A CASE STUDY ON THE STABILITY OF BERM TYPE COASTAL DEFENSE STRUCTURES

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ABSTRACT

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Coastal defense structures have primary importance from obtainabilty of resources and benefits served by the coastal regions point of view. However, the construction of coastal defense structures demand a high amount of investment. Therefore, in order to reduce the risk of collapse of these structures, model studies should be carried during the design process.

In this study, model investigations were carried out on Eastern Black Sea Highway Project regarding the serviceability and damage thus stability parameters. 5 different models were constructed as berm type rubble-mound breakwaters using Van Der Meer's approach and berm design guidelines, with a scale of 1/31.08 and they were tested both for breaking and non-breaking waves. The experiments took place in the Coastal and Harbor Engineering Laboratory of the Middle East Technical University, Civil Engineering Department.

The models were constructed and tested with different berm widths and armor stone sizes forming the back armor layer in order to examine the effect of these design parameters on the stability and serviceability of the coastal defense structure to obtain the optimum alternative cross-section.

Cumulative damage was minimum for the cross-section constructed with berm width 15 m assigning the width of the prototype. Water spray and run-up values were also not significant.

The test results were confirming with Van Der Meer design approach.

Keywords: Rubble-mound Breakwater, Damage, Stability, Berm, Armor Stone

ÖZ

BASAMAK TİP KIYI KORUMA YAPILARININ DENGE DURUMLARININ UYGULAMALI ARAŞTIRILMASI

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Kıyı alanlarının sunduğu kaynaklar ve faydaların elde edilebilirliği konusunda kıyı koruma yapıları birincil öneme sahiptir. Ancak kıyı koruma yapılarının inşaatı büyük bir yatırımı gerektirmektedir. Bu nedenle bu yapıların yıkılmasını önlemek için tasarım sürecinde model deneyleri yapılmalıdır.

Bu çalışmada denge, güvenlik ve kullanılabilirlik gereksinimleri göz önüne alınarak Doğu Karadeniz Sahil Yolu Projesi model deneyleriyle test edilmiştir. 5 farklı basamak tipi taş dolgu dalgakıran modeli 1/31.08 ölçeğiyle inşa edilmiş ve bu modeller kırılan ve kırılmayan dalga etkileri altında test edilmiştir. Deneyler, Orta Doğu Teknik Üniversitesi, İnşaat Mühendisliği Bölümü, Kıyı ve Liman Mühendisliği Laboratuvarı'nda gerçekleştirilmiştir.

Tasarım parametrelerinin kıyı koruma yapısının dayanım ve faydalanılabilirlik özellikleri üzerindeki etkisini inceleyebilmek için, modeller farklı basamak genişlikleri ve taş büyüklükleri ile inşa edilmiş ve test edilmiştir.

Minimum artan hasar değerleri 15 metre basamak genişliğine sahip kesit üzerinde gözlenmiştir. Su sıçrama ve tırmanma değerleri de bu kesit için belirgin değildir.

Test sonuçları Van der Meer yaklaşımıyla tutarlılık göstermiştir.

Anahtar kelimeler: Taş Dolgu Dalgakıran, Hasar, Denge, Basamak, Anroşman

Dedicated to my family and my husband.

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α	angle between the armor face and the horizontal
ξ_m	surf similarity parameter
λ_L	length scale
λ_T	time scale
λ_V	volume scale
λ_W	weight scale
γ_r	specific weight of rock
γ_w	specific weight of water
Δ	relative density of rock in water
d	water depth
D_{50}	diameter value for 50% of number of stones
F_r	Froude number
H	wave height
H_s	deep water significant wave height
$H_{D=0}$	design wave height for zero damage
H_o/L_0	wave steepness
K_D	stability coefficient
m	sea bed slope
N_S	stability parameter
N_W	number of waves that attack to structure in storm duration
P	encounter probability
S_a	damage level

P_b	overall porosity of the breakwater
T	wave period
Tr	return period of design wave
T_S	significant wave period
W	weight of individual armor unit
B_b	berm width
$D_{a,50}$	equivalent cube length of median rock
$D_{a,85}$	85% of the stones have a diameter less than D_{85}
$D_{a,15}$	15% of the stones have a diameter less than D15
P_r	fraction of the rounded stones
G	gravitational force
B	buoyancy force
R	reaction force between armor units
P	wave pressure
D	diameter of armor unit
Sr	relative density
U	water particle velocity
Hb	breaker wave height
N1	number of dislocated armor stones
N	number of total armor stones within the specified layer

CHAPTER 1

INTRODUCTION

Earth surface area is covered by the seas with a percentage of 75% . This means that humankind should use and handle the resources which are obtainable from the seas covering the earth. In order to capture this advantage, people had been always settling in the places that are nearby or by the sea. This resulted in the need of coastal defense structures. Coastal defense structures serve not only for handling the resources of the coastal regions but also for sheltering, transporting and etc. Especially, the coastal structures are built to protect coastal facilities, such as harbors and highways from severe wave action.

Breakwaters are the mostly used type of coastal defense structures. There are also different types of breakwaters. These are briefly classified as detached, reef, floating, vertical-front, piled and rubble-mound breakwaters.

In Turkey rubble-mound breakwaters are mostly used due to some restrictions and availabilities. The selection of type of breakwater depends on the availability of armor units, wave climate, depth of construction, foundation conditions, easiness of maintenance and the simplicity of the construction method.

Design and construction processes of coastal defense structures have to be carried out carefully, since the opposing forces are the forces of nature, which can not be underestimated. The design of these structures should be done considering stability, serviceability and safety as well as economy.

In order to achieve a safe, stable, economic and serviceable coastal protection, it is always recommended that the coastal defense structures must be designed by coastal engineers considering all vital parameters and the constructions must be carried out under their supervision.

The construction of coastal protection structures demand big amounts of investments. Therefore, proper design is important from both contractor and client point of view. To design a stable, safe, economic and serviceable coastal protection structure contemporary design methods and model investigations are of vital importance. Model studies, in most cases lead to the most effective and safest design by optimizing the design where the total cost is kept as minimum but efficiency and stability increased to maximum. The model investigations also require a certain cost, but this cost is almost negligible when compared to the economic benefit achieved and the total cost of the structure.

In Turkey some regions are critical to construct coastal defense structures due to the effect of bathymetry, severe wave climate, coastal topography and agricultural conditions. Eastern Black Sea Region is the hardest place to construct coastal defense structures since the topographic conditions by the coastal line and wave climate conditions of Black Sea are very rough. Therefore, special care must be given to design of coastal protection structures that are to be constructed along the Black Sea Coasts.

However, when the past events took place along the Black Sea Coastal Line are analyzed, negligence in the design of coastal protection structures is barely faced. There is an ongoing project named as Eastern Black Sea Coastal Highway Project. Some collapses also took place at some branches of this project. As a result In the Middle East Technical University, Civil Engineering Department, Coastal and Harbor Engineering Laboratory, a research on rubble- mound coastal protection structure of the Eastern Black Sea Coastal Highway Project had been started by Dedeoğlu R. (2003) and Taşkıran İ. (2003) including the model studies on the proposed cross-section by Karayolları Genel Müdürlüğü and on alternative cross-sections designed by the researchers.

Our model studies were carried out starting from the last model applied by Dedeoğlu R. and Taşkıran İ. in order to design most economic and safe cross-section. Selection of the design wave characteristics from the long-term and

short-term wave statistics, checking the breaking and non-breaking wave conditions at the construction depth of the structure were done for the selected Giresun region as the basic steps in the design procedure. In our country due to availability of rock material and simplicity of the construction method, rubble- mound coastal protection structures are preferred.

In this study a contemporary design method named Van Der Meer Method (CEM, 2003) was used alternative to Hudson Method (CEM, 2003). This method is based on dynamic stability resulting in smaller armor weights. In addition, a new type of rubble-mound breakwaters, berm breakwater design was carried, which is in accordance with Van Der Meer design method.

Model with most optimum safety, stability, serviceability, and economy was determined from five tested model cross-sections.

In chapter 2, the methods used for the design of models are summarized. In addition, a brief summary on breakwater types was given.

In chapter 3, cross-sectional details of the models with model scale and wave flume characteristics are given. Within this chapter, determination of wave properties and model scale is also discussed in detail.

In Chapter 4, inputs of the experiments, measurements and results of the each set of experiments carried out for each model are presented in detailed tables and figures. These tables and figures are also explained considering damage criteria.

In Chapter 5, conclusion and discussion is presented and future studies are recommended.

CHAPTER 2

LITERATURE REVIEW

Coastal regions offer several benefits to the humankind living nearby the sea. In order to take the advantage of using these resources, construction of coastal defense structures is necessary. Since the construction process of the rubble mound breakwaters and other coastal defense structures are expensive and hard because of the fact that the opposing forces are the forces of nature, which cannot be underestimated, design engineers have to carry a comprehensive study in order to determine most optimum conditions for the structure. These conditions are classified as safety, economy and serviceability.

There are several types of breakwaters. Before starting the design concept on rubble mound breakwaters, it is appropriate to summarize the types of breakwaters (CEM, 2003).

2.1 Breakwater Types

2.1.1 Detached breakwaters

Detached breakwaters are small, relatively short, non-shore connected near shore breakwaters with the principal function of reducing beach erosion. They are built parallel to the shore just seaward of the shoreline in shallow water depths. Multiple detached breakwaters spaced along the shoreline can provide protection to substantial shoreline frontages. The gaps between the breakwaters are in most cases on the same order of magnitude as the length of one individual structure.

Each breakwater reflects and dissipates some of the incoming wave energy, thus reducing wave heights in the lee of the structure and reducing shore erosion. Beach material transported along the beach moves into the sheltered area behind the breakwater where it is deposited in the lower wave energy region. The near shore wave pattern, which is strongly influenced by diffraction at the heads of the structures, will cause salient and sometimes tombolos to be formed, thus making the coastline similar to a series of pocket beaches. Once formed, the pockets will cause wave refraction, which helps to stabilize the pocket-shaped coastline.

Detached breakwaters are normally built as rubble-mound structures with fairly low crest levels that allow significant overtopping during storms at high water. The low-crested structures are less visible and help promote a more even distribution of littoral material along the coastline.

Optimizing detached breakwater designs is difficult when large water level variations are present, as is the case on coastlines with a large tidal range or in portions of the Great Lakes, which may experience long-term water level fluctuations.

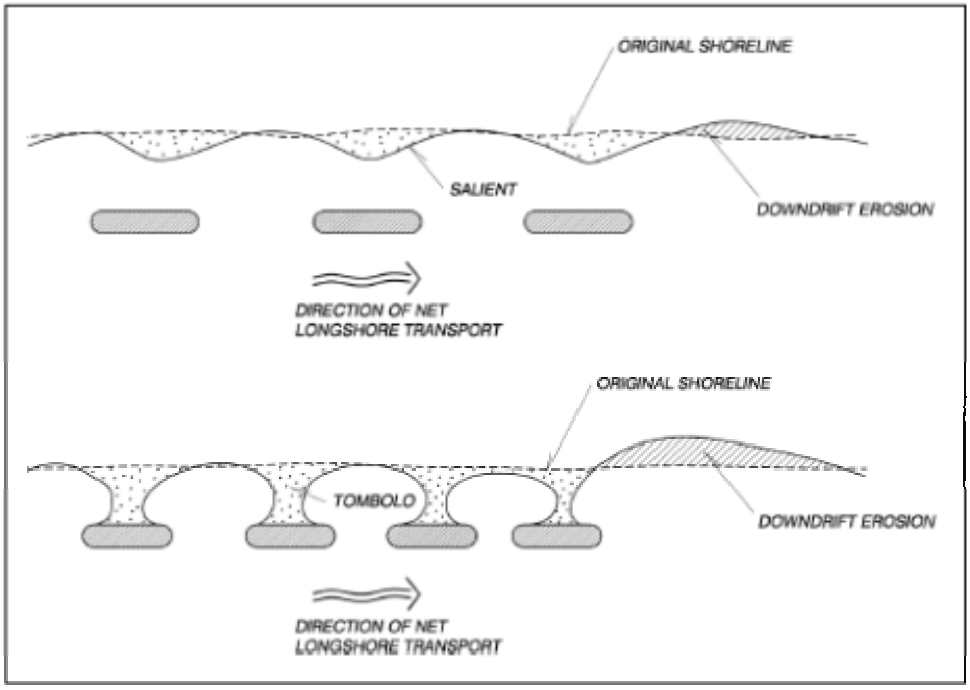

Figure 2.1 Typical beach configurations with detached near shore breakwaters (CEM, 2003)

2.1.2 Reef breakwaters

Reef breakwaters are coast-parallel, long or short submerged structures built with the objective of reducing the wave action on the beach by forcing wave breaking over the reef. Reef breakwaters are normally rubble-mound structures constructed as a homogeneous pile of stone or concrete armor units. The breakwater can be designed to be stable or it may be allowed to reshape under wave action. Reef breakwaters might be narrow crested like detached breakwaters in shallow water or, in deeper water; they might be wide crested with lower crest elevation like most natural reefs that cover a fairly wide rim parallel to the coastline. Besides triggering wave breaking and subsequent energy dissipation, reef breakwaters can be used to regulate wave action by refraction and diffraction. Reef breakwaters represent a no visible hazard to swimmers and boats.

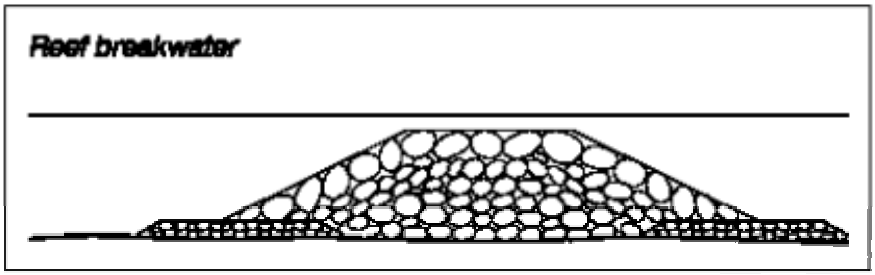

Figure 2.2 Example of a reef breakwater (CEM, 2003)

2.1.3 Floating breakwaters

Floating breakwaters are used in protected regions that experience mild wave climates with very short-period waves. For example, box-shaped reinforced concrete pontoons are used to protect marinas in sheltered areas. Floating docks affixed to piles are also used in marinas.

2.1.4 Vertical-front breakwaters

Vertical-front breakwaters are another major class of breakwater structures. The basic structure element is usually a sand filled caisson made of reinforced concrete, but block work types made of stacked precast concrete blocks are also used. Caisson breakwaters might be divided into the following types:

Conventional, i.e., the caisson is placed on a relatively thin stone bedding layer

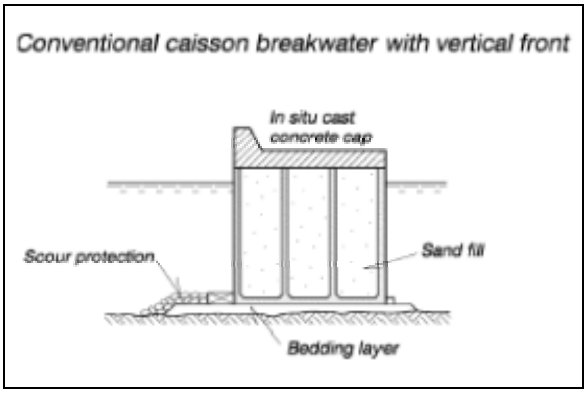

Figure 2.3 Cross-section of Conventional Caisson Breakwater (CEM, 2003)

Vertical composite, i.e., the caisson is placed on a high rubble-mound foundation. This type is economical in deep waters. Concrete caps may be placed on shore-connected caissons.

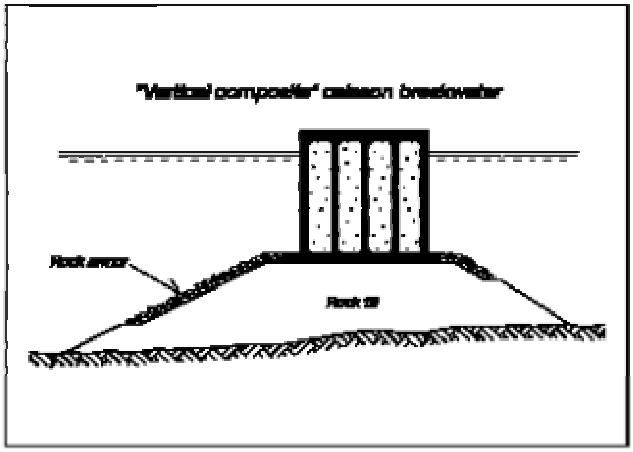

Figure 2.4 Cross-section of Vertical Composite Breakwater (CEM, 2003)

Horizontal composite, i.e., the front of the caisson is covered by armor units or a rubble-mound structure (multilayered or homogeneous). This type is typically used in shallow water; however, there have been applications in deeper water where impulsive wave pressures are likely to occur. The effects of the mound are reduction of wave reflection, wave impact, and wave overtopping.

Depending on bottom conditions, a filter layer may be needed beneath the rubble-mound portion.

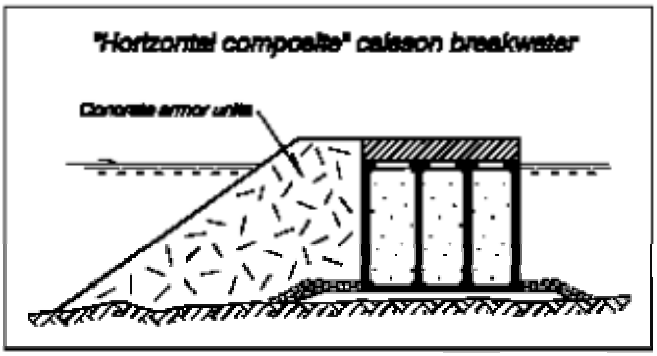

Figure 2.5 Cross-section of Horizontal Composite Breakwater (CEM, 2003)

Sloping top, i.e., the upper part of the front wall above still-water level is given a slope with the effect of a reduction of the wave forces and a much more favorable direction of the wave forces on the sloping front. However, overtopping is larger than for a vertical wall of equal crest level.

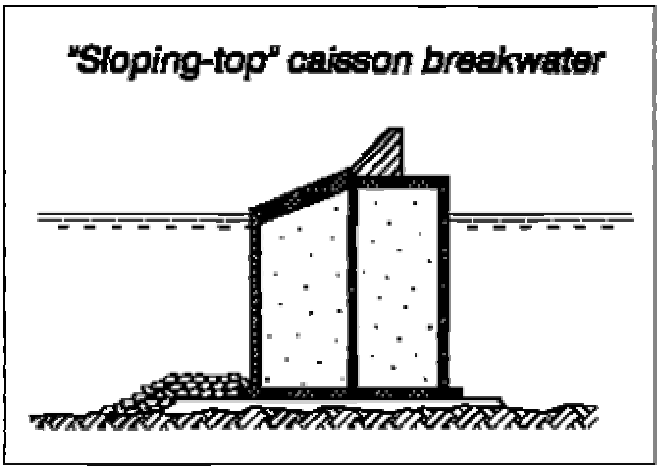

Figure 2.6 Cross-section of Sloping-top Caisson Breakwater (CEM, 2003)

Perforated front wall, i.e., the front wall is perforated by holes or slots with a wave chamber behind. Dissipation of energy reduces both wave forces on the caisson and wave reflection. Caisson breakwaters are generally less economical than rubble-mound structures in shallow water. Moreover, they demand stronger seabed soils than rubble structures. In particular, the block

work type needs to be placed on rock sea beds or on very strong soils due to very high foundation loads and sensitivity to differential settlements.

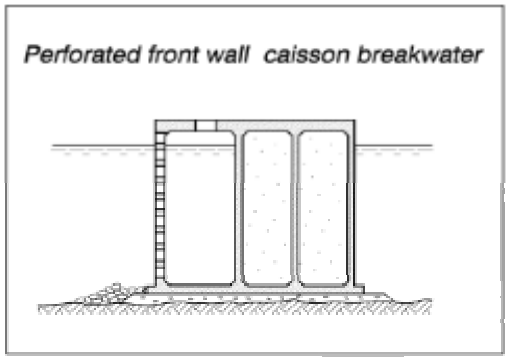

Figure 2.7 Cross-section of Perforated Front Wall Caisson Breakwater (CEM, 2003)

2.1.5 Piled breakwaters

Piled breakwaters consist of an inclined or vertical curtain wall mounted on pile work. This type of breakwater is applicable in less severe wave climates on sites with weak and soft subsoil.

