A MODEL STUDY ON THE STABILITY OF RUBBLE MOUND COASTAL DEFENSE STRUCTURE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

KEMAL CİHAN ŞİMŞEK

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

OCTOBER 2011

Approval of the thesis:

A MODEL STUDY ON THE STABILITY OF RUBBLE MOUND COASTAL DEFENSE STRUCTURE

submitted by **KEMAL CİHAN ŞİMŞEK** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen
Dean, Graduate School of **Natural and Applied Sciences** ________________

Prof. Dr. Güney Özcebe
Head of Department, **Civil Engineering** ________________

Prof. Dr. Ahmet Cevdet Yalçıner
Supervisor, **Civil Engineering Department, METU** ________________

Prof. Dr. Ayşen Ergin
Co-Supervisor, **Civil Engineering Department, METU** ________________

Examining Committee Members:

Assoc. Prof. Dr. Utku Kanoğlu
Engineering Sciences, METU ________________

Prof. Dr. Ahmet Cevdet Yalçıner
Civil Eng. Dept., METU ________________

Prof. Dr. Ayşen Ergin
Civil Eng. Dept., METU ________________

Dr. Işıkhan Güler
Civil Eng. Dept., METU ________________

Dr. Bergüzar Öztunalı Özbahçeci
DLH General Directorate ________________

Date: ________________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Kemal Cihan ŞİMŞEK

Signature :

ABSTRACT

A MODEL STUDY ON THE STABILITY OF RUBBLE MOUND COASTAL DEFENSE STRUCTURE

Şimşek, Kemal Cihan

M.Sc., Department of Civil Engineering

Supervisor: Prof. Dr. Ahmet Cevdet Yalçıner

Co-Supervisor: Prof. Dr. Ayşen Ergin

October 2011, 122 pages

Coastal regions are very important because they provide a lot of resources and benefits for all the humankind. Coastal defense structures protect coastal regions from wave attacks. However, the cost of construction such coastal defense structures are very high and need big investments. Hence, to reach the optimum design and minimize the risk of failure has vital importance during the design stage of these structures. Model studies are the most effective tool in optimizing the design of these structures.

Rubble mound coastal defense structures were constructed with assembly of different sizes of armor stones and front slopes. Rubble mound coastal defense structures were designed by Van der Meer's approach and the stability of the cross sections were tested on the models constructed with a scale of 1:33.485 in the Coastal and Harbor

Engineering Laboratory, Civil Engineering Department, Middle East Technical University. Results of the model studies showed that structures with steep slopes were damaged more than structures with mild slopes and the stability of the structures were directly affected by the armor stone sizes.

In the model studies, different cross sections were tested for stability to obtain the cumulative damages under severe storm conditions. These cumulative damages, which are obtained by stone count method, are converted to the damage parameters, S_d, to compare with the existing studies. It was observed that the results of the stability formulae of Van der Meer for shallow water were very consistent with the results of model studies as they were designed according to Van der Meer approach.

Keywords: Rubble Mound, Stability, Cumulative Damage, Model

ÖZ

TAŞ DOLGU KIYI KORUMA YAPISININ DENGE DURUMU ÜZERİNE MODEL ÇALIŞMASI

Şimşek, Kemal Cihan

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Ahmet Cevdet Yalçıner

Ortak Tez Yöneticisi: Prof. Dr. Ayşen Ergin

Ekim 2011, 122 sayfa

Kıyı bölgeleri, tüm insanlık için birçok kaynak ve fayda sağladığı gerçeği nedeniyle çok önemlidir. Kıyı koruma yapıları, kıyı bölgelerini büyük dalga saldırılarından korumak amacıyla inşa edilir. Fakat bu yapıların inşaatlarının maliyeti oldukça yüksektir ve büyük yatırımlar gerektirir. Bu sebepten ötürü, bu yapıların tasarım aşamasında optimum tasarıma ulaşmak ve çökme riskini en aza indirmek çok önemlidir. Model çalışmaları, bu yapıların tasarım aşamalarında en uygun hale getirilmesi için en etkili araçtır.

Taş dolgu kıyı koruma yapıları, farklı taş büyüklükleri ve eğimlerin bir araya getirilmesi sonucu inşa edilmiştir. Taş dolgu kıyı koruma yapıları Van der Meer'in yaklaşımı kullanılarak dizayn edilmiştir ve kesitlerin denge durumları 1:33.485‘lik ölçekle Orta Doğu Teknik Üniversitesi, İnşaat Mühendisliği Bölümü, Kıyı ve Liman Mühendisliği Laboratuvarı’nda inşa edilmiş olan modeller üzerinde test edilmiştir. Model çalışmalarının sonucunda, dik eğimli yapıların yatık eğimli yapılara göre daha fazla hasar aldığı ve yapıların denge durumlarında taş büyüklüklerinin etkisinin çok fazla olduğu görülmüştür.

Model çalışmalarında, çeşitli kesitlerdeki kıyı koruma yapılarının denge durumları birikimli hasar sonuçlarını elde etmek için farklı fırtına koşulları altında test edilmiştir. Taş sayma yöntemiyle edilmiş olan bu birikimli hasar sonuçları, varolan çalışmalarla karşılaştırmak amacıyla S_d hasar parametrelerine çevrilmiştir. Van der Meer’in formülü kullanılarak elde edilen sonuçların, model çalışmalarında elde edilen sonuçlarla oldukça tutarlı olduğu gözlenmiştir.

Anahtar Kelimeler: Taş Dolgu, Denge, Birikimli Hasar, Model

To my Family and Maroon 5

ACKNOWLEDGEMENTS

I would like to thank my advisor Prof. Dr. Ahmet Cevdet Yalçıner who has been supported me since the beginning of my graduate studies.

I would like to thank Prof. Dr. Ayşen Ergin who was the only reason to come back from Spain and to choose coastal and ocean engineering. I will always feel her love and energy with me and always be passionate to treat the same way she did to entire world throughout my life.

I would like to thank Dr. Işıkhan Güler who always forced me and made me stronger to survive in the life.

I would like to thank my family, Çiğdem Şimşek, Abdurrahman Şimşek, Erdem Şimşek for always believing me and encouraging me to achieve the finish line.

I would like to thank Cüneyt Baykal, also known as "King", who was an amazing colleague and mental coach for me.

I would like to thank Arif Kayışlı and Yusuf Korkut for always helping at the experiments. Without their help, this thesis would not exist.

I would like to thank Hülya Karakuş, Ceren Özer, Dr. Gülizar Özyurt, Mustafa Esen and Pelin Öğünç for sharing the moments during my life in coastal and harbor engineering laboratory.

I would like to thank Uğur Kılınçarslan who always supports me and always being a great bro for me.

I would like to thank METU basketball team who always created funny moments.

I would like to thank Adam Levine and Maroon 5 who always brought an inspiration and encouragement for my thesis.

I would like to thank Ali Tuğrul Yıldız, Zülfü Kerem Tözün, Ömürcan Topal, Mehmet İlhan Şimşek, Melik Haydar Şahin, Harun Öztürk, Barbaros Yontar, Merve Yontar, Pınar Göktaş Tözün, Sabri Can Bozkurt, Ahmet Can Tanyeri, Önder Tolga Okumuş, Çağrı Uçak, Nevzat Kutsi Tekin for always being with me throughout my thesis period.

I would like to thank Onur Sancar, Miran Dzabic, Halit Görgülü, Erdinç Altuntaş, Pınar Berberoğlu, Onur Aytuğar, Serhat Abay, Orhun Günel, Murat Ayhan and Burak Görgülü who are always had fun with me in day and night.

I would like to thank Alt Kat Crew for enduring my passion about Maroon 5 and always creating funny moments. The author will never forget the moments.

I would like to thank Yılgün Gürcan, Ezgi Altıntaş and Baran Çobanoğlu for always creating a joyful moments at the green coverings.

I would like to thank Mustafa Kemal ATATÜRK. I own you my existence. I will always follow your way without any attempt to rest and transfer your doctrine to new generations.

Finally, I would like to thank God for everything.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLES

LIST OF SYMBOLS

H_s	significant wave height at the toe of the structure (m)
T_s	significant wave period (s)
S_d	damage parameter
K_D	stability coefficient
ρ_r	apparent rock density (kg/m^3)
Δ	relative buoyant density of the stone
α	slope angle (°)
N	number of incident waves at the toe
D_{n50}	nominal diameter of the armourstone (m)
ξ_m	surf similarity parameter using the mean wave period, T_m (s)
P	notional permeability of the structure
$H_{2\%}$	wave height exceeded by 2 per cent of the incident waves at the toe (m)
$D_{n50-core}$	nominal diameter of the core material (m)
D_{n50}	nominal diameter of the armourstone (m)
A_e	cross sectional eroded area (m^2)
n	porosity of the armour layer

N_s	stability number
T_m	mean wave period (s)
t	duration time of storm (s)
F_r	Froude number
λ_L	length scale
λ_T	time scale
λ_W	weight scale
h	water depth (m)
ξ_{cr}	critical value of the surf similarity parameter
m	sea bed slope
H_{max}	maximum wave height (m)
H_{min}	minimum wave height (m)
H_m	mean wave height (m)
L	wave length (m)
K_R	reflection coefficient
H_R	reflected wave heights (m)

CHAPTER 1

INTRODUCTION

The surface of the earth is covered by the land with the percentage of 29 %. The remaining surface area of the earth is covered by water has a percentage of 71 %. There is a lot of sources from the seas that is useful for humanity. So, people always settled near the seas which are also called as coastal areas. In order to continue the civilizations at these coastal areas, they must be protected by coastal defense structures. Coastal defense structures decrease the effects of the waves. Rubble mound coastal defense structures are the mostly used type of the defense structures.

The construction process of rubble mound structures are easier than other types of coastal defense structures. Rubble mound structures are built by rock or armour units. This type of structures uses the voids between the armour stones to dissipate the wave energy. In Turkey, mostly rubble mound coastal defense structures are used. Since, these structures are expensive structures, they need to be designed appropriately before the construction phase. Design methodology has vital importance at the design phase.

One of the ways to find the optimum design is model studies. They are not expensive and they do not require so much material and labor. Since, the possible damage of the structure under storm conditions could be investigated by the model studies, such experimental investigations are recommended before finilizing any coastal work. So, model studies have a big role in coastal engineering world.

In this study, the stability of the rubble mound coastal defense structures is investigated by 5 different models, constructed at the Coastal and Harbor Engineering Laboratory of the Middle East Technical University (METU), Ankara. In the design of the structure models, the main parameters were foreshore slope and the size of the armour stone. During the experiments, these parameters were combined differently at the tests carried out on the 5 models. These models are tested under different design wave characteristics and the cumulative damage of the structures, which are obtained by using stone count method, was measured after each wave series. The damages which are obtained by stone count method were converted to the damage parameters, S_d, to use with the damage values which are obtained from stability formulae. The main object of this thesis was to make a comparative study on the amount of damages obtained from model studies with those calculated from existing stability formulas by using the wave conditions of the models. These stability formulae are Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001). By this way, consistency of these formulae is checked.

In Chapter 2, literature survey is given. Previous stabilty formulas, definition and measurement types of the armour layer damage, the transition between stone count method and damage parameter (S_d), damage development concept, and purpose of the study are given in this chapter.

In Chapter 3, the main characteristics of the models, experimental set-up, advantages and the disadvantages of the model studies, model scale, information about wave generation, parts of the rubble mound breakwaters have been described.

In Chapter 4, the results of the model studies are given. In Chapter 5, the presentation and evaluation of results of model studies are shown. The comparison of the experimental results and the results which are obtained from stability formulae are made at Chapter 6 which is discussion of the results part of this thesis. The conclusion and future recommendations are given in Chapter 7.

CHAPTER 2

LITERATURE SURVEY

At the rubble mound coastal defense structures, waves attack front slope and induce wave forces acting on armor units causing movements which are rocking, displacement out of layer, settlement, and sliding. Those armor unit movements can be called as hydraulic instability.

Stability of rubble mound coastal defense structures has vital importance for the coastal regions. Especially, the stability of the seaward sides of these structures is crucial for the lifetime of structure. Concerning the stability of the structures, most important formulas are developed by Hudson (1953), Van der Meer (1988b) and Van Gent et al. (2004). The stability formulas, which are developed by Hudson (1953), Van der Meer (1988b) and Van Gent et al. (2004), have crucial importance at coastal engineering world. Today, most of the coastal engineers use those formulas for the stability of their structures.

2.1 Hudson Formula

By the model tests with regular waves on non-overtopped rock structures with a permeable core, Hudson (1953, 1959) developed Eq.2.1. It shows the relationship between median weight of armourstone, W_{50} (N), wave height at the toe of the structure, H (m) and the other structural parameters (Rock Manual, 2007).

$$W_{50} = \frac{\rho_r \, g \, H^3}{K_D \Delta^3 \cot\alpha} \tag{2.1}$$

where K_D is stability coefficient, ρ_r is the apparent rock density (kg/m^3), Δ is the relative buoyant density of the stone and α is the slope angle.

Hudson formula takes the damage as 0 – 5 percent. The K_D values which are given in the Shore protection manual (SPM) (CERC, 1977) were K_D = 3.5 for breaking waves on the foreshore, and K_D = 4 for non-breaking waves on the foreshore. Those K_D values are for rough, angular, randomly placed armourstone in two layers on breakwater trunk. In SPM (CERC, 1984) it was recommended to use $H_{1/10}$ in Eq.2.1 for the design wave height. Besides, K_D values changed. K_D value for breaking waves decreased 3.5 to 2.0, while for non –breaking waves K_D did not change. Hudson formula is very simple and has wide range of armor units. However, it is for regular waves only and has no description about damage level. Also, wave period and storm duration do not appear directly in the Eq.2.1 (Rock Manual, 2007).

2.2 Van der Meer Formulae – Deep Water Conditions

Van der Meer (1988b) developed formulae for deep water conditions to foresee the stability of armourstone on front slopes of rubble mound coastal defense structures. By the help of the earlier work of Thompson and Shuttler (1975) and with his own model studies, Van der Meer (1988b) derived Eq.2.2 and Eq.2.3. Most of the model studies were performed at deep water at the toe, i.e. h > $3H_{s\text{-}toe.}$ The complexity of these formulae is greater than the Hudson formula. However, these formulae consist of wave period, storm duration, damage level and the structure's permeability (Rock Manual, 2007).

For ***plunging waves*** $(\boldsymbol{\xi_m} < \boldsymbol{\xi_{cr}})$:

$$\frac{H_s}{\Delta D_{n50}} = c_{pl}\, P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi_m{}^{-0.5} \qquad (2.2)$$

For ***surging waves*** ($\xi_m \geq \xi_{cr}$):

$$\frac{H_s}{\Delta D_{n50}} = c_s\, P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \sqrt{\cot\alpha}\ \xi_m{}^{P} \tag{2.3}$$

Where:

N = number of incident waves at the toe, which depends on the duration of the wave conditions

H_s = significant wave height , $H_{1/3}$ of the incident waves at the toe of the structure (m)

D_{n50} = nominal diameter of the armourstone (m)

ξ_m = surf similarity parameter using the mean wave period, T_m (s), from time domain analysis; $\xi_m = \tan\alpha \,/\, \sqrt{(2\pi/g).H_s/T_m{}^2}$

α = slope angle (°)

Δ = relative buoyant density, $\rho_r/\rho_w - 1$

P = notional permeability of the structure; the value of this parameter should be : 0.1≤ P ≤0.6 (see Figure 2.1)

c_{pl} = 6.2

c_s = 1.0

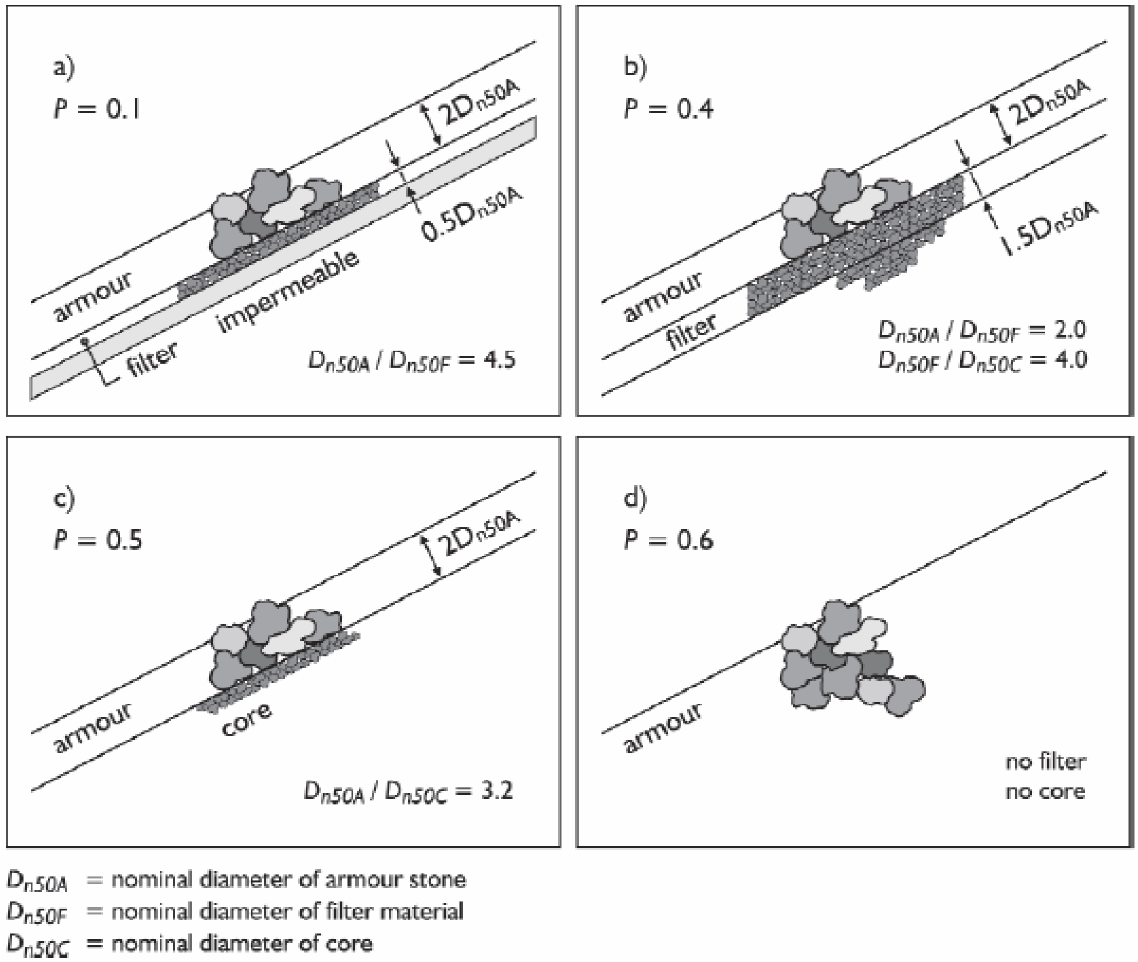

Figure 2.1: Notional permeability factor P for the formulae by Van der Meer (1988b), (Rock Manual,2007)

A critical value of the surf similarity parameter, ξ_{cr}, is derived from the structure slope. As a result, transition from plunging to surging waves is obtained by Eq.2.4. If, the structure slope is more gentle than 1:4 ($\cot\alpha \geq 4$), only plunging condition Eq.2.2 should be applied. Regardless of surf similarity parameter, ξ_m is larger or smaller than the critical value, ξ_{cr}. The ranges of formulae by Van der Meer (1988b) are in Table 2.1 (Rock Manual, 2007).

$$\xi_{cr} = \left[\frac{c_{pl}}{c_s} P^{0.31}\sqrt{\tan\alpha}\right]^{\frac{1}{P+0.5}} \qquad (2.4)$$

For $\xi_m < \xi_{cr}$ waves are plunging and Eq.2 applies.

For $\xi_m \geq \xi_{cr}$ waves are surging and Eq.3 applies.

Table 2.1: Range of validity of parameters in deep water formulae by Van der Meer (1988b), (Rock Manual, 2007)

Parameter	Symbol	Range
Slope angle	$\tan\alpha$	1:6–1:1.5
Number of waves	N	< 7500
Fictitious wave steepness based on T_m	s_{om}	0.01–0.06
Surf similarity parameter using T_m	ξ_m	0.7–7
Relative buoyant density of armourstone	Δ	1–2.1 [1]
Relative water depth at toe	$h/H_{s\text{-}toe}$	> 3 [2]
Notional permeability parameter	P	0.1–0.6
Armourstone gradation	D_{n85}/D_{n15}	< 2.5
Damage–storm duration ratio	$S_d/\sqrt{N}$	< 0.9
Stability number	$H_s/(\Delta D_{n50})$	1–4
Damage level parameter	S_d	$1 < S_d < 20$

In the stability formulae, damage parameter is important. The characteristic values of the damage level parameter, S_d, may be characterized as follows (Rock Manual,2007):

- *Start of damage* , corresponding to no damage (D = 0-5 per cent) in the Hudson formula
- *Intermediate damage*
- *Failure*, corresponding to reshaping of the armour layer such that the filter layer under the armourstone in a double layer is visible.

The limit values of the S_d are related to the slope angle of the structure. For armourstone in a double layer the values in Table 2.2 can be used (Rock Manual, 2007).

Table 2.2: Design values of the damage parameter, S_d, for armourstone in double layer

Slope (cotα)	Damage level		
	Start of damage	Intermediate damage	Failure
1.5	2	3–5	8
2	2	4–6	8
3	2	6–9	12
4	3	8–12	17
6	3	8–12	17

2.3 Van der Meer Formulae – Shallow Water Conditions

The Van der Meer (1988b) formulae are commonly used since 1988. Some modifications about these formulae is made in recent years. A limited extent about the effect of shallow foreshores with depth-limited waves has been addressed by the original work of Van der Meer (1988b) and more recently by further research of Van Gent et al. (2004). Shallow foreshores are where water depth over wave height at toe is smaller than three, $h / H_{s\text{-}toe} < 3$. In this shallow water conditions, wave load changes. So that, wave heights distribution deviates from the Rayleigh distribution. In these conditions, it is better to use 2 per cent wave height, $H_{2\%}$, than by the significant wave height, H_s (Van der Meer, 1988b). The values of the c_{pl} and c_s are also changed. At Van Gent et al. (2004), it is proposed to modify the formulae of Van der Meer (1988b) based on the analysis of the stability of rock armored slopes for shallow water conditions using spectral wave period, $T_{m-1,0}$, instead of mean wave period, T_m, to take into account the shape of the wave energy spectra in Van Gent et al. (2004). So, these modifications lead to new formulae, Eq.2.5 and Eq.2.6. The ranges of formulae are in Table 2.3 (Rock Manual, 2007).

For ***plunging waves*** $(\boldsymbol{\xi_{s-1,0} < \xi_{cr}})$:

$$\frac{H_s}{\Delta D_{n50}} = c_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \left(\xi_{s-1,0}\right)^{-0.5} \quad (2.5)$$

For ***surging waves*** $(\boldsymbol{\xi_{s-1,0} \geq \xi_{cr}})$:

$$\frac{H_s}{\Delta D_{n50}} = c_s P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \sqrt{\cot\alpha} \left(\xi_{s-1,0}\right)^{P} \quad (2.6)$$

Where :

c_{pl} = 8.4

c_s = 1.3

$H_{2\%}$ = wave height exceeded by 2 per cent of the incident waves at the toe (m)

D_{n50} = nominal diameter of the armourstone (m)

$\xi_{s-1,0}$ = surf similarity parameter, using the energy wave period $T_{m-1,0}$;

$$\xi_{s-1,0} = \tan\alpha \,/\, \sqrt{(2\pi/g).H_s/T_{m-1,0}{}^2}$$

$T_{m-1,0}$ = the (spectral) mean energy wave period (s)

Table 2.3: Range of validity of parameter in Van der Meer formulae for shallow water conditions (Rock Manual,2007)

Parameter	Symbol	Range
Slope angle	$\tan\alpha$	1:4–1:2
Number of waves	N	< 3000
Fictitious wave steepness based on T_m	s_{om}	0.01–0.06
Surf similarity parameter using T_m	ξ_m	1–5
Surf similarity parameter using $T_{m-1,0}$	$\xi_{s-1,0}$	1.3–6.5
Wave height ratio	$H_{2\%}/H_s$	1.2–1.4
Deep-water wave height over water depth at toe	H_{so}/h	0.25–1.5
Armourstone gradation	D_{n85}/D_{n15}	1.4–2.0
Core material – armour ratio	$D_{n50\text{-}core}/D_{n50}$	0–0.3
Stability number	$H_s/(\Delta D_{n50})$	0.5–4.5
Damage level parameter	S_d	< 30

The critical value of surf similarity parameter, ξ_{cr}, which shows the value that describes the transition from surging to plunging, can be found by Eq.2.4. If, the structure slope is more gentle than 1:4 ($\cot\alpha \geq 4$), only plunging condition Eq.2.5 should be applied.

Regardless of surf similarity parameter, $\xi_{s-1,0}$ is larger or smaller than the critical value, ξ_{cr}, (Rock Manual, 2007).

2.4 Van Gent – Stability Formula

A basic stability formula, Eq.2.7, is given by Van Gent et al. (2004). The influence of wave period at stability of structures is considered small, so that it is not used in Van Gent et al. (2004). Also, the ratio of $H_{2\%}/H_s$ are not used in Van Gent stability formula, because its influence has small importance. Besides, the effect of the permeability of the structure is incorporated by using stone sizes (Van Gent, 2005).

$$\frac{H_s}{\Delta D_{n50}} = 1.75\sqrt{\cot\alpha}\,(1 + D_{n50-core}/D_{n50})^{2/3}\left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \qquad (2.7)$$

α = slope angle (°)

$D_{n50-core}$ = nominal diameter of the core material (m)

D_{n50} = nominal diameter of the armourstone (m)

2.5 Comparison of the Stability Formulae

The overview of fields of application of four different stability formulae is showed in Table 2.4 and overview of fields of application of the Van der Meer stability formulae is pointed out in Table 2.5 (Rock Manual, 2007).

Table 2.4: Overview of fields of application of different stability formulae for rock-armoured slopes (Rock Manual,2007)

Criterion	Hudson	Van der Meer deep water	Van der Meer shallow water	Van Gent *et al*
Eq no.	5.134 or 5.135	5.136 or 5.137	5.139 or 5.140	5.141
Applicable for deep water? $h > 3H_{s\text{-}toe}$ *	Yes	Yes	No	No
Applicable for **very** shallow water? $H_{s\text{-}toe} < 70\%$ of H_{so} *	No	No	Yes	Yes
Recommended for structures with a permeable core?	Yes, for $K_D = 4$	Yes	Yes	Yes
Recommended for structures with an impermeable core?	No, except with $K_D = 1$ in Eq 5.135	Yes	Yes	No
Design experience with formula	Yes	Yes	Limited	No
Info on number of waves required?	No	Yes	Yes	Yes
Info on wave period required?	No	Yes (T_m)	Yes ($T_{m\text{-}1,0}$)	No
Info on wave height $H_{2\%}$ required?	No	No	Yes	No
Info on permeability P required?	No	Yes	Yes	No
Info on core material D_{n50} required?	No	No	No	Yes

Table 2.5: Overview of fields of application of the Van der Meer stability formulae (Rock Manual,2007)

	Water depth characterisation		
Item	**Very shallow water**	**Shallow water**	**Deep water**
Parameter: Relative water depth at the toe: $h/H_{s\text{-}toe}$ Wave height ratio, $R_H = H_{s\text{-}toe}/H_{so}$	$\approx 1.5 - \approx 2$ $< 70\%$	< 3 $70\% < R_H < 90\%$	> 3 $> 90\%$
Stability formulae: Van der Meer – deep water, Equation nos 5.136 and 5.137 Van der Meer – shallow water Equation nos 5.139 and 5.140			

2.6 Definition of the Armor Layer Damage and Measurement Types of the Damage at Model Studies

Under design conditions, waves attack and their forces can become so large to move or displace the units in the coastal defense structures. This is called as damage at the structures and there are two types of measurement techniques of damage. These are counting the number of displaced units and measuring the eroded surface profile of the armor slope. In both cases the damage is related to a specific sea state of specified duration (Coastal Engineering Manual, 2003).

2.6.1 Stone Count Method

In the stone count method, stones, which are moved around a specified zone around sea water level, are named as displaced stones. In the counting method, generally those stones are taken into account to calculate the proportion of displaced units relative to the total number of units, which are in specified zone (Coastal Engineering Manual, 2003).

Hedar (1960), Hughes (1993) describes measurement of damage through counting the stones. Digital images, videos and visual counting can be used to count the stones. Stone count method is a little bit subjective (Melby, 1999).

2.6.2 Profile Measurement

In this method, profile of the front slope of the structure is taken before and after the tests. Hudson (1959) used this method. In this method, Hudson (1959) has taken some profiles to determine the percentage volume of stones eroded relative to the total volume of stones in the active armor layer. Sounding rod is used with a circular foot to take the profiles. A number of profiles are taken to get the average profile. To get a percent damage, eroded area was divided by the total area. Hudson’s (1959) zero-damage criterion is corresponded to $\%D \leq 1$ percent. This zero damage criterion is used in the Hudson (1959) stability formula (Melby, 1999).

