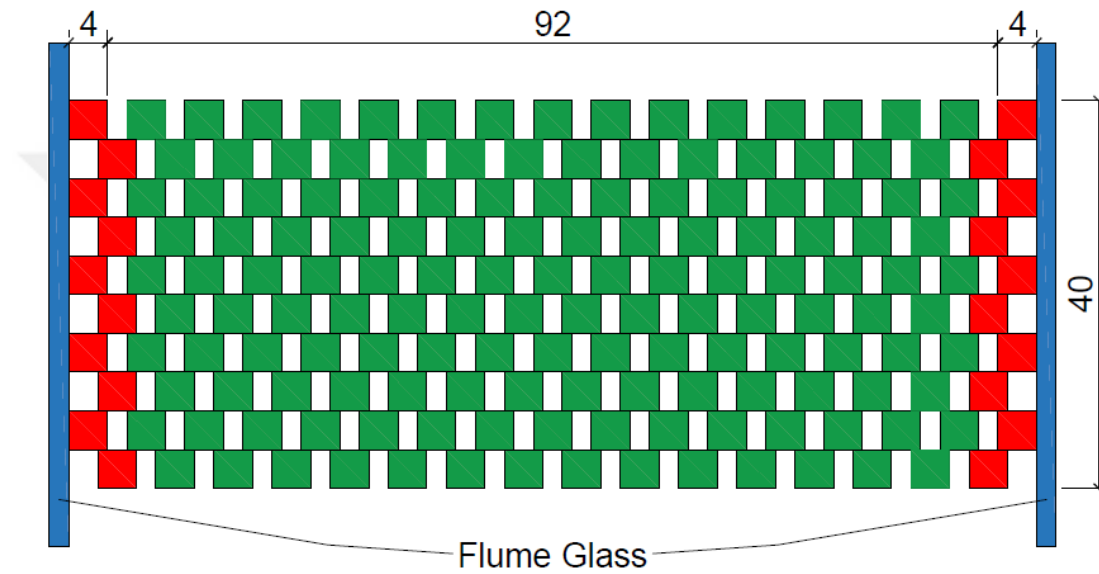


Figure 3.18 Reference area and excluded cubes (units are in cm)

3.6 Definitions of Damage Criteria

To determine the ratio of the damage, various movement and damage parameters were evaluated. These parameters are moving units (M), displaced units (D), recession on berm (Rec) and relative damage (N_0). Before and after each individual test run, pictures of the model were taken with a GoPro camera. Also, during each individual test, videos were recorded to investigate the behavior of each model elaborately. Recorded videos and taken pictures were used to determine movement of the units (Figure 3.19).

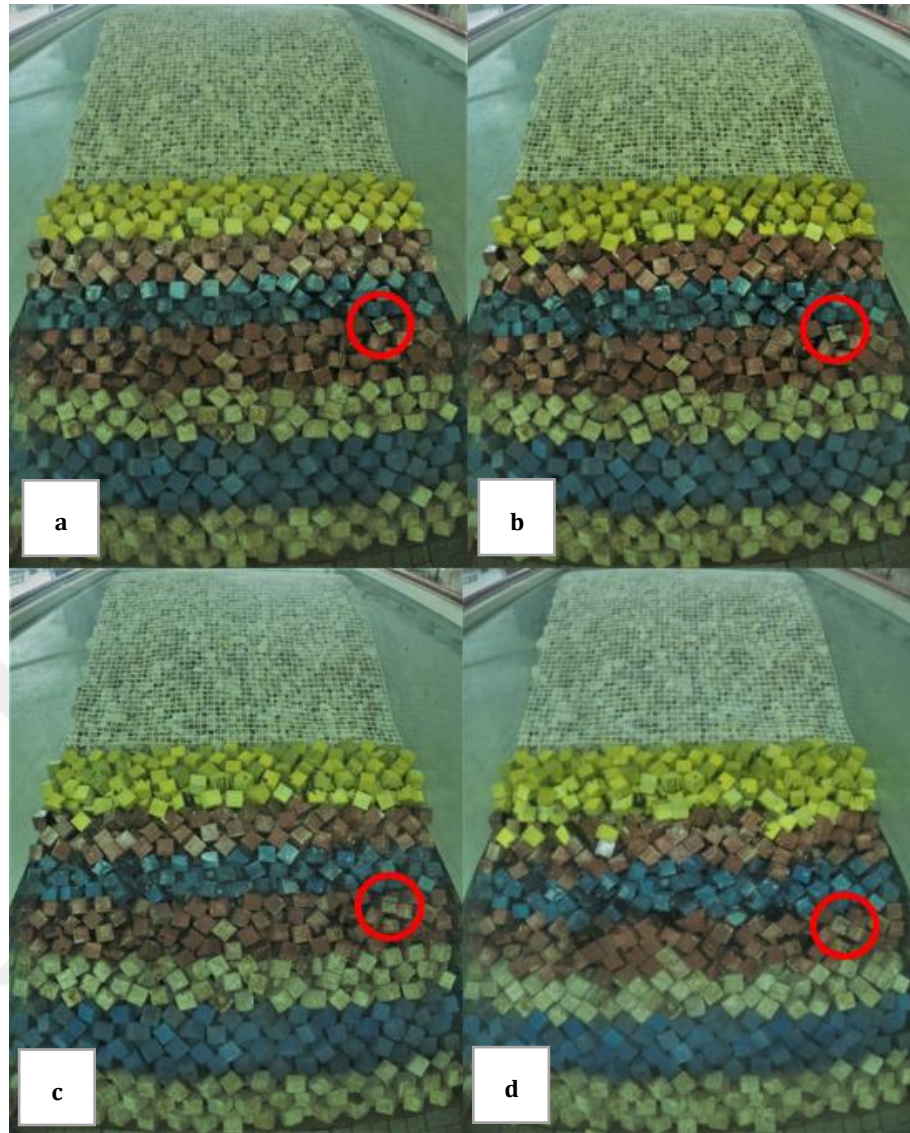


Figure 3.19 Damage process pictures taken by underwater camera (a: starting position, b and c: movement, d: damage)

In the definition of damage, wave characteristics are important as well. For stability calculations, the wave characteristics at the toe of the structure were considered. These considered wave parameters are significant wave height (H_{m0}), peak period (T_p), wave steepness (s_p , $s_{m-1.0}$) and reflection coefficient (C_r).

3.6.1 Block Movements

For breakwaters constructed with concrete armor units, the movement of the units is an important parameter that defines the amount of damage. As aforementioned, movement of the armor layer was observed by using a GoPro underwater camera. In order to categorize the block movements, different categories were defined. Movement and damage classifications are given in Table 3.4.

Table 3.4 Damage definitions for moving (M) and displaced (D) units

Moving units (M)		Displaced units (D)	
M₁	0.0-0.5D _n	D₁	1.0-2.0D _n
M₂	0.5-1.0D _n	D₂	>2.0D _n
M_T	0.0-1.0D _n	D_T	>1.0D _n

The damage ratio is calculated as a percentage (see the equation below). Moving and displaced units are divided to the total number of units in the reference area, then damage ratio is calculated for the intended damage type.

$$\text{Damage ratio (M or D) (\%)} = \frac{\text{Moving or displacing units in the reference area}}{\text{Total number of blocks in the reference area}} \quad (3.2)$$

3.6.2 Relative Damage (N₀)

Definition of the damage can be determined in a different way based on the movement of the armor units. Van der Meer (1998) presented relative damage, N₀, to differently identify the damage in armor layer. The relative damage is the actual quantity of armor units (rocking, displaced etc.) related to a width (along the longitudinal axis of the breakwater) of one nominal diameter D_n. For concrete cubes, the nominal diameter is the side of the cube. In order to diversify the N₀, different definitions were presented by Van der Meer and Heydra (1991). Note that in all these provided formulae below, L is the width of the wave flume which is 92 cm for this study.

1) Number of blocks displaced less than $0.5D_n$ (rocking)

$$N_{0<0.5} = \frac{\text{Number of rocking units } (N_r)}{L/D_n} \quad (3.3)$$

2) Number of blocks displaced more than $0.5D_n$ (sliding)

$$N_{0>0.5} = \frac{\text{Number of sliding units } (N_{sl})}{L/D_n} \quad (3.4)$$

3) Number of blocks displaced out of the layer ($>2.0D_n$) (displacement)

$$N_{0d} = \frac{\text{Number of displaced units } (N_d)}{L/D_n} \quad (3.5)$$

Another damage definition was also presented by Van der Meer (1998) that includes sliding and displacement because these two major parameters mainly cause damage on breakwater armor.

$$N_{0,mov} = N_{0d} + N_{0>0.5} \quad (3.6)$$

For relative damage calculation, displacement has to be defined. According to CEM (2006) position shifting more than $1D_n$ or displacement out of the armor layer can be good indicators. Following equation expresses relative damage and, only includes units passing $1D_n$.

$$N_0 = \frac{\text{Number of } (> 1D_n) \text{ displaced units in reference area}}{L/D_n} \quad (3.7)$$

3.6.3 Recession (Rec)

Design of breakwaters with berm requires more specific considerations than conventional breakwaters because a new term recession involves the complexity. Sigurdarson and Van der Meer (2014) stated that the recession in berm breakwaters is a part of the classification. The recession is an important parameter that strongly affects the stability of the breakwater. For instance, the behavior of the structure determines the shape of the breakwater such as hardly reshaping (HR), partly reshaping (PR) and fully reshaping (FR) (CEM 2006). In this study, the

recession was calculated cumulatively based on camera pictures. A recession depiction can be seen from Figure 3.20.

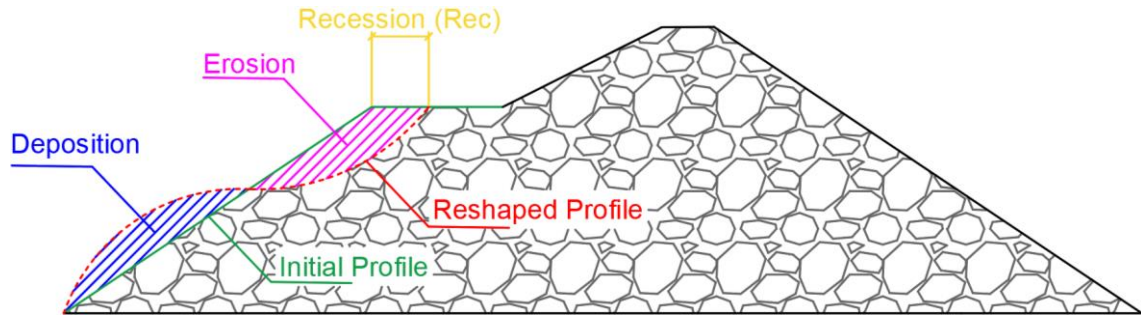


Figure 3.20 Recession on a berm breakwater

First, recession length is calculated and then is divided by cube nominal diameter. In this way, dimensionless recession value is obtained (Rec/D_{n50}). Recession value is read by referring transition line between lower slope and berm. A dimensionless recession calculation is given below (see also Figure 3.21).

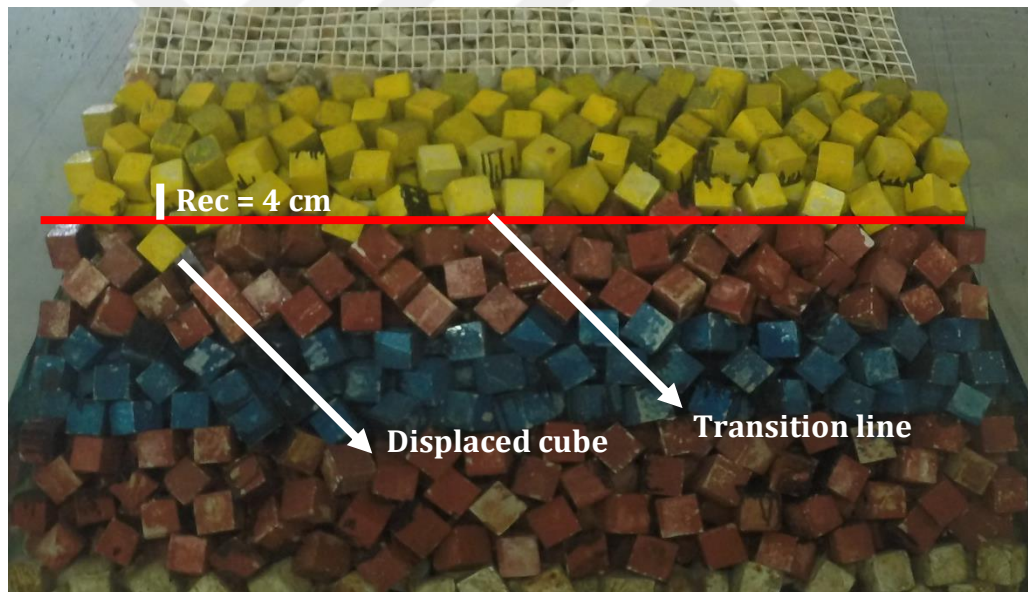


Figure 3.21 Calculation of recession on a berm

$$\frac{Rec}{D_{n50}} = \frac{4}{4} = 1$$

3.7 Wave Conditions

In experiments, irregular waves were generated with a wave generator to represent conditions in nature as close as possible. All generated waves were perpendicular to the normal of the model structure. Before experiments, a total of 13 waves were created with a JONSWAP spectrum with increasing wave height ($\gamma=3.3$). Five wave probes were used in order to measure the wave conditions in the wave flume. Four wave probes were located in front of the wave generator, and the last probe was located at the toe of the structure. Before start of each test run, wave probes were calibrated according to the water depth. H_s , the spectral significant wave height and $T_{m-1.0}$, the mean wave period (also known as mean energy period T_E) were obtained from the measured wave energy spectra. Additionally, see the equations provided below for details on H_{m0} , H_s , $T_{m-1.0}$ and T_E .

$$H_{m0} \cong H_s \cong 4.004\sqrt{m_0} \quad (3.8)$$

$$T_{m-1.0} = T_E = \sqrt{\frac{m_{-1}}{m_0}} \quad (3.9)$$

In the formulae given above, m_i is the i^{th} moment of the wave spectrum. The wave spectrum is also a good parameter to identify various characteristics of ocean waves. i^{th} moment of spectrum is provided below. Note that, the zeroth moment gives the area under spectral curve. So, the area under this curve corresponds to total energy density.

$$m_i = \int_0^{\infty} f^i E(f) df \quad (3.10)$$

In order to test the repeatability of the test programme, additional experiments were performed before the study. Waves were also calibrated using a gravel beach instead of a structure. The design wave height was considered as 0.20 m. After each test, not individual runs, the structure was repaired. Each placement method, regular and irregular, was tested for the peak wave steepness of approximately 0.033. Around 1000 waves were generated for each test run. As mentioned before, the visualization technique was used to determine the damage by using pictures,

and the damage was calculated cumulatively. In addition, the storm duration was calculated considering $N \times T_{m-1.0}$.

Waves were created by using a software named Edinburgh Designs. Starting from $H_s=0.05$ m, waves were created with an increasing H_s until $H_s=0.26$ m. An example is given below for the software (Figure 3.22).

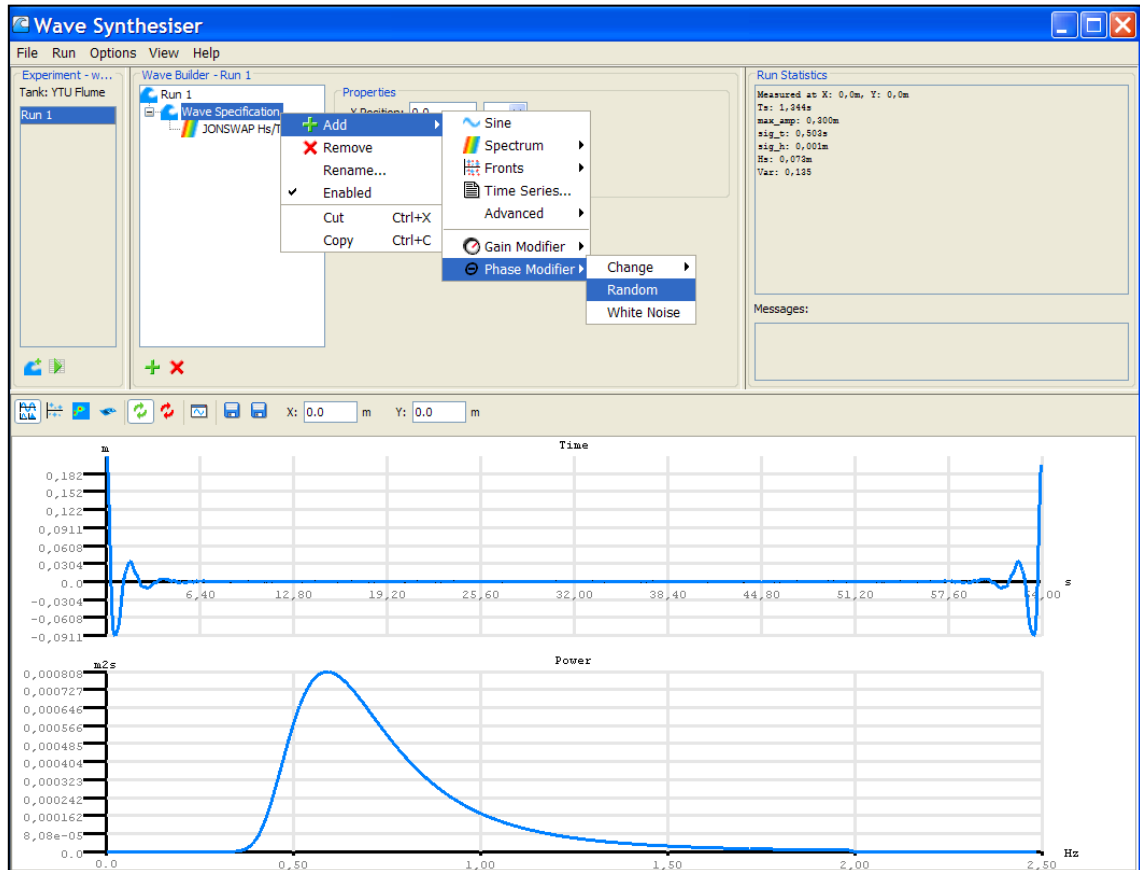


Figure 3.22 A step for creating waves from Edinburgh Designs software

To measure wave characteristics and convert them to a computer data, an 8 channel Wallingford CLE3C30 model wave monitor was used. Also, an additional software provided by the same company was used, HR DAQ.

8 different breakwater models were tested, and irregular waves were used in the tests. Wave conditions for all tests are provided below, from Table 3.5 to Table 3.20.

Table 3.5 Wave parameters for First Layer ND Cubes and Second Layer HD Cubes

d= 55 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.10	0.08	0.07	0.05	0.05	0.77	1.00	0.90	0.83
W2	0.07	1.3	3.3	0.11	0.10	0.09	0.08	0.08	1.02	1.43	1.30	1.16
W3	0.09	1.3	3.3	0.14	0.13	0.12	0.10	0.10	1.01	1.44	1.32	1.17
W4	0.09	1.7	3.3	0.16	0.14	0.13	0.10	0.10	1.32	1.72	1.62	1.53
W5	0.12	1.5	3.3	0.23	0.17	0.16	0.13	0.13	1.14	1.62	1.52	1.34
W6	0.14	1.6	3.3	0.29	0.21	0.20	0.16	0.15	1.20	1.72	1.62	1.44
W7	0.15	1.7	3.3	0.28	0.24	0.21	0.17	0.16	1.26	1.80	1.62	1.53
W8	0.16	1.8	3.3	0.27	0.25	0.23	0.18	0.18	1.34	1.89	1.85	1.63
W9	0.17	1.8	3.3	0.31	0.29	0.25	0.19	0.19	1.34	1.87	1.85	1.63
W10	0.18	2.0	3.3	0.35	0.30	0.26	0.19	0.19	1.42	2.08	2.11	1.76
W11	0.24	1.8	3.3	0.32	0.30	0.27	0.22	0.22	1.30	1.93	1.85	1.62
W12	0.24	2.16	3.3	0.34	0.31	0.30	0.24	0.25	1.50	2.38	2.37	1.82
W13	0.26	2.25	3.3	0.33	0.31	0.30	0.25	0.26	1.52	2.44	2.37	1.88

Table 3.6 Wave parameters for First Layer ND Cubes and Second Layer HD Cubes (cont.)

d= 55 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.09	0.08	0.07	0.05	0.05	0.79	1.01	0.85	0.85	0.045	0.044	0.254
0.10	0.09	0.09	0.07	0.08	1.08	1.42	1.32	1.20	0.036	0.029	0.257
0.13	0.12	0.11	0.10	0.10	1.08	1.43	1.32	1.21	0.044	0.037	0.247
0.17	0.15	0.13	0.10	0.10	1.34	1.77	1.74	1.45	0.031	0.021	0.286
0.23	0.20	0.17	0.13	0.14	1.22	1.57	1.50	1.34	0.050	0.040	0.251
0.25	0.23	0.20	0.16	0.16	1.27	1.68	1.62	1.39	0.053	0.039	0.261
0.27	0.25	0.21	0.16	0.16	1.36	1.81	1.62	1.47	0.047	0.039	0.284
0.29	0.26	0.22	0.16	0.17	1.40	1.95	1.74	1.52	0.047	0.036	0.313
0.30	0.25	0.23	0.18	0.18	1.41	1.92	1.74	1.55	0.048	0.038	0.316
0.26	0.24	0.20	0.16	0.17	1.43	2.15	1.74	1.62	0.042	0.036	0.363
0.30	0.27	0.25	0.20	0.21	1.44	2.03	1.74	1.53	0.058	0.044	0.329
0.32	0.29	0.26	0.19	0.20	1.54	2.31	1.80	1.85	0.038	0.040	0.430
0.32	0.30	0.27	0.21	0.21	1.51	2.50	1.83	1.92	0.037	0.040	0.431

Table 3.7 Wave parameters for Reference Area HD Cubes

d= 55 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.10	0.09	0.07	0.05	0.06	0.77	1.00	0.82	0.83
W2	0.07	1.3	3.3	0.11	0.10	0.10	0.08	0.08	1.02	1.41	1.30	1.16
W3	0.09	1.3	3.3	0.14	0.13	0.12	0.10	0.10	1.02	1.42	1.30	1.17
W4	0.09	1.7	3.3	0.16	0.14	0.13	0.10	0.10	1.30	1.75	1.62	1.52
W5	0.12	1.5	3.3	0.23	0.18	0.17	0.13	0.13	1.14	1.62	1.52	1.34
W6	0.14	1.6	3.3	0.27	0.21	0.20	0.16	0.15	1.21	1.71	1.62	1.43
W7	0.15	1.7	3.3	0.28	0.24	0.21	0.17	0.16	1.28	1.80	1.62	1.52
W8	0.16	1.8	3.3	0.28	0.26	0.23	0.18	0.18	1.37	1.87	1.85	1.63
W9	0.17	1.8	3.3	0.30	0.29	0.25	0.19	0.19	1.36	1.90	1.85	1.62
W10	0.18	2.0	3.3	0.35	0.32	0.26	0.19	0.19	1.42	2.08	2.11	1.76
W11	0.24	1.8	3.3	0.33	0.30	0.27	0.21	0.22	1.30	1.92	1.85	1.60
W12	0.24	2.16	3.3	0.36	0.30	0.27	0.23	0.23	1.48	2.32	2.07	1.82
W13	0.26	2.25	3.3	0.33	0.31	0.30	0.25	0.25	1.49	2.45	2.37	1.87

Table 3.8 Wave parameters for Reference Area HD Cubes (cont.)

d= 55 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.10	0.08	0.07	0.05	0.05	0.79	1.00	0.85	0.84	0.045	0.044	0.298
0.11	0.09	0.09	0.08	0.08	1.08	1.44	1.32	1.21	0.035	0.029	0.289
0.13	0.12	0.12	0.10	0.10	1.08	1.41	1.30	1.21	0.043	0.038	0.279
0.16	0.15	0.13	0.10	0.10	1.29	1.72	1.62	1.49	0.029	0.024	0.320
0.24	0.21	0.17	0.13	0.14	1.22	1.61	1.50	1.38	0.047	0.040	0.263
0.27	0.24	0.21	0.16	0.15	1.27	1.69	1.62	1.45	0.046	0.037	0.272
0.27	0.25	0.21	0.16	0.16	1.34	1.80	1.74	1.52	0.045	0.034	0.315
0.28	0.26	0.22	0.16	0.16	1.40	1.96	1.74	1.57	0.042	0.034	0.336
0.28	0.25	0.23	0.17	0.18	1.40	1.94	1.74	1.56	0.047	0.038	0.339
0.26	0.24	0.20	0.16	0.16	1.41	2.12	1.74	1.59	0.041	0.034	0.389
0.30	0.25	0.24	0.19	0.20	1.45	2.03	1.74	1.56	0.052	0.042	0.356
0.29	0.28	0.26	0.20	0.20	1.53	2.82	1.46	1.72	0.043	0.060	0.440
0.30	0.28	0.26	0.20	0.21	1.60	2.68	1.46	1.76	0.043	0.063	0.464

Table 3.9 Wave parameters for Single Layer HD Cubes with Regular Placement

d= 55 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.10	0.08	0.07	0.05	0.06	0.78	1.00	0.92	0.84
W2	0.07	1.3	3.3	0.11	0.10	0.10	0.08	0.08	1.02	1.41	1.30	1.16
W3	0.09	1.3	3.3	0.14	0.13	0.12	0.10	0.10	1.03	1.41	1.32	1.17
W4	0.09	1.7	3.3	0.16	0.14	0.13	0.10	0.10	1.30	1.77	1.62	1.53
W5	0.12	1.5	3.3	0.23	0.18	0.17	0.14	0.13	1.14	1.62	1.52	1.34
W6	0.14	1.6	3.3	0.27	0.22	0.20	0.16	0.16	1.20	1.72	1.62	1.43
W7	0.15	1.7	3.3	0.29	0.25	0.22	0.17	0.17	1.27	1.79	1.62	1.52
W8	0.16	1.8	3.3	0.29	0.27	0.24	0.18	0.18	1.36	1.90	1.85	1.62
W9	0.17	1.8	3.3	0.32	0.30	0.26	0.20	0.20	1.36	1.89	1.85	1.62
W10	0.18	2.0	3.3	0.36	0.33	0.27	0.20	0.20	1.41	2.08	2.11	1.76
W11	0.24	1.8	3.3	0.34	0.31	0.28	0.22	0.22	1.30	1.92	1.85	1.60
W12	0.24	2.16	3.3	0.39	0.32	0.29	0.24	0.24	1.46	2.29	2.07	1.60
W13	0.26	2.25	3.3	0.33	0.31	0.30	0.26	0.26	1.54	2.47	2.37	1.87

Table 3.10 Wave parameters for Single Layer HD Cubes with Regular Placement (cont.)

d= 55 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.10	0.08	0.07	0.05	0.05	0.80	1.02	0.91	0.85	0.044	0.039	0.310
0.11	0.09	0.09	0.08	0.08	1.08	1.44	1.32	1.22	0.034	0.029	0.315
0.13	0.12	0.12	0.10	0.10	1.09	1.45	1.32	1.23	0.043	0.037	0.306
0.17	0.16	0.14	0.11	0.11	1.35	1.75	1.74	1.52	0.030	0.023	0.361
0.25	0.22	0.18	0.14	0.14	1.24	1.59	1.50	1.40	0.046	0.040	0.324
0.29	0.27	0.22	0.17	0.17	1.28	1.71	1.62	1.47	0.051	0.041	0.333
0.28	0.27	0.23	0.17	0.17	1.36	1.78	1.74	1.54	0.046	0.036	0.370
0.30	0.28	0.24	0.18	0.18	1.41	1.99	1.74	1.58	0.046	0.038	0.390
0.30	0.27	0.25	0.19	0.19	1.42	1.94	1.74	1.58	0.049	0.040	0.382
0.30	0.23	0.21	0.17	0.17	1.42	2.14	1.74	1.61	0.042	0.036	0.435
0.34	0.29	0.27	0.21	0.22	1.44	2.01	1.74	1.58	0.057	0.047	0.415
0.31	0.29	0.27	0.21	0.21	1.53	2.75	1.46	1.58	0.054	0.063	0.487
0.32	0.30	0.27	0.20	0.21	1.51	2.38	1.83	1.76	0.043	0.040	0.485

Table 3.11 Wave parameters for Single Layer ND Cubes with Regular Placement

d= 55 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.10	0.08	0.07	0.05	0.06	0.77	0.99	0.90	0.82
W2	0.07	1.3	3.3	0.11	0.11	0.10	0.08	0.08	1.01	1.41	1.32	1.20
W3	0.09	1.3	3.3	0.14	0.13	0.12	0.10	0.10	1.02	1.40	1.32	1.20
W4	0.09	1.7	3.3	0.16	0.15	0.13	0.10	0.11	1.30	1.77	1.62	1.59
W5	0.12	1.5	3.3	0.23	0.18	0.17	0.14	0.14	1.14	1.62	1.52	1.45
W6	0.14	1.6	3.3	0.27	0.22	0.20	0.16	0.16	1.20	1.72	1.62	1.56
W7	0.15	1.7	3.3	0.29	0.25	0.21	0.17	0.17	1.27	1.79	1.62	1.68
W8	0.16	1.8	3.3	0.29	0.26	0.24	0.18	0.18	1.36	1.89	1.85	1.79
W9	0.17	1.8	3.3	0.32	0.29	0.25	0.20	0.20	1.36	1.88	1.85	1.82
W10	0.18	2.0	3.3	0.35	0.33	0.27	0.20	0.20	1.41	2.06	2.11	1.98
W11	0.24	1.8	3.3	0.35	0.31	0.28	0.22	0.22	1.30	1.90	1.85	1.84
W12	0.24	2.16	3.3	0.38	0.33	0.31	0.25	0.26	1.50	2.44	2.37	1.95
W13	0.26	2.25	3.3	0.35	0.34	0.32	0.26	0.26	1.54	2.53	2.37	1.82

Table 3.12 Wave parameters for Single Layer ND Cubes with Regular Placement (cont.)

d= 55 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.10	0.09	0.07	0.05	0.05	0.79	1.02	0.91	0.84	0.046	0.039	0.312
0.10	0.09	0.09	0.08	0.08	1.07	1.42	1.32	1.31	0.030	0.029	0.319
0.14	0.12	0.12	0.10	0.10	1.07	1.44	1.32	1.26	0.040	0.037	0.314
0.18	0.16	0.14	0.11	0.11	1.34	1.74	1.74	1.70	0.024	0.023	0.369
0.26	0.23	0.19	0.15	0.15	1.23	1.61	1.50	1.59	0.038	0.043	0.334
0.28	0.25	0.22	0.17	0.17	1.27	1.70	1.62	1.80	0.034	0.041	0.343
0.29	0.27	0.23	0.17	0.17	1.35	1.83	1.62	1.53	0.046	0.041	0.380
0.31	0.29	0.24	0.18	0.18	1.41	1.97	1.74	1.58	0.046	0.038	0.395
0.32	0.27	0.25	0.19	0.19	1.40	1.97	1.74	1.56	0.050	0.040	0.398
0.29	0.24	0.21	0.17	0.17	1.42	2.16	1.74	1.60	0.043	0.036	0.442
0.33	0.29	0.27	0.22	0.22	1.43	2.00	1.74	1.55	0.059	0.047	0.420
0.33	0.30	0.27	0.20	0.21	1.49	2.27	1.60	1.58	0.054	0.053	0.487
0.33	0.31	0.28	0.21	0.21	1.46	2.36	1.83	1.70	0.047	0.040	0.486

Table 3.13 Wave parameters for Emerged Berm

d= 45 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.10	0.09	0.07	0.06	0.06	0.76	0.98	0.92	0.82
W2	0.07	1.3	3.3	0.13	0.10	0.09	0.08	0.08	1.00	1.36	1.25	1.15
W3	0.09	1.3	3.3	0.14	0.13	0.12	0.10	0.10	1.01	1.38	1.25	1.16
W4	0.09	1.7	3.3	0.17	0.13	0.13	0.10	0.10	1.28	1.73	1.69	1.51
W4.1	0.10	1.6	3.3	0.20	0.15	0.14	0.11	0.12	1.20	1.65	1.58	1.42
W4.2	0.11	1.7	3.3	0.21	0.16	0.16	0.12	0.13	1.27	1.81	1.69	1.50
W5	0.12	1.5	3.3	0.20	0.19	0.17	0.13	0.13	1.15	1.60	1.58	1.35
W5.1	0.13	1.7	3.3	0.24	0.21	0.19	0.15	0.14	1.25	1.84	1.69	1.51
W6	0.14	1.6	3.3	0.22	0.20	0.19	0.15	0.15	1.21	1.71	1.58	1.43
W7	0.15	1.7	3.3	0.21	0.20	0.19	0.16	0.16	1.29	1.84	1.72	1.54
W8	0.16	1.8	3.3	0.23	0.22	0.20	0.17	0.17	1.32	1.89	1.72	1.60
W9	0.17	1.8	3.3	0.26	0.23	0.22	0.19	0.18	1.32	1.92	1.72	1.61
W10	0.18	2.0	3.3	0.33	0.26	0.24	0.18	0.18	1.38	2.11	1.90	1.73
W11	0.24	1.8	3.3	0.29	0.26	0.23	0.20	0.20	1.31	2.01	1.72	1.61
W12	0.24	2.16	3.3	0.31	0.29	0.25	0.21	0.21	1.41	2.34	2.13	1.87
W13	0.26	2.25	3.3	0.29	0.27	0.25	0.22	0.21	1.40	2.45	2.13	1.90

Table 3.14 Wave parameters for Emerged Berm (cont.)

d= 45 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.11	0.08	0.07	0.05	0.05	0.77	1.01	0.85	0.83	0.046	0.044	0.264
0.11	0.10	0.09	0.08	0.08	1.05	1.47	1.29	1.19	0.036	0.031	0.247
0.13	0.12	0.12	0.10	0.11	1.08	1.43	1.29	1.21	0.048	0.042	0.248
0.16	0.14	0.12	0.10	0.10	1.25	1.71	1.69	1.44	0.031	0.022	0.311
0.19	0.16	0.14	0.11	0.11	1.23	1.65	1.58	1.39	0.036	0.028	0.292
0.18	0.16	0.15	0.11	0.12	1.28	1.73	1.69	1.44	0.037	0.027	0.308
0.23	0.17	0.16	0.13	0.14	1.24	1.65	1.35	1.34	0.050	0.049	0.283
0.22	0.18	0.17	0.13	0.14	1.31	1.83	1.69	1.45	0.043	0.031	0.312
0.22	0.19	0.17	0.14	0.15	1.31	1.72	1.58	1.42	0.048	0.038	0.297
0.24	0.20	0.19	0.15	0.15	1.32	1.85	1.69	1.45	0.046	0.034	0.318
0.23	0.22	0.19	0.15	0.15	1.34	1.97	1.69	1.50	0.043	0.034	0.338
0.27	0.23	0.21	0.16	0.16	1.37	2.14	1.85	1.50	0.046	0.030	0.341
0.22	0.20	0.18	0.14	0.15	1.47	2.35	2.50	1.60	0.038	0.015	0.407
0.27	0.24	0.22	0.18	0.18	1.44	2.38	1.90	1.53	0.049	0.032	0.350
0.30	0.28	0.21	0.15	0.17	1.49	2.45	2.22	1.92	0.030	0.022	0.478
0.29	0.25	0.22	0.16	0.17	1.54	2.50	2.67	1.98	0.028	0.015	0.478

Table 3.15 Wave parameters for Berm at SWL

d= 55 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.10	0.09	0.07	0.05	0.05	0.76	1.00	0.82	0.82
W2	0.07	1.3	3.3	0.10	0.10	0.09	0.08	0.08	1.01	1.46	1.30	1.16
W3	0.09	1.3	3.3	0.13	0.13	0.12	0.10	0.10	1.01	1.42	1.30	1.16
W4	0.09	1.7	3.3	0.16	0.13	0.12	0.10	0.10	1.30	1.78	1.67	1.52
W5	0.12	1.5	3.3	0.22	0.19	0.17	0.13	0.13	1.15	1.59	1.50	1.34
W6	0.14	1.6	3.3	0.27	0.20	0.20	0.15	0.15	1.21	1.69	1.62	1.43
W7	0.15	1.7	3.3	0.28	0.22	0.20	0.16	0.16	1.28	1.79	1.62	1.52
W8	0.16	1.8	3.3	0.26	0.23	0.22	0.17	0.17	1.36	1.88	1.85	1.61
W9	0.17	1.8	3.3	0.25	0.24	0.23	0.18	0.18	1.36	1.90	1.85	1.61
W10	0.18	2.0	3.3	0.31	0.27	0.23	0.18	0.18	1.42	2.05	2.00	1.75
W11	0.24	1.8	3.3	0.29	0.27	0.25	0.21	0.21	1.31	1.95	1.79	1.60
W12	0.24	2.16	3.3	0.30	0.28	0.27	0.22	0.23	1.48	2.41	2.37	1.89
W13	0.26	2.25	3.3	0.30	0.28	0.27	0.24	0.24	1.52	2.49	2.37	1.95

Table 3.16 Wave parameters for Berm at SWL (cont.)

d= 55 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.10	0.08	0.07	0.05	0.05	0.80	1.02	0.85	0.85	0.044	0.044	0.188
0.10	0.09	0.08	0.07	0.08	1.06	1.44	1.30	1.19	0.036	0.030	0.145
0.12	0.12	0.11	0.09	0.09	1.07	1.40	1.30	1.20	0.040	0.034	0.148
0.16	0.13	0.12	0.09	0.10	1.32	1.80	1.74	1.50	0.028	0.021	0.158
0.21	0.20	0.16	0.13	0.13	1.19	1.58	1.41	1.35	0.046	0.042	0.154
0.24	0.22	0.19	0.15	0.15	1.25	1.72	1.60	1.43	0.047	0.038	0.150
0.26	0.23	0.20	0.15	0.15	1.35	1.91	1.74	1.52	0.042	0.032	0.153
0.27	0.24	0.20	0.15	0.16	1.39	1.97	1.74	1.60	0.040	0.034	0.164
0.25	0.23	0.21	0.16	0.17	1.42	2.01	1.74	1.61	0.042	0.036	0.162
0.30	0.23	0.21	0.16	0.16	1.43	2.18	2.11	1.65	0.038	0.023	0.195
0.29	0.25	0.23	0.20	0.19	1.43	2.06	1.74	1.60	0.048	0.040	0.172
0.27	0.26	0.24	0.19	0.20	1.65	2.52	2.37	1.89	0.036	0.023	0.258
0.28	0.27	0.26	0.21	0.21	1.59	2.57	2.37	1.91	0.037	0.024	0.255

Table 3.17 Wave parameters for Submerged Berm

d= 65 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.09	0.08	0.07	0.05	0.05	0.80	1.02	0.90	0.85
W2	0.07	1.3	3.3	0.09	0.09	0.08	0.07	0.07	1.05	1.44	1.26	1.18
W3	0.09	1.3	3.3	0.13	0.12	0.11	0.09	0.09	1.05	1.43	1.33	1.18
W4	0.09	1.7	3.3	0.15	0.14	0.12	0.09	0.09	1.34	1.74	1.67	1.53
W5	0.12	1.5	3.3	0.21	0.15	0.14	0.12	0.12	1.19	1.56	1.52	1.36
W6	0.14	1.6	3.3	0.25	0.19	0.18	0.14	0.14	1.26	1.67	1.67	1.45
W7	0.15	1.7	3.3	0.25	0.20	0.19	0.15	0.15	1.33	1.76	1.67	1.54
W8	0.16	1.8	3.3	0.26	0.22	0.21	0.16	0.16	1.39	1.83	1.85	1.61
W9	0.17	1.8	3.3	0.31	0.25	0.23	0.18	0.18	1.38	1.83	1.85	1.61
W10	0.18	2.0	3.3	0.32	0.30	0.25	0.18	0.18	1.50	2.02	2.11	1.77
W11	0.24	1.8	3.3	0.32	0.30	0.27	0.22	0.22	1.36	1.86	1.85	1.61
W12	0.24	2.16	3.3	0.35	0.34	0.30	0.24	0.23	1.53	2.48	2.07	1.85
W13	0.26	2.25	3.3	0.36	0.34	0.33	0.27	0.25	1.50	2.60	2.37	1.89

Table 3.18 Wave parameters for Submerged Berm (cont.)

d= 65 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.10	0.07	0.06	0.05	0.05	0.80	1.03	0.85	0.85	0.044	0.044	0.251
0.10	0.08	0.08	0.07	0.07	1.05	1.41	1.26	1.17	0.033	0.028	0.239
0.12	0.11	0.10	0.08	0.09	1.07	1.37	1.26	1.17	0.042	0.036	0.233
0.13	0.13	0.11	0.08	0.08	1.32	1.80	1.74	1.53	0.022	0.017	0.239
0.19	0.14	0.13	0.11	0.11	1.16	1.54	1.50	1.33	0.040	0.031	0.216
0.23	0.18	0.16	0.12	0.13	1.23	1.67	1.62	1.44	0.040	0.032	0.205
0.24	0.21	0.19	0.14	0.14	1.31	1.80	1.74	1.54	0.038	0.030	0.204
0.25	0.23	0.21	0.15	0.16	1.39	1.89	1.74	1.63	0.038	0.034	0.200
0.31	0.27	0.24	0.17	0.17	1.42	1.90	1.74	1.65	0.040	0.036	0.190
0.33	0.28	0.24	0.18	0.19	1.52	2.10	2.11	1.80	0.037	0.027	0.186
0.30	0.29	0.27	0.21	0.22	1.47	1.98	1.74	1.68	0.050	0.047	0.163
0.35	0.29	0.28	0.21	0.24	1.76	2.44	2.37	1.98	0.039	0.027	0.188
0.36	0.32	0.30	0.23	0.25	1.86	2.74	2.41	2.04	0.038	0.028	0.180

Table 3.19 Wave parameters for Emerged Berm with HD Cubes over Reference Area

d= 45 cm												
Waves	Input			Output-Offshore (Probe 1)								
	H_s	T_p	γ	H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}
	(m)	(s)	(-)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(s)
W1	0.05	0.9	3.3	0.10	0.09	0.07	0.06	0.06	0.76	0.98	0.92	0.83
W2	0.07	1.3	3.3	0.14	0.10	0.09	0.08	0.08	1.00	1.36	1.25	1.15
W3	0.09	1.3	3.3	0.14	0.13	0.12	0.10	0.10	1.01	1.37	1.26	1.16
W4	0.09	1.7	3.3	0.17	0.13	0.13	0.10	0.11	1.27	1.74	1.72	1.51
W4.1	0.10	1.6	3.3	0.20	0.15	0.14	0.11	0.11	1.20	1.66	1.58	1.42
W4.2	0.11	1.7	3.3	0.21	0.16	0.16	0.12	0.12	1.27	1.78	1.72	1.51
W5	0.12	1.5	3.3	0.20	0.18	0.16	0.13	0.13	1.14	1.58	1.58	1.34
W5.1	0.13	1.7	3.3	0.23	0.20	0.18	0.15	0.14	1.25	1.82	1.72	1.52
W6	0.14	1.6	3.3	0.22	0.20	0.18	0.15	0.15	1.21	1.73	1.58	1.45
W7	0.15	1.7	3.3	0.21	0.19	0.18	0.16	0.16	1.28	1.80	1.74	1.54
W8	0.16	1.8	3.3	0.22	0.21	0.20	0.17	0.16	1.30	1.91	1.74	1.60
W9	0.17	1.8	3.3	0.24	0.22	0.22	0.18	0.17	1.30	1.90	1.74	1.61
W10	0.18	2.0	3.3	0.29	0.25	0.23	0.18	0.18	1.38	2.11	1.90	1.72
W11	0.24	1.8	3.3	0.28	0.25	0.23	0.20	0.19	1.29	1.98	1.72	1.60
W12	0.24	2.16	3.3	0.29	0.27	0.24	0.21	0.21	1.43	2.33	2.13	1.88
W13	0.26	2.25	3.3	0.28	0.26	0.25	0.22	0.21	1.41	2.45	2.13	1.88

Table 3.20 Wave parameters for Emerged Berm with HD Cubes over Reference Area (cont.)

d= 45 cm											
Output-Structure Toe (Probe 5)											
H_{max}	H_{%2}	H_{1/10}	H_{1/3}	H_{m0}	T_{m02}	T_{1/3}	T_p	T_{m-1.0}	S_{m-1.0}	S_p	C_r
(m)	(m)	(m)	(m)	(m)	(m)	(s)	(s)	(s)	(-)	(-)	(%)
0.10	0.07	0.07	0.05	0.05	0.77	1.03	0.85	0.82	0.048	0.044	0.263
0.10	0.10	0.09	0.08	0.08	1.06	1.42	1.29	1.20	0.036	0.031	0.247
0.13	0.12	0.12	0.10	0.10	1.09	1.43	1.29	1.21	0.044	0.038	0.250
0.16	0.14	0.12	0.10	0.10	1.26	1.70	1.69	1.44	0.031	0.022	0.311
0.18	0.16	0.14	0.11	0.11	1.23	1.67	1.58	1.40	0.036	0.028	0.297
0.18	0.16	0.15	0.11	0.12	1.27	1.76	1.69	1.45	0.037	0.027	0.309
0.23	0.17	0.16	0.13	0.13	1.24	1.66	1.35	1.34	0.046	0.046	0.274
0.21	0.18	0.17	0.13	0.13	1.32	1.85	1.69	1.47	0.039	0.029	0.290
0.21	0.18	0.17	0.14	0.15	1.32	1.76	1.62	1.44	0.046	0.037	0.264
0.22	0.20	0.18	0.14	0.15	1.32	1.83	1.69	1.47	0.044	0.034	0.288
0.23	0.21	0.19	0.14	0.15	1.37	2.01	1.69	1.52	0.042	0.034	0.306
0.27	0.21	0.20	0.16	0.17	1.36	2.15	1.85	1.53	0.046	0.032	0.313
0.22	0.22	0.19	0.14	0.16	1.45	2.25	2.50	1.61	0.040	0.016	0.379
0.27	0.24	0.22	0.17	0.18	1.44	2.47	1.90	1.54	0.049	0.032	0.323
0.31	0.29	0.21	0.15	0.17	1.51	2.49	2.23	1.92	0.030	0.022	0.443
0.29	0.24	0.22	0.16	0.17	1.56	2.58	2.66	1.96	0.028	0.015	0.444

3.8 Scale Ratio and Scale Effects

In this experimental study, scaling for the models was not fulfilled by considering a specific prototype. The purpose of creating these models is to understand and solve stability related problems. For a complete similarity, there are 3 conditions. These are geometric similarity, kinematic similarity and dynamic similarity. In this section, model scale and scale effects are going to be discussed.

3.8.1 Geometric Similarity

Shape of the prototype and the model must be same and, maybe the model can be scaled by a constant number to have a geometrically similar model. The ratio between the prototype and the model is the same in each direction for this study. The geometric similarity is shown as follows. This equilibrium is independent from motion and shows only relationship for geometry.

$$C = \frac{X_M}{X_P} = \frac{Y_M}{Y_P} = \frac{Z_M}{Z_P} \quad (3.11)$$

3.8.2 Kinematic Similarity

Kinematic similarity indicates the relationship of motion between model and prototype. If the velocity at any point in the model is proportional by a constant scale factor to the velocity at the homologous point in the prototype flow, it can be said that the model and the prototype is kinematically similar (McKinley 2013). To fulfill a kinematically similar system, geometric similarity is a prerequisite condition. Also note that, for the kinematic similarity, the constant number can be equal to one, less than one or greater than one. It is independent from geometric similarity. A model that has a geometric similarity number less than one may has a kinematic similarity number greater than one.

3.8.3 Dynamic Similarity

Dynamic stability considers ratios of all acting forces on both the model and the prototype. The vectoral forces must have the same proportion. If a completely similar system is desired (e.g. similar viscous and inertial forces), all dimensionless

parameters between the model and the prototype must be similar e.g. the same Reynolds number (Frens 2007, McKinley 2013).

Buckingham π Theorem is a powerful method used in dimensional analysis and the theorem is frequently used in engineering applications. The theorem is used to form a complete set of dimensionless parameters. See the equation below for a mathematical depiction of Buckingham π Theorem.

$$\pi_M = \pi_P = f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \dots, \pi_n) \quad (3.12)$$

Almost in every coastal engineering problem, surface tension and elastic pressure are relatively unimportant. Thus, they can be considered as negligible parameters. As a result, the most important dimensionless parameters are the Froude and the Reynolds numbers (Frens 2007).

The Froude number symbolizes the relative effect of flow inertia and the gravity force in flow fields. In order to obtain desired similarity, the Froude numbers must be equal.

$$F_r = \left(\frac{U}{\sqrt{g \cdot L}} \right)_P = \left(\frac{U}{\sqrt{g \cdot L}} \right)_M \quad (3.13)$$

In the above equation, U, g and L represent velocity, gravitational acceleration and length respectively.

$$C_U = \frac{U_M}{U_P} \quad , \quad C_L = \frac{L_M}{L_P} \quad \text{and} \quad C_g = 1.0 \quad (\text{Gravity was not scaled.}) \quad (3.14)$$

The equation can be written as follows.

$$C_U = \sqrt{C_L} \quad (3.15)$$

Froude's scale law generally homologizes model flows which include inertia forces balanced by the gravity forces acting on free surface flows.

The Reynolds number demonstrates the ratio of inertia forces to viscous forces in a fluid. The formula is provided below.

$$Re = \left(\frac{U \cdot L}{\nu} \right)_P = \left(\frac{U \cdot L}{\nu} \right)_M \quad (3.16)$$

In the Reynolds equation, ν represents kinematic viscosity.

$$C_U = \frac{U_M}{U_P}, \quad C_L = \frac{L_M}{L_P} \quad \text{and} \quad C_v = 1.0 \quad (\text{Water was used in model.}) \quad (3.17)$$

The equation can be written as follows.

$$C_U = \frac{1}{C_L} \quad (3.18)$$

Reynolds scale law is mostly seen in model flows that viscous forces act. In free surface flows, gravity effects are more effective than viscous forces. Thus, Froude scale law was used in this study. Necessary wave heights were also predicted by using Hudson's stability method.

3.8.4 Scale Effects

If a small-scale Froude model is tested with a fluid similar to the prototype, the model is not going to satisfy both Froude and Reynolds equations simultaneously (Frens 2007). This causes viscous scale effects. Other scale effects are surface tension, friction and aeration.

3.8.4.1 Viscous Scale Effect

If Froude law is used to scale model and prototype dimensions geometrically linear, this causes very high viscous forces in small Reynolds numbers. As a result of this, the flow in & out of the core and the under layer is decreases and this leads unreliable results in terms of the experimental studies. For instance, small Reynolds number changes transmitted wave energy, wave reflection and run up velocity (Huges 1993, Burchart *et al.* 1999). According to Hughes (1993), Frens (2007), Wolters *et al.* (2010) and Yüksel *et al.* (2020) if the Reynolds number is higher than 2×10^3 , then viscous scale effects are negligible. Thus, it can be said that the fluid flow in the model structure is turbulent which is close to the nature conditions. In this study, calculation of the Reynolds number is performed as given below.

$$U = \left(\frac{P \cdot H_s \cdot L_m}{2 \cdot d \cdot T} \right) = \left(\frac{0.49 \times 0.14 \times 5.63}{2 \times 0.45 \times 1.16} \right) \cong 0.37 \text{ m/s}$$

$$Re = \left(\frac{U \cdot D_{n50}}{\nu} \right) = \left(\frac{0.37 \times 0.019}{1.33 \times 10^{-6}} \right) \cong 5.28 \times 10^3$$

In these equations, D_{n50} is the nominal diameter of the core material, U is the seepage velocity, T is the mean wave period at toe, L_m is the mean wavelength, d is the water depth, H_s is the significant wave height at the toe and P is the porosity of the core material.

It can be seen from the equations given above the Reynolds number is 5.28×10^3 which is higher than 2×10^3 . If the Reynolds number is higher than 2×10^3 , viscous scale effects are considered negligible. Also, Yüksel *et al.* (2020) and Gülver (2019) performed similar calculations for the Reynolds number.

3.8.4.2 Surface Tension Scale Effect

The scale effect caused by surface tension is important but not all the time. These forces can be neglected if some specific conditions are fulfilled. According to Hughes (1993) if the water depth is higher than 0.02 m and, the wave periods are higher than 0.35 seconds, then surface tension scale effects are neglected. In this study the lowest water depth is 0.45 m and the lowest wave period is approximately 0.80 seconds which are higher than the boundary conditions given above.

3.8.4.3 Friction Scale Effect

Frens (2007) mentioned that if the wave propagation distance is very long, scale effects may be effective in terms of bottom friction. Actually, this is not a case for the scaled experiments of rubble-mound breakwaters because generally these experimental models have relatively large lengths.

Another significant scale effect is the friction between adjacent armor units. Varying frictional forces may lead unreliable test results. For instance, the model structure may perform a more stable behavior than it performs in the nature if the frictional force is abnormally high. In this experimental study, each side of the model cubes was both sanded and painted in order to obtain a smoother surface.

3.8.4.4 Aeration Scale Effect

In accordance with Hughes (1993) and Frens (2007), the air bubbles are different in small-scale models. Because of the Weber number, which is given below, has less similarity between physical model and prototype.

$$We = \frac{\text{Drag force}}{\text{Cohesion force}} = \frac{\rho \cdot U^2 \cdot L}{\sigma} \quad (3.19)$$

In this equation, ρ is the density of the fluid, U is the velocity, L is the diameter of the droplet and σ is the surface tension.

As a result of this, air bubbles in the model are relatively bigger than prototype which corresponds deprivation of the energy is higher in the physical model. Therefore, the run-up in the rubble-mound slope will be affected adversely as well.

3.9 Stability Definitions

For each test run, stability number (N_s) and Hudson stability coefficient are determined. Calculation of the stability number is performed as follows.

$$N_s = \frac{H_{m0}}{\Delta \cdot D_n} \quad (3.20)$$

Hudson stability coefficient (K_D) is obtained from Hudson's formula, and it is shown as provided below.

$$K_D = \frac{H_{m0}^3}{V_b \cdot \cot \alpha \cdot \left(\frac{\rho_s}{\rho_w} - 1 \right)^3} \quad (3.21)$$

If the given equations for N_s and K_D are reorganized, then the following equation is obtained.

$$K_D = \frac{N_s^3}{\cot \alpha} \quad (3.22)$$

The equation, which is given above, is used to calculate stability numbers for each test run. By changing the subscript of the K_D , the stability coefficient K_D can be categorized. K_{D0} represents the start of the damage (0% damage ratio), K_{DH} gives

the stability coefficient between 0%-5% damage ratios and, $K_{D<5\%}$ gives the stability coefficient where the damage ratio reaches 5%.

As is known, behavior of the regularly placed armor layer and irregularly placed armor layer is quite different. The regularly placed armor layer is likely prone to fail if any armor unit is disturbed or dislocated and also, the repairment of this kind of armor pattern is very hard. On the contrary, the irregularly placed armor layer is easy to repair compared to regularly placed armor layer. Also, initiation of the damage is quite different. Therefore, in order to compare regularly and irregularly placed breakwater models properly and, to calculate stability coefficients, K_{DH} for irregular placements and K_{D0} for regular placements are considered.

3.10 Sensitivity Analysis

Before the experimental study, the wave parameters used in this study were validated. At water depths 45 cm, 55 cm and 65 cm, wave heights and wave periods were compared. This validation process was performed by comparing two different flume test results with the same wave inputs with structure (with armor layer) and without structure (without armor layer). Melby and Kobayashi (1988) emphasized on the importance of sensitivity analysis in their experimental study. They used a 1/20 slope in order to fulfill their sensitivity analysis at different water depths. Thus, a 1/20 slope included to the sensitivity analysis. All statistical comparisons and correlation graphics are given at Appendix C. Also, the study by Mahjoobi and Etemad-Shahidi (2008) was taken into account in the calculation of statistical parameters.

DISCUSSION ON CUBE ARMORED BREAKWATERS

4.1 Definitions

Damage levels on cube blocks are summarized in the Table 4.1. M represents the movement, which is lower than $1D_n$, and D represents the damage which is bigger than $1D_n$. Also note that D_n is the nominal diameter of the armor unit. Results were interpreted using these outputs. Additionally, N_0 was calculated by using D_T ($>1.0 D_n$).