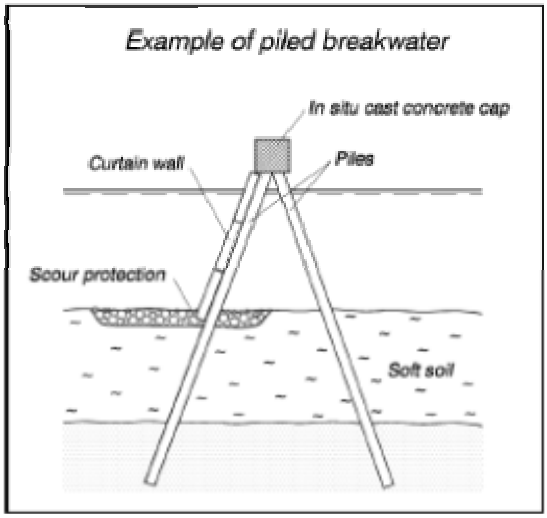

Figure 2.8 Cross-section of Piled Breakwater (CEM, 2003)

2.1.6 Rubble-mound breakwaters

Rubble-mound breakwaters are the most commonly applied type of breakwaters. In its most simple shape, it is a mound of stones. However, a homogeneous structure of stones large enough to resist displacements due to wave forces is very permeable and might cause too much penetration not only of waves, but also of sediments if present in the area. Moreover, large stones are expensive because most quarries yield mainly finer material (quarry run) and only relatively few large stones. Consequently, the conventional rubble-mound structures consist of a core of finer material covered by big blocks forming the so-called armor layer. To prevent finer material being washed out through the armor layer, filter layers must be provided. The filter layer just beneath the armor layer is also called the under layer. Structures consisting of armor layer, filter layer(s), and core are referred to as multilayer structures. The lower part of the armor layer is usually supported by a toe berm except in cases of shallow- water structures. Figure 2.9 shows a conventional type of rubble-mound breakwater. Concrete armor units are used as armor blocks in areas with rough wave climates or at sites where a sufficient amount of large quarry stones is not available.

The front slope of the armor layer is in most cases straight. However, an S-shaped front or a front with a horizontal berm might be used to increase the armor stability and reduce overtopping. For these types of structures, optimization of the profiles might be difficult if there are large water level variations.

Superstructures can serve several purposes, e.g., providing access for vehicles, including cranes for maintenance and repair, and accommodation of installations such as pipelines. The armor units in conventional multilayer structures are designed to stay in place as built, i.e., the profile remains unchanged with displacement of only a minor part of the armor units.

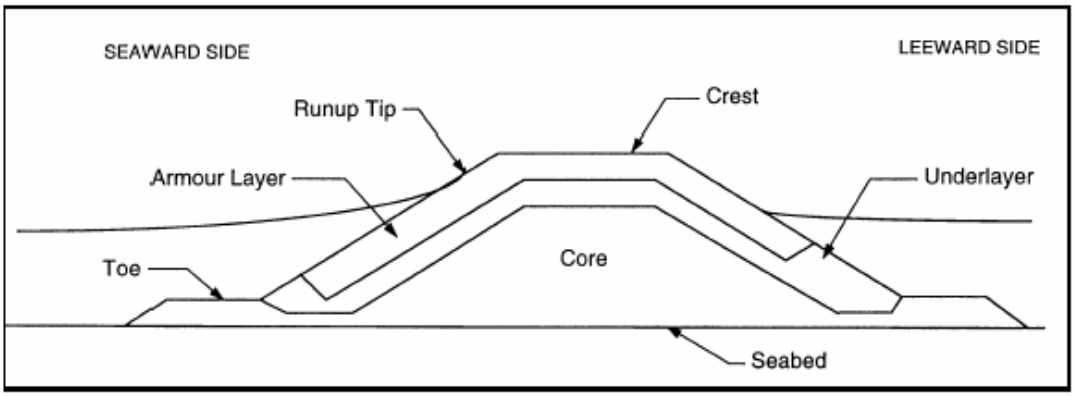

Figure 2.9 Cross-section of typical multi-layer rubble-mound breakwater (Palmer, 1998)

Reshaping rubble-mound breakwaters is based on the principle of natural adjustment of the seaward profile to the actual wave action, as illustrated by Figure 2.10. In this way the most efficient profile in terms of armor stability (and possibly minimum overtopping) is obtained for the given size and quantity of armor stone.

Because of natural reshaping, the structure can be built in a very simple way by first dumping the core material consisting of quarry run, and then dumping the armor stones in a berm profile with seaward slope equal to the natural angle of repose for the stone material. Due to the initial berm profile, this type of structure is also known as a berm breakwater. (Figure 2.11)

Berm breakwaters are constructed with a horizontal berm at or near the SWL, with the berm occupying the full width of the armor layer. This is thought to give lower internal velocities than a conventional armor layer and so smaller armor, either rock or riprap, can be used. The seaward profile retains its original overall shape, but the berm compacts under wave action into a more stable form (MacIntosh and Baird, 1987).

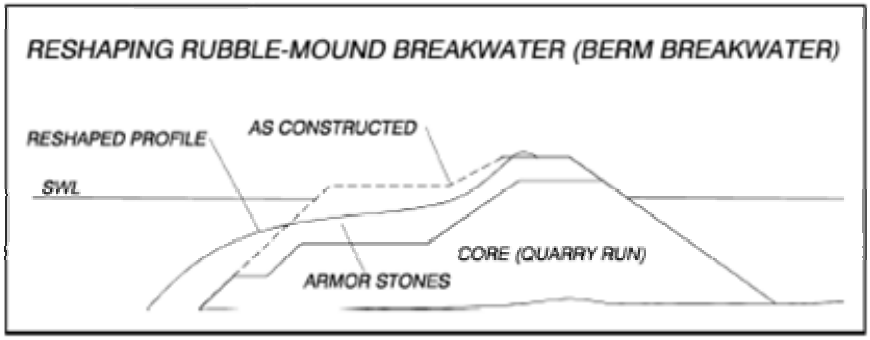

Figure 2.10 Reshaping rubble mound breakwater (CEM, 2003)

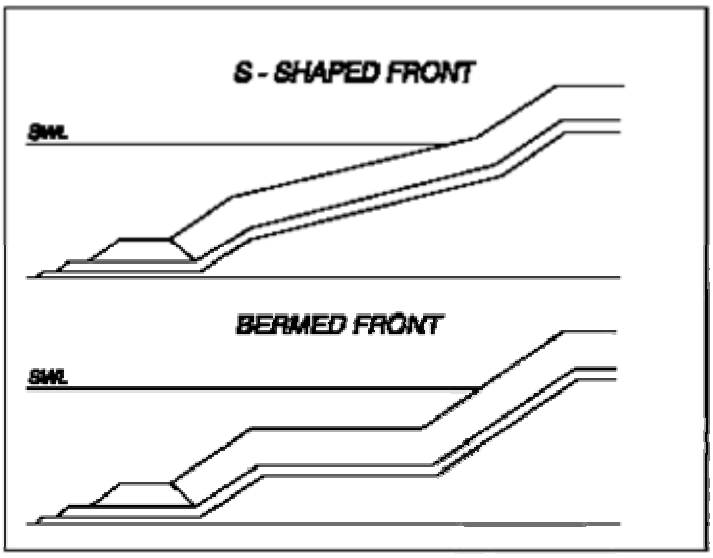

Figure 2.11 Cross-section of Berm Breakwater (CEM, 2003)

In Turkey, due to the obtain ability of natural armor stones and the easiness of maintenance and construction of rubble-mound type of breakwaters, rubble-mound breakwaters are the mostly used type of coastal defense structures.

A well-known formula for the design of armor units for breakwaters is the Hudson formula. This formula is quite old, and has severe limitations. There are several forces acting on breakwaters. These forces acting on breakwaters are deadweight, wave forces (hydraulic pressure and suction), forces of inertia, earth pressure (internal earth fill, earth fill behind the structure), internal

pressure due to water level changes and earthquake forces. Formula is based on a balance of forces to ensure that each armor unit maintains its stability under the forces exerted by a wave attack. The formation of Hudson Formula is shown below as a systematic manner.

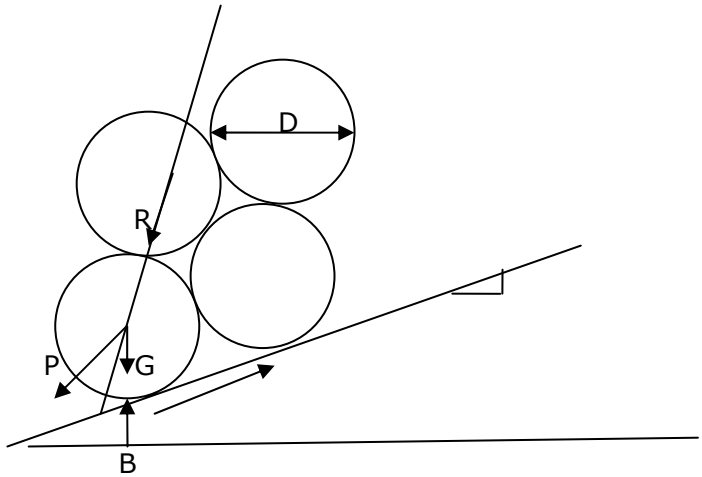

Figure 2.12 Primary Forces Acting on Armor Stones

where;

G: Gravitational force
B: Buoyancy force
R: Reaction force between armor units
P: Wave pressure
D: Diameter of armor unit

In order to find the net vertical force neglecting friction and reaction forces, buoyancy force is subtracted from gravity force and the equation shown below is obtained:

$$G-B= (S_r-1) *\gamma_w*D^3 \qquad (2.1)$$

Where;

S_r= Relative density= $\gamma_s/\gamma_w= \gamma_{stone}/\gamma_{water}$

When wave pressure is formulized, the equation below is obtained:

$$P \approx \rho U^2 D^2 \tag{2.2}$$

where;

D: Diameter of armor unit
U: Water particle velocity

Critical force combination is formed by introducing net vertical and wave pressure forces. It is the first step of the formulation of Hudson Formula. This formulation is shown step by step as follows (Hudson, 1959):

$$C = \frac{G - B}{P} \tag{2.3}$$

$$C = \frac{(S_r - 1)\gamma_w D^3}{\rho U^2 D^2} = \frac{(S_r - 1)gD}{U^2} \tag{2.4}$$

$$In\, case\, of\ breaking\ waves : U \approx C \approx \sqrt{gd_b} \approx \sqrt{gH_b}$$

$$C \approx \frac{(S_r - 1)gD}{gH} \Rightarrow D \approx \frac{H}{(S_r - 1)} C \tag{2.5}$$

$$Weight\, of\ armor\ stones : W \approx \gamma_s D^3$$

$$W \approx \frac{\gamma_s H^3}{(S_r - 1)^3} C \tag{2.6}$$

The final form of the Hudson Formula is:

$$W = \frac{\gamma_s H^3 \tan\alpha}{(S_r - 1)^3 K_D} \tag{2.7}$$

where;

W = median weight of armor unit

γ_s = saturated surface dry unit weight of armor unit

H = design wave height

K_D = stability coefficient (shape factor)

$S_r = \rho_a/\rho_w$ (generally Δ=2.65 for quarry stone, 2.4 for concrete)

α = angle of structure slope

As the Hudson equation is an old approach, it has some restrictions and uncertainties. In the Hudson equation stability coefficient, K_D cannot exceed the values given in Table 2.1 (Coastal Engineering Manual, 2003).

Table 2.1 K_D Values

		Structure Trunk			Structure Head		
		K_D[b]			K_D		Slope
Armor units	n	Placement	Breaking Wave	Non-breaking wave	Breaking Wave	Non-breaking wave	cotα
Quarry stone	2,0	Random					
Smooth rounded	>3	Random	1,2	2,4	1,2	1,9	1,5 to 3,0
Smooth rounded	1,0	Random	1,6	3,2	1,4	2,3	(c)
Rough angular	2,0	Random[d]	(d)	2,9	(d)	2,3	(c)
Rough angular	>3	Random	2,0	4,0	1,9 1,6 1,3	3,2 2,8 2,3	1,5 2,0 3,0
Rough angular	2,0	Special [e]	2,2	4,5	2,1	4,2	(c)
Rough angular	2,0	Special [e]	5,8	7,0	5,3	6,4	(c)
Parallelepiped		Random	7,0-20,0	8,5-24	-	-	(c)
Tetrapod					5,0	6,0	1,5
Quadripod 2	2,0	Random	7,0	8,0	4,5	5,5	2,0
Tribar	2,0	Random	9,0	10,0	3,5 8,3 7,8 6,0	4,0 9,0 8,5 6,5	3,0 1,5 2,0 3,0
Dolos	2,0	Random	15,0	31,0	8,0 7,0	16,0 14,0	2[b] 3,0
Modified Cube	2,0	Random	6,5	7,5	-	5,0	(c)
Hexapod 2	2,0	Random	8,0	9,5	5,0	7,0	(c)
Toskanes	2,0	Random	11,0	22,0	-	-	(c)
Tribar	1,0	Uniform	12,0	15,0	7,5	9,5	(c)
Quarrystone (KRR) Graded angular	-	Random	2,2	2,5	-	-	-

(a) n is the number of wits comprising the thickness of the armor layer.

(b) Applicable to slopes ranging from 1 on 1.5 to 1 on 5.

(c) Until more information is available on the variation of K_D value with slope, the use of K_D should be limited to slopes ranging from 1 on 1.5 to 1 on 3. Some armor units tested on a structure head indicate a KD slope dependence.

(d) The use of a single layer of quarry stone armor units subject to breaking waves is not recommended, and only under special conditions for non-breaking waves. When it is used, the stone must be placed carefully.

(e) Special placement with long axis of stone placed perpendicular structure face.

(f) Long slab-like stone with the lond dimension about three times its shortest dimension.

(g) Refers to no-damage criteria (~5% displacement, rocking, etc); if no rocking (<2 percent) is desired, reduce K_D 50 percent.

(h) Stability of dolos on slopes steeper than 1 on 2 should be substantiated by site-specific model tests.

NOTE: Breaking wave stability coefficients for stone and dolos were developing using a 1V:10H foreslope.

The damage coefficient K_D accounts for all variables other than structure slope, wave height, and the specific gravity of water at the site. These variables include:

1) shape of armor units,
2) number of layers of armor units,
3) manner of placing of armor units,
4) surface roughness and sharpness of edges of armor units,
5) type of wave attacking structure (breaking or non-breaking),
6) part of structure (trunk or head),
7) angle of incidence of wave attack,
8) model scale,
9) size and porosity of under layer material,
10) core height relative to still-water level,
11) crown elevation above still-water level relative to wave height,
12) crest width.

Crest height is calculated with the logic that it prevents minor wave overtopping. The structure is designed satisfying the conditions that uniform armor units are ranging between 0.75W and 1.25W and uniform slopes ranging between 1:1.5 and 1:3 are used. In addition to these restrictions, also the specific weight of armor unit is restricted to the values between 1.9 t/m^3 and 2.9 t/m^3. On the other hand there are some parameters which are not taken into

consideration in Hudson equation. These are incident wave period, type of breaking, structure permeability and duration of storm (i.e. number of waves). Allowable damage level is also not considered since Hudson scheme assumes no damage criterion (i.e.0-5% damage).

It is clear that the reliability of the Hudson formula is rather low. This is caused by the fact that a number of essential parameters are not included in this formula. Because of these problems, Van Der Meer had developed a new stability formula (1987) (which is presently the recommended formula for the design of breakwater armor (PIANC, 1992). In this formula incident wave characteristics and many other parameters have been included, as well a clear distinction between plunging waves and surging waves.

This equation is presented as, (CEM, 2003);

$$N_s = \frac{H_S}{\Delta D_{50}} = 6.2 P_b^{0.18} \left(\frac{S_a}{\sqrt{N_w}} \right)^{0.2} \xi_m^{-0.5} \quad \text{(for plunging waves)} \quad (\xi_m < \xi_{mc}) \qquad (2.8)$$

$$N_s = \frac{H_s}{\Delta D_{50}} = 1.0 P_b^{-0.13} \left(\frac{S_a}{\sqrt{N_w}} \right)^{0.2} \cot\alpha^{0.5} \xi_m^{P_b} \quad \text{(for surging waves)} \quad (\xi_m > \xi_{mc}) \qquad (2.9)$$

The relationship between slope angle α, wave height H and offshore wave length L_0 can be expressed in terms of the Surf Similarity Parameter (ξ_m) or Iribarren Number (Ir) given by:

$$\xi_m = \left(\frac{H_0}{L_0} \right)^{-0.5} * tg\alpha \quad \text{and} \quad \xi_{mc} = \left(6.2 P^{0.31} (tg\alpha)^{0.5} \right)^{1/P+0.5} \qquad (2.10)$$

$$D_{50} = \frac{H_{des}}{\Delta N_s} \qquad (2.11)$$

$$\xi_m = \frac{tg\alpha}{\sqrt{s_m}} \qquad (2.12)$$

where,

H_s: Significant wave height in front of the breakwater
D_{50}: Equivalent cube length of median rock
Δ: Relative density of rock in water
N_s: Stability parameter
P_b: Overall porosity of the breakwater
S_a: Damage level
N_w: Number of waves that attack the structure in storm duration
ξ_m: Surf similarity parameter
α: Angle between armor face and the horizontal
S_m: Steepness of wave

By including the number of waves that attack the structure during a storm, the effect of wave period is imposed into the formula. Proper model studies are very important for the structures designed by this methodology, since there are still uncertainties in the formula.

When the new developments in the coastal engineering field of researches are studied, a new alternative to conventional rubble mound breakwaters is faced. This new type of rubble mound breakwaters is the berm type breakwater. The main starting point of the berm breakwater design is constructing the whole cross section with the same armor unit sizes and leaving it under the wave action to obtain the final s-shaped structure satisfying the dynamic stability criterion. During the last decades, the berm breakwater has proved to be an advantageous construction for sheltering harbors from the rough sea. Due to the high level of energy dissipation in the berm and the dynamic stability logic behind berm type breakwater, the stone weights can be significantly reduced compared to the stone weights used for conventional rubble mound breakwaters.

Since the early 1980's, the berm breakwater design concept is under development, primarily with the aid of physical modeling studies. When the berm width is increased to a sufficiently large value not larger than (B=L/4), the water flowing down from the top slope is not allowed to run off the berm completely before the next wave has broken on the lower slope and is running up. Therefore, a slug of water remains on the berm to offer resistance to the oncoming run-up. The design of berm breakwaters is following different

procedures in different countries. There has been no design equation or firm design criteria set for berm breakwaters similar to design equations for conventional breakwaters. However, as an accepted conventional criteria berm width was taken as B=L/4 in the design. In the design of berm type breakwaters Van Der Meer equations must be used with the combination of proposed equations by Hall (1993) that give the berm widths. These equations are given below as:

$$B_b = D_{a,50}\left[K_b + 7.5\left(\frac{D_{a,85}}{D_{a,15}}\right) - 1.1\left(\frac{D_{a,85}}{D_{a,15}}\right)^2 + 6.1P_r\right] \tag{2.13}$$

Where,

$$K_b = -10.4 + 0.5\left(\frac{H_s}{\Delta_a D_{a,50}}\right)^{2.5} \tag{2.14}$$

Here,

B_b: berm width
$D_{a,50}$: equivalent cube length of median rock
$D_{a,85}$: 85% of the stones have a diameter less than D_{85}
$D_{a,15}$: 15% of the stones have a diameter less than D_{15}
P_r: fraction of the rounded stones
H_s: significant wave height in front of the breakwater
Δ_a: relative density of rock in sea water

In conclusion, berm width could be designed between the values as B_b to B=L/4. For this study, for the design wave conditions, L/4 gives 15 m. and the B calculated for 2.13 gives 7 m. Therefore, in the experiments the berm was taken between the values as 7-15 meters.

In design of rubble-mound coastal defense structures, an other important parameter that should be taken into consideration is the toe protection. The design of armor units of toe layer is based on two main topics, which are the field experience and the primary armor weight. It is proposed that weight of toe armor should be at least one-tenth the primary armor weight. When toe protection is used on a structure being constructed on an erodible bottom

material, adequate thickness and gradations of filter or bedding layers need to be incorporated into the design to prevent the leaching of foundation material. Failure to design of these layers could result in the ultimate failure of the entire structure.

A toe structure of placed armor units, often rock, provides direct support of the armor layer and protects the seabed against a slip circle failure. (Palmer, 1998) Therefore, during the design process of rubble-mound coastal defense structures, it has vital importance to design the toe support of the structure.