Broderick (1983) defined a dimensionless damage parameter S_d, as in Eq.2.8, for the rock armor (Coastal Engineering Manual, 2003).

$$S_d = \frac{A_e}{{D_{n50}}^2} \tag{2.8}$$

A_e = cross sectional eroded area (m^2)

D_{n50} = nominal diameter of armourstone size (m)

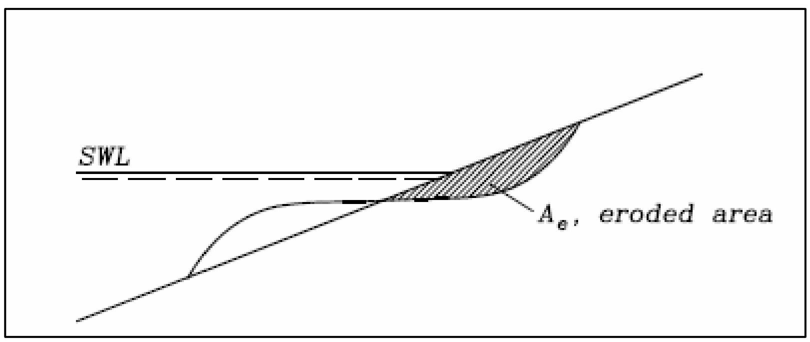

Figure 2.2: General view of eroded area (Coastal Engineering Manual, 2003)

Cross sectional eroded area, A_e, is calculated from the difference between initial and final profile of the structure. The damage parameter, S_d, has been used in Van der Meer (1988b) and Van Gent et al. (2004). In these stability formulas, damage level of the structure is defined by this damage parameter, S_d. In Van der Meer (1988b) and Van Gent et al. (2004), initial and final profiles of the structures have been obtained and damage levels of the structures have been obtained.

2.7 The Transition Between Stone Count Method and Profile Measurement ($N \rightarrow S_d$)

To measure the profiles of the model structures continuously, electronical and automatical devices are needed. However, in some laboratories, such devices do not exist. Stone count method is used to observe the damage. Since, in Van der Meer (1988b) and Van Gent et al. (2004), damage parameter, S_d, which is calculated by profile measurement, is being used, some transition formulas are needed to pass on from stone count method to profile measurement.

Vidal et al. (1995) proposed a parameter as a visual damage parameter, S_v, which is based on number of displaced stones around sea water level. Vidal et al. (1995) found that, great part of the damage occurs between levels ($SWL + H_s/2$) and ($SWL - H_s$), where SWL is still water level. In Eq.2.9, the link between number of stones and damage parameter, S_v, can be seen (Kamali & Hashim, 2009).

$$S_v = \frac{N \, . \, D_{n50}}{(1-n) \, . \, X} \tag{2.9}$$

N = number of displaced stones around sea water level

D_{n50} = nominal diameter of the armourstones (m)

n = porosity of the armour layer

X = length of the trunk section (m)

Burcharth et al. (2006) modified the visual damage parameter. In Burcharth et al. (2006), the transition between displaced armour stones N and Broderick (1983) damage parameter, S_d, has been made. To include the N in the expression for S_d, the eroded area (A_e) can be written as in Eq.2.10 and eroded volume of the cross section (V_e) can be written as in Eq.2.11.

$$A_e = \frac{V_e}{X} \tag{2.10}$$

$$V_e = \frac{N \,.D_{n50}{}^3}{(1-n)} \tag{2.11}$$

N = number of displaced stones around sea water level

D_{n50} = nominal diameter of the armourstones (m)

n = porosity of the armour layer

X = length of the trunk section (m)

By using the formulae of eroded area, eroded volume and damage parameter, S_d, of Broderick (1983), the transition formula, which is given in Eq.2.12, has been developed at Burcharth et al. (2006). In these formulae, N is the displaced armour stones at the active zone. In Coastal Engineering Manual (2003), the active zone is described as the area between one H_s below sea water level to one H_s above sea water level (Kamali & Hashim, 2009).

$$S_d = \frac{N \,.\, D_{n50}}{(1-n) \,.\, X} \tag{2.12}$$

N = number of displaced stones at active zone

D_{n50} = nominal diameter of the armourstones (m)

n = porosity of the armour layer

X = length of the trunk section (m)

2.8 Description of the Cumulative Damage and Measurement Types of Damage Development

All of the stability equations are based on a single storm event. Melby and Kobayashi (1999) have found out the phenomenon of progressive damage, also called as cumulative damage, due to the occurrence of successive storm events. Their work investigated a relationship between multi storm events and stability of the structure. Melby (2001) proposed a method to find the damage of the structure for a series of storms throughout the lifetime. Van der Meer (1988b, 2000) has also presented a method to investigate the development of the damage. Van der Meer stability formulae can be directly used at this Van der Meer (1988b, 2000) damage development method (Rock Manual, 2007).

2.8.1 Damage Development – Melby Method

Sometimes, it is necessary to state precisely the cumulative damage of the structure over successive storms as presented by Melby (2001). By the Eq.2.13, the cumulative damage, S_d, can be computed (Rock Manual, 2007).

$$S_d(t_n) = S_d(t_0) + 0.025\frac{{N_{s,n}}^5}{{T_{m,n}}^b}({t_n}^b - {t_0}^b) \quad (2.13)$$

N_s = $H_s/(\Delta D_{n50})$, the stability number (-), based on the significant wave height, $H_s = H_{1/3}$ (m)

T_m = mean wave period (s)

t_n = duration time of additional storm (s)

t_0 = duration time of storm to reach a damage level $S_d\,(t_0)$ (s)

$S_d(t_n)$ = damage at time t_n

$S_d(t_0)$ = damage at time t_0

n = time counter

b = coefficient determined in experiments, $b = 0.25$

Melby (2001) is based on model studies and has some limitations at its range of validity. In these model studies, wave conditions were depth limited and relatively constant for the subsequent events. The slope angle of the structure was 1:2 and surf similarity parameter, ξ_m, was between 2 and 4. The structures were rock structures with relatively impermeable core, with notional permeability values of $P \leq 0.4$. The ratio of armour and filter stone sizes, $D_{n50\text{-armour}}/D_{n50\text{-filter}}$, was 2.9 in experiments (Rock Manual, 2007).

2.8.2 Damage Development – Van der Meer Method

Van der Meer (1988b, 2000) has described an approach for cumulative damage, which can be used by Van der Meer stability formulae. In this approach, firstly the damage, S_{d1}, is obtained for the first wave condition. After that, by using the second wave condition, number of waves required to give the same damage, which is caused by the first wave condition, is computed. This is signed as N_1'. Then, number of waves of the second wave condition (N_2) is added on to N_1' to obtain N_t; $N_t = N_2 + N_1'$. Finally, the damage under the second wave condition, S_{d2}, with this increased number of waves, N_t, is obtained by using one of the Van der Meer stability formulae. By this way, damage development will be observed as in Figure 2.3 (Rock Manual, 2007).

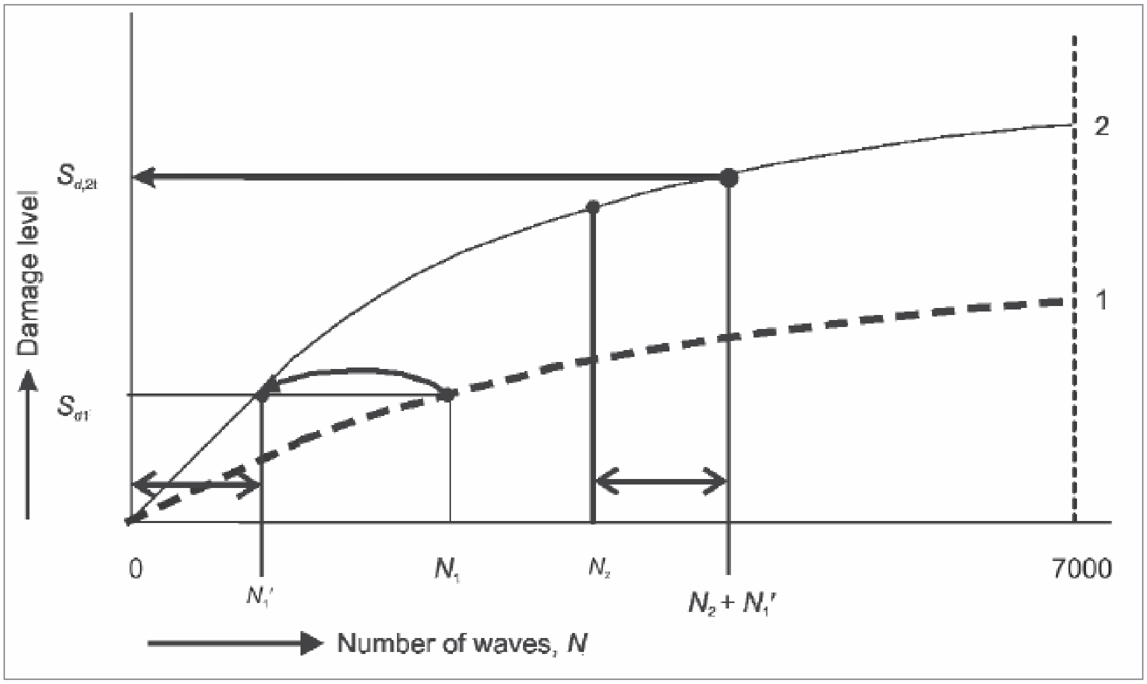

Figure 2.3: Illustration of method to assess cumulative damage (Rock Manual,2007)

CHAPTER 3

MODEL STUDIES

Reproducing the hydraulic phenomenon in a laboratory environment can be defined as hydraulic modeling. There are some advantages and disadvantages of hydraulic modeling.

3.1 Advantages of the Model Studies

The cost, which is required to construct the coastal defense structures, is very high. In order to find the optimum design and reduce the failure risk of the structure, model studies are needed and they have vital importance. In addition, there is a wide range of environmental conditions, which can be simulated and tested in model studies. In recent years, researchers have also found some other advantages of the model studies.

Dalrymple (1985) mentioned two distinct advantages obtained by experimental studies, which are used to model the nearshore structures (Hughes, 1993):

- The cost of the data collection in the small size models is lower than the field data collection.
- The equations, which are governing the processes without simplifying assumptions that have to be made for numerical models, are integrated by physical models.

Kamphuis (1991) pointed out that watching the experiment in operation gives the researcher an quick qualitative impression of the physical processes which in turn can help to focus the study and reduce the planned testing. Le Mehaute (1990) showed six reasons, why experimental studies for the coastal defense structures are needed (Hughes, 1993):

- Model studies are cost effective considering the size of the coastal projects.
- One of the most useful tools in coastal engineering is the laboratory experiment techniques. Because, there is an inherent limits of deterministic fluid mechanics due to turbulence.
- There can be always new techniques to understand the physical relationships.
- By the help of physical models, physics in a controlled environment can be monitored and controlled.
- A contact with the model physically, is the best way for intuitive discovery. It enlarges the imagination and directs creative engineering solutions. This cannot be done by theory or computer.
- Scale models allow reproduction of complex boundary conditions beyond the accuracy of finite step differences.

3.2 Disadvantages of Physical Models

There are also some disadvantages of the physical model studies (Hughes, 1993):

- **Scale effects** are the one of the disadvantages of the model studies. Scale effects are the differences between prototype and model, which comes from the incapability to simulate all forces in the experiment at the proper scale dictated by the scaling criteria. Viscous forces are common scale effect in model studies. They are higher at experimental studies than in the prototype.
- **Laboratory effects** are also a disadvantage for the model studies. They are the differences between prototype and model response that comes from limitations of the laboratory facilities, such as flow and wave generation techniques, solid model boundaries. The laboratory effects can influence the process. Because, suitable approximation of the prototype is impossible.

- Numerical models are cheaper to simulate than physical models.
- In model studies, sometimes all conditions and forces are not included. Wind forces are one of these.

3.3 Model Scale

"Scale selection for all models of coastal defense structures involves a compromise between the desire to model at as large as possible to avoid potential scale effects and the economics of conducting tests at smaller scales" (Hughes, 1993). In the hydraulic model, Froude model law has been used for scaling procedure. In this law, gravity and inertia have a significant effect on the wave motion compared to the surface tension and viscosity. In Froude model law, when the square of the velocity of a water particle (u) is divided by gravitational acceleration (g) and water depth (d), Froude number (F_r) is obtained as in Eq.3.1 (Hughes, 1993).

$$F_r = u^2/gd \tag{3.1}$$

In Froude model law, Froude numbers of model and prototype must be equal. In Eq.3.2, "p" and "m" sub letters denote prototype and model words.

$$(F_r)_p = (F_r)_m \tag{3.2}$$

If the length of the variable in model (L_m) is divided by real length of the prototype (L_p), model scale (λ_L) is obtained as in Eq.3.3. The time scale (λ_T) is also shown in Eq.3.4.

$$\lambda_L = L_m/L_p \tag{3.3}$$

$$\lambda_T = (\lambda_L)^{1/2} \tag{3.4}$$

For defining the weight scale (λ_W), the method of Sharp and Khader (1984) has been used as in Eq.3.5.

$$\lambda_W = (\lambda_L)^3 \frac{(\gamma_r)_m}{(\gamma_r)_p} \left[\frac{(\gamma_r)_p/(\gamma_w)_p - 1}{(\gamma_r)_m/(\gamma_w)_m - 1}\right] \quad (3.5)$$

$(\gamma_r)_m$ = rock density at the model, 2.7 t/m^3

$(\gamma_r)_p$ = rock density at the prototype, 2.6 t/m^3

$(\gamma_w)_m$ = water density at the model, 1.0 t/m^3

$(\gamma_w)_p$ = water density at the prototype, 1.025 t/m^3

The depth of the water at wave flume, available stone sizes, model wave characteristics and wave generating capability have influenced the decision of the scale selection. After all that factors, the model scale is decided to be 1:33.485. The scales of volume, weight and time is given in Table 3.1 by using the model scale.

Table 3.1: Weight, time, length and volume scales which is used in model studies

	MODEL SCALE
LENGTH	λ_L = 1 : 33.485
TIME	λ_T = 1 : 5.787
VOLUME	λ_V = 1 : 37544.9
WEIGHT	λ_W = 1 : 39999.3

3.4 Generation and Analysis of the Waves

To create waves in wave flume, mechanical wave generation technique is used. In this technique, there is a movable partition, which creates waves by oscillation in wave flume. In this model study, hydraulic servo–system piston type wave maker is used as a wave maker. To control this wave maker, there is a stand-alone controller. An input signal is needed to create irregular wave series of prescribed characteristics. A time series is needed to create motion in the wave maker. To do this, Goda's method has been used. Firstly, the target frequency spectrum is needed to be chosen. Bretschneider-Mitsuyasu type spectrum, Eq.3.6, has been chosen as a spectrum for the model waves. Then, a transfer function, Eq.3.7, is needed to convert target spectrum of the water waves to the target spectrum of the wave paddle motion (Goda, 2000).

Bretschneider-Mitsuyasu type spectrum:

$$S(f) = 0.257{H_{1/3}}^2{T_{1/3}}^{-4}f^{-5}exp\left\{-1.03\left(T_{1/3}f\right)^{-4}\right\} \qquad (3.6)$$

$H_{1/3}$ = significant wave height

$T_{1/3}$ =significant wave period

A transfer function for the piston type wave-maker:

$$F_1(f,h) = \frac{4\sinh^2(2\pi h/L)}{4\pi h/L+\sinh(4\pi h/L)} \qquad (3.7)$$

h= water depth (m)

The target spectrum of the wave paddle motion S_G(f) is calculated for the target wave spectrum S_W(f) as in Eq.3.8 (Goda, 2000).

$$S_G(f) = S_W(f)/{F_1}^2(f/h) \qquad (3.8)$$

After that, time series, which is needed for the wave paddle, can be calculated. Then, wave data, which is obtained from the model studies, is needed to be analyzed. Zero-upcrossing method is used to analyze raw wave data. Maxima and minima of the records have been calculated. Maximum wave height (H_{max}), minimum wave height (H_{min}), mean wave height (H_m) and significant wave heights (H_s) and their corresponding wave periods (T) are calculated using this method.

In model studies, the most important item to measure is incident waves and reflection coefficient. The reflection is a very important phenomenon in model studies. Cause, there is a multi-wave-reflection system in wave flume. Waves, which are generated from wave piston, firstly reflect from structure. Then, waves re-reflect from wave piston. This process is continuous and it repeats until reflected waves are fully attenuated. Goda & Suzuki (1976) method is used to calculate incident and reflected wave heights based on spectral resolution like in Figure 3.1. Firstly, upper and lower limits of frequency, f_{min} and f_{max} are determined as in Eq.3.9 and Eq.3.10 (Goda & Suzuki, 1976).

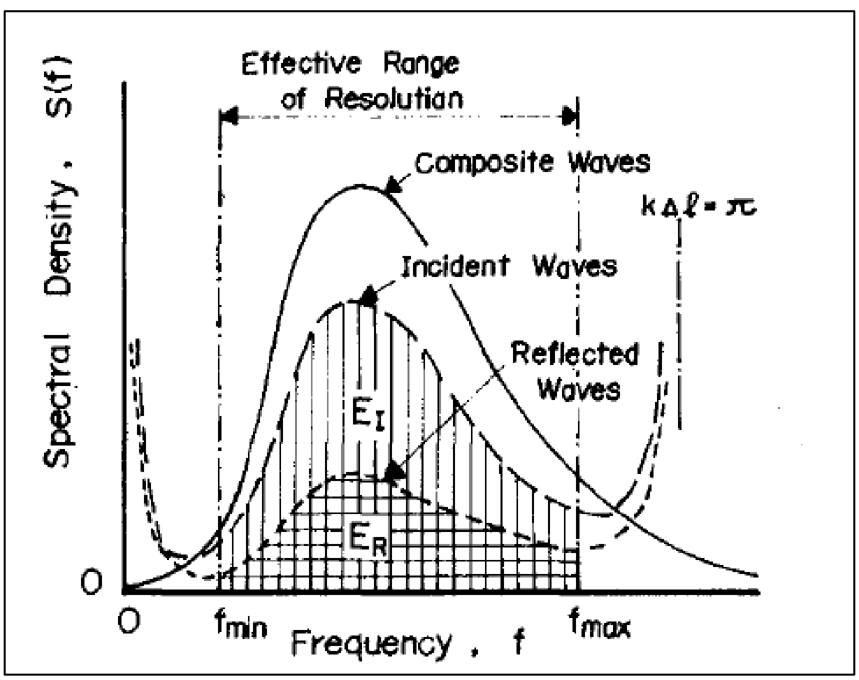

Figure 3.1: Illustration of Spectral Resolution

$$f_{min} : \Delta l / L_{max} = 0.05 \quad (3.9)$$

$$f_{max} : \Delta l / L_{min} = 0.45 \quad (3.10)$$

L_{max} = wavelength corresponding to f_{min} (m)

L_{min} = wavelength corresponding to f_{max} (m)

Δl = distance between gauges (m)

Secondly, energies of the reflected and incident waves are evaluated as in Eq.3.11 and Eq.3.12 (Goda & Suzuki, 1976).

$$E_I = \int_{f_{min}}^{f_{max}} S_I\,(f)\,df \quad (3.11)$$

$$E_R = \int_{f_{min}}^{f_{max}} S_R\,(f)\,df \quad (3.12)$$

Then, overall coefficient of reflection is calculated by Eq.3.13 (Goda & Suzuki, 1976).

$$K_R = \sqrt{E_R / E_I} \quad (3.13)$$

Finally, the incident and reflected wave heights, H_I and H_R are calculated as in Eq.3.14 and Eq.3.15 (Goda & Suzuki, 1976).

$$H_I = \frac{1}{\sqrt{1+{K_R}^2}} H_s \quad (3.14)$$

$$H_R = \frac{K_R}{\sqrt{1+{K_R}^2}} H_s \quad (3.15)$$

3.5 Experimental Set-up

METU, Civil Engineering Department, Coastal and Harbor Engineering Laboratory wave flume, Fig 3.2, is used to simulate the different cross sections. The wave flume is 6.2 m. wide, 28.8 m. long and 1.0 m. deep. In the wave flume, there is also inner channel which is made from Plexiglas walls. This inner channel has 18 m. long, 1.5 m. wide and 1.0 m. depth. That inner channel works to reduce the reflection effects which comes from sides of the wave flume. There is also wave attenuator, placed at the end of the wave flume to reduce the effect of the reflected waves.

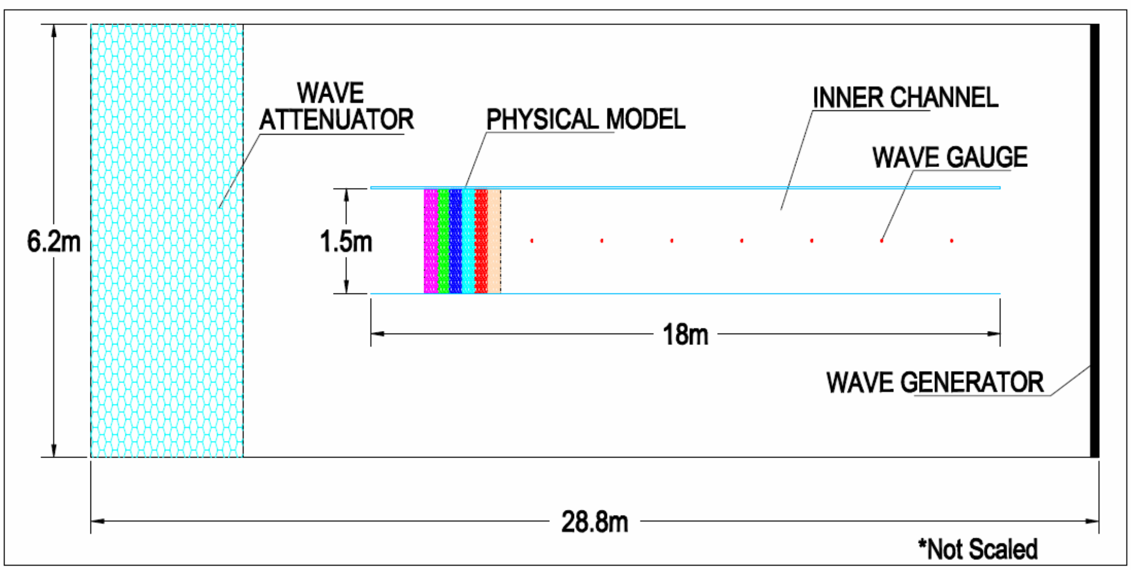

Figure 3.2: Layout of the wave flume

When measuring the waves in the wave flume, the measuring gauges of DHI type 202, which are made of two thin parallel stainless steel electrodes, are used. They are also called as probes. These probes measure the conductivity of the water volume between the two electrodes. If the water volume between that electrodes changes, the conductivity also changes.

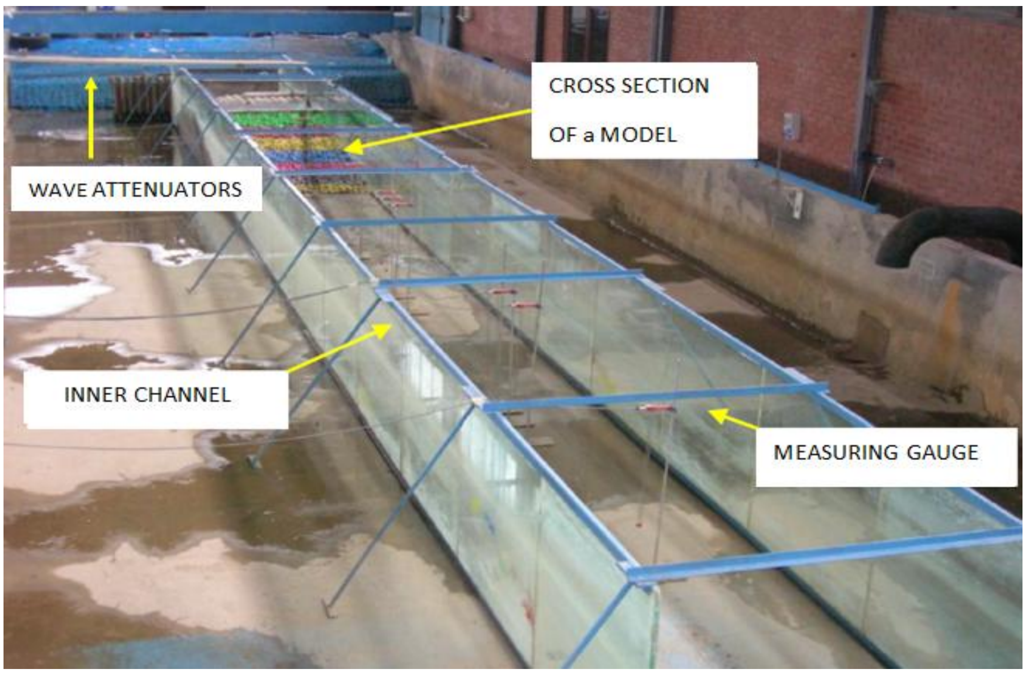

Figure 3.3: Wave flume

DHI Wave Synthesizer and DHI Hydraulic Power Pack type 301/22-PM were used to generate the waves in wave flume. At the generation of the waves, piston type wave-maker, Figure 3.4, is used. It has three main parts, which are wave synthesizer software, hydraulic power pack and hydraulic servo actuator. Digital wave data is converted to the analog signals to the piston by wave synthesizer. Hydraulic servo actuator transfers the analog signals to the piston. Hydraulic power pack maintains the piston pressure, which is necessary.

Figure 3.4: Piston type wave-maker

3.6 Parts of the Rubble Mound Coastal Defense Structure

The typical parts of the rubble mound coastal defense structure are given in Figure 3.5.

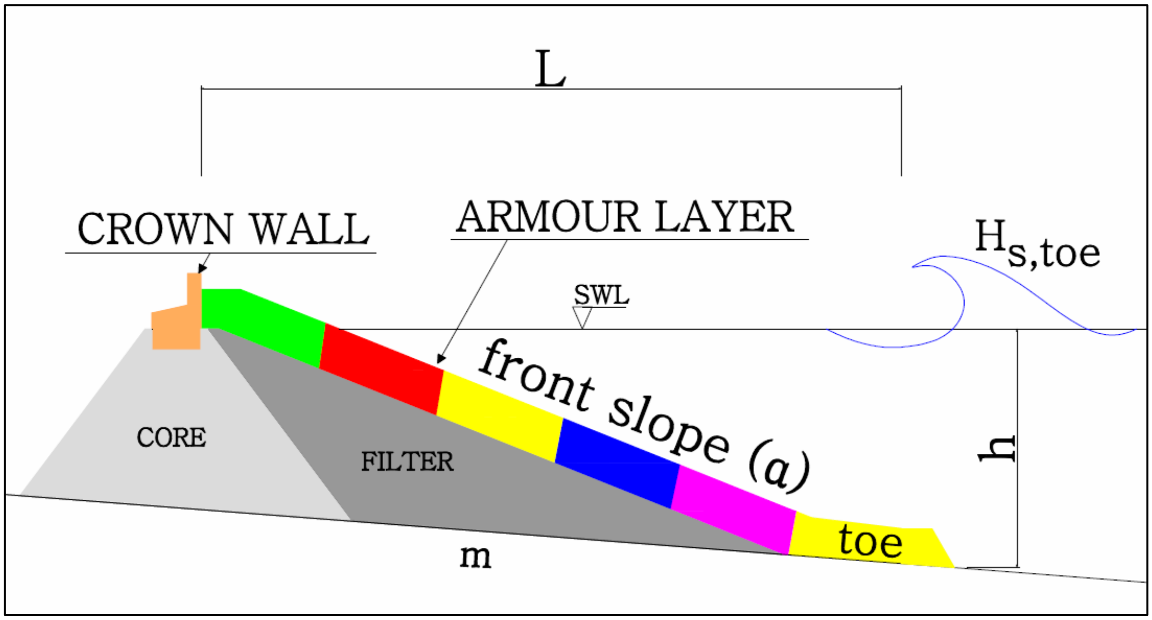

Figure 3.5: Cross section of rubble mound coastal defense structure

$H_{s,toe}$ = Significant wave height at the toe of the structure (m)

h = Water depth at the toe of the structure (m)

m = Seabed slope

α = Slope angle (°)

L = Length of the structure (m)

3.7 Construction of the Models

The inner channel of the wave flume is used to build the cross sections of the model studies. Quarry run material, which is scaled with the weight scale, was used for the construction of the models. The net volume, which is determined by using porosity, was divided by a volume of a single stone to find the number of stones that is used in experiments. All the stones, which are used to construct armour layer, is weighed individually. This work is done to control the weight of the stone whether it is in the range of stone weight or not. The stones are colored different colors to form color stripes to be able to see the movement of the stones within a layer. By this way, damages are observed easily. The stones are placed randomly. In the framework making process of the cross sections, steel bars were used. There was also 1:26.5 foreshore slopes in front of the structure in some model studies.