Table 4.1 Damage definitions for moving (M) and displaced (D) units.

Moving units (M)		Displaced units (D)	
M_1	$0.0-0.5D_n$	D_1	$1.0-2.0D_n$
M_2	$0.5-1.0D_n$	D_2	$>2.0D_n$
M_T	$0.0-1.0D_n$	D_T	$>1.0D_n$

The relative damage N_0 , is calculated by using the following formula. In the formula, L is the width of the flume.

$$N_0 = \frac{\text{Number of } (> 1D_n) \text{ displaced units in reference area}}{L/D_n} \quad (4.1)$$

Importantly, only cubes in the reference were considered and included to calculations. For conventional sections, reference area is $5D_n$ above and $5D_n$ below of the SWL. N_0 was also calculated cumulatively, and glass-bonded cubes were excluded from the analysis phase because boundary conditions effect differently these armor units. Further explanations and other relative damage criteria presented by Van der Meer and Heydra (1991) are given in the Section 3.

For each individual test, stability number N_s is calculated (see the equation given below).

$$N_s = \frac{H_{m0}}{\Delta D_n} \quad (4.2)$$

Stability coefficient K_D which is given below, is used to calculate stability numbers for each test run.

$$K_D = \frac{N_s^3}{\cot \alpha} \quad (4.3)$$

By changing the subscript of the K_D , the stability coefficient K_D can be categorized. K_{D0} represents the start of the damage (0% damage ratio), K_{DH} gives the stability coefficient between 0%-5% damage ratios and, $K_{D<5\%}$ gives the stability coefficient where the damage ratio reaches 5%.

In this study, regular placement method is presented as well. But, as known, behavior of this placement method is quite different when compared to irregular placement method. After displacement of the first cube, a chain reaction can be triggered which causes total failure on the breakwater armor layer and then a possible failure occurs in the lower layers such as armor layer and core layer. This placement style is not repairable. In order to re-construct the armoring system, the armor layer must be removed. For the regular placement method, 0% damage ratio is required. According to this, the significant wave height is considered which is before the first block movement wave series that also used in calculation of K_{D0} .

Calculation of the K_{D0} (0% damage, N_s is calculated using the wave height before the first displacement wave series):

$$K_{D0} = \frac{N_s^3}{\cot \alpha} \quad (4.4)$$

Calculation of the K_{DH} (0%-5% damage, N_s is calculated using the first wave height where the first block movement occurs below 5% damage):

$$K_{DH} = \frac{N_s^3}{\cot \alpha} \quad (4.5)$$

Calculation of the $K_{D<5\%}$ (<5% damage, N_s is calculated using the wave height where the damage just below 5%):

$$K_{D<5\%} = \frac{N_s^3}{\cot \alpha} \quad (4.6)$$

Range of parameters for the experimental study are given below in Table 4.2 for both conventional and berm breakwaters.

Table 4.2 Range of the parameters for the experimental study.

Parameter	Value
Slope angle for conventional breakwaters ($\cot\alpha$)	1/1.5
Lower slope angle - Upper slope angle for berm breakwaters ($\cot\alpha$)	1/1.5 – 1/2.0
Upper slope rock size for berm breakwaters (m) ($D_{n50\text{-upper}}$)	0.034
Cube size for berm and conventional breakwaters (m) (D_n)	0.04
Berm width for berm breakwaters (m) (B)	0.20
Number of waves (N)	1000
Relative density for ND – HD cubes (Δ)	1.40 – 2.15

4.2 Conventional Cube Armored Breakwaters

Conventional breakwaters were tested only for 55 cm water depth. As mentioned in Section 3 and Table 4.2, 1000 waves were generated for each individual test series. All relevant wave characteristics can be seen from the related tables in the following sections. Irregular double layer and regular single layer placement techniques were used and tested for the conventional breakwaters.

4.2.1 Experiment 1: First Layer ND Cubes and Second Layer HD Cubes

This model was tested at 55 cm water depth using irregular placement method. Positions of both high density and normal density cubes and considered reference area can be seen in Figure 4.1.

In this experiment, it can be seen from Table 4.3, Table 4.4 and Table 4.5, the wave heights were low at the start of the experiment, such as W1 ($H_{m0}=0.05$ m) and W2 ($H_{m0}=0.08$ m). Thus, armor layer was stable, but movements were observed for

these wave series. For W3 and W4 wave series, significant wave heights were relatively higher than the previous waves, $H_{m0}=0.10$ m, total movement ratios increased and reached to 14.07% and 22.96%, respectively under these wave conditions, W3 and W4. The wave series W4 was the last series without displacement, stability number (N_s) is 1.16. The first displacement was observed at W5 ($H_{m0}=0.14$ m and $N_s=1.63$). Total displacement was 1.48% and can be seen from Figure 4.3. From W5 to W7 ($H_{m0}=0.16$ m), movements reached their maximum ratio 37.41%, which can be seen in Figure 4.2. Also, at the wave series W7, total displacement ratio reached to 5.56%. W8 ($H_{m0}=0.16$ and $N_s=1.98$) was one of the most important wave conditions for this experiment. Because wave-structure interaction under this wave, test was highly energetic when compared to the previous wave series (see Appendix B), total displacement ratio reached to 20.37%, while total movement ratio decreased to 28.52%. After this wave, variation of movement and displacement ratios were quite low due 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 is $N_s=2.44$. At this wave series, total movement and total displacement were 26.30% and 23.70%, respectively. In W13, wave heights were considerably energetic, and wave forces were quite strong on the armor units. However, filter layer of the model breakwater was never visible through the armor layer. In addition, in the first armor layer (ND), there was no displacement, only movements were observed. Also, as it can be seen from Table 4.3, overtopping started at W7 ($H_{m0}=0.16$ m).

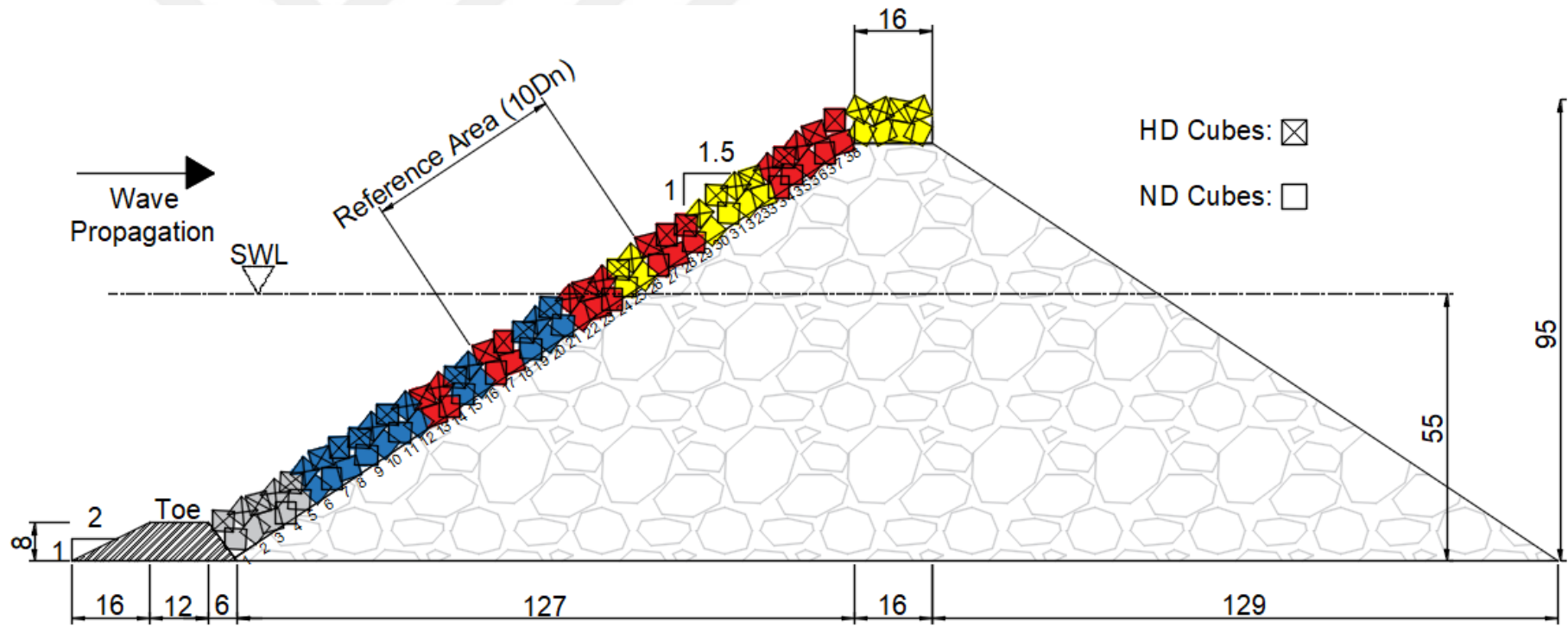


Figure 4.1 Positions of HD and ND cubes for the experiment First Layer ND and Second Layer HD.

Table 4.3 Measured wave parameters at the toe of the breakwater for First Layer ND Cubes and Second Layer HD Cubes

Breakwater $\psi_s=0.59$									
d=55 cm									
Waves	H_{m0} (m)	H_{1/3} (m)	T_{m-1.0} (s)	T_p (s)	S_{m-1.0} (-)	S_p (-)	C_r %	N_s (-)	Overtopping
W1	0.05	0.05	0.85	0.85	0.045	0.044	0.254	0.58	✗
W2	0.08	0.07	1.20	1.32	0.036	0.029	0.257	0.93	✗
W3	0.10	0.10	1.21	1.32	0.044	0.037	0.247	1.16	✗
W4	0.10	0.10	1.45	1.74	0.031	0.021	0.286	1.16	✗
W5	0.14	0.13	1.34	1.50	0.050	0.040	0.251	1.63	✗
W6	0.16	0.16	1.39	1.62	0.053	0.039	0.261	1.86	✗
W7	0.16	0.16	1.47	1.62	0.047	0.039	0.284	1.86	✓
W8	0.17	0.16	1.52	1.74	0.047	0.036	0.313	1.98	✓
W9	0.18	0.18	1.55	1.74	0.048	0.038	0.316	2.09	✓
W10	0.17	0.16	1.62	1.74	0.042	0.036	0.363	1.98	✓
W11	0.21	0.20	1.53	1.74	0.058	0.044	0.329	2.44	✓
W12	0.20	0.19	1.85	1.80	0.038	0.040	0.430	2.33	✓
W13	0.21	0.21	1.92	1.83	0.037	0.040	0.431	2.44	✓

Table 4.4 Damage ratios for First Layer ND Cubes and Second Layer HD Cubes

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M ₁ (QTY)	M ₁ (%)	M ₂ (QTY)	M ₂ (%)	M _T (QTY)	Movement Ratio (%)	D ₁ (QTY)	D ₁ (%)	D ₂ (QTY)	D ₂ (%)	D _T (QTY)	Damage Ratio (%)
W1	4	1.48	0	0.00	4	1.48	0	0.00	0	0.00	0	0.00
W2	26	9.63	0	0.00	26	9.63	0	0.00	0	0.00	0	0.00
W3	37	13.70	1	0.37	38	14.07	0	0.00	0	0.00	0	0.00
W4	58	21.48	4	1.48	62	22.96	0	0.00	0	0.00	0	0.00
W5	77	28.52	28	10.37	105	38.89	4	1.48	0	0.00	4	1.48
W6	78	28.89	28	10.37	106	39.26	7	2.59	0	0.00	7	2.59
W7	59	21.85	42	15.56	101	37.41	15	5.56	0	0.00	15	5.56
W8	28	10.37	49	18.15	77	28.52	53	19.63	2	0.74	55	20.37
W9	29	10.74	50	18.52	79	29.26	53	19.63	3	1.11	56	20.74
W10	27	10.00	48	17.78	75	27.78	56	20.74	4	1.48	60	22.22
W11	23	8.52	52	19.26	75	27.78	56	20.74	4	1.48	60	22.22
W12	20	7.41	53	19.63	73	27.04	55	20.37	7	2.59	62	22.96
W13	20	7.41	51	18.89	71	26.30	57	21.11	7	2.59	64	23.70

Table 4.5 Wave parameters and damage ratios for First Layer ND Cubes and Second Layer HD Cubes

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	H_{m0} (m)	S_p (-)	S_{m-1.0} (-)	C_r %	N_s (-)	M₁ %	M₂ %	M_T %	D₁ %	D₂ %	D_T %	Observation
W1	0.05	0.044	0.045	0.254	0.58	1.48	0.00	1.48	0.00	0.00	0.00	
W2	0.08	0.029	0.036	0.257	0.93	9.63	0.00	9.63	0.00	0.00	0.00	
W3	0.10	0.037	0.044	0.247	1.16	13.70	0.37	14.07	0.00	0.00	0.00	
W4	0.10	0.021	0.031	0.286	1.16	21.48	1.48	22.96	0.00	0.00	0.00	
W5	0.14	0.040	0.050	0.251	1.63	28.52	10.37	38.89	1.48	0.00	1.48	
W6	0.16	0.039	0.053	0.261	1.86	28.89	10.37	39.26	2.59	0.00	2.59	
W7	0.16	0.039	0.047	0.284	1.86	21.85	15.56	37.41	5.56	0.00	5.56	
W8	0.17	0.036	0.047	0.313	1.98	10.37	18.15	28.52	19.63	0.74	20.37	High interaction
W9	0.18	0.038	0.048	0.316	2.09	10.74	18.52	29.26	19.63	1.11	20.74	
W10	0.17	0.036	0.042	0.363	1.98	10.00	17.78	27.78	20.74	1.48	22.22	
W11	0.21	0.044	0.058	0.329	2.44	8.52	19.26	27.78	20.74	1.48	22.22	
W12	0.20	0.040	0.038	0.430	2.33	7.41	19.63	27.04	20.37	2.59	22.96	
W13	0.21	0.040	0.037	0.431	2.44	7.41	18.89	26.30	21.11	2.59	23.70	

Table 4.6 Change of N_0 corresponding to wave parameters for First Layer ND Cubes and Second Layer HD Cubes

Breakwater $\psi_s=0.59$						
d=55 cm						
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	N_s	N_0
	(m)	(m)	(s)	(s)	(-)	(-)
W1	0.05	0.05	0.85	0.85	0.58	0
W2	0.08	0.07	1.20	1.32	0.93	0
W3	0.10	0.10	1.21	1.32	1.16	0
W4	0.10	0.10	1.45	1.74	1.16	0
W5	0.14	0.13	1.34	1.50	1.63	0.17
W6	0.16	0.16	1.39	1.62	1.86	0.3
W7	0.16	0.16	1.47	1.62	1.86	0.65
W8	0.17	0.16	1.52	1.74	1.98	2.39
W9	0.18	0.18	1.55	1.74	2.09	2.43
W10	0.17	0.16	1.62	1.74	1.98	2.61
W11	0.21	0.20	1.53	1.74	2.44	2.61
W12	0.20	0.19	1.85	1.80	2.33	2.7
W13	0.21	0.21	1.92	1.83	2.44	2.78

Triemstra (2000) mentioned on the importance of mobility of armor units for irregular placement methods as well. The mobility of cubes directly affected stability of armor layer for this experiment. As aforementioned, W8 was a critical wave test in this experiment. Flume observations showed that behavior of first armor layer (ND) behaved quite different when compared to second armor layer (HD) in terms of mobility. At W8, ND cubes at the first layer started to move, then these cubes triggered the second armor layer (HD) and increased the movement and displacement capability of the HD units. As a result of this, high-density cubes at the reference area lost their connection with ND cubes, and movements at the first layer considerably increased the instability of the HD cubes (see Figure 4.3 and Figure 4.4). However, after the clamping between adjacent armor units again increased the stability of HD cubes, and this behavior also increased the overall strength of the armor layer. Consequently, high density cubes at the second layer did not allow to fail of the armor layer, then filter layer was never observed through armor layer even after W13. These HD cubes kept ND cubes at the first layer as stable as possible even against massive wave forces (see W13 at Appendix B).

The presented results were drawn with Van der Meer (1988) study for the conventional cube breakwater in Figure 4.5. Figure 4.5 shows that Van der Meer (1988) formula underestimated because the second layer HD has higher relative density for the stability number and the first layer of ND cubes also triggered the displacement of the HD cubes. Relative damage ratio was not sufficiently fit with the Van der Meer (1988) formula, and it shows underestimation.

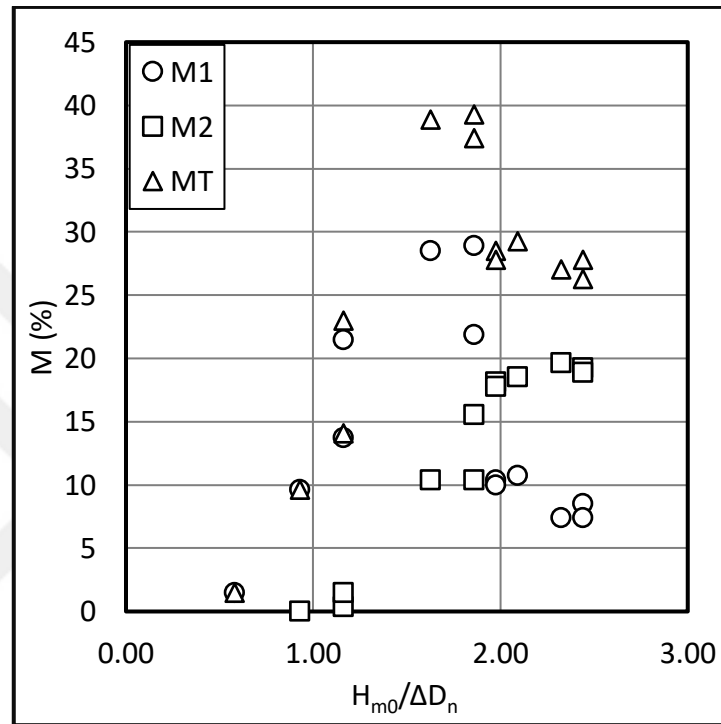


Figure 4.2 Movement ratio in reference area for First Layer ND Cubes and Second Layer HD Cubes

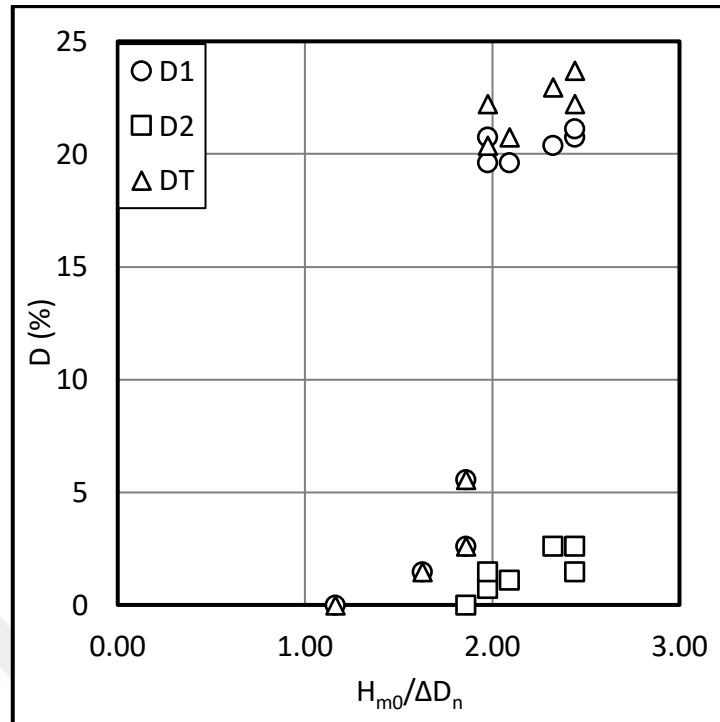


Figure 4.3 Displacement ratio in reference area for First Layer ND Cubes and Second Layer HD Cubes

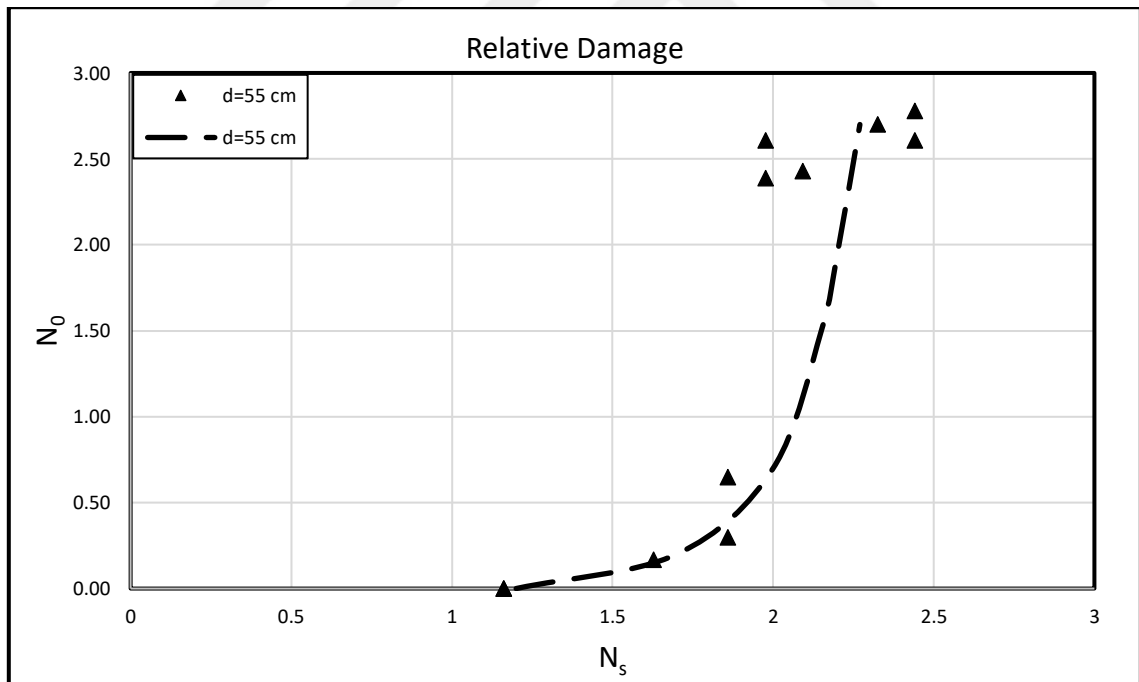


Figure 4.4 Relative damage in reference area for First Layer ND Cubes and Second Layer HD Cubes

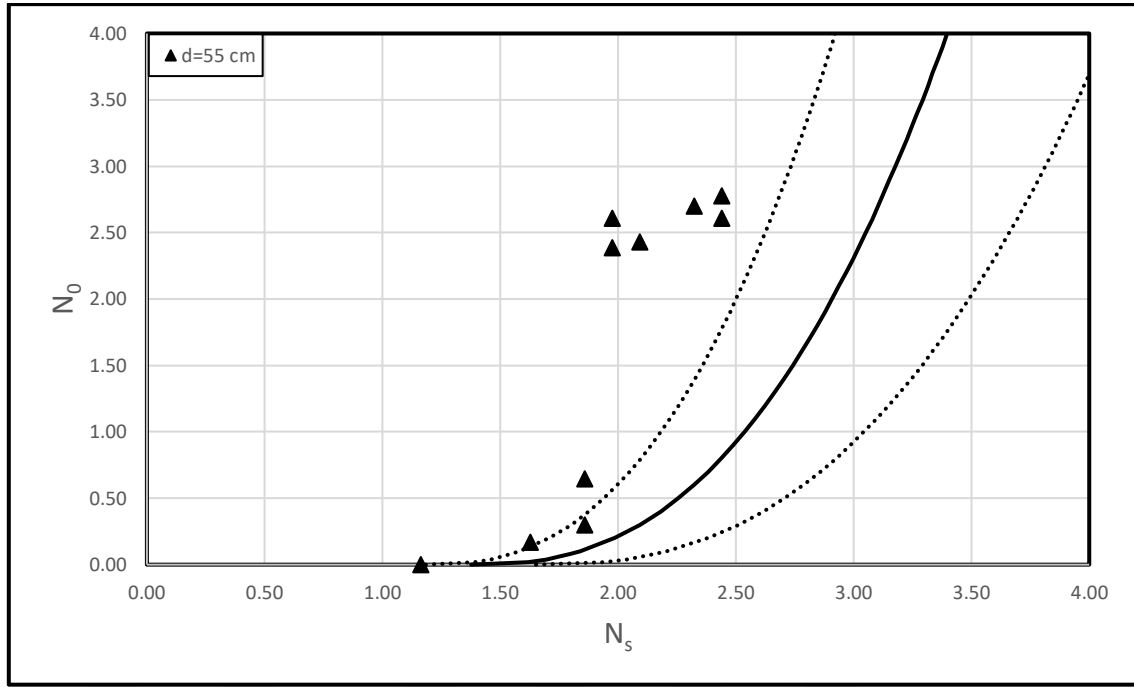


Figure 4.5 Comparison for experimental results of First Layer ND Cubes and Second Layer HD Cubes with the formula by Van der Meer (1988) for conventional cube armored breakwaters.

4.2.2 Experiment 2: Reference Area HD Cubes

The breakwater model was tested at 55 cm water depth using irregular placement method. HD cubes were placed from SWL- H_s ($5D_n$) to the crest which included the first row of the cubes on the crest, i.e. 23 rows in the first layer. ND cubes were placed below ($SSW-H_s$) in the second armor layer, i.e. 16 rows. The first armor layer consisted only ND cubes (Figure 4.6). Figure 4.6 shows reference area and cube arrangement over the slope.

In this experiment, wave heights were low at W1 ($H_{m0}=0.05$ m and $N_s=0.58$) and W2 ($H_{m0}=0.08$ m and $N_s=0.93$) respectively in Table 4.8, Table 4.9 and Table 4.10, however movement ratio M_1 ($D_n < 0.5$) reached 31.11% which emphasizes rocking behavior was dominant on HD cubes at the second layer. The number of rocking cubes increased and reached to their maximum ratio 38.15% for the test condition of W3 ($H_{m0}=0.10$ m and $N_s=1.16$), the first displacement was also observed (Figure 4.7 and Figure 4.8). Total movement ratio became 31.48%, and displacement ratio reached to 18.52% with a sudden increase at W4 ($H_{m0}=0.10$ m and $N_s=1.16$). While total movement ratio suddenly decreased to 10.37% at W5 and total displacement

almost doubled and reached to 39.63%. Displacement ratio increased in a small amount from W6 to W13 because sliding was occurred, and clamping strength increased over the lower slope. Filter layer became visible (close to crest) through 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 45.56% at W13. Overtopping started at W7 ($H_{m0}=0.16$ m) (Table 4.7).

Table 4.7 Measured wave parameters at the toe of the breakwater for Reference Area HD Cubes

Breakwater $\psi_s=0.59$									
d=55 cm									
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	$S_{m-1.0}$	S_p	C_r	N_s	Overtopping
	(m)	(m)	(s)	(s)	(-)	(-)	%	(-)	
W1	0.05	0.05	0.84	0.85	0.045	0.044	0.298	0.58	✗
W2	0.08	0.08	1.21	1.32	0.035	0.029	0.289	0.93	✗
W3	0.10	0.10	1.21	1.30	0.043	0.038	0.279	1.16	✗
W4	0.10	0.10	1.49	1.62	0.029	0.024	0.320	1.16	✗
W5	0.14	0.13	1.38	1.50	0.047	0.040	0.263	1.63	✗
W6	0.15	0.16	1.45	1.62	0.046	0.037	0.272	1.74	✗
W7	0.16	0.16	1.52	1.74	0.045	0.034	0.315	1.86	✓
W8	0.16	0.16	1.57	1.74	0.042	0.034	0.336	1.86	✓
W9	0.18	0.17	1.56	1.74	0.047	0.038	0.339	2.09	✓
W10	0.16	0.16	1.59	1.74	0.041	0.034	0.389	1.86	✓
W11	0.20	0.19	1.56	1.74	0.052	0.042	0.356	2.33	✓
W12	0.20	0.20	1.72	1.46	0.043	0.060	0.440	2.33	✓
W13	0.21	0.20	1.76	1.46	0.043	0.063	0.464	2.44	✓

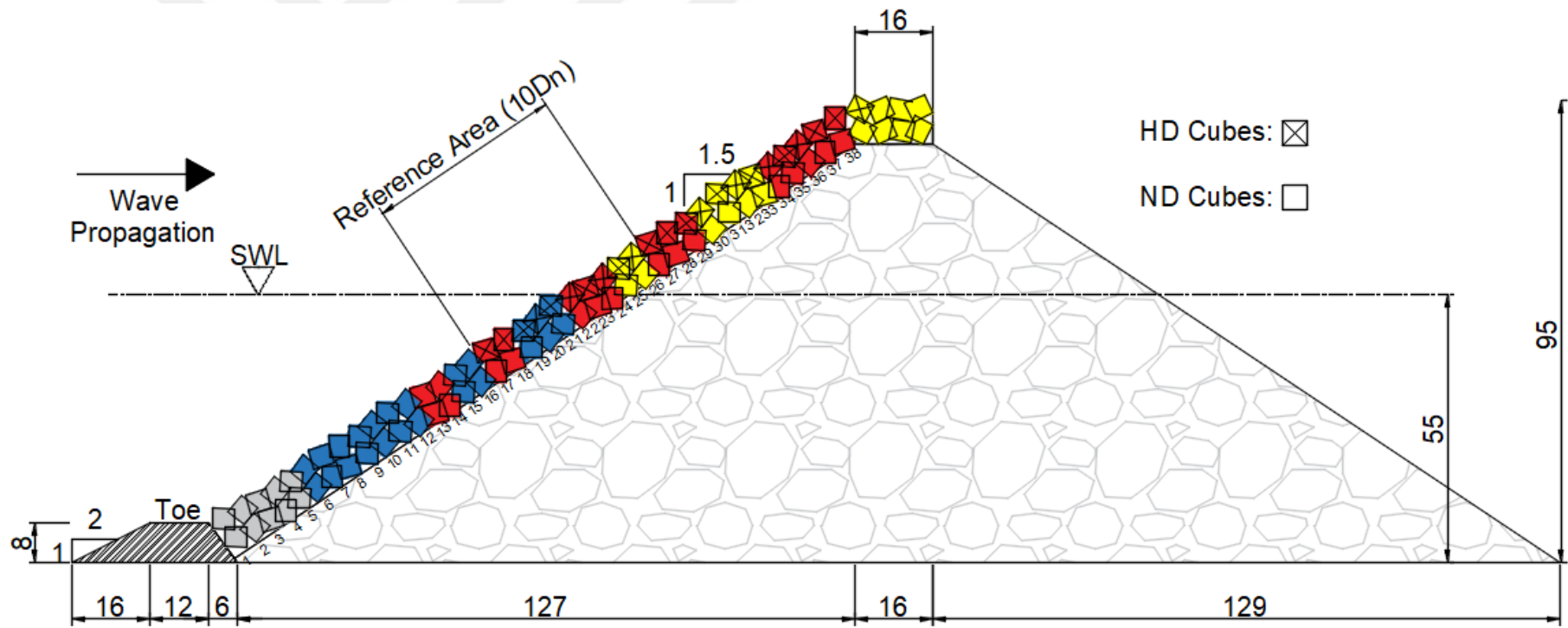


Figure 4.6 Positions of HD and ND cubes for the experiment Reference Area HD Cubes

Table 4.8 Damage ratios for Reference Area HD Cubes

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M₁ (QTY)	M₁ (%)	M₂ (QTY)	M₂ (%)	M_T (QTY)	Movement Ratio (%)	D₁ (QTY)	D₁ (%)	D₂ (QTY)	D₂ (%)	D_T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	84	31.11	0	0.00	84	31.11	0	0.00	0	0.00	0	0.00
W3	103	38.15	1	0.37	104	38.52	3	1.11	1	0.37	4	1.48
W4	28	10.37	57	21.11	85	31.48	45	16.67	5	1.85	50	18.52
W5	1	0.37	27	10.00	28	10.37	67	24.81	40	14.81	107	39.63
W6	0	0.00	23	8.52	23	8.52	61	22.59	51	18.89	112	41.48
W7	0	0.00	23	8.52	23	8.52	61	22.59	51	18.89	112	41.48
W8	0	0.00	17	6.30	17	6.30	47	17.41	71	26.30	118	43.70
W9	0	0.00	17	6.30	17	6.30	44	16.30	74	27.41	118	43.70
W10	0	0.00	17	6.30	17	6.30	44	16.30	74	27.41	118	43.70
W11	0	0.00	14	5.19	14	5.19	46	17.04	75	27.78	121	44.81
W12	0	0.00	13	4.81	13	4.81	46	17.04	76	28.15	122	45.19
W13	0	0.00	12	4.44	12	4.44	47	17.41	76	28.15	123	45.56

Table 4.9 Wave parameters and damage ratios for Reference Area HD Cubes

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	H_{m0} (m)	S_p (-)	$S_{m-1.0}$ (-)	C_r %	N_s (-)	M_1 %	M_2 %	M_T %	D_1 %	D_2 %	D_T %	Observation
W1	0.05	0.044	0.045	0.298	0.58	0.00	0.00	0.00	0.00	0.00	0.00	
W2	0.08	0.029	0.035	0.289	0.93	31.11	0.00	31.11	0.00	0.00	0.00	
W3	0.10	0.038	0.043	0.279	1.16	38.15	0.37	38.52	1.11	0.37	1.48	
W4	0.10	0.024	0.029	0.320	1.16	10.37	21.11	31.48	16.67	1.85	18.52	Sliding
W5	0.14	0.040	0.047	0.263	1.63	0.37	10.00	10.37	24.81	14.81	39.63	Sliding
W6	0.15	0.037	0.046	0.272	1.74	0.00	8.52	8.52	22.59	18.89	41.48	
W7	0.16	0.034	0.045	0.315	1.86	0.00	8.52	8.52	22.59	18.89	41.48	
W8	0.16	0.034	0.042	0.336	1.86	0.00	6.30	6.30	17.41	26.30	43.70	
W9	0.18	0.038	0.047	0.339	2.09	0.00	6.30	6.30	16.30	27.41	43.70	
W10	0.16	0.034	0.041	0.389	1.86	0.00	6.30	6.30	16.30	27.41	43.70	
W11	0.20	0.042	0.052	0.356	2.33	0.00	5.19	5.19	17.04	27.78	44.81	
W12	0.20	0.060	0.043	0.440	2.33	0.00	4.81	4.81	17.04	28.15	45.19	
W13	0.21	0.063	0.043	0.464	2.44	0.00	4.44	4.44	17.41	28.15	45.56	Failure

Table 4.10 Change of N_0 Corresponding to wave parameters for Reference Area HD Cubes

Breakwater $\psi_s=0.59$						
d=55 cm						
Waves	H_{m0} (m)	$H_{1/3}$ (m)	$T_{m-1.0}$ (s)	T_p (s)	N_s (-)	N_0 (-)
W1	0.05	0.05	0.84	0.85	0.58	0
W2	0.08	0.08	1.21	1.32	0.93	0
W3	0.10	0.10	1.21	1.30	1.16	0.17
W4	0.10	0.10	1.49	1.62	1.16	2.17
W5	0.14	0.13	1.38	1.50	1.63	4.65
W6	0.15	0.16	1.45	1.62	1.74	4.87
W7	0.16	0.16	1.52	1.74	1.86	4.87
W8	0.16	0.16	1.57	1.74	1.86	5.13
W9	0.18	0.17	1.56	1.74	2.09	5.13
W10	0.16	0.16	1.59	1.74	1.86	5.13
W11	0.20	0.19	1.56	1.74	2.33	5.26
W12	0.20	0.20	1.72	1.46	2.33	5.3
W13	0.21	0.20	1.76	1.46	2.44	5.35

It is necessary to elaborate the behavior of the model at W4 and W5. Starting from W4 until the end of the W5 wave series, “Sliding” behavior was observed. This behavior was also referred in CEM (2006). The high-density cubes in the second layer pushed the normal density cubes downwards. Mostly normal density cubes lost their positions and dislocated to the toe of the structure (see Appendix B).

26 dislocated cubes counted at the toe of the structure after W13 (4 HD and 22 ND). Sliding damage also changed the packing density below the reference area by increasing it while the packing density above the lower limit of the reference area decreased.

Figure 4.10 shows that the relative damage versus Van der Meer (1988) formula. The stability was found lower than Van der Meer (1988) relative stability due to sliding damage.

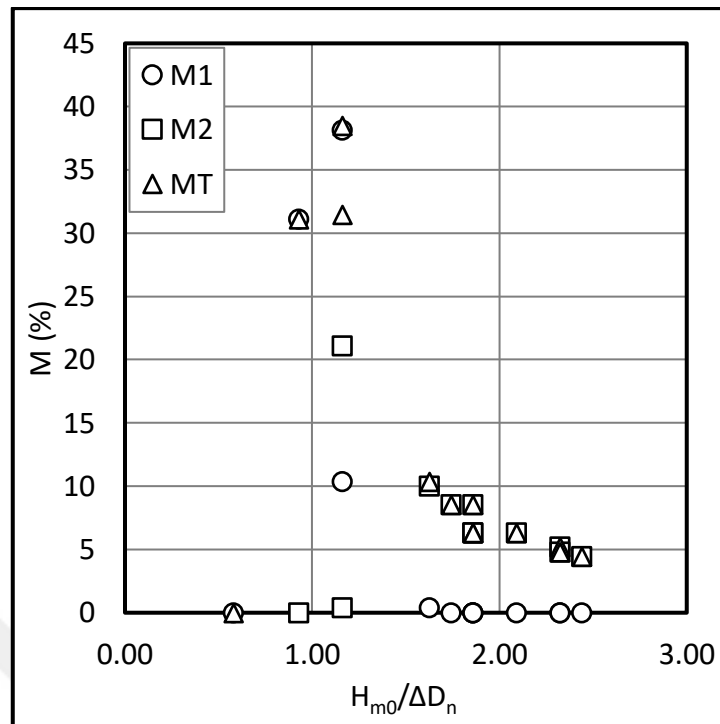


Figure 4.7 Movement ratio in reference area for Reference Area HD Cubes

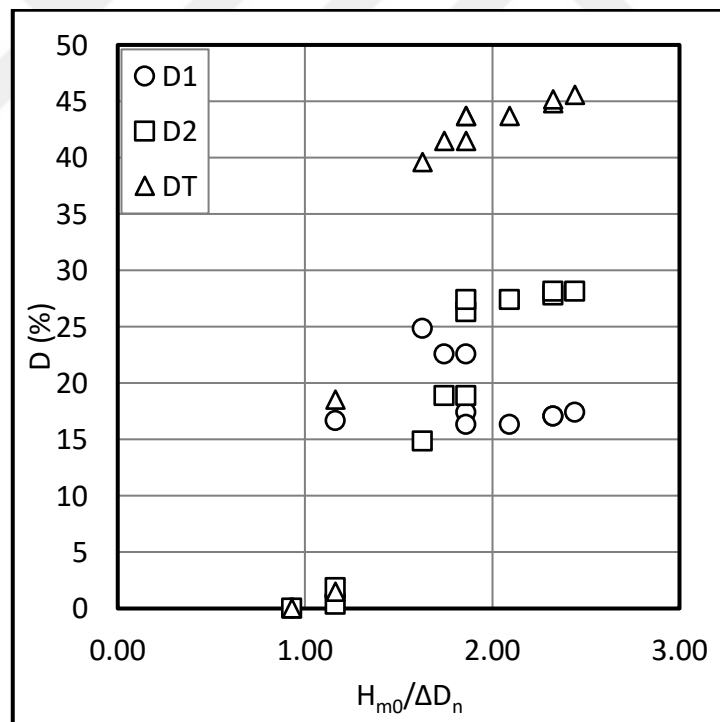


Figure 4.8 Displacement ratio in reference area for Reference Area HD Cubes

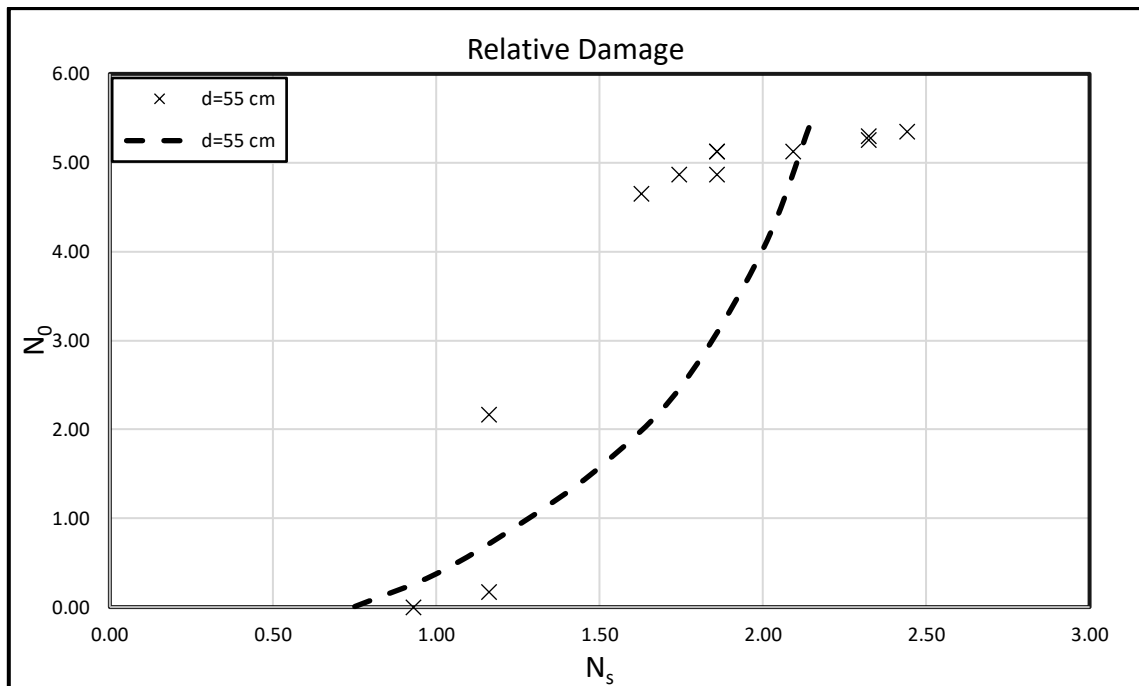


Figure 4.9 Relative damage in reference area for Reference Area HD Cubes

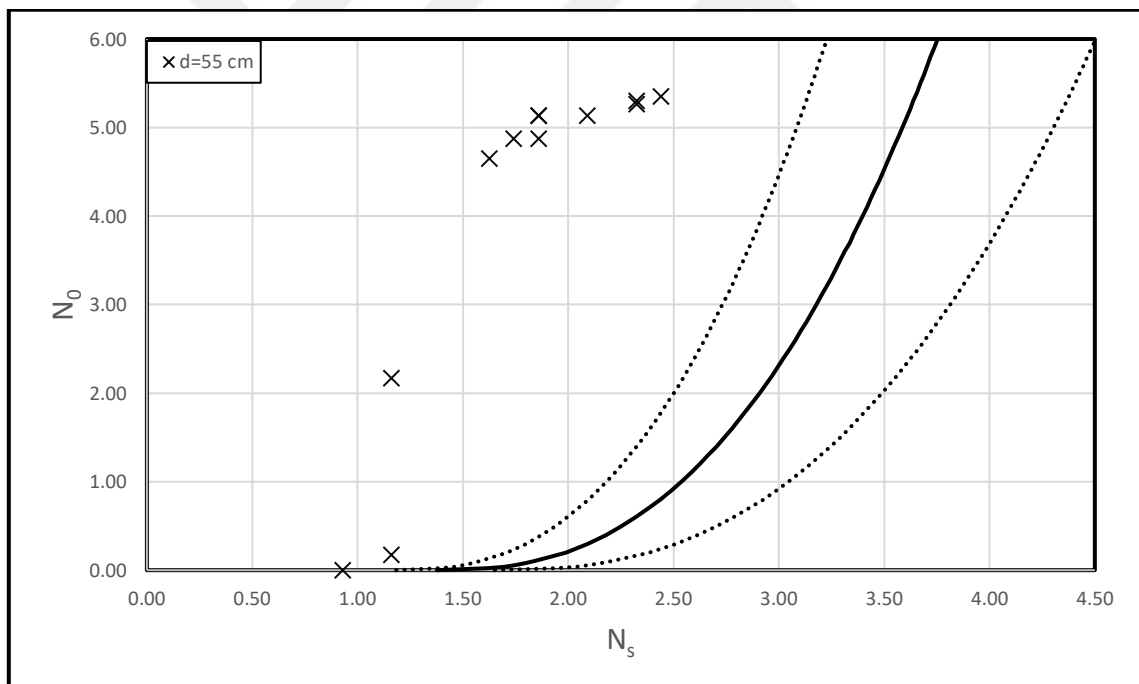


Figure 4.10 Comparison for experimental results of Reference Area HD Cubes with the formula by Van der Meer (1988) for conventional cube armored breakwaters

4.2.3 Experiment 3: Double Layer HD Cubes

Double armor layer HD test was carried out by Gümüşcü (2020) and her results presented in this study to compare the presented test cases. This model was tested at 55 cm water depth using double layer irregular placement method by Gümüşcü (2020). HD cubes were used in the first and second armor layers. Wave conditions were same with the presented experimental study (Table 4.11). Positioning of the HD cubes can be seen in Figure 4.11.

Table 4.11 Measured wave parameters at the toe of the breakwater for Double Layer HD Cubes (Gümüşcü 2020)

Breakwater $\psi_s=0.59$									
d=55 cm									
Waves	H_{m0} (m)	$H_{1/3}$ (m)	$T_{m-1.0}$ (s)	T_p (s)	$S_{m-1.0}$ (-)	S_p (-)	C_r %	N_s (-)	Overtopping
W1	0.05	0.05	0.85	1.00	0.044	0.032	0.286	0.58	×
W2	0.07	0.07	1.19	1.32	0.032	0.026	0.283	0.81	×
W3	0.09	0.09	1.20	1.38	0.040	0.030	0.277	1.05	×
W4	0.11	0.11	1.57	1.71	0.290	0.024	0.318	1.28	×
W5	0.14	0.14	1.41	1.50	0.045	0.040	0.277	1.63	×
W6	0.16	0.17	1.50	1.62	0.046	0.039	0.294	1.86	✓
W7	0.18	0.18	1.59	1.74	0.046	0.038	0.305	2.09	✓
W8	0.19	0.18	1.65	1.74	0.045	0.040	0.345	2.21	✓
W9	0.20	0.20	1.64	1.74	0.048	0.042	0.347	2.33	✓
W10	0.19	0.19	1.68	1.74	0.043	0.040	0.386	2.21	✓
W11	0.23	0.23	1.65	1.74	0.054	0.049	0.366	2.67	✓

HD cubes were found very stable and displacement did not occur. However, the first movement started at W3 with 0.37% and became 6.30% at W4. In W5 and W6 movement ratio almost doubled and reached 12.59% and 24.07%, respectively (Table 4.12, Table 4.13, and Table 4.14). From W7 to W11, movement ratio increased slightly and reached to 30.00% at W11. Only movement was observed under this test condition (Figure 4.12 and Figure 4.13).

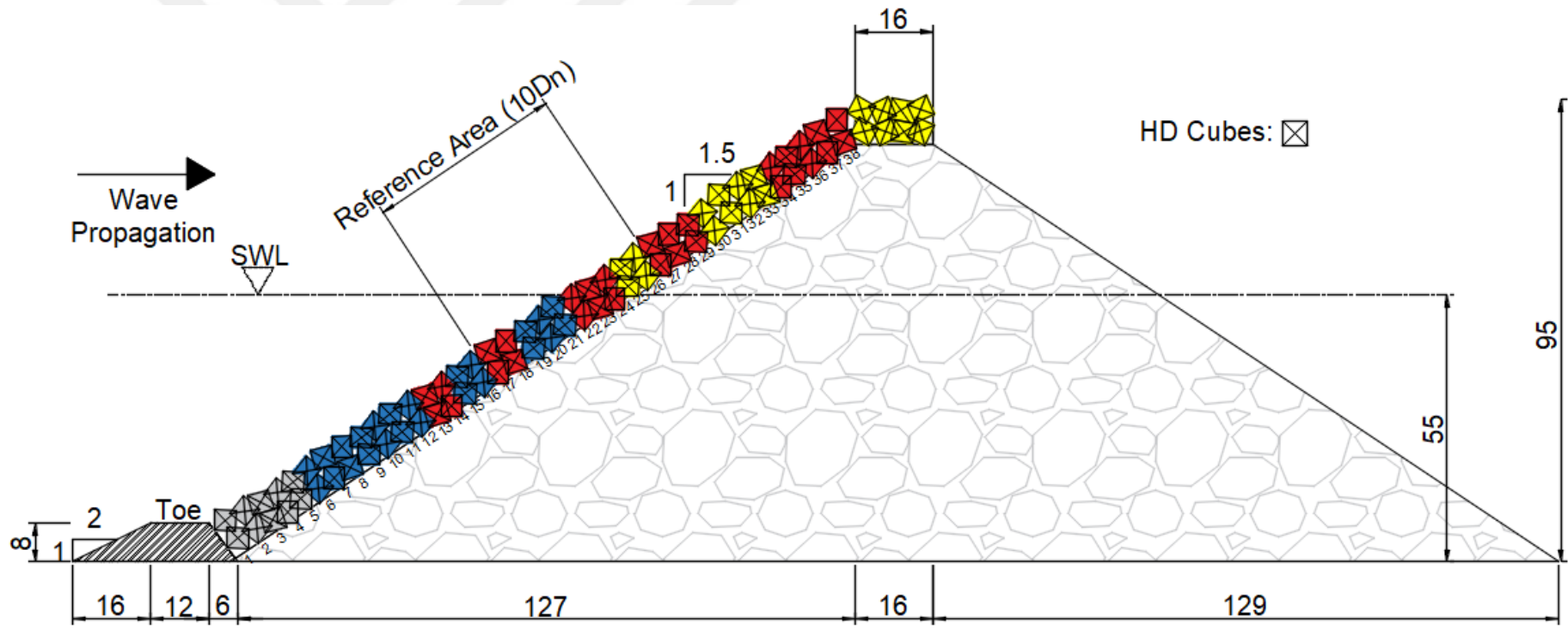


Figure 4.11 Positions of HD cubes for the experiment Double Layer HD Cubes

Table 4.12 Damage ratios for Double Layer HD Cubes (Gümüşcü 2020)

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M ₁ (QTY)	M ₁ (%)	M ₂ (QTY)	M ₂ (%)	M _T (QTY)	Movement Ratio (%)	D ₁ (QTY)	D ₁ (%)	D ₂ (QTY)	D ₂ (%)	D _T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W3	1	0.37	0	0.00	1	0.37	0	0.00	0	0.00	0	0.00
W4	17	6.30	0	0.00	17	6.30	0	0.00	0	0.00	0	0.00
W5	34	12.59	0	0.00	34	12.59	0	0.00	0	0.00	0	0.00
W6	65	24.07	0	0.00	65	24.07	0	0.00	0	0.00	0	0.00
W7	69	25.56	0	0.00	69	25.56	0	0.00	0	0.00	0	0.00
W8	72	26.67	0	0.00	72	26.67	0	0.00	0	0.00	0	0.00
W9	78	28.89	0	0.00	78	28.89	0	0.00	0	0.00	0	0.00
W10	75	27.78	5	1.85	80	29.63	0	0.00	0	0.00	0	0.00
W11	75	27.78	6	2.22	81	30.00	0	0.00	0	0.00	0	0.00

Table 4.13 Wave parameters and damage ratios for Double Layer HD Cubes (Gümüşçü 2020)

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	H_{m0} (m)	S_p (-)	$S_{m-1.0}$ (-)	C_r %	N_s (-)	M_1 %	M_2 %	M_T %	D_1 %	D_2 %	D_T %	Observation
W1	0.05	0.032	0.044	0.286	0.58	0.00	0.00	0.00	0.00	0.00	0.00	
W2	0.07	0.026	0.032	0.283	0.81	0.00	0.00	0.00	0.00	0.00	0.00	
W3	0.09	0.030	0.040	0.277	1.05	0.37	0.00	0.37	0.00	0.00	0.00	
W4	0.11	0.024	0.290	0.318	1.28	6.30	0.00	6.30	0.00	0.00	0.00	
W5	0.14	0.040	0.045	0.277	1.63	12.59	0.00	12.59	0.00	0.00	0.00	
W6	0.16	0.039	0.046	0.294	1.86	24.07	0.00	24.07	0.00	0.00	0.00	
W7	0.18	0.038	0.046	0.305	2.09	25.56	0.00	25.56	0.00	0.00	0.00	
W8	0.19	0.040	0.045	0.345	2.21	26.67	0.00	26.67	0.00	0.00	0.00	
W9	0.20	0.042	0.048	0.347	2.33	28.89	0.00	28.89	0.00	0.00	0.00	
W10	0.19	0.040	0.043	0.386	2.21	27.78	1.85	29.63	0.00	0.00	0.00	
W11	0.23	0.049	0.054	0.366	2.67	27.78	2.22	30.00	0.00	0.00	0.00	

Table 4.14 Change of N_0 corresponding to wave parameters for Double Layer HD Cubes (Gümüşçü 2020)

Breakwater $\psi_s=0.59$						
$d=55$ cm						
Waves	H_{m0} (m)	$H_{1/3}$ (m)	$T_{m-1.0}$ (s)	T_p (s)	N_s (-)	N_0 (-)
W1	0.05	0.05	0.85	1.00	0.58	0
W2	0.07	0.07	1.19	1.32	0.81	0
W3	0.09	0.09	1.20	1.38	1.05	0
W4	0.11	0.11	1.57	1.71	1.28	0
W5	0.14	0.14	1.41	1.50	1.63	0
W6	0.16	0.17	1.50	1.62	1.86	0
W7	0.18	0.18	1.59	1.74	2.09	0
W8	0.19	0.18	1.65	1.74	2.21	0
W9	0.20	0.20	1.64	1.74	2.33	0
W10	0.19	0.19	1.68	1.74	2.21	0
W11	0.23	0.23	1.65	1.74	2.67	0

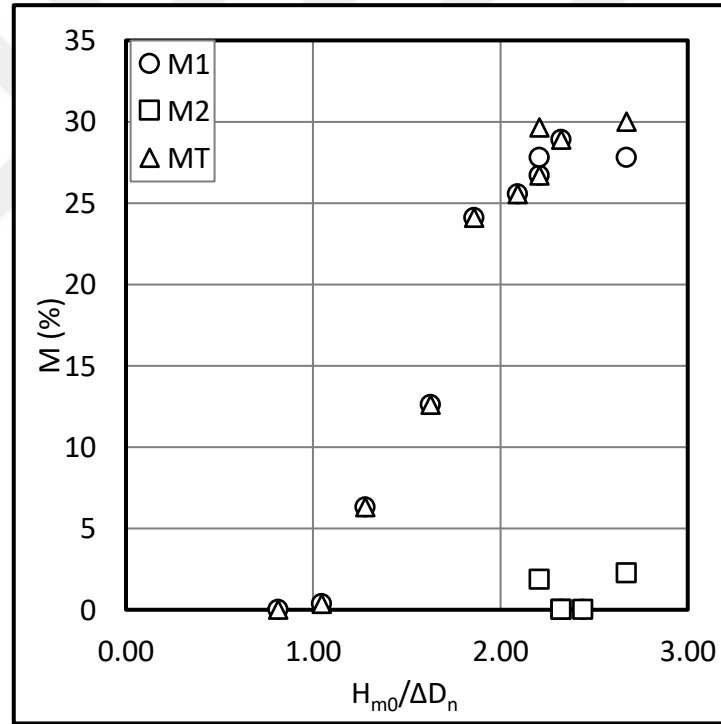


Figure 4.12 Movement ratio in reference area for Double Layer HD Cubes (Gümüşçü 2020)

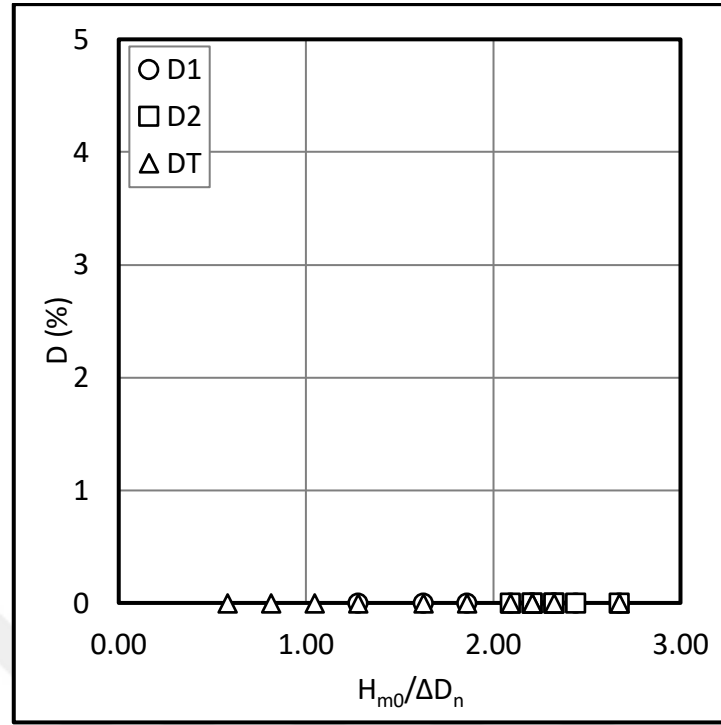


Figure 4.13 Displacement ratio in reference area for Double Layer HD Cubes (Gümüüşcü 2020)

4.2.4 Experiment 4: Single Layer ND Cubes with Regular Placement

The breakwater model was tested at 55 cm water depth using single layer regular placement method with ND cubes. Figure 4.14 shows reference area and cube arrangement of ND cubes over the slope.