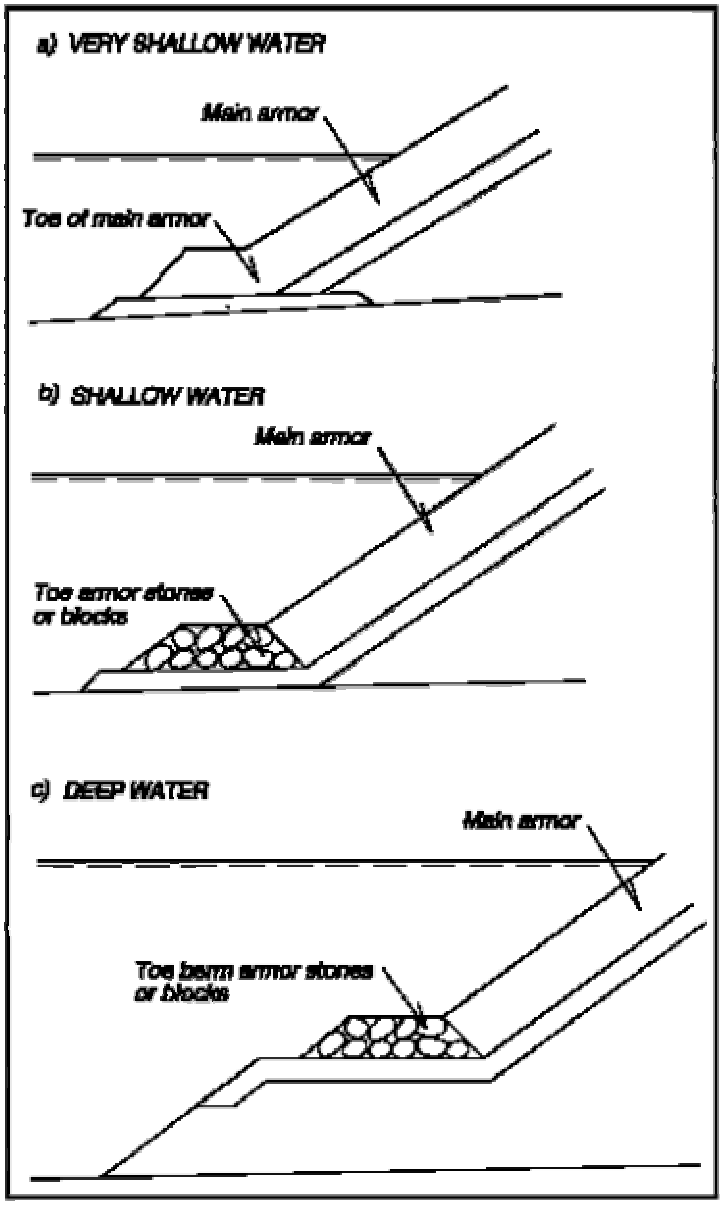

Figure 2.13 Typical Toe and Toe berm Solutions in Rubble-mound Breakwater Design (CEM, 2003)

CHAPTER 3

MODEL STUDIES

3.1 Aim of the Model Studies

Construction process of coastal protection structures are very expensive and difficult. In order to reduce the failure risk of these structures, it is very important to make model investigations according to the given design specifications before the construction process starts. On the other hand, the visualization of the damage characteristics of the structure under severe wave action is only be rendered possible by the model investigations. Therefore, model investigations have vital importance from both contractor and client point of view.

Construction of Black Sea Highway Project have come up with several important problems since the project application has been started. Because of the existing collapsing and failure conditions of the coastal protection structures along the Black Sea Coastal Highway, Ordu-Giresun area was selected as the pilot area to apply the model investigations by some of the researchers. Dedeoğlu R. (2003) and Taşkıran İ. (2003) carried out an experimental work on the stability of coastal defense structure, under construction around Ordu-Giresun region as rubble-mound structure. The tests were carried out by the design wave characteristics where H was ranging between 3.69 and 6.31 meters, T was ranging between 8.21 and 10.47 seconds obtained from the wave climate studies of the site (Özhan and Abdalla, 1999). In their work, they proposed a coastal defense structure which was stable under the design storm waves.

Previous studies were done on the designed cross-sections applied by Karayolları Genel Müdürlüğü. These studies showed that the pre-designed cross-sections were over design or under design projects from engineering point of view. Therefore, the major aim of the model researches made in the Middle East

Technical University, Civil Engineering Department, Coastal and Harbor Engineering Laboratory was to find the most optimum and proper cross-section of the coastal protection structure, rubble-mound breakwater that would withstand the most dangerous storm conditions.

In this research, the stability and damage criteria of the rubble mound coastal protection structures and the continuity of their functionality were studied under two main topics:

i. Stability of the coastal protection structure:

- Failure occurring in the armor layer of the structure by having a certain percentage of dislocated rocks more than the acceptable damage percentage and due to this, loss of stability and serviceability in the whole structure, which will cause total failure

ii. Functional properties of the coastal highway:

- Excessive run-up and water spraying during the storm damaging the highway and hindering the traffic flow as well as causing loss of life due to traffic accidents caused by the negative road conditions
- Severe storm wave action damaging the under layers of the highway structure causing total failure and flooding of the highway

In the Coastal and Harbor Engineering Laboratory, Civil Engineering Department, METU, the researches on Eastern Black Sea Highway Project proceeded according to the steps given below:

a. Determination of the design wave height by studying the long term and short term wave statistics of the region, transforming deep water waves to the construction site, checking breaking wave condition at the construction depth
b. Gathering information of the bathymetry and topography of the pilot region
c. Determination of the model scale
d. Examination of the protection structure cross sections currently under construction for model investigations

e. Construction of the model in the wave flume
f. Calibration tests of wave measuring probes in the wave flume
g. Experiments
h. Evaluation of the experiment results with respect to the damage and run-up criteria
i. Developing new economic solutions and optimizing the developed structure

In the present work the experiment was carried out for the stability of coastal defense structure with the design wave characteristics obtained for the site near Giresun in a model constructed in the wave flume in the Coastal and Harbor Engineering Laboratory, Civil Engineering Department, METU with a model scale of 1/31.08 to obtain the most optimum cross-section both from the stability and economy point of view. In the experiments the reference cross-section was used as proposed.

3.2 Bathymetric Conditions (Properties)

One of the most vital parameters is the sea bottom slope in the determination of the design wave characteristics at the toe of the structure and in the determination of the depth at which the structure is constructed. The pilot application area of the model investigations was selected to be Giresun region. For the determination of the sea bottom characteristics, schematics and drawings of the highway passing through the Giresun City Center were used. The final outcome showed us that the sea bottom slope ranged between 1/30 and 1/40. These were properly applied to the wave flume in which the model investigations took place.

3.3 Wave Climate of the Region and Determination of the Design Wave:

Before starting the model investigations, it is very important to find out the design wave characteristics at which location the prototype will be constructed. In determination of the design wave, extreme wave statistics of the region were used (Özhan and Abdalla, 1999). These were used in the previously

done model investigations. Therefore, all of these parameters were examined once more in order to investigate the reliability of previously used design wave characteristics. During these studies, wave heights with their return period for the Eastern Black Sea Region were obtained from Wind and Wave Atlas for Turkish Coasts Project Report (Özhan and Abdalla, 1999). The significant wave heights and periods for 25 and 50 years of return period of Eastern Black Sea Region are given in Table 3.1.

Table 3.1 Return periods, significant wave heights and periods for the Eastern Black Sea Region (Özhan-Abdalla, 1999)

		25 Years		50 Years	
Coordinates	**Location**	**Hs (m.)**	**Ts (sec.)**	**Hs (m.)**	**Ts (sec.)**
42.00° N, 41.60° E	Poti	6,25	10,27	6,80	10,71
42.00° N, 41.30° E	Poti offshore	6,40	10,39	6,85	10,75
41.75° N, 41.30° E	Batum offshore	6,30	10,31	6,90	10,79
41.75° N, 41.00° E	Hopa offshore	6,30	10,31	7,00	10,87
41.50° N, 41.00° E	Hopa	6,30	10,31	7,00	10,87
41.50° N, 40.70° E	Çayeli offshore	6,25	10,27	6,75	10,67
41.25° N, 40.70° E	Çayeli	5,85	9,93	6,40	10,39
41.25° N, 40.40° E	Rize	5,80	9,89	6,35	10,35
41.25° N, 40.10° E	Sürmene	5,75	9,85	6,30	10,31
41.25° N, 39.80° E	Trabzon	5,80	9,89	6,40	10,39
41.25° N, 39.50° E	Akçaabat	5,80	9,89	6,45	10,43
41.25° N, 39.20° E	Vakfıkebir	6,00	10,06	6,60	10,55
41.25° N, 38.90° E	Tirebolu	6,10	10,14	6,75	10,67
41.25° N, 38.60° E	Çamburnu	6,20	10,23	6,80	10,71
41.25° N, 38.30° E	Giresun	6,20	10,23	6,80	10,71
41.25° N, 38.00° E	Ordu	6,25	10,27	7,00	10,87

An other important parameter in the determination of design wave characteristics is to determine the deep water wave steepness. It was

determined to be H_0/L_0 = 0.038 (Özhan and Abdalla, 1999) representing the general wave characteristics of the region.

When the averages of total storm durations were taken. The storm duration for the region was found out as 8 hours. This value can be considered as the mean value of the total storm durations.

When the Table 3.1 is examined according to the return periods of 25 and 50 years, As seen in Table 3.1, maximum deep water significant wave height is ranging between H_s=5.75 meters with T_s=9.85 seconds (Sürmene) and H_s=6.40 meters with T_s=10.39 seconds (Poti offshore) and the maximum deep water significant wave ranges between H_s=6.30 meters, T_s=10.31 seconds (Sürmene) and H_s=7.00 meters, T_s=10.87 seconds (Hopa), respectively.

After finding out the significant wave heights and periods for the selected regions, the depth at the toe of the structure was determined to be as 7.50 m.. That is the maximum reached depth of construction which is determined by examining the topographic maps of Giresun region, where the construction of the coastal highway coastal defense structure is currently going on.

Waves breaking on the structure have the most hazardous effect on the stability of the structure, since the waves have the maximum energy when they are breaking. This means that the most important point in designing the coastal defense structures is to determine the breaker wave height at the construction depth of the structure. In order to determine the breaking wave properties at the toe of the structure and their deep water properties, the charts given in Coastal Engineering Manual 2003 were used. Breaker wave height at d=7.50 meters was found to be H_b=6.50 meters and deep water wave height correspondent was determined as H_s= 5.80 meters after the application of the computations. Significant wave period was found as T_s = 9.90 seconds with the wave steepness of 0.038 which was determined by Özhan and Abdalla 1999.

An other discussion is the determination of the encounter probability of the design wave during the lifetime of the structure. To compute the occurrence probability of a wave with a certain return period, the following formula is used:

$$P = 1 - (1 - \frac{1}{Rp})^L \tag{3.1}$$

Here,

P: occurrence probability
Rp: return period (years)
L: lifetime of the structure (years).

The defense structure which is planned to be constructed in the Giresun coastal region at depths of 7.50 meters will be attacked by breaking waves of deep water significant wave height of H_s= 5.80 meters and significant period T_s= 9.90 seconds have a return period of 17 years (Özhan and Abdalla, 1999). Generally in Turkey,the life time of coastal protection structures is considered to be between 30 and 50 years. It was decided to use the lifetime of the structure as 40 years, which is the average of 30 and 50 years. The probability of the structure to be under severe wave breaking action at least once in its lifetime was computed to be P=91% (Özler, 2004). Since this wave demonstrates the most critical stability condition for which the structure will encounter in its lifetime, it is necessary to take this wave as the design wave. The waves having larger wave heights will break before they reach the structure, waves having smaller wave heights will break on the structure.

3.4 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 S., 1993). Within the acceptable scale range for rubble-mound structure tests, scale selection decisions are influenced by practical considerations, such as depth of the wave flume, model wave characteristics, wave generating capability and available stone sizes. Considering all of these parameters, model scale was found to be 1/31.08. This similar scale (1/30) was proposed by Jensen and Klington (1983) as the most common and appropriate scale for rubble-mound breakwaters.

The majority of hydraulic models in coastal engineering are scaled according to the Froude Model law, consequently, it is usually the most

important criterion to be considered when designing o coastal scale model. This is because of the fact that, in the models demonstrating sea wave action, viscosity and surface tension of the water usually do not have a significant effect on the wave motion when compared with the effects of gravity and inertia forces.

Applying the model scale into the Froude Model, length, time, volume and weight scales were computed and are given in Table 3.2.

Table 3.2 Scales of Length, Time, Volume and Weight Used in the Model

	Model Scale
Length	$\lambda_L = 1:31.08$
Time	$\lambda_T = \lambda_L^{1/2} = 1:5.58$
Volume	$\lambda_V = \lambda_L^{3} = 1:30022.3$
Weight	$\lambda_w = \lambda_L^{3} \frac{(\gamma_r)_m}{(\gamma_r)_p} \left[\frac{\frac{(\gamma_r)_p}{(\gamma_w)_p} - 1}{\frac{(\gamma_r)_m}{(\gamma_w)_m} - 1} \right]^3 = 1:21297.2$

Here; λ_L: length scale, λ_T: time scale, λ_V: volume scale, λ_W: weight scale, γ_r: specific weight of the stones, γ_w: specific weight of water, p: prototype, m: model.

3.5 Wave Flume and Experiment Set-up Specifications:

The wave flume is 6.2 meters wide, 28.8 meters long and the depth is 1.0 meter with an inner separated canal, which is constructed by placing two

parallel glass walls in order to minimize the effect of reflection of incoming waves. All of the models were built in that separate 1.5 meters width channel. Although the channel is separated, energy dissipaters were placed behind the constructed model in order to prevent the waves reflecting from the boundaries causing undesired agitation in the wave flume and disturbing the incoming waves. But it is clearly known that full prevention from reflection is impossible in experimental environment. Therefore, during the analyze of wave data a computer program (Öztunalı, METU,1998) was used in order to introduce wave reflection phenomena into the model investigations.

The dimensions of the wave flume, the locations of the wave measurement gauges (probes), wave dissipaters and the wave generator are shown in Figure 3.1.

Eight separate measurement gauges of "DHI Model 202" were used in the experiments. Wave measurement gauges take simultaneous data as the experiments are carried out and record the model wave properties (wave height and period). The gauges work as electrodes of an electric resistance meter. The voltage difference created as the waves move along the flume is read by the measurement cabinet from where the data is transferred to a computer to be translated by the software and adjusted by the calibration factor to be recorded as wave data.

The wave generator consists of three main components, which are the power pack, wave motion paddle and the control computer. The DHI Hydraulic Power Pack type 301/22-PM creates the power required to activate the pistons that move the generator paddle. The movement of the paddle is controlled by an integrated computer with special software (DHI Wave Synthesizer) which converts the digitized wave data into analog paddle motion signals.

The height and the period of the wave that can be generated in the flume depend on the water depth of the canal, as well as the technical capabilities of the wave generator. The waves that can be generated with 40 cm. of water depth in front of the generator paddle are the waves with heights ranging between 3-25 cm. and periods ranging between 0.5-15 seconds.

Regular waves were used in the experiments. In the model investigations, increasing wave impacts were created. This means, waves with increasing significant wave height and period were generated by the DHI wave generator forming an 8-hour storm. Run lengths of these individual waves were selected providing that the total storm duration is 8 hours.

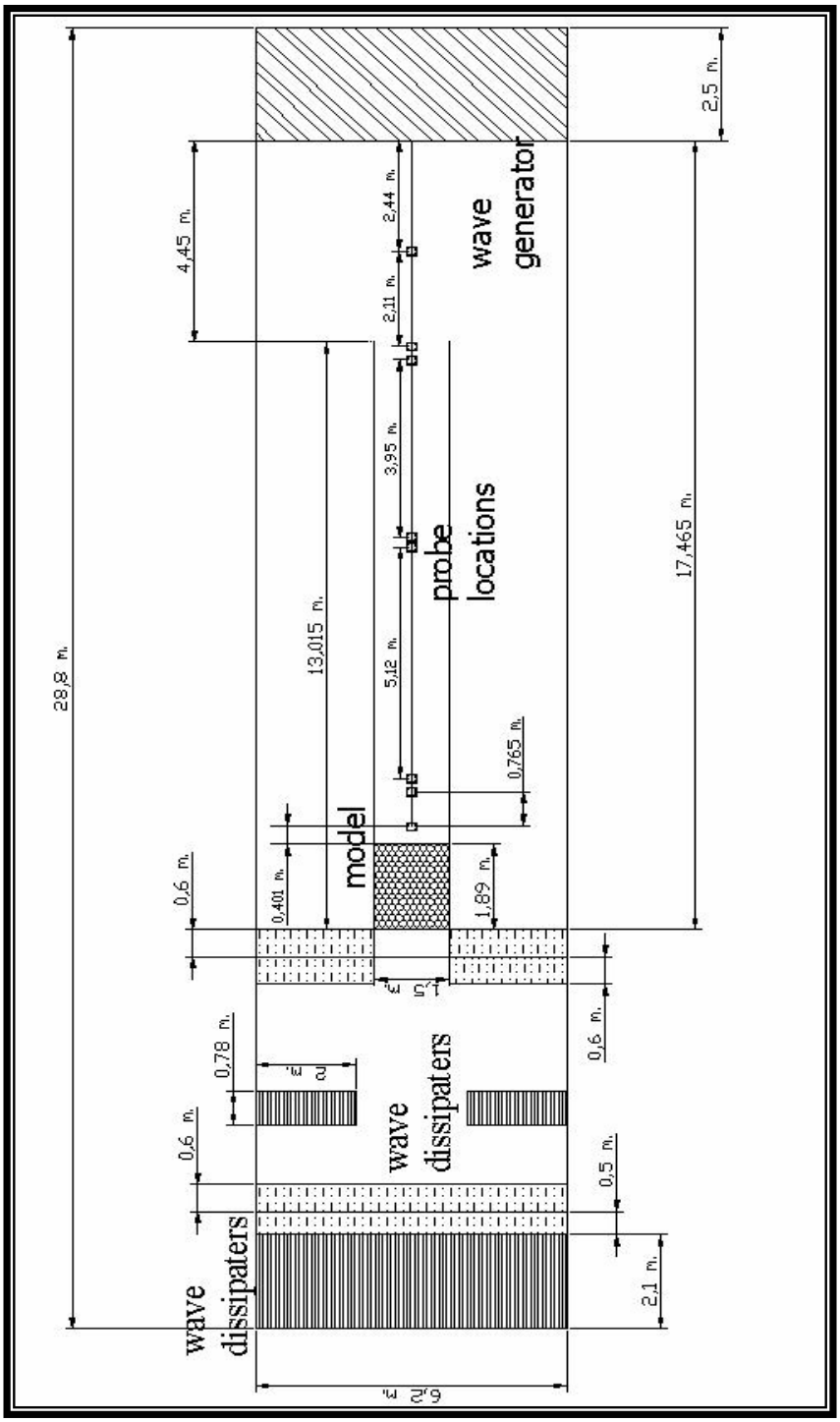

Figure 3.1 Layout of the wave flume and the experiment setup (model, dissipaters, generator and probes)

3.6 Construction of Models

In the previous studies (Dedeoğlu, (2003) and Taşkıran, (2003)) carried out at METU, Civil Engineering Department, Coastal and Harbor Engineering Laboratory, berm width was not changed. Since, the major aim this study was to find the effect of berm width and armor stone sizes on the stability of the structure, the model cross-sections were constructed with different berm widths and armor stone sizes.

All of the stones used for the construction of the models were painted in different colors in order to observe total and also local damages in the armor layers. In addition to that, the stones were selected according to the weight scale and were placed to form 7 color stripes (Figure 3.2).

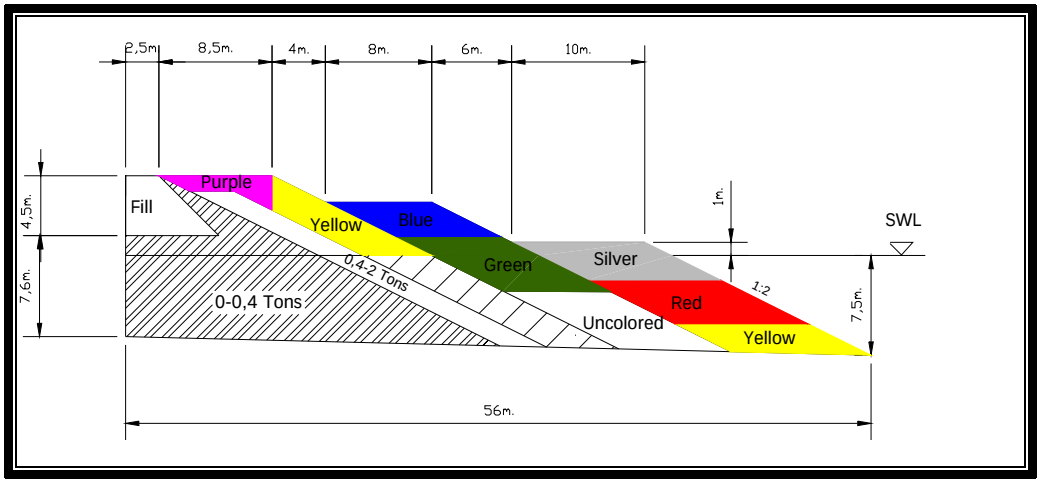

Figure 3.2 Cross-section showing the colored layers constructed

In the present study berm was constructed 1 m above the still water level to have comparative results with a case where berm was constructed 1 m below the still water level (Özler, 2004)

First step in the construction of model cross-sections was to find out the number of stones that would be used in each layer and color stripe. In order to find out the number of stones, total volume was computed. Then, the net volume was computed by applying P=0.4 standard (Coastal Engineering Manual, 2003). Lastly, the number of stones was obtained by dividing the net volume to

the volume of each stone. Number of stones in each layer is presented in the "Distribution of Stone Weights and Color Stripes for the Stone Group" tables.