3.8 Cross-Sections of the Models

There were six models in that physical model studies. Cross sections of the models are constructed at the inner channel of the wave flume. All the models are designed based on Van der Meer design approach with different armor stone sizes and front slopes. In the models, armor stone sizes are ranged as 150 – 200 grams and 200 – 250 grams and front slopes were 1:2, 1:3 and 1:5. The nominal diameters of the armor stones, D_{n50}, are 4.5 cm for the 200 – 250 grams armor stones and 4.2 cm for the 150 – 200 grams stones. The prototype values of these diameters are 1.5 m and 1.4 m for the armor stones. 10 – 50 grams stones was used to form the filter layers and for the core layer 0 – 6.2 grams stones were used which has nominal diameters of 2.4 and 1.3 centimeters. The prototype values of these diameters are 0.8 and 0.43 meters. The water depths at the toe of the models were ranged between 33 - 44.3 centimeters. Furthermore, there was a foreshore slope at Model 1 - Model 4. For Model 5, horizontal bed is applied. The details of the models are presented in the following parts.

3.8.1 Model 1

Cross section and the position of the Model 1 are shown in Figure 3.6 and Figure 3.7 respectively.

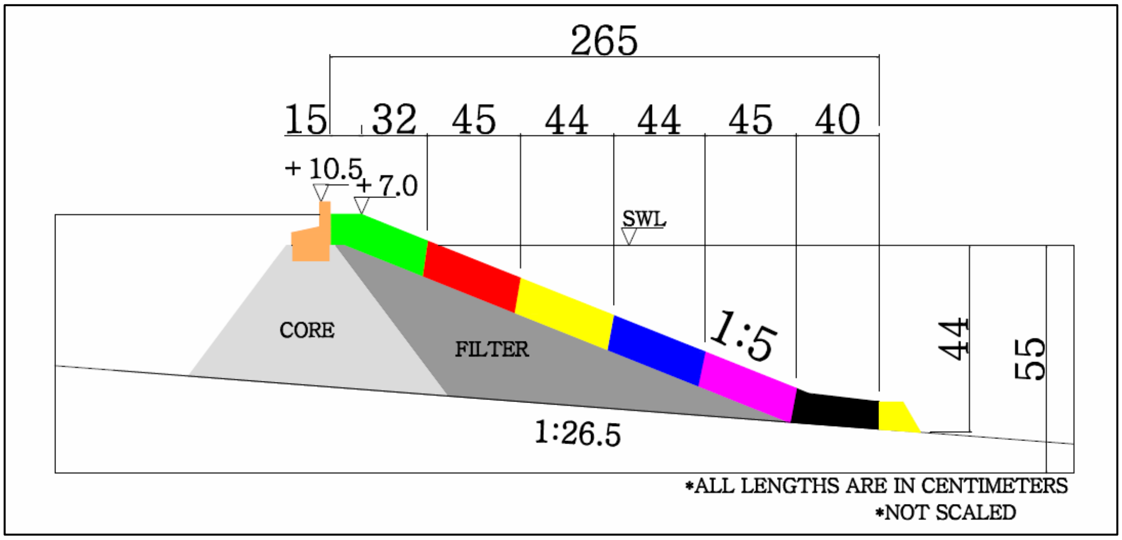

Figure 3.6: Cross section of the Model 1

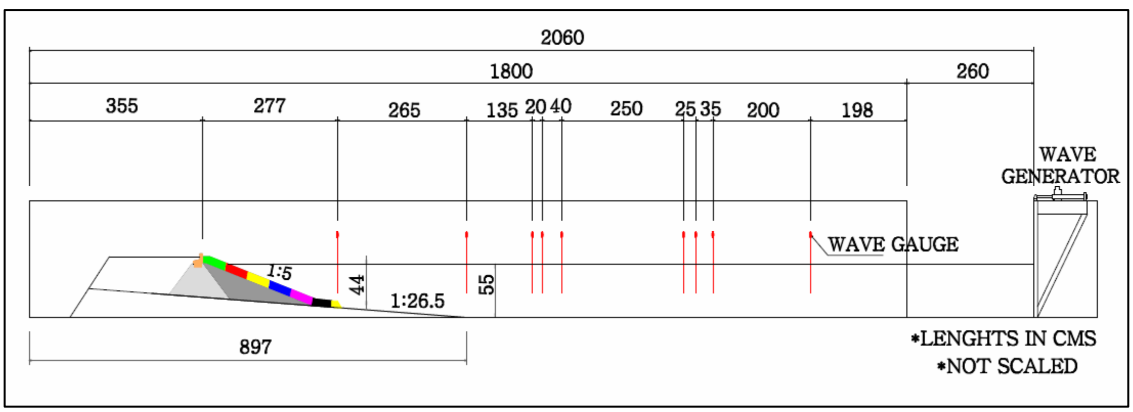

Figure 3.7: The position of the Model 1 at wave flume

In Model 1, the front slope of the structure was 1:5. The stone size, which is used for the armor layer, was 200 – 250 grams in Model 1. The number and distribution of the stones can be obtained from Table 3.2.

Table 3.2: The number and distribution of the stones for Model 1

			WEIGHT	
TYPE OF LAYER	**COLOR**	**NO. OF STONES**	**PROTOTYPE (tons)**	**MODEL (grams)**
ARMOUR LAYER	Green	372	8 - 10	200 - 250
	Red	395		
	Yellow	344		
	Blue	354		
	Pink	375		
	Black	370		
	Toe	74		
	Total	∑ 2284		
			WEIGHT	
TYPE OF LAYER			**PROTOTYPE (tons)**	**MODEL (grams)**
FILTER LAYER			0.4 - 2	10 - 50
CORE LAYER			0 - 0.25	0 - 6.2

3.8.2 Model 2

Cross section and the position of the Model 2 are shown in Figure 3.8 and Figure 3.9 respectively.

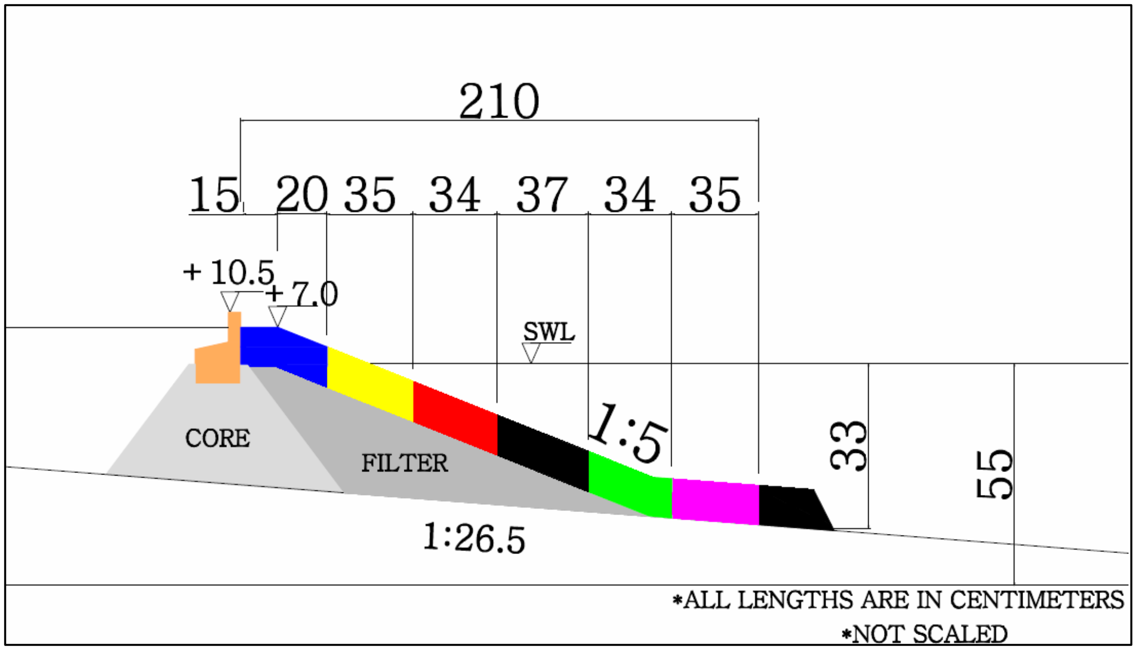

Figure 3.8: Cross section of the Model 2

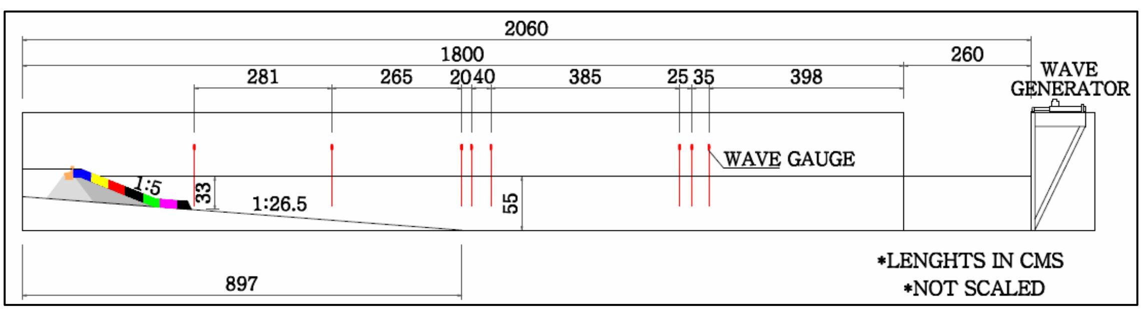

Figure 3.9: The position of the Model 2 at wave flume

In Model 2, the front slope of the structure was 1:5. The stone size, which is used for the armor layer, was 150 – 200 grams in Model 2. The stone size of the filter layer was 10 – 50 grams. In core layer, the stone size was 0 – 6.2 grams. The number and distribution of the stones can be obtained from Table 3.3.

Table 3.3: The number and distribution of the stones for Model 2

			WEIGHT	
TYPE OF LAYER	**COLOR**	**NO OF STONES**	**PROTOTYPE (tons)**	**MODEL (grams)**
ARMOUR LAYER	Blue	353	6 - 8	150 - 200
	Yellow	370		
	Red	345		
	Black	356		
	Green	350		
	Pink	356		
	Toe	200		
	Total	∑ 2330		
			WEIGHT	
TYPE OF LAYER			**PROTOTYPE (tons)**	**MODEL (grams)**
FILTER LAYER			0.4 - 2	10 - 50
CORE LAYER			0 - 0.25	0 - 6.2

3.8.3 Model 3

Cross section and the position of the Model 3 are shown in Figure 3.10 and Figure 3.11 respectively. In that model, the crown wall was higher than other models.

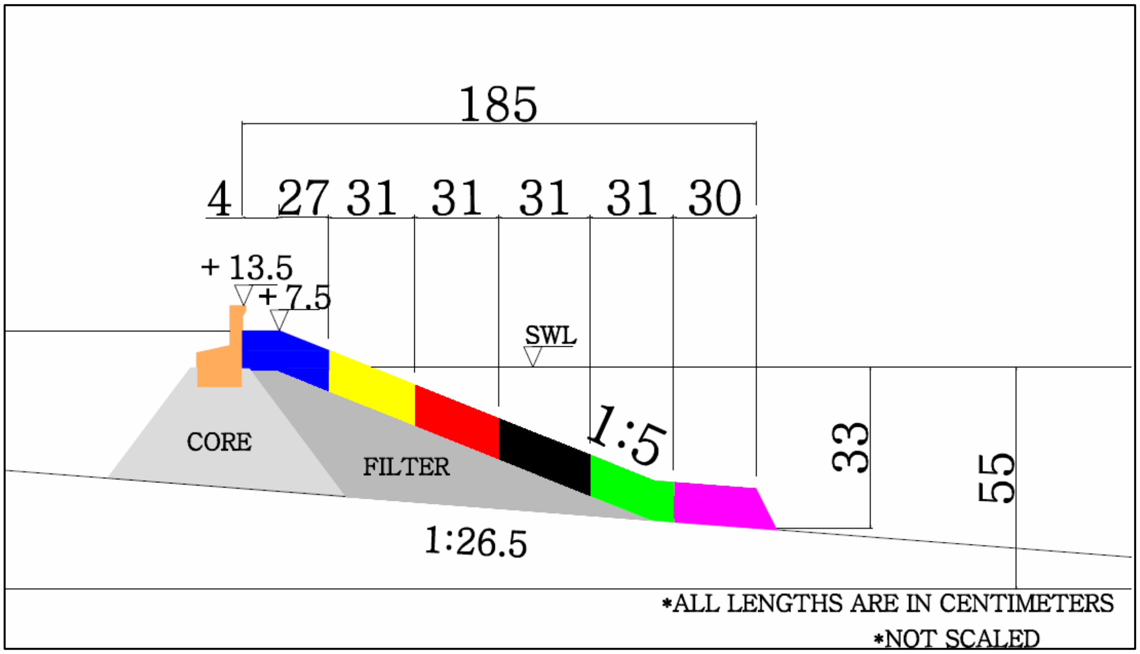

Figure 3.10: Cross section of the Model 3

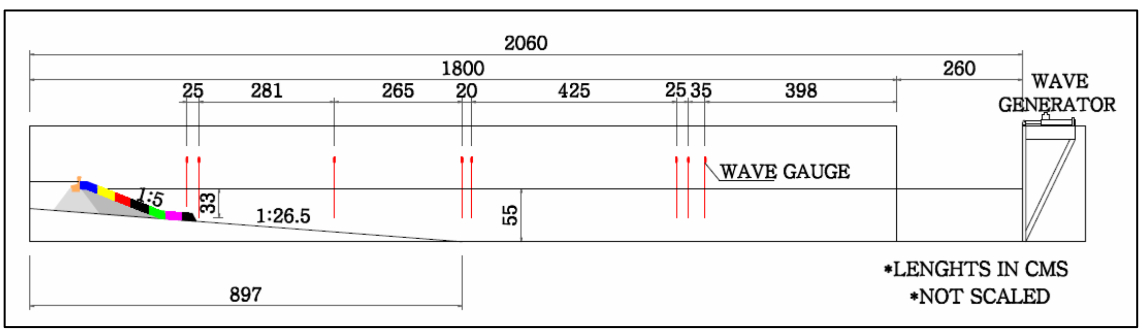

Figure 3.11: The position of the Model 3 at wave flume

In Model 3, the front slope of the structure was 1:5. The stone size, which is used for the armor layer, was 150 – 200 grams in Model 3. The stone size of the filter layer was 10 – 50 grams. In core layer, the stone size was 0 – 6.2 grams. The number and distribution of the stones can be obtained from Table 3.4.

Table 3.4: The number and distribution of the stones for Model 3

			WEIGHT	
TYPE OF LAYER	**COLOR**	**NO OF STONES**	**PROTOTYPE (tons)**	**MODEL (grams)**
ARMOUR LAYER	Blue	345	6 - 8	150 - 200
	Yellow	345		
	Red	345		
	Black	345		
	Green	345		
	Pink	380		
	Total	∑ 2105		
			WEIGHT	
TYPE OF LAYER			**PROTOTYPE (tons)**	**MODEL (grams)**
FILTER LAYER			0.4 - 2	10 - 50
CORE LAYER			0 - 0.25	0 - 6.2

3.8.4 Model 4

Cross section and the position of the Model 4 are shown in Figure 3.12 and Figure 3.13 respectively.

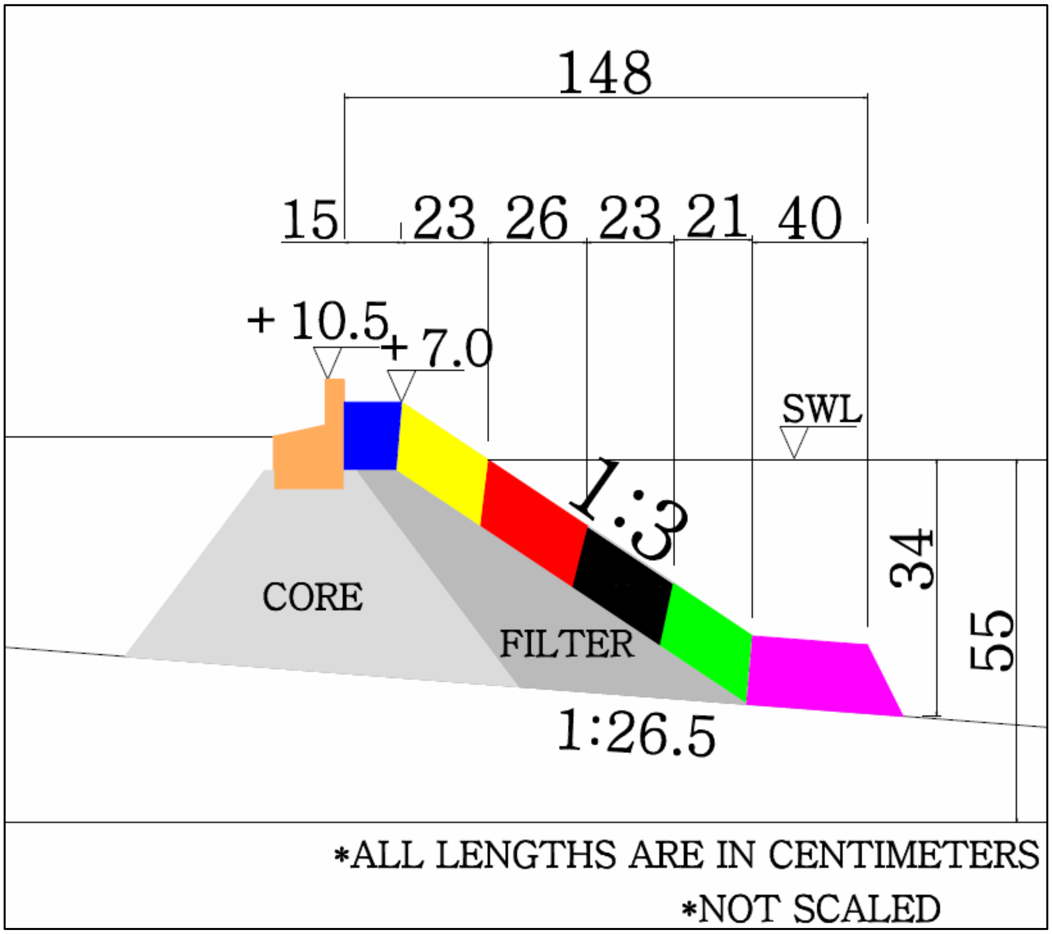

Figure 3.12: Cross section of the Model 4

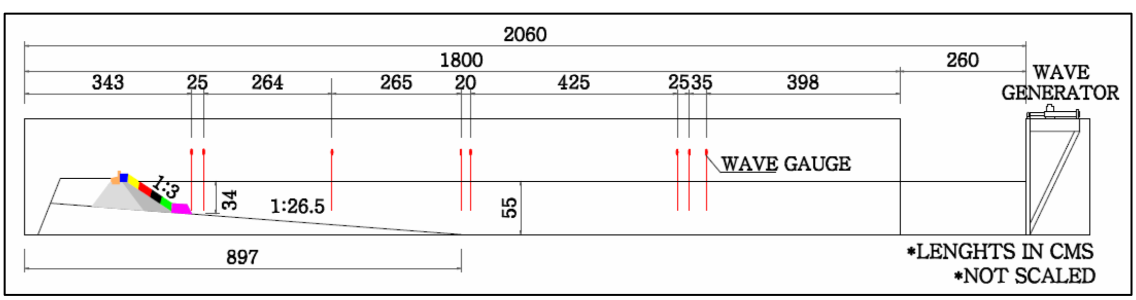

Figure 3.13: The position of the Model 4 at wave flume

In Model 4, the front slope of the structure was 1:3. The stone size, which is used for the armor layer, was 200 – 250 grams in Model 4. The stone size of the filter layer was 10 – 50 grams. In core layer, the stone size was 0 – 6.2 grams. The number and distribution of the stones can be obtained from Table 3.5.

Table 3.5: The number and distribution of the stones for Model 4

			WEIGHT	
TYPE OF LAYER	**COLOR**	**NO OF STONES**	**PROTOTYPE (tons)**	**MODEL (grams)**
ARMOUR LAYER	Blue	140	8 - 10	200 - 250
	Yellow	240		
	Red	240		
	Black	240		
	Green	240		
	Pink	300		
	Total	∑ 1400		
			WEIGHT	
TYPE OF LAYER			**PROTOTYPE (tons)**	**MODEL (grams)**
FILTER LAYER			0.4 - 2	10 - 50
CORE LAYER			0 - 0.25	0 - 6.2

3.8.5 Model 5

In Model 5, 2 types of stone sizes were used for the armor layer. First case (Model 5-1) was 150-200 grams and the second case (Model 5-2) was 200 - 250 grams. The front slope of the structure was 1:2 in both cases. Cross section and the position of the Model 5-1 are shown in Figure 3.14 and Figure 3.15 respectively.

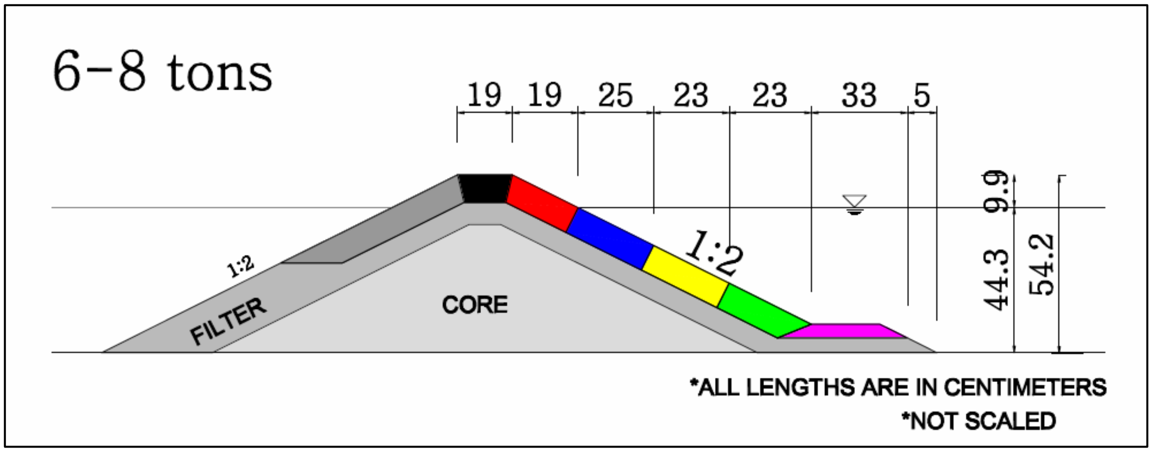

Figure 3.14: Cross section of the Model 5-1

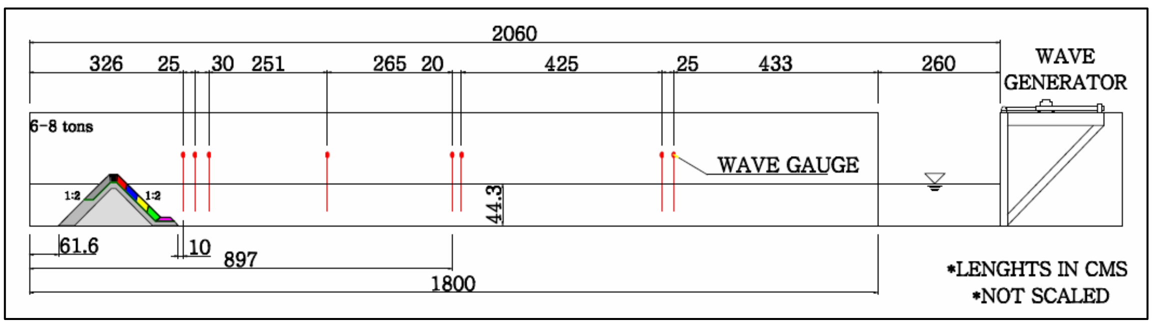

Figure 3.15: The position of the Model 5-1 at wave flume

Cross section and the position of the Model 5-2 are shown in Figure 3.16 and Figure 3.17 respectively.

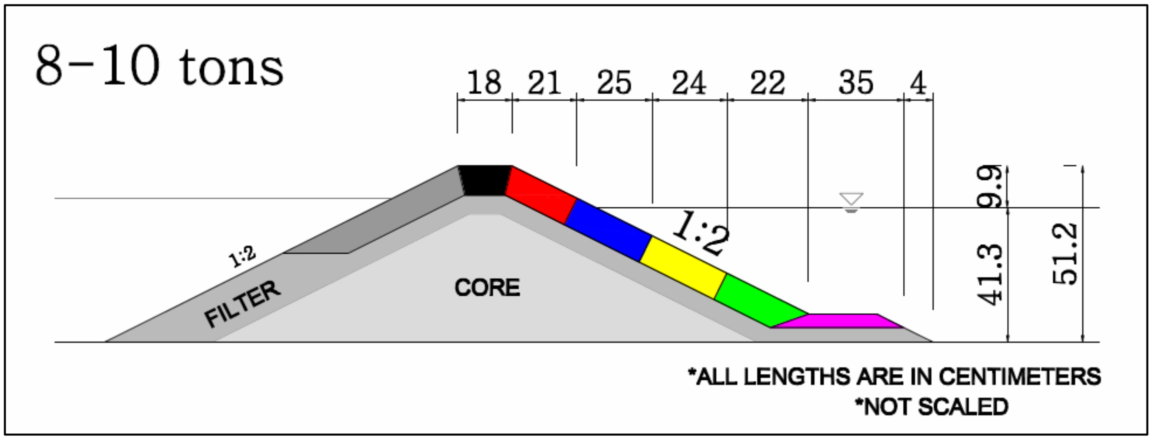

Figure 3.16: Cross section of the Model 5-2

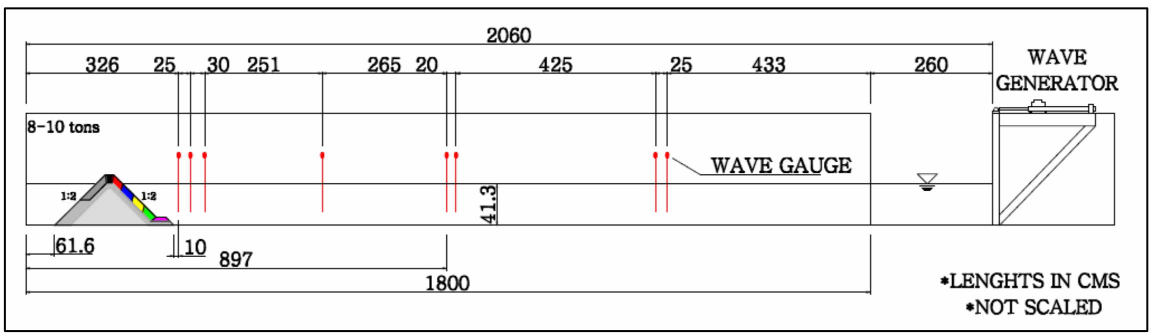

Figure 3.17: The position of the Model 5-2 at wave flume

The stone size, which is used for the armor layer, was 150 – 200 grams for the Model 5-1 and was 200 – 250 grams for the Model 5-2. The stone size of the filter layer was 10 – 50 grams. In core layer, the stone size was 0 – 6.2 grams. The number and distribution of the stones of Model 5-1 can be obtained from Table 3.6. For the Model 5-2, the number and distribution of the stones can be seen from Table 3.7.

Table 3.6: The number and distribution of the stones for the Model 5-1 (p=0.4)

			WEIGHT	
TYPE OF LAYER	**COLOR**	**NO OF STONES**	**PROTOTYPE (tons)**	**MODEL (grams)**
ARMOUR LAYER	Black	170	6 - 8	150 - 200
	Red	250		
	Blue	300		
	Yellow	300		
	Green	285		
	Pink	175		
	Total	∑ 1480		

	WEIGHT	
TYPE OF LAYER	**PROTOTYPE (tons)**	**MODEL (grams)**
FILTER LAYER	0.4 - 2	10 - 50
CORE LAYER	0 - 0.25	0 - 6.2

Table 3.7: The number and distribution of the stones for the Model 5-2 (p=0.4)

			WEIGHT	
TYPE OF LAYER	**COLOR**	**NO OF STONES**	**PROTOTYPE (tons)**	**MODEL (grams)**
ARMOUR LAYER	Black	140	8 - 10	200 - 250
	Red	205		
	Blue	250		
	Yellow	250		
	Green	230		
	Pink	145		
	Total	∑ 1220		

	WEIGHT	
TYPE OF LAYER	**PROTOTYPE (tons)**	**MODEL (grams)**
FILTER LAYER	0.4 - 2	10 - 50
CORE LAYER	0 - 0.25	0 - 6.2

CHAPTER 4

EXPERIMENTS AND RESULTS

In this chapter, experimental results of the model studies with different cross sections are presented for each model separately in terms of:

- Structural damage
- Cumulative damage of the structure
- Incident wave heights at the toe of the structure
- Damage curves
- The transition of the cumulative damages of the structures to the damage parameter (S_d)

Damage percentages at the tested cross sections were the percentage of the displaced armor stones to the total number of armor layer stones. Since the armor stones were colored in each layer differently, the displacements of the stones were observed easily as the stones dislodged and moved from their original location. The damage percentage (D%) of the models was expressed as in Eq.4.1.

$$D\% = {}^{D_d}/_{D_T} * 100 \quad (4.1)$$

$D\%$ = percentage of the damage at the model structures

D_d = number of displaced armour stones at the cross section

D_T = number of total armour stones at the cross section

To see the development of the damages in the models, cumulative damage approach has been used. According to that approach, consecutive wave series, representing a storm, with different wave characteristics were applied to the models. The total combination of these wave series were named as a wave set. The wave sets that were applied to the cross sections were obtained from the wave climate of site-specific sponsored research project. Therefore the wave sets presents the storm conditions selected with certain return periods ,T_r, (e.g. T_r = 10, 50, 100 years) obtained from the extreme wave statistics of the site. Design of the rubble mound coastal defense structures cross sections used in the model studies and the model tests with applied wave sets are presented in Appendix A. These cross sections again designed in accordance with the site specific sponsored research project.