Table 4.16, Table 4.17, and Table 4.18 show that displacement was not observed in the armor layer. Only movements occurred due to high friction between adjacent armor units. Movement started at W1 ($H_{m0}=0.05$ m) and reached to 2.59% at W8 ($H_{m0}=0.18$ m). Afterwards, movement gradually increased and reached to 4.44% at W11. W13 ($H_{m0}=0.21$ m and $N_s=3.75$), the last wave series, movement reached to its maximum point 8.52%. Only 23 cubes (8.52%) performed movement behavior (see Figure 4.15 and Figure 4.16). These cubes moved less than $0.5D_n$, which means that $0.5D_n$ - $1.0D_n$ movement (M_2) was not observed. Overtopping started at W7 ($H_{m0}=0.17$ m) (Table 4.15).

Table 4.15 Measured wave parameters at the toe of the breakwater for Single Layer ND Cubes with Regular Placement

Breakwater $\psi_s=0.59$									
d=55 cm									
Waves	H_{m0}	H_{1/3}	T_{m-1.0}	T_p	S_{m-1.0}	S_p	C_r	N_s	Overtopping
	(m)	(m)	(s)	(s)	(-)	(-)	%	(-)	
W1	0.05	0.05	0.84	0.91	0.046	0.039	0.312	0.89	×
W2	0.08	0.08	1.31	1.32	0.030	0.029	0.319	1.43	×
W3	0.10	0.10	1.26	1.32	0.040	0.037	0.314	1.79	×
W4	0.11	0.11	1.70	1.74	0.024	0.023	0.369	1.96	×
W5	0.15	0.15	1.59	1.50	0.038	0.043	0.334	2.68	×
W6	0.17	0.17	1.80	1.62	0.034	0.041	0.343	3.04	×
W7	0.17	0.17	1.53	1.62	0.046	0.041	0.380	3.04	✓
W8	0.18	0.18	1.58	1.74	0.046	0.038	0.395	3.21	✓
W9	0.19	0.19	1.56	1.74	0.050	0.040	0.398	3.39	✓
W10	0.17	0.17	1.60	1.74	0.043	0.036	0.442	3.04	✓
W11	0.22	0.22	1.55	1.74	0.059	0.047	0.420	3.93	✓
W12	0.21	0.20	1.58	1.60	0.054	0.053	0.487	3.75	✓
W13	0.21	0.21	1.70	1.83	0.047	0.040	0.486	3.75	✓

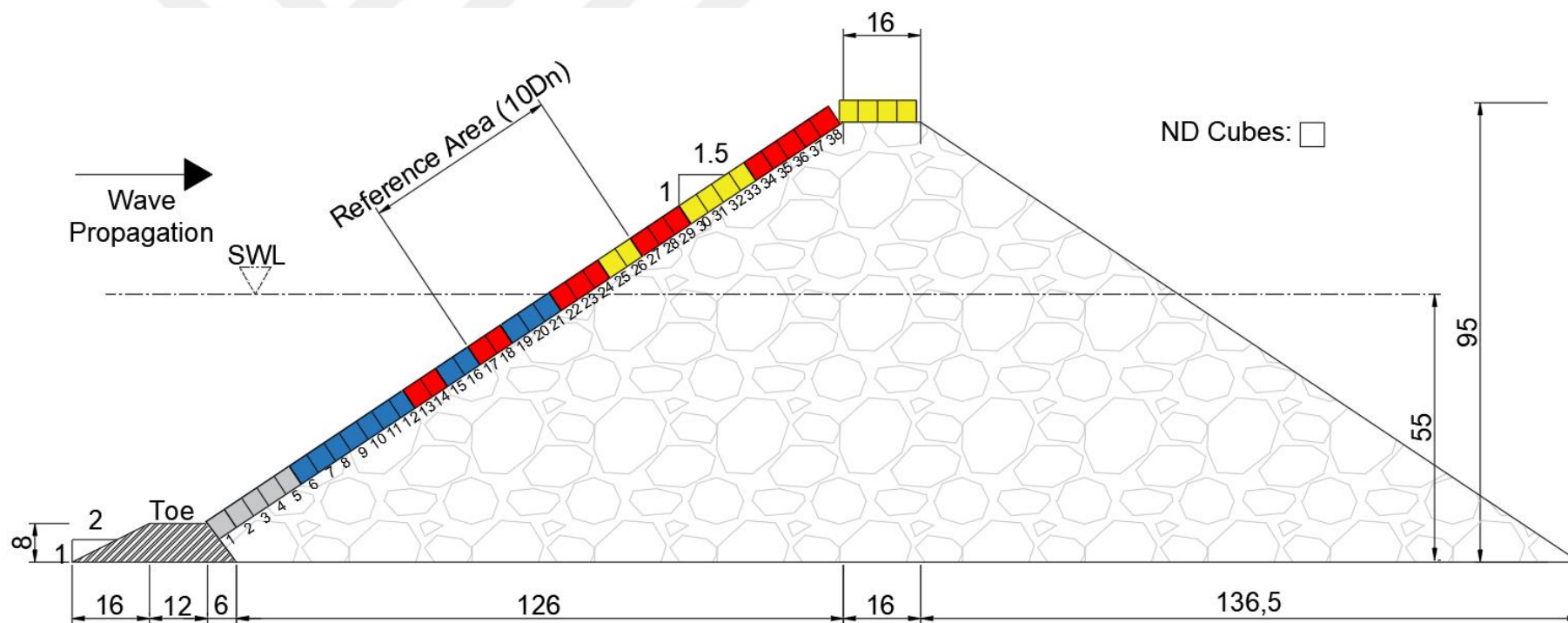


Figure 4.14 Positions of ND cubes for the experiment Single Layer ND Cubes with Regular Placement

Table 4.16 Damage ratios for Single Layer ND Cubes with Regular Placement

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	Damage Ratio For Moving Units						Damage Ratio For Displaced Units					
	M ₁ (QTY)	M ₁ (%)	M ₂ (QTY)	M ₂ (%)	M _T (QTY)	Damage Ratio (%)	D ₁ (QTY)	D ₁ (%)	D ₂ (QTY)	D ₂ (%)	D _T (QTY)	Damage Ratio (%)
W1	1	0.37	0	0.00	1	0.37	0	0.00	0	0.00	0	0.00
W2	2	0.74	0	0.00	2	0.74	0	0.00	0	0.00	0	0.00
W3	2	0.74	0	0.00	2	0.74	0	0.00	0	0.00	0	0.00
W4	4	1.48	0	0.00	4	1.48	0	0.00	0	0.00	0	0.00
W5	6	2.22	0	0.00	6	2.22	0	0.00	0	0.00	0	0.00
W6	6	2.22	0	0.00	6	2.22	0	0.00	0	0.00	0	0.00
W7	6	2.22	0	0.00	6	2.22	0	0.00	0	0.00	0	0.00
W8	7	2.59	0	0.00	7	2.59	0	0.00	0	0.00	0	0.00
W9	8	2.96	0	0.00	8	2.96	0	0.00	0	0.00	0	0.00
W10	11	4.07	0	0.00	11	4.07	0	0.00	0	0.00	0	0.00
W11	12	4.44	0	0.00	12	4.44	0	0.00	0	0.00	0	0.00
W12	19	7.04	0	0.00	19	7.04	0	0.00	0	0.00	0	0.00
W13	23	8.52	0	0.00	23	8.52	0	0.00	0	0.00	0	0.00

Table 4.17 Wave parameters and damage ratios for Single Layer ND Cubes with Regular Placement

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	H_{m0} (m)	S_p (-)	S_{m-1.0} (-)	C_r %	N_s (-)	M₁ %	M₂ %	M_T %	D₁ %	D₂ %	D_T %	Observation
W1	0.05	0.039	0.046	0.312	0.89	0.37	0.00	0.37	0.00	0.00	0.00	
W2	0.08	0.029	0.030	0.319	1.43	0.74	0.00	0.74	0.00	0.00	0.00	
W3	0.10	0.037	0.040	0.314	1.79	0.74	0.00	0.74	0.00	0.00	0.00	
W4	0.11	0.023	0.024	0.369	1.96	1.48	0.00	1.48	0.00	0.00	0.00	
W5	0.15	0.043	0.038	0.334	2.68	2.22	0.00	2.22	0.00	0.00	0.00	
W6	0.17	0.041	0.034	0.343	3.04	2.22	0.00	2.22	0.00	0.00	0.00	
W7	0.17	0.041	0.046	0.380	3.04	2.22	0.00	2.22	0.00	0.00	0.00	
W8	0.18	0.038	0.046	0.395	3.21	2.59	0.00	2.59	0.00	0.00	0.00	
W9	0.19	0.040	0.050	0.398	3.39	2.96	0.00	2.96	0.00	0.00	0.00	
W10	0.17	0.036	0.043	0.442	3.04	4.07	0.00	4.07	0.00	0.00	0.00	
W11	0.22	0.047	0.059	0.420	3.93	4.44	0.00	4.44	0.00	0.00	0.00	
W12	0.21	0.053	0.054	0.487	3.75	7.04	0.00	7.04	0.00	0.00	0.00	
W13	0.21	0.040	0.047	0.486	3.75	8.52	0.00	8.52	0.00	0.00	0.00	

Table 4.18 Change of N_0 corresponding to wave parameters for Single Layer ND Cubes with Regular Placement

Breakwater $\psi_s=0.59$						
$d=55\text{ cm}$						
Waves	H_{m0} (m)	$H_{1/3}$ (m)	$T_{m-1.0}$ (s)	T_p (s)	N_s (-)	N_0 (-)
W1	0.05	0.05	0.84	0.91	0.89	0
W2	0.08	0.08	1.31	1.32	1.43	0
W3	0.10	0.10	1.26	1.32	1.79	0
W4	0.11	0.11	1.70	1.74	1.96	0
W5	0.15	0.15	1.59	1.50	2.68	0
W6	0.17	0.17	1.80	1.62	3.04	0
W7	0.17	0.17	1.53	1.62	3.04	0
W8	0.18	0.18	1.58	1.74	3.21	0
W9	0.19	0.19	1.56	1.74	3.39	0
W10	0.17	0.17	1.60	1.74	3.04	0
W11	0.22	0.22	1.55	1.74	3.93	0
W12	0.21	0.20	1.58	1.60	3.75	0
W13	0.21	0.21	1.70	1.83	3.75	0

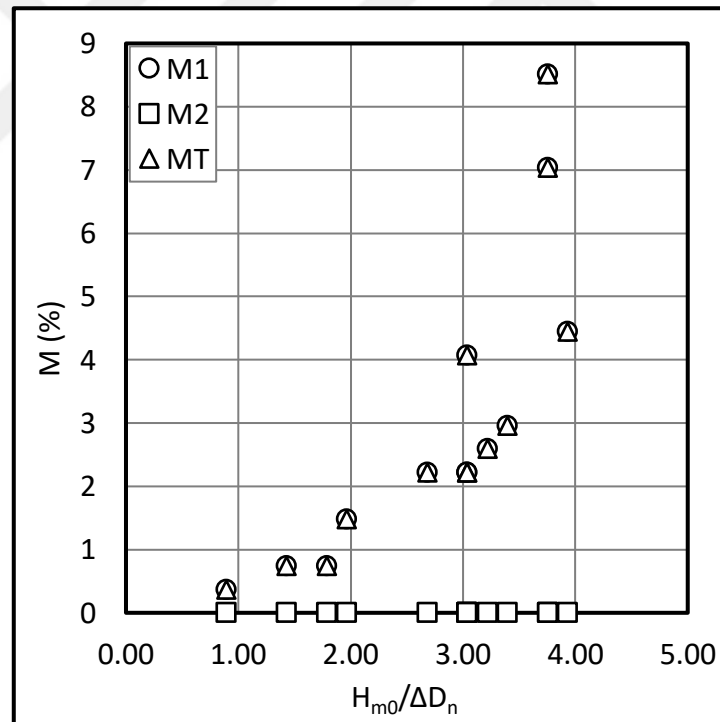


Figure 4.15 Percentage of moving units in reference area for Single Layer ND Cubes with Regular Placement

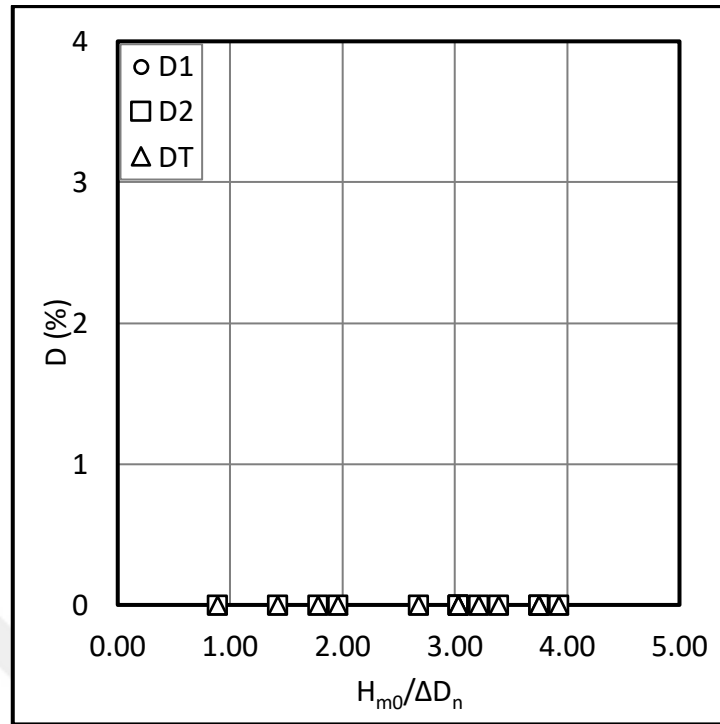


Figure 4.16 Percentage of moving units in reference area for Single Layer ND Cubes with Regular Placement

4.2.5 Experiment 5: Single Layer HD Cubes with Regular Placement

The model breakwater was tested at 55 cm water depth using single layer regular placement method with HD cubes. Figure 4.17 shows reference area and cube arrangement of HD cubes over the slope.

Displacement was not observed in this experiment. Only movements occurred due to high friction between adjacent armor units (Table 4.20, Table 4.21, and Table 4.22). Movement started at W1 ($H_{m0}=0.05$ m) and reached to 2.59% at W5 ($H_{m0}=0.14$ m). Then, movement reached its maximum ratio at W9 ($H_{m0}=0.19$ m), 3.70% (Figure 4.17 and Figure 4.18). From W10 to W13, neither movement nor displacement occurred. Only 10 cubes (3.70%) performed movement behavior, and these cubes moved less than $0.5D_n$. M_2 was not observed through experiment. Overtopping started at W7 (Table 4.19).

Table 4.19 Measured wave parameters at the toe of the breakwater for Single Layer HD Cubes with Regular Placement

Breakwater $\psi_s=0.59$									
d=55 cm									
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	$S_{m-1.0}$	S_p	C_r	N_s	Overtopping
	(m)	(m)	(s)	(s)	(-)	(-)	%	(-)	
W1	0.05	0.05	0.85	0.91	0.044	0.039	0.310	0.58	×
W2	0.08	0.08	1.22	1.32	0.034	0.029	0.315	0.93	×
W3	0.10	0.10	1.23	1.32	0.043	0.037	0.306	1.16	×
W4	0.11	0.11	1.52	1.74	0.030	0.023	0.361	1.28	×
W5	0.14	0.14	1.40	1.50	0.046	0.040	0.324	1.63	×
W6	0.17	0.17	1.47	1.62	0.051	0.041	0.333	1.98	×
W7	0.17	0.17	1.54	1.74	0.046	0.036	0.370	1.98	✓
W8	0.18	0.18	1.58	1.74	0.046	0.038	0.390	2.09	✓
W9	0.19	0.19	1.58	1.74	0.049	0.040	0.382	2.21	✓
W10	0.17	0.17	1.61	1.74	0.042	0.036	0.435	1.98	✓
W11	0.22	0.21	1.58	1.74	0.057	0.047	0.415	2.56	✓
W12	0.21	0.21	1.58	1.46	0.054	0.063	0.487	2.44	✓
W13	0.21	0.20	1.76	1.83	0.043	0.040	0.485	2.44	✓

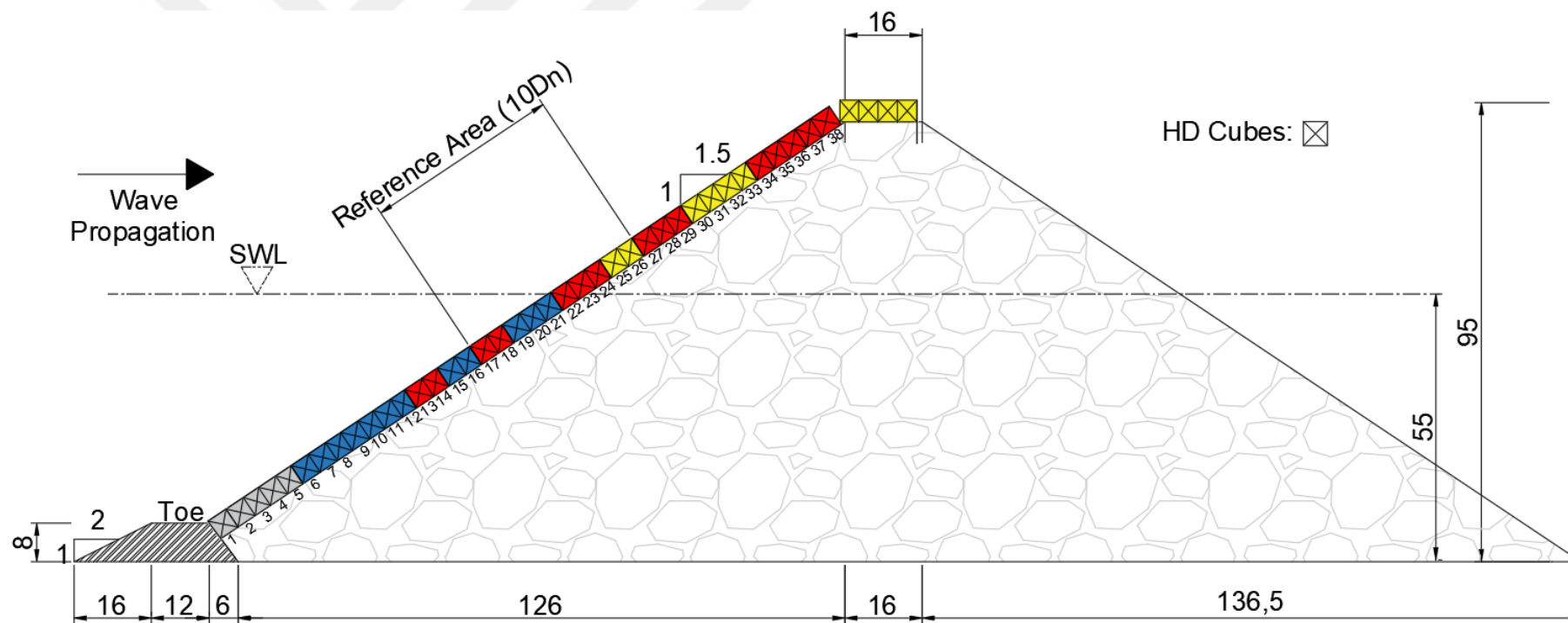


Figure 4.17 Positions of HD cubes for the experiment Single Layer HD Cubes with Regular Placement

Table 4.20 Damage ratios for Single Layer HD Cubes with Regular Placement

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	Damage Ratio For Moving Units						Damage Ratio For Displaced Units					
	M ₁ (QTY)	M ₁ (%)	M ₂ (QTY)	M ₂ (%)	M _T (QTY)	Damage Ratio (%)	D ₁ (QTY)	D ₁ (%)	D ₂ (QTY)	D ₂ (%)	D _T (QTY)	Damage Ratio (%)
W1	1	0.37	0	0.00	1	0.37	0	0.00	0	0.00	0	0.00
W2	1	0.37	0	0.00	1	0.37	0	0.00	0	0.00	0	0.00
W3	3	1.11	0	0.00	3	1.11	0	0.00	0	0.00	0	0.00
W4	3	1.11	0	0.00	3	1.11	0	0.00	0	0.00	0	0.00
W5	7	2.59	0	0.00	7	2.59	0	0.00	0	0.00	0	0.00
W6	8	2.96	0	0.00	8	2.96	0	0.00	0	0.00	0	0.00
W7	8	2.96	0	0.00	8	2.96	0	0.00	0	0.00	0	0.00
W8	9	3.33	0	0.00	9	3.33	0	0.00	0	0.00	0	0.00
W9	10	3.70	0	0.00	10	3.70	0	0.00	0	0.00	0	0.00
W10	10	3.70	0	0.00	10	3.70	0	0.00	0	0.00	0	0.00
W11	10	3.70	0	0.00	10	3.70	0	0.00	0	0.00	0	0.00
W12	10	3.70	0	0.00	10	3.70	0	0.00	0	0.00	0	0.00
W13	10	3.70	0	0.00	10	3.70	0	0.00	0	0.00	0	0.00

Table 4.21 Wave parameters and damage ratios for Single Layer HD Cubes with Regular Placement

Breakwater $\psi_s=0.59$												
d=55 cm												
Waves	H_{m0} (m)	S_p (-)	$S_{m-1.0}$ (-)	C_r %	N_s (-)	M_1 %	M_2 %	M_T %	D_1 %	D_2 %	D_T %	Observation
W1	0.05	0.039	0.044	0.310	0.58	0.37	0.00	0.37	0.00	0.00	0.00	
W2	0.08	0.029	0.034	0.315	0.93	0.37	0.00	0.37	0.00	0.00	0.00	
W3	0.10	0.037	0.043	0.306	1.16	1.11	0.00	1.11	0.00	0.00	0.00	
W4	0.11	0.023	0.030	0.361	1.28	1.11	0.00	1.11	0.00	0.00	0.00	
W5	0.14	0.040	0.046	0.324	1.63	2.59	0.00	2.59	0.00	0.00	0.00	
W6	0.17	0.041	0.051	0.333	1.98	2.96	0.00	2.96	0.00	0.00	0.00	
W7	0.17	0.036	0.046	0.370	1.98	2.96	0.00	2.96	0.00	0.00	0.00	
W8	0.18	0.038	0.046	0.390	2.09	3.33	0.00	3.33	0.00	0.00	0.00	
W9	0.19	0.040	0.049	0.382	2.21	3.70	0.00	3.70	0.00	0.00	0.00	
W10	0.17	0.036	0.042	0.435	1.98	3.70	0.00	3.70	0.00	0.00	0.00	
W11	0.22	0.047	0.057	0.415	2.56	3.70	0.00	3.70	0.00	0.00	0.00	
W12	0.21	0.063	0.054	0.487	2.44	3.70	0.00	3.70	0.00	0.00	0.00	
W13	0.21	0.040	0.043	0.485	2.44	3.70	0.00	3.70	0.00	0.00	0.00	

Table 4.22 Change of N_0 corresponding to wave parameters for Single Layer HD Cubes with Regular Placement

Breakwater $\psi_s=0.59$						
$d=55\text{ cm}$						
Waves	H_{m0} (m)	$H_{1/3}$ (m)	$T_{m-1.0}$ (s)	T_p (s)	N_s (-)	N_0 (-)
W1	0.05	0.05	0.85	0.91	0.58	0
W2	0.08	0.08	1.22	1.32	0.93	0
W3	0.10	0.10	1.23	1.32	1.16	0
W4	0.11	0.11	1.52	1.74	1.28	0
W5	0.14	0.14	1.40	1.50	1.63	0
W6	0.17	0.17	1.47	1.62	1.98	0
W7	0.17	0.17	1.54	1.74	1.98	0
W8	0.18	0.18	1.58	1.74	2.09	0
W9	0.19	0.19	1.58	1.74	2.21	0
W10	0.17	0.17	1.61	1.74	1.98	0
W11	0.22	0.21	1.58	1.74	2.56	0
W12	0.21	0.21	1.58	1.46	2.44	0
W13	0.21	0.20	1.76	1.83	2.44	0

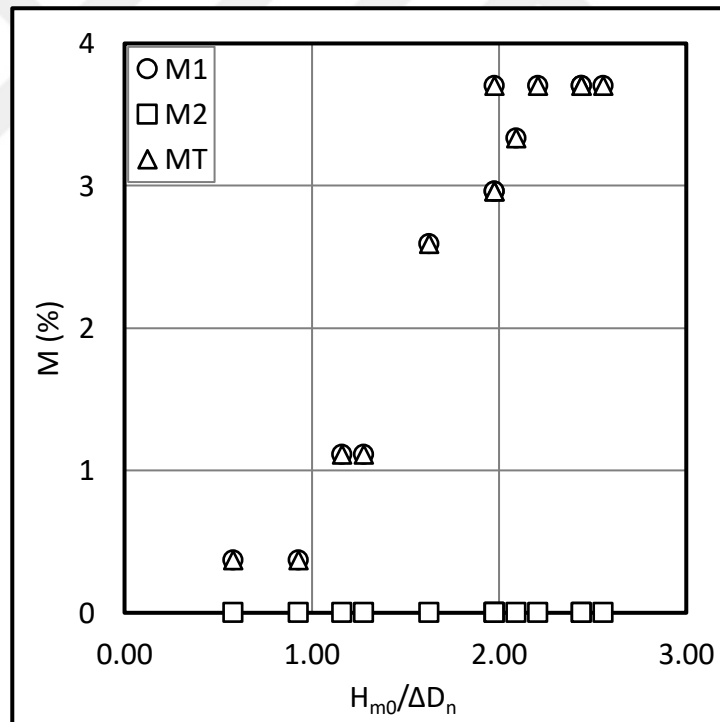


Figure 4.18 Percentage of moving units in reference area for Single Layer HD Cubes with Regular Placement

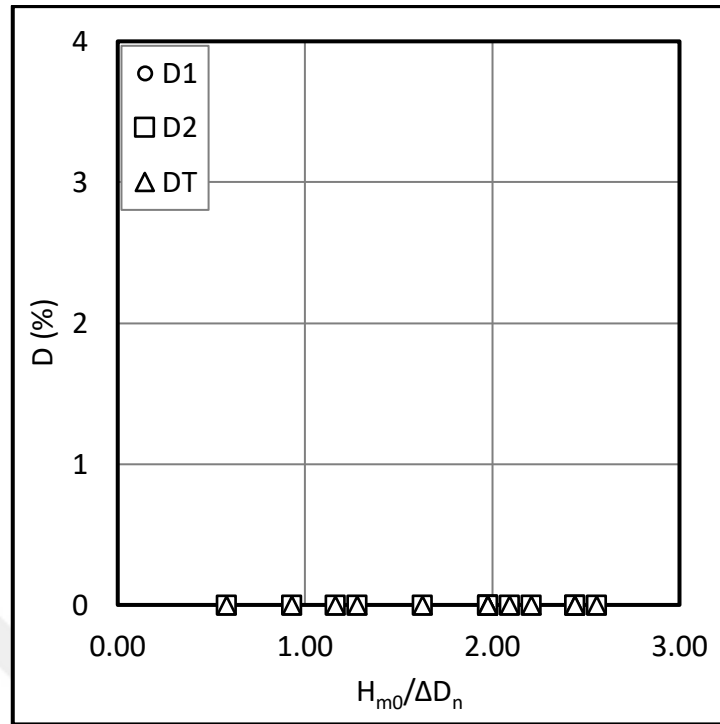


Figure 4.19 Percentage of moving units in reference area for Single Layer HD Cubes with Regular Placement

Table 4.23 and Figure 4.20 show the variation of movement ratios for single layer HD experiment and single layer ND experiment respectively, with respect to stability number. Movements started under small wave attacks for both experiments, and they increased until the end of the tests. Total movement ratio was found lesser for HD cubes than for ND cubes. It was 8.52% at $N_s=3.75$ (for W13) for ND while total movement ratio was 3.70% at $N_s=2.44$ (for W13) for HD. HD cubes showed less movement (almost half percent) than ND cubes.

Table 4.23 Movement ratios corresponding to N_s for Single Layer ND Cubes with Regular Placement and Single Layer HD Cubes with Regular Placement

Waves	HD Cubes		ND Cubes	
	N_s	Movement Ratio	N_s	Movement Ratio
	(-)	(%)	(-)	(%)
W1	0.58	0.37	0.89	0.37
W2	0.93	0.37	1.43	0.74
W3	1.16	1.11	1.79	0.74
W4	1.28	1.11	1.96	1.48
W5	1.63	2.59	2.68	2.22
W6	1.98	2.96	3.04	2.22
W7	1.98	2.96	3.04	2.22
W8	2.09	3.33	3.21	2.59
W9	2.21	3.70	3.39	2.96
W10	1.98	3.70	3.04	4.07
W11	2.56	3.70	3.93	4.44
W12	2.44	3.70	3.75	7.04
W13	2.44	3.70	3.75	8.52

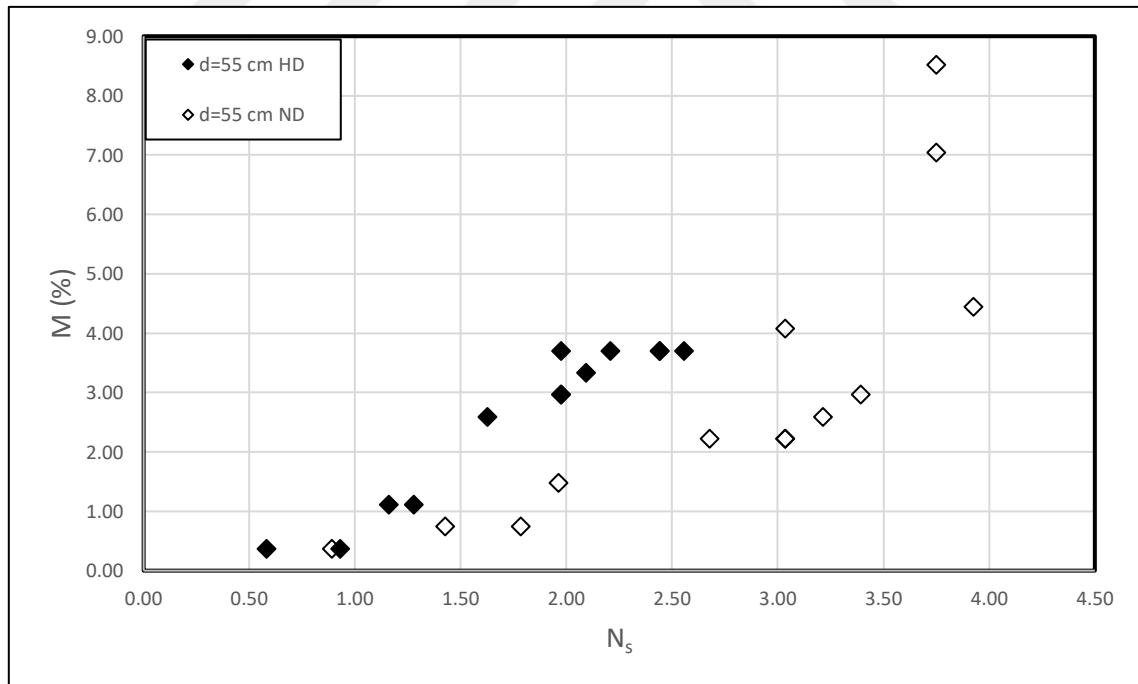


Figure 4.20 Percentage of moving units in reference area for Single Layer ND Cubes with Regular Placement and Single Layer HD Cubes with Regular Placement

4.3 Cube Armored Berm Breakwaters

The high-density cubes (HD) in the second layer and normal density cubes (ND) in the first layer were used in the armor layer of the lower slope and berm of the breakwater for emerged ($d=45\text{cm}$), berm at SWL ($d=55\text{cm}$) and submerged ($d=65\text{cm}$) berms in this case. For all experiments, the upper slope was fixed before each individual experiment (see in Section 3).

4.3.1 Experiment 1: Emerged Berm

Significant wave height was very low at W1 ($H_{m0}=0.05\text{ m}$) and only M_1 ($<0.5D_n$) movement was observed. At W2, still rocking movements were dominant, 15.93%. From W3 to W4.2, M_2 type movements started, and M_T reached to 41.85%. This wave was the last wave without displacement (Table 4.25, Table 4.27, and Table 4.29). At W5 ($H_{m0}=0.14\text{ m}$ and $N_s=1.63$) the first displacements occurred (Figure 4.22 and Figure 4.23). The displacement ratio was 1.11% for this wave series. Until wave series W6 ($H_{m0}=0.15\text{ m}$), the displacement ratio was constant, but total movement ratio changed and reached to its maximum point with 48.52%. At W7 ($H_{m0}=0.15\text{ m}$) displacements started again and reached to 1.85% slightly. In W9 displacements started again and increased until the end of the experiment. From W9 to W11, displacement ratios are given in Table 4.25, Table 4.27, and Table 4.29. These ratios are 2.96%, 4.44% and 5.56% for W9, W10 and W11, respectively. One of the most important observations on this experiment is that sudden damage was not observed. The damage increased gradually. The reference area and cube arrangements can be seen in Figure 4.21. 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 was never became visible thorough armor layer, and no cubes dislocated to the toe of the structure. In addition, overtopping did not occur throughout the experiment (Table 4.24).

Stability number versus relative damage was drawn with Van der Meer (1988) formula in Figure 4.25. The change of relative damage agreed with the lower limit of Van der Meer formula.

Table 4.24 Measured wave parameters at the toe of the breakwater for Emerged Berm

Breakwater with Berm $\psi_s=0.59$									
d=45 cm									
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	$S_{m-1.0}$	S_p	C_r	N_s	Overtopping
	(m)	(m)	(s)	(s)	(-)	(-)	%	(-)	
W1	0.05	0.05	0.83	0.85	0.046	0.044	0.264	0.58	×
W2	0.08	0.08	1.19	1.29	0.036	0.031	0.247	0.93	×
W3	0.11	0.10	1.21	1.29	0.048	0.042	0.248	1.28	×
W4	0.10	0.10	1.44	1.69	0.031	0.022	0.311	1.16	×
W4.1	0.11	0.11	1.39	1.58	0.036	0.028	0.292	1.28	×
W4.2	0.12	0.11	1.44	1.69	0.037	0.027	0.308	1.40	×
W5	0.14	0.13	1.34	1.35	0.050	0.049	0.283	1.63	×
W5.1	0.14	0.13	1.45	1.69	0.043	0.031	0.312	1.63	×
W6	0.15	0.14	1.42	1.58	0.048	0.038	0.297	1.74	×
W7	0.15	0.15	1.45	1.69	0.046	0.034	0.318	1.74	×
W8	0.15	0.15	1.50	1.69	0.043	0.034	0.338	1.74	×
W9	0.16	0.16	1.50	1.85	0.046	0.030	0.341	1.86	×
W10	0.15	0.14	1.60	2.50	0.038	0.015	0.407	1.74	×
W11	0.18	0.18	1.53	1.90	0.049	0.032	0.350	2.09	×
W12	0.17	0.15	1.92	2.22	0.030	0.022	0.478	1.98	×
W13	0.17	0.16	1.98	2.67	0.028	0.015	0.478	1.98	×

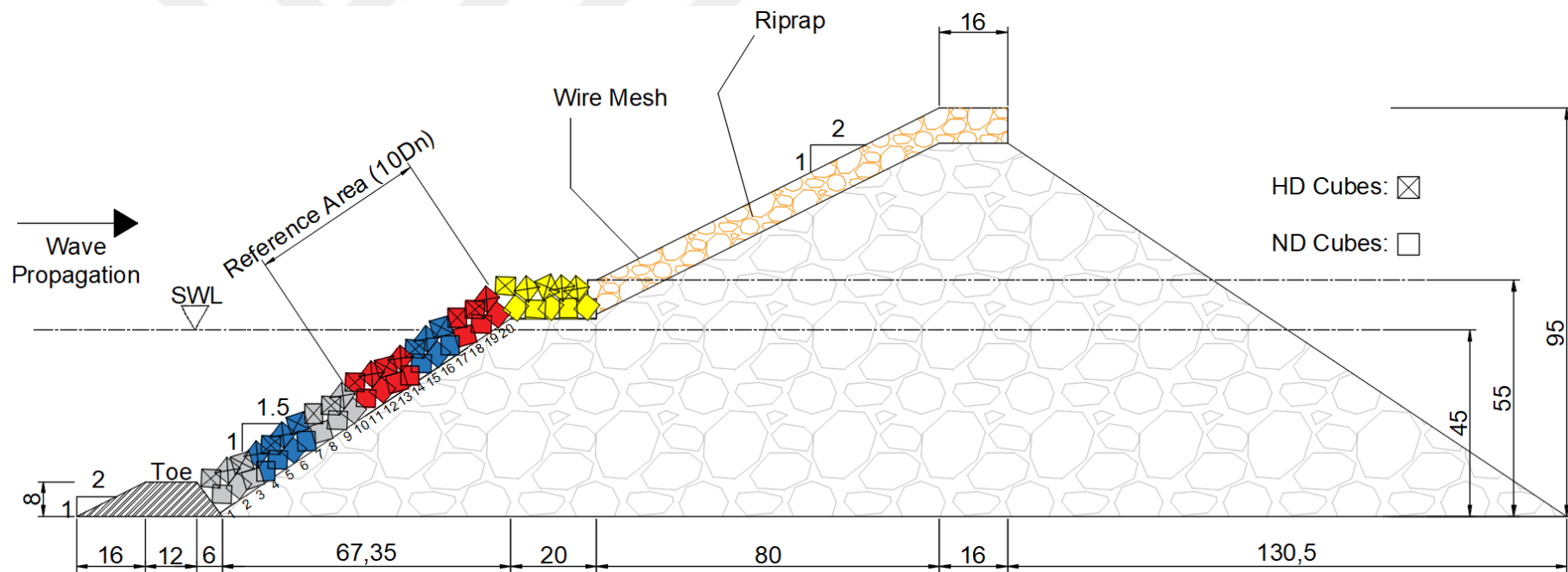


Figure 4.21 Positions of HD and ND cubes for the experiment Emerged Berm

Table 4.25 Damage ratios for lower slope of Emerged Berm

Breakwater with Berm $\psi_s=0.59$												
d=45 cm (Lower Slope)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M ₁ (QTY)	M ₁ (%)	M ₂ (QTY)	M ₂ (%)	M _T (QTY)	Movement Ratio (%)	D ₁ (QTY)	D ₁ (%)	D ₂ (QTY)	D ₂ (%)	D _T (QTY)	Damage Ratio (%)
W1	7	2.59	0	0.00	7	2.59	0	0.00	0	0.00	0	0.00
W2	43	15.93	0	0.00	43	15.93	0	0.00	0	0.00	0	0.00
W3	52	19.26	1	0.37	53	19.63	0	0.00	0	0.00	0	0.00
W4	57	21.11	1	0.37	58	21.48	0	0.00	0	0.00	0	0.00
W4.1	75	27.78	8	2.96	83	30.74	0	0.00	0	0.00	0	0.00
W4.2	100	37.04	13	4.81	113	41.85	0	0.00	0	0.00	0	0.00
W5	101	37.41	28	10.37	129	47.78	3	1.11	0	0.00	3	1.11
W5.1	99	36.67	31	11.48	130	48.15	3	1.11	0	0.00	3	1.11
W6	98	36.30	33	12.22	131	48.52	3	1.11	0	0.00	3	1.11
W7	82	30.37	48	17.78	130	48.15	5	1.85	0	0.00	5	1.85
W8	77	28.52	53	19.63	130	48.15	5	1.85	0	0.00	5	1.85
W9	66	24.44	61	22.59	127	47.04	8	2.96	0	0.00	8	2.96
W10	59	21.85	64	23.70	123	45.56	12	4.44	0	0.00	12	4.44
W11	51	18.89	69	25.56	120	44.44	15	5.56	0	0.00	15	5.56
W12	41	15.19	69	25.56	110	40.74	25	9.26	0	0.00	25	9.26
W13	35	12.96	59	21.85	94	34.81	38	14.07	3	1.11	41	15.19

Table 4.26 Damage ratios for berm of Emerged Berm

Breakwater with Berm $\psi_s=0.59$												
d=45 cm (Berm)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M ₁ (QTY)	M ₁ (%)	M ₂ (QTY)	M ₂ (%)	M _T (QTY)	Movement Ratio (%)	D ₁ (QTY)	D ₁ (%)	D ₂ (QTY)	D ₂ (%)	D _T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	6	4.44	0	0.00	6	4.44	0	0.00	0	0.00	0	0.00
W3	8	5.93	0	0.00	8	5.93	0	0.00	0	0.00	0	0.00
W4	8	5.93	3	2.22	11	8.15	0	0.00	0	0.00	0	0.00
W4.1	17	12.59	3	2.22	20	14.81	0	0.00	0	0.00	0	0.00
W4.2	20	14.81	3	2.22	23	17.04	0	0.00	0	0.00	0	0.00
W5	38	28.15	4	2.96	42	31.11	0	0.00	0	0.00	0	0.00
W5.1	40	29.63	5	3.70	45	33.33	0	0.00	0	0.00	0	0.00
W6	43	31.85	5	3.70	48	35.56	0	0.00	0	0.00	0	0.00
W7	49	36.30	6	4.44	55	40.74	0	0.00	0	0.00	0	0.00
W8	52	38.52	5	3.70	57	42.22	1	0.74	0	0.00	1	0.74
W9	48	35.56	13	9.63	61	45.19	1	0.74	0	0.00	1	0.74
W10	48	35.56	16	11.85	64	47.41	2	1.48	0	0.00	2	1.48
W11	44	32.59	20	14.81	64	47.41	2	1.48	1	0.74	3	2.22
W12	36	26.67	27	20.00	63	46.67	2	1.48	2	1.48	4	2.96
W13	27	20.00	32	23.70	59	43.70	6	4.44	2	1.48	8	5.93

Table 4.27 Wave parameters and damage ratios for lower slope of Emerged Berm

Breakwater with Berm $\psi_s=0.59$												
d=45 cm (Lower Slope)												
Waves	H _{m0} (m)	S _p (-)	S _{m-1.0} (-)	C _r %	N _s (-)	M ₁ %	M ₂ %	M _T %	D ₁ %	D ₂ %	D _T %	Observation
W1	0.05	0.044	0.046	0.264	0.58	2.59	0.00	2.59	0.00	0.00	0.00	
W2	0.08	0.031	0.036	0.247	0.93	15.93	0.00	15.93	0.00	0.00	0.00	
W3	0.11	0.042	0.048	0.248	1.28	19.26	0.37	19.63	0.00	0.00	0.00	
W4	0.10	0.022	0.031	0.311	1.16	21.11	0.37	21.48	0.00	0.00	0.00	
W4.1	0.11	0.028	0.036	0.292	1.28	27.78	2.96	30.74	0.00	0.00	0.00	
W4.2	0.12	0.027	0.037	0.308	1.40	37.04	4.81	41.85	0.00	0.00	0.00	
W5	0.14	0.049	0.050	0.283	1.63	37.41	10.37	47.78	1.11	0.00	1.11	
W5.1	0.14	0.031	0.043	0.312	1.63	36.67	11.48	48.15	1.11	0.00	1.11	
W6	0.15	0.038	0.048	0.297	1.74	36.30	12.22	48.52	1.11	0.00	1.11	
W7	0.15	0.034	0.046	0.318	1.74	30.37	17.78	48.15	1.85	0.00	1.85	
W8	0.15	0.034	0.043	0.338	1.74	28.52	19.63	48.15	1.85	0.00	1.85	
W9	0.16	0.030	0.046	0.341	1.86	24.44	22.59	47.04	2.96	0.00	2.96	
W10	0.15	0.015	0.038	0.407	1.74	21.85	23.70	45.56	4.44	0.00	4.44	
W11	0.18	0.032	0.049	0.350	2.09	18.89	25.56	44.44	5.56	0.00	5.56	
W12	0.17	0.022	0.030	0.478	1.98	15.19	25.56	40.74	9.26	0.00	9.26	
W13	0.17	0.015	0.028	0.478	1.98	12.96	21.85	34.81	14.07	1.11	15.19	

Table 4.28 Wave parameters and damage ratios for berm of Emerged Berm

Breakwater with Berm $\psi_s=0.59$											
d=45 cm (Berm)											
Waves	H_{m0}	S_p	S_{m-1.0}	C_r	N_s	M₁	M₂	M_T	D₁	D₂	D_T
	(m)	(-)	(-)	%	(-)	%	%	%	%	%	%
W1	0.05	0.044	0.046	0.264	0.58	0.00	0.00	0.00	0.00	0.00	0.00
W2	0.08	0.031	0.036	0.247	0.93	4.44	0.00	4.44	0.00	0.00	0.00
W3	0.11	0.042	0.048	0.248	1.28	5.93	0.00	5.93	0.00	0.00	0.00
W4	0.10	0.022	0.031	0.311	1.16	5.93	2.22	8.15	0.00	0.00	0.00
W4.1	0.11	0.028	0.036	0.292	1.28	12.59	2.22	14.81	0.00	0.00	0.00
W4.2	0.12	0.027	0.037	0.308	1.40	14.81	2.22	17.04	0.00	0.00	0.00
W5	0.14	0.049	0.050	0.283	1.63	28.15	2.96	31.11	0.00	0.00	0.00
W5.1	0.14	0.031	0.043	0.312	1.63	29.63	3.70	33.33	0.00	0.00	0.00
W6	0.15	0.038	0.048	0.297	1.74	31.85	3.70	35.56	0.00	0.00	0.00
W7	0.15	0.034	0.046	0.318	1.74	36.30	4.44	40.74	0.00	0.00	0.00
W8	0.15	0.034	0.043	0.338	1.74	38.52	3.70	42.22	0.74	0.00	0.74
W9	0.16	0.030	0.046	0.341	1.86	35.56	9.63	45.19	0.74	0.00	0.74
W10	0.15	0.015	0.038	0.407	1.74	35.56	11.85	47.41	1.48	0.00	1.48
W11	0.18	0.032	0.049	0.350	2.09	32.59	14.81	47.41	1.48	0.74	2.22
W12	0.17	0.022	0.030	0.478	1.98	26.67	20.00	46.67	1.48	1.48	2.96
W13	0.17	0.015	0.028	0.478	1.98	20.00	23.70	43.70	4.44	1.48	5.93

Table 4.29 Change of N_0 corresponding to wave parameters for lower slope of Emerged Berm

Breakwater With Berm $\psi_s=0.59$						
Lower Slope						
d=45 cm						
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	N_s	N_0
	(m)	(m)	(s)	(s)	(-)	(-)
W1	0.05	0.05	0.83	0.85	0.58	0
W2	0.08	0.08	1.19	1.29	0.93	0
W3	0.11	0.10	1.21	1.29	1.28	0
W4	0.10	0.10	1.44	1.69	1.16	0
W4.1	0.11	0.11	1.39	1.58	1.28	0
W4.2	0.12	0.11	1.44	1.69	1.40	0
W5	0.14	0.13	1.34	1.35	1.63	0.13
W5.1	0.14	0.13	1.45	1.69	1.63	0.13
W6	0.15	0.14	1.42	1.58	1.74	0.13
W7	0.15	0.15	1.45	1.69	1.74	0.22
W8	0.15	0.15	1.50	1.69	1.74	0.22
W9	0.16	0.16	1.50	1.85	1.86	0.35
W10	0.15	0.14	1.60	2.50	1.74	0.52
W11	0.18	0.18	1.53	1.90	2.09	0.65
W12	0.17	0.15	1.92	2.22	1.98	1.09
W13	0.17	0.16	1.98	2.67	1.98	1.78

Table 4.30 and Figure 4.26 show dimensionless recession number change for this experiment. From W1 to W7, there were no displacements in the berm of the model breakwater. At W8 ($H_{m0}=0.15$ and $N_s=1.74$), the first displacement was observed in the 1st row of the berm, close to lower slope. In other words, recession started at the 1st row of the berm. At W9, there was no additional displaced cube observed. However, recession reached to the 2nd of the berm with an additional displaced cube at W10 ($H_{m0}=0.15$ m). At W11, one more cube displaced from the berm, but recession was still constant at 2nd row (Table 4.26 and Table 4.28). Also, 5 cubes dislocated from berm to lower slope.

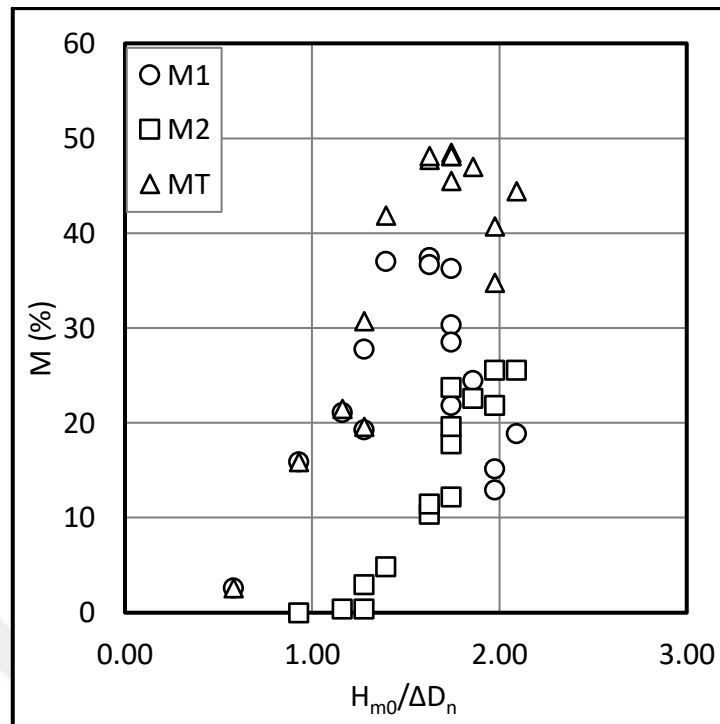


Figure 4.22 Percentage of moving units in reference area for Emerged Berm

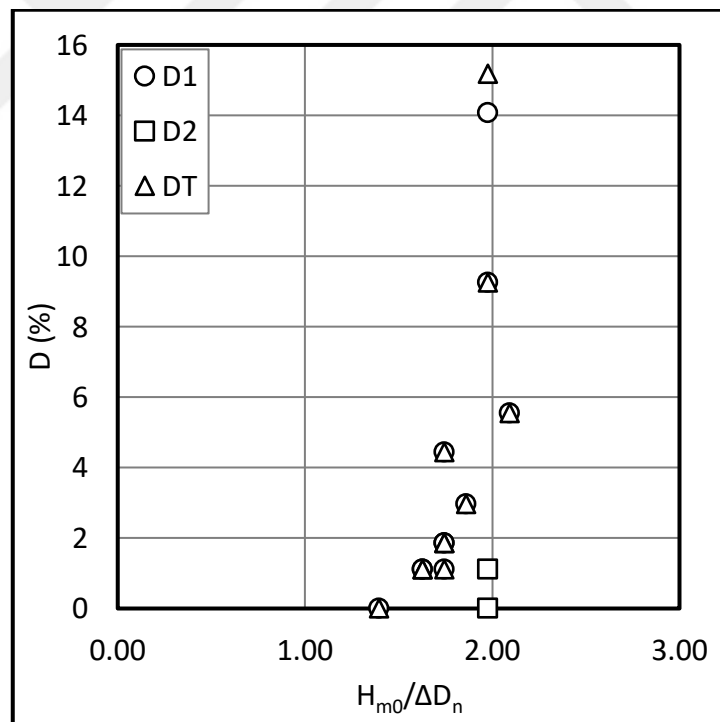


Figure 4.23 Percentage of moving units in reference area for Emerged Berm

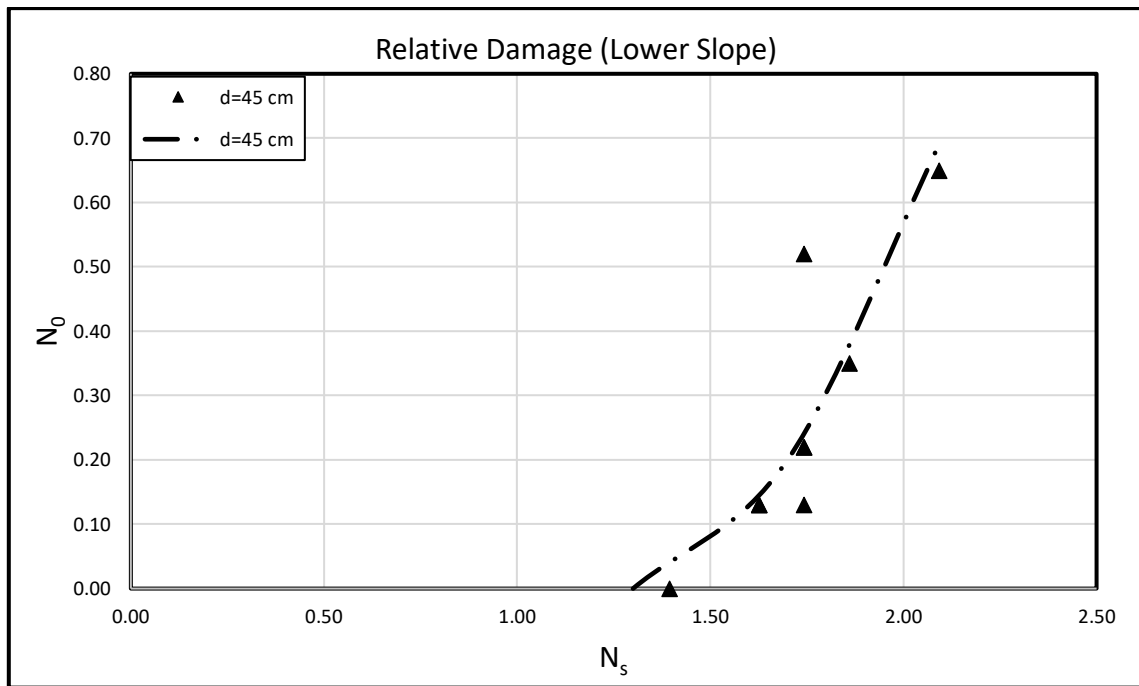


Figure 4.24 Relative damage in reference area for Emerged Berm

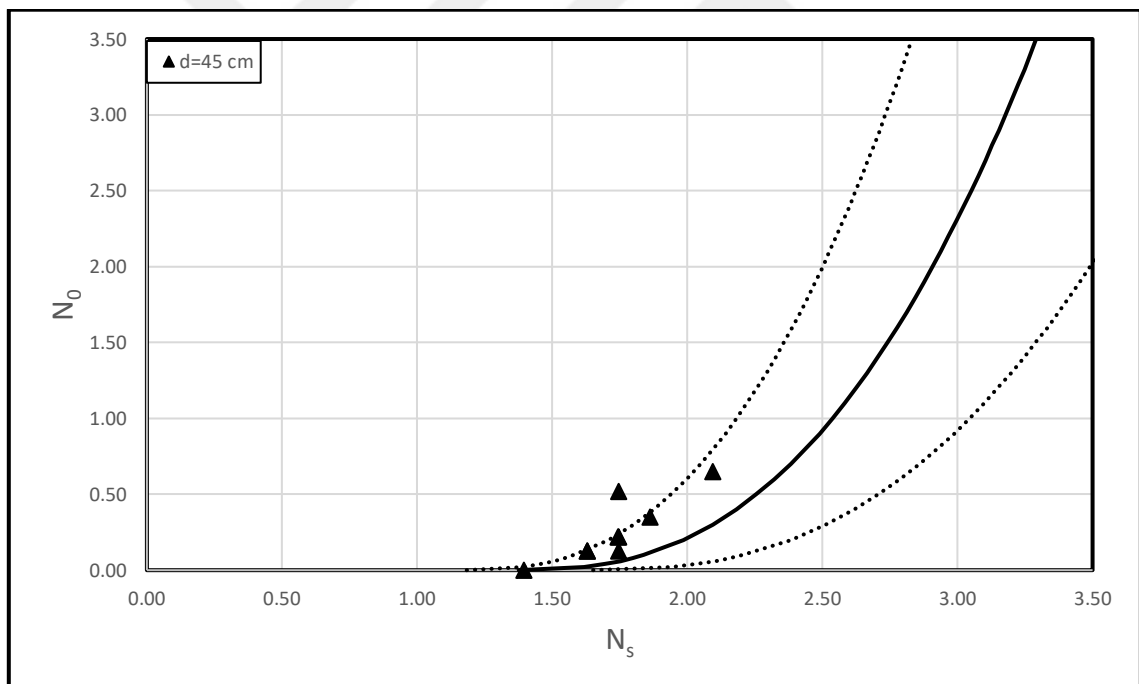


Figure 4.25 Comparison for experimental results of Emerged Berm with the formula by Van der Meer (1988) for conventional cube armored breakwaters

Table 4.30 Displacements and dimensionless recession numbers for Emerged Berm

Waves	Rec (d=45 cm)			
	H_{m0}	$H_s/\Delta D_n$	D_T (QTY)	Rec/D_n
	(m)	(-)	(-)	(-)
W1	0.05	0.58	0	0
W2	0.08	0.93	0	0
W3	0.11	1.28	0	0
W4	0.10	1.16	0	0
W4.1	0.11	1.28	0	0
W4.2	0.12	1.40	0	0
W5	0.14	1.63	0	0
W5.1	0.14	1.63	0	0
W6	0.15	1.74	0	0
W7	0.15	1.74	0	0
W8	0.15	1.74	1	1
W9	0.16	1.86	1	1
W10	0.15	1.74	2	2
W11	0.18	2.09	3	2
W12	0.17	1.98	4	2
W13	0.17	1.98	8	3

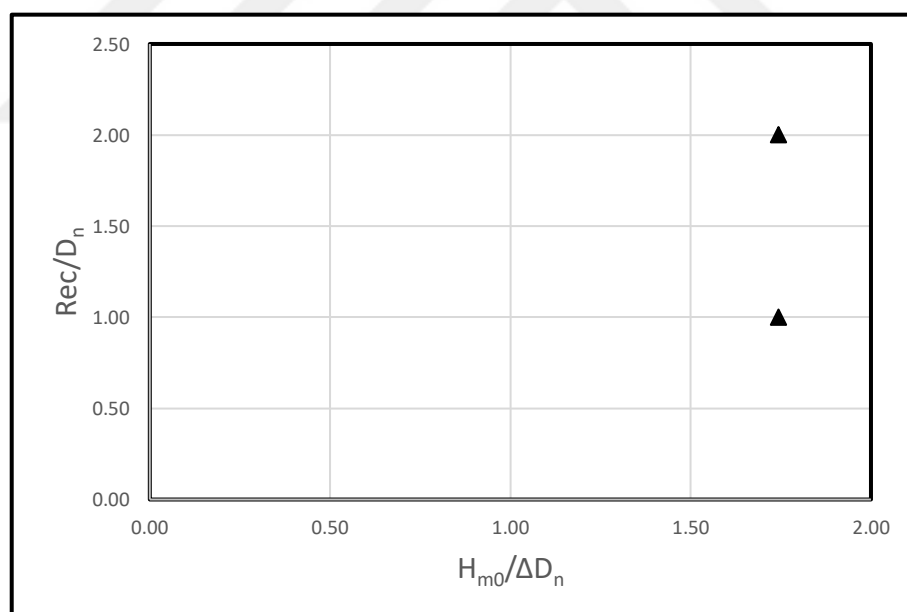


Figure 4.26 Stability number (N_s) and dimensionless recession (Rec) graphic for Emerged Berm

4.3.2 Experiment 2: Berm at SWL

There was no movement at W1 in the lower slope. The first movements were observed in the W2. After that, no additional movement occurred at W3. At W4 ($H_{m0}=0.10$ m and $N_s=1.16$), the total movement ratio became 8.15%, and both M_1 and M_2 type movements were observed (Table 4.32, Table 4.34, and Table 4.36). 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 (Figure 4.28 and Figure 4.29). From W6 to W10, total movement and displacement ratios increased gradually. At W10 ($H_{m0}=0.16$ m and $N_s=1.86$) total movement and displacement became 41.48% and 5.19%, respectively. In addition, 41.48% was the highest total movement ratio for this experiment. After this wave, the ratio decreased gradually. At W11 ($H_{m0}=0.19$ m and $N_s=2.21$) displacement ratio almost doubled and reached to 11.85%. After this wave series, total displacement ratio increased and reached to its maximum ratio 17.78%, at W13 ($H_{m0}=0.21$ m and $N_s=2.44$). Additionally, flume observations showed that lower slope stability affected by berm recession. Wave run-down forces were substantially influential on some displaced cubes in the first row of the berm. Some cubes in the lower slope were exposed additional external forces due to these displaced cubes (see Appendix B). However, high-density cubes kept normal density cubes as stable as possible and only one dislocated high-density cube was observed at the toe of the structure. Overtopping started at W12 (Table 4.31). Arrangements of bot ND and HD is given in Figure 4.27.