The stone sizes range given for a certain layer was distributed around the mean stone size value as given in the "Distribution of Stone Weights and Color Stripes for the Stone Group" tables for each model tested.

Armor layers were divided into color stripes, which allowed damage observations more reliable and accurate. Frames for each model cut from iron bars were welded together forming the whole cross section with the under layers. The frames were placed firmly then the under layers, the armor layers were constructed. In order to prevent reinforcement by the frames, bars framing the armor layers were cut off.

As the under layers apply very little effect on the stability of the breakwater in our model investigations, the materials and existing cross-section of these layers were kept the same throughout the tests.

3.7 Models

Model cross-sections 1, 2 and 3 were designed based on Van Der Meer equations (Equations 2.8-2.12). In these models armor stones forming the back and front armor layers were in the range of (4-6) tons. After performing the experiments on Model 1, Model 2 and Model 3, it was observed that due to the berm effect weight of armors used in the back armor layer would be decreased. Therefore, in Model 4 and Model 5 armors ranging between (2-6) tons were used forming the back armor layers in order to examine the stability of each armor unit under the severe wave conditions. All the models were constructed satisfying the condition of the berm being 1 meter above the still water level.

3.7.1 Model 1

This model (Figure 3.3) study was based on the reconstruction of the last cross-section studied by Dedeoğlu (2003) and Taşkıran (2003). The specified berm with 10 meters width was constructed as being 1 m. above still water

level. The cross-section was formed by five layers named as front armor, back armor, filter and core layers. The primary importance was given specifically on front and back armor layers, which were the starting point of discussions of the further coming, designed models. In this model, armor stones forming the front and back armor layers were in the range of (4-6) tons. The filter layers and the core layer were made up of (2-6) tons and (0.4-2) tons, respectively. The number of stones used in each layer and color stripe is given in Table 3.3 and Table 3.4.

Table 3.3 Distribution of stone weights and color stripes for the back armor layer of Model 1

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	373	4	200
30%	226	5	250
30%	189	6	300
Color stripes of the layer and number of stones			
Royal Blue	263		
Green	263		Σ788
Uncolored	262		

Table 3.4 Distribution of stone weights and color stripes for the front armor layer of Model 1

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	373	4	200
30%	226	5	250
30%	189	6	300
Color stripes of the layer and number of stones			
Silver	263		
Red	263		Σ788
Yellow	262		

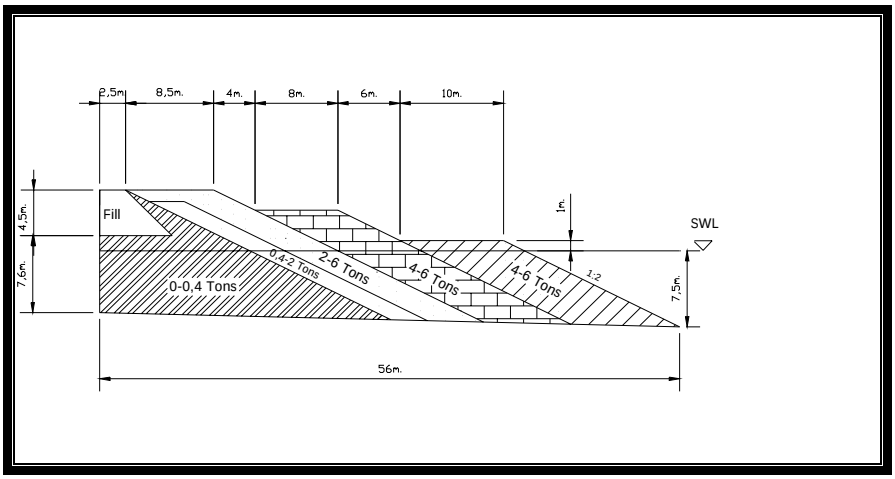

Figure 3.3 Cross-section of Model 1 (Prototype Values)

This model was tested with two sets of experiments which were carried on 23rd and 26th of July, 2004, respectively.

3.7.2 Model 2

In this model, the berm width was extended as 15 meters. Cross-sectional details are given in Figure 3.4. Stones that were forming front and back armor layers were ranging between (4-6) tons. The filter layers and the core layer were made up of (2-6) tons and (0.4-2) tons, respectively. The number of stones used in each layer and color stripe is given in Table 3.5 and Table 3.6.

Table 3.5 Distribution of stone weights and color stripes for the back armor layer of Model 2

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	373	4	200
30%	226	5	250
30%	189	6	300
Color stripes of the layer and number of stones			
Royal Blue	263		
Green	263	∑788	
Uncolored	262		

Table 3.6 Distribution of stone weights and color stripes for the front armor layer of Model 2

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	558	4	200
30%	336	5	250
30%	279	6	300
Color stripes of the layer and number of stones			
Silver	391		
Red	391	∑1173	
Yellow	391		

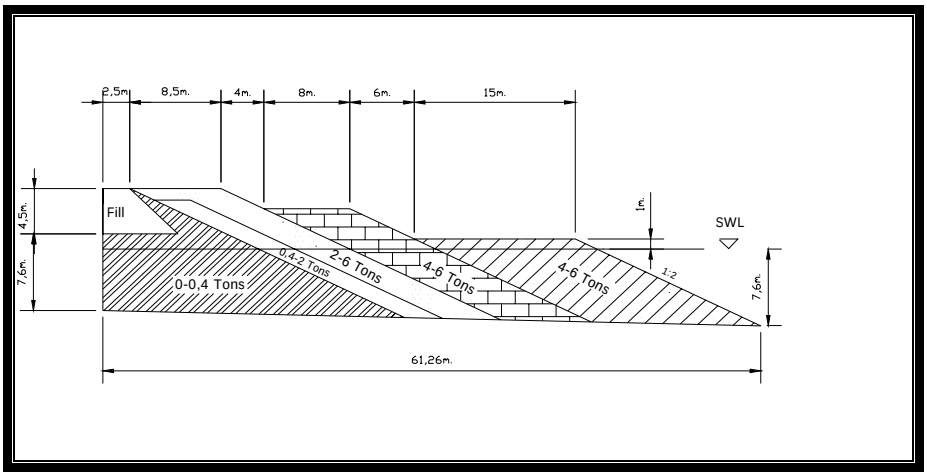

Figure 3.4 Cross-section of Model 2 (Prototype Values)

This model was tested with two sets of experiments which were carried on 28th and 29th of July, 2004, respectively.

3.7.3 Model 3

In this model, the berm width was shortened as 5 meters. Cross-sectional details are given in Figure 3.5. Stones that were forming front and back armor layers were ranging between (4-6) tons. The filter layers and the core layer were made up of (2-6) tons and (0.4-2) tons, respectively. The number of stones used in each layer and color stripe is given in Table 3.7 and Table 3.8.

Table 3.7 Distribution of stone weights and color stripes for the back armor layer of Model 3

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	373	4	200
30%	226	5	250
30%	189	6	300
Color stripes of the layer and number of stones			
Royal Blue	263		
Green	263		∑788
Uncolored	262		

Table 3.8 Distribution of stone weights and color stripes for the front armor layer of Model 3

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	207	4	200
30%	128	5	250
30%	104	6	300
Color stripes of the layer and number of stones			
Silver	149		
Red	151		∑439
Yellow	139		

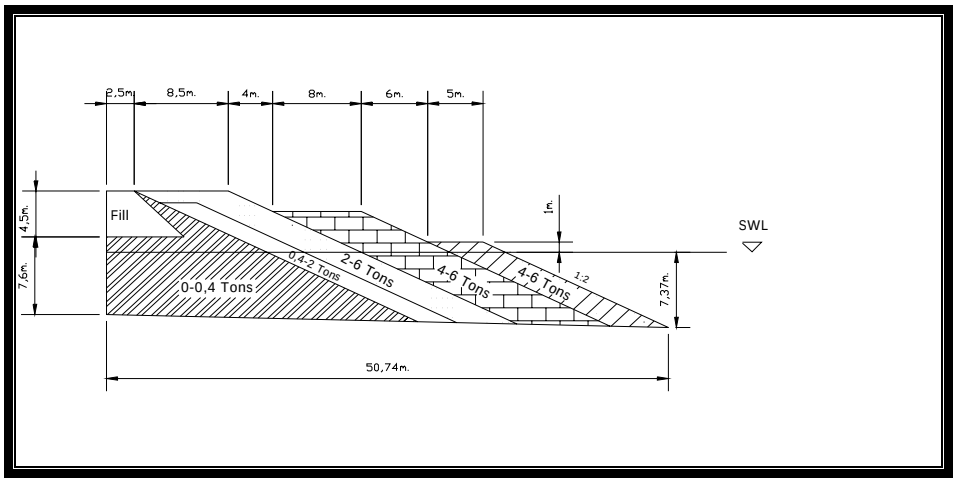

Figure 3.5 Cross-section of Model 3 (Prototype Values)

This model was tested with two sets of experiments which were carried on 17th and 18th of August, 2004, respectively.

3.7.4 Model 4

In this model, the berm width which was used in the model was 15 meters. Cross-sectional details are given in Figure 3.6. In this model, stone sizes forming the back armor layer were changed from (4-6) tons to (2-6) tons. Front armor layer was kept same as in the previous models as being (4-6) tons. The filter layers and the core layer were made up of (2-6) tons and (0.4-2) tons, respectively. The number of stones used in each layer is given in Table 3.9 and Table 3.10

Table 3.9 Distribution of stone weights and color stripes for the back armor layer of Model 4

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
15%	299	2	100
35%	465	3	150
35%	342	4	200
15%	100	6	300
Color stripes of the layer and number of stones			
Royal Blue	430		
Green	394	∑1206	
Uncolored	382		

Table 3.10 Distribution of stone weights and color stripes for the front armor layer of Model 4

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	562	4	200
30%	338	5	250
30%	281	6	300
Color stripes of the layer and number of stones			
Silver	391		
Red	399	∑1181	
Yellow	391		

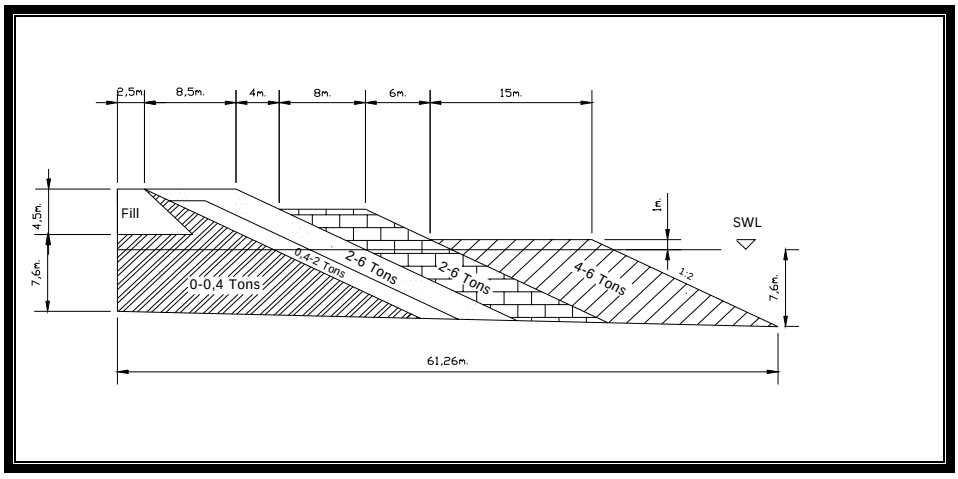

Figure 3.6 Cross-section of Model 4 (Prototype Values)

This model was tested with two sets of experiments which were both carried on 2nd of September, 2004, respectively.

3.7.5 Model 5

In this model, the berm width which was used in the model was 10 meters. Cross-sectional details are given in Figure 3.7. In this model, stone sizes forming the back armor layer were changed from (4-6) tons to (2-6) tons. Front armor layer was kept same as in the previous models as being (4-6) tons. The filter layers and the core layer were made up of (2-6) tons and (0.4-2) tons, respectively. The number of stones used in each layer and color stripe is given in Table 3.11 and Table 3.12.

Table 3.11 Distribution of stone weights and color stripes for the back armor layer of Model 5

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
15%	299	2	100
35%	465	3	150
35%	342	4	200
15%	100	6	300
Color stripes of the layer and number of stones			
Royal Blue	430		
Green	394	∑1206	
Uncolored	382		

Table 3.12 Distribution of stone weights and color stripes for the front armor layer of Model 5

% of the total Volume	Number of stones	Weight	
		Prototype (tons)	Model (gr.)
40%	365	4	200
30%	219	5	250
30%	185	6	300
Color stripes of the layer and number of stones			
Silver	225		
Red	275	∑769	
Yellow	269		

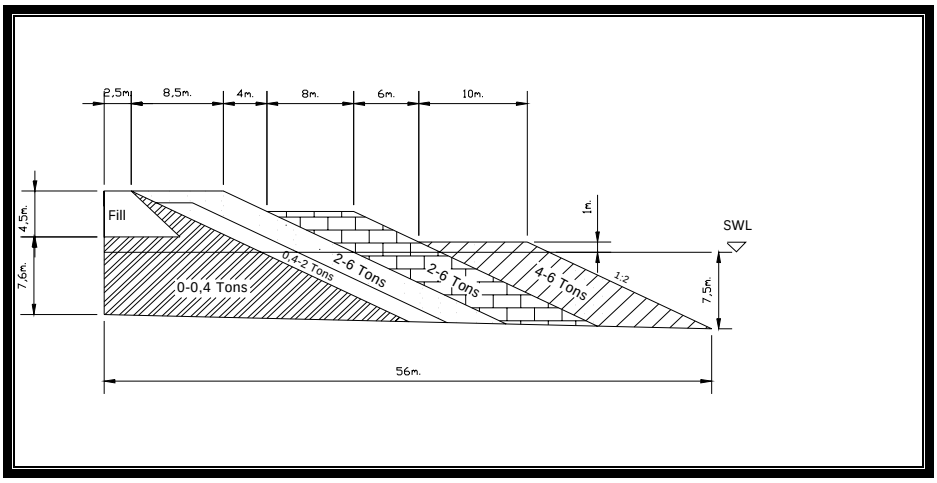

Figure 3.7 Cross-section of Model 5 (Prototype Values)

This model was tested with two sets of experiments, which were both carried on 31st of August, 2004, respectively.

CHAPTER 4

EXPERIMENTS AND DISCUSSION OF RESULTS

In this chapter, experiments of the model studies of coastal protection structure with differing cross-sections are given in a detailed manner. Each model experiment is presented by wave characteristics, damage as displaced armor stones, run-up and water spray tables and damage curves for local and total damages.

For the examination of experiment outcomes, the clear definition of damage criteria must be set. Damage is defined as the removal or breakage of individual armor units or sliding of the armor layer totally. A pre-determined, acceptable level of damage is tolerated under design conditions (10%) which is calculated as:

$D= N_1/N$

Where;

N1: number of dislocated armor stones,
N: number of total armor stones within the specified layer.

In the experiments, local and total damages were defined in terms of dislocated stones in specified layer and specified cross-section, respectively.

When using a model to determine threshold damage conditions, a small amount of damage must be observed (0-5%) which is generally referred to as the "no damage" condition. It is important to assess how damage observed in

the model will relate to performance of the full size structure and to interpret model results accordingly.

One approach is to express the number of units damaged as a percentage of the total number of units on the slope. One drawback is that the value calculated depends on the number of units in the armor layer, making comparison of different cross sections and armor types difficult. A better approach is to express damage as the percentage of armor units displaced from the layer of active armor removal (Ouellet, 1973).

Total damage curves show the cumulative distribution of damage of the armor layers and the local damage curves illustrate the cumulative local damages of layers at which critical and vital damage levels were observed exceeding the critical damage level (10%).

In the experiments observation of run-up and water spray were done. Water spray examinations were divided into 4 different levels that shows the severity of run-up which was very important from the highway serviceability point of view. These levels were named as Minor, Tolerable, Significant and Excessive. Run-up was observed in order to examine whether overtopping was occurring or not. Run-up conditions were noted down as showing the maximum level of run-up travel within the highest reached layer. Maximum run-up level was 4.5 meters above the still-water level. Overtopping was not faced.

Model construction (Figures 3.3-3.7) is based on the comparison of berm width and armor unit weight effect on the stability of the coastal defense structure.

Experiments are divided into two as Set 1 and Set 2 for each model study. Each set of experiment was carried with the same wave data, characteristics and wave flume characteristics such as regular waves created by the wave maker, wave period, wave height and water depth of the flume. Water depth in the flume was kept same throughout the model studies as 40 centimeters in front of the paddle forming a 7.5 meters water depth at the toe of the structure as provided for the prototype coastal protection structure.

During the model studies two sets of experiments for five different models were carried. Two sets of experiments were done in order to see the reliability of the experiments outcomes. It was clearly seen that the experiment outcome data was reliable. These outcomes of two sets were handled separately and then were shown on the same damage curve figure for each of the models.

Before starting each set of experiments, calibration of the wave measuring system, wave gauges, was made properly in order not to obtain misleading outcome data. For these types of experiment setups, proper calibration is very important and effective. In addition to the calibration for each set of experiments, also replacement of stones of each stripe and layers, which were displaced by the storm impact, was done, since each set of the experiments was independent from each other.

4.1 Experiments on Model 1

4.1.1 Set 1 and Set 2 Experiments

These set of experiments were carried out on the Model 1 (Fig.3.3) having 10 meters berm width which was previously determined as the recommended cross-section by Dedeoğlu (2003) and Taşkıran (2003).

The design wave height and period which were selected according to the wave climate and regional studies were created incrementally by the DHI wave synthesizer in order to demonstrate the beginning and the ending of the storm were given to the model. Increments applied in steps to wave height and wave period were almost 0.30 meters and 0.30 seconds, respectively. All these waves forming the storm were given for duration of 9 minutes contributing to a storm of 8 hours. The wave data of the model is given in Table 4.1 and Table 4.2 for Set 1 and Set 2 experiments.

Table 4.1 Test Wave Data of Model 1, Set 1

model# 1 (Set1)		**Experiment Date:** July 23, 2004				
Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	T (sec.)	1. Probe	7. Probe	H(m.)	T(sec.)	Cr (ref. coeff.)
3,69	8,21	3,23	3,15	3,18	8,12	0,137
3,97	8,47	3,70	3,35	3,27	8,35	0,207
4,19	8,71	4,03	3,40	3,46	8,43	0,094
4,45	8,95	4,65	4,32	3,50	8,56	0,142
4,70	9,18	4,50	4,39	3,43	8,82	0,275
4,97	9,41	4,88	4,56	4,11	8,87	0,126
5,23	9,63	5,25	5,08	4,28	9,20	0,087
5,50	9,85	5,71	5,22	4,20	9,43	0,086
5,77	10,06	5,81	5,47	4,32	9,62	0,201
6,04*	10,27	6,06	5,68	5,36	9,84	0,219*
6,31**	10,47	6,54	5,91	5,46	10,04	0,15**

* Breaking at the toe of the structure
** Broken waves

Table 4.2 Test Wave Data of Model 1, Set 2

model# 1 (Set2)		**Experiment Date:** July 26, 2004				
Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,51	3,62	3,66	8,12	0,122
3,97	8,47	3,84	3,76	3,89	8,35	0,172
4,19	8,71	4,01	3,74	3,94	8,41	0,086
4,45	8,95	4,71	4,27	4,29	8,54	0,171
4,70	9,18	4,70	4,40	4,49	8,86	0,213
4,97	9,41	4,99	4,54	4,64	8,80	0,110
5,23	9,63	5,35	4,87	5,40	9,22	0,085
5,50	9,85	5,82	5,10	4,68	9,44	0,098
5,77	10,06	5,90	5,35	5,58	9,59	0,174
6,04*	10,27	6,24	5,70	6,27	9,92	0,196*
6,31**	10,47	6,68	6,01	6,51	10,00	0,133**

* Breaking at the toe of the structure

The first two columns show the wave characteristics given as input by the computer. Third and the fourth columns demonstrate the wave heights recorded by the wave gauges (probes). The actual incoming wave properties

obtained from the reflection analysis and the reflection coefficient are given in the last three columns.

The results of observation of the displaced armor stones, run-up and water spray of Set 1 and Set 2 experiments are given in Table 4.3 and Table 4.4 .