In the experiments, the number of displaced stones in every color stripes was counted after each wave series in one wave set. To get the cumulative damage of the models, the cross sections were kept as damaged, until it was the last wave series in one wave set. At the end of each wave series, displaced stones in every color stripes were counted. After the final wave series was given and the final damages of the models were noted, cross sections were reconstructed as original cross section to start a new wave set. In addition, digital pictures were taken between each of the wave series.

For a comparative study for cumulative damages of the cross sections, Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001) are used by converting the cumulative damage values during the experiments to damage parameters, S_d, which is developed by Broderick (1983). Since, in all of the model studies h / $H_{s\text{-}toe}$ values were smaller than 3, it was appropriate to use Van der Meer (shallow water) formulae together with Van Gent et al. (2004) and Melby (2001). The transition from number of displaced stones in active zone to damage parameter is performed by using Burcharth et al. (2006)

method, which is described in Chapter 2. Burcharth et al. (2006) have used number of displaced stones in the active zone where is the area between one H_s below sea water level to one H_s above sea water level according to Coastal Engineering Manual (2003). In model studies, active zones were determined by this active zone criterion and the stones, which were displaced at this zone, were identified. By this way, the transition from number of displaced stones in active zone to damage parameter, S_d, had been completed.

During the experiments, wave parameters, which are obtained from the measurements of wave gauges in the wave flume, are:

- H_s : significant wave heights of the incident waves at the toe of the structure (m)
- T_s : significant wave periods (sec)
- $H_{s,5Hs}$: significant wave heights at the $5H_s$ seaward of the structure toe which is used for Melby (2001) equation (m)
- $H_{2\%}$: wave heights exceeded by 2 per cent of the incident waves at the toe (m)
- T_m : mean wave periods (sec)
- T_{m-1} : energy wave periods (sec)
- N : number of waves
- t : durations of the wave sets (hour)

The values of the wave parameters for the irregular wave series are given in Table A.4 – Table A.29.

In addition, to stone count method, in Model 5, the damage was also measured by profile measurement method. Firstly, initial profile of the cross section is obtained by averaging the seven parallel profile measurements along the slope. Then, final profile of the cross section is determined by the same way, by averaging the seven parallel profile measurements along the slope after finishing each wave set. Eroded areas of the cross section were the difference between these average initial profiles and average final profiles. Finally, damage parameter, S_d, is found by using Broderick (1983) method which is described previously in Chapter 2.

Before starting the experiments, all of the wave gauges were cleaned and the parts of the piston type wave maker were controlled whether any bolt at the wave maker is loosened or not. In addition, at the beginning of the wave sets, calibration of the wave measuring system was done.

During the experiments under severe storm conditions, overtopping was observed. Since this study was confined only to the stability of the structure, that is the damage of the structure profile, overtopping observations were not included and discussed in this thesis.

4.1 Model 1

Cross sectional properties of Model 1 has been presented in Chapter 3. Model 1 was built with 1:5 slope at its front slope. 200-250 grams stones were used to form the armor layer of the structure. The porosity was 0.43. Five wave sets were given to the Model 1.

The wave conditions, number of stones, which were displaced in every color stripe, cumulative percent damages are represented in Table A.4 – Table A.8 as an outcome of the 5 wave sets in Appendix A.

For Model 1, within the active zone, damage (S_d) is computed by the method given by Burcharth et al. (2006), in order to be able to compare with the formulae of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001). To use this method, firstly the active zone of the Model 1 was determined according to the Coastal Engineering Manual (2003) criteria as it is described in Chapter 2. The active zone of the Model 1 is shown in Figure 4.1.

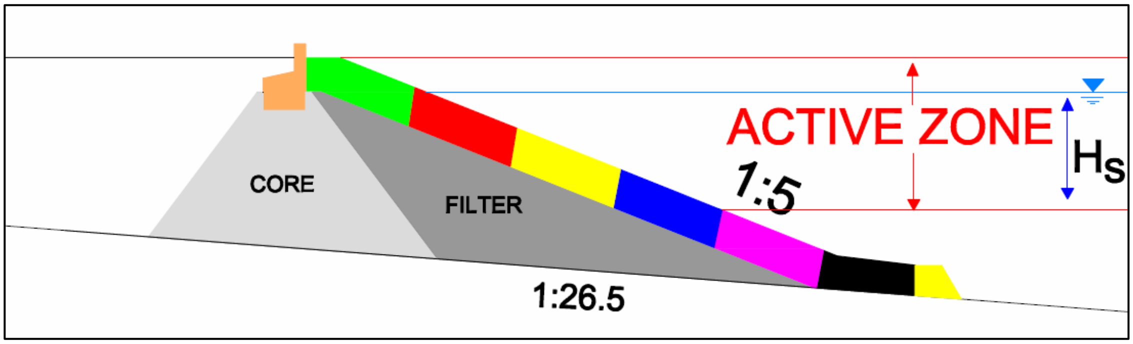

Figure 4.1: Active zone of Model 1

In Table 4.1 - Table 4.5, converted damage parameters of Model 1 are shown as a result of these 5 wave sets. Example computation for the transition between the number of displaced stones in active zone and damage parameter (S_d) is given in Appendix B. All of the other computations are made as it is in the example.

Table 4.1: Cumulative damage parameters (S_d) of Model 1, Set 1

Damage parameters (S_d) and no of displaced stones at active zone (p=0.43)					
No of displaced stones (active zone)	9	18	42	83	132
Damage parameters (S_d)	0.5	0.9	2.2	4.4	6.9

Table 4.2: Cumulative damage parameters (S_d) of Model 1, Set 2

Damage parameters (S_d) and no of displaced stones at active zone (p=0.43)						
No of displaced stones (active zone)	6	26	70	105	152	214
Damage parameters (S_d)	0.3	1.4	3.7	5.5	8.0	11.3

Table 4.3: Cumulative damage parameters (S_d) of Model 1, Set 3

Damage parameters (S_d) and no of displaced stones at active zone (p=0.43)					
No of displaced stones (active zone)	5	24	60	94	132
Damage parameters (S_d)	0.3	1.3	3.2	4.9	6.9

Table 4.4: Cumulative damage parameters (S_d) of Model 1, Set 4

Damage parameters (S_d) and no of displaced stones at active zone (p=0.43)					
No of displaced stones (active zone)	6	9	15	19	52
Damage parameters (S_d)	0.3	0.5	0.8	1.0	2.7

Table 4.5: Cumulative damage parameters (S_d) of Model 1, Set 5

Damage parameters (S_d) and no of displaced stones at active zone (p=0.43)					
No of displaced stones (active zone)	9	11	14	16	56
Damage parameters (S_d)	0.5	0.6	0.7	0.8	2.9

The damage parameter values are compared with the values, which come from stability formulae, in later chapters. For Model 1, Set 2 the filter layer was almost visible valued as complete damage condition.

4.2 Model 2

Cross sectional properties of Model 2 have been presented in Chapter 3. Model 2 was built with 1:5 slope at its front slope. 150-200 grams stones were used to form the armor layer of the structure. The porosity was 0.4. Four wave sets were given to the Model 2.

The wave conditions, number of stones, which were displaced in every color stripe, cumulative percent damages are represented in Table A.9 – Table A.12 as an outcome of these 4 wave sets in Appendix A.

For Model 2, within the active zone, damage (S_d) is computed by the method given by Burcharth et al. (2006), in order to be able to compare with the formulae of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001). To use this method, firstly the active zone of the Model 2 was determined according to the Coastal Engineering Manual (2003) criteria as it is described in Chapter 2. The active zone of the Model 2 is shown in Figure 4.2.

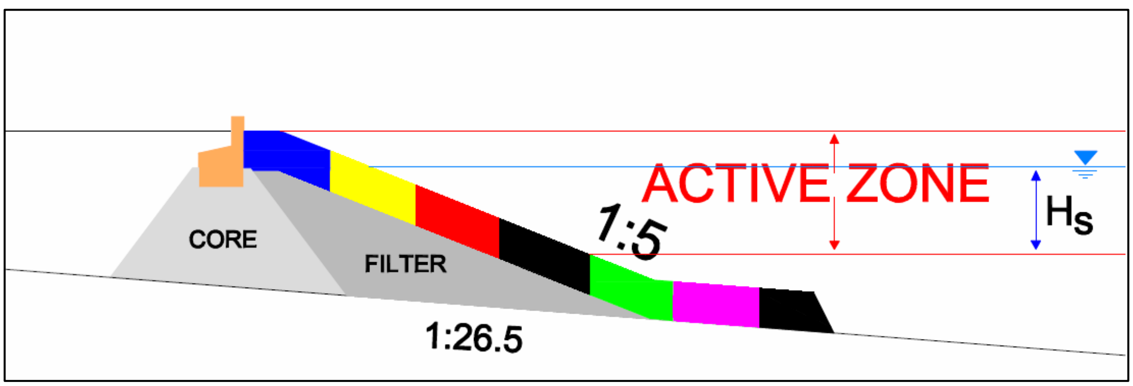

Figure 4.2: Active zone of Model 2

In Table 4.6 - Table 4.9, converted damage parameters of Model 2 are shown as a result of these 4 wave sets.

Table 4.6: Cumulative damage parameters (S_d) of Model 2, Set 1

Damage parameters (S_d) and no of displaced stones at active zone								
No of displaced stones (active zone)	19	25	27	35	47	62	80	94
Damage parameters (S_d)	0.9	1.2	1.3	1.6	2.2	2.9	3.7	4.4

Table 4.7: Cumulative damage parameters (S_d) of Model 2, Set 2

Damage parameters (S_d) and no of displaced stones at active zone										
No of displaced stones (active zone)	6	9	13	14	17	20	45	55	68	70
Damage parameters (S_d)	0.3	0.4	0.6	0.6	0.8	0.9	2.1	2.6	3.2	3.3

Table 4.8: Cumulative damage parameters (S_d) of Model 2, Set 3

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	5	33	58	78	106	121	152	175	208	225	251
Damage parameters (S_d)	0.2	1.5	2.7	3.6	4.9	5.6	7.1	8.2	9.7	10.5	11.7

Table 4.9: Cumulative damage parameters (S_d) of Model 2, Set 4

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	1	34	64	88	126	166	193	231	254	272	317
Damage parameters (S_d)	0.0	1.6	3.0	4.1	5.9	7.7	9.0	10.8	11.9	12.7	14.8

The damage parameter values are compared with the values, which come from stability formulae, in later chapters. For Model 2, Set 3 and Set 4 the filter layer was visible valued as complete damage condition. Model tests at this stage completely stopped.

4.3 Model 3

Cross sectional properties of Model 3 have been presented in Chapter 3. Model 3 was built with 1:5 slope at its front slope. 150-200 grams stones were used to form the armor layer of the structure. The porosity was 0.4. One wave set was given to the Model 3.

The wave conditions, number of stones, which were displaced in every color stripe, cumulative percent damages are represented in Table A.13 as an outcome of that 1 wave set in Appendix A.

For Model 3, within the active zone, damage (S_d) is computed by the method given by Burcharth et al. (2006), in order to be able to compare with the formulae of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001). To use this method, firstly the active zone of the Model 3 was determined according to the Coastal Engineering Manual (2003) criteria. The active zone of Model 3 is shown in Figure 4.3.

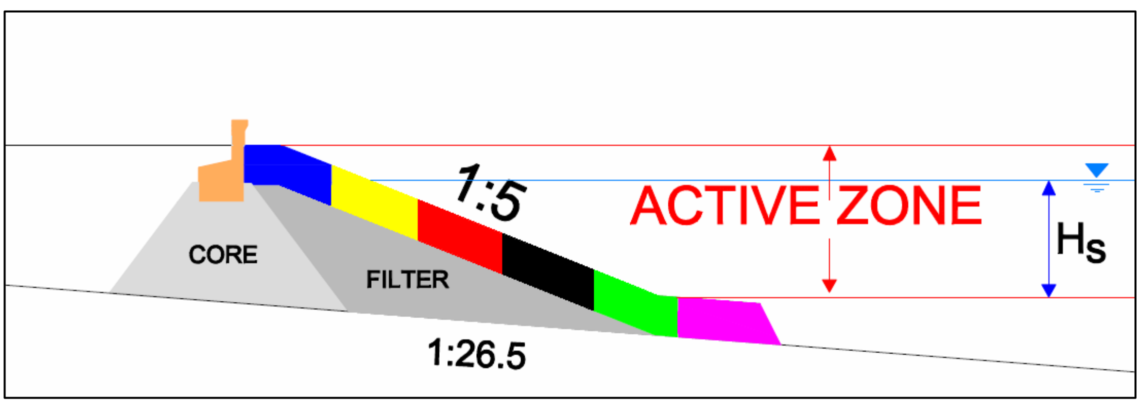

Figure 4.3: Active zone of Model 3

In Table 4.10, converted damage parameters of Model 3 are shown because of the wave set.

Table 4.10: Cumulative damage parameters (S_d) of Model 3, Set 1

Damage parameters (S_d) and no of displaced stones at active zone						
No of displaced stones (active zone)	7	25	52	69	94	126
Damage parameters (S_d)	0.3	1.2	2.4	3.2	4.4	5.9

The damage parameter values are compared with the values, which come from stability formulae, in later chapters.

4.4 Model 4

Cross sectional properties of Model 4 have been presented in Chapter 3. Model 4 was built with 1:3 slope at its front slope. 200-250 grams stones were used to form the armor layer of the structure. The porosity was 0.4. Nine wave sets were given to the Model 4.

The wave conditions, number of stones, which were, displaced in every color stripe, cumulative percent damages are represented in Table A.14 – Table A.22 as an outcome of these 9 wave sets in Appendix A.

For Model 4, within the active zone, damage (S_d) is computed by the method given by Burcharth et al. (2006), in order to be able to compare with the formulae of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001). To use this method, firstly the active zone of the Model 4 was determined according to the Coastal Engineering Manual (2003) criteria. The active zone of Model 4 is shown in Figure 4.4.

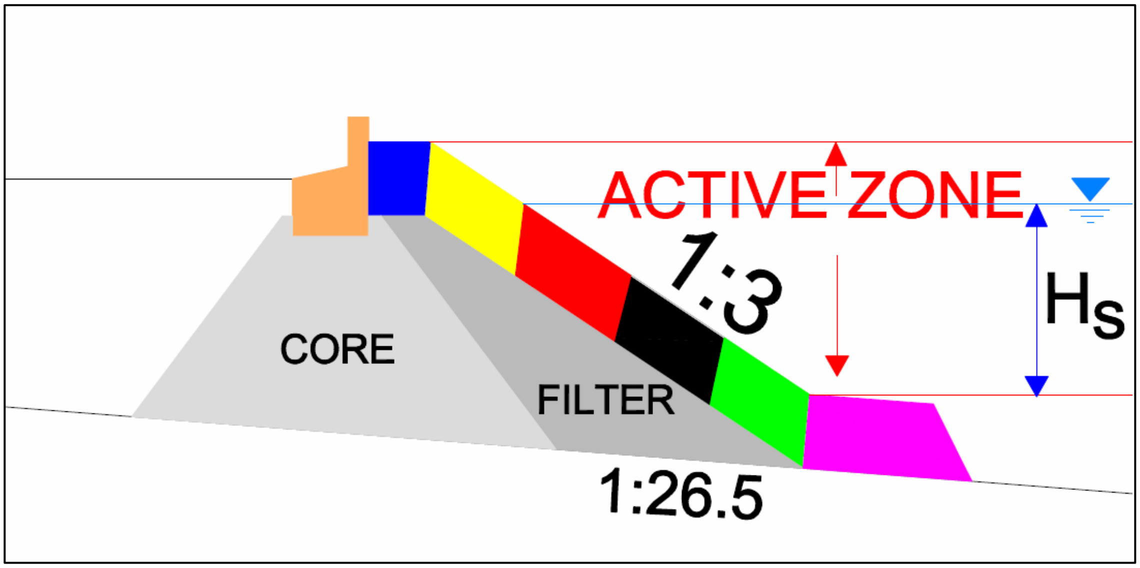

Figure 4.4: Active zone of Model 4

In Table 4.11 - Table 4.19 converted damage parameters of Model 4 are shown as a result of these 9 wave sets.

Table 4.11: Cumulative damage parameters (S_d) of Model 4, Set 1

Damage parameters (S_d) and no of displaced stones at active zone									
No of displaced stones (active zone)	33	38	49	61	74	78	84	99	115
Damage parameters (S_d)	1.7	1.9	2.5	3.1	3.7	3.9	4.2	5.0	5.8

Table 4.12: Cumulative damage parameters (S_d) of Model 4, Set 2

Damage parameters (S_d) and no of displaced stones at active zone								
No of displaced stones (active zone)	30	46	61	66	84	94	112	127
Damage parameters (S_d)	1.5	2.3	3.1	3.3	4.2	4.7	5.6	6.4

Table 4.13: Cumulative damage parameters (S_d) of Model 4, Set 3

Damage parameters (S_d) and no of displaced stones at active zone												
No of displaced stones (active zone)	1	46	77	99	134	150	173	195	224	229	231	270
Damage parameters (S_d)	0.1	2.3	3.9	5.0	6.7	7.5	8.7	9.8	11.2	11.5	11.6	13.5

Table 4.14: Cumulative damage parameters (S_d) of Model 4, Set 4

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	2	66	104	132	169	191	188	227	263	309	323
Damage parameters (S_d)	0.1	3.3	5.2	6.6	8.5	9.6	9.4	11.4	13.2	15.5	16.2

Table 4.15: Cumulative damage parameters (S_d) of Model 4, Set 5

Damage parameters (S_d) and no of displaced stones at active zone								
No of displaced stones (active zone)	40	69	79	94	120	137	153	165
Damage parameters (S_d)	2.0	3.5	4.0	4.7	6.0	6.9	7.7	8.3

Table 4.16: Cumulative damage parameters (S_d) of Model 4, Set 6

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	12	78	116	140	165	189	226	252	287	329	353
Damage parameters (S_d)	0.6	3.9	5.8	7.0	8.3	9.5	11.3	12.6	14.4	16.5	17.7

Table 4.17: Cumulative damage parameters (S_d) of Model 4, Set 7

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	11	59	88	139	161	201	212	261	271	292	339
Damage parameters (S_d)	0.6	3.0	4.4	7.0	8.1	10.1	10.6	13.1	13.6	14.6	17.0

Table 4.18: Cumulative damage parameters (S_d) of Model 4, Set 8

Damage parameters (S_d) and no of displaced stones at active zone								
No of displaced stones (active zone)	57	77	91	99	108	116	132	145
Damage parameters (S_d)	2.9	3.9	4.6	5.0	5.4	5.8	6.6	7.3

Table 4.19: Cumulative damage parameters (S_d) of Model 4, Set 9

Damage parameters (S_d) and no of displaced stones at active zone								
No of displaced stones (active zone)	35	58	68	81	111	141	162	177
Damage parameters (S_d)	1.8	2.9	3.4	4.1	5.6	7.1	8.1	8.9

The damage parameter values were compared with the values, which come from stability formulae, in later chapters. For Model 4, Set 3, Set 4, Set 6 and Set 7 the filter layer was visible. As before, these results were valued as complete damage. Model studies stopped at this stage.

4.5 Model 5

Cross sectional properties of Model 5 has been presented in Chapter 3. Model 5 was built with 1:2 slope at its front slope. In first 3 wave sets, 150 - 200 grams stones were used to form the armor layer of the structure. The porosity of the structure was 0.4 at the wave sets. Finally, in last 4 wave sets, 200 - 250 grams stones were used to form the armor layer of the structure. The water depth was also different in that last 4 wave sets as it is shown in Chapter 3. The porosity was 0.4. Totally 7 wave sets had been given to Model 5.

The wave conditions, number of stones, which were, displaced in every color stripe, cumulative percent damages are represented in Table A.23 – Table A.29 as an outcome of these 7 wave sets in Appendix A.

For Model 5, within the active zone, damage (S_d) is computed by the method given by Burcharth et al. (2006), in order to be able to compare with the formulae of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001). To use this method, firstly the active zones of the Model 5 for the both cases was determined according to the Coastal Engineering Manual (2003) criteria as it is described in Chapter 2. The active zones of the Model 5 are shown in Figure 4.5 and Figure 4.6.

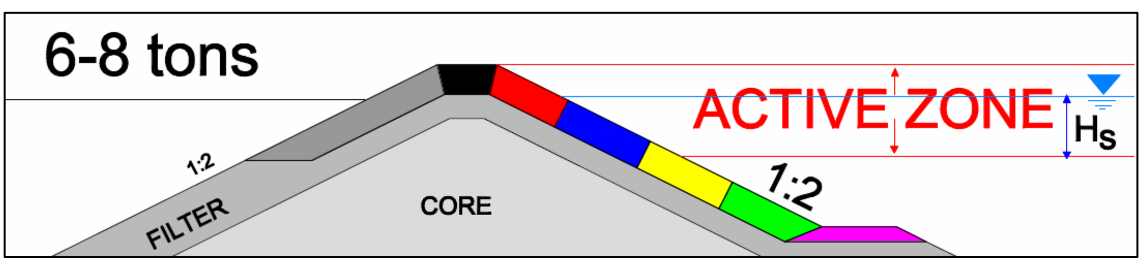

Figure 4.5: Active zone of Model 5 (for the first 3 wave sets)

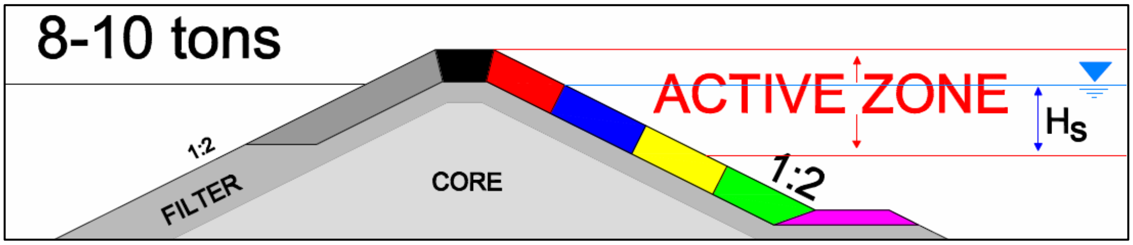

Figure 4.6: Active zone of Model 5 (for the last 4 wave sets)

In Table 4.20 - Table 4.26, converted damage parameters of Model 5 are shown as a result of these 7 wave sets.

Table 4.20: Cumulative damage parameters (S_d) of Model 5, Set 1

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	0	13	21	56	68	77	84	94	107	119	123
Damage parameters (S_d)	0.0	0.6	1.0	2.7	3.2	3.7	4.0	4.5	5.1	5.7	5.9

Table 4.21: Cumulative damage parameters (S_d) of Model 5, Set 2

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	0	12	18	25	42	46	53	78	86	96	104
Damage parameters (S_d)	0.0	0.6	0.9	1.2	2.0	2.2	2.5	3.7	4.1	4.6	4.9

Table 4.22: Cumulative damage parameters (S_d) of Model 5, Set 3

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	0	12	23	35	47	56	60	67	72	76	86
Damage parameters (S_d)	0.0	0.6	1.1	1.7	2.2	2.7	2.9	3.2	3.4	3.6	4.1

Table 4.23: Cumulative damage parameters (S_d) of Model 5, Set 4

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	0	16	21	24	27	30	38	42	46	48	50
Damage parameters (S_d)	0.0	0.8	1.1	1.2	1.4	1.5	1.9	2.1	2.3	2.4	2.5

Table 4.24: Cumulative damage parameters (S_d) of Model 5, Set 5

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	0	12	16	22	27	34	42	47	49	50	53
Damage parameters (S_d)	0.0	0.6	0.8	1.1	1.4	1.7	2.1	2.4	2.5	2.5	2.7

Table 4.25: Cumulative damage parameters (S_d) of Model 5, Set 6

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	0	11	22	27	33	35	36	41	46	57	59
Damage parameters (S_d)	0.0	0.6	1.1	1.4	1.7	1.8	1.8	2.1	2.3	2.9	3.0

Table 4.26: Cumulative damage parameters (S_d) of Model 5, Set 7

Damage parameters (S_d) and no of displaced stones at active zone											
No of displaced stones (active zone)	0	7	11	15	19	23	25	37	40	41	45
Damage parameters (S_d)	0.0	0.4	0.6	0.8	1.0	1.2	1.3	1.9	2.0	2.1	2.3

In addition to stone count method, in Model 5 there has also been performed the profile measurement technique, which is described in Chapter 2, to determine the damage. In measurement method, the profiles of the cross section have been taken at the beginning of the wave set and at the end of the wave set. The eroded areas of the cross section have been found from differences of this two profile measurements. The damage parameters, which are obtained by this way, are shown in Table 4.27 with their wave set numbers.

Table 4.27: Damage parameters (S_d) by profile measurements, Model 5

Damage parameter, S_d, from eroded area method (Model 5)							
Wave set number	1	2	3	4	5	6	7
S_d from profile measurements	4.8	3.8	2.7	2.0	2.0	2.5	2.3
S_d from stone count method	5.9	4.9	4.1	2.5	2.7	3.0	2.3

As it can be observed from Table 4.27, the damage parameters (S_d) which were calculated from profile measurement method were almost consistent with the damage parameter values (S_d) which were calculated by transition formula of Burcharth et al. (2006). The results showed that the transition formula was very successful to define damage parameters (S_d) by stone count method.

CHAPTER 5

PRESENTATION AND EVALUATION OF RESULTS OF MODEL STUDIES

In this chapter, results of the model studies are given by using the wave conditions, which were used during the experiments of the models, in the several stability formulae. Those results were obtained by using formulae of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001). The wave conditions of the model studies were performed with Van der Meer, Van Gent and Melby equations. Then, the damage parameters, S_d, of the models has been found by stability equations to compare with the experimental values. However, Hudson (1953) stability equation had not been used in comparison process because of its damage definition as it is described in Chapter 2.

In Chapter 2, Hudson (1953) stability equation has been presented. The parameters and the damage range of the equation have been described. However, in this thesis, Hudson (1953) stability equation is not used as a comparative study. Because, in equation, the damage of the structure had been defined in a constant range. The equation has defined it as a "zero damage criterion". In Hudson (1953) equation, damage had been taken as zero – 5 percent. Nevertheless, in our model studies, damage of the models were not stayed in one range, it was increased as the wave conditions were increased. In addition, there was not any damage parameter in Hudson (1953) stability equation. For these reasons, that equation was not used as a comparison material.

First equation that was used as a comparison study was Melby (2001) equation. This method has been descried in Chapter 2. In that equation, basic wave parameters, which are significant wave height and mean wave period of the wave conditions at the wave flume had been used. However, as it is described in Melby (1999), those parameters were defined $5H_s$ seaward of the structure toe. These parameters are shown in Appendix A for all of the wave sets. In Melby (2001), firstly, the damage parameter of the first storm has been defined by first storm characteristics and then the damage parameter of the second storm had been calculated by using both first storm and second storm characteristics. Damage development of the structures was calculated by this method. The details of this method are given in Chapter 2.

The modified Van der Meer equation for shallow water conditions, which was developed by Van Gent et al. (2004), was the second comparison material. In all of the model studies $h / H_{s\text{-}toe}$ values was smaller than 3, so Van der Meer (shallow water) formulae are used as a comparative material rather than Van der Meer (deep water). This method is described detailed in Chapter 2. In this method, significant wave height of the incident waves at the toe of the structure, H_s, the wave heights which were exceeded by 2 per cent of the incident waves at the toe, $H_{2\%}$ and the energy wave periods, $T_{m-1,0}$, of the wave conditions in experiments were used. These wave parameters were given in Appendix A for all of the wave sets. The notional permeability factor was 0.4 for all of the models. This equation had been used to obtain the damage parameters of the models. The damage development method of Van der Meer, which is described in Chapter 2, has also been used together with that equation to see the increase in the S_d values. Firstly, the wave parameters had been used in that equation. Then, the damage parameter was obtained by this way. After that, the number of waves, which is required to give the same damage to the structure by the second wave conditions, was calculated by the damage development method of Van der Meer. Finally, after adding that required number of waves and the number of waves of the second wave condition, the second damage parameters has been found. All the damage values are calculated in this way.