Figure 4.31 shows that the stability number versus relative damage curve conforms with the lower limit of Van der Meer (1988) formula. Relative damage increased gradually with Van der Meer Formula.

Table 4.31 Measured wave parameters at the toe of the breakwater for Berm at SWL

Breakwater with Berm $\psi_s=0.59$									
d=55 cm									
Waves	H_{m0}	H_{1/3}	T_{m-1.0}	T_p	S_{m-1.0}	S_p	C_r	N_s	Overtopping
	(m)	(m)	(s)	(s)	(-)	(-)	%	(-)	
W1	0.05	0.05	0.85	0.85	0.044	0.044	0.188	0.58	×
W2	0.08	0.07	1.19	1.30	0.036	0.030	0.145	0.93	×
W3	0.09	0.09	1.20	1.30	0.040	0.034	0.148	1.05	×
W4	0.10	0.09	1.50	1.74	0.028	0.021	0.158	1.16	×
W5	0.13	0.13	1.35	1.41	0.046	0.042	0.154	1.51	×
W6	0.15	0.15	1.43	1.60	0.047	0.038	0.150	1.74	×
W7	0.15	0.15	1.52	1.74	0.042	0.032	0.153	1.74	×
W8	0.16	0.15	1.60	1.74	0.040	0.034	0.164	1.86	×
W9	0.17	0.16	1.61	1.74	0.042	0.036	0.162	1.98	×
W10	0.16	0.16	1.65	2.11	0.038	0.023	0.195	1.86	×
W11	0.19	0.20	1.60	1.74	0.048	0.040	0.172	2.21	×
W12	0.20	0.19	1.89	2.37	0.036	0.023	0.258	2.33	✓
W13	0.21	0.21	1.91	2.37	0.037	0.024	0.255	2.44	✓

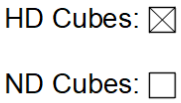


Figure 4.27 Positions of HD and ND cubes for the experiment Berm at SWL

Table 4.32 Damage ratios for lower slope of Berm at SWL

Breakwater with Berm $\psi_s=0.59$												
d=55 cm (Lower Slope)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M₁ (QTY)	M₁ (%)	M₂ (QTY)	M₂ (%)	M_T (QTY)	Movement Ratio (%)	D₁ (QTY)	D₁ (%)	D₂ (QTY)	D₂ (%)	D_T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	2	0.74	0	0.00	2	0.74	0	0.00	0	0.00	0	0.00
W3	2	0.74	0	0.00	2	0.74	0	0.00	0	0.00	0	0.00
W4	17	6.30	5	1.85	22	8.15	0	0.00	0	0.00	0	0.00
W5	54	20.00	6	2.22	60	22.22	1	0.37	0	0.00	1	0.37
W6	85	31.48	6	2.22	91	33.70	4	1.48	0	0.00	4	1.48
W7	85	31.48	6	2.22	91	33.70	5	1.85	0	0.00	5	1.85
W8	89	32.96	15	5.56	104	38.52	10	3.70	0	0.00	10	3.70
W9	91	33.70	14	5.19	105	38.89	12	4.44	0	0.00	12	4.44
W10	79	29.26	33	12.22	112	41.48	14	5.19	1	0.37	15	5.56
W11	72	26.67	26	9.63	98	36.30	26	9.63	6	2.22	32	11.85
W12	74	27.41	28	10.37	102	37.78	26	9.63	7	2.59	33	12.22
W13	32	11.85	55	20.37	87	32.22	35	12.96	13	4.81	48	17.78

Table 4.33 Damage ratios for berm of Berm at SWL

Breakwater with Berm $\psi_s=0.59$												
d=55 cm (Berm)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M₁ (QTY)	M₁ (%)	M₂ (QTY)	M₂ (%)	M_T (QTY)	Movement Ratio (%)	D₁ (QTY)	D₁ (%)	D₂ (QTY)	D₂ (%)	D_T (QTY)	Damage Ratio (%)
W1	6	4.44	1	0.74	7	5.19	0	0.00	0	0.00	0	0.00
W2	7	5.19	1	0.74	8	5.93	0	0.00	0	0.00	0	0.00
W3	12	8.89	1	0.74	13	9.63	0	0.00	0	0.00	0	0.00
W4	28	20.74	7	5.19	35	25.93	0	0.00	0	0.00	0	0.00
W5	43	31.85	7	5.19	50	37.04	1	0.74	0	0.00	1	0.74
W6	55	40.74	10	7.41	65	48.15	2	1.48	0	0.00	2	1.48
W7	54	40.00	10	7.41	64	47.41	3	2.22	0	0.00	3	2.22
W8	34	25.19	27	20.00	61	45.19	6	4.44	0	0.00	6	4.44
W9	29	21.48	32	23.70	61	45.19	6	4.44	0	0.00	6	4.44
W10	25	18.52	32	23.70	57	42.22	10	7.41	0	0.00	10	7.41
W11	21	15.56	32	23.70	53	39.26	9	6.67	5	3.70	14	10.37
W12	15	11.11	34	25.19	49	36.30	13	9.63	5	3.70	18	13.33
W13	4	2.96	33	24.44	37	27.41	20	14.81	10	7.41	30	22.22

Table 4.34 Wave parameters and damage ratios for lower slope of Berm at SWL

Breakwater with Berm $\psi_s=0.59$												
d=55 cm (Lower Slope)												
Waves	H _{m0} (m)	S _p (-)	S _{m-1.0} (-)	C _r %	N _s (-)	M ₁ %	M ₂ %	M _T %	D ₁ %	D ₂ %	D _T %	Observation
W1	0.05	0.044	0.044	0.188	0.58	0.00	0.00	0.00	0.00	0.00	0.00	
W2	0.08	0.030	0.036	0.145	0.93	0.74	0.00	0.74	0.00	0.00	0.00	
W3	0.09	0.034	0.040	0.148	1.05	0.74	0.00	0.74	0.00	0.00	0.00	
W4	0.10	0.021	0.028	0.158	1.16	6.30	1.85	8.15	0.00	0.00	0.00	
W5	0.13	0.042	0.046	0.154	1.51	20.00	2.22	22.22	0.37	0.00	0.37	
W6	0.15	0.038	0.047	0.150	1.74	31.48	2.22	33.70	1.48	0.00	1.48	
W7	0.15	0.032	0.042	0.153	1.74	31.48	2.22	33.70	1.85	0.00	1.85	
W8	0.16	0.034	0.040	0.164	1.86	32.96	5.56	38.52	3.70	0.00	3.70	
W9	0.17	0.036	0.042	0.162	1.98	33.70	5.19	38.89	4.44	0.00	4.44	
W10	0.16	0.023	0.038	0.195	1.86	29.26	12.22	41.48	5.19	0.37	5.56	
W11	0.19	0.040	0.048	0.172	2.21	26.67	9.63	36.30	9.63	2.22	11.85	
W12	0.20	0.023	0.036	0.258	2.33	27.41	10.37	37.78	9.63	2.59	12.22	
W13	0.21	0.024	0.037	0.255	2.44	11.85	20.37	32.22	12.96	4.81	17.78	

Table 4.35 Wave parameters and damage ratios for berm of Berm at SWL

Breakwater with Berm $\psi_s=0.59$											
d=55 cm (Berm)											
Waves	H_{m0}	S_p	S_{m-1.0}	C_r	N_s	M₁	M₂	M_T	D₁	D₂	D_T
	(m)	(-)	(-)	%	(-)	%	%	%	%	%	%
W1	0.05	0.044	0.044	0.188	0.58	4.44	0.74	5.19	0.00	0.00	0.00
W2	0.08	0.030	0.036	0.145	0.93	5.19	0.74	5.93	0.00	0.00	0.00
W3	0.09	0.034	0.040	0.148	1.05	8.89	0.74	9.63	0.00	0.00	0.00
W4	0.10	0.021	0.028	0.158	1.16	20.74	5.19	25.93	0.00	0.00	0.00
W5	0.13	0.042	0.046	0.154	1.51	31.85	5.19	37.04	0.74	0.00	0.74
W6	0.15	0.038	0.047	0.150	1.74	40.74	7.41	48.15	1.48	0.00	1.48
W7	0.15	0.032	0.042	0.153	1.74	40.00	7.41	47.41	2.22	0.00	2.22
W8	0.16	0.034	0.040	0.164	1.86	25.19	20.00	45.19	4.44	0.00	4.44
W9	0.17	0.036	0.042	0.162	1.98	21.48	23.70	45.19	4.44	0.00	4.44
W10	0.16	0.023	0.038	0.195	1.86	18.52	23.70	42.22	7.41	0.00	7.41
W11	0.19	0.040	0.048	0.172	2.21	15.56	23.70	39.26	6.67	3.70	10.37
W12	0.20	0.023	0.036	0.258	2.33	11.11	25.19	36.30	9.63	3.70	13.33
W13	0.21	0.024	0.037	0.255	2.44	2.96	24.44	27.41	14.81	7.41	22.22

Table 4.36 Change of N_0 corresponding to wave parameters for lower slope of Berm at SWL

Breakwater With Berm $\psi_s=0.59$						
Lower Slope						
d=55 cm						
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	N_s	N_0
	(m)	(m)	(s)	(s)	(-)	(-)
W1	0.05	0.05	0.85	0.85	0.58	0
W2	0.08	0.07	1.19	1.30	0.93	0
W3	0.09	0.09	1.20	1.30	1.05	0
W4	0.10	0.09	1.50	1.74	1.16	0
W5	0.13	0.13	1.35	1.41	1.51	0.04
W6	0.15	0.15	1.43	1.60	1.74	0.17
W7	0.15	0.15	1.52	1.74	1.74	0.22
W8	0.16	0.15	1.60	1.74	1.86	0.43
W9	0.17	0.16	1.61	1.74	1.98	0.52
W10	0.16	0.16	1.65	2.11	1.86	0.65
W11	0.19	0.20	1.60	1.74	2.21	1.39
W12	0.20	0.19	1.89	2.37	2.33	1.43
W13	0.21	0.21	1.91	2.37	2.44	2.09

Table 4.37 and Figure 4.32 show dimensionless recession number for this experiment. From W1 to W4, there was no displacement in the berm. At W5 ($H_{m0}=0.13$ m and $N_s=1.51$), first displacement occurred at 2nd row and movements were observed for other cubes close to the water side. From W6 to W9, displacements occurred in both 1st row and 2nd row of the berm, but recession was still in the 2nd row. At W10 ($H_{m0}=0.16$ m and $N_s=1.86$), recession started at 3rd row of the berm at the second layer (Table 4.33 and Table 4.35). At W11 ($H_{m0}=0.19$ m and $N_s=2.21$), new displacements were observed but these displaced cubes were in 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 5th row at the second layer, total number of displaced cubes reached to 18. At the last wave series W13 ($H_{m0}=0.21$ m and $N_s=2.44$), 12 more cubes displaced, and total displacement reached to 30. Since the berm level was at SWL, it was strongly affected by wave forces. See Appendix B for damage process of the berm and its effect in the lower slope. Also, 12 cubes dislocated from berm to lower slope.

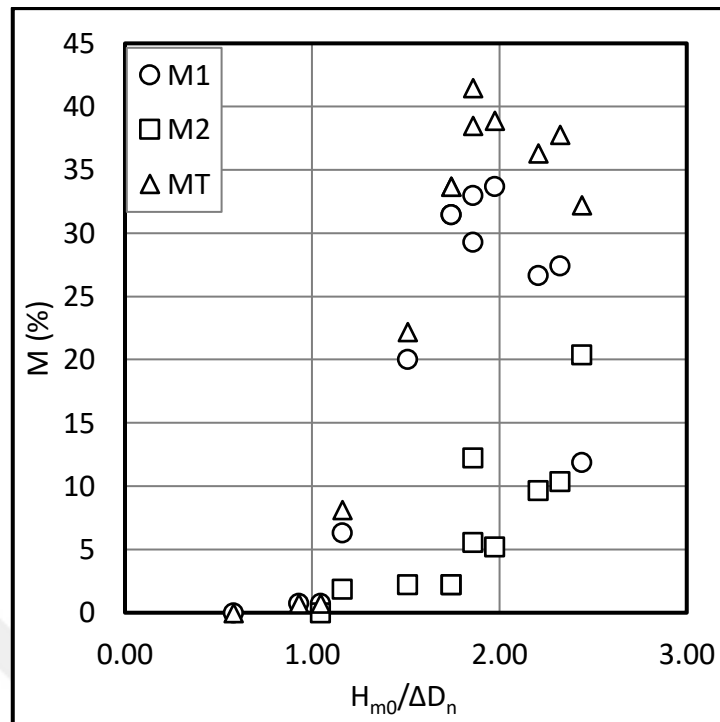


Figure 4.28 Percentage of moving units in reference area for Berm at SWL

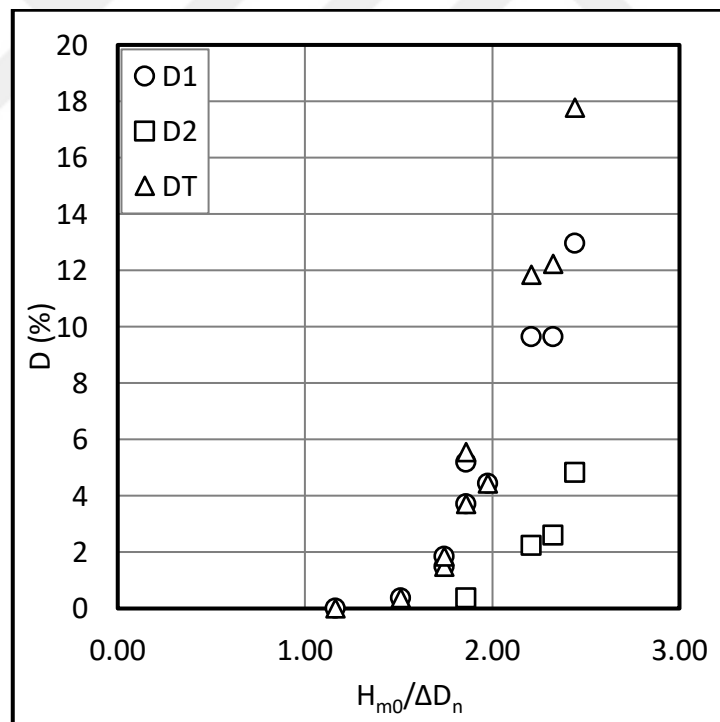


Figure 4.29 Percentage of moving units in reference area for Berm at SWL

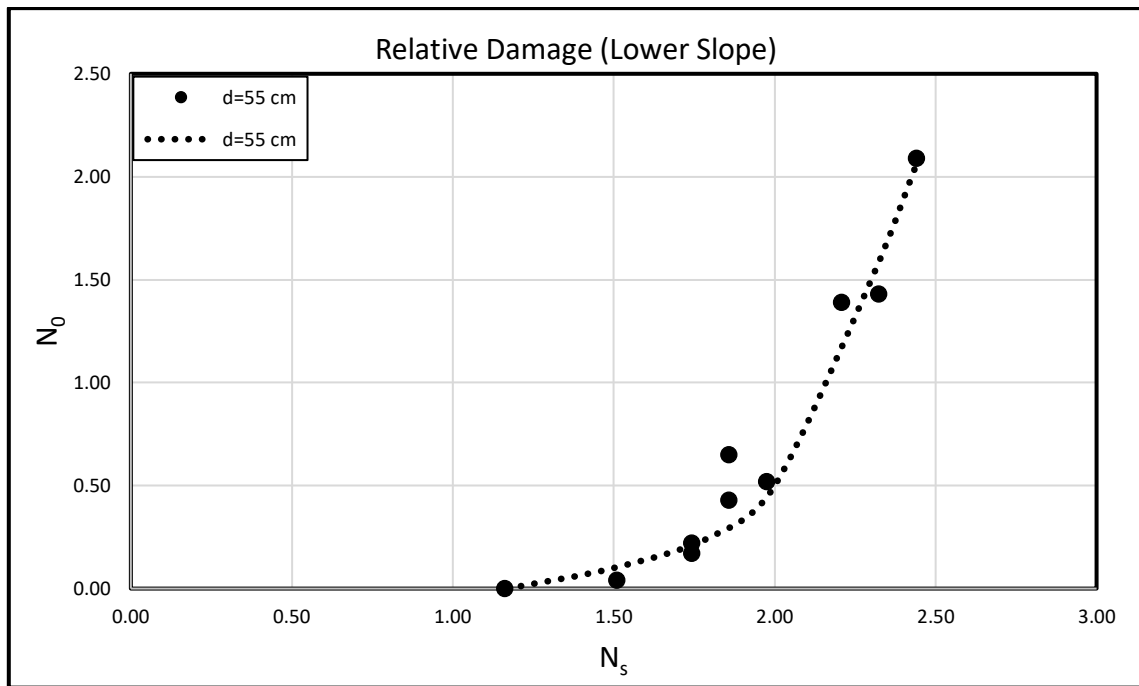


Figure 4.30 Relative damage in reference area for Emerged Berm

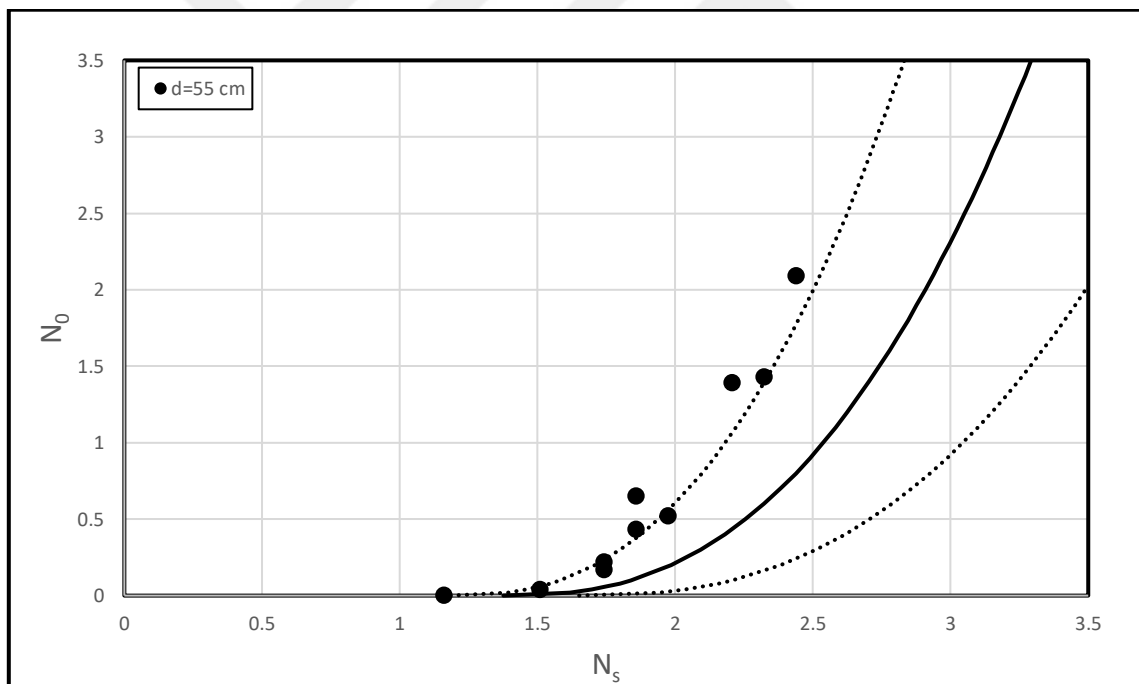


Figure 4.31 Comparison for experimental results of Berm at SWL with the formula by Van der Meer (1988) for conventional cube armored breakwaters

Table 4.37 Displacements and dimensionless recession numbers for Berm at SWL.

Waves	Rec (d=55 cm)			
	H_{m0}	$H_s/\Delta D_n$	D_T (QTY)	Rec/D_n
	(m)	(-)	(-)	(-)
W1	0.05	0.58	0	0
W2	0.08	0.93	0	0
W3	0.09	1.05	0	0
W4	0.10	1.16	0	0
W5	0.13	1.51	1	2
W6	0.15	1.74	2	2
W7	0.15	1.74	3	2
W8	0.16	1.86	6	2
W9	0.17	1.98	6	2
W10	0.16	1.86	10	3
W11	0.19	2.21	14	3
W12	0.20	2.33	18	5
W13	0.21	2.44	30	5

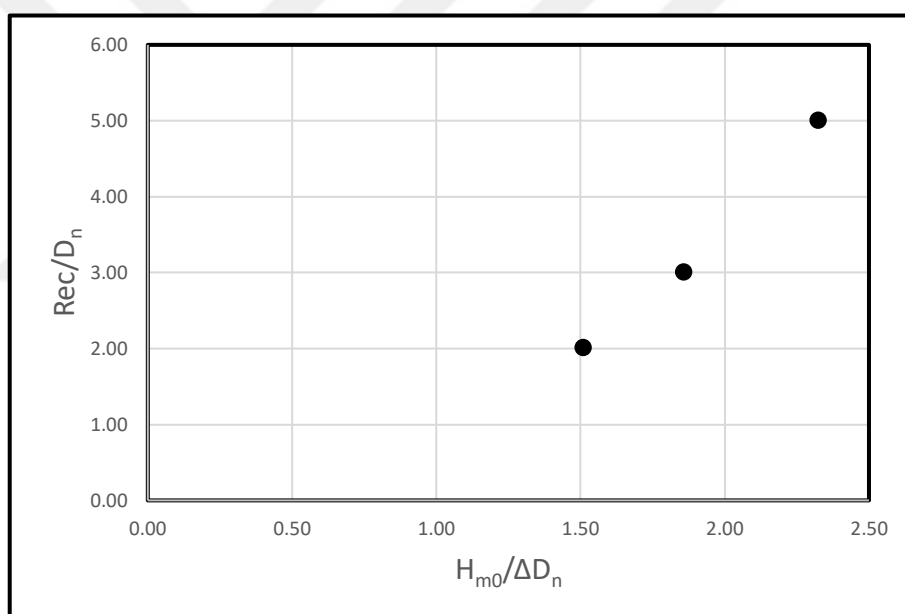


Figure 4.32 Stability number (N_s) and dimensionless recession (Rec) graphic for Berm at SWL.

4.3.3 Experiment 3: Submerged Berm

Water depth for this experiment is 65 cm. Cube arrangements of HD and ND cubes is given in Figure 4.33. Table 4.39, Table 4.41, and Table 4.43 show that there was no movement at the first two wave series of W1 and W2. Movements started at W3 ($H_{m0}=0.09$ m) with 3.33%. From W4 to W7, displacement was not observed but, total movement ratio reached to 36.67%. Flume observations showed that wave forces acting on lower slope was relatively low at wave series from W1 to W7. However, at W8 ($H_{m0}=0.16$ m and $N_s=1.86$), wave forces were slightly greater than the previous wave series. The first displacement occurred in this wave series (also see Figure 4.34 and Figure 4.35). Displacement ratio increased to 0.74% at W9. Starting from W1, rocking (M_1) was observed densely in the lower slope. It reached to its maximum ratio at W11 with 38.89%. Also, total movement ratio M_T reached its maximum ratio at W12 with 45.56%. 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 increase was gradual. At W13, total displacement at lower slope was 4.81%. It can be concluded and also seen in Appendix B, wave forces acting in the lower slope is relatively low. Therefore, movements were dominant in the lower slope. Most of the wave forces were found more effective on the upper slope of the model breakwater. However, run-down forces were effective in the lower slope significantly for the high energetic waves. Table 4.38 show that overtopping started at W6.

Figure 4.37 shows that the stability number-relative damage curve agreed with the upper limit of Van der Meer (1988) formula. It showed that lower slope was found more stable for submerged berm case.

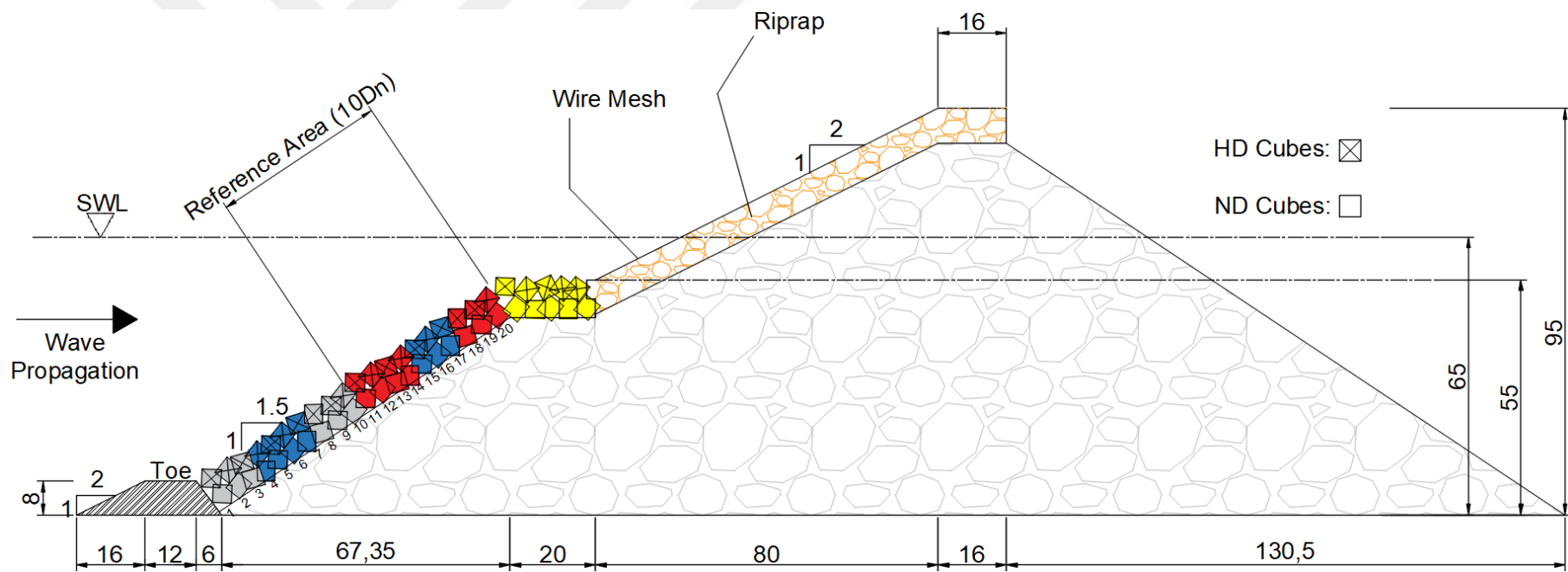


Figure 4.33 Positions of HD and ND cubes for the experiment Submerged Berm

Table 4.38 Measured wave parameters at the toe of the breakwater for Submerged Berm

Breakwater with Berm $\psi_s=0.59$									
d=65 cm									
Waves	H_{m0} (m)	H_{1/3} (m)	T_{m-1.0} (s)	T_p (s)	S_{m-1.0} (-)	S_p (-)	C_r %	N_s (-)	Overtopping
W1	0.05	0.05	0.85	0.85	0.044	0.044	0.251	0.58	✗
W2	0.07	0.07	1.17	1.26	0.033	0.028	0.239	0.81	✗
W3	0.09	0.08	1.17	1.26	0.042	0.036	0.233	1.05	✗
W4	0.08	0.08	1.53	1.74	0.022	0.017	0.239	0.93	✗
W5	0.11	0.11	1.33	1.50	0.040	0.031	0.216	1.28	✗
W6	0.13	0.12	1.44	1.62	0.040	0.032	0.205	1.51	✓
W7	0.14	0.14	1.54	1.74	0.038	0.030	0.204	1.63	✓
W8	0.16	0.15	1.63	1.74	0.038	0.034	0.200	1.86	✓
W9	0.17	0.17	1.65	1.74	0.040	0.036	0.190	1.98	✓
W10	0.19	0.18	1.80	2.11	0.037	0.027	0.186	2.21	✓
W11	0.22	0.21	1.68	1.74	0.050	0.047	0.163	2.56	✓
W12	0.24	0.21	1.98	2.37	0.039	0.027	0.188	2.79	✓
W13	0.25	0.23	2.04	2.41	0.038	0.028	0.180	2.91	✓

Table 4.39 Damage ratios for lower slope of Submerged Berm

Breakwater with Berm $\psi_s=0.59$												
d=65 cm (Lower Slope)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M ₁ (QTY)	M ₁ (%)	M ₂ (QTY)	M ₂ (%)	M _T (QTY)	Movement Ratio (%)	D ₁ (QTY)	D ₁ (%)	D ₂ (QTY)	D ₂ (%)	D _T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W3	9	3.33	0	0.00	9	3.33	0	0.00	0	0.00	0	0.00
W4	40	14.81	0	0.00	40	14.81	0	0.00	0	0.00	0	0.00
W5	53	19.63	9	3.33	62	22.96	0	0.00	0	0.00	0	0.00
W6	82	30.37	9	3.33	91	33.70	0	0.00	0	0.00	0	0.00
W7	87	32.22	12	4.44	99	36.67	0	0.00	0	0.00	0	0.00
W8	94	34.81	12	4.44	106	39.26	1	0.37	0	0.00	1	0.37
W9	94	34.81	17	6.30	111	41.11	2	0.74	0	0.00	2	0.74
W10	99	36.67	15	5.56	114	42.22	6	2.22	0	0.00	6	2.22
W11	105	38.89	13	4.81	118	43.70	9	3.33	0	0.00	9	3.33
W12	97	35.93	26	9.63	123	45.56	9	3.33	2	0.74	11	4.07
W13	91	33.70	31	11.48	122	45.19	11	4.07	2	0.74	13	4.81

Table 4.40 Damage ratios for berm of Submerged Berm

Breakwater with Berm $\psi_s=0.59$												
d=65 cm (Berm)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M₁ (QTY)	M₁ (%)	M₂ (QTY)	M₂ (%)	M_T (QTY)	Movement Ratio (%)	D₁ (QTY)	D₁ (%)	D₂ (QTY)	D₂ (%)	D_T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	1	0.74	0	0.00	1	0.74	0	0.00	0	0.00	0	0.00
W3	5	3.70	0	0.00	5	3.70	0	0.00	0	0.00	0	0.00
W4	26	19.26	0	0.00	26	19.26	0	0.00	0	0.00	0	0.00
W5	54	40.00	1	0.74	55	40.74	0	0.00	0	0.00	0	0.00
W6	65	48.15	2	1.48	67	49.63	0	0.00	0	0.00	0	0.00
W7	54	40.00	12	8.89	66	48.89	1	0.74	0	0.00	1	0.74
W8	42	31.11	23	17.04	65	48.15	2	1.48	0	0.00	2	1.48
W9	32	23.70	31	22.96	63	46.67	4	2.96	0	0.00	4	2.96
W10	27	20.00	33	24.44	60	44.44	7	5.19	0	0.00	7	5.19
W11	17	12.59	33	24.44	50	37.04	16	11.85	1	0.74	17	12.59
W12	16	11.85	24	17.78	40	29.63	24	17.78	3	2.22	27	20.00
W13	15	11.11	22	16.30	37	27.41	26	19.26	4	2.96	30	22.22

Table 4.41 Wave parameters and damage ratios for lower slope of Submerged Berm

Breakwater with Berm $\psi_s=0.59$												
d=65 cm (Lower Slope)												
Waves	H _{m0} (m)	S _p (-)	S _{m-1.0} (-)	C _r %	N _s (-)	M ₁ %	M ₂ %	M _T %	D ₁ %	D ₂ %	D _T %	Observation
W1	0.05	0.044	0.044	0.251	0.58	0.00	0.00	0.00	0.00	0.00	0.00	
W2	0.07	0.028	0.033	0.239	0.81	0.00	0.00	0.00	0.00	0.00	0.00	
W3	0.09	0.036	0.042	0.233	1.05	3.33	0.00	3.33	0.00	0.00	0.00	
W4	0.08	0.017	0.022	0.239	0.93	14.81	0.00	14.81	0.00	0.00	0.00	
W5	0.11	0.031	0.040	0.216	1.28	19.63	3.33	22.96	0.00	0.00	0.00	
W6	0.13	0.032	0.040	0.205	1.51	30.37	3.33	33.70	0.00	0.00	0.00	
W7	0.14	0.030	0.038	0.204	1.63	32.22	4.44	36.67	0.00	0.00	0.00	
W8	0.16	0.034	0.038	0.200	1.86	34.81	4.44	39.26	0.37	0.00	0.37	
W9	0.17	0.036	0.040	0.190	1.98	34.81	6.30	41.11	0.74	0.00	0.74	
W10	0.19	0.027	0.037	0.186	2.21	36.67	5.56	42.22	2.22	0.00	2.22	
W11	0.22	0.047	0.050	0.163	2.56	38.89	4.81	43.70	3.33	0.00	3.33	
W12	0.24	0.027	0.039	0.188	2.79	35.93	9.63	45.56	3.33	0.74	4.07	
W13	0.25	0.028	0.038	0.180	2.91	33.70	11.48	45.19	4.07	0.74	4.81	

Table 4.42 Wave parameters and damage ratios for berm of Submerged Berm

Breakwater with Berm $\psi_s=0.59$											
d=65 cm (Berm)											
Waves	H_{m0}	S_p	S_{m-1.0}	C_r	N_s	M₁	M₂	M_T	D₁	D₂	D_T
	(m)	(-)	(-)	%	(-)	%	%	%	%	%	%
W1	0.05	0.044	0.044	0.251	0.58	0.00	0.00	0.00	0.00	0.00	0.00
W2	0.07	0.028	0.033	0.239	0.81	0.74	0.00	0.74	0.00	0.00	0.00
W3	0.09	0.036	0.042	0.233	1.05	3.70	0.00	3.70	0.00	0.00	0.00
W4	0.08	0.017	0.022	0.239	0.93	19.26	0.00	19.26	0.00	0.00	0.00
W5	0.11	0.031	0.040	0.216	1.28	40.00	0.74	40.74	0.00	0.00	0.00
W6	0.13	0.032	0.040	0.205	1.51	48.15	1.48	49.63	0.00	0.00	0.00
W7	0.14	0.030	0.038	0.204	1.63	40.00	8.89	48.89	0.74	0.00	0.74
W8	0.16	0.034	0.038	0.200	1.86	31.11	17.04	48.15	1.48	0.00	1.48
W9	0.17	0.036	0.040	0.190	1.98	23.70	22.96	46.67	2.96	0.00	2.96
W10	0.19	0.027	0.037	0.186	2.21	20.00	24.44	44.44	5.19	0.00	5.19
W11	0.22	0.047	0.050	0.163	2.56	12.59	24.44	37.04	11.85	0.74	12.59
W12	0.24	0.027	0.039	0.188	2.79	11.85	17.78	29.63	17.78	2.22	20.00
W13	0.25	0.028	0.038	0.180	2.91	11.11	16.30	27.41	19.26	2.96	22.22

Table 4.43 Change of N_0 corresponding to wave parameters for lower slope of Submerged Berm

Breakwater With Berm $\psi_s=0.59$						
Lower Slope						
d=65 cm						
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	N_s	N_0
	(m)	(m)	(s)	(s)	(-)	(-)
W1	0.05	0.05	0.85	0.85	0.58	0
W2	0.07	0.07	1.17	1.26	0.81	0
W3	0.09	0.08	1.17	1.26	1.05	0
W4	0.08	0.08	1.53	1.74	0.93	0
W5	0.11	0.11	1.33	1.50	1.28	0
W6	0.13	0.12	1.44	1.62	1.51	0
W7	0.14	0.14	1.54	1.74	1.63	0
W8	0.16	0.15	1.63	1.74	1.86	0.04
W9	0.17	0.17	1.65	1.74	1.98	0.09
W10	0.19	0.18	1.80	2.11	2.21	0.26
W11	0.22	0.21	1.68	1.74	2.56	0.39
W12	0.24	0.21	1.98	2.37	2.79	0.48
W13	0.25	0.23	2.04	2.41	2.91	0.57

Table 4.44 and Figure 4.38 show recession number for this experiment. From W1 to W6, there was no displacement in the berm but, movements were observable at the berm for both M_1 and M_2 . At W7 ($H_{m0}=0.14$ m and $N_s=1.63$) recession started at 2nd row of the berm with one cube. At W8 and W9 additional displacements were observed but these displaced cubes were in the 1st and 2nd row of the berm. Thus, recession was still in the 2nd row. Also, at W8 and W9, 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 in the berm, and recession reached to 3rd row. W11 ($H_{m0}=0.22$ m and $N_s=2.56$) was the first wave series that recession reached to 5th row of the berm. Also, displacements occurred in 4th row as well. Run-down forces were effective on the berm. At wave series W12 and W13, additional displacements were observed in the berm of the breakwater. At W13 ($H_{m0}=0.25$ m and $N_s=2.91$), total number of displaced cubes were 30 which corresponds to 22.22% of the cubes in the berm (Table 4.40 and Table 4.42). All displaced cubes were observed from the second layer of the berm, and the berm kept its shape stable through experiment. 8 cubes dislocated from berm to lower slope.

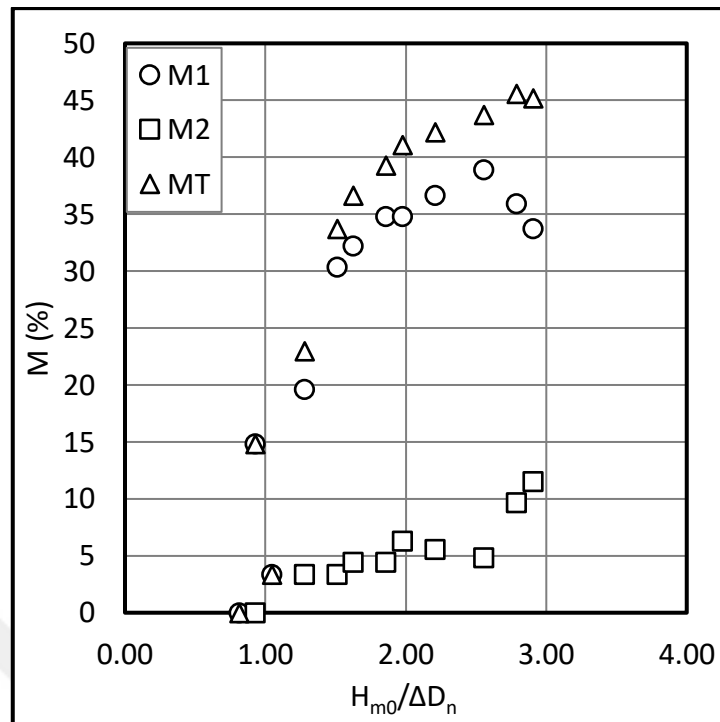


Figure 4.34 Percentage of moving units in reference area for Submerged Berm

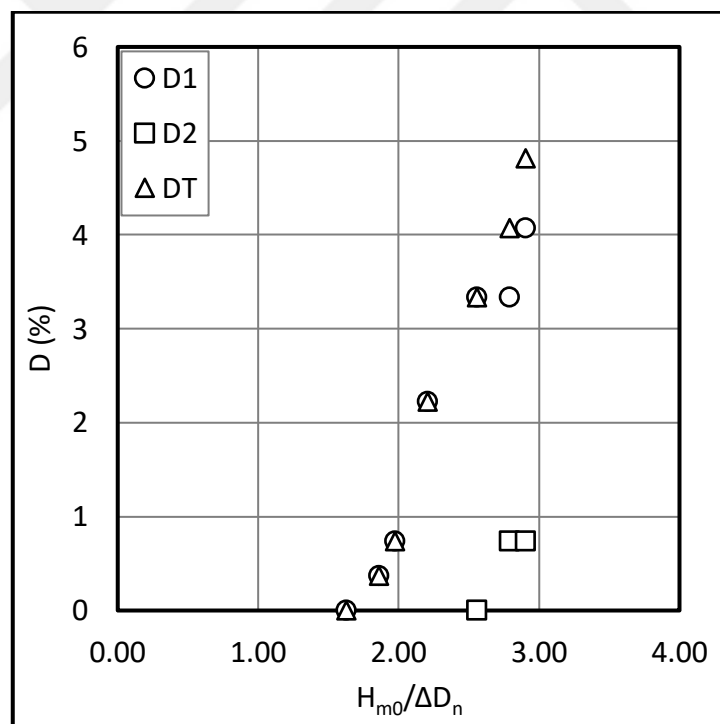


Figure 4.35 Percentage of moving units in reference area for Submerged Berm

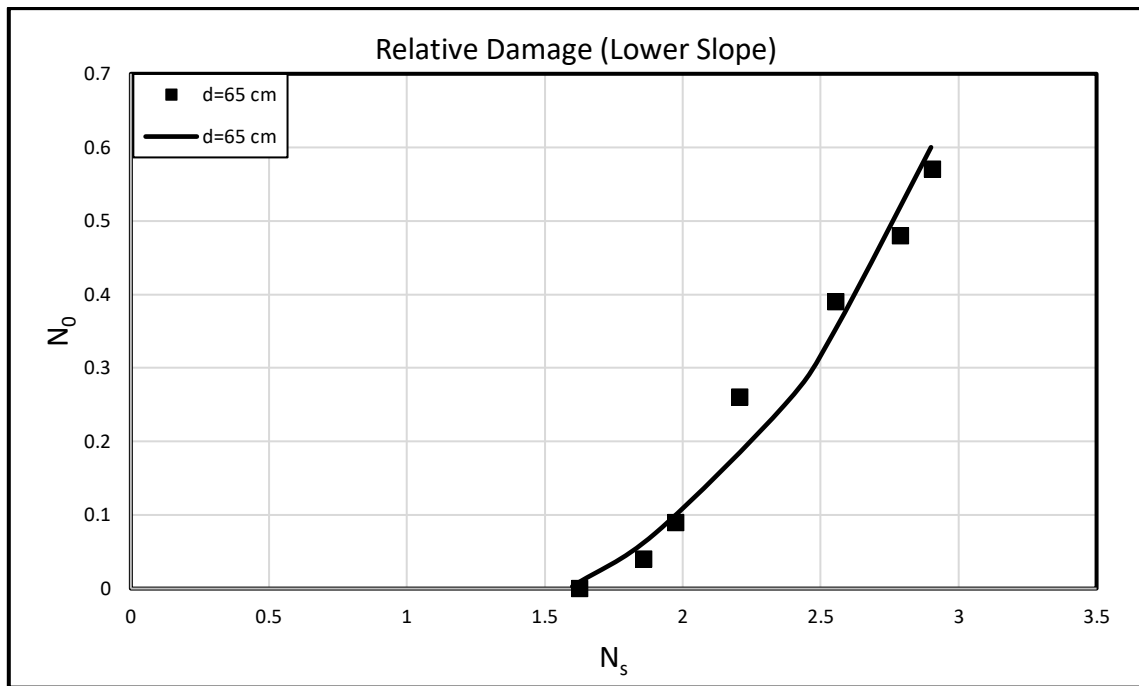


Figure 4.36 Relative damage in reference area for Submerged Berm

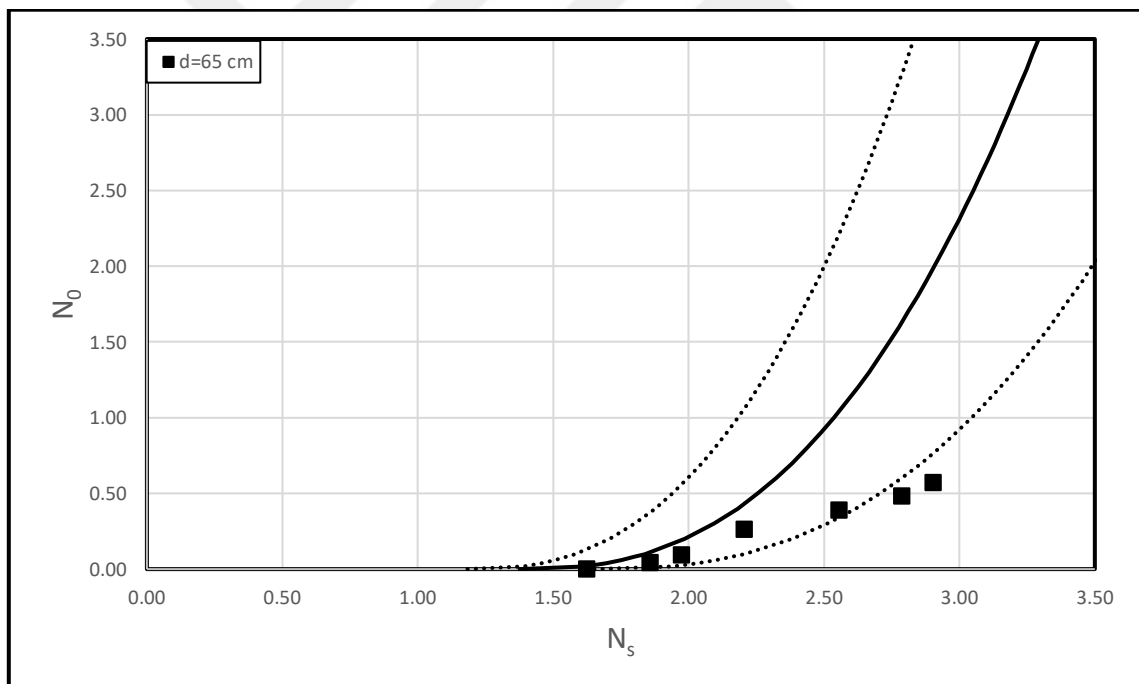


Figure 4.37 Comparison for experimental results of Submerged Berm with the formula by Van der Meer (1988) for conventional cube armored breakwaters

Table 4.44 Displacements and dimensionless recession numbers for Submerged Berm

Waves	Rec (d=65 cm)			
	H_{m0}	$H_s/\Delta D_n$	D_T (QTY)	Rec/D_n
	(m)	(-)	(-)	(-)
W1	0.05	0.58	0	0
W2	0.07	0.81	0	0
W3	0.09	1.05	0	0
W4	0.08	0.93	0	0
W5	0.11	1.28	0	0
W6	0.13	1.51	0	0
W7	0.14	1.63	1	2
W8	0.16	1.86	2	2
W9	0.17	1.98	4	2
W10	0.19	2.21	7	3
W11	0.22	2.56	17	5
W12	0.24	2.79	27	5
W13	0.25	2.91	30	5

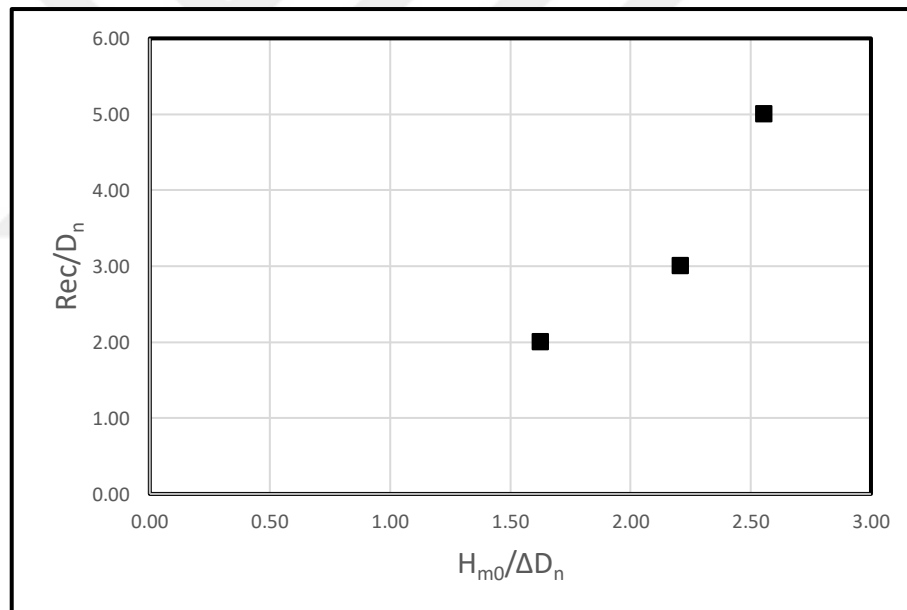


Figure 4.38 Stability number (N_s) and dimensionless recession (Rec) graphic for Submerged Berm

4.3.4 Experiment 4: Emerged Berm with HD Cubes over Reference Area

Arrangements of HD and ND cubes is given in Figure 4.39. Table 4.46, Table 4.48, and Table 4.50 show that there was no movement at first wave series, W1. Rocking started at W2 ($H_{m0}=0.08$ m) and it was 4.81%, and then increased to its maximum point 35.19% at W3. Note that, only rocking (M_1) occurred in these wave series. At W4 ($H_{m0}=0.10$ m and $N_s=1.16$), rocking ratio decreased, but M_2 movement started to initiate, and it reached 16.67%. After W4, total movement ratio was 50.00%, which is half of the considered cubes in the reference area. At wave series W4.1 and W4.2, M_1 ratio (rocking ratio) decreased and M_2 ratio increased but, total movement ratio M_T was constant at 50.00% (maximum M_T). At W5 ($H_{m0}=0.13$ m and $N_s=1.51$), M_T suddenly decreased to 5.93% and first displacement occurred in this wave series with 37.41% (Figure 4.39, Figure 4.40, and Figure 4.41). “Sliding” behavior was observed in the lower slope of the model breakwater. CEM (2006) also mentioned about this behavior. This behavior changed packing density of the breakwater. Packing density decreased at the top of the reference area while the packing density increased significantly at the lower parts of the reference area. At W5.1, displacement ratio reached to 44.44%. After this wave series, neither displacement nor movement were observed remarkably in the lower slope of the breakwater from wave series W6 to W13. In addition, early movements and “Sliding” behavior in the lower slope, significantly affected recession on the breakwater berm. The lower slope armor layer showed significant damage, but core layer was never visible through the armor layer. It can be seen from Table 4.45, overtopping was not observed through the experiment.

Figure 4.42 shows that the stability number versus relative damage did not agree with Van der Meer (1988) formula and it was found less stable due to the sliding damage.