Table 4.3 Results of Set 1 Experiments on Model 1
(Damage, Wave Run-up and Water Spray)

DATE: July 24, 2004 (Set#1 Experiments)										
Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower mid blue	-
3,97 8,47	9	-	-	-	-	-	-	-	mid blue layer	-
4,19 8,71	9	-	-	-	-	-	-	-	mid blue layer	-
4,45 8,95	9	-	-	-	-	-	-	-	upper mid blue	-
4,70 9,18	9	-	-	-	-	2(u)	-	-	upper blue	-
4,97 9,41	9	-	-	-	-	2(u)	-	-	upper blue	-
5,23 9,63	9	-	-	1(d)	-	2(u)	-	-	upper blue	M
5,50 9,85	9	-	-	1(d)	-	3(u)	-	-	upper yellow	M
5,77 10,06	9	-	-	1(d)	-	4(u) 6(d)	6(d)	-	upper yellow	S
6,04 10,27	9	-	-	1(d) 3(u)	-	5(u) 9(d)	10(d)	-	lower purple	E
6,31 10,47	9	-	-	1(d) 3(u)	-	5(u) 9(d)	10(d)	-	lower purple	S

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up
2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers
3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor (M), tolerable (T), significant (S), excessive (E)
4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the

Table 4.4 Results of Set 2 Experiments on Model 1

(Damage, Wave Run-up and Water Spray)

DATE: July 26, 2004 (Set#2 Experiments)										
Ho (m.) To (sec.)	Duration (min.)	**D A M A G E**							**Run-up**	**Water Spray**
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower mid blue	-
3,97 8,47	9	-	-	-	-	-	-	-	mid blue layer	-
4,19 8,71	9	-	-	-	-	-	-	-	mid blue layer	-
4,45 8,95	9	-	-	-	-	-	-	-	upper mid blue	-
4,70 9,18	9	-	-	-	-	-	-	-	upper blue	-
4,97 9,41	9	-	-	-	-	-	-	1(d)	mid yellow	-
5,23 9,63	9	-	-	-	-	3(d)	4(d)	1(d)	upper yellow	M
5,50 9,85	9	-	-	-	-	1(u) 3(d)	4(d)	1(d)	upper yellow	T
5,77 10,06	9	-	-	-	-	2(u) 4(d)	6(d)	1(d)	lower purple	E
6,04 10,27	9	-	-	-	-	3(u) 4(d)	10(d)	1(d)	mid purple	E
6,31 10,47	9	-	-	-	-	4(u) 6(d)	11(d)	1(d)	lower purple	S

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the

Using Table 4.3 and 4.4 local and total damages for Set 1 and Set 2 experiments were calculated and presented in Table 4.5 and 4.6.

Table 4.5 Local and Total Damage (%) of the Set 1 Experiment on Model 1

	Colored Sections For Model # 1										Date : July 23, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	**263**		**88**		**262**		**263**		**263**		**788**		**351**		***1139***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,45	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,70	0	0,00%	0	0,00%	2	0,76%	0	0,00%	0	0,00%	2	0,25%	0	0,00%	0,18%
4,97	0	0,00%	0	0,00%	2	0,76%	0	0,00%	0	0,00%	2	0,25%	0	0,00%	0,18%
5,23	1	0,38%	0	0,00%	2	0,76%	0	0,00%	0	0,00%	2	0,25%	1	0,13%	0,26%
5,50	1	0,38%	0	0,00%	3	1,15%	0	0,00%	0	0,00%	3	0,38%	1	0,13%	0,35%
5,77	1	0,38%	0	0,00%	10	3,82%	6	2,28%	0	0,00%	16	2,03%	1	0,13%	1,49%
6,04	4	1,52%	0	0,00%	14	5,34%	10	3,80%	0	0,00%	24	3,05%	4	0,51%	2,46%
6,31	4	1,52%	0	0,00%	14	5,34%	10	3,80%	0	0,00%	24	3,05%	4	0,51%	2,46%

NOTES 1) **D.S.**= **#** of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

Table 4.6 Local and Total Damage (%) of the Set 2 Experiment on Model 1

	Colored Sections For Model # 1										Date : July 26, 2004 (SET2)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	**263**		**88**		**262**		**263**		**263**		**788**		**351**		***1139***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,45	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,70	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	1	0,38%	1	0,13%	0	0,00%	0,09%
5,23	0	0,00%	0	0,00%	3	1,15%	4	1,52%	1	0,38%	8	1,02%	0	0,00%	0,70%
5,50	0	0,00%	0	0,00%	4	1,53%	4	1,52%	1	0,38%	9	1,14%	0	0,00%	0,79%
5,77	0	0,00%	0	0,00%	6	2,29%	6	2,28%	1	0,38%	13	1,65%	0	0,00%	1,14%
6,04	0	0,00%	0	0,00%	7	2,67%	10	3,80%	1	0,38%	18	2,28%	0	0,00%	1,58%
6,31	0	0,00%	0	0,00%	10	3,82%	11	4,18%	1	0,38%	22	2,79%	0	0,00%	1,93%

NOTES 1) **D.S.**= **#** of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of stones took place in the red and the silver stripes which were the stripes forming the berm. However, when the damage curves and tables were examined, it was observed that neither local nor total damage reached the 10%, which is the upper critical damage limit. This is shown on the Figure 4.1.

The damage level or percentage that was observed shows that the cross-section with 10 meters berm width is stable under storm conditions according to the pre-set stability criteria.

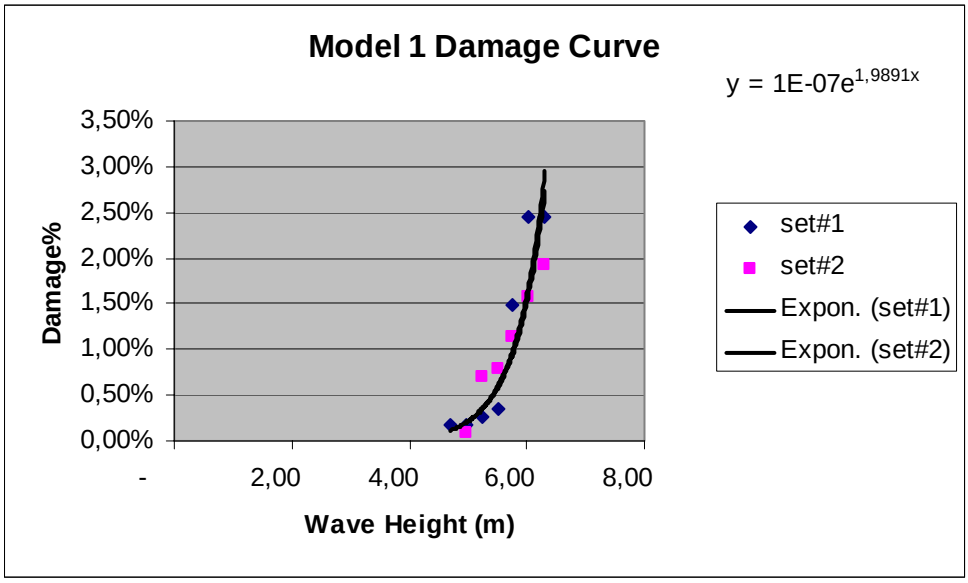

Figure 4.1 Damage vs. Wave Height Curve of Set1 and Set2 Experiments Model 1

As it is seen from Fig. 4.1 damage curves for Set 1 and Set 2 experiments gives very close results.

Based on this outcome, damage value observed for Model 1 was still below 2.50%.

4.2 Experiments on Model 2

4.2.1 Set 1 and Set 2 Experiments

This model (Fig. 3.4) was constructed with 15 meters berm width, which was the calculated berm width according to the wave length and berm width interactions. This model was tested in order to see and prove the reliability of proposed berm width giving 0-5% damage level according to the suggested equations and calculations.

The same design wave height and period, which were selected according to the wave climate and regional studies at the beginning of the experimental works, were used also for this cross-section. All these waves forming the storm were given for duration of 9 minutes contributing to a storm of 8 hours. The wave data of the model is given in Table 4.7 and Table 4.8 for Set 1 and Set 2 experiments.

Table 4.7 Test Wave Data of Model 2, Set 1

model# 2 (set1) Experiment Date: July 28, 2004

Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,11	3,01	3,14	8,13	0,107
3,97	8,47	3,20	3,10	3,36	8,37	0,146
4,19	8,71	3,50	3,15	3,07	8,43	0,092
4,45	8,95	4,04	3,26	3,86	8,59	0,112
4,70	9,18	4,19	3,57	3,91	8,87	0,192
4,97	9,41	4,55	3,72	3,80	8,82	0,132
5,23	9,63	4,74	4,66	4,35	9,19	0,075
5,50	9,85	4,89	4,51	3,90	9,39	0,093
5,77	10,06	5,21	4,81	5,06	9,60	0,220
6,04*	10,27	5,63	5,59	5,73	9,89	0,236
6,31**	10,47	6,37	5,98	5,28	10,05	0,152

* Breaking at the toe of the structure

** Broken waves

Table 4.8 Test Wave Data of Model 2, Set 2

model# 2 (set2) **Experiment Date:** July 29, 2004

Computer Input		Probe Measurements		Reflection Analysis		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,10	3,01	3,30	8,13	0,100
3,97	8,47	3,21	3,07	3,53	8,37	0,139
4,19	8,71	3,55	3,26	3,26	8,40	0,084
4,45	8,95	3,92	3,34	4,01	8,61	0,109
4,70	9,18	4,07	3,25	3,90	8,85	0,193
4,97	9,41	4,67	3,72	4,20	8,80	0,155
5,23	9,63	4,81	4,19	4,50	9,18	0,066
5,50	9,85	5,01	4,35	4,17	9,42	0,088
5,77	10,06	5,19	4,87	5,11	9,61	0,193
6,04*	10,27	5,71	5,35	6,06	9,88	0,219
6,31**	10,47	6,21	5,79	5,56	10,07	0,159

* Breaking at the toe of the structure

** Broken waves

The results of observation of the displaced armor stones, run-up and water spray of Set 1 and Set 2 experiments are given in Table 4.9 and Table 4.10 .

Table 4.9 Results of Set 1 Experiments on Model 2

(Damage, Wave Run-up and Water Spray)

DATE: July 28, 2004 (Set#1 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	-	-	-	lower mid blue	-
4,19 8,71	9	-	-	-	-	-	-	-	mid blue layer	-
4,45 8,95	9	-	-	-	-	-	1(d)	-	upper mid blue	-
4,70 9,18	9	-	-	-	-	-	1(d)	-	upper blue layer	-
4,97 9,41	9	-	-	-	-	1(d)	1(d)	-	lower yellow	-
5,23 9,63	9	-	-	-	-	1(u) 2(d)	2(d)	-	upper mid	-
5,50 9,85	9	-	-	-	-	1(u) 3(d)	2(d)	-	upper yellow	M
5,77 10,06	9	-	-	1(d)	-	1(u) 3(d)	2(d)	-	upper yellow	T/S
6,04 10,27	9	-	-	1(d)	-	1(u) 3(d)	4(d)	-	lower mid	E
6,31 10,47	9	-	-	1(d)	-	1(u) 3(d)	4(d)	-	lower purple	S

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Table 4.10 Results of Set 2 Experiments on Model 2
(Damage, Wave Run-up and Water Spray)

DATE: July 29, 2004 (Set#2 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	-	-	-	lower mid blue	-
4,19 8,71	9	-	-	-	-	-	-	-	mid blue layer	-
4,45 8,95	9	-	-	-	-	-	-	-	upper mid blue	-
4,70 9,18	9	-	-	-	-	-	-	-	upper blue layer	-
4,97 9,41	9	-	-	-	-	-	-	-	lower yellow	-
5,23 9,63	9	-	-	-	-	1(d)	1(d)	-	upper yellow	M
5,50 9,85	9	-	-	-	-	1(d)	1(d)	-	upper yellow	M
5,77 10,06	9	-	-	-	-	1(d)	3(d)	-	upper yellow	T
6,04 10,27	9	-	-	-	-	2(d)	4(d)	-	lower purple	E
6,31 10,47	9	-	-	-	-	3(d)	5(d)	-	lower purple	S

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Using Table 4.9 and 4.10 local and total damages for Set 1 and Set 2 experiments were calculated and presented in Table 4.11 and 4.12.

Table 4.11 Local and Total Damage (%) of the Set 1 Experiment on Model 2

	Colored Sections For Model # 2										Date : July 28, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***263***		***88***		***391***		***391***		***391***		***1173***		***351***		***1524***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,45	0	0,00%	0	0,00%	0	0,00%	1	0,26%	0	0,00%	1	0,09%	0	0,00%	0,07%
4,70	0	0,00%	0	0,00%	0	0,00%	1	0,26%	0	0,00%	1	0,09%	0	0,00%	0,07%
4,97	0	0,00%	0	0,00%	1	0,26%	1	0,26%	0	0,00%	2	0,17%	0	0,00%	0,13%
5,23	0	0,00%	0	0,00%	3	0,77%	2	0,51%	0	0,00%	5	0,43%	0	0,00%	0,33%
5,50	0	0,00%	0	0,00%	4	1,02%	2	0,51%	0	0,00%	6	0,51%	0	0,00%	0,39%
5,77	1	0,38%	0	0,00%	4	1,02%	2	0,51%	0	0,00%	6	0,51%	1	0,13%	0,46%
6,04	1	0,38%	0	0,00%	4	1,02%	4	1,02%	0	0,00%	8	0,68%	1	0,13%	0,59%
6,31	1	0,38%	0	0,00%	4	1,02%	4	1,02%	0	0,00%	8	0,68%	1	0,13%	0,59%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

Table 4.12 Local and Total Damage (%) of the Set 2 Experiment on Model 2

	Colored Sections For Model # 2										Date : July 29, 2004 (SET2)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***263***		***88***		***391***		***391***		***391***		***1173***		***351***		***1524***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,45	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,70	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
5,23	0	0,00%	0	0,00%	1	0,26%	1	0,26%	0	0,00%	2	0,17%	0	0,00%	0,13%
5,50	0	0,00%	0	0,00%	1	0,26%	1	0,26%	0	0,00%	2	0,17%	0	0,00%	0,13%
5,77	0	0,00%	0	0,00%	1	0,26%	3	0,77%	0	0,00%	4	0,34%	0	0,00%	0,26%
6,04	0	0,00%	0	0,00%	2	0,51%	4	1,02%	0	0,00%	6	0,51%	0	0,00%	0,39%
6,31	0	0,00%	0	0,00%	3	0,77%	5	1,28%	0	0,00%	8	0,68%	0	0,00%	0,52%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of stones took place in the red and the silver stripes which were the stripes forming th berm. However, when the damage curves and tables were examined, it was observed that neither local nor total damage reached the 10%, which is the upper critical damage limit. This is shown on the Figure 4.2

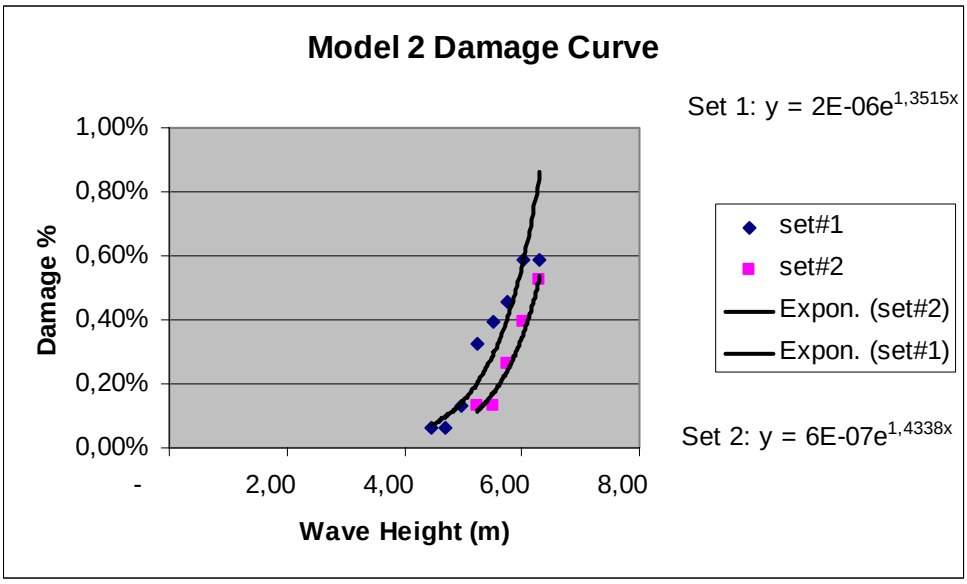

Figure 4.2 Damage vs. Wave Height Curve of Set1 and Set2 Experiments Model 2

As it is seen from Fig. 4.2 damage curves for Set 1 and Set 2 experiments gives close results.

After the figure is examined, it is proved that 0-5% damage level will be faced when the proposed equations which were used to calculate berm width are used in good agreement with Van Der Meer (Equations 2.13-2.14).

Figure 4.2 shows that Model 2 is stable under storm conditions and according to the observations run-up and spray conditions do not have a important effect on the serviceability function of the highway.

Based on this outcome, damage value observed for Model 2 was still below 0.80%.

4.3 Experiments on Model 3

4.3.1 Set 1 and Set 2 Experiments

This model (Fig. 3.5) was constructed width 5 meters berm width to visualize the berm width effect on stability of the structure. Since, in Model 1 critical damage level was not reached, it was appropriate to make the berm width smaller and see the result.

The same design wave height and period which were selected according to the wave climate and regional studies at the beginning of the experimental works were used also for this cross-section. All these waves forming the storm were given for a duration of 9 minutes contributing to a storm of 8 hours. The wave data of the model is given in Table 4.13 and Table 4.14 for Set 1 and Set 2 experiments.

Table 4.13 Test Wave Data of Model 3, Set 1

model# 3 (set1) **Experiment Date:** August 17, 2004

Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,13	3,10	3,00	8,11	0,152
3,97	8,47	3,41	3,20	3,19	8,35	0,134
4,19	8,71	3,53	3,31	3,30	8,38	0,095
4,45	8,95	4,41	3,66	3,42	8,56	0,202
4,70	9,18	4,57	3,78	3,61	8,82	0,146
4,97	9,41	4,79	3,94	3,89	8,83	0,120
5,23	9,63	4,88	4,14	4,55	9,24	0,077
5,50	9,85	5,12	4,31	4,06	9,48	0,150
5,77	10,06	5,90	4,56	4,46	9,60	0,139
6,04*	10,27	5,79	4,97	4,80	9,89	0,096
6,31**	10,47	6,07	5,28	5,20	10,05	0,103

* Breaking at the toe of the structure
** Broken waves

Table 4.14 Test Wave Data of Model 3, Set 2

model# 3 (set2) **Experiment Date:** August 18, 2004

Computer Input		Probe Measurements		Reflection Analysis		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,12	3,22	3,05	8,12	0,121
3,97	8,47	3,42	3,29	3,15	8,33	0,152
4,19	8,71	3,58	3,44	3,30	8,39	0,065
4,45	8,95	4,28	4,07	3,43	8,54	0,167
4,70	9,18	4,44	3,67	3,54	8,82	0,201
4,97	9,41	4,76	4,04	3,91	8,82	0,097
5,23	9,63	4,93	4,10	4,45	9,24	0,055
5,50	9,85	5,08	4,59	4,17	9,49	0,106
5,77	10,06	5,59	4,66	4,37	9,59	0,163
6,04*	10,27	5,72	4,91	4,76	9,88	0,116
6,31**	10,47	5,97	5,13	5,09	10,06	0,080

* Breaking at the toe of the structure

** Broken waves

The results of observation of the displaced armor stones, run-up and water spray of Set 1 and Set 2 experiments are given in Table 4.15 and Table 4.16 .

Table 4.15 Results of Set 1 Experiments on Model 3

(Damage, Wave Run-up and Water Spray)

DATE: August 17, 2004 (Set#1 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	-	-	-	mid lower	-
4,19 8,71	9	-	-	-	-	-	-	-	mid blue layer	M
4,45 8,95	9	-	-	-	-	1(u) 5(d)	2(d)	-	upper blue layer	M/T
4,70 9,18	9	-	-	-	-	1(u) 5(d)	2(d)	-	lower yellow	T/S
4,97 9,41	9	-	-	-	-	2(u) 5(d)	4(d)	-	mid yellow	S
5,23 9,63	9	-	-	1(d)	-	2(u) 7(d)	4(d)	-	lower purple	E
5,50 9,85	9	-	-	1(d)	-	2(u) 10(d)	5(d)	-	mid purple	E
5,77 10,06	9	-	-	1(d)	-	2(u) 17(d)	14(d)	-	upper purple	E
6,04 10,27	9	-	-	1(d)	-	2(u) 26(d)	16(d)	-	mid purple	E
6,31 10,47	9	-	-	1(d)	-	2(u) 27(d)	16(d)	-	upper yellow	E

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Table 4.16 Results of Set 2 Experiments on Model 3
(Damage, Wave Run-up and Water Spray)

DATE: August 18, 2004 (Set#2 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	1(d)	1(d)	-	lower mid blue	-
4,19 8,71	9	-	-	-	-	1(d)	1(d)	-	mid blue layer	M
4,45 8,95	9	-	-	-	-	2(d)	3(d)	-	upper blue layer	M
4,70 9,18	9	-	-	-	-	2(d)	3(d)	-	lower yellow	T
4,97 9,41	9	-	-	-	-	2(d)	5(d)	-	mid yellow	S
5,23 9,63	9	-	-	1(d)	-	9(d)	11(d)	-	lower purple	E
5,50 9,85	9	-	-	1(d)	-	1(u) 11(d)	13(d)	-	mid purple	E
5,77 10,06	9	-	-	1(d)	-	2(u) 18(d)	13(d)	-	upper purple	E
6,04 10,27	9	-	-	1(d)	-	2(u) 24(d)	17(d)	-	mid purple	E
6,31 10,47	9	-	-	1(d)	-	2(u) 26(d)	17(d)	-	upper yellow	E

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Using Table 4.15 and 4.16 local and total damages for Set 1 and Set 2 experiments were calculated and presented in Table 4.17 and 4.18.