The final equation to compare the stability formulae and experimental studies was Van Gent et al. (2004) equation. This equation is represented in Chapter 2. The significant wave heights of the incident waves at the toe of the structure of the wave conditions in model studies were used to find the damage parameters. The wave parameters were given in Appendix A for all of the wave sets. There was not any wave period usage in that method. The damage development method of Van der Meer was used together with that Van Gent et al. (2004) equation to get the values of the damage parameters, S_d, by the wave parameters. Summary of Model parameters are given Appendix B.

The structural parameters, which are dimensions of the structure, materials used for the construction and slope angles of the structures, were given in Chapter 3. These parameters were used as a parameters at the equations.

5.1 Model 1

The results, which come from equations of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001), are shown in Table 5.1–Table 5.5 for all of the wave sets of this model. In the tables, N_T (VDM) means total cumulative number of waves, which is obtained from Van der Meer damage development method for Van der Meer shallow water formula. Sample calculation of N_T (VDM) is given in Appendix B.

Table 5.1: Model 1, Set 1

Damage parameters (S_d) from stability equations					
H_s (m)	3.8	7.0	7.3	7.5	7.8
T_s (sec)	8.7	12.0	12.4	12.8	13.1
N	990	1042	1981	2946	3989
N_T (VDM)	990	1056	2660	5250	7643
Melby	1.0	5.4	11.6	18.0	25.1
Van der Meer	0.1	0.8	1.6	2.4	3.5
Van Gent	0.1	2.3	4.6	7.2	10.4

Table 5.2: Model 1, Set 2

Damage parameters (S_d) from stability equations						
H_s (m)	3.6	6.4	6.9	7.0	7.2	7.5
T_s (sec)	8.9	12.0	12.4	12.9	13.1	13.1
N	944	1076	2445	2954	3958	4005
N_T (VDM)	944	1091	3011	5683	8259	10407
Melby	0.6	2.9	6.8	10.5	14.5	19.1
Van der Meer	0.1	0.6	1.4	2.0	2.7	3.5
Van Gent	0.1	1.6	3.7	5.4	7.5	9.9

Table 5.3: Model 1, Set 3

Damage parameters (S_d) from stability equations					
H_s (m)	3.8	6.9	7.2	7.4	7.6
T_s (sec)	8.8	12.0	12.3	12.8	13.1
N	980	1039	2023	2988	3804
N_T (VDM)	980	1049	2830	5603	7413
Melby	0.8	4.4	9.4	14.5	20.1
Van der Meer	0.1	0.8	1.5	2.3	3.2
Van Gent	0.1	2.2	4.3	6.6	9.4

Table 5.4: Model 1, Set 4

Damage parameters (S_d) from stability equations					
H_s (m)	5.2	5.1	5.2	5.2	6.6
T_s (sec)	10.1	10.1	10.2	10.1	11.7
N	2061	1981	2081	2080	3673
N_T (VDM)	2061	4140	5592	8721	5610
Melby	4.7	5.4	6.0	6.5	8.8
Van der Meer	0.4	0.6	0.8	0.9	1.5
Van Gent	0.7	1.0	1.2	1.4	3.4

Table 5.5: Model 1, Set 5

Damage parameters (S_d) from stability equations					
H_s (m)	5.7	5.7	5.7	5.7	7.2
T_s (sec)	10.2	10.2	10.1	10.0	11.7
N	2096	2081	2102	2124	3735
N_T (VDM)	2096	4178	6250	8421	5637
Melby	8.3	9.7	10.8	11.6	15.7
Van der Meer	0.6	0.9	1.1	1.3	2.2
Van Gent	1.2	1.7	2.1	2.4	5.7

5.2 Model 2

The results, which come from equations of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001), are shown in Table 5.6 – Table 5.9 for all of the wave sets of this model.

Table 5.6: Model 2, Set 1

Damage parameters (S_d) from stability equations								
H_s (m)	5.8	5.8	6.1	6.0	7.5	7.7	7.6	7.6
T_s (sec)	10.2	10.2	10.4	10.3	12.1	12.1	12.2	12.1
N	2062	2051	1676	2068	910	919	924	940
N_T (VDM)	2062	4363	7095	8438	2396	2973	4118	6019
Melby	9.4	11.2	12.6	13.9	15.6	17.1	18.6	19.9
Van der Meer	0.9	1.3	1.4	1.7	2.1	2.5	2.9	3.1
Van Gent	1.7	2.4	3.0	3.6	5.4	7.2	8.4	9.5

Table 5.7: Model 2, Set 2

Damage parameters (S_d) from stability equations										
H_s (m)	5.8	5.8	5.8	6.1	5.8	7.3	7.2	7.3	7.2	7.1
T_s (sec)	10.3	10.3	10.3	10.3	10.3	12.1	12.1	12.0	11.9	12.1
N	2034	2056	2041	320	1721	922	982	988	600	927
N_T (VDM)	2034	4211	5945	4983	9365	2754	3941	3891	5542	7390
Melby	14.6	17.5	19.4	19.7	20.9	22.9	24.6	26.3	27.3	28.6
Van der Meer	0.8	1.1	1.4	1.4	1.6	1.9	2.2	2.6	2.7	2.9
Van Gent	1.7	2.4	3.0	3.1	3.5	5.0	6.1	7.1	7.6	8.3

Table 5.8: Model 2, Set 3

Damage parameters (S_d) from stability equations											
H_s (m)	4.0	7.2	7.5	7.5	8.0	7.9	7.9	8.0	8.1	8.0	8.0
T_s (sec)	8.8	12.1	12.5	12.6	13.4	13.3	13.5	13.4	13.2	13.3	13.4
N	984	1005	994	1003	988	1029	983	1013	1015	1017	1011
N_T (VDM)	984	1025	1709	3049	2660	3082	4408	5650	6660	7806	9564
Melby	1.6	7.7	12.5	16.1	20.2	23.5	26.4	29.3	31.9	34.3	36.4
Van der Meer	0.2	1.1	1.8	2.2	2.7	3.3	3.8	4.2	4.5	4.9	5.1
Van Gent	0.2	3.6	5.6	7.1	9.2	10.8	12.1	13.5	14.9	16.0	17.1

Table 5.9: Model 2, Set 4

Damage parameters (S_d) from stability equations											
H_s (m)	3.8	7.2	7.4	7.4	7.9	7.8	7.8	7.9	8.1	8.2	8.3
T_s (sec)	8.8	12.1	12.5	12.6	13.4	13.4	13.5	13.2	13.3	13.3	13.4
N	978	1001	1016	1018	992	991	993	1020	1010	1022	1006
N_T (VDM)	978	1014	1803	2877	2538	3766	4573	6979	6063	6426	6719
Melby	1.6	9.0	14.5	18.6	23.2	26.9	30.2	33.3	36.3	39.2	42.0
Van der Meer	0.1	1.2	1.7	2.2	2.8	3.2	3.7	4.0	4.4	4.7	5.1
Van Gent	0.1	3.4	5.3	6.7	8.5	10.0	11.3	12.5	14.1	15.6	17.1

5.3 Model 3

The results, which come from equations of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001), are shown in Table 5.10 for the wave set of this model.

Table 5.10: Model 3, Set 1

Damage parameters (S_d) from stability equations						
H_s (m)	3.6	6.7	7.0	7.3	7.4	7.4
T_s (sec)	10.3	12.2	12.8	12.7	12.8	12.8
N	1007	985	1002	1053	1002	1000
N_T (VDM)	1007	1003	1625	2515	2986	4066
Melby	1.1	5.8	9.4	12.5	15.0	17.2
Van der Meer	0.1	0.8	1.3	1.7	2.1	2.4
Van Gent	0.1	2.4	3.8	5.4	6.6	7.7

5.4 Model 4

The results, which come from equations of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001), are shown in Table 5.11 – Table 5.19 for all of the wave sets of this model.

Table 5.11: Model 4, Set 1

Damage parameters (S_d) from stability equations									
H_s (m)	6.0	6.0	6.1	6.1	7.6	7.4	7.7	7.7	7.6
T_s (sec)	10.4	10.2	10.3	10.2	11.8	11.5	11.9	11.9	11.9
N	2024	2049	2037	2038	915	455	443	911	923
N_T (VDM)	2024	4018	6254	7491	2642	2413	3560	5053	6418
Melby	9.0	10.7	11.8	12.6	13.9	14.3	15.1	16.3	17.5
Van der Meer	2.2	3.2	3.9	4.6	5.7	6.3	6.7	7.4	8.0
Van Gent	5.2	7.6	9.5	11.2	16.0	17.6	19.7	23.2	26.0

Table 5.12: Model 4, Set 2

Damage parameters (S_d) from stability equations								
H_s (m)	6.1	6.0	6.0	6.0	7.7	7.7	7.7	7.7
T_s (sec)	10.2	10.3	10.3	10.3	11.8	11.9	11.8	11.9
N	1986	1993	2002	2026	905	897	911	913
N_T (VDM)	1986	4247	5752	9719	2796	3177	4983	4972
Melby	11.5	13.7	15.1	16.2	17.7	19.1	20.4	21.6
Van der Meer	2.5	3.4	4.3	4.8	5.8	6.9	7.6	8.4
Van Gent	5.7	7.9	9.5	10.9	16.4	20.7	24.1	27.3

Table 5.13: Model 4, Set 3

Damage parameters (S_d) from stability equations												
H_s (m)	4.1	7.7	8.0	7.9	8.3	8.4	8.4	8.5	8.5	8.6	8.5	8.5
T_s (sec)	8.8	11.8	12.5	12.1	13.0	12.9	12.8	12.8	12.7	12.7	12.9	12.8
N	987	1006	992	1002	1024	976	990	1024	1052	855	157	1019
N_T (VDM)	987	1023	1954	2625	2429	3816	4163	5473	7148	6263	5719	7434
Melby	1.4	6.9	11.7	15.0	18.7	21.9	24.6	27.3	29.7	31.6	31.8	33.8
Van der Meer	0.5	3.6	5.1	6.5	8.5	9.9	11.3	12.5	13.6	14.6	14.8	16.0
Van Gent	0.6	13.3	20.6	25.5	32.2	37.7	42.7	48.1	52.9	56.6	57.3	61.2

Table 5.14: Model 4, Set 4

Damage parameters (S_d) from stability equations											
H_s (m)	4.1	7.6	7.9	8.0	8.3	8.0	8.1	8.4	8.4	8.4	8.4
T_s (sec)	8.7	12.1	12.3	12.3	13.0	12.9	12.9	12.8	12.8	12.9	12.7
N	981	1001	988	998	999	1019	1011	1031	1044	1048	1021
N_T (VDM)	981	1013	1794	2769	2486	4681	5633	5643	5589	7813	7955
Melby	1.1	6.8	11.5	14.8	18.4	21.1	23.6	26.1	28.3	30.3	32.1
Van der Meer	0.4	3.6	5.3	6.7	8.6	9.7	10.7	11.9	13.2	14.2	15.2
Van Gent	0.5	12.6	19.7	25.1	31.4	35.3	39.2	44.4	49.1	53.4	57.3

Table 5.15: Model 4, Set 5

Damage parameters (S_d) from stability equations								
H_s (m)	6.2	6.2	6.2	6.2	7.6	7.7	7.7	7.6
T_s (sec)	10.4	10.2	10.2	10.2	11.8	11.7	11.8	11.7
N	2012	2015	2037	2009	912	909	914	911
N_T (VDM)	2012	3919	6616	8020	3317	4091	4886	6564
Melby	10.9	12.8	14.1	15.2	16.6	18.0	19.4	20.6
Van der Meer	2.7	3.8	4.6	5.3	6.3	7.1	7.9	8.5
Van Gent	6.4	9.1	11.1	12.8	17.4	21.2	24.4	27.0

Table 5.16: Model 4, Set 6

Damage parameters (S_d) from stability equations											
H_s (m)	4.1	7.7	8.1	8.1	8.4	8.4	8.4	8.6	8.6	8.6	8.6
T_s (sec)	8.7	12.0	12.2	12.2	13.0	12.9	13.0	12.8	12.8	12.7	12.8
N	981	1010	1006	1022	997	986	1030	1029	1033	1066	1030
N_T (VDM)	981	1023	1735	2596	2521	3627	5123	5318	5661	6850	8320
Melby	1.1	7.3	12.2	15.8	19.5	22.6	25.5	28.5	30.9	33.1	35.3
Van der Meer	0.4	3.4	5.3	6.8	8.7	10.3	11.5	12.8	14.1	15.4	16.4
Van Gent	0.5	12.8	20.8	26.6	33.1	38.5	43.3	49.3	54.7	59.4	63.9

Table 5.17: Model 4, Set 7

Damage parameters (S_d) from stability equations											
H_s (m)	4.2	7.6	7.8	8.0	8.1	8.1	8.3	8.6	8.6	8.5	8.6
T_s (sec)	9.3	11.9	12.4	12.3	12.9	13.2	12.9	12.8	12.8	13.1	12.8
N	842	1002	1012	1001	1003	1017	1020	1030	1020	1029	1015
N_T (VDM)	842	1019	1805	2930	3110	4302	4305	4704	6210	7410	7912
Melby	2.6	8.9	13.4	17.0	20.7	23.5	26.0	28.6	30.9	33.1	35.1
Van der Meer	0.5	3.8	5.7	7.0	8.6	9.8	11.2	12.7	13.9	14.9	16.0
Van Gent	0.6	12.5	18.7	24.4	29.3	33.7	38.9	44.9	50.3	54.7	59.2

Table 5.18: Model 4, Set 8

Damage parameters (S_d) from stability equations								
H_s (m)	6.2	6.1	6.1	6.1	7.4	7.5	7.4	7.3
T_s (sec)	10.2	10.3	10.3	10.2	11.8	11.7	11.8	11.7
N	1986	1993	2037	2038	912	909	914	911
N_T (VDM)	1986	4244	7456	8539	3322	4104	5150	6867
Melby	9.0	10.6	11.7	12.5	13.7	14.9	16.0	17.0
Van der Meer	2.6	3.6	4.3	4.9	5.7	6.5	7.2	7.7
Van Gent	6.1	8.4	10.2	11.8	15.8	19.1	21.7	23.8

Table 5.19: Model 4, Set 9

Damage parameters (S_d) from stability equations								
H_s (m)	6.2	6.2	6.2	6.2	7.6	7.6	7.6	7.7
T_s (sec)	10.5	10.3	10.3	10.3	11.9	11.8	11.6	11.7
N	1995	2012	2010	2048	898	919	915	922
N_T (VDM)	1995	4210	6396	8143	3386	4231	5679	5561
Melby	12.0	14.2	15.6	16.7	18.4	19.8	21.2	22.5
Van der Meer	2.8	3.9	4.7	5.5	6.4	7.2	7.9	8.6
Van Gent	6.4	8.9	10.8	12.4	17.2	20.7	23.6	26.6

5.5 Model 5

The results, which come from equations of Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001), are shown in Table 5.20 – Table 5.26 for all of the wave sets of this model.

Table 5.20: Model 5, Set 1

Damage parameters (S_d) from stability equations											
H_s (m)	2.1	3.9	4.4	4.3	4.6	4.6	4.6	5.2	5.1	5.2	5.2
T_s (sec)	5.5	7.9	8.4	8.4	8.8	8.7	8.7	9.4	9.4	9.4	9.6
N	1024	997	1019	1040	1012	1003	1010	1032	1010	990	985
N_T (VDM)	1024	1000	1368	2209	3108	2991	5044	2668	4129	4345	4772
Melby	0.1	0.7	1.1	1.5	1.8	2.2	2.5	2.9	3.3	3.8	4.1
Van der Meer	0.0	0.8	1.5	2.1	2.5	3.1	3.5	4.4	5.1	5.8	6.5
Van Gent	0.1	1.7	3.3	4.3	5.6	6.8	7.8	10.4	12.2	14.0	15.5

Table 5.21: Model 5, Set 2

Damage parameters (S_d) from stability equations											
H_s (m)	2.1	3.9	4.3	4.3	4.3	4.5	4.6	5.1	5.1	5.2	5.1
T_s (sec)	5.5	7.8	8.5	8.5	8.5	8.7	8.8	9.6	9.4	9.5	9.5
N	1016	997	1018	1029	1029	1016	1003	988	1028	1009	992
N_T (VDM)	1016	999	1350	2810	3839	4100	3949	2516	3679	4537	5833
Melby	0.1	0.6	1.0	1.3	1.6	1.9	2.2	2.6	3.0	3.4	3.7
Van der Meer	0.0	0.8	1.6	2.0	2.3	2.7	3.1	4.0	4.7	5.3	5.8
Van Gent	0.1	1.6	3.0	4.0	4.8	5.9	6.9	9.4	11.4	13.1	14.5

Table 5.22: Model 5, Set 3

Damage parameters (S_d) from stability equations											
H_s (m)	2.1	3.8	4.2	4.4	4.6	4.6	4.5	5.2	5.1	5.1	5.1
T_s (sec)	5.7	7.9	8.4	8.4	8.8	8.7	8.7	9.6	9.7	9.6	9.5
N	1028	993	1021	1016	1020	998	968	997	988	993	988
N_T (VDM)	1028	996	1389	2154	2769	3501	5603	2523	3240	5295	6123
Melby	0.1	0.5	0.8	1.2	1.5	1.9	2.1	2.5	2.9	3.3	3.7
Van der Meer	0.0	0.7	1.4	1.9	2.4	2.9	3.2	4.1	4.9	5.4	5.9
Van Gent	0.1	1.5	2.8	4.1	5.4	6.5	7.3	9.7	11.6	13.2	14.6

Table 5.23: Model 5, Set 4

Damage parameters (S_d) from stability equations											
H_s (m)	2.2	4.0	4.3	4.4	4.6	4.6	4.6	5.3	5.3	5.3	5.3
T_s (sec)	5.6	8.0	8.6	8.4	8.8	8.9	8.8	9.6	9.6	9.5	9.5
N	1002	983	1029	1001	998	1003	1005	993	1000	996	1006
N_T (VDM)	1002	988	1405	2248	2485	4032	4883	2333	3333	4408	5543
Melby	0.1	0.6	1.0	1.3	1.6	1.8	2.0	2.4	2.7	3.0	3.3
Van der Meer	0.0	0.6	1.1	1.4	1.9	2.1	2.4	3.2	3.8	4.3	4.8
Van Gent	0.1	1.4	2.5	3.3	4.2	5.0	5.8	8.0	9.7	11.2	12.5

Table 5.24: Model 5, Set 5

Damage parameters (S_d) from stability equations											
H_s (m)	2.1	4.0	4.3	4.5	4.7	4.6	4.5	5.3	5.3	5.3	5.1
T_s (sec)	5.5	8.0	8.6	8.6	8.7	8.8	8.9	9.3	9.6	9.7	9.5
N	1012	1013	1013	1007	999	1020	996	993	968	985	1001
N_T (VDM)	1012	1016	1431	2072	2549	3795	5214	2519	2927	4475	5888
Melby	0.1	0.4	0.8	1.1	1.4	1.6	1.8	2.1	2.4	2.7	3.0
Van der Meer	0.0	0.6	1.1	1.5	1.9	2.2	2.4	3.1	3.8	4.4	4.8
Van Gent	0.1	1.4	2.4	3.5	4.6	5.4	5.9	8.0	9.8	11.3	12.2

Table 5.25: Model 5, Set 6

Damage parameters (S_d) from stability equations											
H_s (m)	2.1	4.1	4.4	4.5	4.7	4.6	4.7	5.3	5.4	5.3	5.1
T_s (sec)	5.6	7.9	8.6	8.5	8.9	8.8	8.9	9.5	9.6	9.5	9.7
N	991	979	1029	993	998	990	998	997	971	991	1015
N_T (VDM)	991	980	1507	2237	2990	3286	4789	2467	3055	5102	7550
Melby	0.1	0.5	0.8	1.1	1.4	1.6	1.9	2.2	2.6	2.9	3.1
Van der Meer	0.0	0.7	1.2	1.7	2.0	2.4	2.7	3.5	4.3	4.8	5.1
Van Gent	0.1	1.5	2.7	3.7	4.7	5.4	6.1	8.4	10.4	11.8	12.6

Table 5.26: Model 5, Set 7

Damage parameters (S_d) from stability equations											
H_s (m)	2.0	3.8	4.2	4.1	4.4	4.4	4.3	4.9	4.9	4.9	4.8
T_s (sec)	5.5	7.9	8.5	8.5	9.0	8.9	8.9	9.8	9.9	9.9	10.0
N	1022	981	1010	1024	1005	937	1009	986	1005	996	1009
N_T (VDM)	1022	984	1308	2599	2532	3304	5803	2712	4191	4366	5904
Melby	0.1	0.3	0.6	0.8	1.0	1.2	1.3	1.6	1.8	2.0	2.2
Van der Meer	0.0	0.4	0.9	1.2	1.5	1.8	1.9	2.4	2.8	3.2	3.5
Van Gent	0.0	1.0	2.0	2.5	3.3	3.9	4.3	5.7	6.8	7.6	8.4

CHAPTER 6

DISCUSSION OF RESULTS

Compatibility of results of model studies with the existing data and formulae is very important to verify the experimental outcomes. Therefore, when carrying out a comparative study between stability formulae results and results of experimental studies, a table of non-dimensional test parameters is needed. The ranges of parameters in this model studies are shown in Table 6.1.

Table 6.1: Ranges of parameters in model studies

Parameter	Symbol	Range
Slope angle	tan α	1:5 - 1:2
Number of waves	N	< 4000
Fictitious wave steepness based on T_m	s_{om}	0.035 - 0.06
Surf similarity parameter using T_m	ξ_m	0.9 - 2.5
Surf similarity parameter using $T_{m-1,0}$	$\xi_{s-1,0}$	0.8 - 2.5
Wave height ratio	$H_{2\%}/H_s$	1.1 - 1.5
Armourstone gradation	D_{n85}/D_{n15}	1.4 - 2.0
Core material - armour ratio	Dn50-core/Dn50	0.05 - 0.31
Stability number	$H_s/(\Delta D_{n50})$	0.7 - 3.5
Damage level parameter	S_d	< 20

The damage parameters (S_d), which are obtained by experimental studies and computed from stability formulae are given in Chapter 4 and Chapter 5. In Chapter 4, damage parameters obtained from model studies are given. In Chapter 5, damage parameters (S_d), which are computed from stability formulae, are presented.

In Figure 6.1, the damage parameters are presented all together. In the graph presentation of S_d values obtained under various design parameters, S_d vs $H_s/\Delta D_{n50}$ are used as a horizontal and vertical axis as it is used in Rock Manual (2007). Similarly, the results of S_d values of this study are presented in Figure 6.1 together with the results of stability formulae. The trend lines of these results are drawn as shown in Figure 6.2.

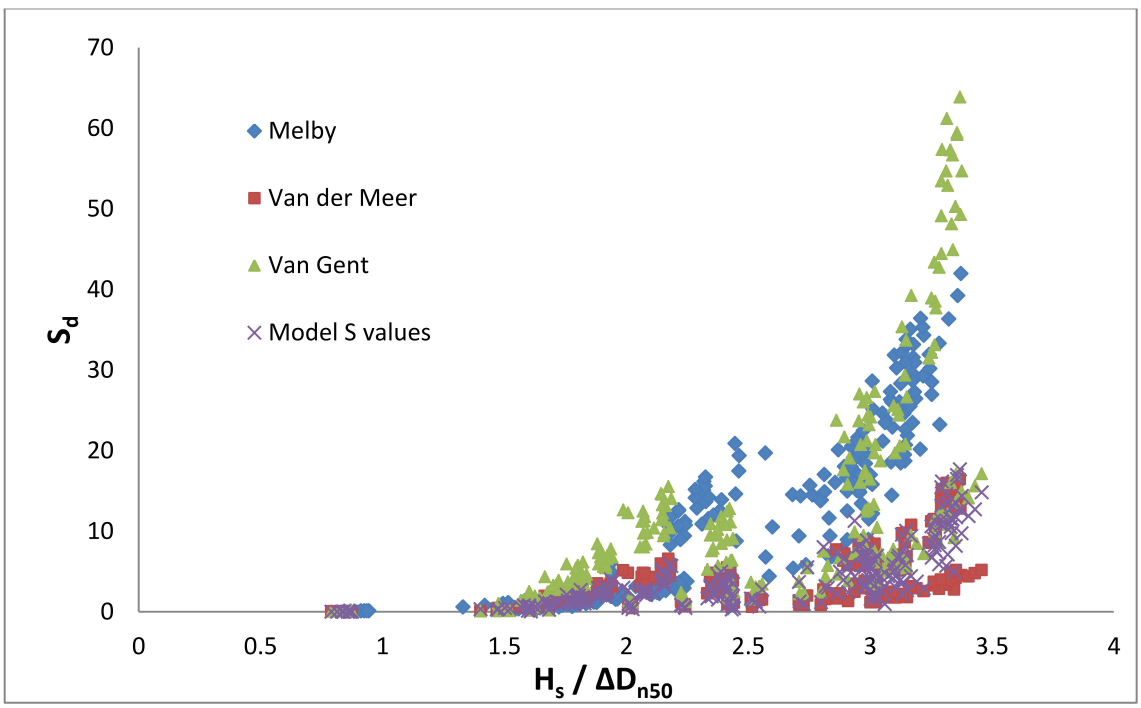

Figure 6.1: The comparison of S_d values

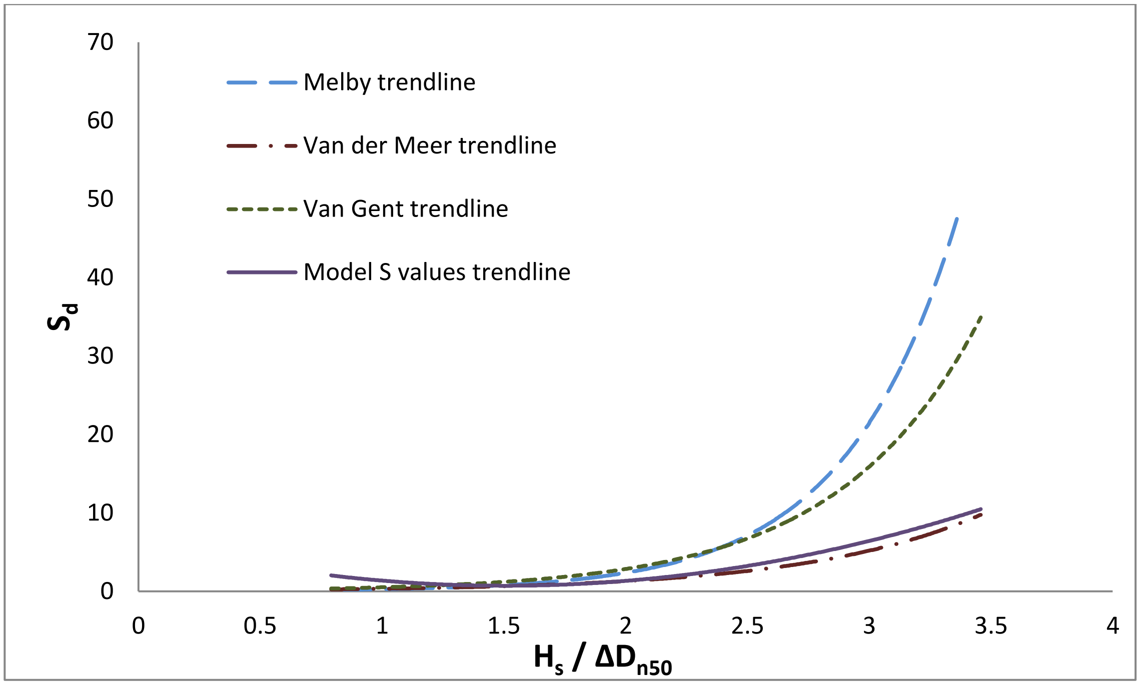

Figure 6.2: The comparison of trendlines of S_d values

As it can be observed from Figure 6.2, stability formula of Van der Meer for shallow water conditions (plunging) have almost the same trend with the present experimental studies where the cross sections at the model studies are designed according to the Van der Meer's approach. Melby (2001) formula's trend is not close to the trend of the experiments, since, it is derived from only one structure slope, which is 1:2. In Figure 6.3, Model 5 (1:2 structure slope) data and Melby data for Model 5 have been drawn together for comparison. From Figure 6.3, it was observed that structure slope has vital importance for Melby (2001). As it is seen from Figure 6.3, Melby data and the model studies give comparable results up to H_s / ΔD_{n50} = 1.8. For larger values of H_s / ΔD_{n50}, model results give larger S_d values. In order to be able to drive a conclusion, more number of model studies has to be carried out. Also, Van Gent et al. (2004) stability formula's trend not being close to the trend of model experiments could be due to the wave period not included in the formula and not using wave height exceeded by 2 per cent of the incident waves at the toe ($H_{2\%}$).