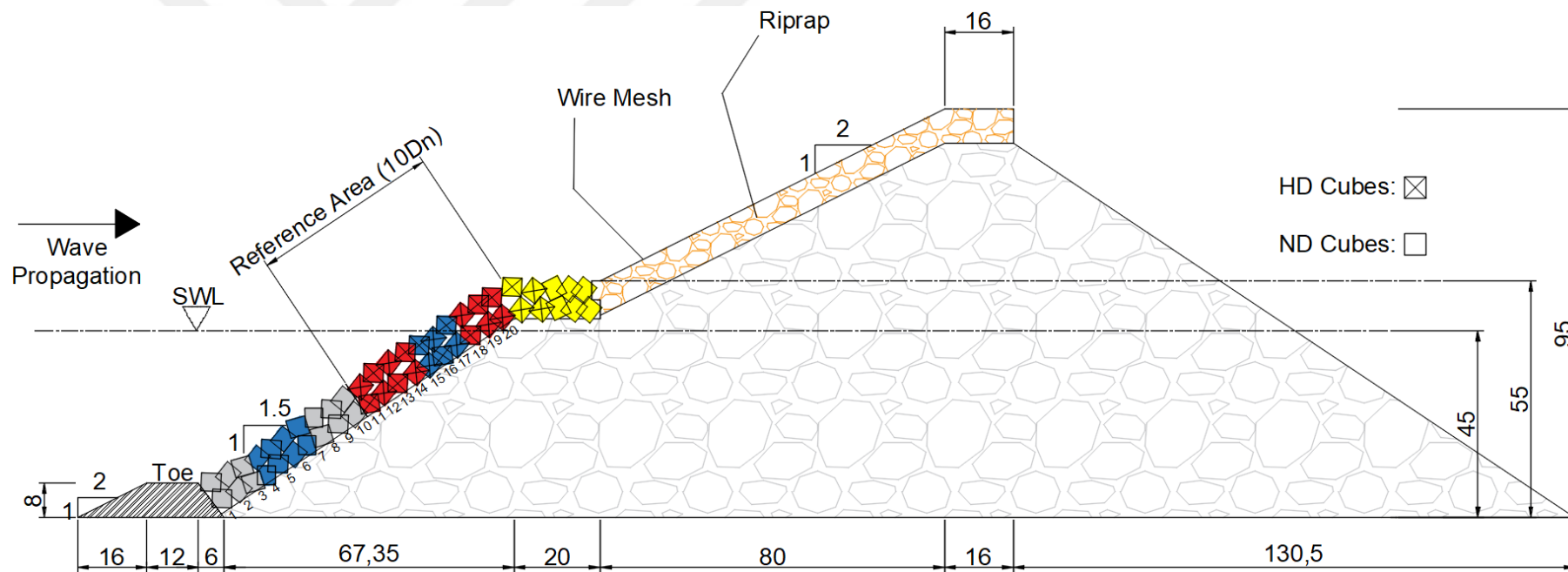


Figure 4.39 Positions of HD and ND cubes for the experiment Emerged Berm with HD Cubes over Reference Area

Table 4.45 Measured wave parameters at the toe of the breakwater for Emerged Berm with HD Cubes over Reference Area

Breakwater with Berm $\psi_s=0.59$									
d=45 cm									
Waves	H_{m0} (m)	H_{1/3} (m)	T_{m-1.0} (s)	T_p (s)	S_{m-1.0} (-)	S_p (-)	C_r %	N_s (-)	Overtopping
W1	0.05	0.05	0.82	0.85	0.048	0.044	0.263	0.58	×
W2	0.08	0.08	1.20	1.29	0.036	0.031	0.247	0.93	×
W3	0.10	0.10	1.21	1.29	0.044	0.038	0.250	1.16	×
W4	0.10	0.10	1.44	1.69	0.031	0.022	0.311	1.16	×
W4.1	0.11	0.11	1.40	1.58	0.036	0.028	0.297	1.28	×
W4.2	0.12	0.11	1.45	1.69	0.037	0.027	0.309	1.40	×
W5	0.13	0.13	1.34	1.35	0.046	0.046	0.274	1.51	×
W5.1	0.13	0.13	1.47	1.69	0.039	0.029	0.290	1.51	×
W6	0.15	0.14	1.44	1.62	0.046	0.037	0.264	1.74	×
W7	0.15	0.14	1.47	1.69	0.044	0.034	0.288	1.74	×
W8	0.15	0.14	1.52	1.69	0.042	0.034	0.306	1.74	×
W9	0.17	0.16	1.53	1.85	0.046	0.032	0.313	1.98	×
W10	0.16	0.14	1.61	2.50	0.040	0.016	0.379	1.86	×
W11	0.18	0.17	1.54	1.90	0.049	0.032	0.323	2.09	×
W12	0.17	0.15	1.92	2.23	0.030	0.022	0.443	1.98	×
W13	0.17	0.16	1.96	2.66	0.028	0.015	0.444	1.98	×

Table 4.46 Damage ratios for lower slope of Emerged Berm with HD Cubes over Reference Area

Breakwater with Berm $\psi_s=0.59$												
d=45 cm (Lower Slope)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M₁ (QTY)	M₁ (%)	M₂ (QTY)	M₂ (%)	M_T (QTY)	Movement Ratio (%)	D₁ (QTY)	D₁ (%)	D₂ (QTY)	D₂ (%)	D_T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	13	4.81	0	0.00	13	4.81	0	0.00	0	0.00	0	0.00
W3	95	35.19	0	0.00	95	35.19	0	0.00	0	0.00	0	0.00
W4	90	33.33	45	16.67	135	50.00	0	0.00	0	0.00	0	0.00
W4.1	75	27.78	60	22.22	135	50.00	0	0.00	0	0.00	0	0.00
W4.2	73	27.04	62	22.96	135	50.00	0	0.00	0	0.00	0	0.00
W5	1	0.37	15	5.56	16	5.93	101	37.41	18	6.67	119	44.07
W5.1	0	0.00	15	5.56	15	5.56	102	37.78	18	6.67	120	44.44
W6	0	0.00	15	5.56	15	5.56	102	37.78	18	6.67	120	44.44
W7	0	0.00	14	5.19	14	5.19	102	37.78	19	7.04	121	44.81
W8	0	0.00	14	5.19	14	5.19	102	37.78	19	7.04	121	44.81
W9	0	0.00	14	5.19	14	5.19	98	36.30	23	8.52	121	44.81
W10	0	0.00	14	5.19	14	5.19	98	36.30	23	8.52	121	44.81
W11	0	0.00	14	5.19	14	5.19	98	36.30	23	8.52	121	44.81
W12	0	0.00	14	5.19	14	5.19	98	36.30	23	8.52	121	44.81
W13	0	0.00	14	5.19	14	5.19	97	35.93	24	8.89	121	44.81

Table 4.47 Damage ratios for berm of Emerged Berm with HD Cubes over Reference Area

Breakwater with Berm $\psi_s=0.59$												
d=45 cm (Berm)												
Waves	Damage Ratio for Moving Units						Damage Ratio for Displaced Units					
	M₁ (QTY)	M₁ (%)	M₂ (QTY)	M₂ (%)	M_T (QTY)	Movement Ratio (%)	D₁ (QTY)	D₁ (%)	D₂ (QTY)	D₂ (%)	D_T (QTY)	Damage Ratio (%)
W1	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W2	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
W3	29	21.48	0	0.00	29	21.48	0	0.00	0	0.00	0	0.00
W4	53	39.26	8	5.93	61	45.19	1	0.74	0	0.00	1	0.74
W4.1	52	38.52	10	7.41	62	45.93	1	0.74	0	0.00	1	0.74
W4.2	53	39.26	11	8.15	64	47.41	1	0.74	0	0.00	1	0.74
W5	40	29.63	15	11.11	55	40.74	7	5.19	4	2.96	11	8.15
W5.1	40	29.63	15	11.11	55	40.74	8	5.93	4	2.96	12	8.89
W6	40	29.63	15	11.11	55	40.74	8	5.93	4	2.96	12	8.89
W7	37	27.41	17	12.59	54	40.00	9	6.67	4	2.96	13	9.63
W8	26	19.26	26	19.26	52	38.52	11	8.15	4	2.96	15	11.11
W9	12	8.89	37	27.41	49	36.30	14	10.37	4	2.96	18	13.33
W10	12	8.89	37	27.41	49	36.30	14	10.37	4	2.96	18	13.33
W11	12	8.89	36	26.67	48	35.56	15	11.11	4	2.96	19	14.07
W12	7	5.19	36	26.67	43	31.85	20	14.81	4	2.96	24	17.78
W13	7	5.19	30	22.22	37	27.41	24	17.78	6	4.44	30	22.22

Table 4.48 Wave parameters and damage ratios for lower slope of Emerged Berm with HD Cubes over Reference Area

Breakwater with Berm $\psi_s=0.59$												
d=45 cm (Lower Slope)												
Waves	H _{m0} (m)	S _p (-)	S _{m-1.0} (-)	C _r %	N _s (-)	M ₁ %	M ₂ %	M _T %	D ₁ %	D ₂ %	D _T %	Observation
W1	0.05	0.044	0.048	0.263	0.58	0.00	0.00	0.00	0.00	0.00	0.00	
W2	0.08	0.031	0.036	0.247	0.93	4.81	0.00	4.81	0.00	0.00	0.00	
W3	0.10	0.038	0.044	0.250	1.16	35.19	0.00	35.19	0.00	0.00	0.00	
W4	0.10	0.022	0.031	0.311	1.16	33.33	16.67	50.00	0.00	0.00	0.00	
W4.1	0.11	0.028	0.036	0.297	1.28	27.78	22.22	50.00	0.00	0.00	0.00	
W4.2	0.12	0.027	0.037	0.309	1.40	27.04	22.96	50.00	0.00	0.00	0.00	
W5	0.13	0.046	0.046	0.274	1.51	0.37	5.56	5.93	37.41	6.67	44.07	Sliding
W5.1	0.13	0.029	0.039	0.290	1.51	0.00	5.56	5.56	37.78	6.67	44.44	
W6	0.15	0.037	0.046	0.264	1.74	0.00	5.56	5.56	37.78	6.67	44.44	
W7	0.15	0.034	0.044	0.288	1.74	0.00	5.19	5.19	37.78	7.04	44.81	
W8	0.15	0.034	0.042	0.306	1.74	0.00	5.19	5.19	37.78	7.04	44.81	
W9	0.17	0.032	0.046	0.313	1.98	0.00	5.19	5.19	36.30	8.52	44.81	
W10	0.16	0.016	0.040	0.379	1.86	0.00	5.19	5.19	36.30	8.52	44.81	
W11	0.18	0.032	0.049	0.323	2.09	0.00	5.19	5.19	36.30	8.52	44.81	
W12	0.17	0.022	0.030	0.443	1.98	0.00	5.19	5.19	36.30	8.52	44.81	
W13	0.17	0.015	0.028	0.444	1.98	0.00	5.19	5.19	35.93	8.89	44.81	

Table 4.49 Wave parameters and damage ratios for berm of Emerged Berm with HD Cubes over Reference Area

Breakwater with Berm $\psi_s=0.59$											
d=45 cm (Berm)											
Waves	H_{m0}	S_p	S_{m-1.0}	C_r	N_s	M₁	M₂	M_T	D₁	D₂	D_T
	(m)	(-)	(-)	%	(-)	%	%	%	%	%	%
W1	0.05	0.044	0.048	0.263	0.58	0.00	0.00	0.00	0.00	0.00	0.00
W2	0.08	0.031	0.036	0.247	0.93	0.00	0.00	0.00	0.00	0.00	0.00
W3	0.10	0.038	0.044	0.250	1.16	21.48	0.00	21.48	0.00	0.00	0.00
W4	0.10	0.022	0.031	0.311	1.16	39.26	5.93	45.19	0.74	0.00	0.74
W4.1	0.11	0.028	0.036	0.297	1.28	38.52	7.41	45.93	0.74	0.00	0.74
W4.2	0.12	0.027	0.037	0.309	1.40	39.26	8.15	47.41	0.74	0.00	0.74
W5	0.13	0.046	0.046	0.274	1.51	29.63	11.11	40.74	5.19	2.96	8.15
W5.1	0.13	0.029	0.039	0.290	1.51	29.63	11.11	40.74	5.93	2.96	8.89
W6	0.15	0.037	0.046	0.264	1.74	29.63	11.11	40.74	5.93	2.96	8.89
W7	0.15	0.034	0.044	0.288	1.74	27.41	12.59	40.00	6.67	2.96	9.63
W8	0.15	0.034	0.042	0.306	1.74	19.26	19.26	38.52	8.15	2.96	11.11
W9	0.17	0.032	0.046	0.313	1.98	8.89	27.41	36.30	10.37	2.96	13.33
W10	0.16	0.016	0.040	0.379	1.86	8.89	27.41	36.30	10.37	2.96	13.33
W11	0.18	0.032	0.049	0.323	2.09	8.89	26.67	35.56	11.11	2.96	14.07
W12	0.17	0.022	0.030	0.443	1.98	5.19	26.67	31.85	14.81	2.96	17.78
W13	0.17	0.015	0.028	0.444	1.98	5.19	22.22	27.41	17.78	4.44	22.22

Table 4.50 Change of N_0 corresponding to wave parameters for lower slope of Emerged Berm with HD Cubes over Reference Area

Breakwater With Berm $\psi_s=0.59$						
Lower Slope						
d=45 cm						
Waves	H_{m0}	$H_{1/3}$	$T_{m-1.0}$	T_p	N_s	N_0
	(m)	(m)	(s)	(s)	(-)	(-)
W1	0.05	0.05	0.82	0.85	0.58	0
W2	0.08	0.08	1.20	1.29	0.93	0
W3	0.10	0.10	1.21	1.29	1.16	0
W4	0.10	0.10	1.44	1.69	1.16	0
W4.1	0.11	0.11	1.40	1.58	1.28	0
W4.2	0.12	0.11	1.45	1.69	1.40	0
W5	0.13	0.13	1.34	1.35	1.51	5.17
W5.1	0.13	0.13	1.47	1.69	1.51	5.22
W6	0.15	0.14	1.44	1.62	1.74	5.22
W7	0.15	0.14	1.47	1.69	1.74	5.26
W8	0.15	0.14	1.52	1.69	1.74	5.26
W9	0.17	0.16	1.53	1.85	1.98	5.26
W10	0.16	0.14	1.61	2.50	1.86	5.26
W11	0.18	0.17	1.54	1.90	2.09	5.26
W12	0.17	0.15	1.92	2.23	1.98	5.26
W13	0.17	0.16	1.96	2.66	1.98	5.26

Table 4.51 and Figure 4.44 show dimensionless recession number in this experiment. Recession was not observed at wave series W1, W2 and W3. Only M_1 (rocking) movements were observed at wave W3. Displacement at berm started at W4 ($H_{m0}=0.10$ m and $N_s=1.16$) at 1st row and then remained constant until the end of the wave series W4.2. At W5 ($H_{m0}=0.13$ m and $N_s=1.51$), 10 more displacements occurred in the berm ("Sliding" behavior occurred in the lower slope at this wave) and recession started at 3rd row. At the end of the wave series W5.1, recession was still at 3rd row (Table 4.47 and Table 4.49). 14 cubes dislocated from berm to lower slope. Also, 2 ND cubes dislocated from berm to upper slope due to massive wave forces at W13.

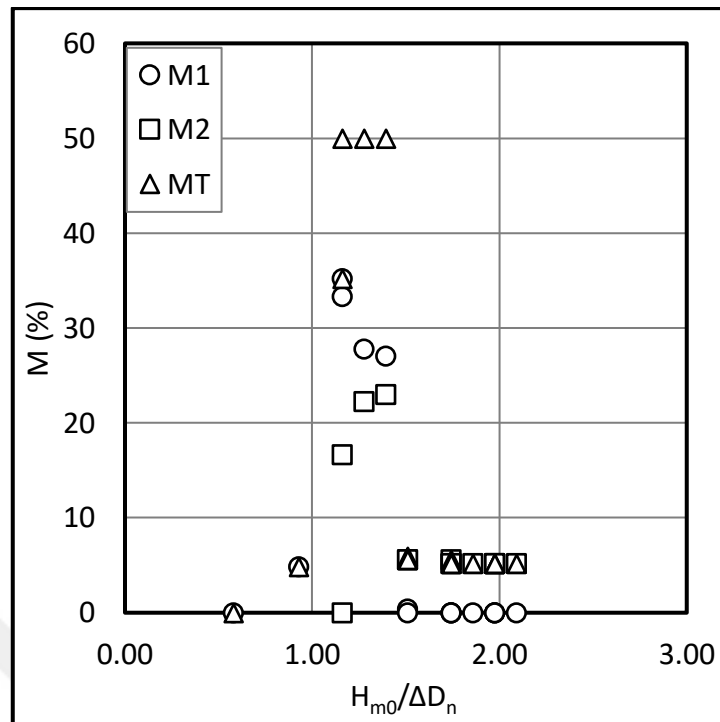


Figure 4.40 Percentage of moving units in reference area for Emerged Berm with HD Cubes over Reference Area

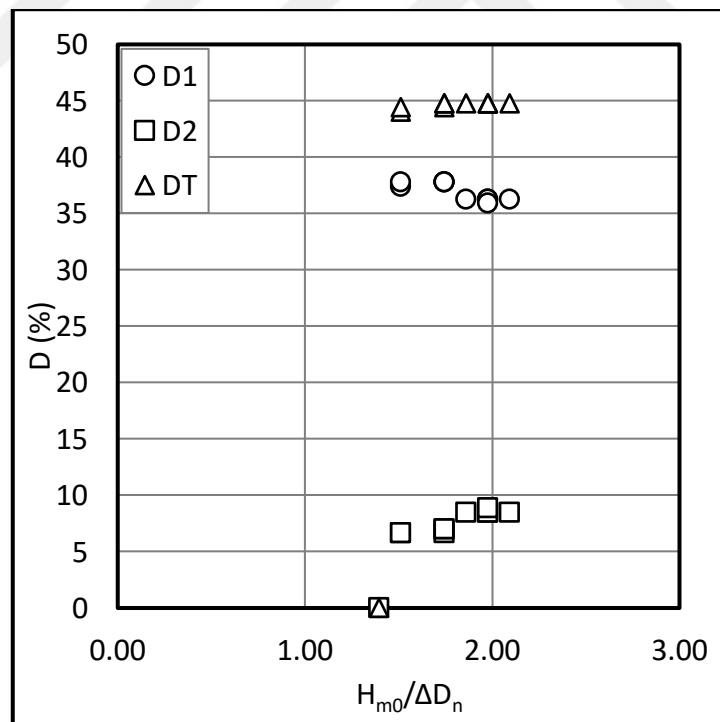


Figure 4.41 Percentage of moving units in reference area for Emerged Berm with HD Cubes over Reference Area

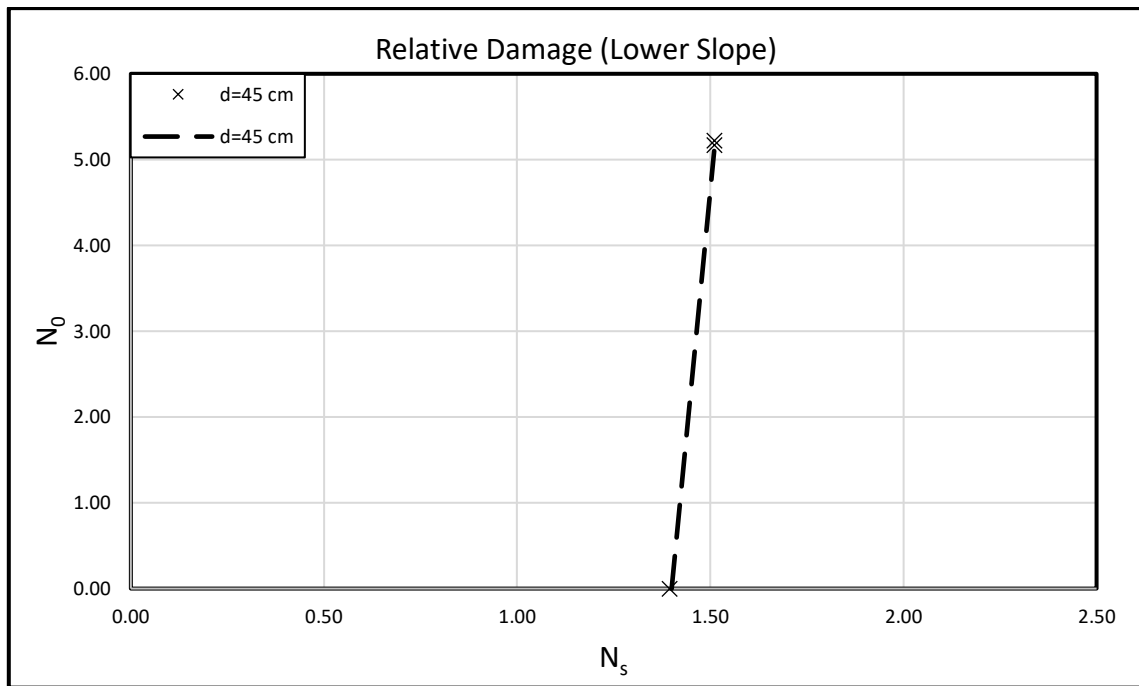


Figure 4.42 Relative damage in reference area for Emerged Berm with HD Cubes over Reference Area

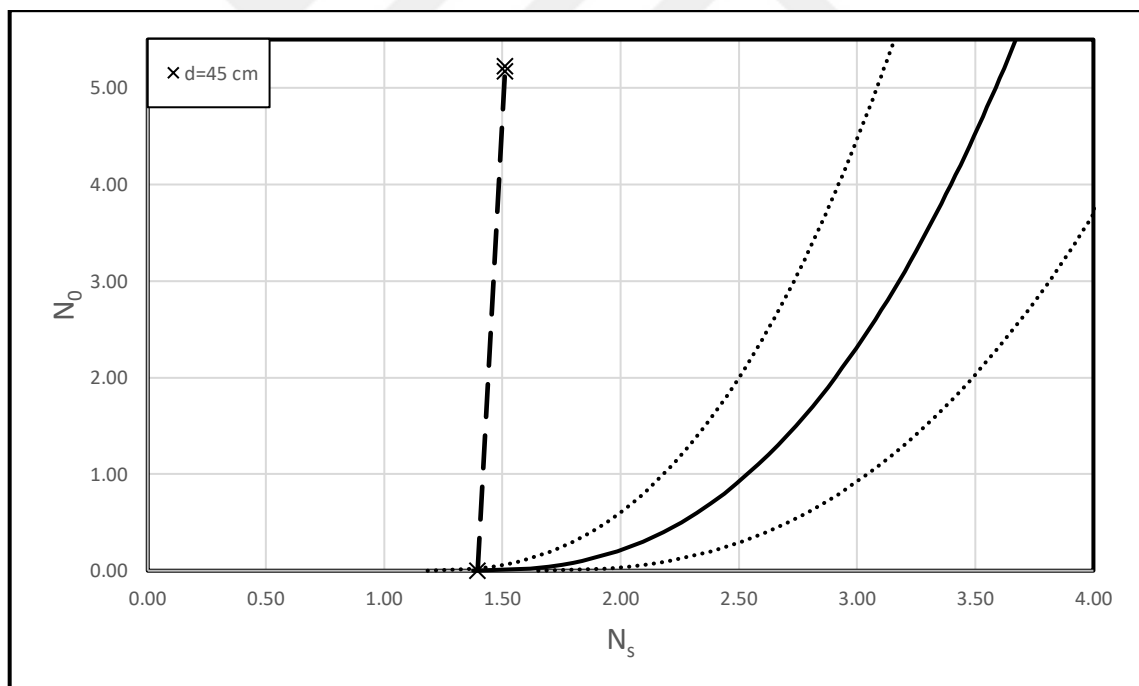


Figure 4.43 Comparison for experimental results of Emerged Berm with HD Cubes over Reference Area with the formula by Van der Meer (1988) for conventional cube armored breakwaters

Table 4.51 Displacements and dimensionless recession numbers for Emerged Berm with HD Cubes over Reference Area

Waves	Rec (d=45 cm)			
	H_{m0}	$H_s/\Delta D_n$	D_T (QTY)	Rec/D_n
	(m)	(-)	(-)	(-)
W1	0.05	0.58	0	0
W2	0.08	0.93	0	0
W3	0.10	1.16	0	0
W4	0.10	1.16	1	1
W4.1	0.11	1.28	1	1
W4.2	0.12	1.40	1	1
W5	0.13	1.51	11	3
W5.1	0.13	1.51	12	3
W6	0.15	1.74	12	3
W7	0.15	1.74	13	3
W8	0.15	1.74	15	3
W9	0.17	1.98	18	4
W10	0.16	1.86	18	4
W11	0.18	2.09	19	4
W12	0.17	1.98	24	5
W13	0.17	1.98	30	5

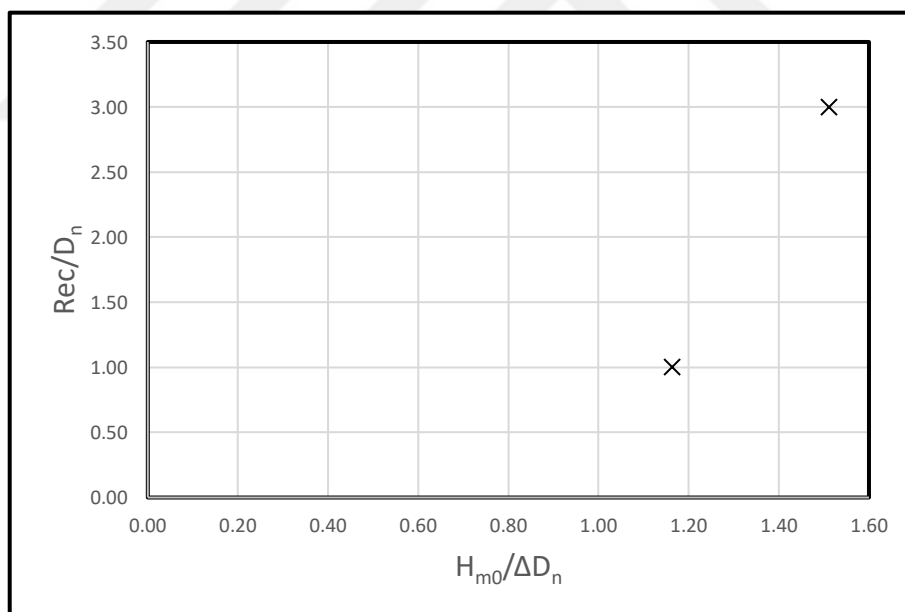


Figure 4.44 Stability number (N_s) and dimensionless recession (Rec) graphic for Emerged Berm with HD Cubes over Reference Area

4.4 Discussion

This section covers comparison and assessment of presented experiments. Additional experiments are also given in the following sections by Gümüşçü (2020) and Altunsu (2019). Gümüşçü (2020) studied HD cube armored conventional breakwaters, and Altunsu (2019) studied ND cube armored berm breakwaters.

4.4.1 Discussion on Cube Armored Conventional Breakwaters

Table 4.52 shows damage initiation parameters for the experiments that are going to be discussed in this section. Presented experiments were tested at 0.55 m water depth using irregular placement method. Since no damage occurred for regular placements, they were not included to the following table.

Table 4.52 Damage initiation parameters for cube armored conventional breakwaters

Damage Initiation Parameters for Conventional Cube Armored Breakwaters			
Experiment	Wave	H_{m0} (m)	N_s
First Layer ND Cubes and Second Layer HD Cubes (▲)	W5	0.14	1.63
Reference Area HD Cubes (✕)	W3	0.10	1.16
Double Layer ND Cubes (△)	W3	0.10	1.79
First Layer ND Cubes and Second Layer HD Cubes (Smooth Surface) (●)	W5	0.13	1.41

Figure 4.45 shows that displacements started in the earlier waves for Double Layer ND when compared to First Layer ND and Second Layer HD. However, the stability number of Double Layer ND was relatively higher than of First Layer ND and Second Layer HD because of considering the relative density for HD cubes. . Even though, the experiment First Layer ND and Second Layer HD is not compatible with the Van der Meer (1988) formula, N_0 (relative damage) was almost half of the Double Layer ND experiment. The reason of incompatibility is underestimation of HD cubes and damage trigger of ND cubes at the first layer.

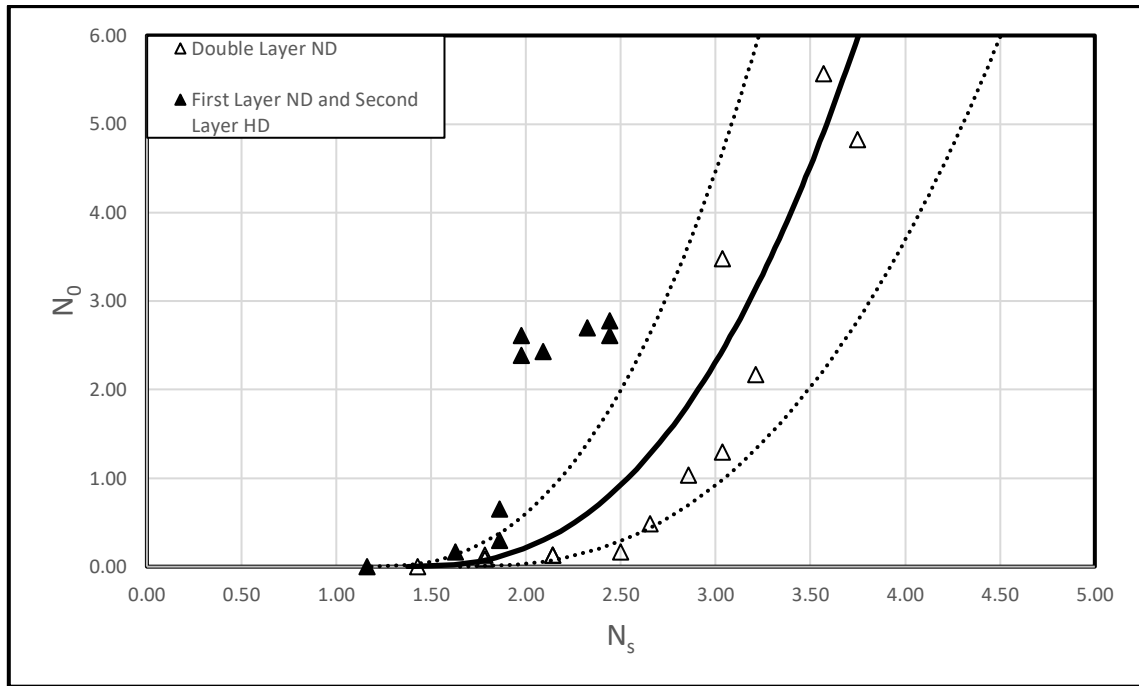


Figure 4.45 Comparison of First Layer ND Cubes - Second Layer HD Cubes and Double Layer ND Cubes

Comparison of First Layer ND Cubes - Second Layer HD Cubes and Reference Area HD cube breakwater is presented in Figure 4.46. It can be concluded that both experiments are incompatible with Van der Meer (1988) formula. For the experiment Reference Area HD, displacements started earlier than experiment First Layer ND - Second Layer HD. Then, the relative damage N_0 for experiment Reference Area HD, was almost twice of experiment First Layer ND - Second Layer HD at the end of the experiment.

Quantity of dislocated HD cubes on Reference Area was considerably higher than the First Layer ND cube- Second Layer HD cube breakwater. Also, sliding damage was observed in experiment Double Layer ND.

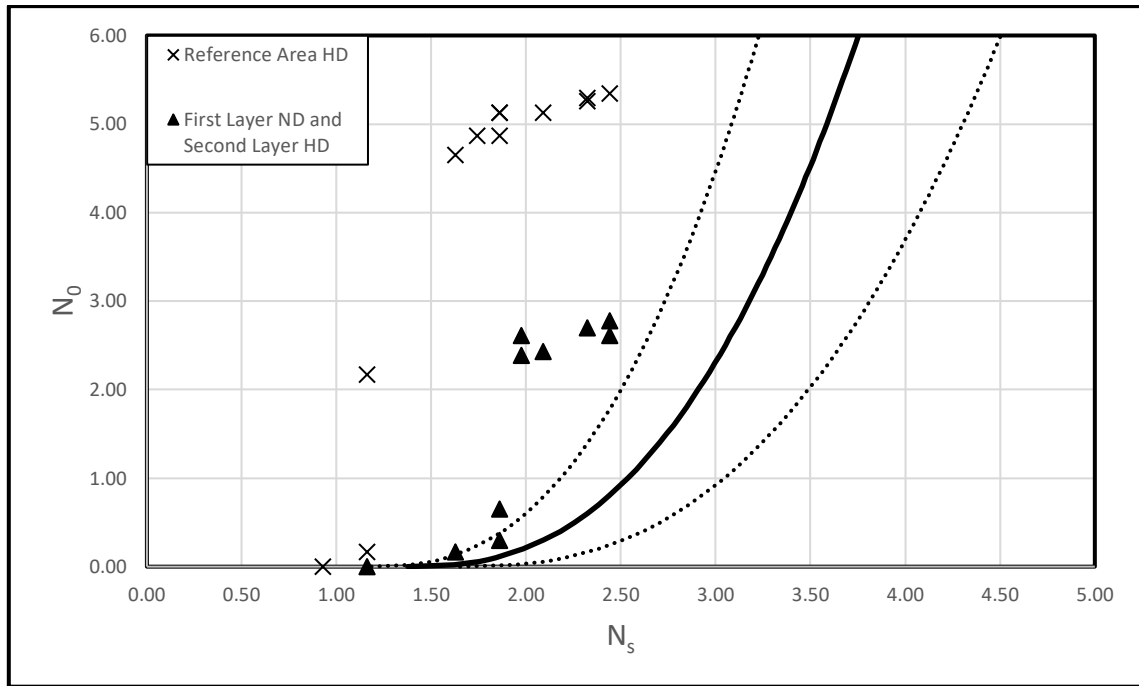


Figure 4.46 Comparison of First Layer ND Cubes - Second Layer HD Cubes and Reference Area HD Cubes

Figure 4.47d demonstrates distribution of roughly placed cubes and smoothly placed cubes for experiment First Layer ND and Second Layer HD. An additional experiment was conducted using a different irregular placement method (see Figure 4.47). In this method cubes were mostly placed to obtain smooth surface using irregular placement method. Colored cubes represent smoothly placed cubes (see Figure 4.47b), and black cubes represent roughly placed cubes (Figure 4.47c).

Figure 4.48 shows that displacements started in same wave series. In early waves displacements in the experiment for the first layer ND and the second layer HD (Smooth Surface) occurred earlier than the experiment first layer ND and the second layer HD for rough surface. However, in the following waves, damage ratio of the first layer ND and the second layer HD for rough surface became greater than the first layer ND and the second layer HD for smooth surface. This means that the experiment for smooth surface performed better stability than the experiment for rough surface under the same wave conditions.

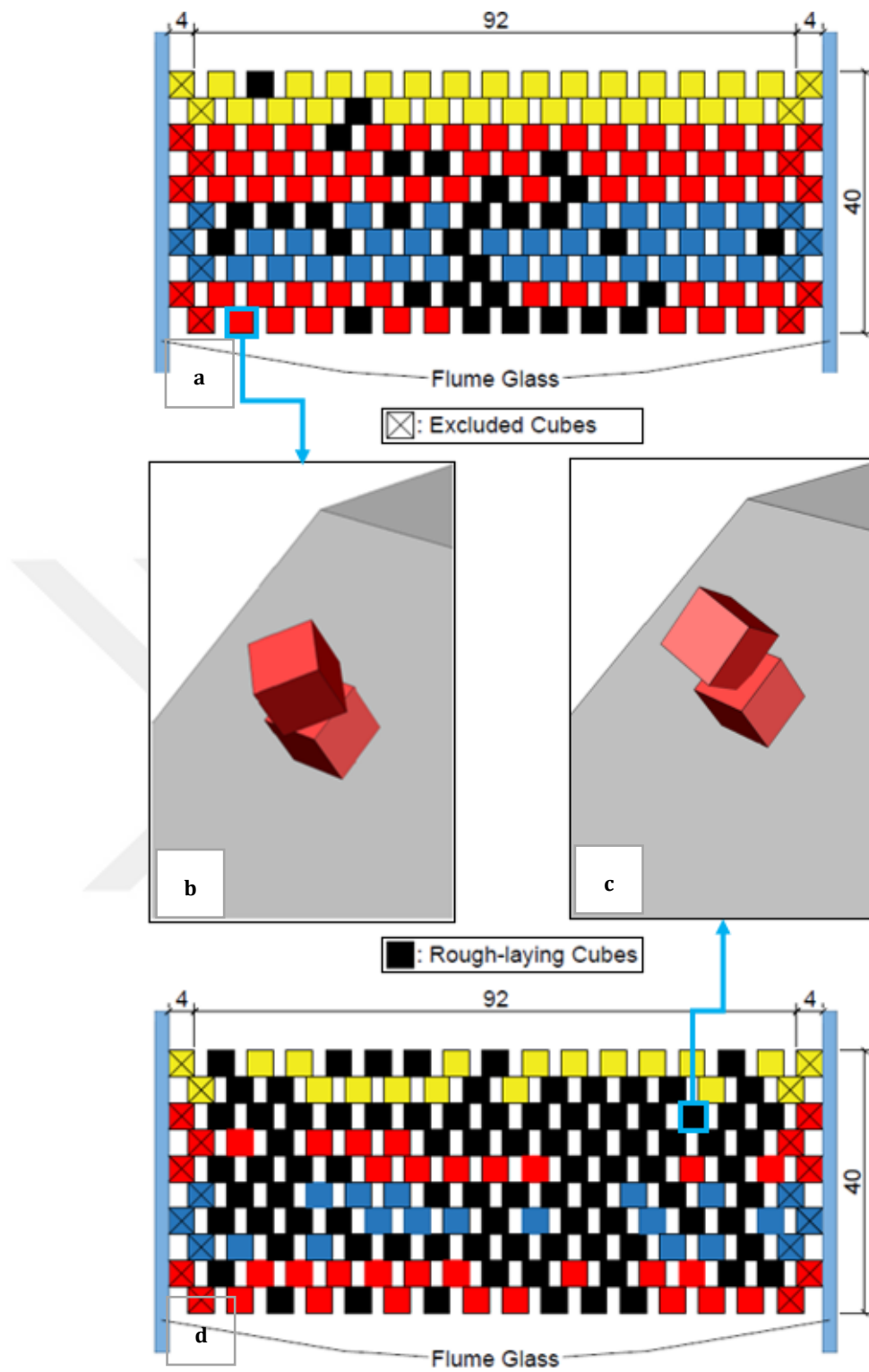


Figure 4.47 Roughly placed cube distributions for experiments First Layer ND Cubes and Second Layer HD Cubes

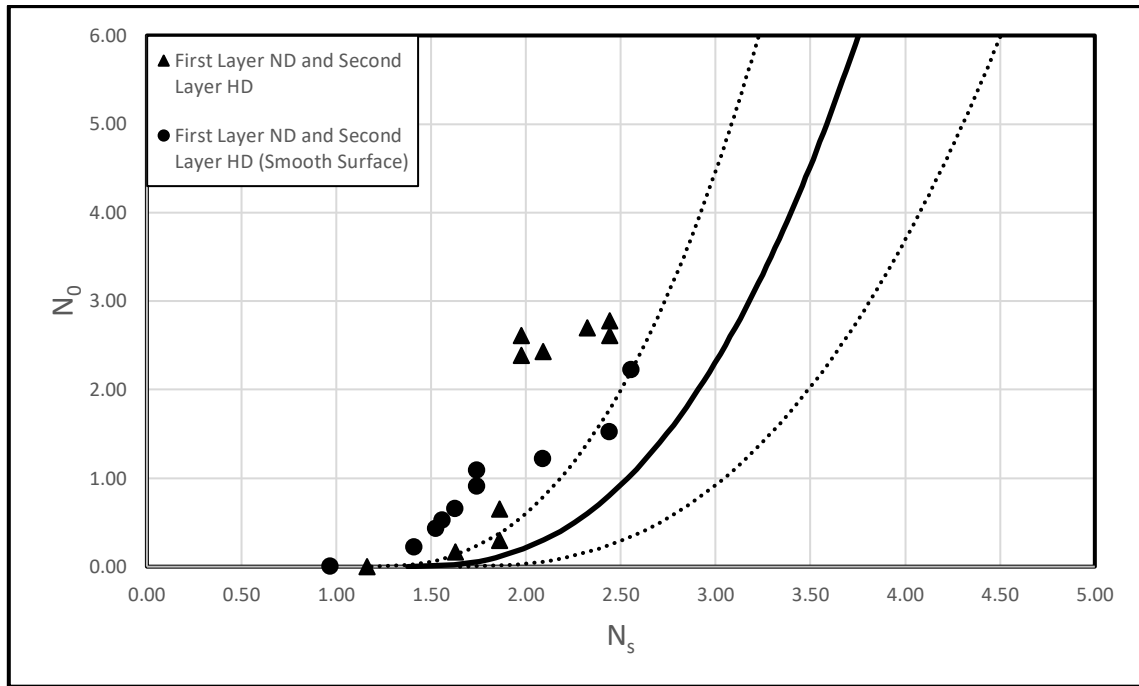


Figure 4.48 Comparison for rough surface and smooth surface experiments

4.4.2 Discussion on Cube Armored Berm Breakwaters

Table 4.53 shows damage initiation parameters at lower slope for the experiments that are going to be discussed in this section. Also, damage initiation parameters of the berms are given in Table 4.54. Presented experiments were tested at 0.45 m, 0.55 m, and 0.65 m water depths using irregular placement method for the berm width of $5D_n$. Results of HD experiments are also compared with results of ND cubes performed by Altunsu (2019) for cube armored berm breakwaters.

Table 4.53 Damage initiation parameters for the lower slope

Damage Initiation Parameters for Cube Armored Berm Breakwaters (Lower Slope)				
Experiment	Wave	H_{m0} (m)	N_s	N_s
			(Measurement)	(Formula)
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	-
Emerged Berm* (△)	W3	0.10	1.79	1.82
Berm at SWL* (○)	W4	0.10	1.79	1.91
Submerged Berm* (□)	W6	0.13	2.32	2.03

* Altunsu (2019).

Figure 4.49 shows comparison of HD cubes for berm breakwaters. According to the figure, displacements started at close stability numbers (N_s) for berm at SWL and emerged berm. Displacements started at higher stability numbers for submerged berm. More displacements were observed in berm at SWL, and the less displacements occurred in submerged berm.

Although the HD cubes were used at the second layer of the armor layer, the results of presented experiments for berm breakwaters were found compatible with Van der Meer (1988) formula.

Table 4.54 Damage initiation parameters for the berm

Damage Initiation Parameters for Cube Armored Berm Breakwaters (Berm)			
Experiment	Wave	H_{m0} (m)	N_s
Emerged Berm (▲)	W8	0.15	1.74
Berm at SWL (●)	W5	0.13	1.51
Submerged Berm (■)	W7	0.14	1.63
Emerged Berm with HD Cubes over Reference Area (✕)	W4	0.10	1.16
Emerged Berm* (△)	W5	0.14	2.5
Berm at SWL* (○)	W4	0.10	1.79
Submerged Berm* (□)	W4	0.08	1.43

* Altunsu (2019).

Figure 4.51 and Figure 4.52 show comparisons of HD and ND cubes for berm breakwaters for emerged berm, berm at SWL and submerged berm. Displacements for ND cubes started at lower wave heights, and displacements for HD cubes started at higher wave heights (Table 4.53). HD cubes performed more stable than ND cubes at lower slope of berm breakwaters. Figure 4.51 shows that damage curves for HD cubes and ND cubes are compatible with each other at 0.45 m, 0.55 m, and 0.65 m water depths.

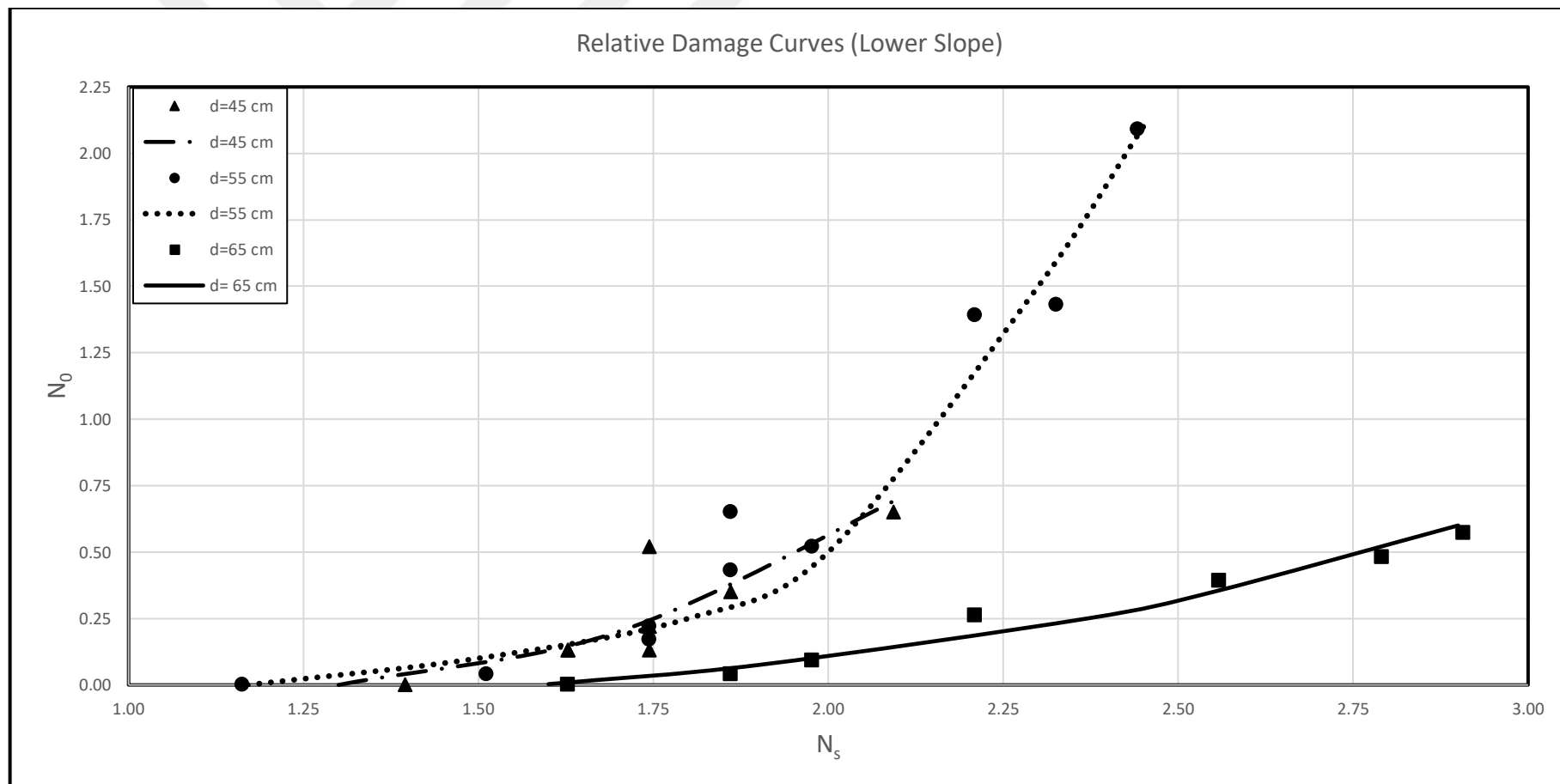


Figure 4.49 Relative damage comparison of lower slopes for berm breakwaters (HD)

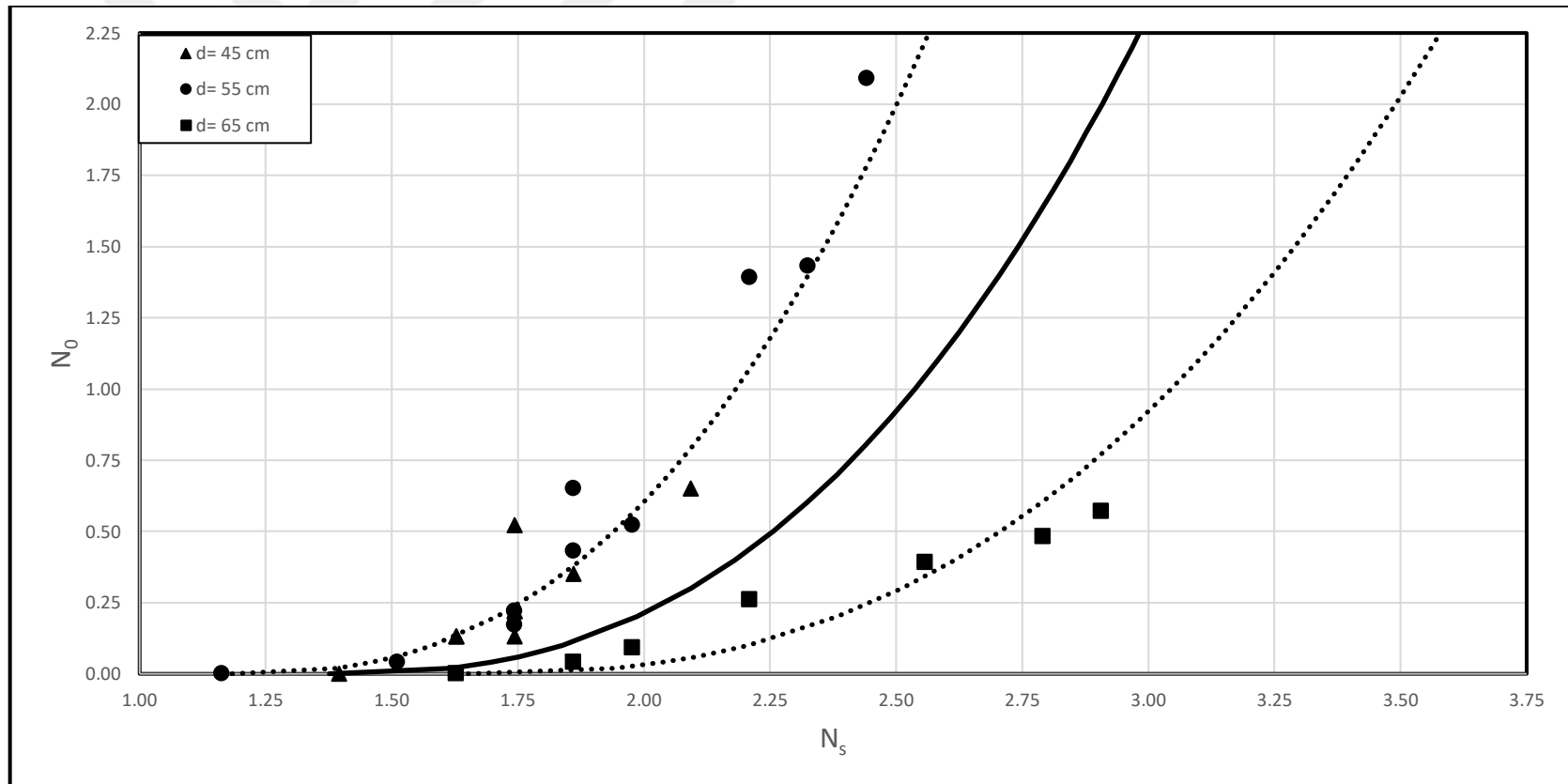


Figure 4.50 Comparison for experimental results of berm breakwaters for HD cubes with the formula by Van der Meer (1988) for conventional cube armored breakwaters

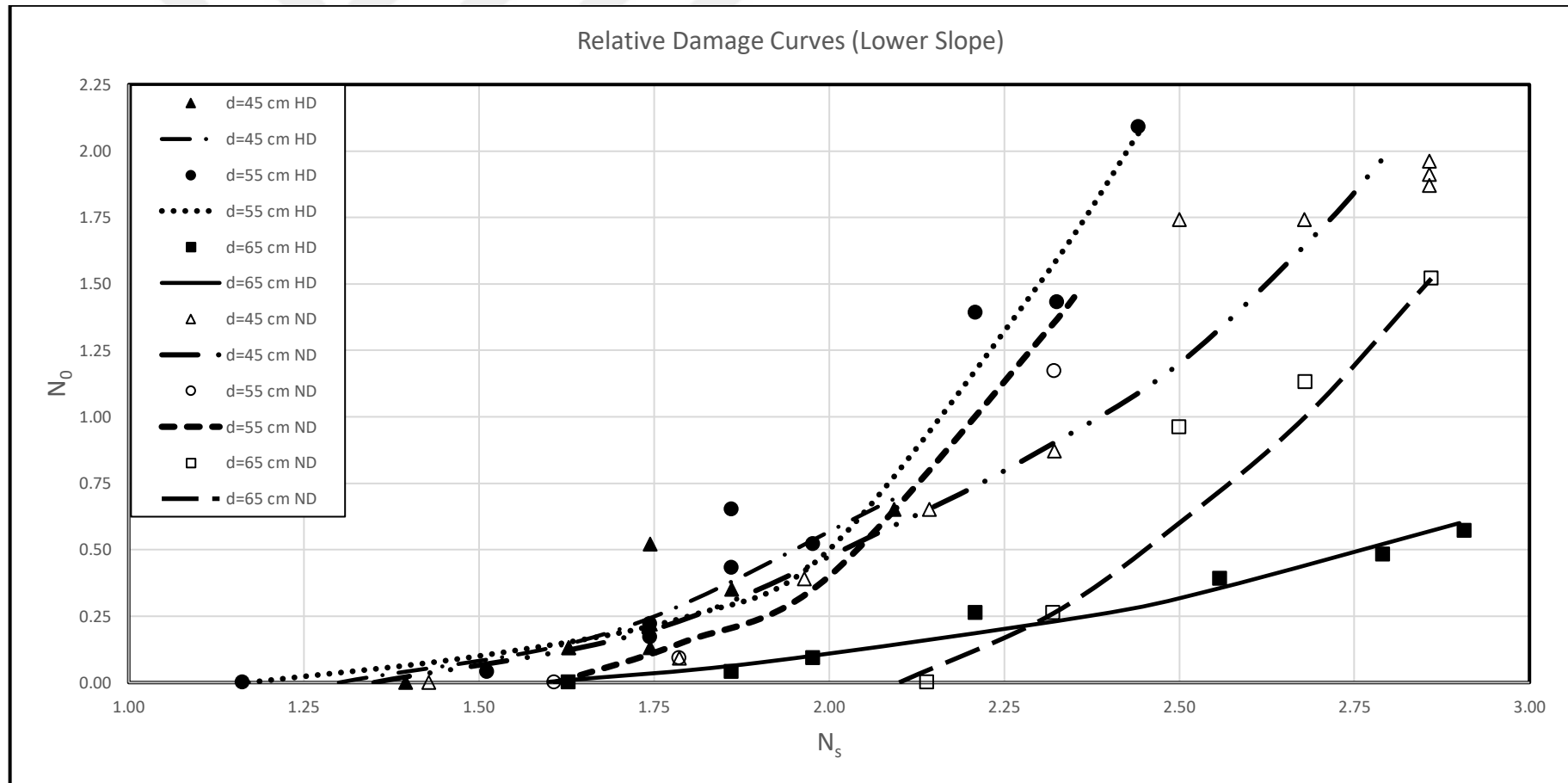


Figure 4.51 Relative damage comparison of lower slopes for berm breakwaters (HD-ND)

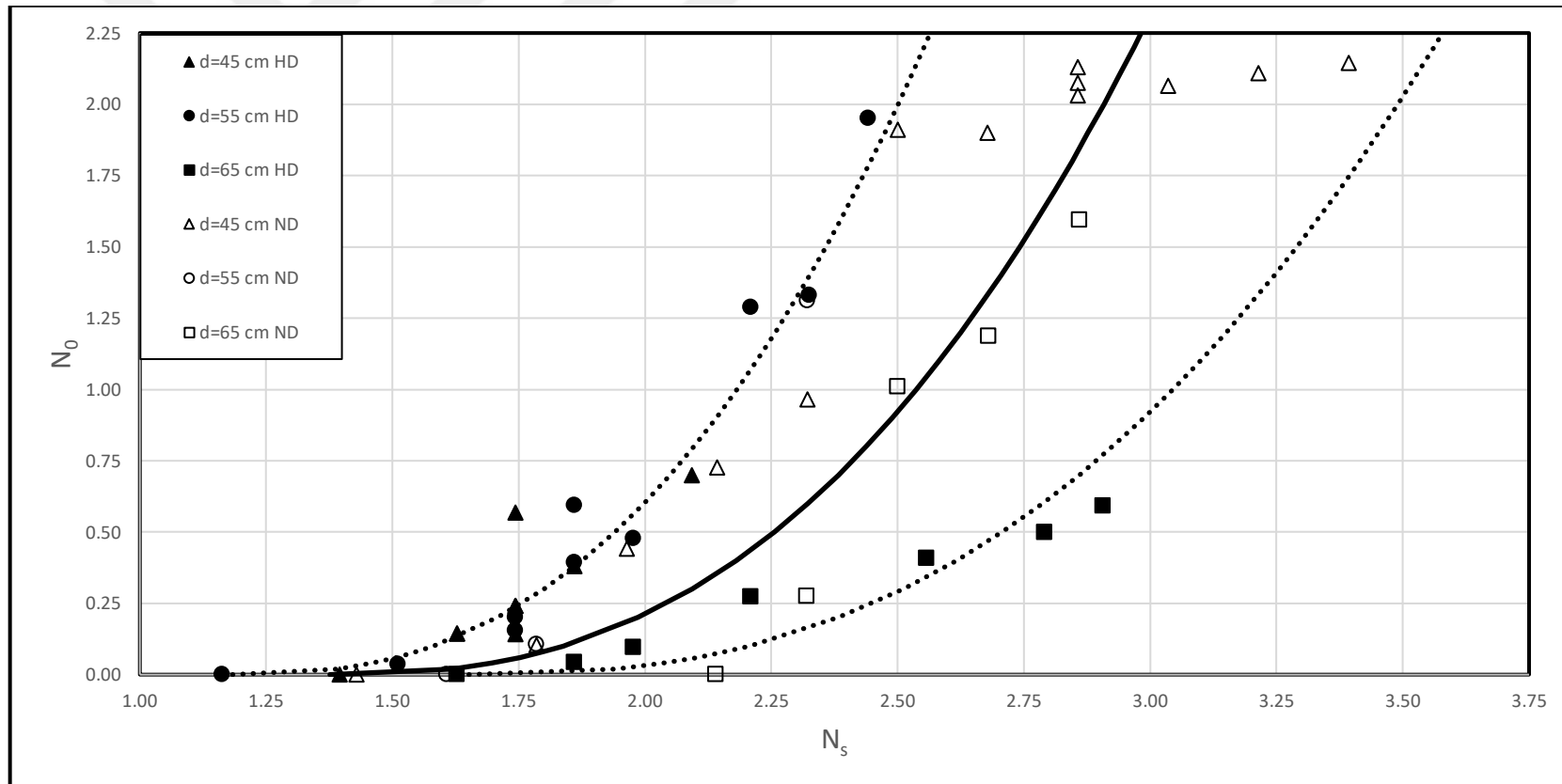


Figure 4.52 Comparison for experimental results of berm breakwaters for HD and ND cubes with the formula by Van der Meer (1988) for conventional cube armored breakwaters

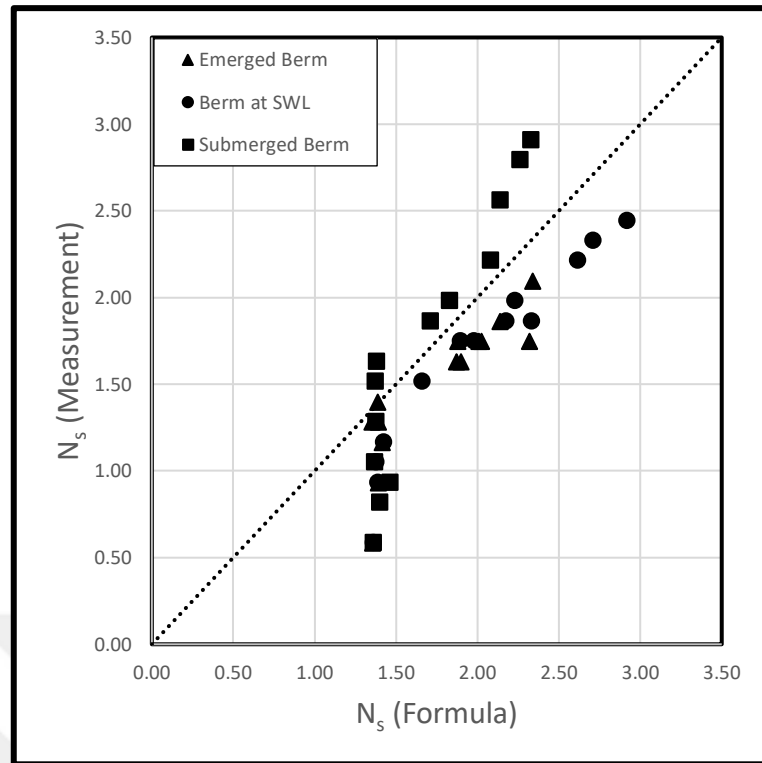


Figure 4.53 Measured stability parameter versus predicted stability parameter

Figure 4.53 represents measured stability parameter and predicted stability parameter for berm breakwaters. The predicted stability parameter was calculated by referring Yüksel *et al.* (2020).