Table 4.17 Local and Total Damage (%) of the Set 1 Experiment on Model 3

	Colored Sections For Model # 3										Date : August 17, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***263***		***88***		***149***		***151***		***139***		***439***		***351***		***790***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,45	0	0,00%	0	0,00%	6	4,03%	2	1,32%	0	0,00%	8	1,82%	0	0,00%	1,01%
4,70	0	0,00%	0	0,00%	6	4,03%	2	1,32%	0	0,00%	8	1,82%	0	0,00%	1,01%
4,97	0	0,00%	0	0,00%	7	4,70%	4	2,65%	0	0,00%	11	2,51%	0	0,00%	1,39%
5,23	1	0,38%	0	0,00%	9	6,04%	4	2,65%	0	0,00%	13	2,96%	1	0,28%	1,77%
5,50	1	0,38%	0	0,00%	12	8,05%	5	3,31%	0	0,00%	17	3,87%	1	0,28%	2,28%
5,77	1	0,38%	0	0,00%	19	12,75%	14	9,27%	0	0,00%	33	7,52%	1	0,28%	4,30%
6,04	1	0,38%	0	0,00%	28	18,79%	16	10,60%	0	0,00%	44	10,02%	1	0,28%	5,70%
6,31	1	0,38%	0	0,00%	29	19,46%	16	10,60%	0	0,00%	45	10,25%	1	0,28%	5,82%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

Table 4.18 Local and Total Damage (%) of the Set 2 Experiment on Model 3

	Colored Sections For Model # 3										Date : August 18, 2004 (SET2)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***263***		***88***		***149***		***151***		***139***		***439***		***351***		***790***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	1	0,67%	1	0,66%	0	0,00%	2	0,46%	0	0,00%	0,25%
4,19	0	0,00%	0	0,00%	1	0,67%	1	0,66%	0	0,00%	2	0,46%	0	0,00%	0,25%
4,45	0	0,00%	0	0,00%	2	1,34%	3	1,99%	0	0,00%	5	1,14%	0	0,00%	0,63%
4,70	0	0,00%	0	0,00%	2	1,34%	3	1,99%	0	0,00%	5	1,14%	0	0,00%	0,63%
4,97	0	0,00%	0	0,00%	2	1,34%	5	3,31%	0	0,00%	7	1,59%	0	0,00%	0,89%
5,23	1	0,38%	0	0,00%	9	6,04%	11	7,28%	0	0,00%	20	4,56%	1	0,28%	2,66%
5,50	1	0,38%	0	0,00%	12	8,05%	13	8,61%	0	0,00%	25	5,69%	1	0,28%	3,29%
5,77	1	0,38%	0	0,00%	20	13,42%	13	8,61%	0	0,00%	33	7,52%	1	0,28%	4,30%
6,04	1	0,38%	0	0,00%	26	17,45%	17	11,26%	0	0,00%	43	9,79%	1	0,28%	5,57%
6,31	1	0,38%	0	0,00%	28	18,79%	17	11,26%	0	0,00%	45	10,25%	1	0,28%	5,82%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of stones took place in the red and the silver stripes which were the stripes forming th berm. When the damage curves and tables are examined, it is seen that the local damages in the red and silver stripes forming the upper section of berm are very critical. They are leading to a damage value of 20%. However, the total damage does not reach 10% which is the upper critical damage limit. This is shown on the Figure 4.3 and Figure 4.4.

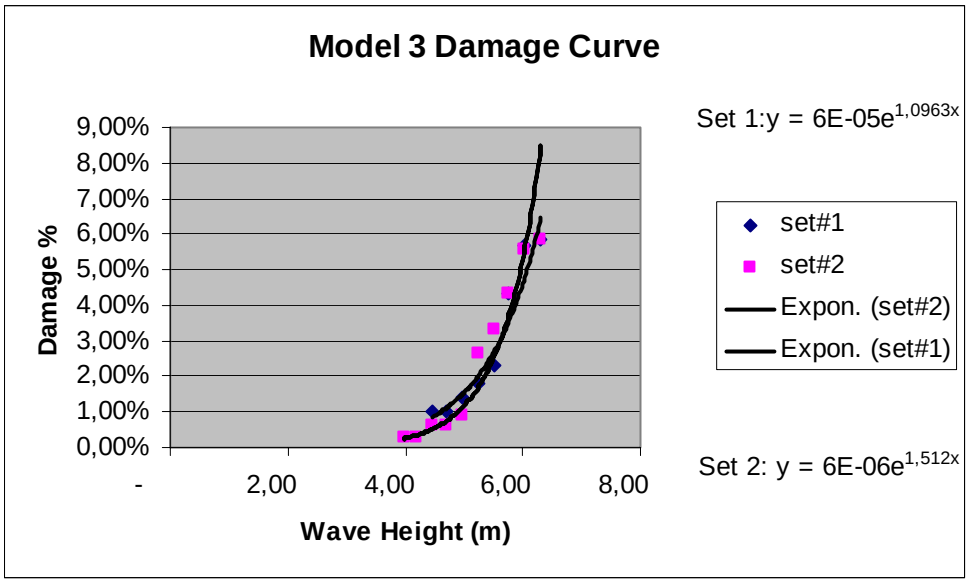

Figure 4.3 Damage vs. Wave Height Curve of Set1 and Set2 Experiments Model 3

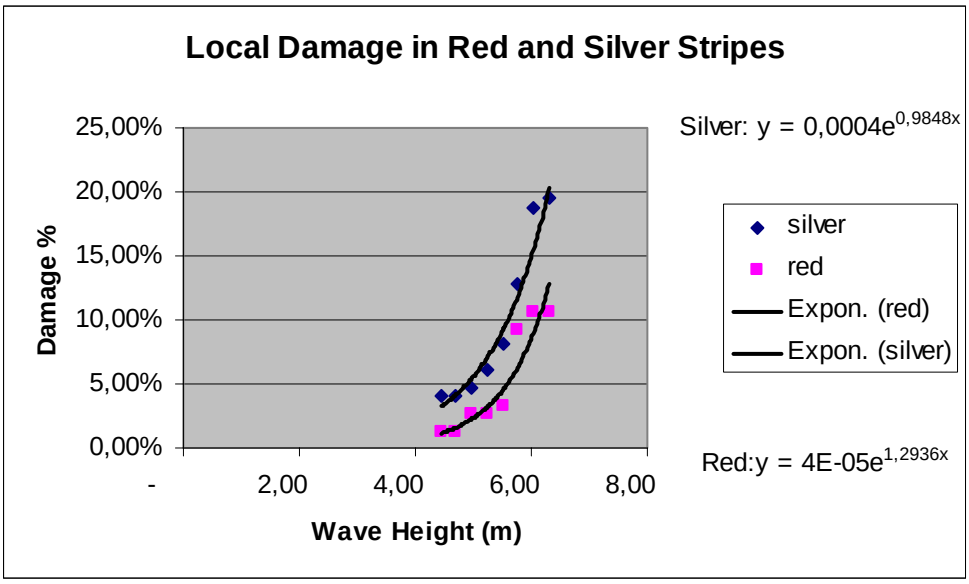

Figure 4.4 Local Damage vs. Wave Height Curve of Set1 and Set2 Experiments on Model 3

As it is seen from Fig. 4.3 damage curves for Set 1 and Set 2 experiments are in good agreement.

Figures 4.3 and 4.4 shows that Model 3 encounters critical damages in the stripes forming the berm. In contrast, when the local damage is analyzed, it does not exceed the critical damage percentage (10%). In addition to that, water spray and run-up conditions are also play a hazardous role on the structure. These results clearly displays the importance of energy dissipation on the berm that affects the stability of the structure.

4.4 Experiments on Model 4:

4.4.1 Set 1 and Set 2 Experiments

The model (Fig. 3.6) was constructed with 15 meters berm width. In this model armor units forming the back armor layer were changing from (4-6) tons to (2-6) tons in order to see the effect of back armor layer on the stability of the structure.

The same design wave height and period which were selected according to the wave climate and regional studies at the beginning of the experimental works were used also for this cross-section. All these waves forming the storm were given for a duration of 9 minutes contributing to a storm of 8 hours. The wave data of the model is given in Table 4.19 and Table 4.20 for Set 1 and Set 2 experiments.

Table 4.19 Test Wave Data of Model 4, Set 1

model# 4 (set1) **Experiment Date:** September 2, 2004

Computer Input		Probe Measurements		Reflection Analysis		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,17	3,01	3,39	8,12	0,098
3,97	8,47	3,23	3,07	3,56	8,36	0,134
4,19	8,71	3,67	3,11	3,23	8,40	0,118
4,45	8,95	4,21	3,27	4,23	8,63	0,087
4,70	9,18	4,13	3,32	3,85	8,81	0,174
4,97	9,41	4,67	3,72	4,27	8,73	0,196
5,23	9,63	4,87	4,35	4,38	9,17	0,099
5,50	9,85	4,81	4,27	4,19	9,45	0,085
5,77	10,06	5,31	4,56	5,04	9,62	0,178
6,04*	10,27	5,47	5,43	6,12	9,86	0,179
6,31**	10,47	6,03	5,91	5,58	10,06	0,159

* Breaking at the toe of the structure
** Broken waves

Table 4.20 Test Wave Data of Model 4, Set 2

model# 4 (set2) **Experiment Date:** September 2, 2004

Computer Input		Probe Measurements		Reflection Analysis		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,11	3,04	3,41	8,12	0,098
3,97	8,47	3,32	3,07	3,54	8,35	0,140
4,19	8,71	3,59	3,14	3,38	8,38	0,107
4,45	8,95	4,22	3,57	4,17	8,63	0,084
4,70	9,18	4,17	3,41	3,82	8,79	0,175
4,97	9,41	4,68	3,74	4,31	8,78	0,188
5,23	9,63	4,91	4,35	4,37	9,17	0,105
5,50	9,85	4,85	4,04	4,09	9,40	0,100
5,77	10,06	5,43	4,81	5,39	9,63	0,191
6,04*	10,27	5,48	5,28	6,15	9,88	0,210
6,31**	10,47	6,06	5,79	5,61	10,04	0,168

* Breaking at the toe of the structure
** Broken waves

The results of observation of the displaced armor stones, run-up and water spray of Set 1 and Set 2 experiments are given in Table 4.21 and Table 4.22.

Table 4.21 Results of Set 1 Experiments on Model 4
(Damage, Wave Run-up and Water Spray)

DATE: September 2, 2004 (Set#1 Experiments)										
Ho (m.) To (sec.)	Duration (min.)	**D A M A G E**							**Run-up**	**Water Spray**
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	1(d)	-	-	lower mid blue layer	-
4,19 8,71	9	-	-	-	-	2(d)	-	-	mid blue layer	M
4,45 8,95	9	-	-	-	-	5(d)	-	-	mid blue layer	M
4,70 9,18	9	-	-	-	-	5(d)	-	-	upper mid blue layer	M
4,97 9,41	9	-	-	-	-	7(d)	-	-	upper blue layer	M
5,23 9,63	9	-	-	-	-	13(d)	-	1(d)	mid yellow layer	S
5,50 9,85	9	-	-	-	-	17(d)	1(d)	1(d)	upper yellow layer	S/E
5,77 10,06	9	-	-	-	-	24(d)	1(d)	1(d)	lower purple layer	E
6,04 10,27	9	-	-	-	-	38(d)	1(d)	1(d)	lower purple layer	E
6,31 10,47	9	-	-	-	-	38(d)	1(d)	1(d)	lower mid purple layer	E
NOTES:	1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.									
	2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.									
	3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**									
	4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.									

Table 4.22 Results of Set 2 Experiments on Model 4
(Damage, Wave Run-up and Water Spray)

DATE: September 2, 2004 (Set#2 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	-	-	-	lower mid blue	-
4,19 8,71	9	-	-	-	-	2(d)	-	-	mid blue layer	M
4,45 8,95	9	-	-	-	-	3(d)	-	-	mid blue layer	M
4,70 9,18	9	-	-	-	-	4(d)	-	-	upper mid blue	M
4,97 9,41	9	-	-	-	-	7(d)	-	-	upper blue layer	M
5,23 9,63	9	-	-	-	-	12(d)	-	-	mid yellow	S
5,50 9,85	9	-	-	-	-	12(d)	1(d)	-	upper yellow	S/E
5,77 10,06	9	-	-	-	-	18(d)	1(d)	-	lower purple	E
6,04 10,27	9	-	-	-	-	20(d)	2(d)	-	lower purple	E
6,31 10,47	9	-	-	-	-	26(d)	2(d)	-	lower mid	E

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Using Table 4.21 and 4.22 local and total damages for Set 1 and Set 2 experiments were calculated and presented in Table 4.23 and 4.24.

Table 4.23 Local and Total Damage (%) of the Set 1 Experiment on Model 4

	Colored Sections For Model # 4										Date : September 2, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***430***		***132***		***391***		***399***		***391***		***1181***		***562***		***1743***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	1	0,26%	0	0,00%	0	0,00%	1	0,08%	0	0,00%	0,06%
4,19	0	0,00%	0	0,00%	2	0,51%	0	0,00%	0	0,00%	2	0,17%	0	0,00%	0,11%
4,45	0	0,00%	0	0,00%	5	1,28%	0	0,00%	0	0,00%	5	0,42%	0	0,00%	0,29%
4,70	0	0,00%	0	0,00%	5	1,28%	0	0,00%	0	0,00%	5	0,42%	0	0,00%	0,29%
4,97	0	0,00%	0	0,00%	7	1,79%	0	0,00%	0	0,00%	7	0,59%	0	0,00%	0,40%
5,23	0	0,00%	0	0,00%	13	3,32%	0	0,00%	1	0,26%	14	1,19%	0	0,00%	0,80%
5,50	0	0,00%	0	0,00%	17	4,35%	1	0,25%	1	0,26%	19	1,61%	0	0,00%	1,09%
5,77	0	0,00%	0	0,00%	24	6,14%	1	0,25%	1	0,26%	26	2,20%	0	0,00%	1,49%
6,04	0	0,00%	0	0,00%	38	9,72%	1	0,25%	1	0,26%	40	3,39%	0	0,00%	2,29%
6,31	0	0,00%	0	0,00%	38	9,72%	1	0,25%	1	0,26%	40	3,39%	0	0,00%	2,29%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

Table 4.24 Local and Total Damage (%) of the Set 2 Experiment on Model 4

	Colored Sections For Model # 4										Date : September 2, 2004 (SET2)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***430***		***132***		***391***		***399***		***391***		***1181***		***562***		***1743***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	2	0,51%	0	0,00%	0	0,00%	2	0,17%	0	0,00%	0,11%
4,45	0	0,00%	0	0,00%	3	0,77%	0	0,00%	0	0,00%	3	0,25%	0	0,00%	0,17%
4,70	0	0,00%	0	0,00%	4	1,02%	0	0,00%	0	0,00%	4	0,34%	0	0,00%	0,23%
4,97	0	0,00%	0	0,00%	7	1,79%	0	0,00%	0	0,00%	7	0,59%	0	0,00%	0,40%
5,23	0	0,00%	0	0,00%	12	3,07%	0	0,00%	0	0,00%	12	1,02%	0	0,00%	0,69%
5,50	0	0,00%	0	0,00%	12	3,07%	1	0,25%	0	0,00%	13	1,10%	0	0,00%	0,75%
5,77	0	0,00%	0	0,00%	18	4,60%	1	0,25%	0	0,00%	19	1,61%	0	0,00%	1,09%
6,04	0	0,00%	0	0,00%	20	5,12%	2	0,50%	0	0,00%	22	1,86%	0	0,00%	1,26%
6,31	0	0,00%	0	0,00%	26	6,65%	2	0,50%	0	0,00%	28	2,37%	0	0,00%	1,61%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of stones took place in the red and the silver stripes which were the stripes forming the berm. However, when the damage curves and tables were examined, it was observed that neither local nor total damage reached the 10%, which is the upper critical damage limit. This is shown on the Figure 4.5

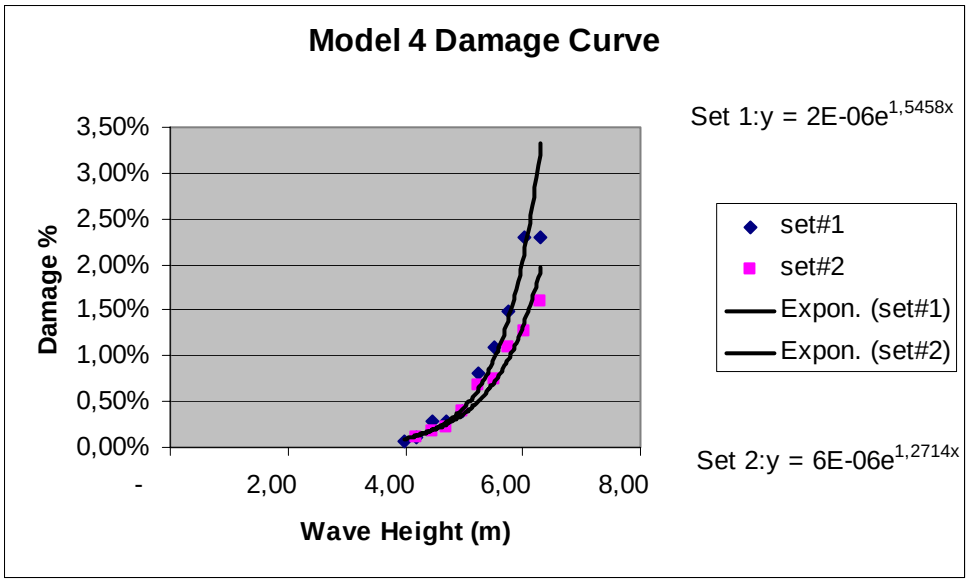

Figure 4.5 Damage vs. Wave Height Curve of Set1 and Set2 Experiments Model 4

When the results of experiments are examined, the major outcome is the effect of armor unit weight change in the back armor layer on the front armor layer. It causes an increase in the local damage of the layers forming the front armor layer and the total damage of the structure. In addition, this model is stable under the storm conditions.

As it is seen from Fig. 4.5 damage curves for Set 1 and Set 2 experiments gives very close results.

Based on this outcome, damage value observed for Model 4 was still below 2.50%.

4.5 Experiments on Model 5

4.5.1 Set 1 and Set 2 Experiments

The Model (Fig. 3.7) was constructed with 10 meters berm width. In this model armor units forming the back armor layer were changing from (4-6) tons to (2-6) tons in order to see the effect of back armor layer on the stability of the structure.

The same design wave height and period which were selected according to the wave climate and regional studies at the beginning of the experimental works were used also for this cross-section. The wave data of the model is given in Table 4.25 and Table 4.26 for Set 1 and Set 2 experiments.

Table 4.25 Test Wave Data of Model 5, Set 1

model# 5 (set1) **Experiment Date:** August 31, 2004

Computer Input		Probe Measurements		Reflection Analysis		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,04	3,13	3,03	8,13	0,101
3,97	8,47	3,17	3,29	3,24	8,38	0,163
4,19	8,71	3,34	3,51	3,44	8,37	0,086
4,45	8,95	4,26	3,76	3,53	8,59	0,132
4,70	9,18	4,01	3,41	3,48	8,83	0,241
4,97	9,41	4,56	3,71	4,01	8,77	0,135
5,23	9,63	4,91	4,07	4,27	9,18	0,070
5,50	9,85	4,75	4,35	3,82	9,42	0,111
5,77	10,06	5,43	4,10	4,25	9,64	0,196
6,04*	10,27	5,18	5,28	5,43	9,91	0,216
6,31**	10,47	5,95	5,59	5,54	10,07	0,143

* Breaking at the toe of the structure
** Broken waves

Table 4.26 Test Wave Data of Model 5, Set 2

model# 5 (Set2) Experiment Date: August 31, 2004						
Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,01	3,16	3,04	8,12	0,112
3,97	8,47	3,17	3,26	3,19	8,36	0,169
4,19	8,71	3,31	3,55	3,41	8,37	0,084
4,45	8,95	4,22	3,72	3,49	8,57	0,144
4,70	9,18	3,96	3,44	3,50	8,82	0,246
4,97	9,41	4,36	3,72	4,05	8,76	0,137
5,23	9,63	4,87	4,04	4,25	9,22	0,077
5,50	9,85	4,71	4,32	3,81	9,43	0,114
5,77	10,06	5,37	4,07	4,20	9,65	0,205
6,04*	10,27	5,28	5,19	5,51	9,87	0,213
6,31**	10,47	5,87	5,81	5,61	10,08	0,145

* Breaking at the toe of the structure

** Broken waves

The results of observation of the displaced armor stones, run-up and water spray of Set 1 and Set 2 experiments are given in Table 4.27 and Table 4.28 .