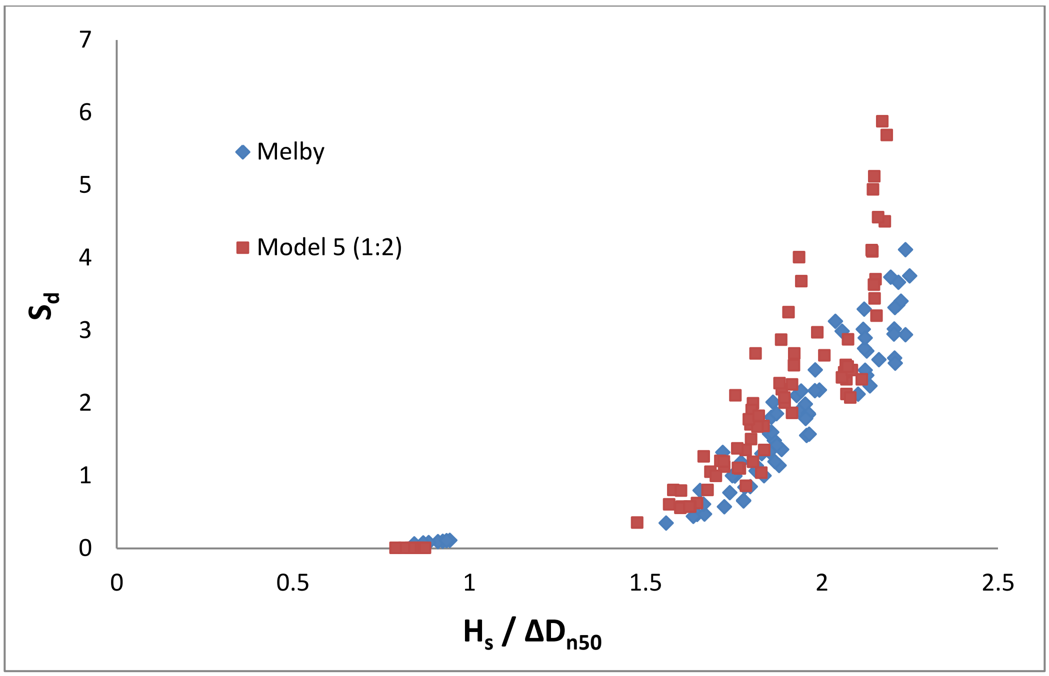

Figure 6.3: The comparison of Model 5 (1:2) and Melby (2001)

From that point, stability formula of Van der Meer for shallow water conditions (plunging) is used as a main comparative base between stability formulas and results of experimental studies for Models 1 – 5. As it is shown in Figure 6.4, firstly the trend line of the equation (Van der Meer shallow water, plunging) and the % 90 confidence level lines has been drawn. In Van der Meer (shallow water, plunging) equation, model parameters are used as input where h / $H_{s\text{-toe}}$ values were smaller than 3 and plunging breaking condition existed for all of the model studies. The sample computation for plunging breaking condition is given in the Appendix B. Then, results of experimental data are plotted in terms of $S_d/\sqrt{N}$ vs $H_s/\Delta D_{n50}$. $\xi^{0.5}$. $P^{-0.18}$. $(H_{2\%}/H_s)$, as y and x axis respectively.

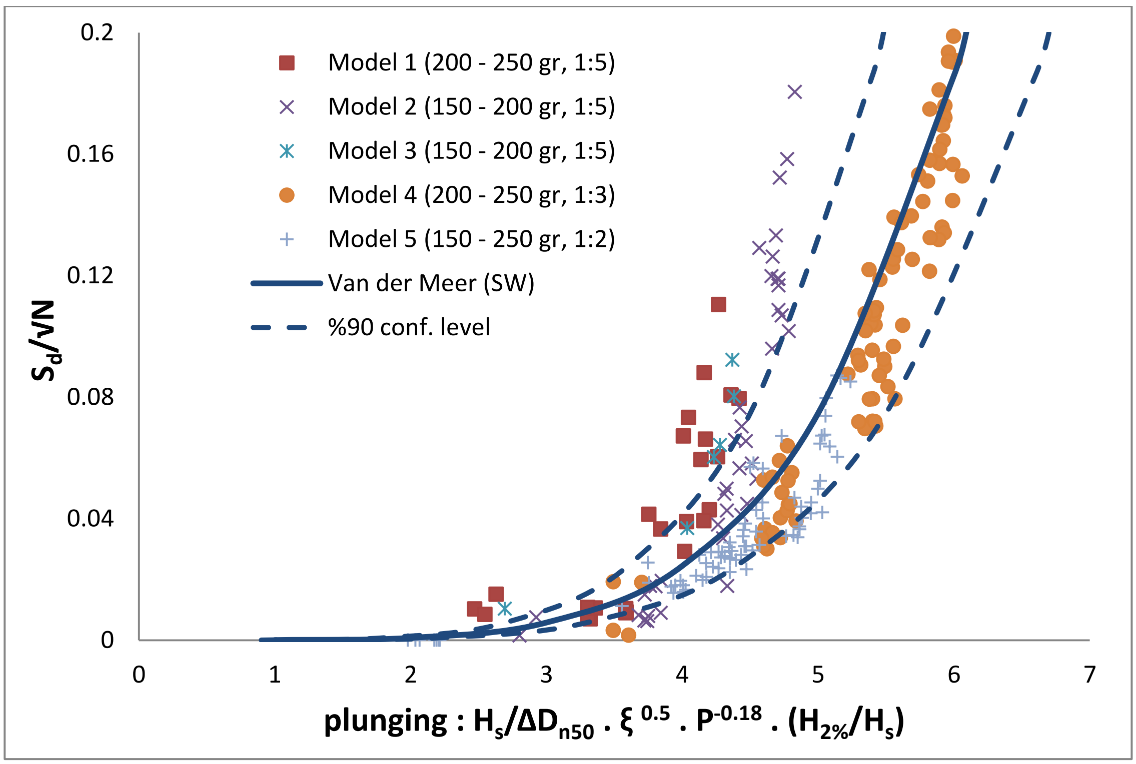

Figure 6.4: The comparison of experimental data with Van der Meer formula for shallow water conditions

From Figure 6.4, it can be seen that Model 4 with structure slope 1:3 and Model 5 with structure slope 1:2 data are in the interval of the % 90 confidence level lines of the equation given within the structure slope range 1:2 – 1:4. Therefore, it can be seen from the figure that the results for Model 4 and Model 5 are consistent with the Van der Meer approach. The structure slopes of other Models were 1:5 which is not in the range of the Van der Meer (Shallow water, plunging) stability formula. This data could be viewed to review the ranges of validity of Van der Meer (Shallow water, plunging) equation. However, in order to be able to make a firm statement, more number of experiments needed to be carried out.

In Figure 6.5, the damage parameters are presented all together for Model 1 - 5 separately. In the graph presentation of S_d values obtained under various design parameters, S_d vs $H_s/\Delta D_{n50}$ are used as a horizontal and vertical axis as it is used in Rock Manual (2007). The trend lines of these results are drawn as shown in Figure 6.6.

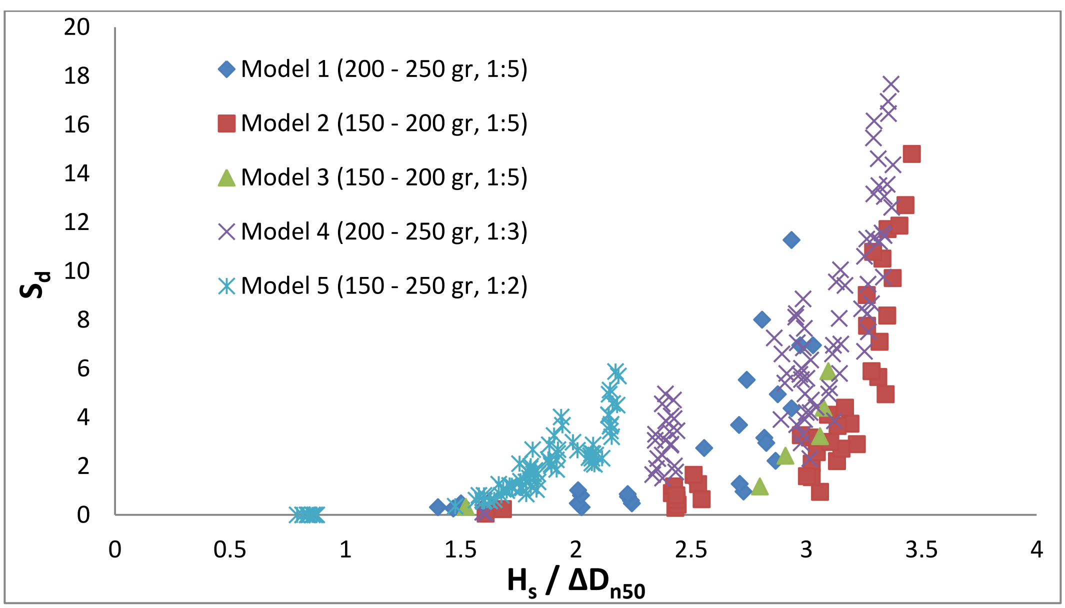

Figure 6.5: The damage parameters (S_d) of Model 1 - 5

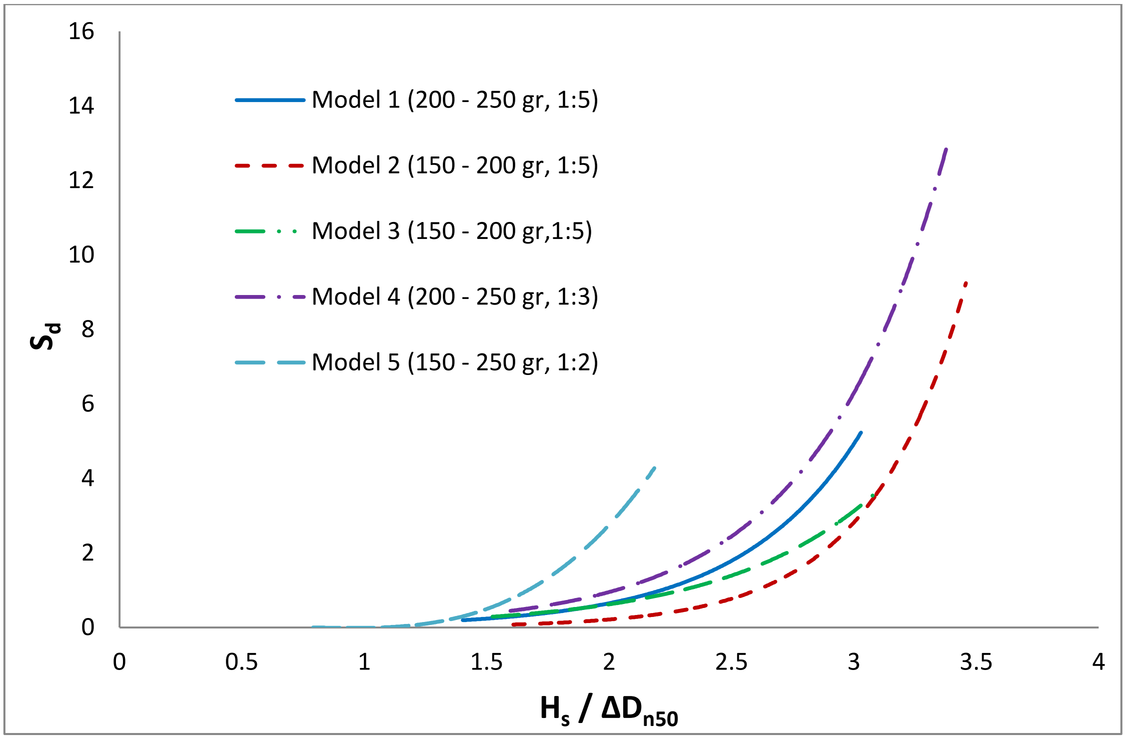

Figure 6.6: The trendlines of the damage parameters (S_d) of Model 1 - 5

From Figure 6.6, the comparisons between the damage parameters (S_d) of Model 1 – 5 has been made. It is seen that in Model 5, which has 1:2 structure slope, increase of the damage parameter (S_d) was faster than other models which have milder slopes. The first comparison was made between Model 1 and Model 4. In these models, the armorstone sizes were same, but they had different structure slopes. In Model 1 and Model 4, 200 – 250 grams stones are used as an armorstones. The structure slope of Model 1 was 1:5, the structure slope of Model 4 was 1:3. The difference between Model 1 and Model 4 can be seen from Figure 6.7.

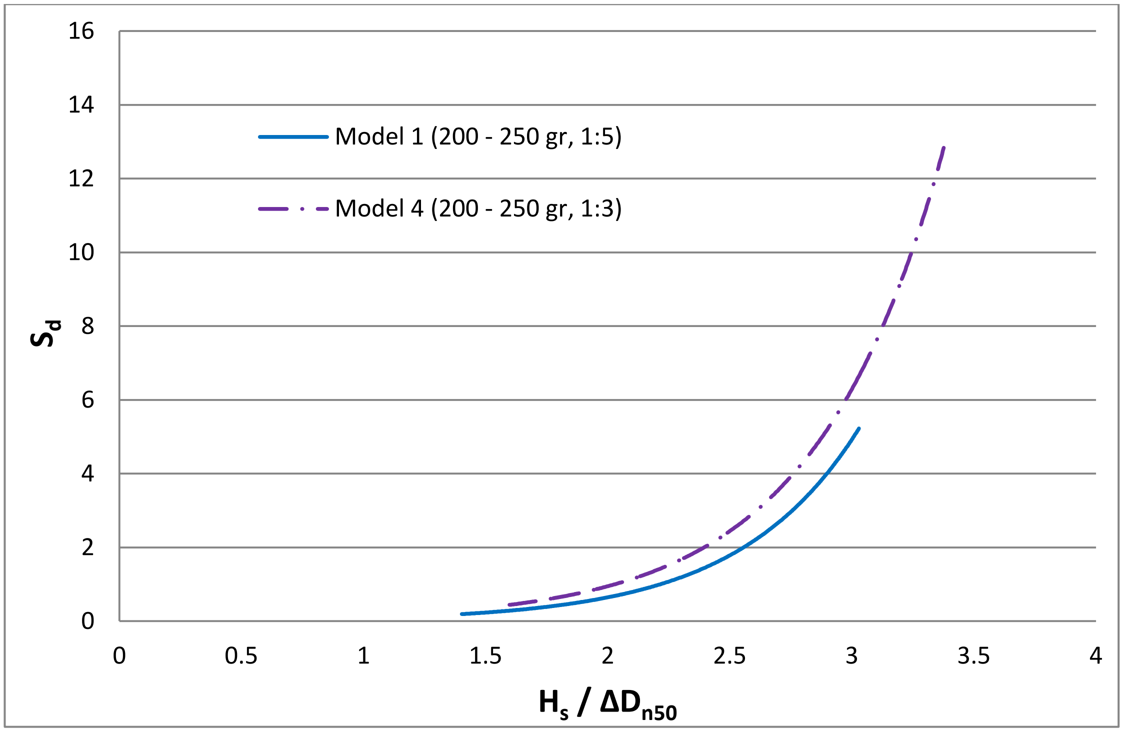

Figure 6.7: The comparison of S_d values of Model 1 and Model 4

From Figure 6.7, it can be observed that, within the same x axis value (H_s / ΔD_{n50}), they have different S_d value. This is due to the structure slopes of the cross sections. The damage parameter (S_d) value of the Model 4 is greater than Model 1. Because, the structure slope of the Model 4 is steeper than Model 1.

The second comparison was made between Model 1 and Model 2. In these models, the armorstone sizes were different, but they had same structure slopes. In Model 1 and Model 2, 1:5 structure slope was used as a front slope. The armorstone size of Model 1 was 200 – 250 grams, the armorstone size of Model 2 was 150 – 200 grams. The difference between the test results of Model 1 and Model 2 can be seen from Figure 6.8.

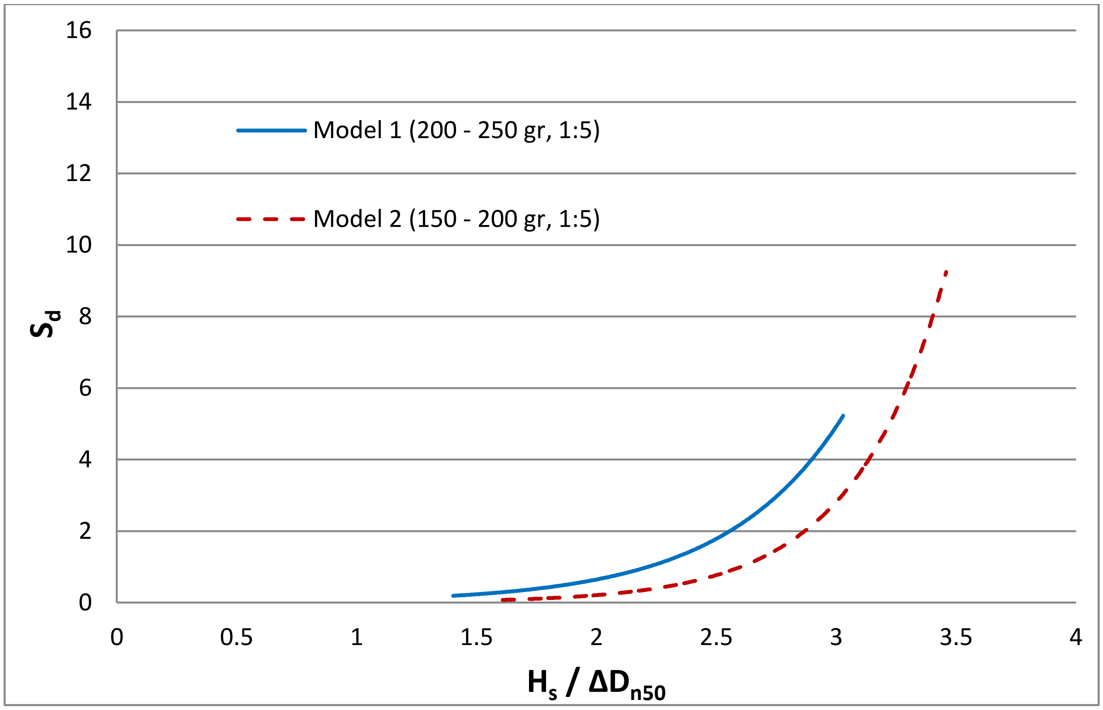

Figure 6.8: The comparison of S_d values of Model 1 and Model 2

From Figure 6.8, it can be observed that, within the same damage parameter value (S_d), they have different x axis value (H_s / ΔD_{n50}). This is due to the armorstone sizes of the cross sections. Within the same wave conditions (H_s) and same damage parameter (S_d) values, the H_s / ΔD_{n50} value of the Model 2 is greater than Model 1. Because, the armorstone size of the Model 2 is smaller than Model 1.

Most important outcome of this study is to show the possibility of using the transition formula, which was developed by Burcharth et al. (2006), for converting the damage obtained from stone count method to area based damage parameter, S_d. This is very important for coastal and harbor engineering laboratories in developing countries which do not have devices to take structure profiles before and after the experiments. By this transition formula, it will be easier to use the existing stability formulae, which are using damage parameters obtained from eroded areas.

CHAPTER 7

CONCLUSION

By the results of the present study, the consistency of the stability formulae, which are Van der Meer (shallow water), Van Gent et al. (2004) and Melby (2001), were controlled by using the test results and those computed from stability formulae. Especially, the effects of the structure slope and armor stone sizes were taken into account and 5 different models were constructed at the Ocean Engineering Research Center, Middle East Technical University (METU), Ankara.

In Model 1, Model 2, Model 3, the structure slopes was 1:5. For the Model 4 and Model 5 the structure slopes was 1:3 and 1:2 respectively. In Model 1, Model 4 the sizes of the armour stones was 200 – 250 grams (8 – 10 tons in prototype) in the model studies. In Model 2, Model 3 the sizes of the armour stones was 150 – 200 grams (6 – 8 tons in prototype). At Model 5, both of the armour stone sizes which are 200 – 250 grams (8 – 10 tons in prototype) and 150 – 200 grams (6 – 8 tons in prototype) are used seperately. The sizes of the stones at the filter and core layer were same for all the models. The size of the material at the core layer was 0 – 6.2 grams (0 – 0.25 tons in prototype). The size of the stones at the filter layer was 10 – 50 grams (0.4 – 2 tons in prototype).

At the experiments, different irregular wave sets composed of wave series with different wave characteristics have been generated. After each wave series, the number of displaced stones have been counted to obtain the accumulated damage for each wave set. These values obtained from stone count method have been converted to the damage parameters, S_d, by the formula of Burcharth et al. (2006). Then, values of the damage parameters were calculated by using the wave conditions of the experiments in the stability formulae. Finally, the values of the damage parameters which has been obtained from stability formulae and model studies are compared in order to compare the test results with the formulae. The results showed that Van der Meer formulae for shallow water conditions is more comparable than Melby (2001) and Van Gent et al. (2004).

After that, the data, which came from experimental studies, have been analyzed in detail. Moreover, it is found out that, Model 1, Model 2, Model 3 are not in the same trend with the equation of Van der Meer for shallow water conditions. Nevertheless, Model 4 and Model 5 are in the trend of the equation and their data are in the 90 percent intervals of Van der Meer (shallow water, plunging) equation. The structure slopes of the Model 4 and Model 5 (1:3 and 1:2) are in the slope range of the Van der Meer formulae for shallow water conditions (1:2 – 1:4). However, the slopes of the Model 1, Model 2, Model 3 (1:5) are not in the slope range of the Van der Meer formulae for shallow water conditions (1:2 – 1:4). Those results showed that Van der Meer formulae for shallow water conditions are very dependent to range of the slope parameter and that parameter has effective role at the Van der Meer formulae for shallow water conditions.

In conclusion, it can be seen from the present study that the transition formula of Burcharth et al. (2006) which converts the number of displaced stones in active zone to the damage parameters, (S_d), gives reliable results at defining the damage of the models.

As a recommendation for future studies, different values of porosity in models for the same cross sections can be used to examine the effect of porosity at the stability of the coastal defense structures. Also, different size materials can be used in filter and core layers, to see the effect of these layers. Since, the material sizes which is used in this study were always same for all cross sections.

A new data can be added to data set which is developed in this study. By this way, the confidence level of data set will be increased about its results and its consistency. To do this, different front slopes, different armour stone sizes, different wave sets can be used in the models.

For a future consideration, the relationship between damage development and the stability formula of Hudson (1953) can be developed. Therefore, Hudson (1953) formula can be used as a comparison material for model studies which has successive wave sets.

For the future studies, the effect of overtopping on the stability of structure slope must be included in the measurements. In addition, work that is more detailed can be studied to compare the stability formulae Van der Meer (shallow water) and Van Gent et al. (2004) for different storm conditions, structure slope and armor stone sizes.

REFERENCES

Broderick, L. L. (1983). “Riprap stability, a progress report”. In: J R Weggel (ed), *Proc speciality conf design, const, maint and perf coastal structures, Arlington, VA, 9–11 Mar*. ASCE, New York, 320–330

Burcharth, H. F., Kramer, M., Lamberti, A. and Zanuttigh, B. (2006). “Structural stability of detached low crested breakwaters”. *Coastal Engineering*, **53(4)**: 381–394

CERC (1977). *Shore protection manual [SPM], 3rd edn*. Coastal Engineering Research Center, US Army Corps of Engineers, Vicksburg, MS

CERC (1984). *Shore protection manual [SPM], 4th edn*. Coastal Engineering Research Center, US Army Corps of Engineers, Vicksburg, MS

CIRIA, CUR, CETMEF (2007). *Rock Manual*. “The use of rock in hydraulic engineering (2nd edition)”. **C683**, London: CIRIA

Dalrymple, R. A. (1985). “Introduction to Physical Models in Coastal Engineering” in *Physical Modelling in Coastal Engineering*, R.A. Dalrymple, Ed., A. A. Balkena, Rotterdam, The Netherlands, 3-9

Goda, Y. (2000). “Random seas and design of maritime structures”. *Advanced series on ocean engineering*, **vol 15**, World Scientific, Singapore

Goda, Y. and Suzuki, Y. (1976) “Estimation of incident and reflected waves in random wave experiments” *Proc. 15th Int. Conf. Coastal Engrg,* Hawaii

Hedar, P. A. (1960). “Stability of rock-fill breakwaters” [in Swedish]. Doctoral thesis. Univ of Göteborg, Sweden

Hudson, R. Y. (1953). “Wave forces on breakwaters”. *Trans Am Soc Civ Engrs*, **118**: 653–674

Hudson, R. Y. (1959). “Laboratory investigations of rubble mound breakwaters”. *J Waterways & Harbors Div, Am Soc Civ Engrs,* **85**, Paper no 2171, 93–121

Hudson, R. Y., Hermann, F. A., Sager, R. A., Whalin, R. W., Keulegan, G. H., Chatham, C. E., and Hales, L. Z. (1979). "Coastal Hydraulic Models" Special Report No.5, US Army Engineer Waterways Experiment Station, Vicksburg, Missisippi

Hughes S. A. (1993). "Physical Models and laboratory techniques in coastal engineering".*Advanced series on ocean engineering,* **vol 7**, World Scientific, Singapore

Kamali, B. and Hashim, R. (2009). "Recent Advances in Stability Formulae and Damage Description of Breakwater Armour Layer". *Australian Journal of Basic and Applied Sciences* , **3(3)**: 2717-2827

Kamphuis, J. W. (1991). "Physical Modelling" in *Handbook of Coastal and Ocean Engineering*, J. B. Herbich, Ed., **Vol 2**, Gulf Publishing Company, Houston, Texas

Le Méhauté, B. (1990). "Similitude" in *Ocean Engineering Science*, B. Le Méhauté, Ed., Part B in the series *The Sea*, John Wiley and Sons, New York, **9:** 955-980

Melby, J. A. (1999). "Damage Progression on Rubble-Mound Breakwaters" Technical Report CHL-99-17, U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Melby, J. A. (2001). *Damage development on stone armored breakwaters and revetments.* ERDC/CHL CHETN-III-64, US Army Engineer Research and Development Center, Vicksburg, MS

Melby, J. A. and Kobayashi, N. (1999). "Damage progression on breakwaters". In: B L Edge (ed), *Proc 26th int conf coastal engg, Copenhagen, 22–26 Jun 1998*. ASCE, Reston, VA, 1884–1897

Sharp, J. J., and Khader, M. H. A. (1984). "Scale Effects in Harbour Models Involving Permeable Rubble Mound Structures" *Symposium on Scale Effects in Modelling Hydraulic Structures*, ed. H. Kobus, IAHR, 7.12-1 – 7.12-5

Thompson, D. M. and Shuttler, R. M. (1975). *Riprap design for wind wave attack. A laboratory study in random waves.* Report EX 707, Hydraulics Research, Wallingford

USACE (2003). *Coastal engineering manual [CEM]* Engineer Manual 1110-2-1100, US Army Corps of Engineers, CHL-ERDC, WES, Vicksburg, MS

Van der Meer, J. W. (1988b). "Rock slopes and gravel beaches under wave attack". PhD thesis, Delft University of Technology, Delft. Also Delft Hydraulics publication no: 396

Van der Meer, J. W. (2000). "Design of concrete armour layers". In: I. J. Losada (ed), *Proc 3rd int conf. coastal structures, Santander, Spain, 7–10 June.* 1999. ASCE, New York, USA, A A Balkema, Rotterdam, **1**: 213–221

Van Gent, M. R. A. (2005). "On the stability of rock slopes". In: C. Zimmermann, R. G. Dean and V. Penchev (eds), *Environmentally friendly coastal protection*. NATO Science Series, Springer, New York, **53**: 73–92

Van Gent, M. R. A., Smale, A. J. and Kuiper, C. (2004). "Stability of rock slopes with shallow foreshores". In: J. A. Melby (ed), *Proc 4th int coastal structures conf, Portland, OR, 26–30 Aug 2003*. ASCE, Reston, VA

Vidal, C., Losada, M. A. and Mansard, E. P. D. (1995). "Stability of low-crested rubble-mound breakwater heads". *J Waterway, Port, Coastal and Ocean Engg*, **121**: 114–122

APPENDIX A

CROSS SECTION COMPUTATIONS, THE WAVE CONDITIONS AND THE CUMULATIVE DAMAGE TABLES OF MODELS

The cross section computations carried out for an experimental sponsored study in Ocean Engineering Research Center, Middle East Technical University (METU), Ankara are based on the project site topography and design wave characteristics. This master thesis then developed with the framework of a basic research by extending the above mentioned study. Computations to design the rubble mound coastal defense structure (armor stone size, structural front slope) and model wave sets together with cumulative damage tables of models are given in the following parts of this appendix. Model dimensions are obtained in accordance with Froude law.