4.4.3 Reflection Coefficients

Reflection coefficients are given in Figure 4.54 and Figure 4.55. The reflection coefficients were drawn with wave steepness ($s_{m-1.0}$) for both conventional cross-sections and berm cross-sections.

Figure 4.54 shows that reflection coefficients varies between 0.25 and 0.50. The figure depicts that, reflection coefficients for regular placement methods were found relatively higher than reflection coefficients for irregular placement methods. This is because of the surface smoothness of the regular placement method. Since irregularly placed cubes have rough surfaces, they dissipate incident waves more.

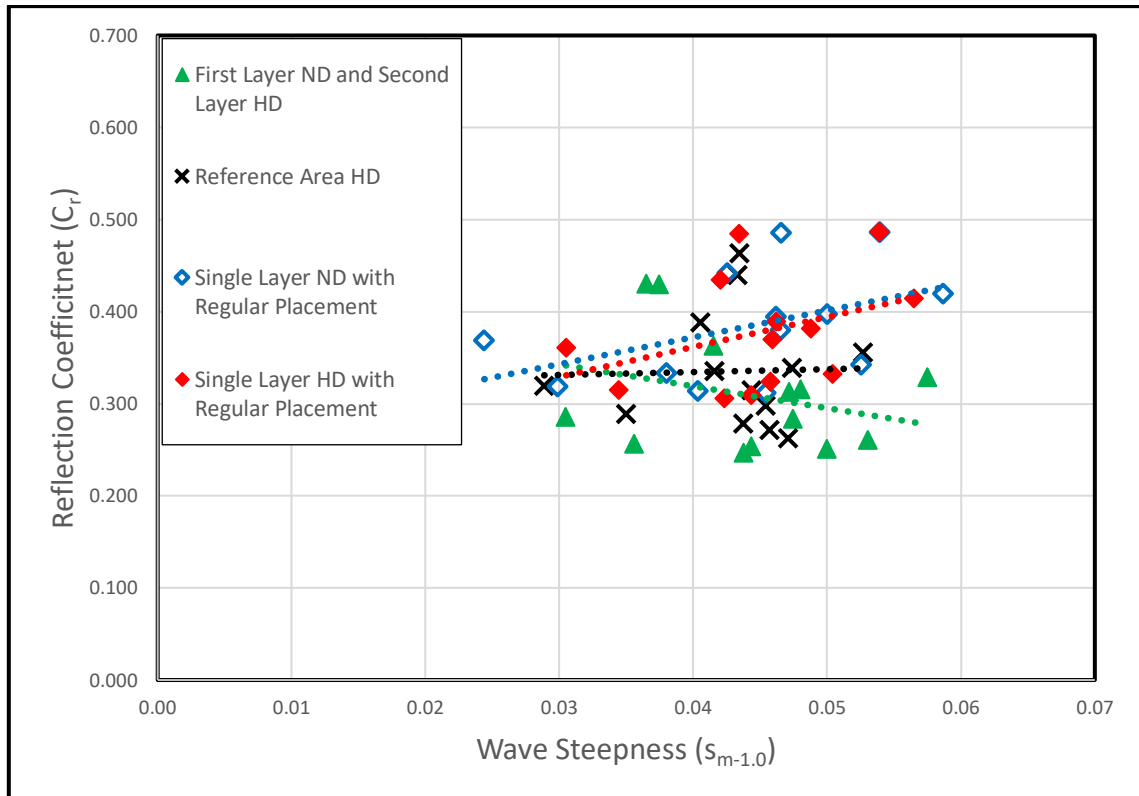


Figure 4.54 Reflection coefficients for conventional breakwaters

Change of reflection coefficients for berm breakwaters are provided in Figure 4.55. For emerged berms (45 cm water depth), reflection coefficients varies between 0.25 and 0.48. Reflection coefficients were found between 0.15 and 0.25 for berm at SWL. For submerged berm, reflection coefficients varied between 0.16 and 0.25. As is seen from the Figure 4.55, highest reflection coefficients were found on emerged berms, and lowest reflection was found on the berm at SWL.

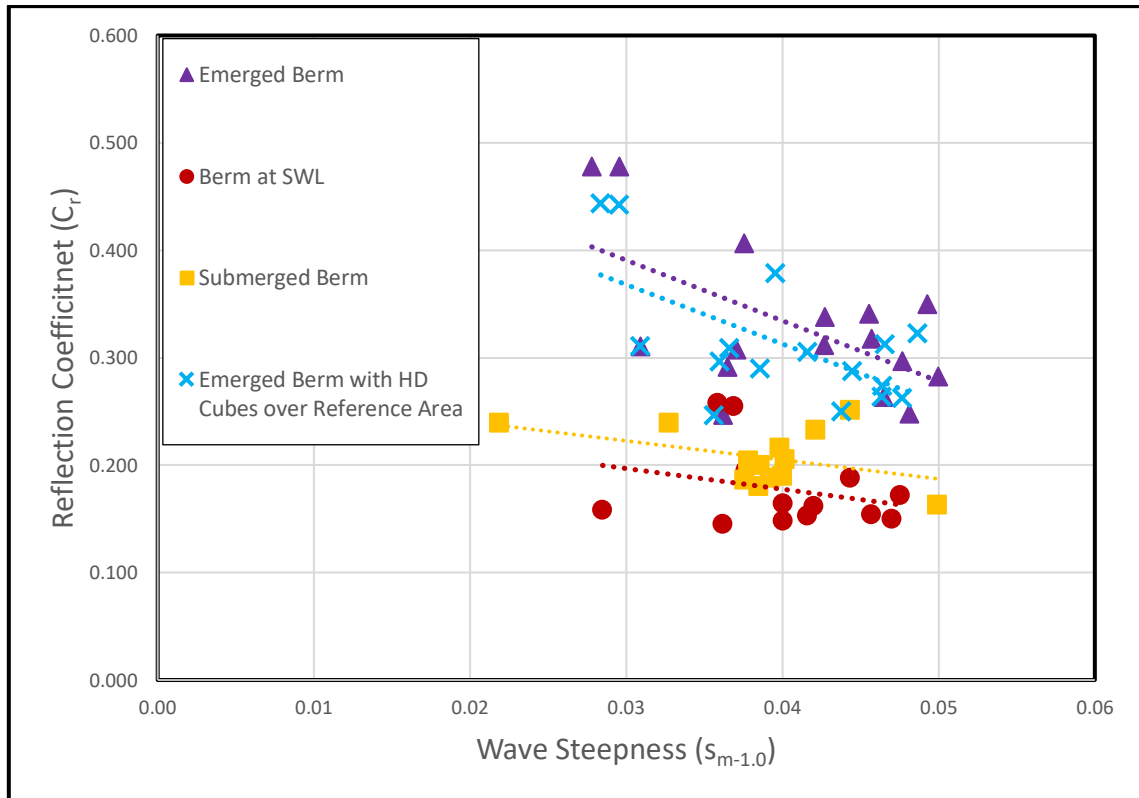


Figure 4.55 Reflection coefficients for berm breakwaters

4.4.4 Evaluation of Stability Coefficients (K_D)

In the previous sections, stability coefficient (K_D) was defined, and its calculation method was provided (see page 105). The stability value for the regular methods is calculated from the last stability parameter where no displacements occurred (K_{D0}). The Hudson stability value for the irregular methods is calculated from the stability parameter where the first displacement occurred below 5% (K_{DH}). Also, the highest stability value below 5% damage, makes the irregular method comparable to the regular method ($K_{D<5\%}$).

There are many studies presented on the literature on K_D values and N_s values for cube armor layer blocks such as Brorsen *et al.* (1975), Van der Meer (1988), Rock Manual (2007), Yüksel (2011), Muttray and Reedijk (2009), and Yüksel *et al.* (2020). These studies were summarized in the following tables (Table 4.55 and Table 4.56).

Table 4.55 K_D and N_s values for double layer cubes (for trunk section)

K_D and N_s Values for Double Layer Cubes (Trunk)				
Author	Condition	Slope ($\cot \alpha$)	K_D	N_s
Yüksel (2011)	Non-breaking Breaking	1.5	4.5 - 3.5	1.89
Brorsen <i>et al.</i> (1975)	Non-breaking Breaking	1.5 to 2.0	4.0 - 3.88	1.8 - 2.0
Van der Meer (1988)	Non-breaking Breaking	1.5	3.27 - 2.25	1.5 - 1.7
Rock Manual (2007)	Non-breaking Breaking	1.5 to 3.0	7.5 - 6.5	2.13 - 2.69
Muttray and Reedijk (2009)	Non-breaking Breaking	1.5 to 3.0	7.5 - 6.5	2.13 - 2.69

Table 4.56 K_D and N_s values for double layer irregular cubes for berm breakwaters ($5D_n$ berm width) (Yüksel *et al.* 2020)

Emerged Berm	N_s	1.43	N_s	1.79	N_s	2.10
	K_{D0}	1.94	K_{DH}	3.82	$K_{D<5\%}$	6.16
Berm at SWL	N_s	1.61	N_s	1.79	N_s	2.03
	K_{D0}	2.77	K_{DH}	3.82	$K_{D<5\%}$	5.59
Submerged Berm	N_s	2.14	N_s	2.32	N_s	2.32
	K_{D0}	6.56	K_{DH}	8.32	$K_{D<5\%}$	8.32

Table 4.55 and Table 4.56 summarize K_D and N_s values from the literature for conventional breakwater and berm breakwaters, respectively. For conventional breakwaters with HD cubes performed in this study, the stability coefficients were found slightly lower than the studies retrieved from the literature (see Table 4.55), but it was found lower for the reference area was only HD because serious failure occurred due to sliding damage (K_{DH} of First Layer ND - Second Layer HD=2.88, K_{DH} of Reference Area HD=1.05). However, K_D of First Layer ND - Second Layer HD was found compatible with Van der Meer (1988). For berm breakwaters performed in this study with HD cubes, all stability coefficients were found lower than the study of Yüksel *et al.* 2020 (K_{DH} of Emerged Berm=2.88, K_{DH} of Berm at SWL=2.30, K_{DH} of Submerged Berm=4.29). As mentioned earlier, the stability coefficients derived from this study with HD cubes were found lower than the studies of Brorsen *et al.* (1975), Van der Meer (1988), Rock Manual (2007), Yüksel

(2011) and Yüksel et al. (2020). But note that, ND cubes were used in these studies as armor material. Since HD cubes used in this study have greater relative density, this reduces the value of K_D .

Using the given formula (4.3), the stability coefficient was calculated for each wave series for this study. The stability coefficients are also given in more detail in the Appendix A. In this section, K_D values will be presented in two different tables according to their damage percentage of the relevant wave series. Table 4.57 was categorized according to K_{D0} , K_{DH} , and $K_{D<5\%}$ stability coefficients. Table 4.58 was classified according to 0%, 1%, 3%, 5%, 10% and 15% damage ratios.

Table 4.57 Stability coefficients for conventional breakwaters and berm breakwaters (K_{D0} , K_{DH} , $K_{D<5\%}$)

First Layer ND - Second Layer HD	D_T	0.00	D_T	1.48	D_T	2.59
	N_s	1.16	N_s	1.63	N_s	1.86
	K_{D0}	1.05	K_{DH}	2.88	$K_{D<5\%}$	4.29
Reference Area HD	D_T	0.00	D_T	1.48	D_T	1.48
	N_s	0.93	N_s	1.16	N_s	1.16
	K_{D0}	0.54	K_{DH}	1.05	$K_{D<5\%}$	1.05
Double Layer ND	D_T	0.00	D_T	0.77	D_T	4.19
	N_s	1.43	N_s	1.79	N_s	2.66
	K_{D0}	1.94	K_{DH}	3.80	$K_{D<5\%}$	12.51
Emerged Berm	D_T	0.00	D_T	1.11	D_T	4.44
	N_s	1.40	N_s	1.63	N_s	1.74
	K_{D0}	1.81	K_{DH}	2.88	$K_{D<5\%}$	3.54
Berm at SWL	D_T	0.00	D_T	0.37	D_T	4.44
	N_s	1.16	N_s	1.51	N_s	1.98
	K_{D0}	1.05	K_{DH}	2.30	$K_{D<5\%}$	5.15
Submerged Berm	D_T	0.00	D_T	0.37	D_T	-
	N_s	1.63	N_s	1.86	N_s	-
	K_{D0}	2.88	K_{DH}	4.29	$K_{D<5\%}$	-
Emerged Berm HD Cubes over Reference Area	D_T	0.00	D_T	-	D_T	-
	N_s	1.40	N_s	-	N_s	-
	K_{D0}	1.81	K_{DH}	-	$K_{D<5\%}$	-

Table 4.58 Stability coefficients for conventional breakwaters and berm breakwaters (0%, 1%, 3%, 5%, 10%, 15%)

		0%	1%	3%	5%	10%	15%
First Layer ND - Second Layer HD	N_s	1.16	1.48	1.86	1.86	1.90	1.94
	K_D	1.05	2.15	4.31	4.31	4.54	4.84
Reference Area HD	N_s	0.93	1.08	1.16	1.16	1.16	1.16
	K_D	0.54	0.85	1.02	1.02	1.02	1.02
Double Layer ND	N_s	1.43	2.03	2.36	2.70	2.98	3.07
	K_D	1.94	5.55	8.73	13.04	17.61	19.36
Emerged Berm	N_s	1.40	1.61	1.86	2.04	-	-
	K_D	1.81	2.77	4.31	5.66	-	-
Berm at SWL	N_s	1.16	1.64	1.78	2.00	2.15	2.38
	K_D	1.05	2.94	3.80	5.31	6.65	9.03
Submerged Berm	N_s	1.63	2.02	2.48	-	-	-
	K_D	2.88	5.50	10.24	-	-	-
Emerged Berm HD Cubes over Reference Area	N_s	1.40	1.40	1.40	1.41	1.43	1.44
	K_D	1.81	1.84	1.86	1.88	1.93	1.98

For conventional breakwaters, at zero total displacement ($D_T=0\%$), stability coefficient (K_{D0}) of Double Layer ND is higher when compared to Reference Area HD and First Layer ND – Second Layer HD. This is because of the low relative density of the used concrete cubes on the experiment Double Layer ND. The same parameter correlations also can be seen in the following stability coefficients such

as K_{DH} and $K_{DH<5\%}$ (Table 4.57). Stability coefficients for Reference Area HD were also found quite low than the other experiments. As mentioned in the previous sections, the reason of this is the sliding occurred on the armor layer of the model breakwater. Similar relationships can also be found in the Table 4.58.

According to the parameters given in Table 4.57 and Table 4.58, important results were obtained in berm breakwater experiments in terms of stability coefficients. In comparison of experiments Emerged Berm, Berm at SWL and Submerged Berm, the experiment Submerged Berm performed better. Hence, it has the highest stability coefficients. On the other hand, Berm at SWL has the lowest stability coefficients. In addition, two models were tested at 45 cm water depth, and Emerged Berm has the highest stability coefficients compared to Emerged Berm HD Cubes over Reference Area. This difference occurred because of the sliding on the armor layer of the experiment Emerged Berm HD Cubes over Reference Area.

5 CONCLUSIONS

The main purpose of this experimental study was to determine the influence of different placement methods on conventional cross-section and berm cross section of breakwaters using normal density and high-density cubes. The experiments were performed at the 2D wave flume in the Hydraulics and Coastal & Harbor Engineering Laboratory at Yıldız Technical University. In total, 8 different experiments were performed in the wave flume. Concrete cubes were placed in the armor layer of the breakwaters by hand, using regular and irregular placement methods.

In the experiments, JONSWAP spectrum and wave steepness with $s_{0p}=0.033$ were used. The design wave height was considered as $H_{m0}=20$ cm, and the reference area was chosen accordingly, $10D_n$. For breakwater models with berm, the slope of the lower section was $1/1.5$ and the slope of the upper section was $1/2$. Conventional breakwater models had $1/1.5$ slope. In addition, all used wave parameters were validated before the study.

According to the results of the study, the relative damage (N_0) parameter indicated that breakwater with Submerged Berm model performed superior against Berm at SWL and Emerged Berm. Also, the lowest stability was found for the breakwater with Berm at SWL due to the direct wave forces on the transition zone between the lower slope and the berm. In addition to these experiments, the stability of breakwater with Emerged Berm consisting of HD Cubes over Reference Area was found very low, and the armor layer was observed to slide down on. Nevertheless, the filter layer never became visible through the armor layer for all experiments performed breakwater with berm cross-sections. This was because of the stability of the high-density cubes placed on the first layer. These cubes kept normal-density cubes stable. Also, HD cubes were compared with ND cubes, and HD cubes behaved more stable than ND cubes in the lower slope of berm breakwaters.

Behaviors of the breakwaters with HD and ND cubes at 0.45 m, 0.55 m, and 0.65 m water depths were found to be compatible with each other.

Results of the conventional breakwater cross sections with regular placement method showed that, movements only observed in the armor layer of the breakwaters for both normal-density and high-density cubes. Both breakwater models maintained their stability throughout the experiments. Also, total movement ratio of the experiment Single Layer ND Cubes was higher than the Single Layer HD Cubes.

The performances of conventional breakwaters with irregular placement methods were evaluated, and important findings were obtained. Although sliding damage occurred in the armor layer of these breakwaters, HD cubes at the first layer kept ND cubes at the second layer stable. Also, comparison of two conventional breakwaters with high-density cubes but different placement showed that the model breakwater having more rough-lying cubes was found less stable than the other model due to the high mobility of the rough-lying cubes.

The compatibilities of the performed experiments with the Van der Meer's (1988) study were also evaluated in this study. For berm type breakwaters, following experiments were found compatible with the study performed by Van der Meer (1988): Emerged Berm, Berm at SWL and Submerged Berm. However, the breakwater with Emerged Berm model and HD Cubes over Reference Area was not found compatible with the Van der Meer's (1988) study. For conventional breakwaters with First Layer ND Cubes – Second Layer HD Cubes and also breakwater with Reference Area HD Cubes were found to be incompatible with the Van der Meer's (1988) formula. The reason for this incompatibility is the sliding occurred on the armor layer due to hybrid use of the HD and ND cubes on the armor layer. In addition, the K_D values were found to be lower than the studies taken from the literature due to the higher relative density of the HD cubes.

In conclusion, high-density concrete cube blocks were found to be more stable than normal-density cubes and hence the concrete volume decreased 70% when compared to ND cubes. Design wave height (H_D) for high density cubes was found 1.5 times of normal density cubes in this study. This study also showed some

underestimations from Van der Meer's (1988) study due to relative density and the hybrid use of both HD and ND cubes.



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DAMAGE RATIOS AND STABILITY COEFFICIENTS

Table A-1 Stability coefficients for First Layer ND Cubes and Second Layer HD Cubes

Breakwater $\psi_s=0.59$							
d=55 cm							
Waves	H _{m0}	N _s	N ₀	D _T	K _D		Observation
	(m)	(-)	(-)	(%)	(-)		
W1	0.05	0.58	0.00	0.00	0.13		
W2	0.08	0.93	0.00	0.00	0.54		
W3	0.10	1.16	0.00	0.00	1.05		
W4	0.10	1.16	0.00	0.00	1.05	K _{D0}	
W5	0.14	1.63	0.17	1.48	2.88	K _{DH}	
W6	0.16	1.86	0.30	2.59	4.29	K _{D<5%}	
W7	0.16	1.86	0.65	5.56	4.29		
W8	0.17	1.98	2.39	20.37	5.15		
W9	0.18	2.09	2.43	20.74	6.11		
W10	0.17	1.98	2.61	22.22	5.15		
W11	0.21	2.44	2.61	22.22	9.71		
W12	0.20	2.33	2.70	22.96	8.39		
W13	0.21	2.44	2.78	23.70	9.71		

Table A-2 Stability coefficients for Reference Area HD Cubes

Breakwater $\psi_s=0.59$							
d=55 cm							
Waves	H _{m0}	N _s	N ₀	D _T	K _D		Observation
	(m)	(-)	(-)	(%)	(-)		
W1	0.05	0.58	0.00	0.00	0.13		
W2	0.08	0.93	0.00	0.00	0.54	K _{D0}	
W3	0.10	1.16	0.17	1.48	1.05	K _{DH} =K _{D<5%}	
W4	0.10	1.16	2.17	18.52	1.05		Sliding
W5	0.14	1.63	4.65	39.63	2.88		Sliding
W6	0.15	1.74	4.87	41.48	3.54		
W7	0.16	1.86	4.87	41.48	4.29		
W8	0.16	1.86	5.13	43.70	4.29		
W9	0.18	2.09	5.13	43.70	6.11		
W10	0.16	1.86	5.13	43.70	4.29		
W11	0.20	2.33	5.26	44.81	8.39		
W12	0.20	2.33	5.30	45.19	8.39		
W13	0.21	2.44	5.35	45.56	9.71		Failure

Table A-3 Stability coefficients for Double Layer ND Cubes

Breakwater $\psi_s=0.59$							
d=55 cm							
Waves	H _{m0} (m)	N _s (-)	N ₀ (-)	D _T (%)	K _D (-)		Observation
W1	0.05	0.89	0.00	0.00	0.47		
W2	0.08	1.43	0.00	0.00	1.94	K _{D0}	
W3	0.10	1.79	0.09	0.77	3.80	K _{DH}	
W4	0.10	1.79	0.13	1.11	3.80		
W4.1	0.12	2.14	0.13	1.11	6.56		
W4.2	0.12	2.14	0.13	1.11	6.56		
W5	0.14	2.50	0.17	1.45	10.42		
W6	0.16	2.66	0.49	4.19	12.51	K _{D<5%}	
W7	0.16	2.86	1.04	8.89	15.55		
W8	0.17	3.04	1.30	11.12	18.65		
W9	0.18	3.21	2.17	18.55	22.14		
W10	0.17	3.04	3.48	29.75	18.65		
W11	0.21	3.75	4.83	41.30	35.16		
W12	0.20	3.57	5.57	47.62	30.37		

Table A-4 Stability coefficients for Single Layer HD Cubes

Breakwater $\psi_s=0.59$							
d=55 cm							
Waves	H _{m0} (m)	N _s (-)	N ₀ (-)	D _T (%)	K _D (-)		Observation
W1	0.05	0.58	0.00	0.00	0.13		
W2	0.08	0.93	0.00	0.00	0.54		
W3	0.10	1.16	0.00	0.00	1.05		
W4	0.11	1.28	0.00	0.00	1.40		
W5	0.14	1.63	0.00	0.00	2.88		
W6	0.17	1.98	0.00	0.00	5.15		
W7	0.17	1.98	0.00	0.00	5.15		
W8	0.18	2.09	0.00	0.00	6.11		
W9	0.19	2.21	0.00	0.00	7.19		
W10	0.17	1.98	0.00	0.00	5.15		
W11	0.22	2.56	0.00	0.00	11.16		
W12	0.21	2.44	0.00	0.00	9.71		
W13	0.21	2.44	0.00	0.00	9.71		

Table A-5 Stability coefficients for Single Layer ND Cubes

Breakwater $\psi_s=0.59$							
d=55 cm							
Waves	H _{m0}	N _s	N ₀	D _T	K _D		Observation
	(m)	(-)	(-)	(%)	(-)		
W1	0.05	0.89	0.00	0.00	0.47		
W2	0.08	1.43	0.00	0.00	1.94		
W3	0.10	1.79	0.00	0.00	3.80		
W4	0.11	1.96	0.00	0.00	5.05		
W5	0.15	2.68	0.00	0.00	12.81		
W6	0.17	3.04	0.00	0.00	18.65		
W7	0.17	3.04	0.00	0.00	18.65		
W8	0.18	3.21	0.00	0.00	22.14		
W9	0.19	3.39	0.00	0.00	26.04		
W10	0.17	3.04	0.00	0.00	18.65		
W11	0.22	3.93	0.00	0.00	40.42		
W12	0.21	3.75	0.00	0.00	35.16		
W13	0.21	3.75	0.00	0.00	35.16		

Table A-6 Stability coefficients for Emerged Berm

Breakwater $\psi_s=0.59$							
d=45 cm							
Waves	H _{m0}	N _s	N ₀	D _T	K _D		Observation
	(m)	(-)	(-)	(%)	(-)		
W1	0.05	0.58	0.00	0.00	0.13		
W2	0.08	0.93	0.00	0.00	0.54		
W3	0.11	1.28	0.00	0.00	1.40		
W4	0.10	1.16	0.00	0.00	1.05		
W4.1	0.11	1.28	0.00	0.00	1.40		
W4.2	0.12	1.40	0.00	0.00	1.81	K _{D0}	
W5	0.14	1.63	0.13	1.11	2.88	K _{DH}	
W5.1	0.14	1.63	0.13	1.11	2.88		
W6	0.15	1.74	0.13	1.11	3.54		
W7	0.15	1.74	0.22	1.85	3.54		
W8	0.15	1.74	0.22	1.85	3.54		
W9	0.16	1.86	0.35	2.96	4.29		
W10	0.15	1.74	0.52	4.44	3.54	K _{D<5%}	
W11	0.18	2.09	0.65	5.56	6.11		
W12	0.17	1.98	1.09	9.26	5.15		
W13	0.17	1.98	1.78	15.19	5.15		

Table A-7 Stability coefficients for Berm at SWL

Breakwater $\psi_s=0.59$						
d=55 cm						
Waves	H_{m0} (m)	N_s (-)	N_0 (-)	D_T (%)	K_D (-)	Observation
W1	0.05	0.58	0.00	0.00	0.13	
W2	0.08	0.93	0.00	0.00	0.54	
W3	0.09	1.05	0.00	0.00	0.76	
W4	0.10	1.16	0.00	0.00	1.05	K_{D0}
W5	0.13	1.51	0.04	0.37	2.30	K_{DH}
W6	0.15	1.74	0.17	1.48	3.54	
W7	0.15	1.74	0.22	1.85	3.54	
W8	0.16	1.86	0.43	3.70	4.29	
W9	0.17	1.98	0.52	4.44	5.15	$K_{D<5\%}$
W10	0.16	1.86	0.65	5.56	4.29	
W11	0.19	2.21	1.39	11.85	7.19	
W12	0.20	2.33	1.43	12.22	8.39	
W13	0.21	2.44	2.09	17.78	9.71	

Table A-8 Stability coefficients for Submerged Berm

Breakwater $\psi_s=0.59$						
d=65 cm						
Waves	H_{m0} (m)	N_s (-)	N_0 (-)	D_T (%)	K_D (-)	Observation
W1	0.05	0.58	0.00	0.00	0.13	
W2	0.07	0.81	0.00	0.00	0.36	
W3	0.09	1.05	0.00	0.00	0.76	
W4	0.08	0.93	0.00	0.00	0.54	
W5	0.11	1.28	0.00	0.00	1.40	
W6	0.13	1.51	0.00	0.00	2.30	
W7	0.14	1.63	0.00	0.00	2.88	K_{D0}
W8	0.16	1.86	0.04	0.37	4.29	K_{DH}
W9	0.17	1.98	0.09	0.74	5.15	
W10	0.19	2.21	0.26	2.22	7.19	
W11	0.22	2.56	0.39	3.33	11.16	
W12	0.24	2.79	0.48	4.07	14.49	
W13	0.25	2.91	0.57	4.81	16.38	

Table A-9 Stability coefficients for Emerged Berm HD Cubes over Reference Area

Breakwater $\psi_s=0.59$							
d=45 cm							
Waves	H_{m0}	N_s	N_0	D_T	K_D		Observation
	(m)	(-)	(-)	(%)	(-)		
W1	0.05	0.58	0.00	0.00	0.13		
W2	0.08	0.93	0.00	0.00	0.54		
W3	0.10	1.16	0.00	0.00	1.05		
W4	0.10	1.16	0.00	0.00	1.05		
W4.1	0.11	1.28	0.00	0.00	1.40		
W4.2	0.12	1.40	0.00	0.00	1.81	K_{D0}	
W5	0.13	1.51	5.17	44.07	2.30		Sliding
W5.1	0.13	1.51	5.22	44.44	2.30		
W6	0.15	1.74	5.22	44.44	3.54		
W7	0.15	1.74	5.26	44.81	3.54		
W8	0.15	1.74	5.26	44.81	3.54		
W9	0.17	1.98	5.26	44.81	5.15		
W10	0.16	1.86	5.26	44.81	4.29		
W11	0.18	2.09	5.26	44.81	6.11		
W12	0.17	1.98	5.26	44.81	5.15		
W13	0.17	1.98	5.26	44.81	5.15		

MOVEMENT AND DAMAGE PROCESSES FOR ALL EXPERIMENTS

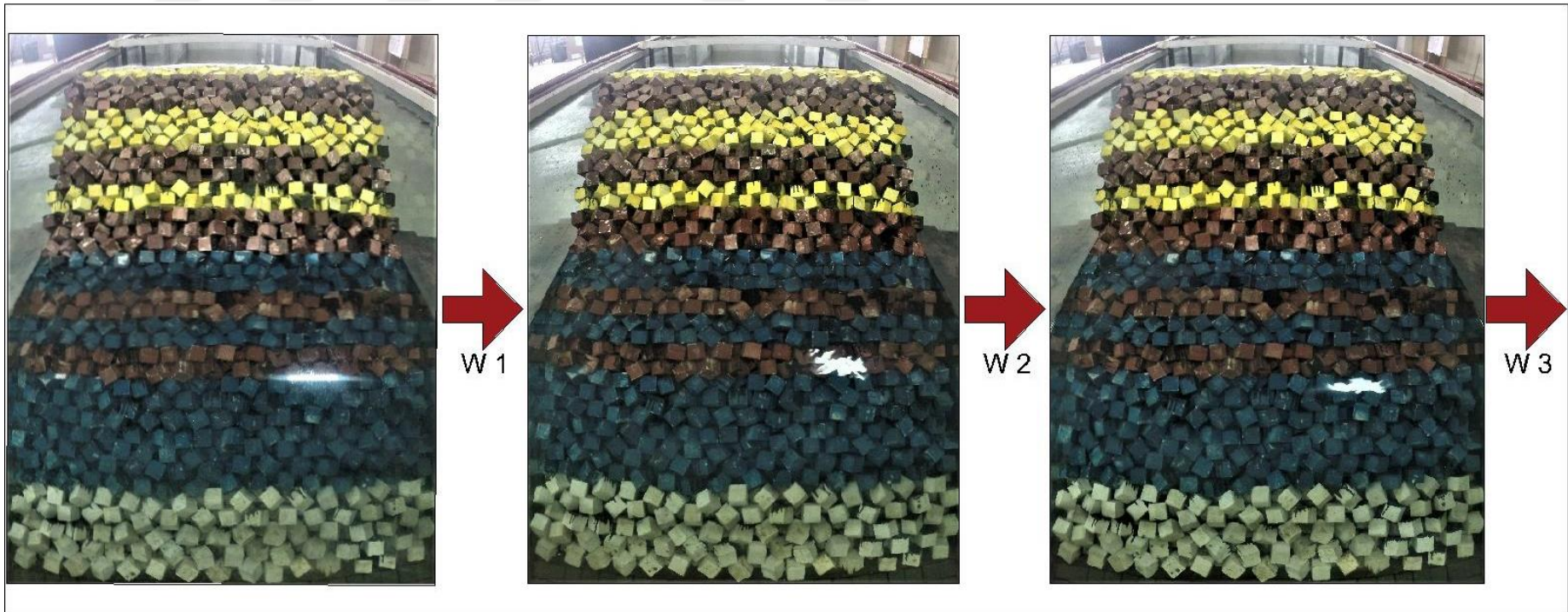


Figure B-1 Movement and damage process (1) for Experiment 1: First Layer ND Cubes and Second Layer HD Cubes

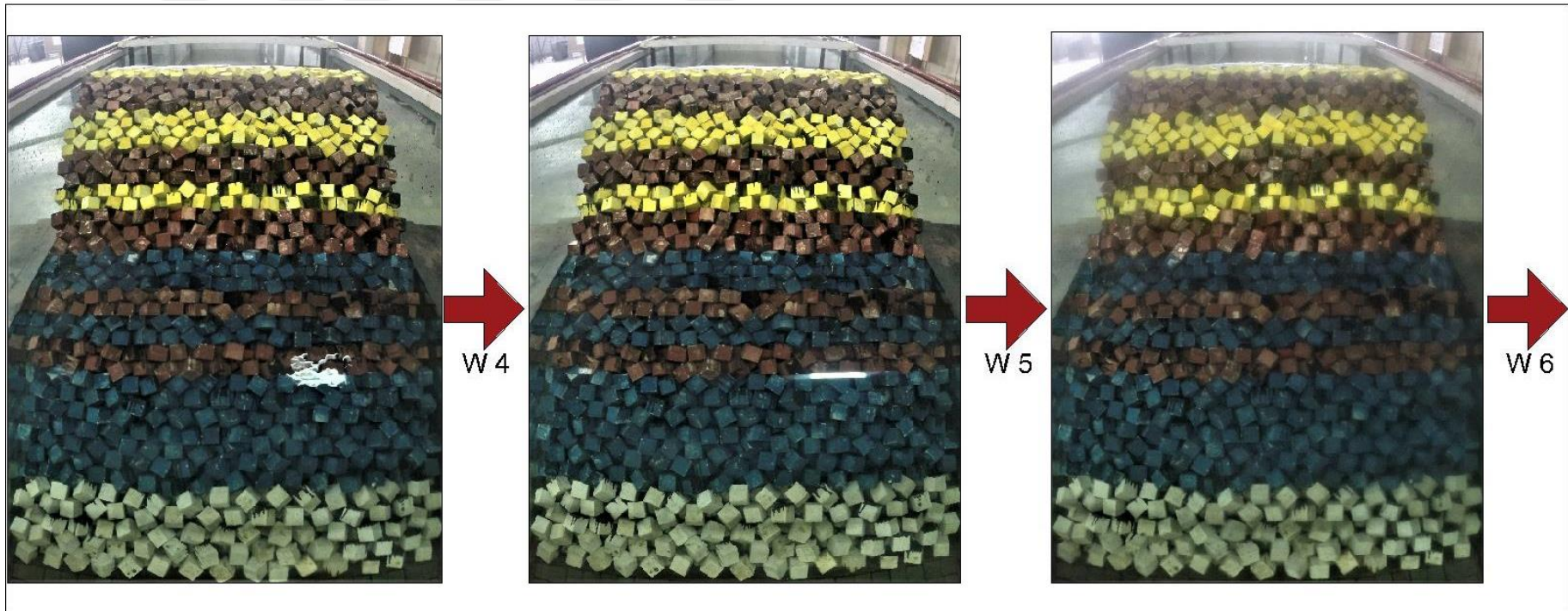


Figure B-2 Movement and damage process (2) for Experiment 1: First Layer ND Cubes and Second Layer HD Cubes

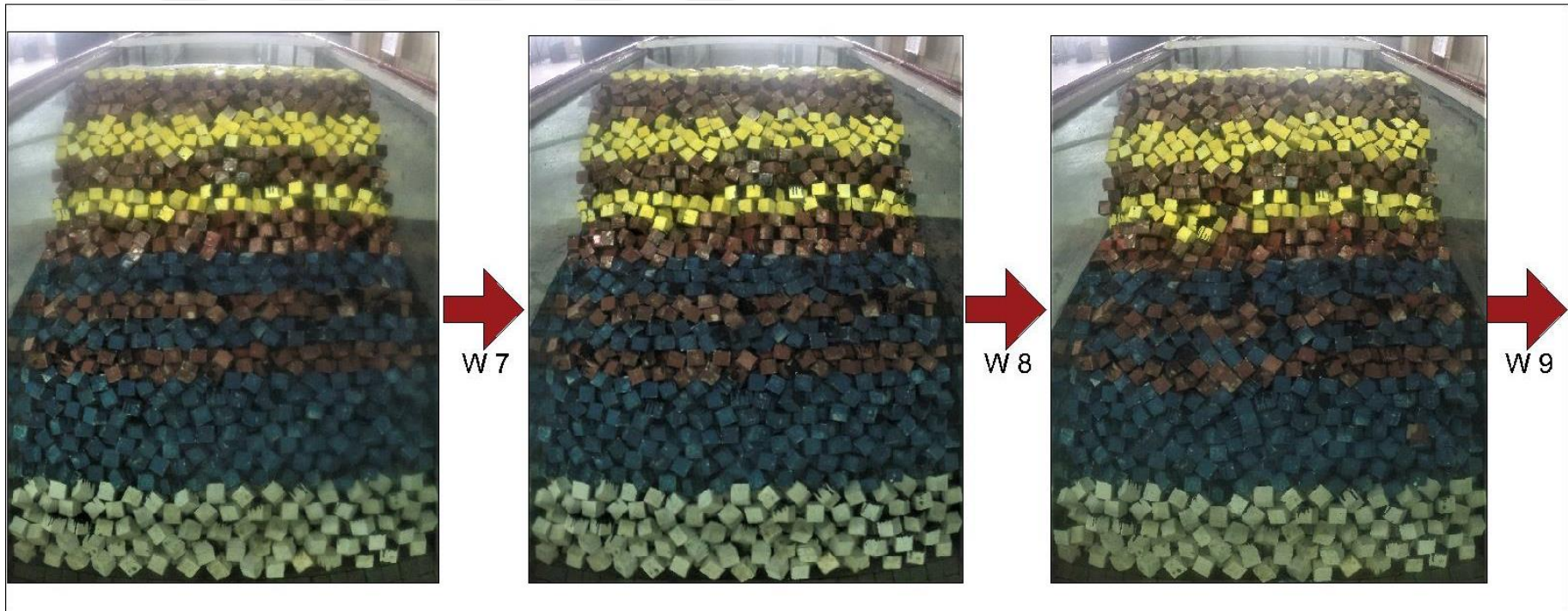


Figure B-3 Movement and damage process (3) for Experiment 1: First Layer ND Cubes and Second Layer HD Cubes

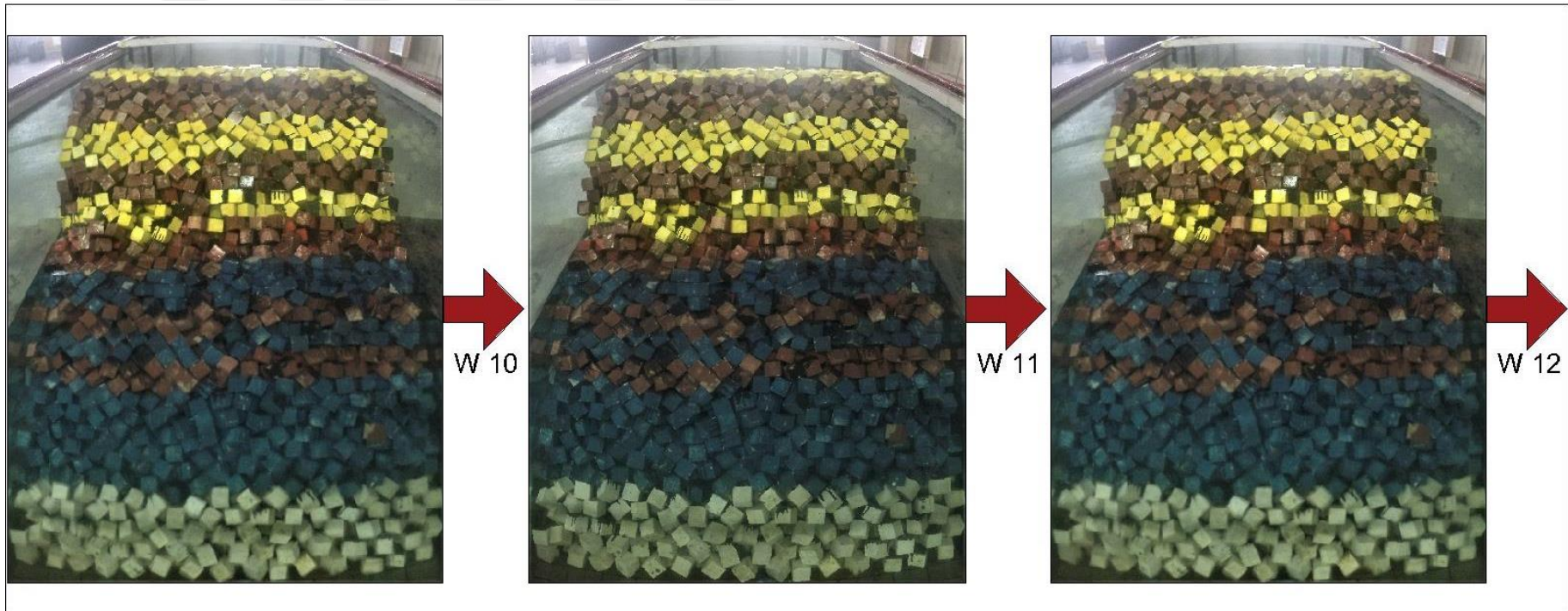


Figure B-4 Movement and damage process (4) for Experiment 1: First Layer ND Cubes and Second Layer HD Cubes

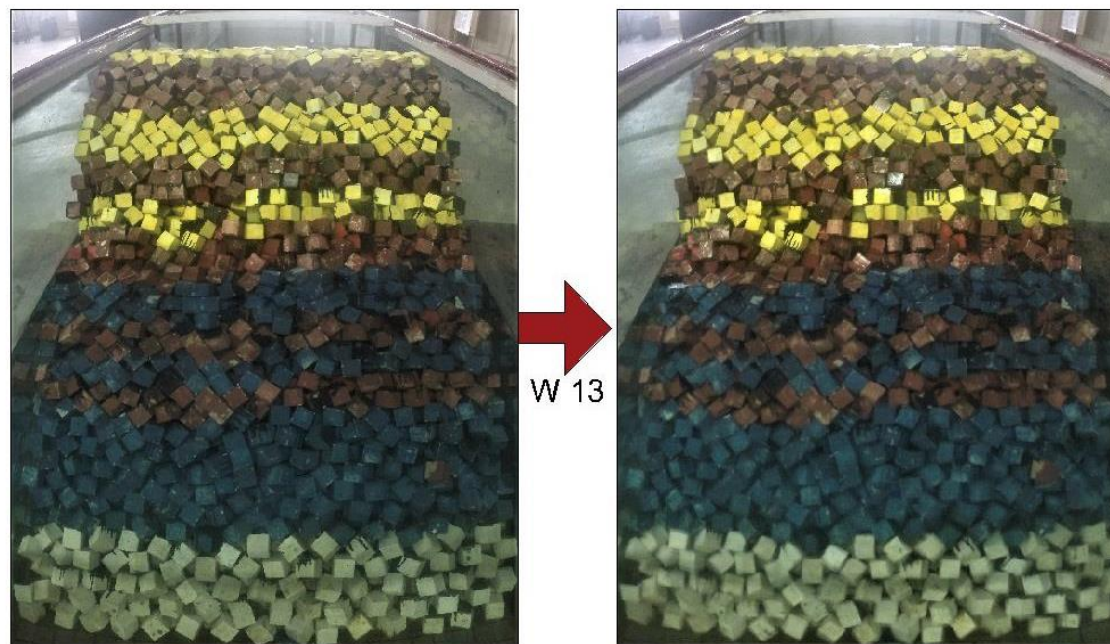


Figure B-5 Movement and damage process (5) for Experiment 1: First Layer ND Cubes and Second Layer HD Cubes

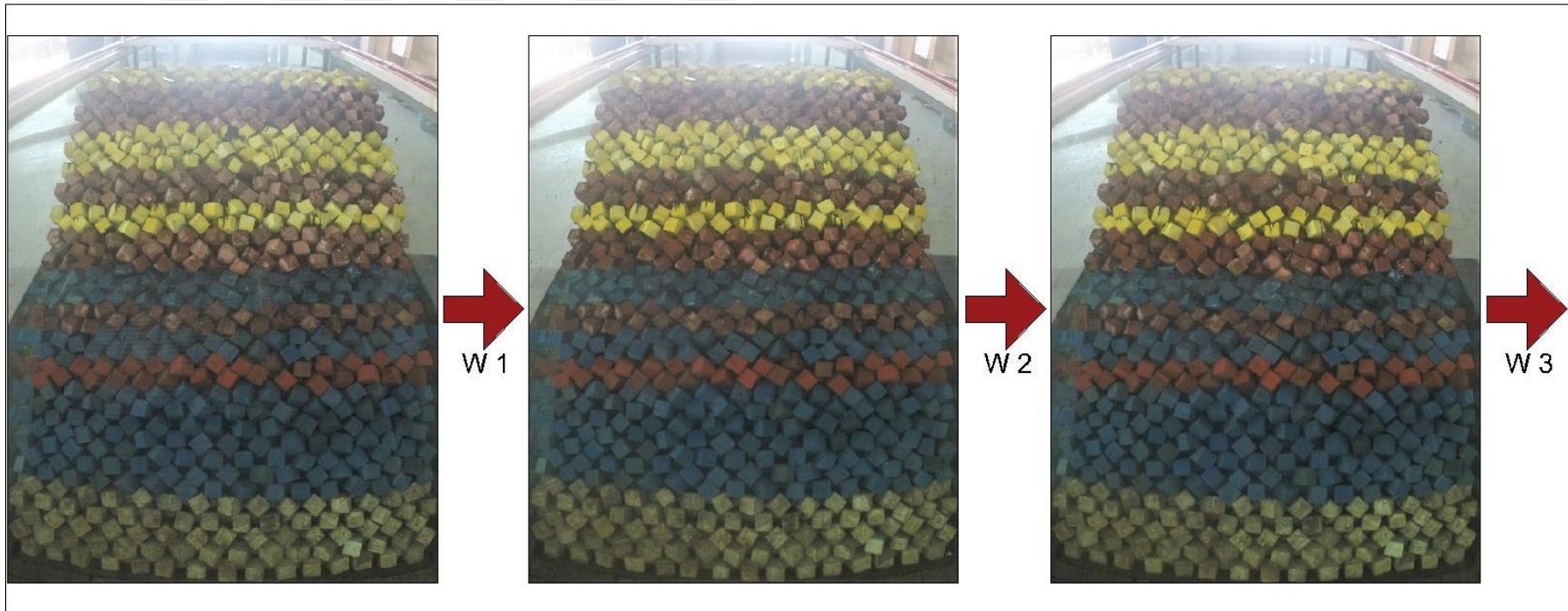


Figure B-6 Movement and damage process (1) for Experiment 2: Reference Area HD Cubes

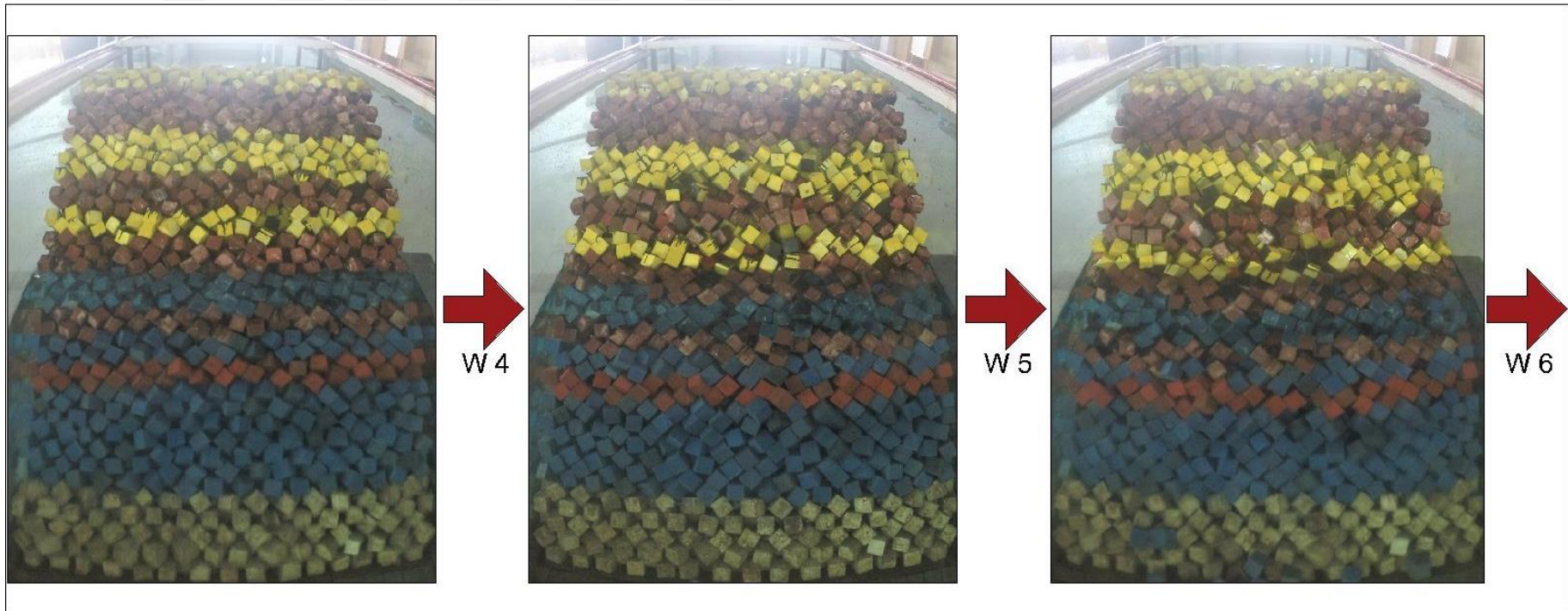


Figure B-7 Movement and damage process (2) for Experiment 2: Reference Area HD Cubes

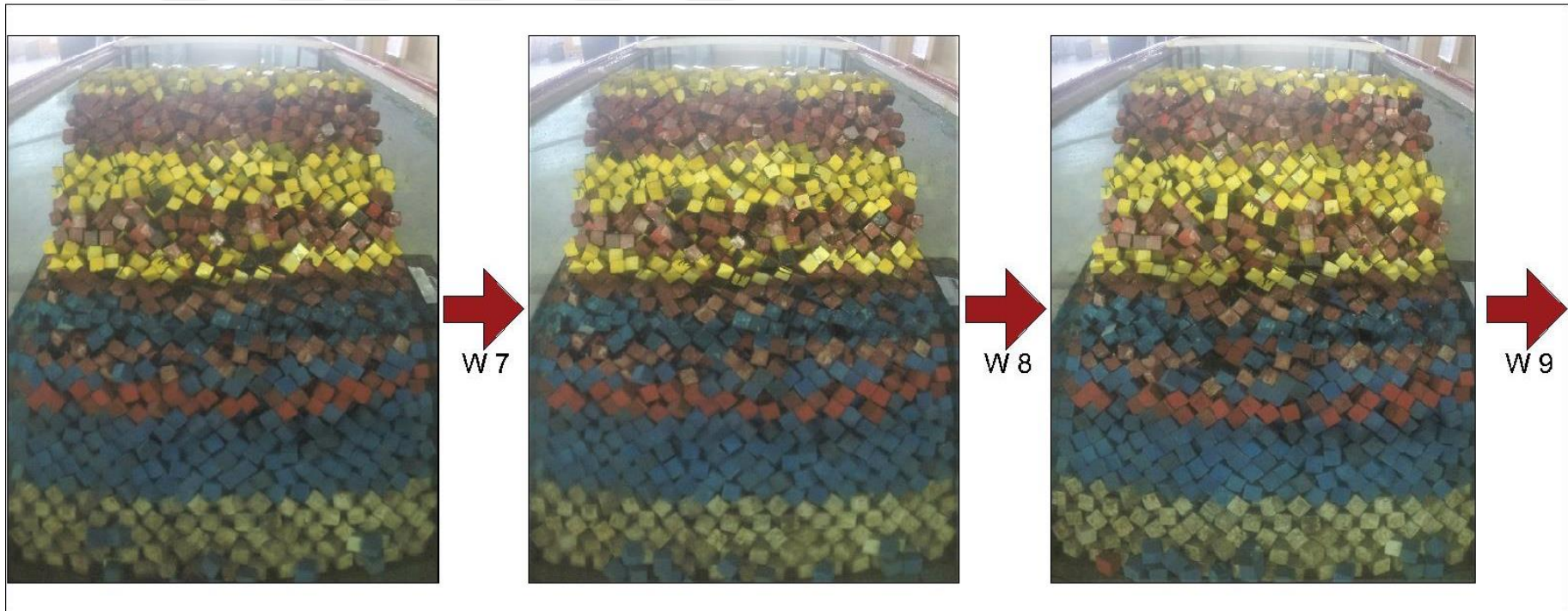


Figure B-8 Movement and damage process (3) for Experiment 2: Reference Area HD Cubes