Table 4.27 Results of Set 1 Experiments on Model 5

(Damage, Wave Run-up and Water Spray)

DATE: August 31, 2004 (Set#1 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	1(d)	1(d)	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	1(d)	1(d)	-	lower blue layer	-
4,19 8,71	9	-	-	-	-	1(d)	1(d)	-	lower mid blue	-
4,45 8,95	9	-	-	-	-	3(d)	3(d)	-	mid blue layer	-
4,70 9,18	9	-	-	-	-	1(u) 3(d)	3(d)	-	upper mid blue	-
4,97 9,41	9	-	-	-	-	1(u) 5(d)	3(d)	-	upper blue layer	-
5,23 9,63	9	-	-	-	-	1(u) 12(d)	9(d)	-	upper yellow	S
5,50 9,85	9	-	-	-	-	1(u) 13(d)	12(d)	-	upper yellow	E
5,77 10,06	9	-	-	-	-	1(u) 20(d)	12(d)	-	lower purple	E
6,04 10,27	9	-	-	-	-	2(u) 20(d)	13(d)	-	mid purple	E
6,31 10,47	9	-	-	-	-	2(u) 22(d)	13(d)	-	lower purple	E

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Table 4.28 Results of Set 2 Experiments on Model 5
(Damage, Wave Run-up and Water Spray)

DATE: August 31, 2004 (Set#2 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	1(d)	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	-	3(d)	-	lower blue layer	-
4,19 8,71	9	-	-	-	-	1(u)	3(d)	-	lower mid blue	-
4,45 8,95	9	-	-	-	-	2(u)	3(d)	1(d)	mid blue layer	-
4,70 9,18	9	-	-	-	-	4(u)	3(d)	1(d)	upper mid blue	-
4,97 9,41	9	-	-	-	-	4(u)	5(d)	1(d)	upper blue layer	M
5,23 9,63	9	-	-	-	-	5(u) 3(d)	5(d)	1(d)	upper yellow	S
5,50 9,85	9	-	-	-	-	5(u) 3(d)	5(d)	1(d)	upper yellow	E
5,77 10,06	9	-	-	-	-	5(u) 4(d)	5(d)	1(d)	lower purple	E
6,04 10,27	9	-	-	-	-	5(u) 12(d)	9(d)	1(d)	mid purple	E
6,31 10,47	9	-	-	-	-	6(u) 14(d)	14(d)	1(d)	lower purple	E

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Using Table 4.27 and 4.28 local and total damages for Set 1 and Set 2 experiments were calculated and presented in Table 4.29 and 4.30.

Table 4.29 Local and Total Damage (%) of the Set 1 Experiment on Model 5

	Colored Sections For Model # 5										Date : August 31, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***430***		***132***		***225***		***275***		***269***		***769***		***562***		***1331***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	1	0,44%	1	0,36%	0	0,00%	2	0,26%	0	0,00%	0,15%
3,97	0	0,00%	0	0,00%	1	0,44%	1	0,36%	0	0,00%	2	0,26%	0	0,00%	0,15%
4,19	0	0,00%	0	0,00%	1	0,44%	1	0,36%	0	0,00%	2	0,26%	0	0,00%	0,15%
4,45	0	0,00%	0	0,00%	3	1,33%	3	1,09%	0	0,00%	6	0,78%	0	0,00%	0,45%
4,70	0	0,00%	0	0,00%	4	1,78%	3	1,09%	0	0,00%	7	0,91%	0	0,00%	0,53%
4,97	0	0,00%	0	0,00%	6	2,67%	3	1,09%	0	0,00%	9	1,17%	0	0,00%	0,68%
5,23	0	0,00%	0	0,00%	13	5,78%	9	3,27%	0	0,00%	22	2,86%	0	0,00%	1,65%
5,50	0	0,00%	0	0,00%	14	6,22%	12	4,36%	0	0,00%	26	3,38%	0	0,00%	1,95%
5,77	0	0,00%	0	0,00%	21	9,33%	12	4,36%	0	0,00%	33	4,29%	0	0,00%	2,48%
6,04	0	0,00%	0	0,00%	22	9,78%	13	4,73%	0	0,00%	35	4,55%	0	0,00%	2,63%
6,31	0	0,00%	0	0,00%	24	10,67%	13	4,73%	0	0,00%	37	4,81%	0	0,00%	2,78%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

Table 4.30 Local and Total Damage (%) of the Set 2 Experiment on Model 5

	Colored Sections For Model # 5										Date : August 31, 2004 (SET2)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***430***		***132***		***225***		***275***		***269***		***769***		***562***		***1331***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	1	0,36%	0	0,00%	1	0,13%	0	0,00%	0,08%
3,97	0	0,00%	0	0,00%	0	0,00%	3	1,09%	0	0,00%	3	0,39%	0	0,00%	0,23%
4,19	0	0,00%	0	0,00%	1	0,44%	3	1,09%	0	0,00%	4	0,52%	0	0,00%	0,30%
4,45	0	0,00%	0	0,00%	2	0,89%	3	1,09%	1	0,37%	6	0,78%	0	0,00%	0,45%
4,70	0	0,00%	0	0,00%	4	1,78%	3	1,09%	1	0,37%	8	1,04%	0	0,00%	0,60%
4,97	0	0,00%	0	0,00%	4	1,78%	5	1,82%	1	0,37%	10	1,30%	0	0,00%	0,75%
5,23	0	0,00%	0	0,00%	8	3,56%	5	1,82%	1	0,37%	14	1,82%	0	0,00%	1,05%
5,50	0	0,00%	0	0,00%	8	3,56%	5	1,82%	1	0,37%	14	1,82%	0	0,00%	1,05%
5,77	0	0,00%	0	0,00%	9	4,00%	5	1,82%	1	0,37%	15	1,95%	0	0,00%	1,13%
6,04	0	0,00%	0	0,00%	17	7,56%	9	3,27%	1	0,37%	27	3,51%	0	0,00%	2,03%
6,31	0	0,00%	0	0,00%	20	8,89%	14	5,09%	1	0,37%	35	4,55%	0	0,00%	2,63%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of stones took place in the red and the silver stripes which were the stripes forming the berm. When the damage curves and tables are examined, it is seen that the local damage in the silver stripe forming the upper section of berm is critical. It is leading to a damage value of 11%. However, the total damage does not reach 10%, which is the upper critical damage limit. This is shown on the Figure 4.6 and Figure 4.7.

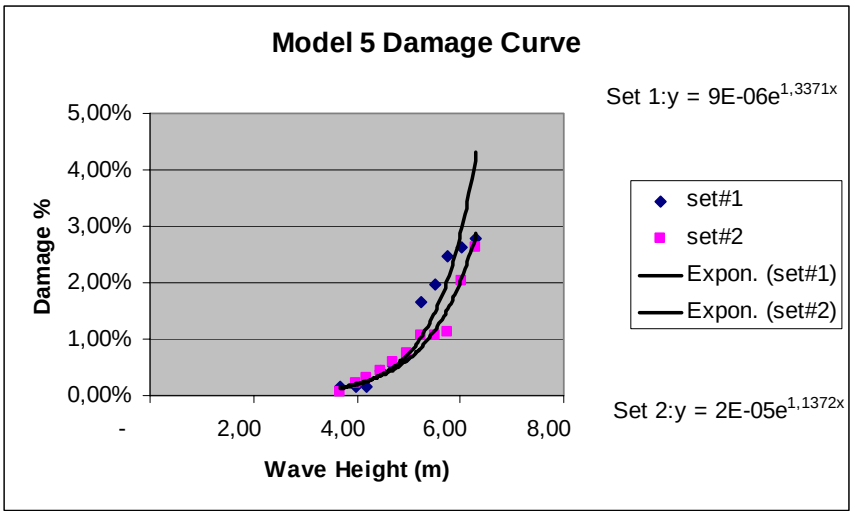

Figure 4.6 Damage vs. Wave Height Curve of Set1 and Set2 Experiments Model 5

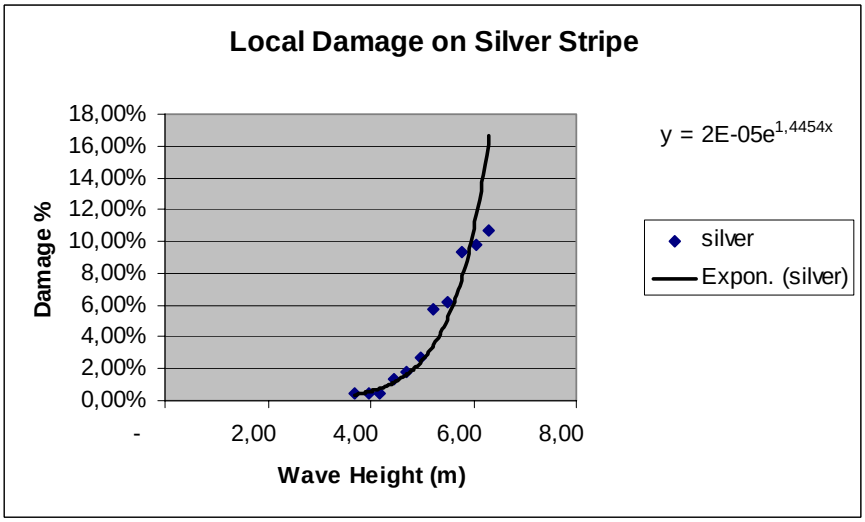

Figure 4.7 Local Damage vs. Wave Height Curve of Set1 and Set2 Experiments Model 5

As it is seen from Figure 4.6 damage curves for Set 1 and Set 2 experiments gives close results.

Since the one of the layers reach to a damage percentage exceeding the upper critical level of damage (10%), the structure is said to be unstable under severe wave conditions. This is because of the fact that, stability was related not only the total cumulative damage but also local damages in the layers forming the coastal defense structure.

4.6 Experiments E1, E2 and E3

After the completion of experiments on the alternative models, additional experiments were carried out to observe the effects of wave irregularity, wave steepness and storm duration in the model studies. For this purpose 3 additional sets of experiments were carried out by using the cross-section of Model 4 which was one of the tested cross-sections (Özler, 2004). Additional experiments are named as E1, E2 and E3 for wave irregularity, wave steepness and storm duration, respectively. The cross-sectional details are given in Figure 4.8 and details of each experiment are given in the following parts.

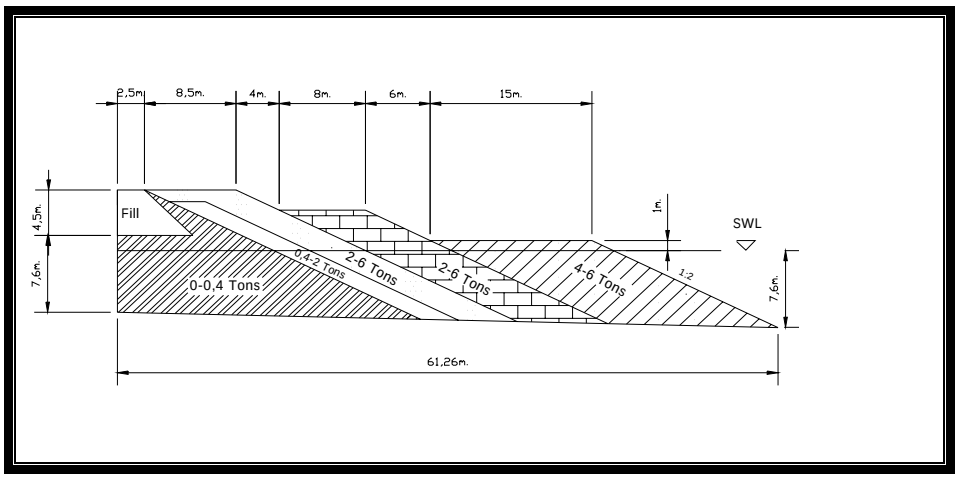

Figure 4.8 Cross-section of Model 4 (Prototype Values)

4.6.1 Experiment E1

In the model studies, regular waves were generated as significant wave heights representing a storm. However, in nature the waves do not have a regular pattern. In order to compare the results of model waves, generated as regular or irregular, on the damage of the breakwater cross-section, experiment E1 was carried out. DHI Wave Synthesizer was used for the generation of irregular waves. The surface elevation spectrum was chosen to be JONSWAP spectrum. Irregular waves generated in 11 time steps with 9 minutes durations. The wave data of the model is given in Table 4.31 for the experiment.

Wave heights and periods where the occurrence probability of each individual wave generally is in good agreement with Rayleigh distribution. Significant wave height, average of the highest 1/3 of n waves, is the statistical definition used to represent the wind waves.

Table 4.31 Test Wave Data of E1 Model 4

model# 4 (irregular) **Experiment Date:** September 8, 2004

Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	2,33	2,28	2,27	7,55	0,180
3,97	8,47	2,48	2,44	2,41	7,86	0,183
4,19	8,71	2,79	2,68	2,53	8,09	0,182
4,45	8,95	2,95	2,78	2,70	8,28	0,186
4,70	9,18	3,11	2,92	2,64	8,46	0,180
4,97	9,41	3,26	3,04	2,78	8,65	0,176
5,23	9,63	3,35	3,17	2,91	8,91	0,185
5,50	9,85	3,41	3,26	3,06	9,00	0,184
5,77	10,06	3,72	3,54	3,15	9,16	0,182
6,04*	10,27	3,98	3,61	3,25	9,40	0,189
6,31**	10,47	4,66	4,09	3,32	9,40	0,197

* Breaking at the toe of the structure
** Broken waves

The results of observation of the displaced armor stones, run-up and water spray of experiment are given in Table 4.32.

Table 4.32 Results of Experiment E1 on Model 4
(Damage, Wave Run-up and Water Spray)

DATE: September 8, 2004 (Set#1 Experiments)										
Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 8,47	9	-	-	-	-	-	-	-	lower blue layer	-
4,19 8,71	9	-	-	-	-	1(d)	-	-	mid blue layer	-
4,45 8,95	9	-	-	-	-	3(d)	-	-	mid blue layer	M
4,70 9,18	9	-	-	-	-	5(d)	-	-	upper mid blue layer	M
4,97 9,41	9	-	-	-	-	5(d)	-	-	upper blue layer	T
5,23 9,63	9	-	-	-	-	7(d)	-	-	upper yellow layer	S
5,50 9,85	9	-	-	-	-	10(d)	-	-	lower purple layer	S
5,77 10,06	9	-	-	-	-	11(d)	-	-	lower purple layer	E
6,04 10,27	9	-	-	-	-	11(d)	-	-	lower purple layer	E
6,31 10,47	9	-	-	-	-	13(d)	-	-	lower mid purple layer	E

NOTES:
1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.
2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.
3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**
4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Using Table 4.32 local and total damages for experiment were calculated and presented in Table 4.33.

Table 4.33 Local and Total Damage (%) of the Experiment E1 on Model 4

	Colored Sections For Model # 4 (Irregular)										Date : September 8, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***430***		***132***		***391***		***399***		***391***		***1181***		***562***		***1743***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	1	0,26%	0	0,00%	0	0,00%	1	0,08%	0	0,00%	0,06%
4,45	0	0,00%	0	0,00%	3	0,77%	0	0,00%	0	0,00%	3	0,25%	0	0,00%	0,17%
4,70	0	0,00%	0	0,00%	5	1,28%	0	0,00%	0	0,00%	5	0,42%	0	0,00%	0,29%
4,97	0	0,00%	0	0,00%	5	1,28%	0	0,00%	0	0,00%	5	0,42%	0	0,00%	0,29%
5,23	0	0,00%	0	0,00%	7	1,79%	0	0,00%	0	0,00%	7	0,59%	0	0,00%	0,40%
5,50	0	0,00%	0	0,00%	10	2,56%	0	0,00%	0	0,00%	10	0,85%	0	0,00%	0,57%
5,77	0	0,00%	0	0,00%	11	2,81%	0	0,00%	0	0,00%	11	0,93%	0	0,00%	0,63%
6,04	0	0,00%	0	0,00%	11	2,81%	0	0,00%	0	0,00%	11	0,93%	0	0,00%	0,63%
6,31	0	0,00%	0	0,00%	13	3,32%	0	0,00%	0	0,00%	13	1,10%	0	0,00%	0,75%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of the armor stones took place in the silver stripe, which was one of the stripes forming the berm. When the damage curves and tables are examined, it was observed that neither local nor total damage reached the 10%, which is the upper critical damage limit. This is shown on the Figure 4.9.

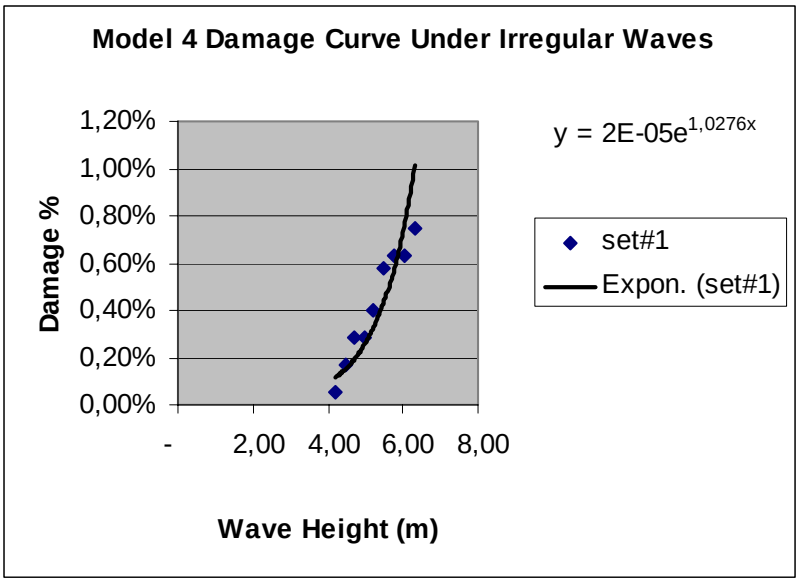

Figure 4.9 Damage vs. Wave Height Curve of E1 Model 4

When the outcome of the experiment with irregular wave (Figure 4.9) is compared with the outcome of the experiments with regular waves (Figure 4.5) on the same model, it was seen that test with regular waves is much more critical than the test with irregular waves. It might be due to the fact that, during the test period of experiments with regular wave generation, 100% of the waves attacking the structure were of significant wave height. However, in case of irregular waves almost 84% of the waves attacking the structure were smaller than significant wave height.

4.6.2 Experiment E2

Wave steepness value was taken as 0.038 for the selected region as mentioned in part 3.3. In order to observe the effect of wave steepness the value increased to 0.043. Increased steepness causes the incoming waves to break at the toe of the structure, which will create the most critical condition from the stability point of view.

Wave heights kept same and corresponding wave period calculated by using the wave steepness value of 0.043. Wave heights and corresponding wave period values are given in the computer input column of Table 4.34. The results of reflection analysis results are also tabulated in Table 4.34.

Table 4.34 Test Wave Data of E2 Model 4

model# 4 (stpns.=0.043) Experiment Date: September 9, 2004

Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	7,41	3,11	3,14	3,03	7,29	0,215
3,97	7,69	3,72	3,41	3,60	7,48	0,152
4,19	7,90	3,57	3,44	3,32	7,62	0,214
4,45	8,14	3,75	3,51	3,81	8,02	0,096
4,70	8,37	4,19	3,47	3,89	8,19	0,159
4,97	8,61	3,98	3,54	4,12	8,27	0,150
5,23	8,83	5,15	4,04	3,89	8,40	0,144
5,50	9,05	5,18	3,85	4,04	8,58	0,100
5,77	9,27	4,97	4,19	4,85	8,80	0,184
6,04*	9,50	6,06	5,12	4,37	8,94	0,140
6,31*	9,70	6,15	5,28	5,01	9,25	0,076

* Breaking at the toe of the structure

The results of observation of the displaced armor stones, run-up and water spray of experiment are given in Table 4.35.

Table 4.35 Results of Experiment E2 on Model 4

(Damage, Wave Run-up and Water Spray)

DATE: September 9, 2004 (Set#1 Experiments)										
Ho (m.) To (sec.)	Duration (min.)	**D A M A G E**							**Run-up**	**Water Spray**
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 7,41	9	-	-	-	-	-	-	-	lower blue layer	-
3,97 7,69	9	-	-	-	-	-	-	-	lower blue layer	-
4,19 7,90	9	-	-	-	-	-	-	-	lower mid blue	-
4,45 8,14	9	-	-	-	-	-	-	-	mid blue layer	-
4,70 8,37	9	-	-	-	-	1(d)	-	-	upper blue layer	-
4,97 8,61	9	-	-	-	-	1(d)	-	-	upper blue layer	M
5,23 8,83	9	-	-	-	-	3(d)	-	-	upper mid	T/S
5,50 9,05	9	-	-	-	-	1(u) 4(d)	-	-	upper yellow	S
5,77 9,27	9	-	-	-	-	1(u) 4(d)	-	-	lower purple	E
6,04 9,50	9	-	-	-	-	1(u) 7(d)	-	-	lower purple	E
6,31 9,70	9	-	-	-	-	1(u) 18(d)	-	-	lower purple	E
NOTES:	1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.									
	2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.									
	3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**									
	4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.									