A.1 Cross Section Computations

At the design stage of cross sections, the structural front slopes and level of damages are assigned within the framework of design purposes and bottom topography. Wave characteristics are obtained from various wave analyses. All the cross sections were designed based on the stability formulae of Van der Meer (shallow water) which is described in Chapter 2. The armor stone sizes of the cross sections are obtained from these formulas. The computations are shown in Table A.1 – Table A.3. In these tables, parameters, which were shown, are:

H_s = Significant wave height at the toe of the structure (m)

α = Structural front slope

S_d = damage parameter

h = depth of water at the toe of the structure (m)

D_{n50} = Nominal diameter of the armor stone (m)

W_{50} = Weight of the armor stone (tons)

Table A.1: Results of Cross Section Computation (1:5 front slope, 6–8 tons)

Cross Section Computation					
Hs (m)	α	S_d	h (m)	D_{n50} (m)	W_{50} (tons)
6.07	1:5	3	10.5	1.4	7.07

Table A.2: Results of Cross Section Computation (1:5 front slope, 8–10 tons)

Cross Section Computation					
H_s (m)	α	S_d	h (m)	D_{n50} (m)	W_{50} (tons)
6.31	1:5	3	14	1.48	8.5

Table A.3: Results of Cross Section Computation (1:2 front slope)

Cross Section Computation					
H_s (m)	α	S_d	h (m)	D_{n50} (m)	W_{50} (tons)
4.37	1:2	3	14.5	1.44	7.94

A.2 The Wave Conditions and the Cumulative Damage Tables of Models

A.2.1 Model 1

Table A.4: Model 1, Set 1

Wave Conditions at model studies in prototype values					
H_s (m)	3.8	7.0	7.3	7.5	7.8
T_s (sec)	8.7	12.0	12.4	12.8	13.1
$H_{s,5Hs}$ (m)	3.8	6.9	7.3	7.4	7.7
H 2% (m)	5.5	8.7	9.1	9.2	9.5
T_m (sec)	7.6	9.9	10.4	10.8	11.1
T_{m-1} (sec)	8.4	10.5	10.8	11.1	11.3
N	990	1042	1981	2946	3989
t (hour)	2.0	2.7	5.6	8.6	11.9
Cumulative damage percentages (%) and the number of displaced stones (n)					
Green, % (n)	0 (0)	0 (0)	0.5 (2)	0.5 (2)	0.5 (2)
Red, % (n)	1.5 (6)	3.3 (13)	7.6 (30)	13.2 (52)	22.5 (89)
Yellow, % (n)	0.9 (3)	1.5 (5)	2.9 (10)	8.1 (28)	11.9 (41)
Blue, % (n)	0 (0)	0 (0)	0 (0)	0.3 (1)	0 (0)
Pink, % (n)	0 (0)	0.5 (2)	0.5 (2)	0.5 (2)	0.5 (2)
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Toe, % (n)	0 (0)	0 (0)	4.1 (3)	4.1 (3)	6.8 (5)
Total, % (n)	0.4 (9)	0.9 (20)	2.1 (47)	3.9 (88)	6.1 (139)

Table A.5: Model 1, Set 2

Wave Conditions at model studies in prototype values						
H_s (m)	3.6	6.4	6.9	7.0	7.2	7.5
T_s (sec)	8.9	12.0	12.4	12.9	13.1	13.1
$H_{s, ,5Hs}$ (m)	3.4	6.1	6.6	6.7	6.9	7.5
H 2% (m)	5.1	8.0	8.6	8.6	8.8	9.2
T_m (sec)	7.5	9.7	10.5	10.7	11.1	11.1
T_{m-1} (sec)	8.4	10.5	10.9	11.0	11.3	11.3
N	944	1076	2445	2954	3958	4005
t (hour)	2.0	2.7	5.6	8.6	11.9	11.9
Cumulative damage percentages (%) and the number of displaced stones (n)						
Green, % (n)	0 (0)	0.3 (1)	0.5 (2)	0.3 (1)	0.3 (1)	4.6 (17)
Red, % (n)	1.3 (5)	4.8 (19)	13.9 (55)	22 (87)	29.9 (118)	37 (146)
Yellow, % (n)	0.3 (1)	1.7 (6)	3.5 (12)	4.9 (17)	9.6 (33)	14.8 (51)
Blue, % (n)	0 (0)	0 (0)	0.3 (1)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Toe, % (n)	0 (0)	0 (0)	1.4 (1)	1.4 (1)	2.7 (2)	2.7 (2)
Total, % (n)	0.3 (6)	1.1 (26)	3.1 (71)	4.6 (106)	6.7 (154)	9.5 (216)

Table A.6: Model 1, Set 3

Wave Conditions at model studies in prototype values					
H_s (m)	3.8	6.9	7.2	7.4	7.6
T_s (sec)	8.8	12.0	12.3	12.8	13.1
$H_{s,5Hs}$ (m)	3.6	6.6	6.9	7.1	7.4
H 2% (m)	5.3	8.8	9.0	9.0	9.4
T_m (sec)	7.6	9.8	10.3	10.7	11.1
T_{m-1} (sec)	8.4	10.5	10.8	11.0	11.3
N	980	1039	2023	2988	3804
t (hour)	2.0	2.7	5.6	8.6	11.9
Cumulative damage percentages (%) and the number of displaced stones (n)					
Green, % (n)	0 (0)	0.5 (2)	0.5 (2)	0.5 (2)	0.3 (1)
Red, % (n)	1.3 (5)	4.6 (18)	9.9 (39)	15.7 (62)	22 (87)
Yellow, % (n)	0 (0)	1.2 (4)	5.5 (19)	8.7 (30)	12.8 (44)
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Toe, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total, % (n)	0.2 (5)	1.1 (24)	2.6 (60)	4.1 (94)	5.8 (132)

Table A.7: Model 1, Set 4

Wave Conditions at model studies in prototype values					
H_s (m)	5.2	5.1	5.2	5.2	6.6
T_s (sec)	10.1	10.1	10.2	10.1	11.7
$H_{s,5Hs}$ (m)	5.0	4.9	5.0	4.9	6.3
H 2% (m)	7.1	7.1	7.2	7.1	8.3
T_m (sec)	8.6	8.5	8.5	8.4	10.0
T_{m-1} (sec)	9.4	9.4	9.4	9.4	10.4
N	2061	1981	2081	2080	3673
t (hour)	4.8	4.3	4.8	4.8	10.0
Cumulative damage percentages (%) and the number of displaced stones (n)					
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Red, % (n)	1 (4)	1.3 (5)	2.3 (9)	2.8 (11)	9.1 (36)
Yellow, % (n)	0.6 (2)	1.2 (4)	1.7 (6)	2 (7)	4.7 (16)
Blue, % (n)	0 (0)	0 (0)	0 (0)	0.3 (1)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Toe, % (n)	1.4 (1)	1.4 (1)	1.4 (1)	1.4 (1)	1.4 (1)
Total, % (n)	0.3 (7)	0.4 (10)	0.7 (16)	0.9 (20)	2.3 (53)

Table A.8: Model 1, Set 5

Wave Conditions at model studies in prototype values					
H_s (m)	5.7	5.7	5.7	5.7	7.2
T_s (sec)	10.2	10.2	10.1	10.0	11.7
$H_{s,5Hs}$ (m)	5.6	5.6	5.6	5.6	7.1
H 2% (m)	7.9	7.9	7.9	7.9	9.2
T_m (sec)	8.5	8.5	8.5	8.4	10.0
T_{m-1} (sec)	9.4	9.4	9.4	9.4	10.4
N	2096	2081	2102	2124	3735
t (hour)	4.8	4.3	4.8	4.8	10.0
Cumulative damage percentages (%) and the number of displaced stones (n)					
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Red, % (n)	2 (8)	2.5 (10)	3.3 (13)	3.8 (15)	11.1 (44)
Yellow, % (n)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	3.5 (12)
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Toe, % (n)	1.4 (1)	1.4 (1)	1.4 (1)	1.4 (1)	1.4 (1)
Total, % (n)	0.4 (10)	0.5 (12)	0.7 (15)	0.7 (17)	2.5 (57)

A.2.2 Model 2

Table A.9: Model 2, Set 1

Wave Conditions at model studies in prototype values								
H_s (m)	5.8	5.8	6.1	6.0	7.5	7.7	7.6	7.6
T_s (sec)	10.2	10.2	10.4	10.3	12.1	12.1	12.2	12.1
$H_{s,5Hs}$ (m)	5.4	5.4	5.7	5.7	7.1	7.1	7.1	7.2
H 2% (m)	7.9	7.8	7.8	7.9	9.5	9.7	9.6	9.4
T_m (sec)	8.7	8.7	8.8	8.7	10.0	10.1	10.0	10.1
T_{m-1} (sec)	9.4	9.4	9.2	9.2	10.0	10.0	10.0	10.0
N	2062	2051	1676	2068	910	919	924	940
t (hour)	4.8	4.8	4.0	4.8	2.5	2.5	2.5	2.5
Cumulative damage percentages (%) and the number of displaced stones (n)								
Blue, % (n)	0.6 (2)	1.1 (4)	1.1 (4)	1.1 (4)	1.4 (5)	1.4 (5)	1.4 (5)	1.7 (6)
Yellow, % (n)	2.4 (9)	3.2 (12)	3.5 (13)	4.1 (15)	5.7 (21)	7.3 (27)	8.4 (31)	10.5 (39)
Red, % (n)	0.9 (3)	1.4 (5)	1.7 (6)	2.6 (9)	3.5 (12)	4.3 (15)	6.7 (23)	8.4 (29)
Black, % (n)	1.4 (5)	1.1 (4)	1.1 (4)	2 (7)	2.5 (9)	4.5 (16)	5.9 (21)	5.6 (20)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Toe, %(n)	1 (2)	2 (4)	2 (4)	2 (4)	2 (4)	3 (6)	3 (6)	3 (6)
Total, % (n)	0.9 (21)	1.2 (29)	1.3 (31)	1.7 (39)	2.2 (51)	2.9 (69)	3.7 (86)	4.3 (100)

Table A.10: Model 2, Set 2

Wave Conditions at model studies in prototype values										
H_s (m)	5.8	5.8	5.8	6.1	5.8	7.3	7.2	7.3	7.2	7.1
T_s (sec)	10.3	10.3	10.3	10.3	10.3	12.1	12.1	12.0	11.9	12.1
$H_{s,5Hs}$ (m)	5.9	5.9	5.9	6.1	5.8	7.4	7.3	7.4	7.4	7.2
H 2% (m)	7.8	7.7	7.8	8.1	7.6	9.1	9.0	9.3	9.1	8.9
T_m (sec)	8.9	8.9	8.8	9.0	8.7	10.2	9.9	10.1	9.9	10.4
T_{m-1} (sec)	9.2	9.2	9.2	9.2	9.3	10.0	10.0	10.0	9.9	10.0
N	2034	2056	2041	320	1721	922	982	988	600	927
t (hour)	4.8	4.8	4.8	0.7	4.1	2.5	2.5	2.5	1.6	2.5
Cumulative damage percentages (%) and the number of displaced stones (n)										
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Yellow, % (n)	1.1 (4)	1.4 (5)	2.2 (8)	2.2 (8)	2.7 (10)	3 (11)	6.5 (24)	7.8 (29)	10 (37)	10.3 (38)
Red, % (n)	0.3 (1)	0.6 (2)	0.6 (2)	0.9 (3)	1.2 (4)	1.4 (5)	2.6 (9)	3.2 (11)	3.8 (13)	4.1 (14)
Black, % (n)	0.3 (1)	0.6 (2)	0.8 (3)	0.8 (3)	0.8 (3)	1.1 (4)	3.4 (12)	4.2 (15)	5.1 (18)	5.1 (18)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)
Toe, % (n)	1.5 (3)	1.5 (3)	2.5 (5)	2.5 (5)	2.5 (5)	2.5 (5)	3.5 (7)	3.5 (7)	4 (8)	4 (8)
Total, % (n)	0.4 (9)	0.5 (12)	0.8 (18)	0.8 (19)	0.9 (22)	1.1 (25)	2.3 (53)	2.7 (63)	3.3 (77)	3.4 (79)

Table A.11: Model 2, Set 3

Wave Conditions at model studies in prototype values											
H_s (m)	4.0	7.2	7.5	7.5	8.0	7.9	7.9	8.0	8.1	8.0	8.0
T_s (sec)	8.8	12.1	12.5	12.6	13.4	13.3	13.5	13.4	13.2	13.3	13.4
$H_{s,5Hs}$ (m)	3.9	6.9	7.2	7.2	7.7	7.6	7.6	7.7	7.8	7.7	7.7
H 2% (m)	5.8	9.1	9.4	9.2	9.7	9.9	9.8	9.8	9.9	9.8	9.7
T_m (sec)	7.8	10.2	10.4	10.5	11.2	11.0	11.2	11.4	11.4	11.2	11.4
T_{m-1} (sec)	8.5	9.9	10.3	10.3	10.7	10.7	10.8	10.7	10.7	10.7	10.7
N	984	1005	994	1003	988	1029	983	1013	1015	1017	1011
t (hour)	2.0	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.0
Cumulative damage percentages (%) and the number of displaced stones (n)											
Blue, % (n)	0 (0)	0 (0)	0.6 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0.6 (2)
Yellow, % (n)	1.4 (5)	4.9 (18)	8.4 (31)	10.3 (38)	12.4 (46)	13.2 (49)	16.2 (60)	17.3 (64)	20 (74)	21.1 (78)	24.6 (91)
Red, % (n)	0 (0)	2.6 (9)	4.1 (14)	7.5 (26)	11 (38)	13.3 (46)	17.1 (59)	19.1 (66)	21.7 (75)	23.5 (81)	26.7 (92)
Black, % (n)	0 (0)	1.7 (6)	3.1 (11)	3.9 (14)	6.2 (22)	7.3 (26)	9.3 (33)	12.4 (44)	16.3 (58)	18.3 (65)	18.5 (66)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0.3 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Toe, % (n)	0 (0)	1.5 (3)	1.5 (3)	2 (4)	2 (4)	2.5 (5)	2.5 (5)	3 (6)	3 (6)	3.5 (7)	3.5 (7)
Total, % (n)	0.2 (5)	1.5 (36)	2.6 (61)	3.5 (82)	4.8 (111)	5.4 (126)	6.7 (157)	7.8 (181)	9.2 (214)	10 (232)	11.1 (258)

Table A.12: Model 2, Set 4

Wave Conditions at model studies in prototype values											
H_s (m)	3.8	7.2	7.4	7.4	7.9	7.8	7.8	7.9	8.1	8.2	8.3
T_s (sec)	8.8	12.1	12.5	12.6	13.4	13.4	13.5	13.2	13.3	13.3	13.4
$H_{s,5Hs}$ (m)	3.9	7.2	7.4	7.4	7.9	7.8	7.8	7.9	7.9	8.0	8.1
H 2% (m)	5.5	9.1	9.3	9.2	9.7	9.6	9.7	9.5	9.9	10.0	10.1
T_m (sec)	7.9	10.2	10.4	10.5	11.2	11.1	11.2	11.3	11.3	11.3	11.3
T_{m-1} (sec)	8.5	10.0	10.3	10.3	10.8	10.8	10.8	10.6	10.7	10.7	10.7
N	978	1001	1016	1018	992	991	993	1020	1010	1022	1006
t (hour)	2.0	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.0
Cumulative damage percentages (%) and the number of displaced stones (n)											
Blue, % (n)	0 (0)	0.3 (1)	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0.6 (2)	0.6 (2)	0.8 (3)	1.1 (4)	1.1 (4)
Yellow, % (n)	0.3 (1)	5.1 (19)	8.6 (32)	12.7 (47)	17.8 (66)	22.4 (83)	25.4 (94)	27.3 (101)	27.8 (103)	28.4 (105)	31.1 (115)
Red, % (n)	0 (0)	2.6 (9)	6.1 (21)	7.8 (27)	13 (45)	16.5 (57)	20.9 (72)	27.2 (94)	31.6 (109)	33.6 (116)	40 (138)
Black, % (n)	0 (0)	1.4 (5)	3.1 (11)	3.7 (13)	3.9 (14)	7 (25)	7 (25)	9.6 (34)	11 (39)	13.2 (47)	16.9 (60)
Green, % (n)	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0 (0)	0 (0)	0.3 (1)	0.6 (2)	0.9 (3)	0.9 (3)	0.9 (3)
Pink, % (n)	0 (0)	0.3 (1)	0.3 (1)	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)
Toe, % (n)	0 (0)	1 (2)	2 (4)	2 (4)	2.5 (5)	2.5 (5)	2.5 (5)	2.5 (5)	3 (6)	3 (6)	3 (6)
Total, % (n)	0 (1)	1.6 (38)	3 (70)	4 (93)	5.7 (132)	7.4 (172)	8.6 (200)	10.3 (239)	11.3 (264)	12.1 (282)	14 (327)

A.2.3 Model 3

Table A.13: Model 3, Set 1

Wave Conditions at model studies in prototype values						
H_s (m)	3.6	6.7	7.0	7.3	7.4	7.4
T_s (sec)	10.3	12.2	12.8	12.7	12.8	12.8
$H_{s,5Hs}$ (m)	3.6	6.5	6.8	7.0	7.0	7.0
H 2% (m)	5.2	8.4	8.8	9.0	9.2	9.2
T_m (sec)	7.9	10.2	10.5	10.2	10.3	10.4
T_{m-1} (sec)	8.4	9.8	10.1	10.1	10.1	10.1
N	1007	985	1002	1053	1002	1000
t (hour)	2.0	2.7	2.8	2.8	2.8	2.8
Cumulative damage percentages (%) and the number of displaced stones (n)						
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0.3 (1)	0.9 (3)
Red, % (n)	0.6 (2)	2.6 (9)	6.1 (21)	8.7 (30)	13 (45)	18 (62)
Yellow, % (n)	0.3 (1)	0.6 (2)	3.2 (11)	4.9 (17)	6.4 (22)	7.8 (27)
Blue, % (n)	1.2 (4)	4.1 (14)	5.5 (19)	6.1 (21)	7.2 (25)	9.3 (32)
Pink, % (n)	0 (0)	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0.6 (2)
Black, % (n)	0.3 (1)	2.1 (8)	4.2 (16)	3.4 (13)	4.5 (17)	4.7 (18)
Toe, % (n)	0.4 (8)	1.6 (33)	3.2 (68)	3.9 (82)	5.3 (111)	6.8 (144)
Total, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0.3 (1)	0.9 (3)

A.2.4 Model 4

Table A.14: Model 4, Set 1

Wave Conditions at model studies in prototype values									
H_s (m)	6.0	6.0	6.1	6.1	7.6	7.4	7.7	7.7	7.6
T_s (sec)	10.4	10.2	10.3	10.2	11.8	11.5	11.9	11.9	11.9
$H_{s,5Hs}$ (m)	5.7	5.7	5.6	5.7	7.2	7.0	7.5	7.5	7.4
H 2% (m)	7.9	7.9	7.9	8.0	9.4	9.6	9.5	9.3	9.2
T_m (sec)	9.0	8.9	9.0	8.9	10.4	10.2	10.5	10.4	10.4
T_{m-1} (sec)	9.5	9.6	9.6	9.6	10.3	10.3	10.2	10.3	10.3
N	2024	2049	2037	2038	915	455	443	911	923
t (hour)	4.8	4.8	4.8	4.8	2.5	1.3	1.3	2.5	2.5
Cumulative damage percentages (%) and the number of displaced stones (n)									
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Yellow, % (n)	0.4 (1)	0.8 (2)	2.5 (6)	4.2 (10)	7.5 (18)	7.8 (19)	8.8 (21)	10.8 (26)	13.3 (32)
Red, % (n)	9.2 (22)	9.6 (23)	11.3 (27)	13.8 (33)	14.6 (35)	15.7 (38)	17.1 (41)	20 (48)	23.3 (56)
Black, % (n)	4.2 (10)	5.4 (13)	6.7 (16)	7.5 (18)	8.8 (21)	8.8 (21)	9.2 (22)	10.4 (25)	10.8 (26)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.4 (1)
Pink, % (n)	1.3 (4)	1.3 (4)	1.3 (4)	1.3 (4)	1.3 (4)	1.3 (4)	1.7 (5)	1.7 (5)	1.7 (5)
Total, % (n)	2.6 (37)	3 (42)	3.8 (53)	4.6 (65)	5.6 (78)	5.9 (82)	6.4 (89)	7.4 (104)	8.6 (120)

Table A.15: Model 4, Set 2

Wave Conditions at model studies in prototype values								
H_s (m)	6.1	6.0	6.0	6.0	7.7	7.7	7.7	7.7
T_s (sec)	10.2	10.3	10.3	10.3	11.8	11.9	11.8	11.9
$H_{s,5Hs}$ (m)	6.0	6.0	5.9	5.9	7.5	7.5	7.5	7.6
H 2% (m)	8.1	8.0	8.0	7.8	9.4	9.6	9.4	9.6
T_m (sec)	9.0	8.9	9.0	9.0	10.5	10.5	10.4	10.4
T_{m-1} (sec)	9.6	9.6	9.6	9.6	10.3	10.3	10.3	10.3
N	1986	1993	2002	2026	905	897	911	913
t (hour)	4.8	4.8	4.8	4.8	2.5	2.5	2.5	2.5
Cumulative damage percentages (%) and the number of displaced stones (n)								
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Yellow, % (n)	1.7 (4)	1.7 (4)	4.2 (10)	5.4 (13)	10.8 (26)	13.8 (33)	17.9 (43)	24.2 (58)
Red, % (n)	6.7 (16)	11.7 (28)	13.3 (32)	13.8 (33)	15.8 (38)	17.1 (41)	19.6 (47)	20 (48)
Black, % (n)	3.3 (8)	5 (12)	7.1 (17)	7.5 (18)	7.5 (18)	7.5 (18)	8.3 (20)	7.9 (19)
Green, % (n)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)
Pink, % (n)	1.7 (5)	1.7 (5)	1.7 (5)	1.7 (5)	1.7 (5)	1.7 (5)	1.7 (5)	1.7 (5)
Total, % (n)	2.5 (35)	3.6 (51)	4.7 (66)	5.1 (71)	6.4 (89)	7.1 (99)	8.4 (117)	9.4 (132)

Table A.16: Model 4, Set 3

Wave Conditions at model studies in prototype values												
H_s (m)	4.1	7.7	8.0	7.9	8.3	8.4	8.4	8.5	8.5	8.6	8.5	8.5
T_s (sec)	8.8	11.8	12.5	12.1	13.0	12.9	12.8	12.8	12.7	12.7	12.9	12.8
$H_{s,5Hs}$ (m)	4.1	7.2	7.7	7.6	8.1	8.1	8.0	8.2	8.1	8.1	7.9	8.1
H 2% (m)	5.9	9.5	9.5	9.7	10.3	10.1	10.3	10.3	10.1	10.5	10.4	10.4
T_m (sec)	7.9	10.3	10.5	10.5	11.0	11.3	11.2	11.1	11.4	11.2	11.7	11.3
T_{m-1} (sec)	8.6	10.3	10.6	10.6	10.9	10.9	10.9	10.9	10.9	10.8	11.2	10.9
N	987	1006	992	1002	1024	976	990	1024	1052	855	157	1019
t (hour)	2.0	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.0	2.5	0.5	3.0
Cumulative damage percentages (%) and the number of displaced stones (n)												
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0.7 (1)	1.4 (2)	2.1 (3)	5 (7)	7.1 (10)	8.3 (11)	11.4 (16)	13.6 (19)
Yellow, % (n)	0 (0)	8.8 (21)	14.2 (34)	19.6 (47)	29.2 (70)	33.8 (81)	37.5 (90)	40.8 (98)	46.3 (111)	47.1 (113)	49.6 (119)	54.6 (131)
Red, % (n)	0 (0)	7.5 (18)	13.8 (33)	15.8 (38)	19.2 (46)	20.8 (50)	25 (60)	28.3 (68)	33.8 (81)	34.1 (83)	34.7 (86)	39.2 (94)
Black, % (n)	0.4 (1)	2.9 (7)	4.2 (10)	5.8 (14)	6.7 (16)	6.7 (16)	7.5 (18)	8.3 (20)	8.3 (20)	8.3 (20)	8.8 (21)	10 (24)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0.4 (1)	0.4 (1)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)	0.8 (2)
Pink, % (n)	0 (0)	0.3 (1)	1 (3)	1.7 (5)	1.7 (5)	2.3 (7)	2.7 (8)	2.7 (8)	2.7 (8)	2.7 (8)	2.7 (8)	2.7 (8)
Total, % (n)	0.1 (1)	3.4 (47)	5.7 (80)	7.4 (104)	9.9 (139)	11.2 (157)	12.9 (181)	14.5 (203)	16.6 (232)	16.6 (237)	17.1 (239)	19.9 (278)

Table A.17: Model 4, Set 4

Wave Conditions at model studies in prototype values											
H_s (m)	4.1	7.6	7.9	8.0	8.3	8.0	8.1	8.4	8.4	8.4	8.4
T_s (sec)	8.7	12.1	12.3	12.3	13.0	12.9	12.9	12.8	12.8	12.9	12.7
$H_{s,5Hs}$ (m)	3.9	7.3	7.7	7.6	8.0	7.8	7.9	8.0	8.0	8.0	8.0
H 2% (m)	5.6	9.5	9.6	9.7	10.2	9.8	9.8	10.1	10.3	10.1	10.2
T_m (sec)	7.8	10.3	10.7	10.5	11.0	11.2	11.1	11.2	11.1	11.2	11.3
T_{m-1} (sec)	8.8	10.3	10.6	10.6	10.9	10.9	11.0	10.9	10.9	10.9	11.0
N	981	1001	988	998	999	1019	1011	1031	1044	1048	1021
t (hour)	2.0	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.0
Cumulative damage percentages (%) and the number of displaced stones (n)											
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.7 (1)	2.9 (4)	4.3 (6)	10 (14)
Yellow, % (n)	0 (0)	6.7 (16)	11.3 (27)	17.5 (42)	26.7 (64)	31.3 (75)	27.9 (67)	37.5 (90)	45.8 (110)	54.6 (131)	55.4 (133)
Red, % (n)	0.8 (2)	15.4 (37)	22.1 (53)	27.5 (66)	34.6 (83)	37.5 (90)	40.8 (98)	46.7 (112)	51.3 (123)	57.9 (139)	58.8 (141)
Black, % (n)	0 (0)	5.4 (13)	10 (24)	10 (24)	9.2 (22)	10.8 (26)	9.6 (23)	10 (24)	10.8 (26)	13.3 (32)	14.2 (34)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.4 (1)	0.4 (1)
Pink, % (n)	0 (0)	1 (3)	1.3 (4)	1.7 (5)	1.7 (5)	1.7 (5)	2 (6)	2.7 (8)	3 (9)	3 (9)	2.7 (8)
Total, % (n)	0.1 (2)	4.9 (69)	7.7 (108)	9.8 (137)	12.4 (174)	14 (196)	13.9 (194)	16.8 (235)	19.4 (272)	22.7 (318)	23.6 (331)

Table A.18: Model 4, Set 5

Wave Conditions at model studies in prototype values								
H_s (m)	6.2	6.2	6.2	6.2	7.6	7.7	7.7	7.6
T_s (sec)	10.4	10.2	10.2	10.2	11.8	11.7	11.8	11.7
$H_{s,5Hs}$ (m)	5.9	5.9	5.8	5.8	7.4	7.5	7.6	7.5
H 2% (m)	8.2	8.2	8.1	8.2	9.4	9.4	9.5	9.3
T_m (sec)	9.1	9.0	8.9	8.9	10.4	10.5	10.6	10.4
T_{m-1} (sec)	9.6	9.6	9.6	9.6	10.3	10.4	10.3	10.3
N	2012	2015	2037	2009	912	909	914	911
t (hour)	4.8	4.8	4.8	4.8	2.5	2.5	2.5	2.5
Cumulative damage percentages (%) and the number of displaced stones (n)								
Blue, % (n)	0.7 (1)	0.7 (1)	0.7 (1)	0.7 (1)	2.9 (4)	2.9 (4)	3.6 (5)	3.6 (5)
Yellow, % (n)	2.5 (6)	4.2 (10)	5.8 (14)	9.6 (23)	15 (36)	17.9 (43)	20 (48)	21.3 (51)
Red, % (n)	10 (24)	19.2 (46)	20.8 (50)	22.9 (55)	27.9 (67)	31.7 (76)	35.4 (85)	39.2 (94)
Black, % (n)	3.3 (8)	4.6 (11)	5.4 (13)	5.8 (14)	5 (12)	5.4 (13)	5.8 (14)	5.8 (14)
Green, % (n)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)
Pink, % (n)	0.7 (2)	1.3 (4)	1.3 (4)	1.3 (4)	1.3 (4)	1.3 (4)	1.3 (4)	1.3 (4)
Total, % (n)	3 (42)	5.2 (73)	5.9 (83)	7 (98)	8.9 (124)	10.1 (141)	11.2 (157)	12.1 (169)

