EXPERIMENTAL STUDY ON STABILITY OF DIFFERENT TYPES OF ARMOR UNITS USED IN SHORE PROTECTION STRUCTURE

M.Sc. Engineering Thesis

by

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Dhaka

November 2013

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Submitted to

Department of Water Resources Engineering,
Bangladesh University of Engineering and Technology, Dhaka
in partial fulfillment of the requirement for the degree of
Master of Science in Water Resources Engineering

Department of Water Resources Engineering
Bangladesh University of Engineering and Technology (BUET)
Dhaka

November 2013

Bangladesh University of Engineering and Technology, Dhaka

Department of Water Resources Engineering

Certification of Thesis

The thesis titled "**EXPERIMENTAL STUDY ON STABILITY OF DIFFERENT TYPES OF ARMOR UNITS USED IN SHORE PROTECTION STRUCTURE**", submitted by Md. Ismail Hossain, Roll No. 0411162055F, Session April 2011, to the Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Water Resources Engineering and approved as to its style and content. Examination held on November 10, 2013.

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Candidate's Declaration

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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ACKNOWLEDGEMENT

First of all, the author expresses his gratitude and reverence to the Almighty Allah for providing the capability to successfully complete the thesis. Then he expresses his profound gratitude and respect to his supervisor, Dr. Md. Ataur Rahman, Professor, Department of Water Resources Engineering, BUET for his constant supervision, proper guidance and help throughout the thesis work and for the report preparation. He makes the author interested and enthusiastic to the field of coastal hydraulics. His continuous direction, advice and help encouraged the author throughout the research work with a great extent.

Sincere appreciation is due to Dr. Md. Sabbir Mostafa Khan, Professor and Head, Department of Water Resources Engineering, BUET, for his timely co-operation and guidance.

The author also intends to express her gratitude to Dr. Md. Abdul Matin, Professor, Department of Water Resources Engineering, BUET, for his valuable comments, careful review and suggestion. He is also grateful to Dr. Md. Khorshed Alam, Former-Professor, Department of Water Resources Engineering, BUET, for his kind consent to be a member of the examination board. His precious comments, constructive criticism and suggestions in this study are duly appreciated.

The author is very much grateful to Sudip Sarker, postgraduate student, Department of WRE, BUET, for his sincere assistance in the collection of data during the laboratory experiments. The author also acknowledges the great help and support provided by all laboratory staff of Hydraulics and River Engineering Laboratory, DWRE, BUET.

Finally, the author would like to dedicate this dissertation to his mother who is the source of her constant encouragement. She is so much grateful to his family for their sacrifice and patience throughout the thesis work.

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Abstract

Protection of coast and shore against the erosive force of waves, currents and storm surges can be performed in many ways. Protection of coast and hinterland against flooding adds various types to the protective measure. The role of different types of armor unit is very important in the stability of shore protection structures. Stability of armor units depends on the slope of the bank, subsoil, filter and protection of toe. In this study, C.C. blocks, X-blocks and Tetrapods are considered as an armor unit. C.C. blocks are uniformly and staggeredly placed on the revetment in filter condition-1. Tetrapod and X- block were placed on the revetment in filter condition 1 & 2 (filter condition-1: stone chips were used and filter condition-2: stone chips were not used as filter materials).

To investigate the performance of various types of armor units, laboratory experimental studies are carried out in a two dimensional wave flume (21.3 m long, 0.76 m wide and 0.74 m deep) in Hydraulics and River Engineering Laboratory at Bangladesh University of Engineering and Technology. A set of experiment is carried out at 50 cm still water depth with fixed 1:4 slope for four different wave periods (1.5 sec, 1.6 sec, 1.8 sec and 2.0 sec) in the wave flume. Run duration was six minutes for each of 24 runs. A total of 24 run was conducted with six different conditions, the water surface elevations at different locations are measured manually.