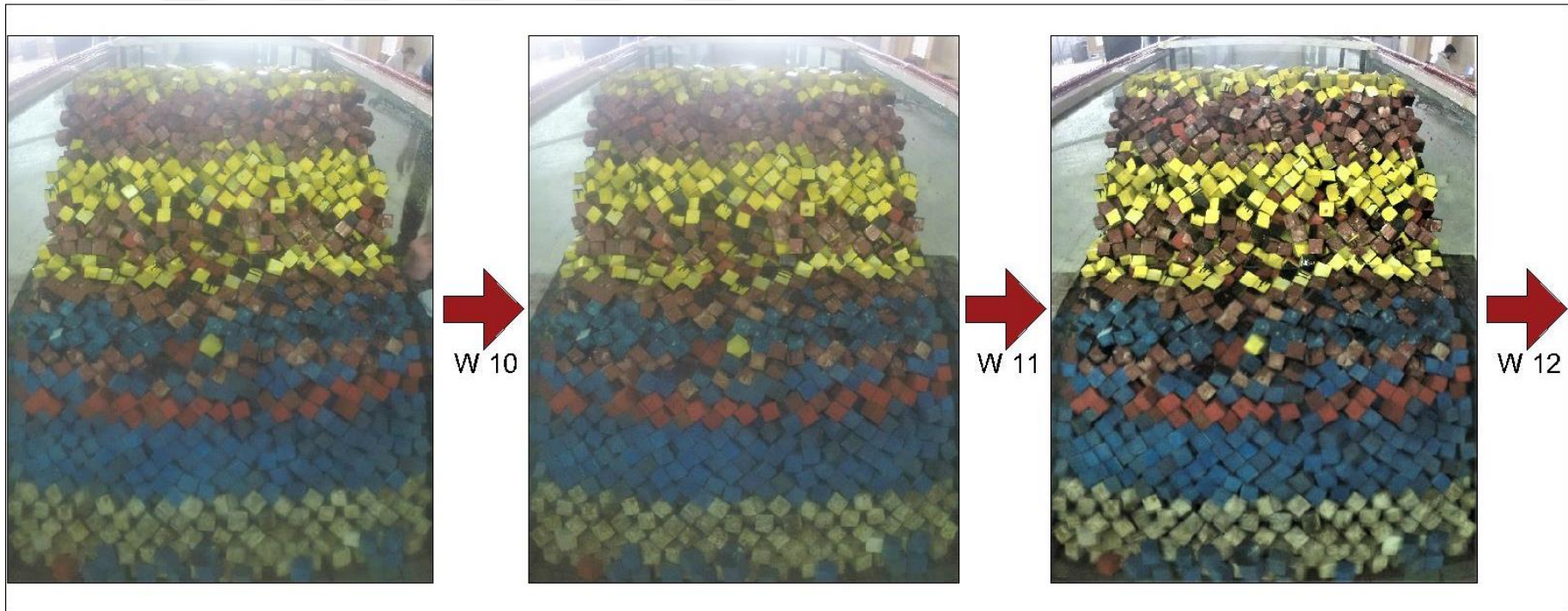


Figure B-9 Movement and damage process (4) for Experiment 2: Reference Area HD Cubes

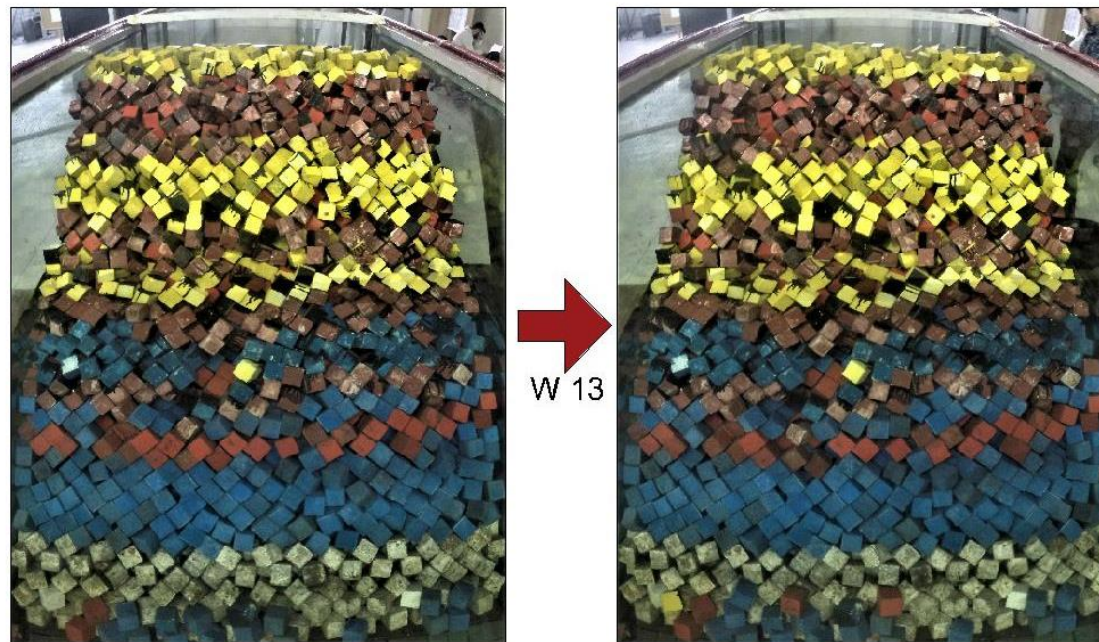


Figure B-10 Movement and damage process (5) for Experiment 2: Reference Area HD Cubes



Figure B-11 Movement process (1) for Experiment 3: Single Layer HD Cubes with Regular Placement (no damage)

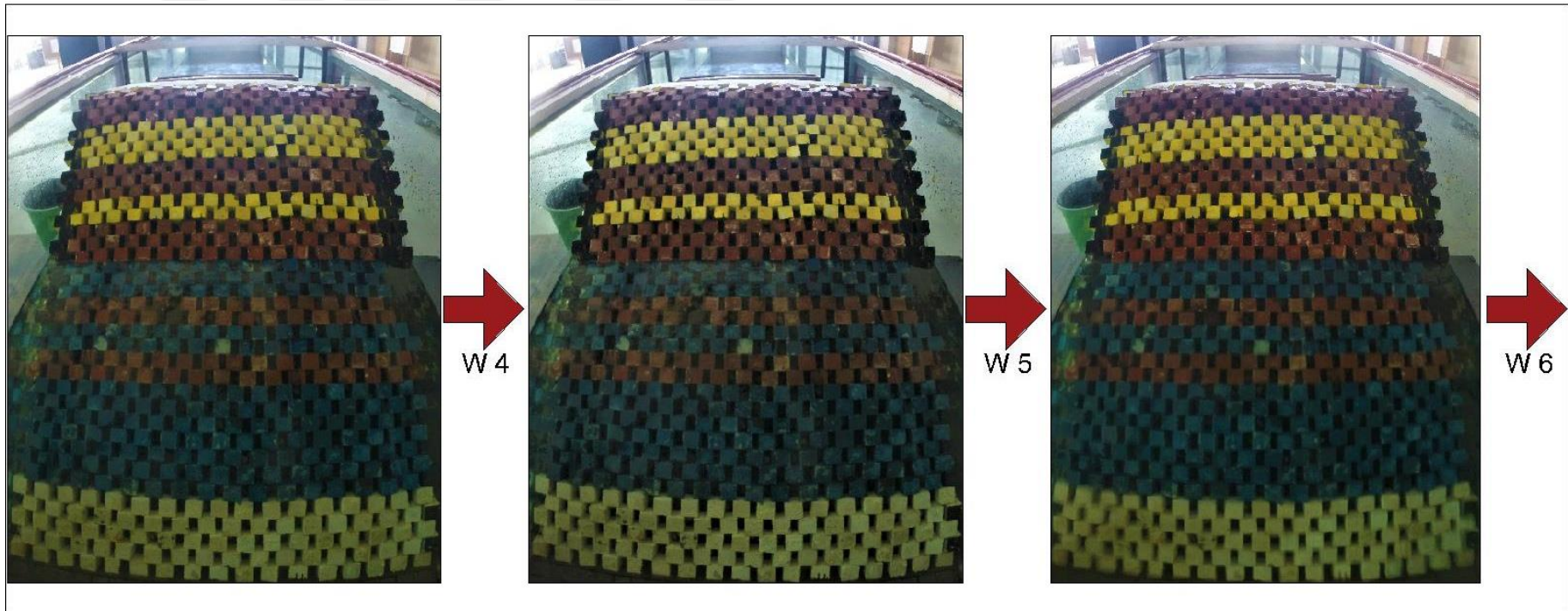


Figure B-12 Movement process (2) for Experiment 3: Single Layer HD Cubes with Regular Placement (no damage)

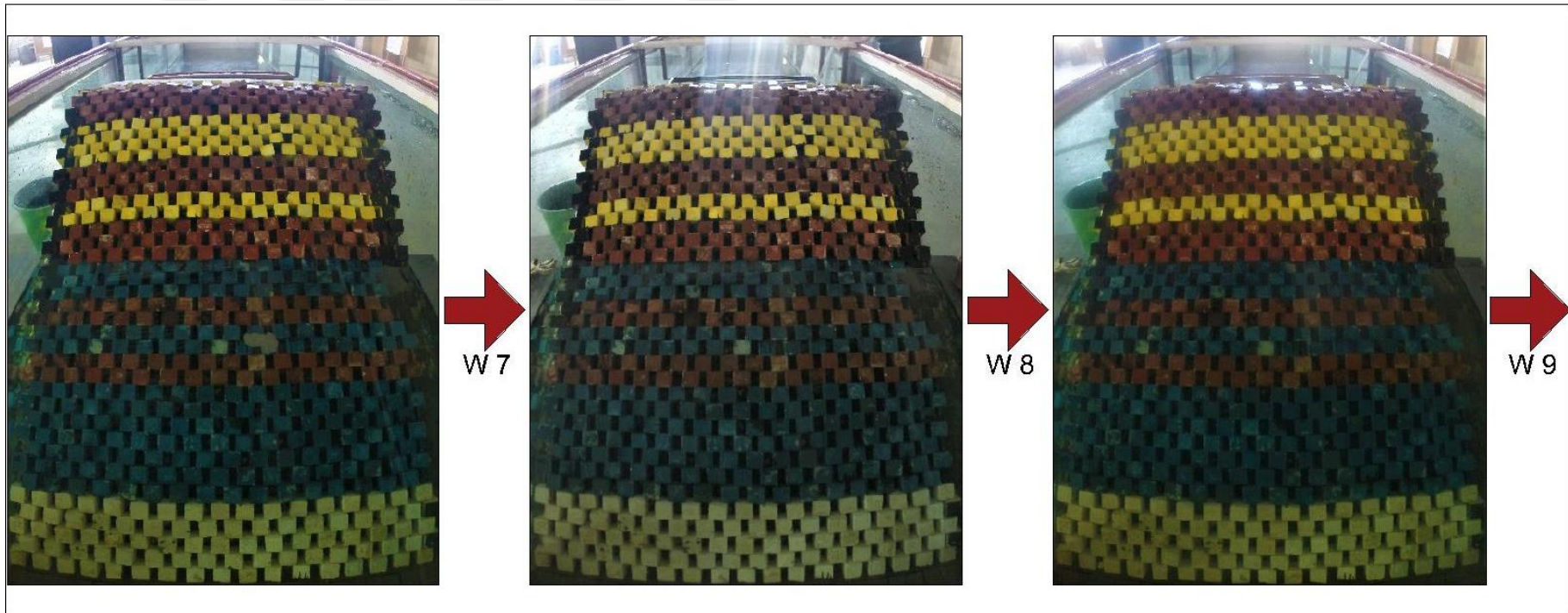


Figure B-13 Movement process (3) for Experiment 3: Single Layer HD Cubes with Regular Placement (no damage)

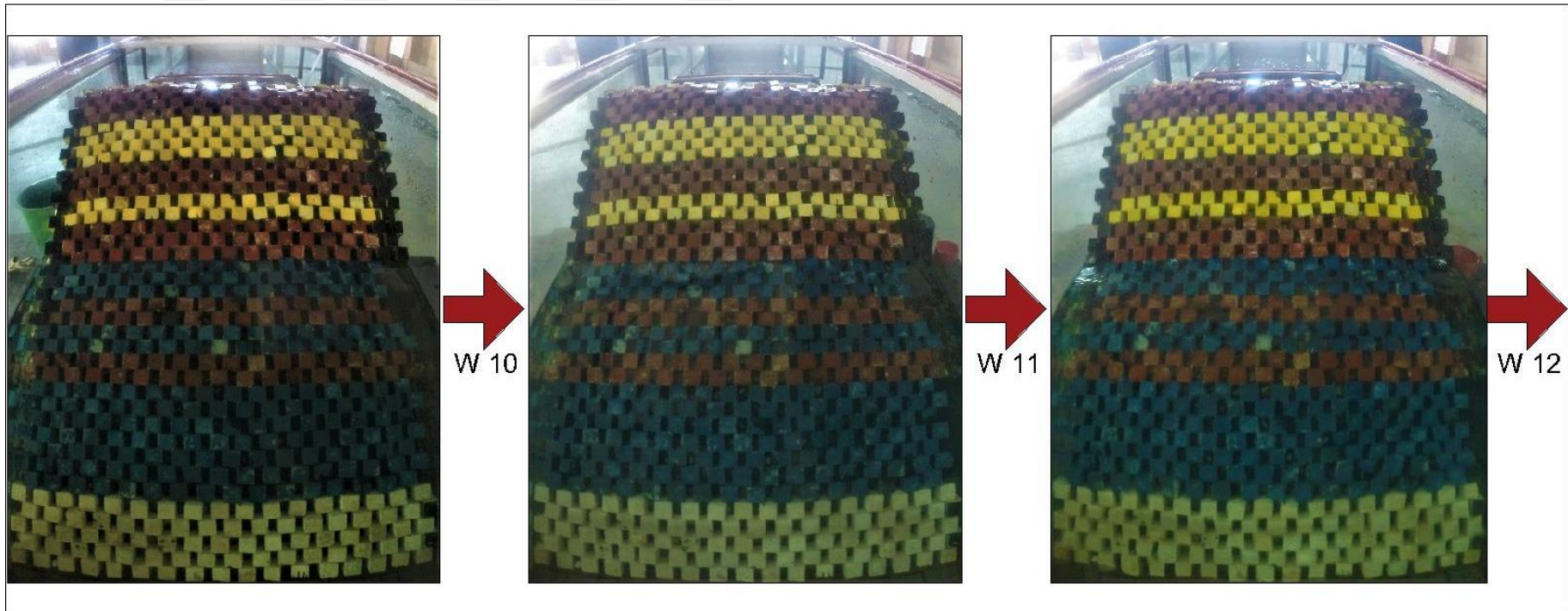


Figure B-14 Movement process (4) for Experiment 3: Single Layer HD Cubes with Regular Placement (no damage)

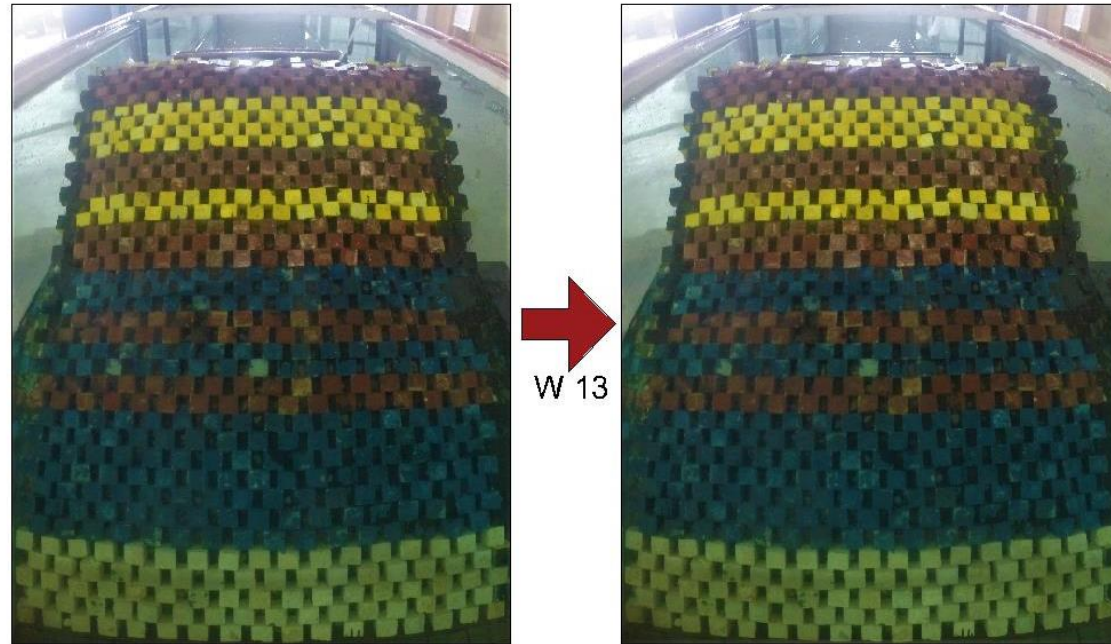


Figure B-15 Movement process (5) for Experiment 3: Single Layer HD Cubes with Regular Placement (no damage)

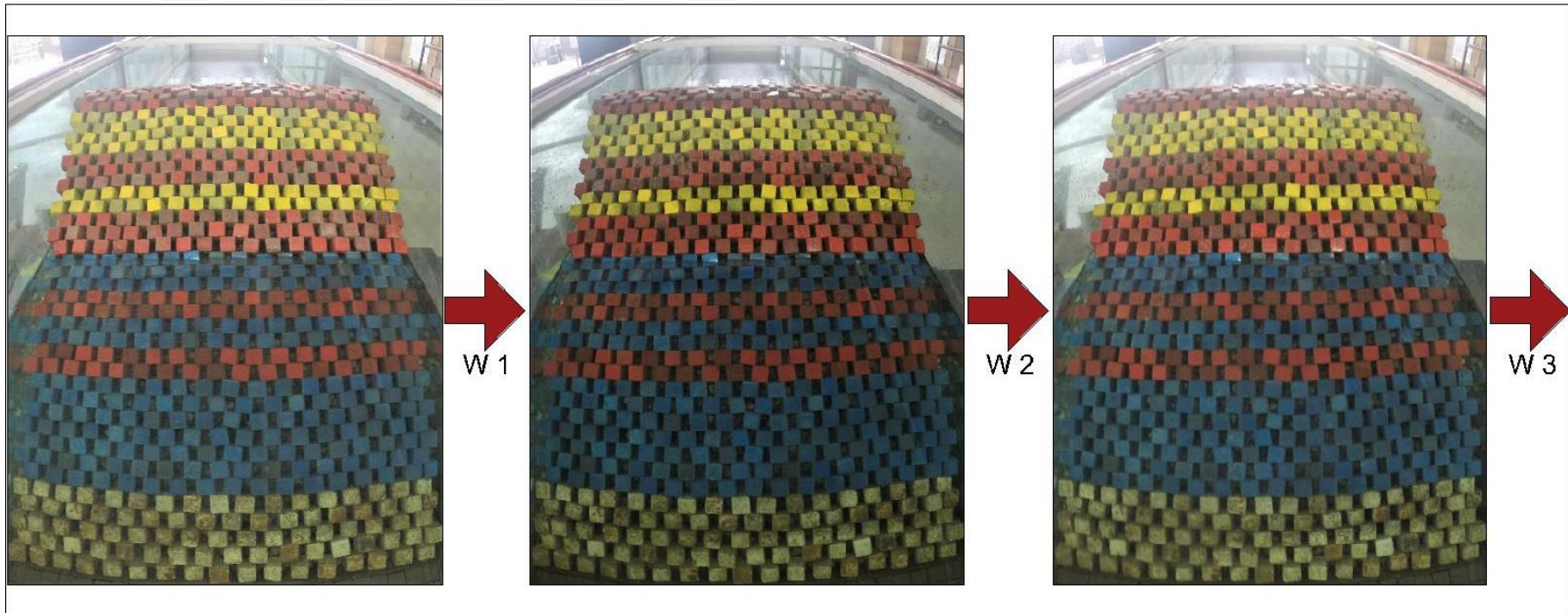


Figure B-16 Movement process (1) for Experiment 4: Single Layer ND Cubes with Regular Placement (no damage)

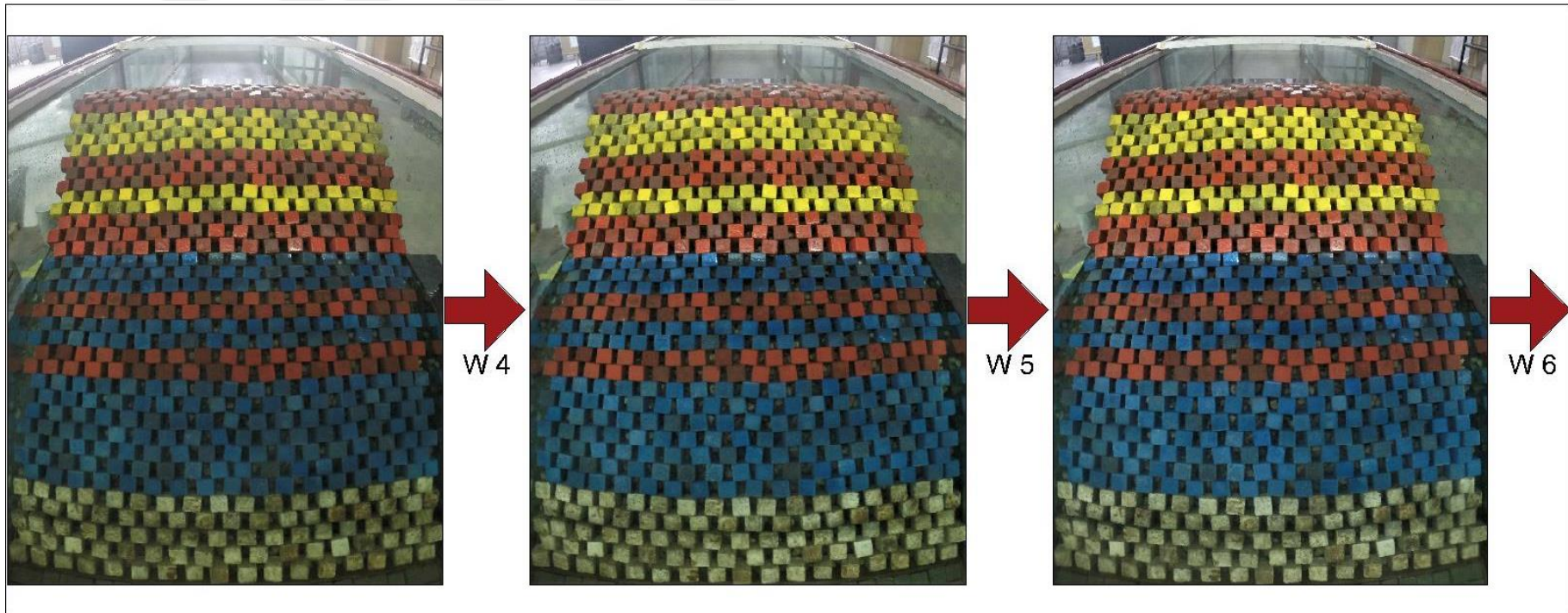


Figure B-17 Movement process (2) for Experiment 4: Single Layer ND Cubes with Regular Placement (no damage)

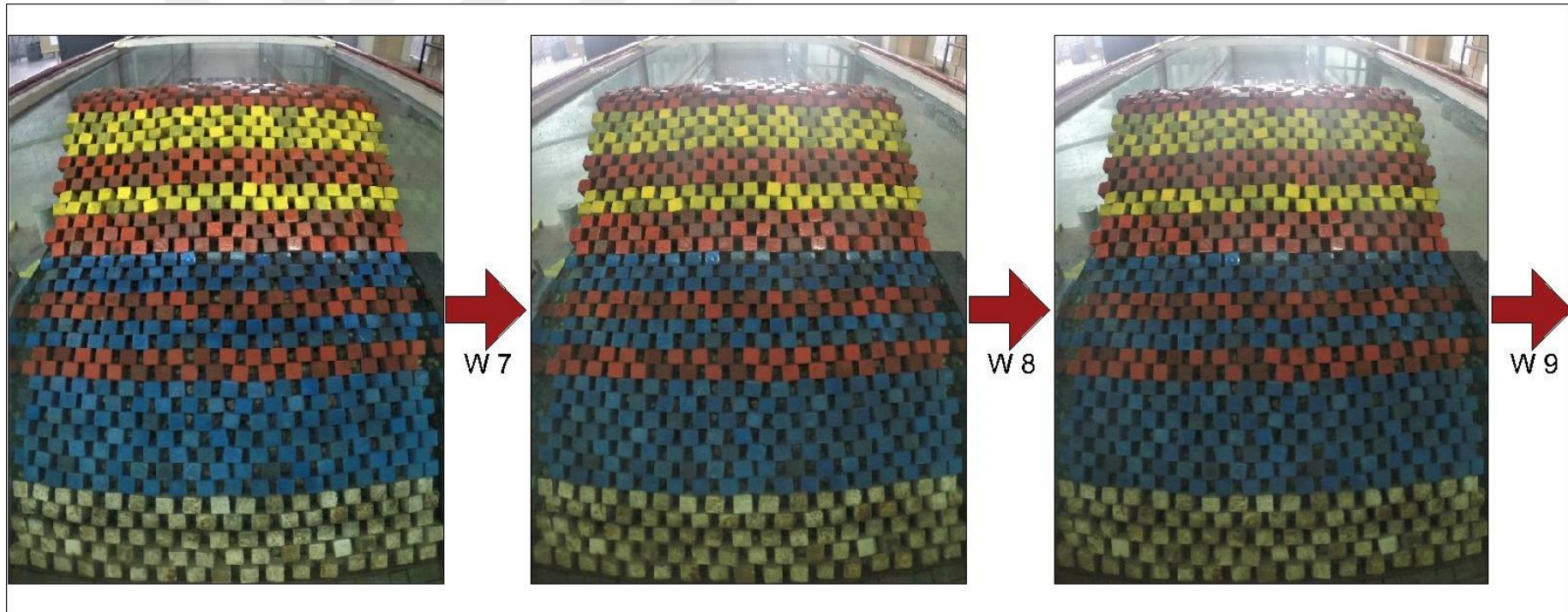


Figure B-18 Movement process (3) for Experiment 4: Single Layer ND Cubes with Regular Placement (no damage)

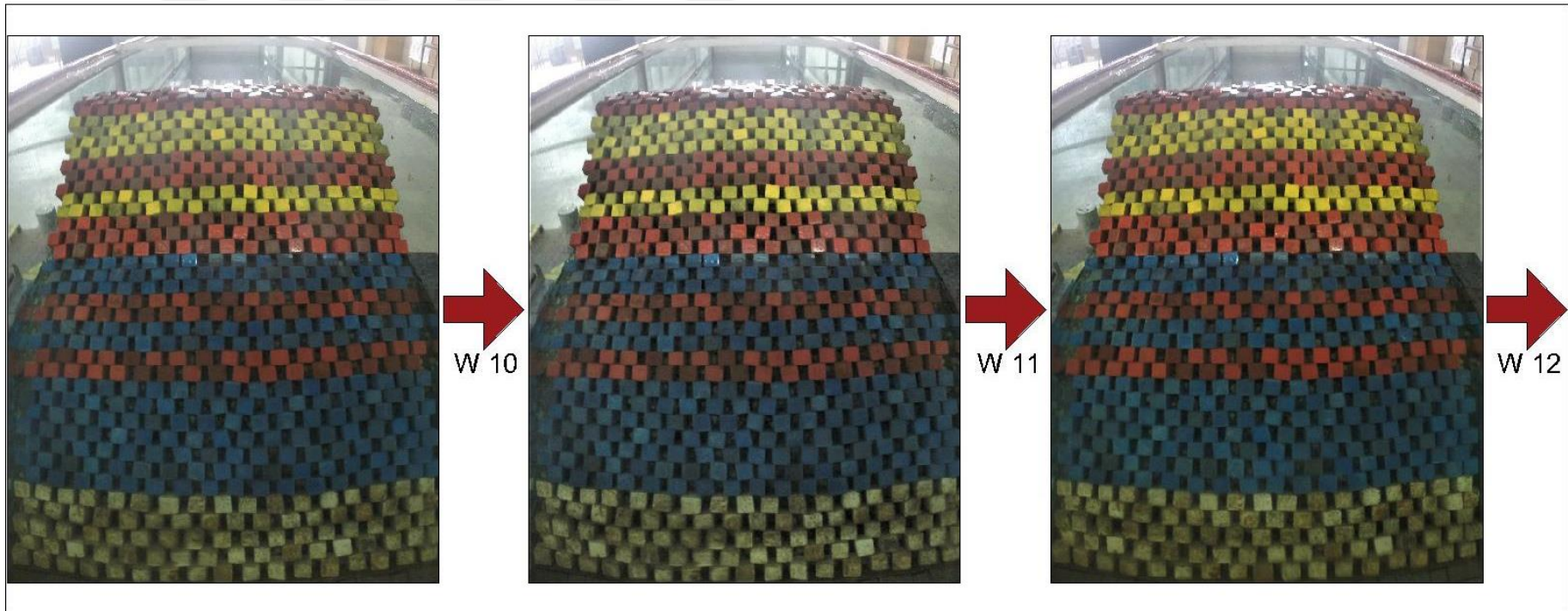


Figure B-19 Movement process (4) for Experiment 4: Single Layer ND Cubes with Regular Placement (no damage)

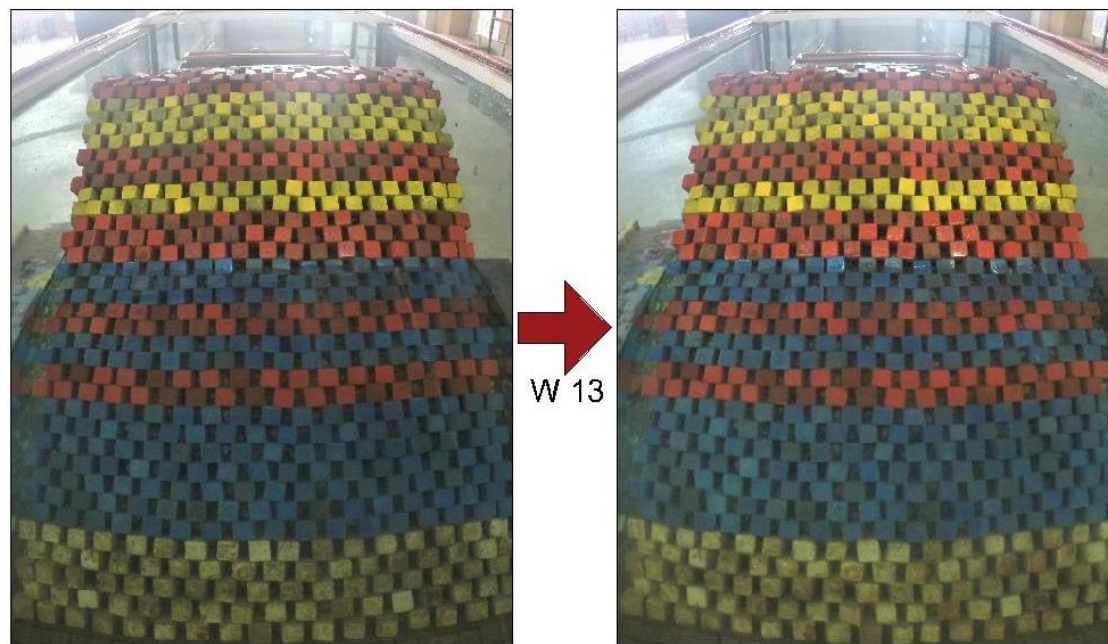


Figure B-20 Movement process (5) for Experiment 4: Single Layer ND Cubes with Regular Placement (no damage)