Table A.19: Model 4, Set 6

Wave Conditions at model studies in prototype values											
H_s (m)	4.1	7.7	8.1	8.1	8.4	8.4	8.4	8.6	8.6	8.6	8.6
T_s (s)	8.7	12.0	12.2	12.2	13.0	12.9	13.0	12.8	12.8	12.7	12.8
$H_{s,5Hs}$ (m)	3.9	7.4	7.7	7.7	8.0	8.1	8.1	8.3	8.2	8.1	8.2
H 2% (m)	5.6	9.4	9.7	9.8	10.3	10.2	10.1	10.4	10.5	10.5	10.4
T_m (s)	7.8	10.4	10.6	10.5	11.0	11.2	11.1	11.3	11.3	11.3	11.3
T_{m-1} (s)	8.8	10.3	10.6	10.6	10.9	11.0	10.9	10.9	10.9	10.9	10.9
N	981	1010	1006	1022	997	986	1030	1029	1033	1066	1030
t (h)	2.0	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.0
Cumulative damage percentages (%) and the number of displaced stones (n)											
Blue	0 (0)	2.9 (4)	2.9 (4)	2.9 (4)	2.1 (3)	5.7 (8)	7.1 (10)	10 (14)	8.6 (12)	22.9 (32)	26.4 (37)
Yellow	0 (0)	4.6 (11)	8.3 (20)	13.8 (33)	19.6 (47)	23.3 (56)	29.6 (71)	36.3 (87)	45.4 (109)	50.8 (122)	61.7 (148)
Red	4.2 (10)	20.8 (50)	30.8 (74)	35.4 (85)	39.2 (94)	42.1 (101)	50.8 (122)	52.1 (125)	57.1 (137)	60 (144)	57.9 (139)
Black	0.8 (2)	5.4 (13)	7.5 (18)	7.5 (18)	8.8 (21)	10 (24)	9.6 (23)	10.8 (26)	12.1 (29)	12.9 (31)	12.1 (29)
Green	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.7 (2)	1 (3)	1.3 (4)	1.3 (4)
Total	0.9 (12)	5.6 (79)	8.4 (117)	10.1 (141)	11.9 (166)	13.6 (190)	16.2 (227)	18.1 (254)	20.7 (290)	23.8 (333)	25.5 (357)

Table A.20: Model 4, Set 7

Wave Conditions at model studies in prototype values											
H_s (m)	4.2	7.6	7.8	8.0	8.1	8.1	8.3	8.6	8.6	8.5	8.6
T_s (s)	9.3	11.9	12.4	12.3	12.9	13.2	12.9	12.8	12.8	13.1	12.8
$H_{s,5Hs}$ (m)	4.6	7.4	7.6	7.7	8.1	7.8	7.9	8.1	8.1	8.1	8.1
H 2% (m)	6.0	9.6	9.7	9.7	9.9	9.9	10.2	10.4	10.3	10.3	10.4
T_m (s)	8.0	10.5	10.4	10.4	11.3	11.1	11.0	11.2	11.3	11.1	11.4
T_{m-1} (s)	8.7	10.3	10.6	10.6	10.9	10.9	11.0	10.9	10.9	11.0	10.9
N	842	1002	1012	1001	1003	1017	1020	1030	1020	1029	1015
t (h)	2.0	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.0
Cumulative damage percentages (%) and the number of displaced stones (n)											
Blue	0 (0)	0 (0)	1.4 (2)	2.1 (3)	4.3 (6)	6.4 (9)	7.1 (10)	7.1 (10)	7.1 (10)	10.7 (15)	19.3 (27)
Yellow	0 (0)	7.1 (17)	10.4 (25)	19.6 (47)	25 (60)	27.1 (65)	31.7 (76)	39.6 (95)	41.7 (100)	42.5 (102)	52.5 (126)
Red	4.2 (10)	14.6 (35)	22.1 (53)	30.4 (73)	31.7 (76)	42.5 (102)	40.8 (98)	52.1 (125)	54.2 (130)	59.2 (142)	63.8 (153)
Black	0.4 (1)	2.9 (7)	3.3 (8)	6.7 (16)	7.9 (19)	10.4 (25)	11.7 (28)	12.9 (31)	12.9 (31)	13.8 (33)	13.8 (33)
Green	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink	0 (0)	0.7 (2)	1 (3)	1.3 (4)	1.7 (5)	1.7 (5)	1.7 (5)	2 (6)	2 (6)	2 (6)	2.3 (7)
Total	0.8 (11)	4.4 (61)	6.5 (91)	10.2 (143)	11.9 (166)	14.7 (206)	15.5 (217)	19.1 (267)	19.8 (277)	21.3 (298)	24.7 (346)

Table A.21: Model 4, Set 8

Wave Conditions at model studies in prototype values								
H_s (m)	6.2	6.1	6.1	6.1	7.4	7.5	7.4	7.3
T_s (sec)	10.2	10.3	10.3	10.2	11.8	11.7	11.8	11.7
$H_{s,5Hs}$ (m)	5.7	5.7	5.6	5.7	7.2	7.2	7.3	7.2
H 2% (m)	8.2	8.1	7.9	8.0	9.2	9.2	9.2	9.0
T_m (sec)	9.0	8.9	9.0	8.9	10.4	10.5	10.6	10.4
T_{m-1} (sec)	9.6	9.6	9.6	9.6	10.3	10.4	10.3	10.3
N	1986	1993	2037	2038	912	909	914	911
t (hour)	4.8	4.8	4.8	4.8	2.5	2.5	2.5	2.5
Cumulative damage percentages (%) and the number of displaced stones (n)								
Blue, % (n)	2.1 (3)	2.9 (4)	3.6 (5)	3.6 (5)	3.6 (5)	4.3 (6)	4.3 (6)	4.3 (6)
Yellow, % (n)	1.7 (4)	3.8 (9)	5 (12)	5.4 (13)	7.5 (18)	8.8 (21)	10.8 (26)	13.3 (32)
Red, % (n)	16.3 (39)	22.1 (53)	25.8 (62)	26.3 (63)	26.7 (64)	27.9 (67)	31.3 (75)	33.3 (80)
Black, % (n)	4.6 (11)	4.6 (11)	5 (12)	7.5 (18)	8.8 (21)	9.2 (22)	10.4 (25)	10.8 (26)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.4 (1)
Pink, % (n)	1 (3)	1 (3)	0 (0)	1.3 (4)	1.3 (4)	1.7 (5)	1.7 (5)	1.7 (5)
Total, % (n)	4.3 (60)	5.7 (80)	6.5 (91)	7.4 (103)	8 (112)	8.6 (121)	9.8 (137)	10.7 (150)

Table A.22: Model 4, Set 9

Wave Conditions at model studies in prototype values								
H_s (m)	6.2	6.2	6.2	6.2	7.6	7.6	7.6	7.7
T_s (sec)	10.5	10.3	10.3	10.3	11.9	11.8	11.6	11.7
$H_{s,5Hs}$ (m)	6.0	6.0	6.0	6.0	7.6	7.6	7.5	7.6
H 2% (m)	8.3	8.2	8.2	8.2	9.4	9.4	9.3	9.5
T_m (sec)	9.2	8.9	8.9	8.9	10.5	10.4	10.4	10.3
T_{m-1} (sec)	9.6	9.6	9.6	9.6	10.4	10.4	10.4	10.4
N	1995	2012	2010	2048	898	919	915	922
t (hour)	4.8	4.8	4.8	4.8	2.5	2.5	2.5	2.5
Cumulative damage percentages (%) and the number of displaced stones (n)								
Blue, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	1.4 (2)	3.6 (5)	4.3 (6)	4.3 (6)
Yellow, % (n)	2.9 (7)	4.2 (10)	5.8 (14)	6.7 (16)	8.8 (21)	17.9 (43)	23.8 (57)	25.8 (62)
Red, % (n)	9.6 (23)	16.3 (39)	17.5 (42)	20 (48)	26.3 (63)	27.9 (67)	30.4 (73)	34.6 (83)
Black, % (n)	2.1 (5)	3.8 (9)	5 (12)	6.7 (16)	10 (24)	10.4 (25)	10.4 (25)	10.4 (25)
Green, % (n)	0 (0)	0 (0)	0 (0)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)
Pink, % (n)	0.7 (2)	1 (3)	1.3 (4)	1.3 (4)	1.7 (5)	1.7 (5)	1.3 (4)	1.3 (4)
Total, % (n)	2.6 (37)	4.4 (61)	5.1 (72)	6.1 (85)	8.3 (116)	10.4 (146)	11.9 (166)	12.9 (181)

A.2.5 Model 5

Table A.23: Model 5, Set 1

Wave Conditions at model studies in prototype values											
H_s (m)	2.1	3.9	4.4	4.3	4.6	4.6	4.6	5.2	5.1	5.2	5.2
T_s (sec)	5.5	7.9	8.4	8.4	8.8	8.7	8.7	9.4	9.4	9.4	9.6
$H_{s,5Hs}$ (m)	2.3	4.3	4.5	4.5	4.7	4.8	4.7	5.3	5.3	5.4	5.3
H 2% (m)	2.9	5.3	5.9	6.0	6.0	6.3	6.1	6.9	6.7	6.8	6.9
T_m (sec)	5.2	7.1	7.5	7.5	7.7	7.8	7.8	8.1	8.2	8.4	8.5
T_{m-1} (sec)	5.4	7.3	7.7	7.7	7.9	8.0	8.0	8.3	8.4	8.6	8.7
N	1024	997	1019	1040	1012	1003	1010	1032	1010	990	985
t (hour)	1.4	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3
Cumulative damage percentages (%) and the number of displaced stones (n)											
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0.6 (1)	1.2 (2)	1.2 (2)	1.2 (2)	1.2 (2)	3.5 (6)	4.7 (8)
Red, % (n)	0 (0)	0 (0)	0 (0)	7.2 (18)	10.4 (26)	12.8 (32)	14.8 (37)	18.8 (47)	22 (55)	26 (65)	26.8 (67)
Blue, % (n)	0 (0)	1.7 (5)	3.7 (11)	12.7 (38)	14 (42)	15 (45)	15.7 (47)	15.7 (47)	17.3 (52)	18 (54)	18.7 (56)
Yellow, % (n)	0 (0)	6.7 (20)	9 (27)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.7 (2)	0.7 (2)	0.7 (2)	0.7 (2)
Green, % (n)	0 (0)	0 (0)	0.4 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0.6 (1)	0.6 (1)	0.6 (1)	0.6 (1)	0.6 (1)	0.6 (1)	1.1 (2)	1.7 (3)	1.7 (3)
Total, % (n)	0 (0)	1.7 (25)	2.7 (40)	3.9 (58)	4.8 (71)	5.5 (81)	5.9 (88)	6.7 (99)	7.6 (113)	8.8 (130)	9.2 (136)

Table A.24: Model 5, Set 2

Wave Conditions at model studies in prototype values											
H_s (m)	2.1	3.9	4.3	4.3	4.3	4.5	4.6	5.1	5.1	5.2	5.1
T_s (sec)	5.5	7.8	8.5	8.5	8.5	8.7	8.8	9.6	9.4	9.5	9.5
$H_{s,5Hs}$ (m)	2.2	4.1	4.4	4.4	4.4	4.6	4.7	5.3	5.3	5.3	5.3
H 2% (m)	2.9	5.4	5.9	5.8	5.8	5.9	6.1	6.7	6.7	6.7	6.6
T_m (sec)	5.1	7.0	7.5	7.5	7.5	7.7	7.8	8.4	8.1	8.3	8.4
T_{m-1} (sec)	5.3	7.2	7.7	7.7	7.7	7.9	8.0	8.6	8.3	8.5	8.6
N	1016	997	1018	1029	1029	1016	1003	988	1028	1009	992
t (hour)	1.4	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3
Cumulative damage percentages (%) and the number of displaced stones (n)											
Black, % (n)	0 (0)	0 (0)	0.6 (1)	0.6 (1)	0.6 (1)	0.6 (1)	0.6 (1)	1.2 (2)	1.8 (3)	2.9 (5)	4.1 (7)
Red, % (n)	0 (0)	1.6 (4)	2 (5)	3.2 (8)	7.6 (19)	8.4 (21)	10 (25)	16 (40)	18.4 (46)	21.6 (54)	24 (60)
Blue, % (n)	0 (0)	2.7 (8)	4.3 (13)	5.7 (17)	7.7 (23)	8.3 (25)	9.3 (28)	12.7 (38)	13.3 (40)	14 (42)	14.7 (44)
Yellow, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total, % (n)	0 (0)	0.8 (12)	1.3 (19)	1.8 (26)	2.9 (43)	3.2 (47)	3.6 (54)	5.4 (80)	6 (89)	6.8 (101)	7.5 (111)

Table A.25: Model 5, Set 3

Wave Conditions at model studies in prototype values											
H_s (m)	2.1	3.8	4.2	4.4	4.6	4.6	4.5	5.2	5.1	5.1	5.1
T_s (sec)	5.7	7.9	8.4	8.4	8.8	8.7	8.7	9.6	9.7	9.6	9.5
$H_{s,5Hs}$ (m)	2.2	3.9	4.3	4.5	4.7	4.7	4.6	5.3	5.3	5.3	5.3
H 2% (m)	2.9	5.3	5.8	5.9	6.1	6.1	5.9	6.7	6.8	6.6	6.6
T_m (sec)	5.2	7.1	7.5	7.5	7.7	7.9	7.7	8.4	8.4	8.4	8.4
T_{m-1} (sec)	5.4	7.3	7.7	7.7	7.9	8.1	7.9	8.6	8.6	8.6	8.6
N	1028	993	1021	1016	1020	998	968	997	988	993	988
t (hour)	1.4	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3
Cumulative damage percentages (%) and the number of displaced stones (n)											
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0.6 (1)	1.2 (2)	1.2 (2)	1.2 (2)	0.6 (1)	1.2 (2)	1.8 (3)
Red, % (n)	0 (0)	1.6 (4)	3.2 (8)	6.4 (16)	9.2 (23)	11.2 (28)	12 (30)	13.2 (33)	14 (35)	14.8 (37)	16.8 (42)
Blue, % (n)	0 (0)	2.7 (8)	5 (15)	6.3 (19)	8 (24)	9.3 (28)	10 (30)	11.3 (34)	12.3 (37)	13 (39)	14.7 (44)
Yellow, % (n)	0 (0)	0 (0)	0 (0)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)	0.3 (1)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total, % (n)	0 (0)	0.8 (12)	1.6 (23)	2.4 (36)	3.3 (49)	4 (59)	4.3 (63)	4.7 (70)	5 (74)	5.3 (79)	6.1 (90)

Table A.26: Model 5, Set 4

Wave Conditions at model studies in prototype values											
H_s (m)	2.2	4.0	4.3	4.4	4.6	4.6	4.6	5.3	5.3	5.3	5.3
T_s (sec)	5.6	8.0	8.6	8.4	8.8	8.9	8.8	9.6	9.6	9.5	9.5
$H_{s,5Hs}$ (m)	2.4	4.6	4.5	4.7	4.7	4.8	4.8	5.5	5.5	5.4	5.4
H 2% (m)	3.1	5.4	5.9	5.9	6.2	6.1	6.1	6.9	6.9	6.9	6.9
T_m (sec)	5.2	7.1	7.6	7.6	7.8	7.8	7.8	8.4	8.4	8.3	8.3
T_{m-1} (sec)	5.4	7.3	7.8	7.8	8.0	8.0	8.0	8.6	8.6	8.5	8.5
N	1002	983	1029	1001	998	1003	1005	993	1000	996	1006
t (hour)	1.4	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3
Cumulative damage percentages (%) and the number of displaced stones (n)											
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.7 (1)	0.7 (1)	0.7 (1)	0.7 (1)	0.7 (1)
Red, % (n)	0 (0)	1.5 (3)	1.5 (3)	2 (4)	2.4 (5)	3.4 (7)	6.3 (13)	8.3 (17)	8.8 (18)	9.8 (20)	10.7 (22)
Blue, % (n)	0 (0)	5.2 (13)	7.2 (18)	8 (20)	8.8 (22)	9.2 (23)	10 (25)	10 (25)	11.2 (28)	11.2 (28)	11.2 (28)
Yellow, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.7 (1)
Total, % (n)	0 (0)	1.3 (16)	1.7 (21)	2 (24)	2.2 (27)	2.5 (30)	3.2 (39)	3.6 (44)	3.9 (48)	4.1 (50)	4.3 (53)

Table A.27: Model 5, Set 5

Wave Conditions at model studies in prototype values											
H_s (m)	2.1	4.0	4.3	4.5	4.7	4.6	4.5	5.3	5.3	5.3	5.1
T_s (sec)	5.5	8.0	8.6	8.6	8.7	8.8	8.9	9.3	9.6	9.7	9.5
$H_{s,5Hs}$ (m)	2.3	4.2	4.5	4.6	4.8	4.8	4.6	5.4	5.4	5.4	5.3
H 2% (m)	3.0	5.4	5.8	6.1	6.2	6.2	6.0	6.9	7.0	6.9	6.9
T_m (sec)	5.2	7.0	7.5	7.6	7.8	7.7	7.8	8.4	8.6	8.4	8.3
T_{m-1} (sec)	5.4	7.2	7.7	7.8	8.0	7.9	8.0	8.6	8.8	8.6	8.5
N	1012	1013	1013	1007	999	1020	996	993	968	985	1001
t (hour)	1.4	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3
Cumulative damage percentages (%) and the number of displaced stones (n)											
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.4 (2)	2.1 (3)	2.9 (4)	2.9 (4)	2.9 (4)
Red, % (n)	0 (0)	2 (4)	2.4 (5)	3.4 (7)	4.4 (9)	5.9 (12)	7.8 (16)	8.8 (18)	9.3 (19)	9.8 (20)	11.2 (23)
Blue, % (n)	0 (0)	3.2 (8)	4.4 (11)	6 (15)	7.2 (18)	8.8 (22)	10.4 (26)	11.6 (29)	12 (30)	12 (30)	12 (30)
Yellow, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total, % (n)	0 (0)	1 (12)	1.3 (16)	1.8 (22)	2.2 (27)	2.8 (34)	3.6 (44)	4.1 (50)	4.3 (53)	4.4 (54)	4.7 (57)

Table A.28: Model 5, Set 6

Wave Conditions at model studies in prototype values											
H_s (m)	2.1	4.1	4.4	4.5	4.7	4.6	4.7	5.3	5.4	5.3	5.1
T_s (sec)	5.6	7.9	8.6	8.5	8.9	8.8	8.9	9.5	9.6	9.5	9.7
$H_{s,5Hs}$ (m)	2.2	4.3	4.6	4.6	4.8	4.7	4.8	5.5	5.5	5.4	5.2
H 2% (m)	2.9	5.7	6.0	6.1	6.2	6.3	6.3	7.1	7.1	6.9	6.7
T_m (sec)	5.2	7.1	7.6	7.7	7.8	7.9	7.8	8.3	8.5	8.4	8.4
T_{m-1} (sec)	5.4	7.3	7.8	7.9	8.0	8.1	8.0	8.5	8.7	8.6	8.6
N	991	979	1029	993	998	990	998	997	971	991	1015
t (hour)	1.4	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3
Cumulative damage percentages (%) and the number of displaced stones (n)											
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.7 (1)	0.7 (1)	0.7 (1)
Red, % (n)	0 (0)	2 (4)	3.4 (7)	3.4 (7)	4.9 (10)	5.4 (11)	5.4 (11)	6.3 (13)	7.3 (15)	11.2 (23)	11.2 (23)
Blue, % (n)	0 (0)	2.8 (7)	6 (15)	8 (20)	9.2 (23)	9.6 (24)	10 (25)	11.2 (28)	12.4 (31)	13.6 (34)	14.4 (36)
Yellow, % (n)	0 (0)	0 (0)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)	0.4 (1)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total, % (n)	0 (0)	0.9 (11)	1.9 (23)	2.3 (28)	2.8 (34)	3 (36)	3 (37)	3.4 (42)	3.9 (48)	4.8 (59)	5 (61)

Table A.29: Model 5, Set 7

Wave Conditions at model studies in prototype values											
H_s (m)	2.0	3.8	4.2	4.1	4.4	4.4	4.3	4.9	4.9	4.9	4.8
T_s (sec)	5.5	7.9	8.5	8.5	9.0	8.9	8.9	9.8	9.9	9.9	10.0
$H_{s,5Hs}$ (m)	2.2	4.0	4.3	4.2	4.5	4.5	4.4	5.0	5.0	5.0	5.0
H 2% (m)	2.8	5.0	5.7	5.6	5.8	5.9	5.7	6.3	6.2	6.3	6.3
T_m (sec)	5.1	7.1	7.6	7.5	7.8	7.8	7.7	8.5	8.4	8.5	8.3
T_{m-1} (sec)	5.3	7.3	7.8	7.7	8.0	8.0	7.9	8.7	8.6	8.7	8.5
N	1022	981	1010	1024	1005	937	1009	986	1005	996	1009
t (hour)	1.4	1.9	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3
Cumulative damage percentages (%) and the number of displaced stones (n)											
Black, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Red, % (n)	0 (0)	0.5 (1)	1 (2)	1.5 (3)	2 (4)	2.9 (6)	2.9 (6)	5.9 (12)	5.9 (12)	5.9 (12)	6.8 (14)
Blue, % (n)	0 (0)	2.4 (6)	3.6 (9)	4.8 (12)	6 (15)	6.8 (17)	7.2 (18)	9.6 (24)	10.4 (26)	10.8 (27)	11.6 (29)
Yellow, % (n)	0 (0)	0 (0)	0.4 (1)	0.8 (2)	0.8 (2)	0.8 (2)	1.2 (3)	1.2 (3)	2 (5)	2.4 (6)	2.4 (6)
Green, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pink, % (n)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total, % (n)	0 (0)	0.6 (7)	1 (12)	1.4 (17)	1.7 (21)	2 (25)	2.2 (27)	3.2 (39)	3.5 (43)	3.7 (45)	4 (49)

APPENDIX B

IMAGES FROM MODEL STUDIES AND CALCULATIONS OF PARAMETERS

B.1 Images from Model Studies

Figure B.1: Side view of cross section

Figure B.2: Front view of cross section

Figure B.3: Side view of Model 5

Figure B.4: Top view of Model 5

B.2 Calculations of Parameters

B.2.1 Damage Parameter (S_d) Calculation from Stone Count Method

Damage parameters (S_d) are calculated by the formula of Burcharth et al. (2006). The number of displaced stones in the active zone is converted to the damage parameter (S_d) by this equation which is described in Chapter 2. Number of displaced stones in active zone (N), porosity (n), diameter of armourstones (D_{n50}) and length of the trunk section (X) are used as an inputs in this equation B.1.

$$S_d = \frac{N \, . \, D_{n50}}{(1-n) \, . \, X} \tag{B.1}$$

Sample example of damage parameter (S_d) calculation for Model 1, Set 1 is given below.

Example: In the last wave series for Set 1 at Model 1, the number of displaced stones at active zone was 132, the porosity was 0.43, diameter of armorstones was 4.5 cm and length of the trunk section was 150 cm. The damage parameter (S_d) which was calculated from these inputs was 6.9.

N = 132 D_{n50} = 4.5 cm n = 0.43 X = 150 cm, then the calculated S_d = 6.9 for Model 1, Set 1.

B.2.2 Calculation for Plunging Wave Condition

All of the wave conditions in this study were plunging. The most critical wave condition was occurred at the last wave series of Model 5, Set 7. The calculated value of the surf similarity parameter (Eq.B.2) was close to the critical value of the surf similarity parameter (Eq.B.3). However, it was still under the value of critical surf similarity parameter which was plunging wave condition. The equations are given in Chapter 2.

H_s = 4.81 m $T_{m-1,0}$ = 8.52 s $\tan\alpha$ = 0.5 c_{pl} = 8.4 c_s = 1.3 P = 0.4

$$\xi_{s-1,0} = \tan\alpha \,/\, \sqrt{(2\pi/g).H_s/{T_{m-1,0}}^2} \tag{B.2}$$

$$\xi_{cr} = \left[\frac{c_{pl}}{c_s}\, P^{0.31}\sqrt{\tan\alpha}\right]^{\frac{1}{P+0.5}} \tag{B.3}$$

$\xi_{s-1,0}$ = 2.424 and ξ_{cr} = 3.945 where $\xi_{s-1,0} < \xi_{cr}$, plunging wave condition

B.2.3 Calculation of Total Number of Waves (N_t) in Van der Meer Damage Development Method

The sample example of calculation of the total number of waves (N_t) according to Van der Meer damage development method (Figure B.5) is given for the last wave series of Model 1, Set 1. Van der Meer damage development method is described in Chapter 2.

The damage parameter (S_d), which is obtained from the previous wave series (H_s = 7.52 m, $T_{m-1,0}$ = 11.09 s) was 2.43 (S_d = 2.43). This damage parameter is calculated by Van der Meer (Shallow water, plunging) and Van der Meer damage development method. The N_1' value of the last wave series is calculated by Van der Meer (shallow water, plunging) (Eq.B.4), which was developed by Van Gent et al. (2004), by using the the damage parameter of the previous wave series with the initial wave conditions (S_d = 2.43). Then, the total number of waves is calculated by adding the N_1' with the initial number of waves of the last wave series. The equations are given in Chapter 2.

$$\frac{H_s}{\Delta D_{n50}} = c_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \left(\xi_{s-1,0}\right)^{-0.5} \qquad \text{(B.4)}$$

H_s= 7.76 m $\xi_{s-1,0}$= 1.02 m $H_{2\%}$= 9.52 m S_d= 2.43

P= 0.4 c_{pl}= 8.4 D_{n50}= 1.5 m Δ= 1.7

Then the calculated value of the N_1' is equal to 3654 (N_1'= 3654). Then N_t is equal to:

N_t = N_1' + $N_{2;}$ N_1'=3654 and N_2=3989 then N_t=7643

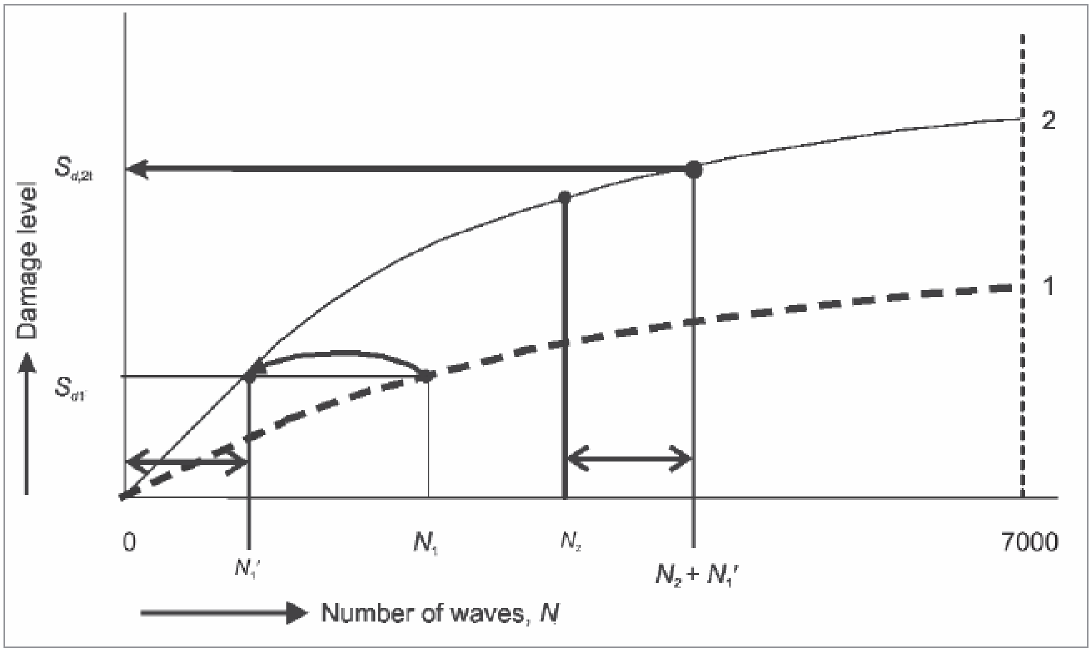

Figure B.5: Illustration of method to assess cumulative damage (Rock Manual,2007)

B.3 Summary of Model Parameters

Table B.1: Summary of Model Parameters

Model	water depth at toe (h)		slope angle	stone weight (W_{50})	
	p (m)	m (cm)	α	p (tons)	m (grams)
1	14	44	1:5	8 - 10	200 - 250
2	11	33	1:5	6 - 8	150 - 200
3	11	33	1:5	6 - 8	150 - 200
4	11.3	34	1:3	8 - 10	200 - 250
5 - 1	14	44	1:2	6 - 8	150 - 200
5 - 2	13.5	41	1:2	8 - 10	200 - 250
*h = water depth at toe (m) *α= slope angle * W_{50} = armorstone weight (tons, grams)				p = prototype m = model	