Using Table 4.35 local and total damages for experiment were calculated and presented in Table 4.36.

Table 4.36 Local and Total Damage (%) of the Experiment E2 on Model 4

	Colored Sections For Model # 4 (Steepness = 0.043)										Date : September 9, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***430***		***132***		***391***		***399***		***391***		***1181***		***562***		***1743***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
3,97	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,19	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,45	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0	0,00%	0,00%
4,70	0	0,00%	0	0,00%	1	0,26%	0	0,00%	0	0,00%	1	0,08%	0	0,00%	0,06%
4,97	0	0,00%	0	0,00%	1	0,26%	0	0,00%	0	0,00%	1	0,08%	0	0,00%	0,06%
5,23	0	0,00%	0	0,00%	3	0,77%	0	0,00%	0	0,00%	3	0,25%	0	0,00%	0,17%
5,50	0	0,00%	0	0,00%	5	1,28%	0	0,00%	0	0,00%	5	0,42%	0	0,00%	0,29%
5,77	0	0,00%	0	0,00%	5	1,28%	0	0,00%	0	0,00%	5	0,42%	0	0,00%	0,29%
6,04	0	0,00%	0	0,00%	8	2,05%	0	0,00%	0	0,00%	8	0,68%	0	0,00%	0,46%
6,31	0	0,00%	0	0,00%	19	4,86%	0	0,00%	0	0,00%	19	1,61%	0	0,00%	1,09%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of the armor stones took place in the silver stripe, which was one of the stripes forming the berm. When the damage curves and tables are examined, it was observed that neither local nor total damage reached the 10%, which is the upper critical damage limit. This is shown on the Figure 4.10.

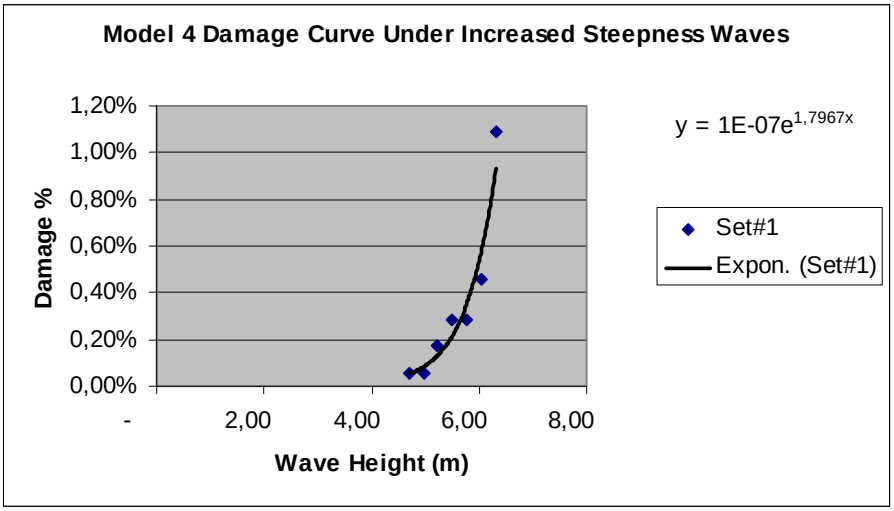

Figure 4.10 Damage vs. Wave Height Curve of Experiment E2 Model 4

When the results of the experiment E2 (steepness: 0.043) is compared with the results of the previous experiments (steepness: 0.038) done on Model 4, for the increased steepness of waves attacking the structure the damage level of the structure is smaller.

In general, as the steepness is increased the chance of waves breaking at larger depths is increased. Therefore, structure is likely to expose to broken waves resulting in lower damage.

4.6.3 Experiment E3

Model 4 (Fig. 3.6) was tested with individual regular waves generated for a duration of 12 minutes in order to see the affect of increase in the number of waves attacking the structure on the stability and damage level of the structure.

The same design wave height and period which were selected according to the wave climate and regional studies at the beginning of the experimental works were used also for this cross-section. The wave data of the model is given in Table 4.37 for the experiment.

Table 4.37 Test Wave Data of E3 Model 4

model# 4 (dur.=12min.) Experiment Date: September 16, 2004

Computer Input		**Probe Measurements**		**Reflection Analysis**		
H (m.)	*T (sec.)*	*1. Probe*	*7. Probe*	*H(m.)*	*T(sec.)*	*Cr (ref. coeff.)*
3,69	8,21	3,11	3,07	3,15	8,13	0,093
3,97	8,47	3,14	3,11	3,40	8,33	0,144
4,19	8,71	3,41	3,20	3,05	8,35	0,103
4,45	8,95	3,86	3,35	3,94	8,62	0,088
4,70	9,18	3,95	3,11	3,39	8,76	0,156
4,97	9,41	4,35	3,57	4,08	8,85	0,168
5,23	9,63	4,78	3,91	4,01	9,17	0,101
5,50	9,85	4,59	4,07	3,72	9,44	0,108
5,77	10,06	5,03	4,56	4,97	9,64	0,202
6,04*	10,27	5,06	4,91	5,59	9,88	0,195
6,31**	10,47	5,91	5,74	5,01	10,09	0,164

* Breaking at the toe of the structure
** Broken waves

The results of observation of the displaced armor stones, run-up and water spray of experiment are given in Table 4.38.

Table 4.38 Results of Experiment E3 on Model 4

(Damage, Wave Run-up and Water Spray)

DATE: September 16, 2004 (Set#1 Experiments)

Ho (m.) To (sec.)	Duration (min.)	DAMAGE							Run-up	Water Spray
		Purple	YellowI	Blue	Green	Silver	Red	YellowII		
3,69 8,21	12	-	-	-	-	1(d)	-	-	lower blue layer	-
3,97 8,47	12	-	-	-	-	4(d)	1(d)	-	lower mid blue layer	-
4,19 8,71	12	-	-	-	-	4(d)	1(d)	-	mid blue layer	M
4,45 8,95	12	-	-	-	-	8(d)	1(d)	-	mid blue layer	M
4,70 9,18	12	-	-	-	-	8(d)	1(d)	-	upper mid blue layer	M
4,97 9,41	12	-	-	-	-	9(d)	1(d)	-	upper blue layer	T
5,23 9,63	12	-	-	-	-	11(d)	1(d)	-	mid yellow layer	S
5,50 9,85	12	-	-	-	-	14(d)	1(d)	-	upper yellow layer	E
5,77 10,06	12	-	-	-	-	21(d)	1(d)	-	lower purple layer	E
6,04 10,27	12	-	-	-	-	29(d)	3(d)	-	lower purple layer	E
6,31 10,47	12	-	-	-	-	33(d)	3(d)	-	lower mid purple layer	E

NOTES:

1) At the last wave height which is 6,31 m. first 3-4 waves reached the lower 1/3 part of the purple layer but due to wave breaking which was between the first and second probes the run-up was reduced.

2) In the Run-up column, the level where the run-up reached is given in terms of the colored layers.

3) In the Water Spray column, the degree of water spray observed is described in terms of ; minor **(M)**, tolerable **(T)**, significant **(S)**, excessive **(E)**

4) In the Damage columns, the letters (u) & (d) represent "up" & "down" where; (u) means that the final position of the stone is an upper layer than its original position and (d) means the opposite.

Using Table 4.38 local and total damages for experiment were calculated and presented in Table 4.39.

Table 4.39 Local and Total Damage (%) of the Experiment E3 on Model 4

	Colored Sections For Model # 8 (Steepness = 0.043)										Date : September 16, 2004 (SET1)				
	Blue		Green (1/3)		Silver		Red		Yellow		FA		BA		Total Damage
# of stones	***430***		***132***		***391***		***399***		***391***		***1181***		***562***		***1743***
Wave Height (m)	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	D.S.	SD	
3,69	0	0,00%	0	0,00%	1	0,26%	0	0,00%	0	0,00%	1	0,08%	0	0,00%	0,06%
3,97	0	0,00%	0	0,00%	4	1,02%	1	0,25%	0	0,00%	5	0,42%	0	0,00%	0,29%
4,19	0	0,00%	0	0,00%	4	1,02%	1	0,25%	0	0,00%	5	0,42%	0	0,00%	0,29%
4,45	0	0,00%	0	0,00%	8	2,05%	1	0,25%	0	0,00%	9	0,76%	0	0,00%	0,52%
4,70	0	0,00%	0	0,00%	8	2,05%	1	0,25%	0	0,00%	9	0,76%	0	0,00%	0,52%
4,97	0	0,00%	0	0,00%	9	2,30%	1	0,25%	0	0,00%	10	0,85%	0	0,00%	0,57%
5,23	0	0,00%	0	0,00%	11	2,81%	1	0,25%	0	0,00%	12	1,02%	0	0,00%	0,69%
5,50	0	0,00%	0	0,00%	14	3,58%	1	0,25%	0	0,00%	15	1,27%	0	0,00%	0,86%
5,77	0	0,00%	0	0,00%	21	5,37%	1	0,25%	0	0,00%	22	1,86%	0	0,00%	1,26%
6,04	0	0,00%	0	0,00%	29	7,42%	3	0,75%	0	0,00%	32	2,71%	0	0,00%	1,84%
6,31	0	0,00%	0	0,00%	33	8,44%	3	0,75%	0	0,00%	36	3,05%	0	0,00%	2,07%

NOTES 1) **D.S.**= # of displaced stones in that particular section 2) **SD** = Spatial damage in that particular colored section 3) **FA** = Front armor layer,including sections *Silver, Red* and *Yellow* 4) **BA** = Back armor layer, including sections *Blue* and 1/3 of *Green*

During the observations, it was seen that the major displacement of the armor stones took place in the silver stripe, which was one of the stripes forming the berm. When the damage curves and tables are examined, it was observed that neither local nor total damage reached the 10%, which is the upper critical damage limit. This is shown on the Figure 4.11.

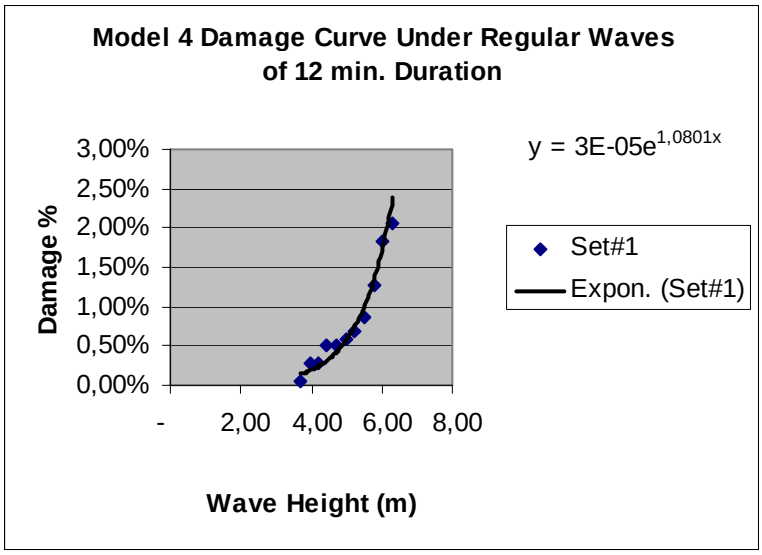

Figure 4.11 Damage vs. Wave Height Curve of Experiments E3 Model 4

When the results of the experiment E3 are compared with the results of the previous experiments (Figure 4.5) done on Model 4, the increase of the number of waves that attack the structure does not seriously effect the damage level of the structure. There occurs a slight change in the total and local damages of the structure. This shows us that the previously made experiments are reliable.

CHAPTER 5

CONCLUSION

The model studies were carried out on the cross-section of coastal defense structures (rubble-mound breakwaters) for the Eastern Black Sea Highway Project. Ordu-Giresun area had been selected as the pilot area to apply the model investigations (Dedeoğlu R. (2003) and Taşkıran İ. (2003)). In the present study, the same pilot area was selected in order to build on the previous studies. The major aim was to apply experimental studies to improve the previously proposed cross-sections and to obtain the most economical, safe and servicable cross-section.

During these studies, wave heights with their return period for the Eastern Black Sea Region were obtained from Wind and Wave Atlas for Turkish Coasts Project Report (Özhan and Abdalla, 1999). The most critical cross-section of the defense structure which was planned to be constructed in the Giresun coastal region was at depths of 7.50 meters that would be attacked by breaking waves of deep water significant wave height of H_s= 5.80 meters and significant period T_s= 9.90 seconds having a return period of 17 years (Özhan and Abdalla, 1999). Generally in Turkey,the life time of coastal protection structures is considered to be between 30 and 50 years. It was decided to use an average life time as 40 years. The probability of the structure to be under severe wave breaking action at least once in its lifetime was computed to be P=91% (Özler, 2004). In each experiment, 11 individual test waves forming a storm having the significant wave height and period discussed above were generated. In the experiments, the significant wave heights and periods were ranging between 3.69 and 6.31 meters, 8.21 and 10.47 seconds, respectively.

The starting point of the experimental studies was the model constructed with a scale of 1/31.08 which was the last tested cross-section by Dedeoğlu (2003) and Taşkıran (2003). The experimental works proceeded with the changes in berm widths and armor stone sizes to see the berm width and armor stone size effects on the stability of the structure. The models were constructed with a berm being 1 meter above still water level. Berm breakwaters are mostly constructed as being above still water level as the construction is much simpler than the ones constructed below still water level. When the outcomes were examined, it was observed that a cross-section with smaller sized armor stones forming the back armor layer (2-6 tons) with a berm width of 15 meters constructed was stable under the storm conditions. This berm width was the recommended width resulting in (0-5%) damage by Van Der Meer (CEM, 2003) using the given equations. In addition, the stated percentage damage was also obtained.

Tests were carried out on the models constructed by berm widths as 5-10-15 meters and back armor layer stone sizes as (4-6) tons and (2-6) tons.

Minimum cumulative total damage was observed as 1% on the Model 2 (Figure 3.4) which was constructed with 15 meters berm width and (4-6) tons front and back armor layer stone sizes.

Maximum total damage was observed on Model 3 (Figure 3.5) as 10% resulting in 20% local damage in the layers forming the berm. This was faced on the model having 5 meters berm width and (4-6) tons front and back armor layer stone sizes.

When the damage of models with the same berm width but different back armor stone sizes were compared, it was observed that the stone size reduction increased the cumulative local damage of the layers forming the berm. This might be due to the reason that, when smaller armor stone sizes are used at back armor layer porosity decreases which causes higher reflection resulting higher superposed wave heights at the berm.

Finally, when the cumulative total and local damages of the experiments on Models 1-5 were examined according to the stability and economy criterion, there occurred two cross-sections to be analyzed, Model 4 and Model 5. Model 4

(Figure 3.6) had a total cumulative damage percentage of 3.50 % having local cumulative damage below critical damage level (10%). However, Model 5 (Figure 3.7) had a total cumulative damage percentage of 4.50% but resulting in a 16% local cumulative damage exceeding the critical damage level. Therefore, Model 4 with 15 meters berm width and (2-6) tons and (4-6) tons sized armor units forming back and front armor layers, respectively, found to be stable under storm condition tested.

When the cumulative total damage of the experiment with irregular wave (Figure 4.9) was compared with the outcome of the experiments with regular waves (Figure 4.5) on the same model, it was seen that test with regular waves were more critical than the test with irregular waves both being under 5% damage. It might be because, during the test period of experiments with regular wave generation, 100% of the waves attacking the structure were of significant wave height. However, in case of irregular waves almost 84% of the waves attacking the structure were smaller than significant wave height. On the other hand, carrying out model studies with irregular waves are the recommended procedure since, irregular waves represent the wind waves in nature better than the regular waves.

Effect of increase in wave steepness was also tested with an additional set of experiment (E2). Wave steepness was increased from 0.038 to 0.043.The results of the experiment E2 (steepness: 0.043) showed that the damage percentage decreased to 1% from 3.5% for the same model tested with smaller steepness as the chance of waves breaking at higher depths before reaching the structure increased.

Lastly, Model 4 (Figure 4.6) was tested for a longer storm duration (E3) to see the effect of change in the number of waves attacking the structure. Durations of storms were increased from 8 hours to 11 hours. However, the increase of the number of waves that attack the structure did not seriously affect the damage level of the structure.

When berms were constructed above still water level, energy dissipation of the waves traveling along the width of the berm was increased due to the pores and impurities between the armor stones forming the berm. This resulted

in lower wave run-up and water spray when compared with the model investigations done on the berms being below still water level (Özler, 2004).

Toe protection is very important from failure point of view. In the present study only damage criteria is examined. However, for a widened work failure modes and protections should also be taken into consideration resulting in more advanced design of toe protection.

It is highly recommended that, in the future studies effect of filter layers must be studied, since the filter layers were kept same throughout the present study. In addition, irregularity impact should also be examined in order to clear up the misunderstood parts of irregular wave generation outcomes.

Economical analysis should be carried out for the recommended alternative.

An other recommendation for the future studies is based on artificial units. For the regions having rough climates like Eastern Black Sea, it might be a more economical solution to use artificial units.

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APPENDIX

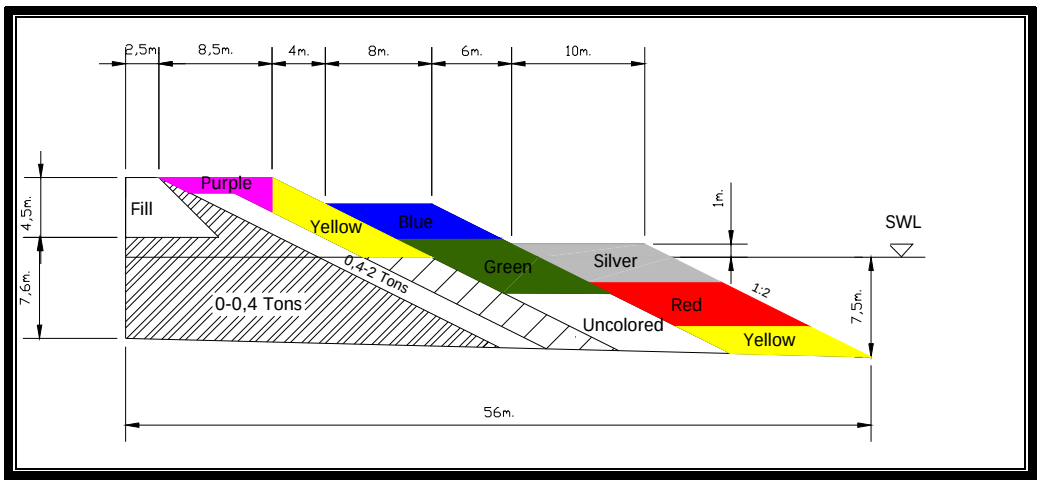

Figure A.1 Colored stripes of Model 4

Figure A.2 Front View of Model 4

Figure A.3 Side view of Model 3

Figure A.4 Wave effect and run-up

Figure A.5 Breaking of Waves on the Berm of Model 4

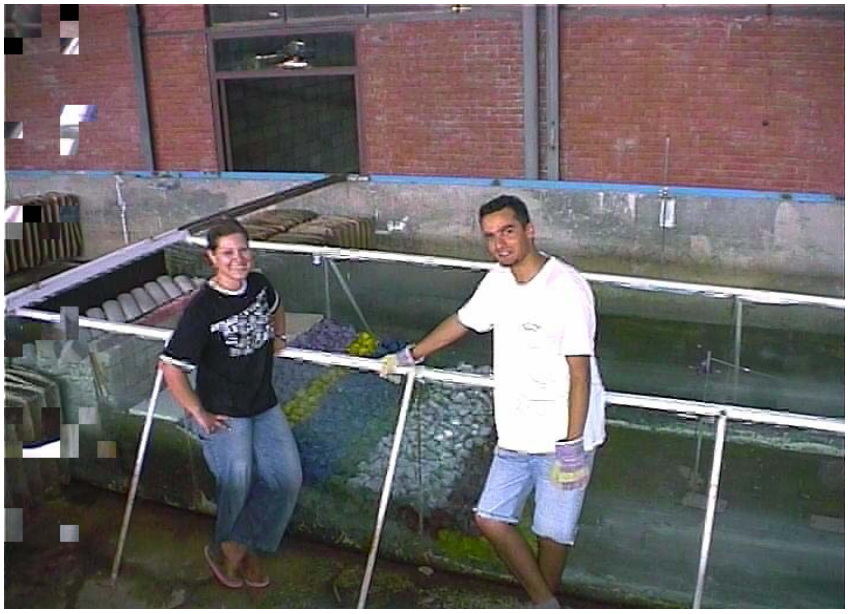

Figure A.6 Construction of Models