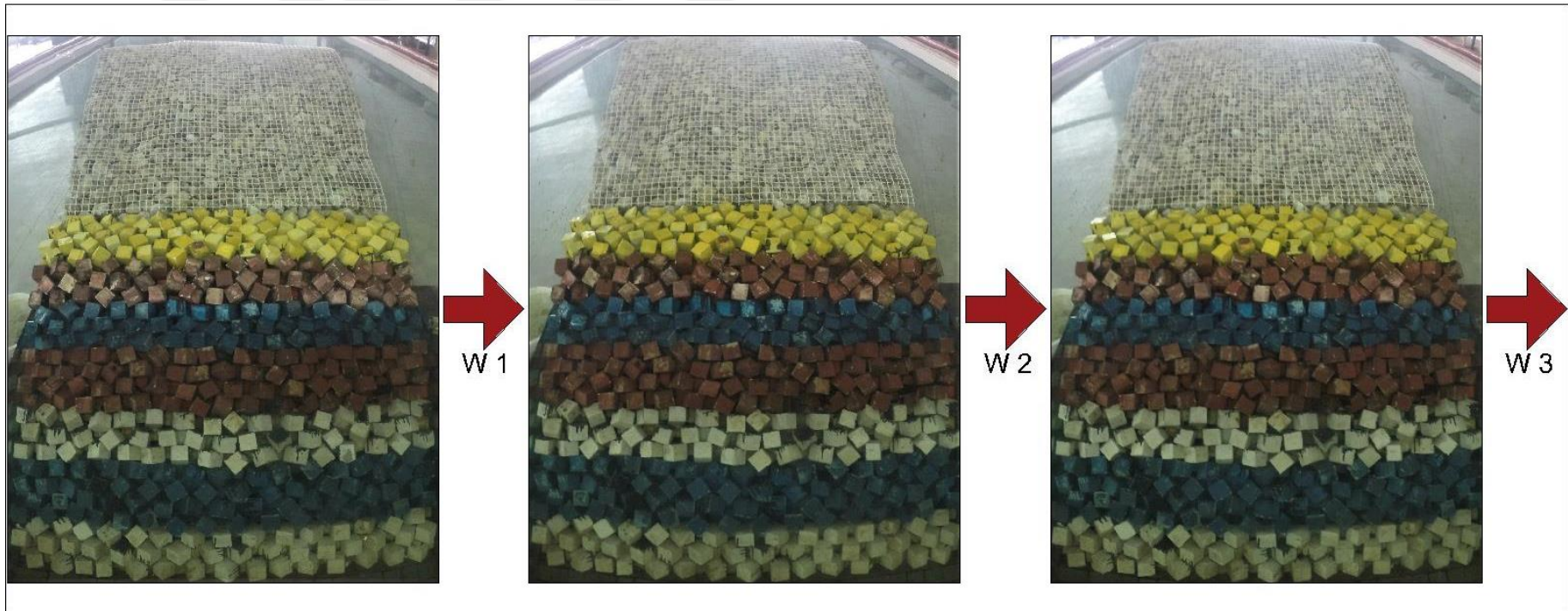


Figure B-21 Movement and damage process (1) for Experiment 1: Emerged Berm

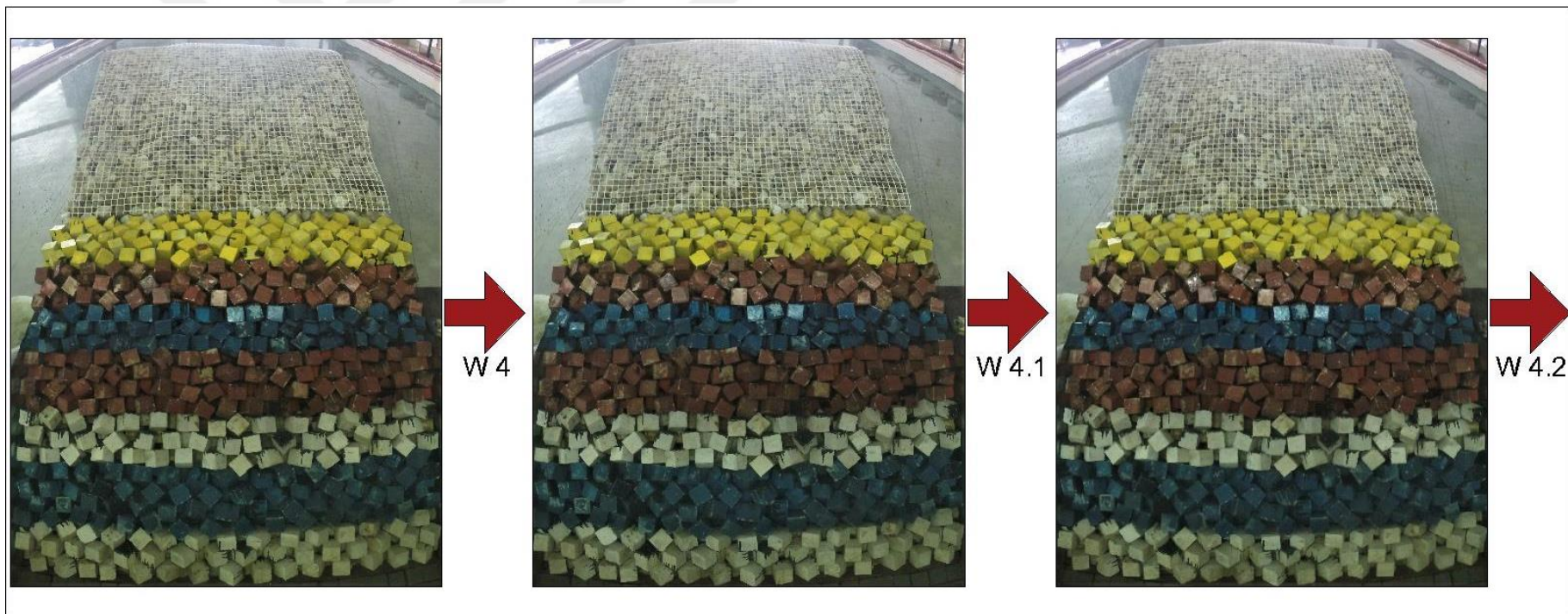


Figure B-22 Movement and damage process (2) for Experiment 1: Emerged Berm

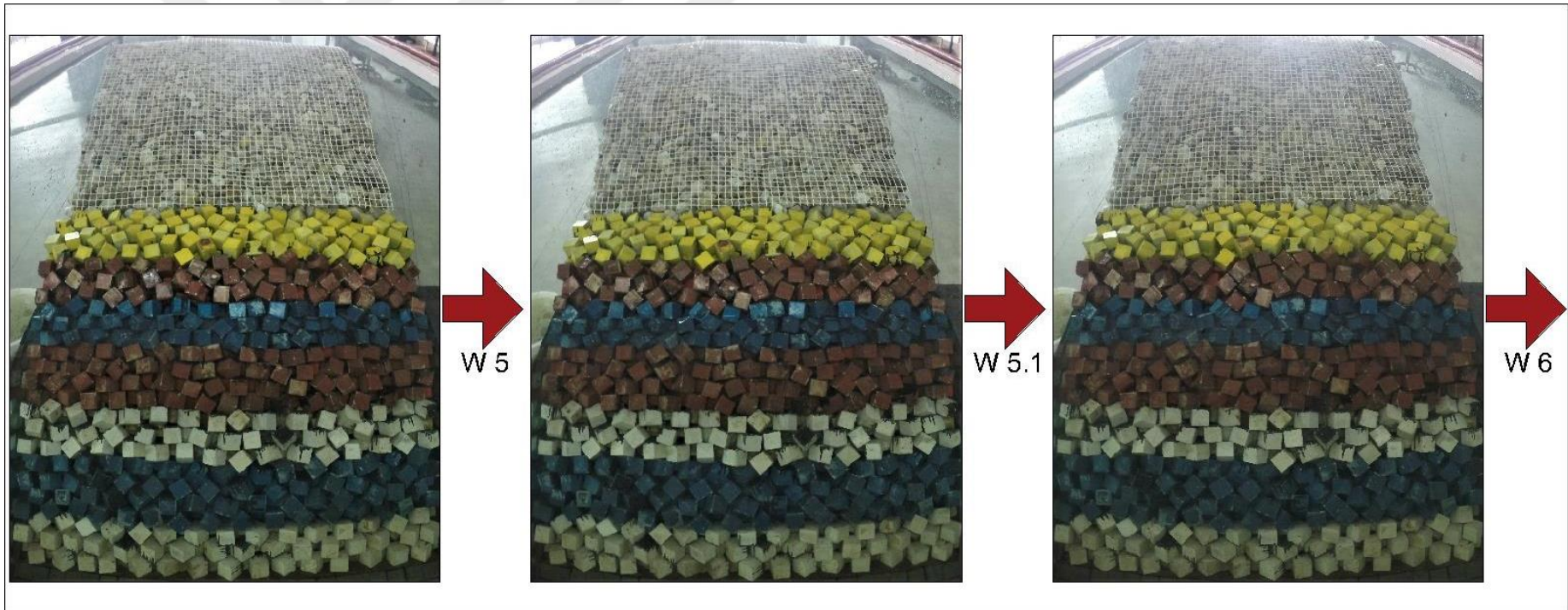


Figure B-23 Movement and damage process (3) for Experiment 1: Emerged Berm

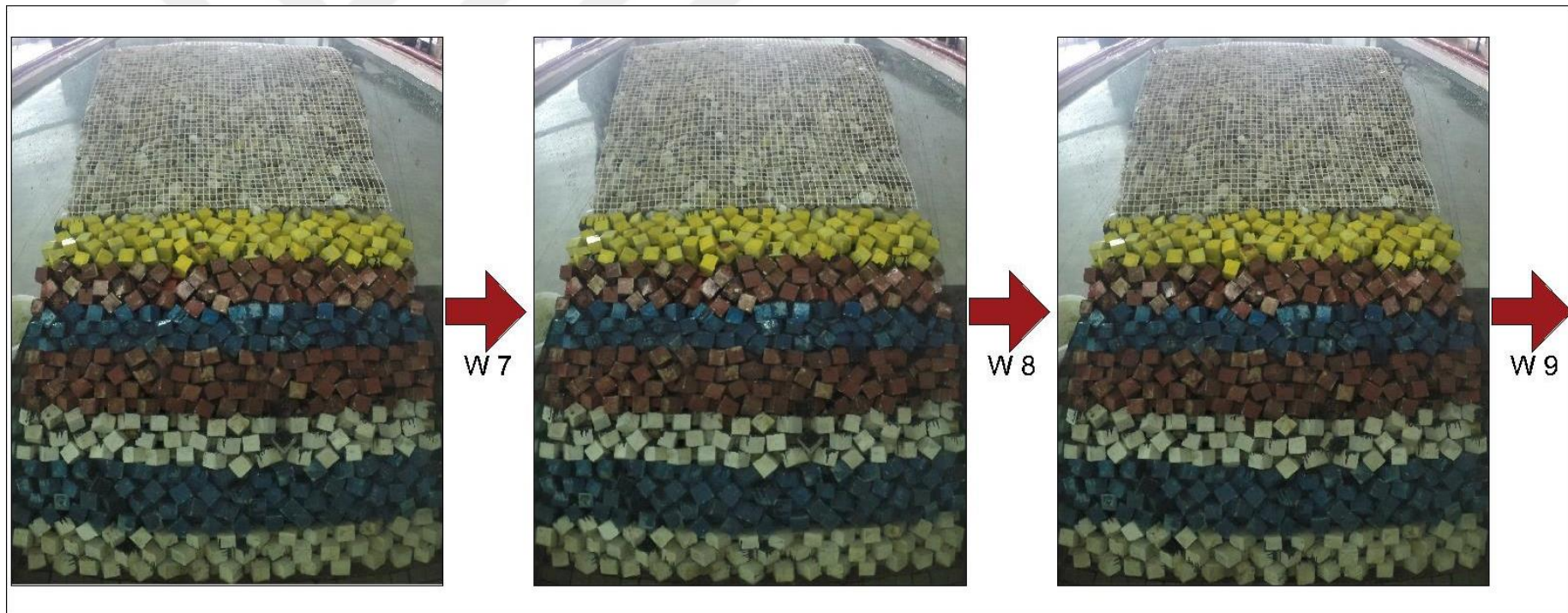


Figure B-24 Movement and damage process (4) for Experiment 1: Emerged Berm

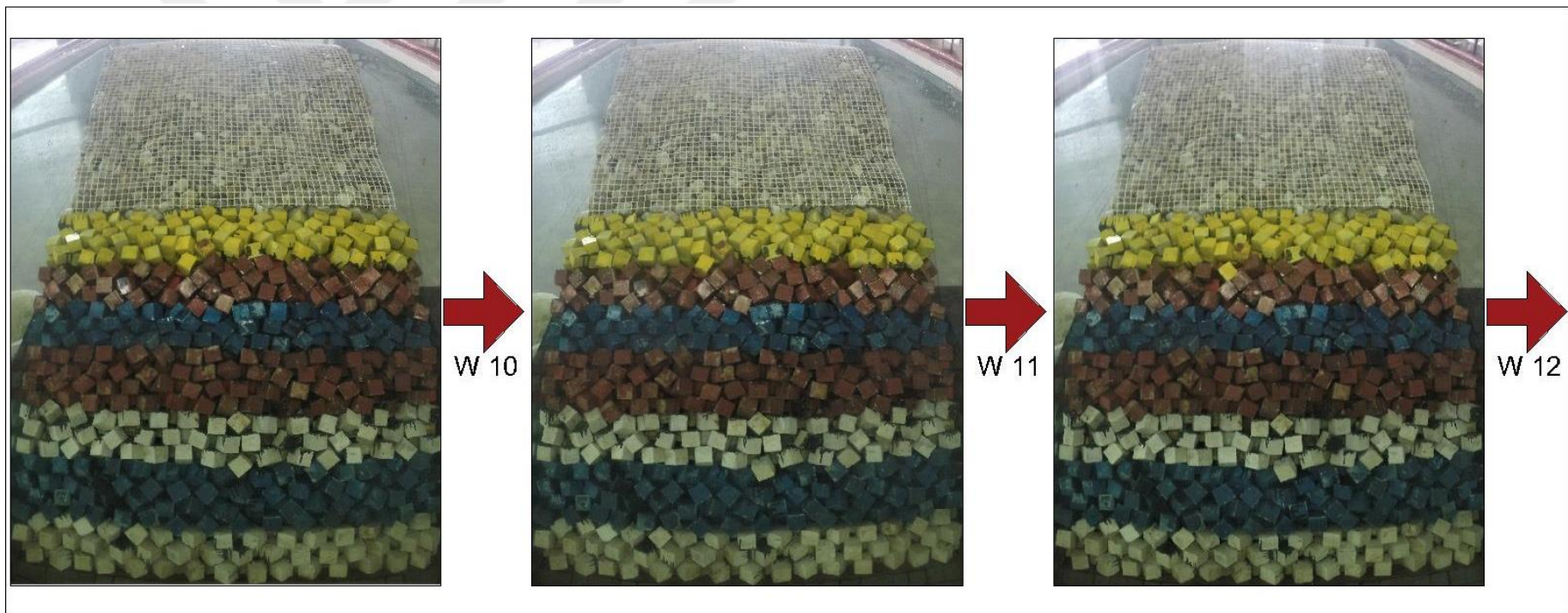


Figure B-25 Movement and damage process (5) for Experiment 1: Emerged Berm

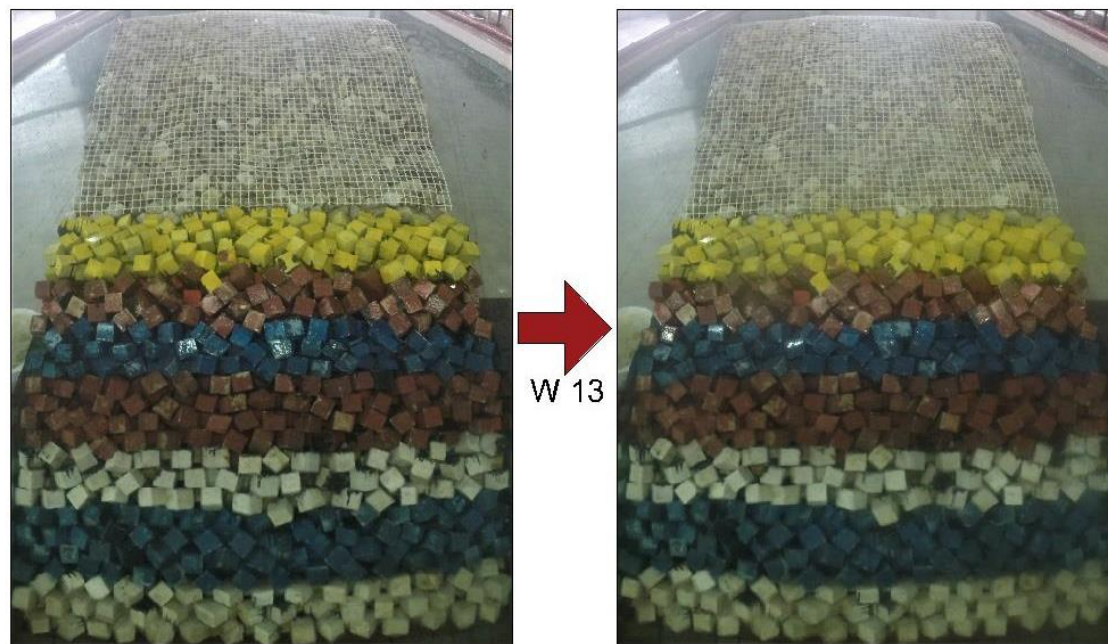


Figure B-26 Movement and damage process (6) for Experiment 1: Emerged Berm

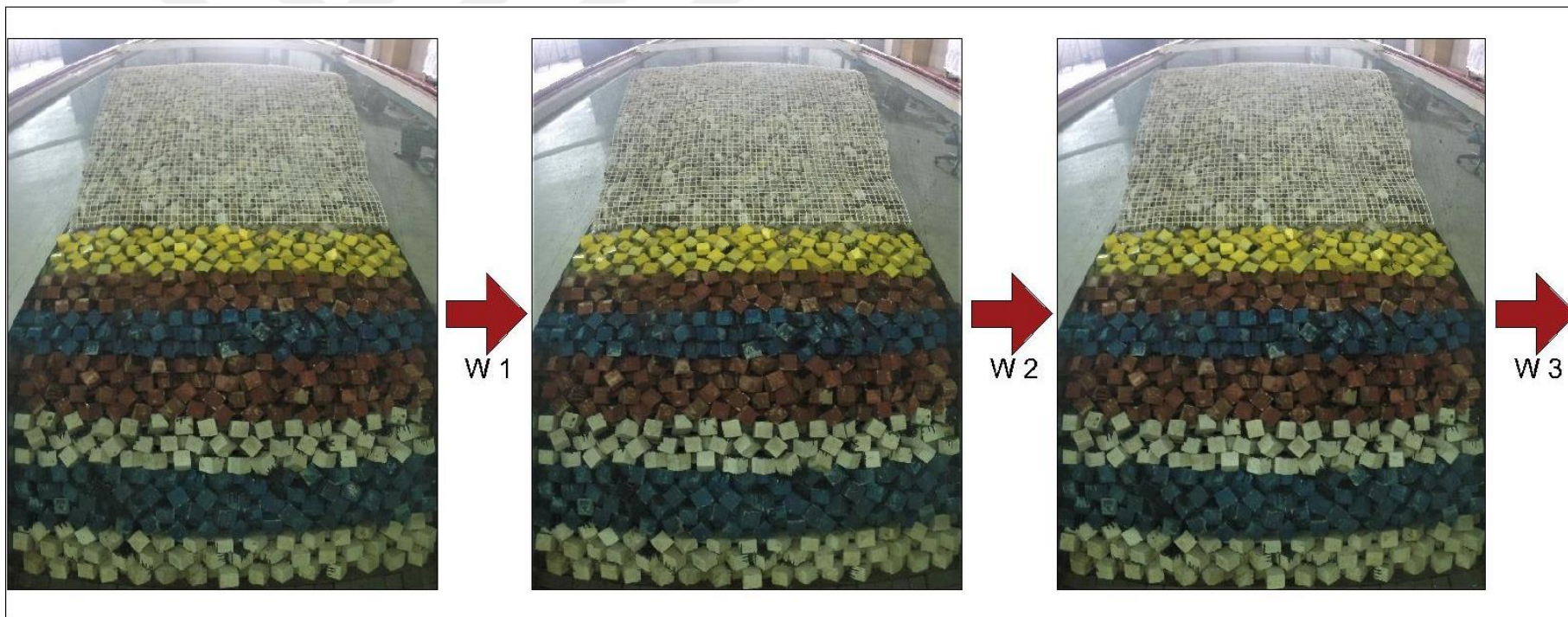


Figure B-27 Movement and damage process (1) for Experiment 2: Berm at SWL

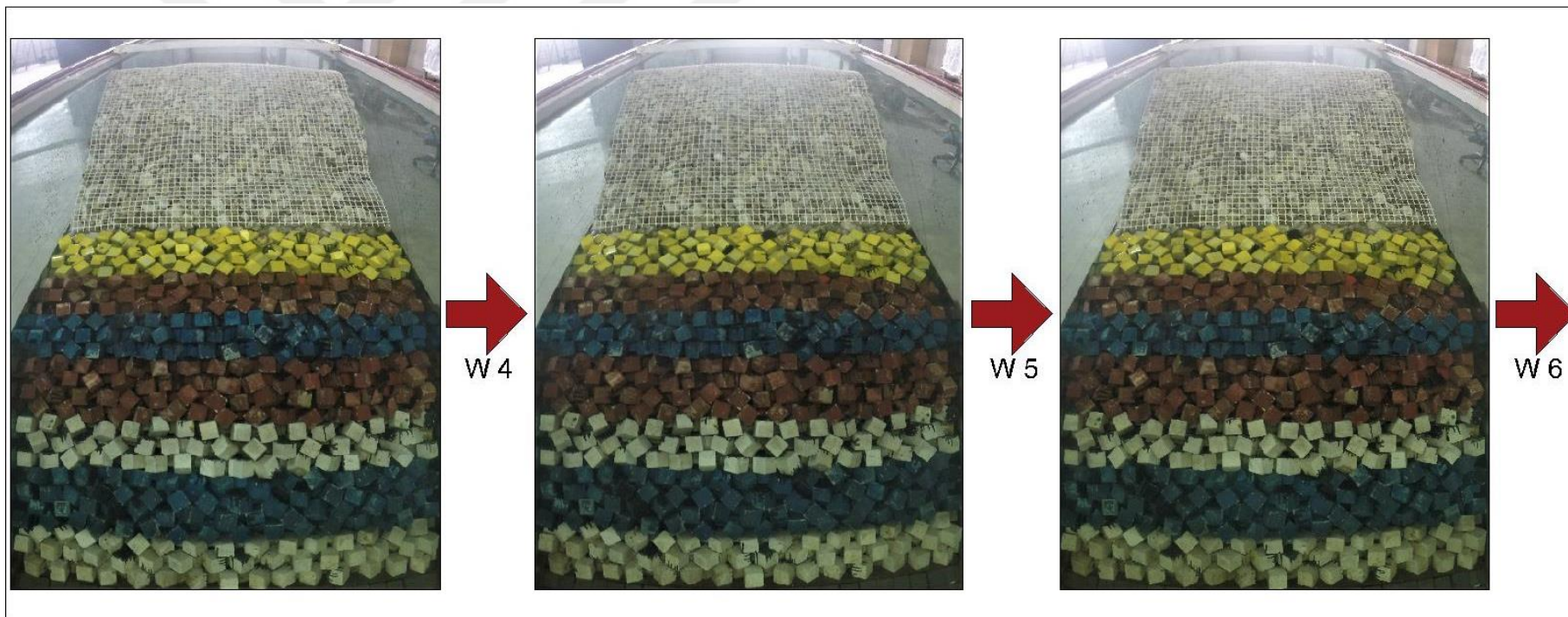


Figure B-28 Movement and damage process (2) for Experiment 2: Berm at SWL

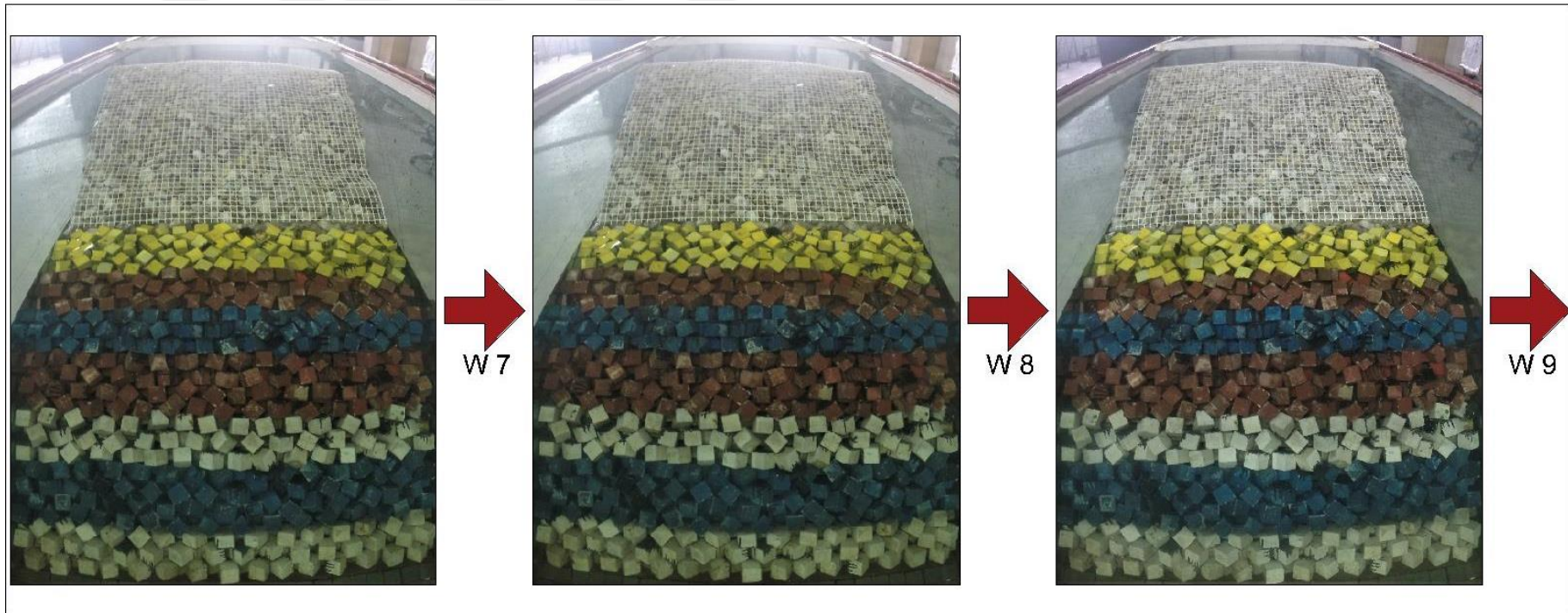


Figure B-29 Movement and damage process (3) for Experiment 2: Berm at SWL

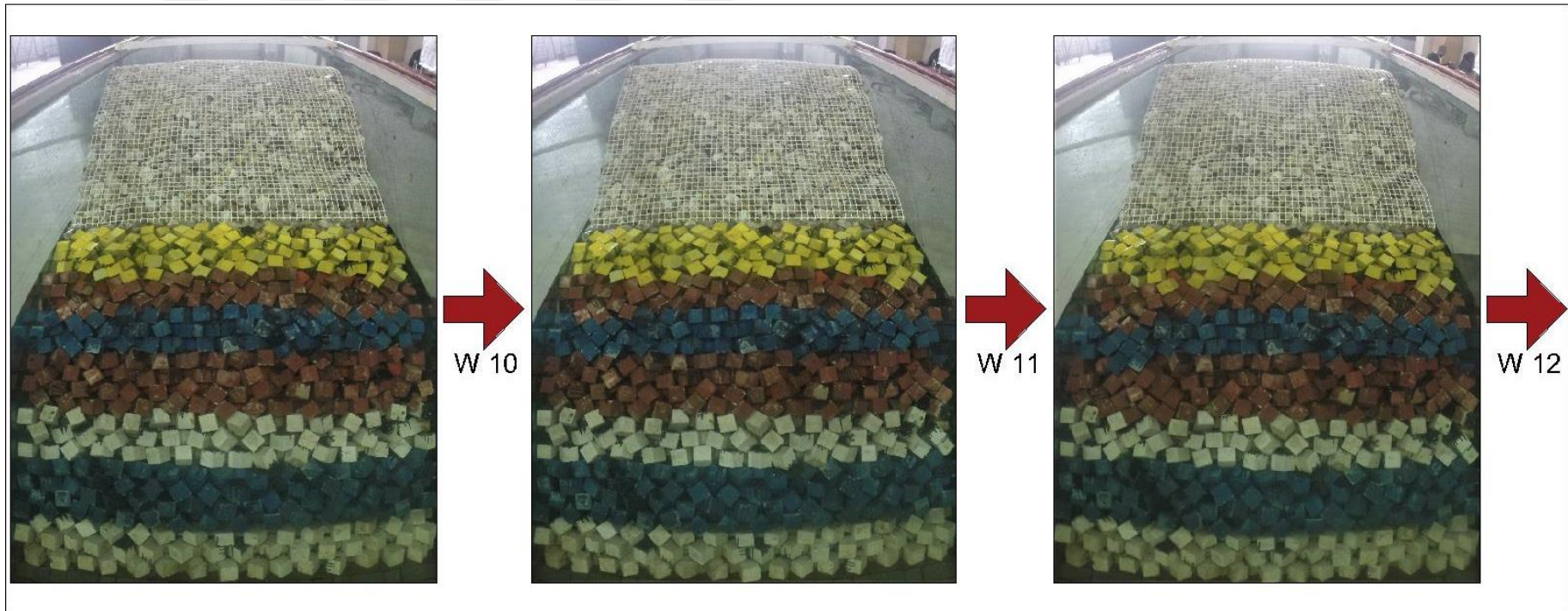


Figure B-30 Movement and damage process (4) for Experiment 2: Berm at SWL

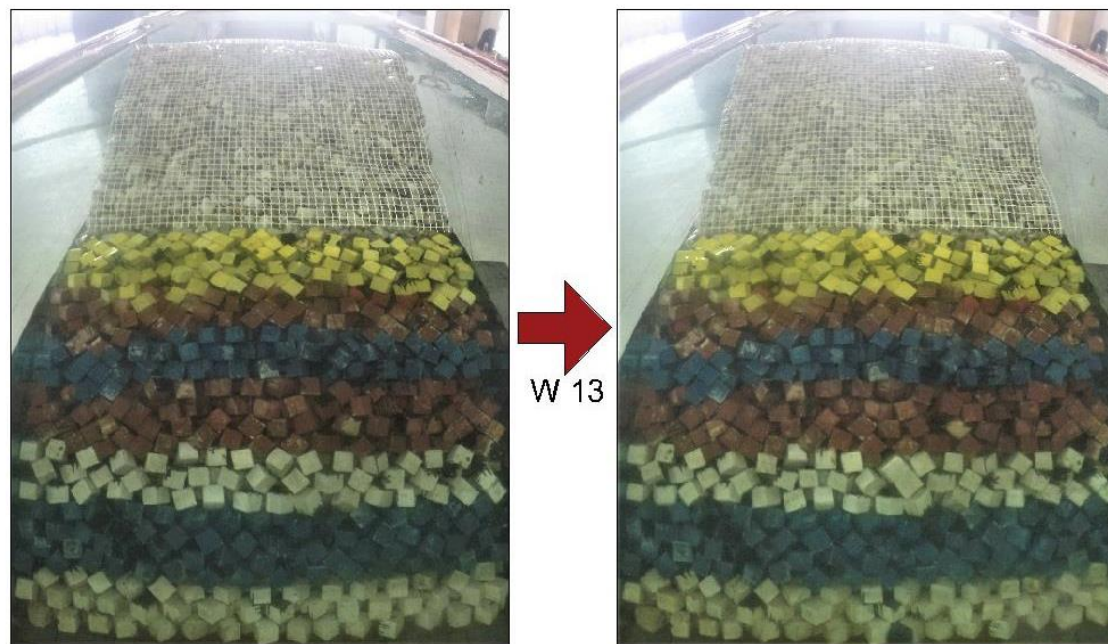


Figure B-31 Movement and damage process (5) for Experiment 2: Berm at SWL

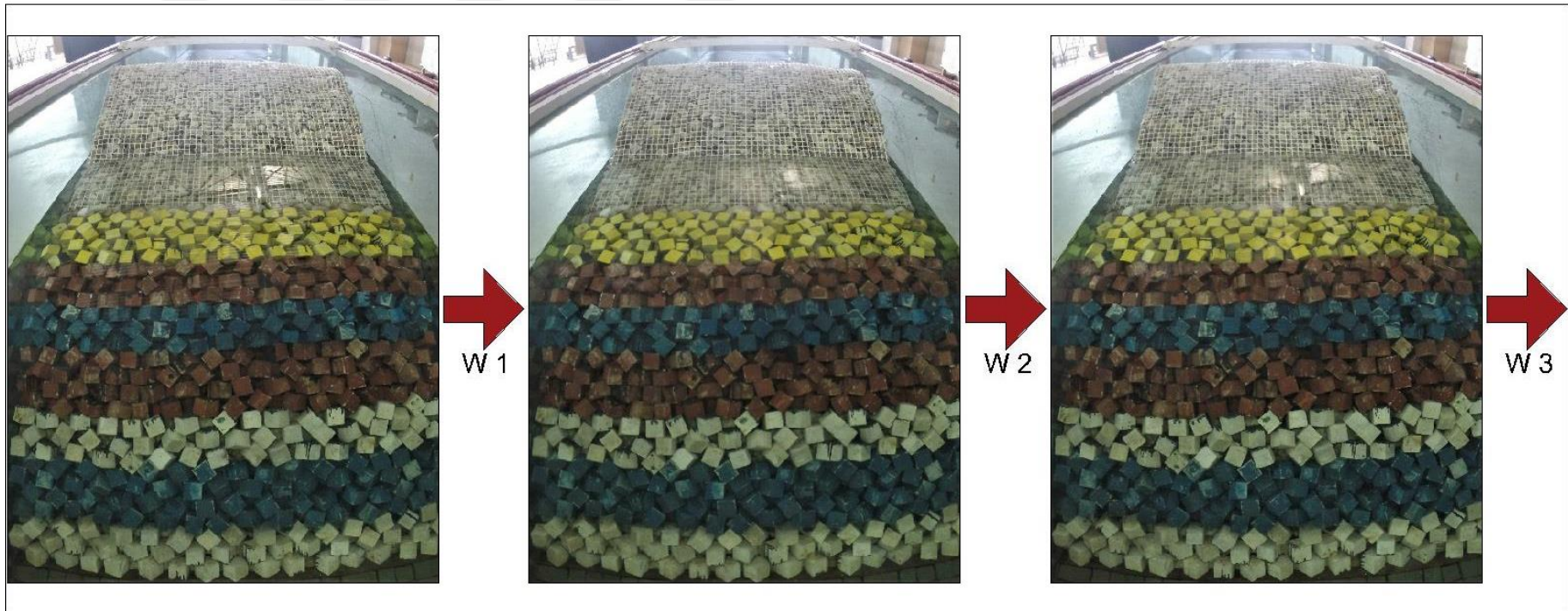


Figure B-32 Movement and damage process (1) for Experiment 3: Submerged Berm

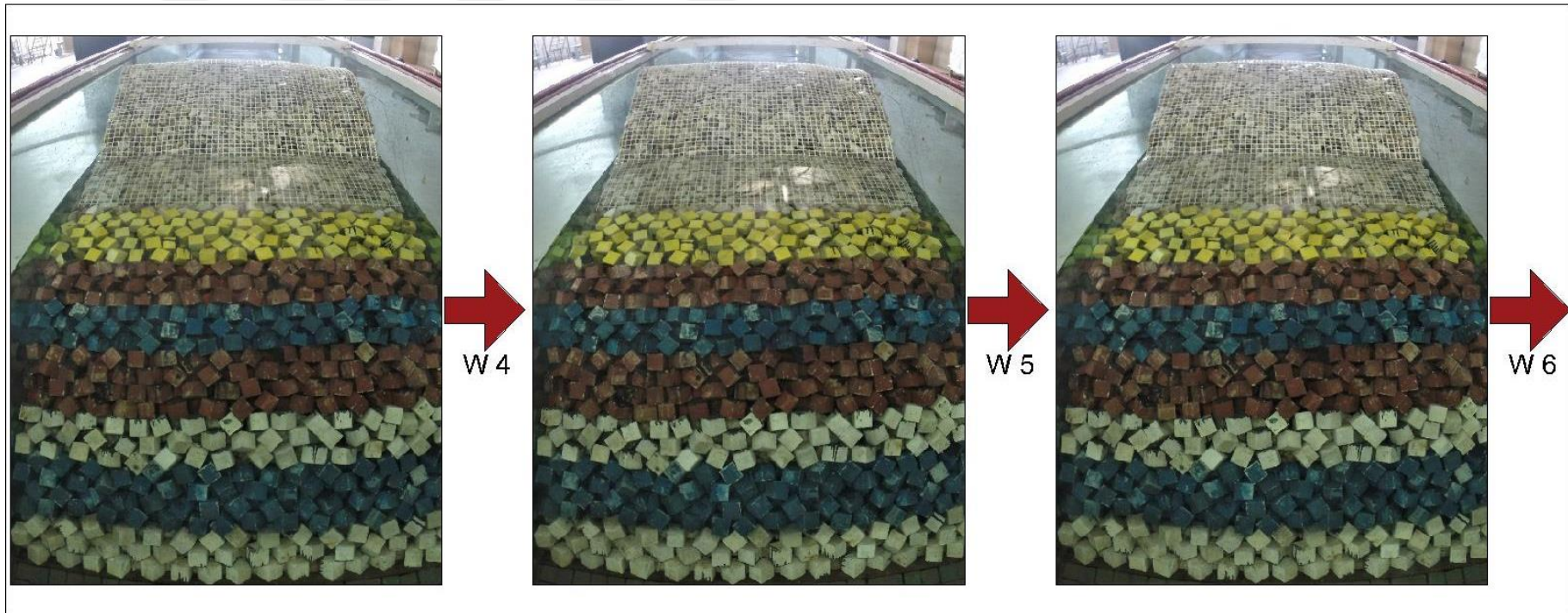


Figure B-33 Movement and damage process (2) for Experiment 3: Submerged Berm

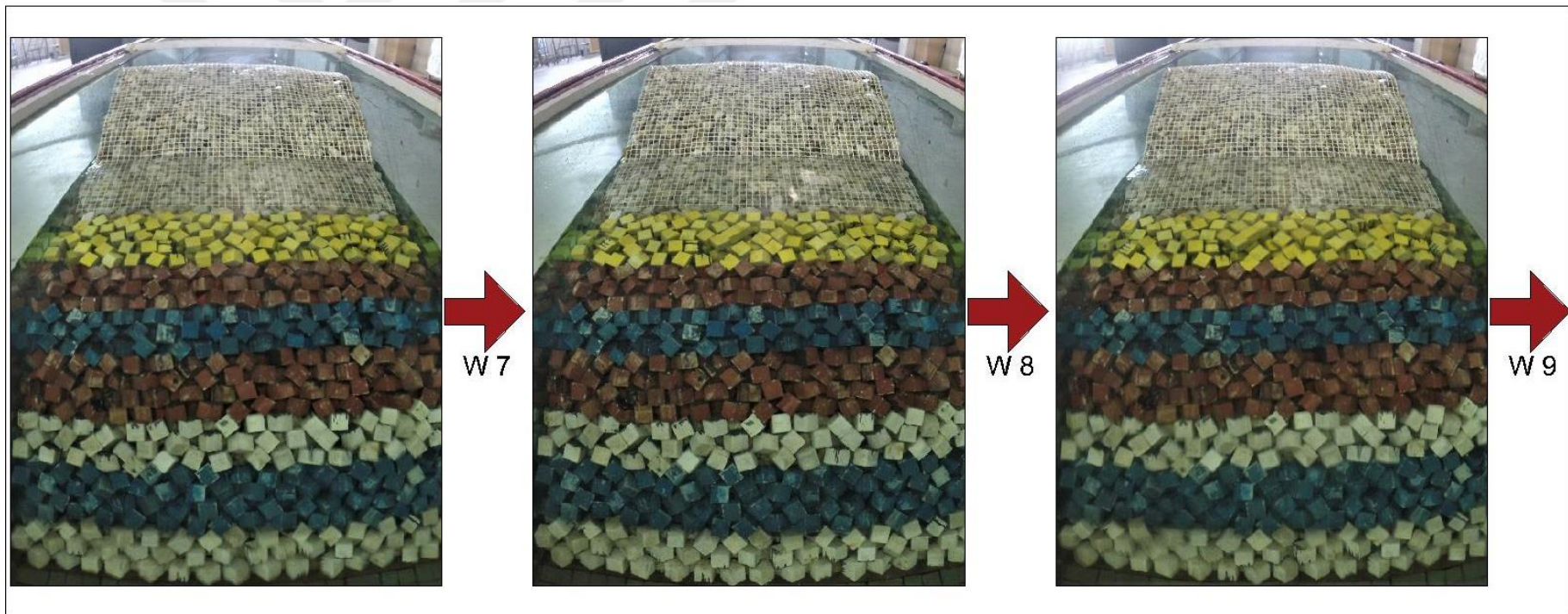


Figure B-34 Movement and damage process (3) for Experiment 3: Submerged Berm

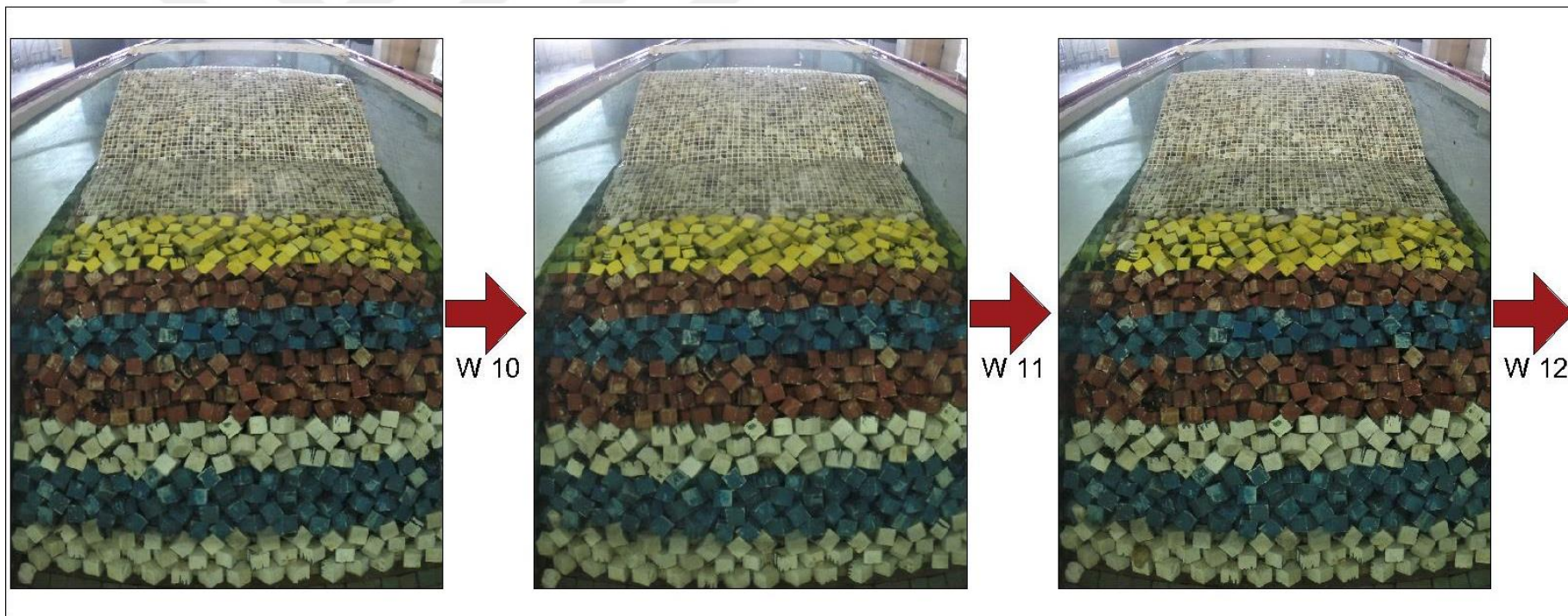


Figure B-35 Movement and damage process (4) for Experiment 3: Submerged Berm

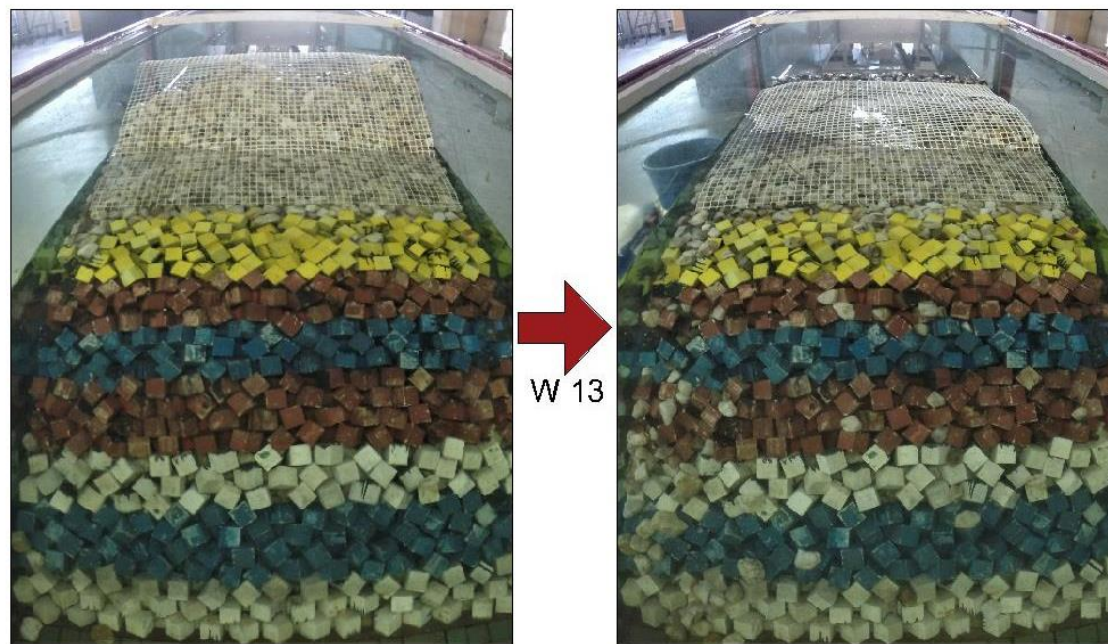


Figure B-36 Movement and damage process (5) for Experiment 3: Submerged Berm

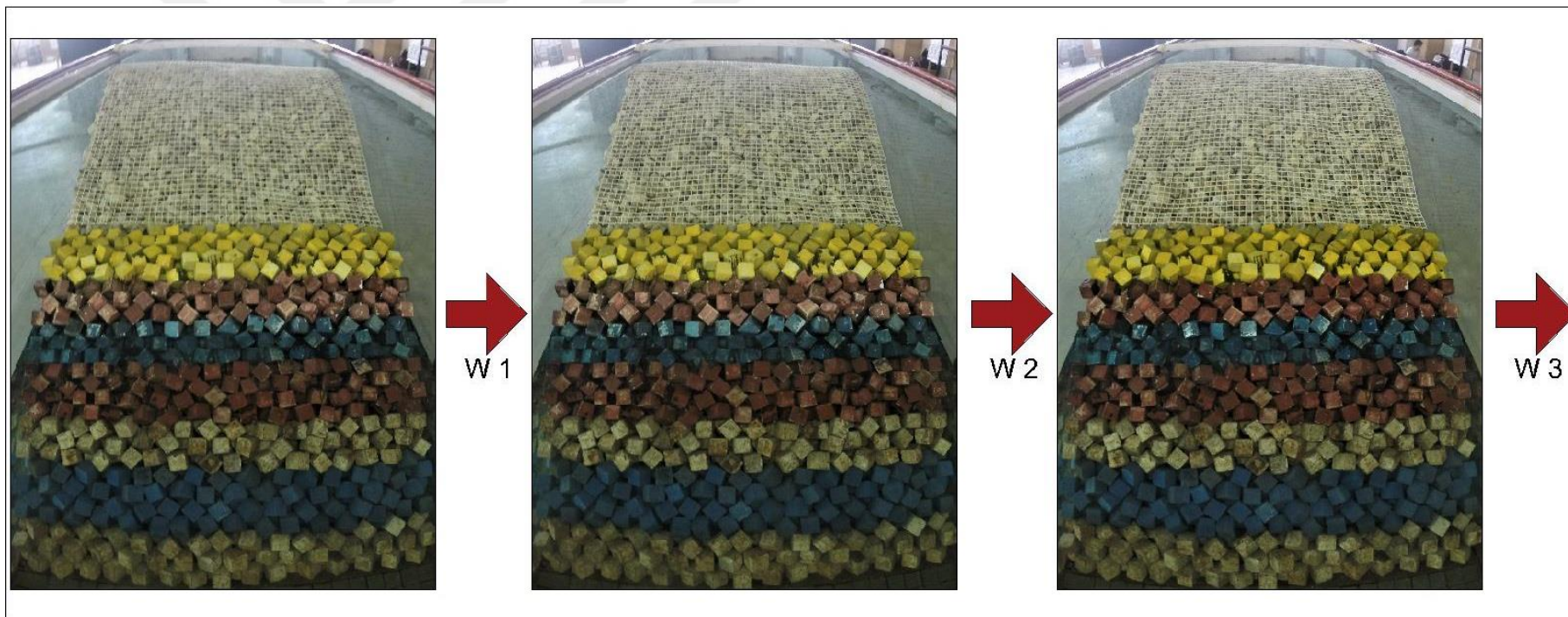


Figure B-37 Movement and damage process (1) for Experiment 4: Emerged Berm with HD Cubes over Reference Area

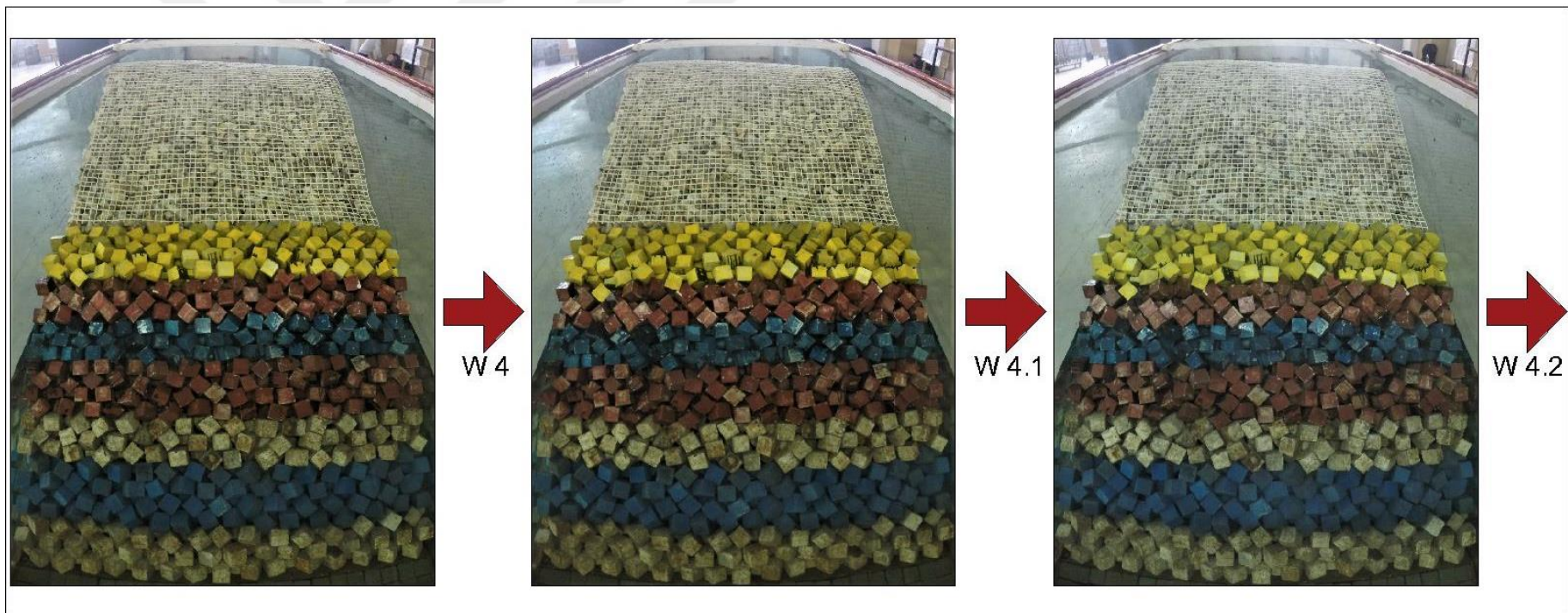


Figure B-38 Movement and damage process (2) for Experiment 4: Emerged Berm with HD Cubes over Reference Area

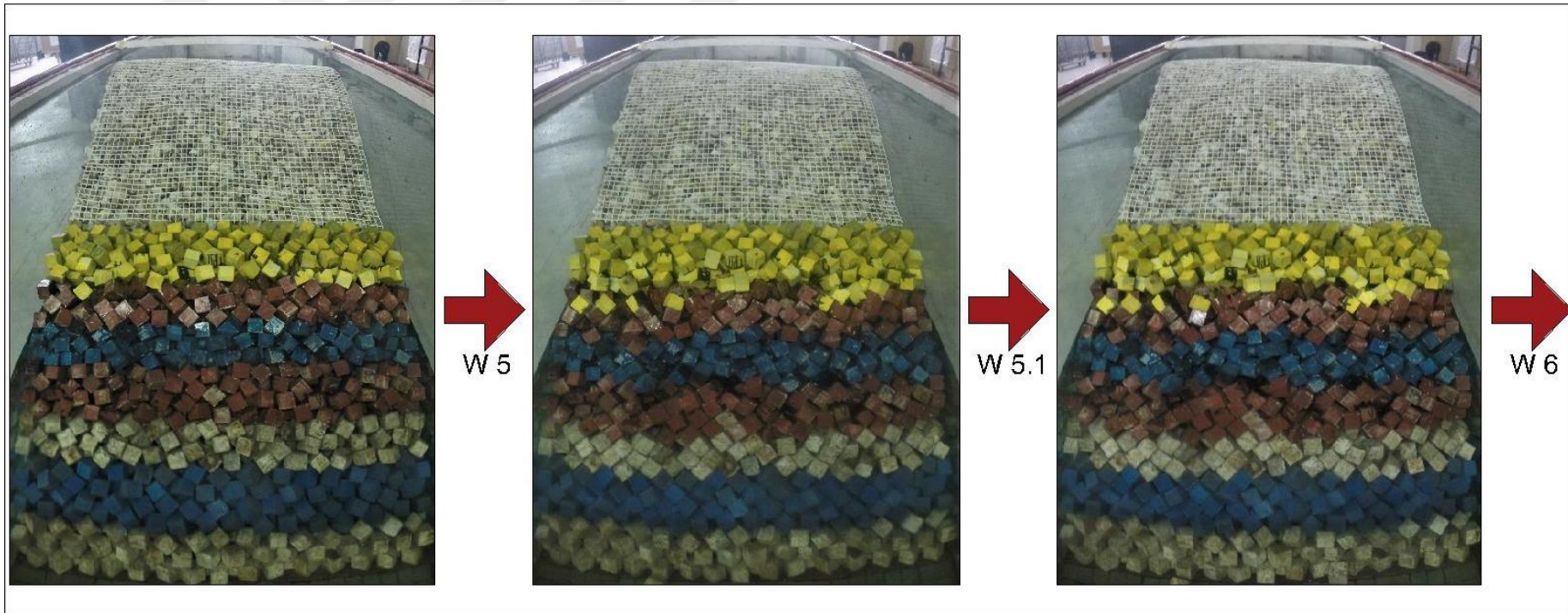


Figure B-39 Movement and damage process (3) for Experiment 4: Emerged Berm with HD Cubes over Reference Area

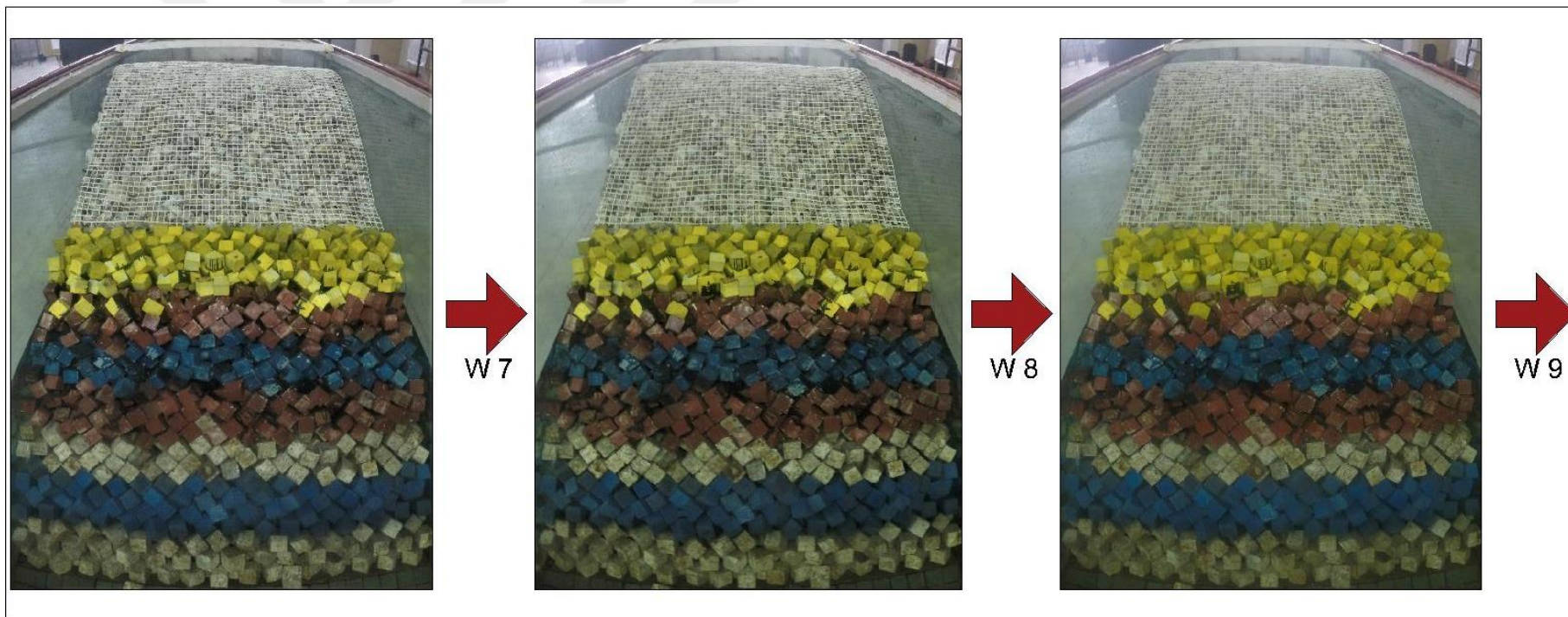


Figure B-40 Movement and damage process (4) for Experiment 4: Emerged Berm with HD Cubes over Reference Area

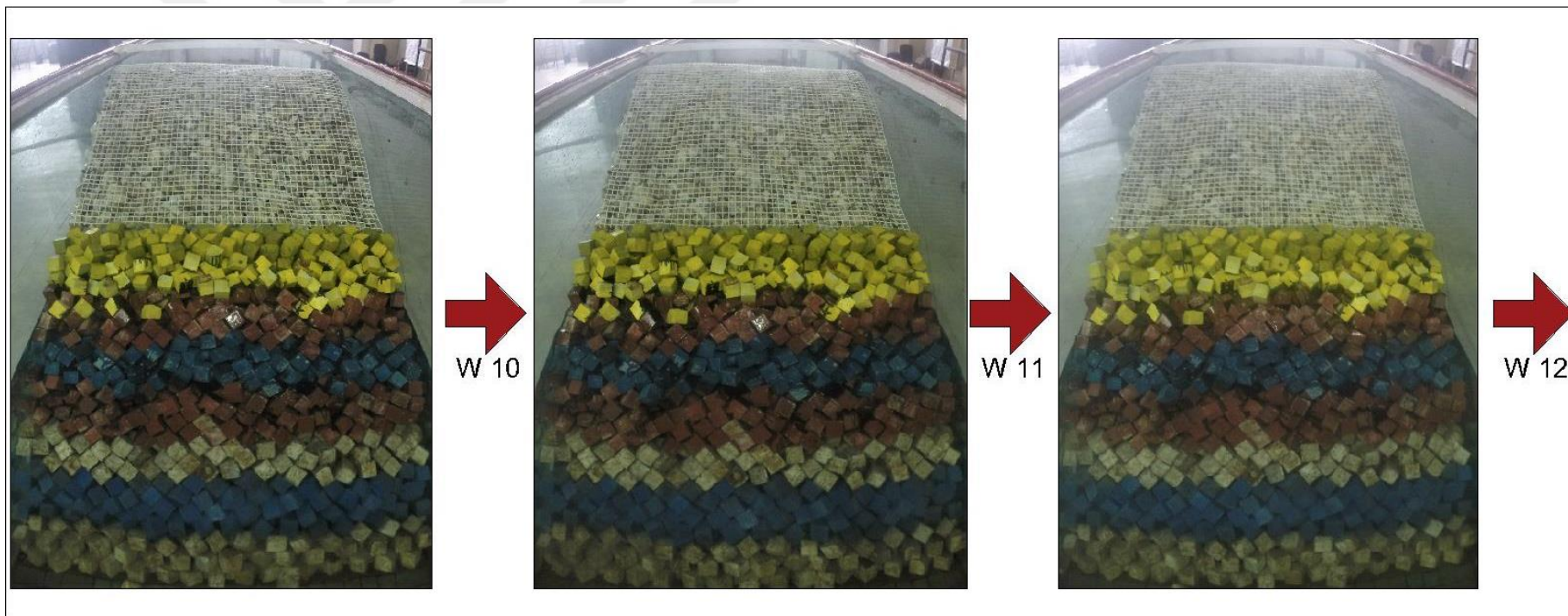


Figure B-41 Movement and damage process (5) for Experiment 4: Emerged Berm with HD Cubes over Reference Area

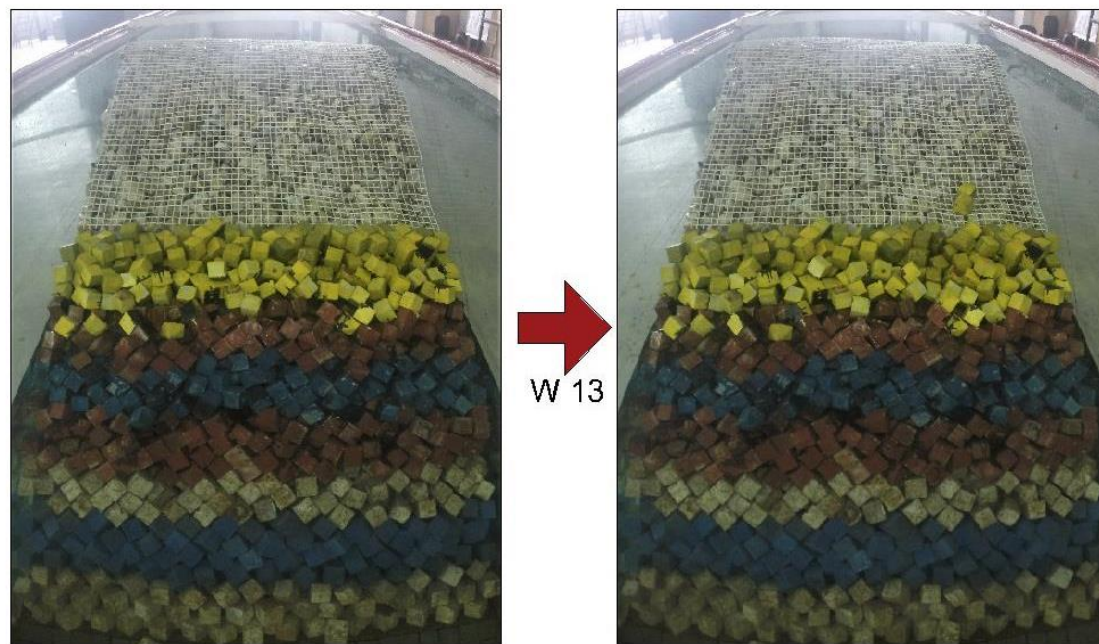


Figure B-42 Movement and damage process (6) for Experiment 4: Emerged Berm with HD Cubes over Reference Area

STATISTICAL PARAMETERS

Table C-1 Statistical parameters for the First Layer ND Cubes and Second Layer HD Cubes

d=55 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.87	0.05	0.85
W2	0.07	1.15	0.08	1.20
W3	0.09	1.17	0.10	1.21
W4	0.10	1.57	0.10	1.45
W5	0.12	1.39	0.14	1.34
W6	0.15	1.51	0.16	1.39
W7	0.17	1.61	0.16	1.47
W8	0.18	1.67	0.17	1.52
W9	0.20	1.71	0.18	1.55
W10	0.19	1.83	0.17	1.62
W11	0.22	1.72	0.21	1.53
W12	0.22	2.00	0.20	1.85
W13	0.23	2.07	0.21	1.92
Standard Deviation H_{m0} (σ)				0.054
Standard Deviation T_{m-1.0} (σ)				0.311
Root Mean Square Error H_{m0} (RMSE)				0.014
Root Mean Square Error T_{m-1.0} (RMSE)				0.134
Correlation Coefficient H_{m0} (r)				0.985
Correlation Coefficient T_{m-1.0} (r)				0.985
Scatter Index H_{m0} (SI)				0.094
Scatter Index T_{m-1.0} (SI)				0.089

Table C-2 Statistical parameters for the Reference Area HD Cubes

d=55 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.87	0.05	0.84
W2	0.07	1.15	0.08	1.21
W3	0.09	1.17	0.10	1.21
W4	0.10	1.57	0.10	1.49
W5	0.12	1.39	0.14	1.38
W6	0.15	1.51	0.15	1.45
W7	0.17	1.61	0.16	1.52
W8	0.18	1.67	0.16	1.57
W9	0.20	1.71	0.18	1.56
W10	0.19	1.83	0.16	1.59
W11	0.22	1.72	0.20	1.56
W12	0.22	2.00	0.20	1.72
W13	0.23	2.07	0.21	1.76
Standard Deviation H_{m0} (σ)				0.054
Standard Deviation T_{m-1.0} (σ)				0.298
Root Mean Square Error H_{m0} (RMSE)				0.017
Root Mean Square Error T_{m-1.0} (RMSE)				0.157
Correlation Coefficient H_{m0} (r)				0.983
Correlation Coefficient T_{m-1.0} (r)				0.977
Scatter Index H_{m0} (SI)				0.112
Scatter Index T_{m-1.0} (SI)				0.104

Table C-3 Statistical parameters for the Single Layer HD Cubes

d=55 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.87	0.05	0.85
W2	0.07	1.15	0.08	1.22
W3	0.09	1.17	0.10	1.23
W4	0.10	1.57	0.11	1.52
W5	0.12	1.39	0.14	1.40
W6	0.15	1.51	0.17	1.47
W7	0.17	1.61	0.17	1.54
W8	0.18	1.67	0.18	1.58
W9	0.20	1.71	0.19	1.58
W10	0.19	1.83	0.17	1.61
W11	0.22	1.72	0.22	1.58
W12	0.22	2.00	0.21	1.58
W13	0.23	2.07	0.21	1.76
Standard Deviation H_{m0} (σ)				0.055
Standard Deviation T_{m-1.0} (σ)				0.294
Root Mean Square Error H_{m0} (RMSE)				0.013
Root Mean Square Error T_{m-1.0} (RMSE)				0.173
Correlation Coefficient H_{m0} (r)				0.982
Correlation Coefficient T_{m-1.0} (r)				0.946
Scatter Index H_{m0} (SI)				0.086
Scatter Index T_{m-1.0} (SI)				0.115

Table C-4 Statistical parameters for the Single Layer ND Cubes

d=55 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.87	0.05	0.84
W2	0.07	1.15	0.08	1.31
W3	0.09	1.17	0.10	1.26
W4	0.10	1.57	0.11	1.70
W5	0.12	1.39	0.15	1.59
W6	0.15	1.51	0.17	1.80
W7	0.17	1.61	0.17	1.53
W8	0.18	1.67	0.18	1.58
W9	0.20	1.71	0.19	1.56
W10	0.19	1.83	0.17	1.60
W11	0.22	1.72	0.22	1.55
W12	0.22	2.00	0.21	1.58
W13	0.23	2.07	0.21	1.70
Standard Deviation H_{m0} (σ)				0.055
Standard Deviation T_{m-1.0} (σ)				0.295
Root Mean Square Error H_{m0} (RMSE)				0.014
Root Mean Square Error T_{m-1.0} (RMSE)				0.216
Correlation Coefficient H_{m0} (r)				0.976
Correlation Coefficient T_{m-1.0} (r)				0.774
Scatter Index H_{m0} (SI)				0.092
Scatter Index T_{m-1.0} (SI)				0.141

Table C-5 Statistical parameters for the Emerged Berm

d=45 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.86	0.05	0.83
W2	0.07	1.12	0.08	1.19
W3	0.09	1.14	0.11	1.21
W4	0.10	1.54	0.10	1.44
W4.1	0.10	1.43	0.11	1.39
W4.2	0.12	1.54	0.12	1.44
W5	0.11	1.34	0.14	1.34
W5.1	0.14	1.54	0.14	1.45
W6	0.14	1.44	0.15	1.42
W7	0.16	1.56	0.15	1.45
W8	0.17	1.67	0.15	1.50
W9	0.18	1.66	0.16	1.50
W10	0.18	1.82	0.15	1.60
W11	0.19	1.67	0.18	1.53
W12	0.19	2.01	0.17	1.92
W13	0.20	2.08	0.17	1.98
Standard Deviation H_{m0} (σ)				0.040
Standard Deviation T_{m-1.0} (σ)				0.289
Root Mean Square Error H_{m0} (RMSE)				0.017
Root Mean Square Error T_{m-1.0} (RMSE)				0.109
Correlation Coefficient H_{m0} (r)				0.947
Correlation Coefficient T_{m-1.0} (r)				0.976
Scatter Index H_{m0} (SI)				0.128
Scatter Index T_{m-1.0} (SI)				0.073

Table C-6 Statistical parameters for the Berm at SWL

d=55 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.87	0.05	0.85
W2	0.07	1.15	0.08	1.19
W3	0.09	1.17	0.09	1.20
W4	0.10	1.57	0.10	1.50
W5	0.12	1.39	0.13	1.35
W6	0.15	1.51	0.15	1.43
W7	0.17	1.61	0.15	1.52
W8	0.18	1.67	0.16	1.60
W9	0.20	1.71	0.17	1.61
W10	0.19	1.83	0.16	1.65
W11	0.22	1.72	0.19	1.60
W12	0.22	2.00	0.20	1.89
W13	0.23	2.07	0.21	1.91
Standard Deviation H_{m0} (σ)				0.054
Standard Deviation T_{m-1.0} (σ)				0.314
Root Mean Square Error H_{m0} (RMSE)				0.019
Root Mean Square Error T_{m-1.0} (RMSE)				0.098
Correlation Coefficient H_{m0} (r)				0.986
Correlation Coefficient T_{m-1.0} (r)				0.993
Scatter Index H_{m0} (SI)				0.126
Scatter Index T_{m-1.0} (SI)				0.064

Table C-7 Statistical parameters for the Submerged Berm

d=65 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.87	0.05	0.85
W2	0.07	1.16	0.07	1.18
W3	0.09	1.16	0.09	1.18
W4	0.10	1.58	0.09	1.53
W5	0.11	1.38	0.12	1.36
W6	0.14	1.49	0.14	1.45
W7	0.16	1.58	0.15	1.54
W8	0.17	1.66	0.16	1.61
W9	0.19	1.66	0.17	1.61
W10	0.18	1.81	0.18	1.77
W11	0.21	1.68	0.24	1.61
W12	0.22	1.76	0.24	1.85
W13	0.24	2.06	0.26	1.89
Standard Deviation H_{m0} (σ)				0.061
Standard Deviation T_{m-1.0} (σ)				0.300
Root Mean Square Error H_{m0} (RMSE)				0.014
Root Mean Square Error T_{m-1.0} (RMSE)				0.065
Correlation Coefficient H_{m0} (r)				0.981
Correlation Coefficient T_{m-1.0} (r)				0.984
Scatter Index H_{m0} (SI)				0.093
Scatter Index T_{m-1.0} (SI)				0.043

Table C-8 Statistical parameters for the Emerged Berm HD Cubes over the Reference Area

d=45 cm				
Waves	Structure Toe (Probe 5)		Structure Toe (Probe 5)	
	Without Structure		With Structure	
	H_{m0}	T_{m-1.0}	H_{m0}	T_{m-1.0}
	(m)	(s)	(m)	(s)
W1	0.05	0.86	0.05	0.82
W2	0.07	1.12	0.08	1.20
W3	0.09	1.14	0.10	1.21
W4	0.10	1.54	0.10	1.44
W4.1	0.10	1.43	0.11	1.40
W4.2	0.12	1.54	0.12	1.45
W5	0.11	1.34	0.13	1.34
W5.1	0.14	1.54	0.13	1.47
W6	0.14	1.44	0.15	1.44
W7	0.16	1.56	0.15	1.47
W8	0.17	1.67	0.15	1.52
W9	0.18	1.66	0.17	1.53
W10	0.18	1.82	0.16	1.61
W11	0.19	1.67	0.18	1.54
W12	0.19	2.01	0.17	1.92
W13	0.20	2.08	0.17	1.96
Standard Deviation H_{m0} (σ)				0.041
Standard Deviation T_{m-1.0} (σ)				0.289
Root Mean Square Error H_{m0} (RMSE)				0.014
Root Mean Square Error T_{m-1.0} (RMSE)				0.101
Correlation Coefficient H_{m0} (r)				0.971
Correlation Coefficient T_{m-1.0} (r)				0.979
Scatter Index H_{m0} (SI)				0.107
Scatter Index T_{m-1.0} (SI)				0.068

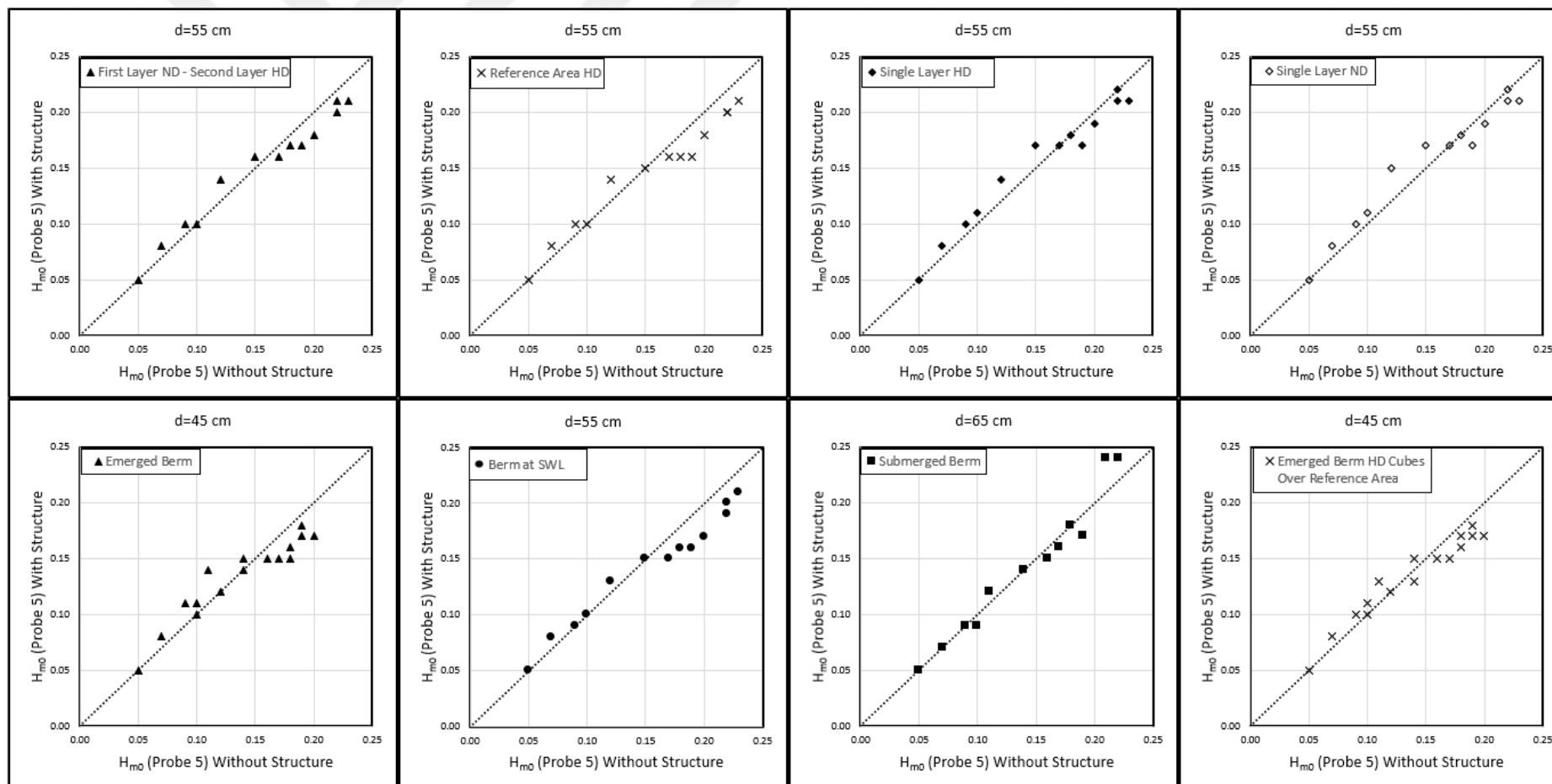


Figure C-1 Correlation of wave heights at toe (without structure-with structure)

D

CALCULATION PROCEDURES OF D_T AND N_0

Appendix D explains calculations of total damage ratio (D_T) and relative damage (N_0) occurred in the armor layer of the breakwaters. The breakwater model Berm at SWL will be used as an example. Also, W10 is selected to show calculations. Same procedure was applied to other breakwater models. Notice that $L=92$ cm and $D_n=4$ cm.

Total cube quantity in the first layer (in reference area) = 135

Total cube quantity in the second layer (in reference area) = 135

Total cube quantity in the armor layer (in reference area) = 270

Movements and damages occurred in the reference area

$$\text{at W10 (QTY)} = \begin{cases} M_1 = 79 \\ M_2 = 33 \\ D_1 = 14 \\ D_2 = 1 \end{cases}$$

Total movement (M_T) and total damage (D_T)

$$\text{occured in the reference area at W10 (QTY)} = \begin{cases} M_T = 112 \\ D_T = 15 \end{cases}$$

$$\text{Total damage ratio } (D_T) = \frac{15}{270} * 100 = 5.56\%$$

$$N_0 = \frac{\text{Number of } (> 1D_n) \text{ displaced units in reference area}}{L/D_n} \quad (D.1)$$

$$\text{Relative damage } (N_0) = \frac{15}{92/4} = 0.65$$

PUBLICATIONS FROM THE THESIS

Conference Papers

1. Yuksel, Y., van Gent, M., Cevik, E., Kaya, H. A., Gumuscu, I., Yuksel, Z. T., & Yalciner, A. C. (2020). Stability of High Density Cubes in Rubble Mound Breakwaters. *Coastal Engineering Proceedings*, (36v), 4-4.