In this study, Armor unit are designed for 15 cm wave height and 1:4 slopes by using Hudson (1961) equation. The Performance of C.C. block was found good when it was uniformly placed on the revetment for wave period of 1.5 sec but for wave period of 1.6, 1.8, and 2.0 sec revetment was unstable. Moreover, the revetment was stable when C.C. block was staggerdly placed on the revetment for wave period of 1.5 and 1.6 sec. but it was unstable for wave period of 1.8 and 2.0 sec. Again, the revetment was stable when tetrapod placed in filter condition-1 on the revetment for wave period of 1.5, 1.6, and 1.8 sec but for wave period of 2.0 sec the revetment was unstable. Finally, tetrapod was placed in filter condition-2 on the revetment and the performance of tetrapod was found well for all the wave periods. Performance of X-block was well when it was placed in filter condition-1 for wave period of 1.5 and 1.6 sec but the revetment was unstable for wave period of 1.8 and 2.0 sec. Again X-block was placed in filter condition-2 on the revetment and the performance of X-block in filter condition-2 was found well for wave period of 1.5, 1.6 and 1.8 sec but the revetment was unstable for wave period of 2.0 sec. So, the performance of tetrapod in filter condition-2 was better than any other types of block.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In many countries of the world, the coastal zones have become the subject of major concern due to favourable use of coastal areas. But this is limited because of the existence of wave actions, severe storm surges and tsunamis etc. Waves are generated and developed in seas, lakes, rivers or any other large mass of water mainly due to wind. It may be produced due to movement of marine vessels, explosion of earthquakes also. Worldwide erosion due to waves is a problem in the conservation of beaches and shoreline, maintenance of dock and harbour, reclamation of land for airport and industry, roads and dams, human settlement etc.

There are two basic types of wave erosion control methods. Those are vegetation and structural measures. Vegetation method involves plantation of trees and woody shrub and the mechanism to check wave erosion is the soil binding properties with large root system and dumping of wave energy along its propagation. It is widely used in shore, stream bank and human settlement. This method is environment friendly, but needs a certain time to be functional. It is suitable when land is cheap and available for reasonable width and length.

Structural measures are immediate measures which include sea wall, sea dikes, gravity wall, bulkheads, groins, jetties, revetments and breakwaters. Sea wall, groins, jetties are massive structure that dissipate full force of waves and adopted for shoreline protection. Sea dikes are onshore structure with the principal function of protecting low laying area against flooding. Bulkheads, gravity wall are the term for structures primarily intended to retain or prevent sliding of the land. Breakwaters are the front line defence, structure to protected shorelines against wave action. Breakwaters are built to reduce wave action in an area in the lee of the structure. Wave action is reduced through a combination of reflection and dissipation of incoming wave energy. Revetment is used as a direct protective structure against moderated waves.

There are various types armor units like loose stones and boulders, C.C. block, tetrapod, coreloc and X-block, tetrahedron, toskane, A-jacks, dolos and tribar etc used in shore protection work. Protective works against wave erosion in coastal region of Bangladesh normally consist of boulder and cement concrete (C.C.) blocks with revetment. The marine drive road in cox's bazaar has been protected by using C.C. block but this road was not sustained in long time. Damage was seen on the road. Now a day many developed countries in the world are protected their coast by using various types of armor units such as Tetrapod, X-block, Coreloc etc. In Bangladesh coastal bank protection by using armor unit is at initial stage.

Tetrapod and X-blocks are called armor units is a simple, robust and reliable armor unit. It has considerable structural integrity as an individual element and has a great hydraulic stability the armor layer. These are used for coastal applications typically in areas with rough wave climates or where insufficient quality and size of available quarry stone is available. Tetrapod and X-block can be manufactured in various size and are installed either a uniform or random pattern.

Coastal area lies in the southern part of Bangladesh and is open to sea. Besides waves produced by wind and tides, the coastal area is attacked by storm surges. The storm surges have been noted to be some 3m to 6m in height. Bank protection structures are subjected to waves and currents. In many occasions, wave forces cause failure of structures. Therefore, proper knowledge regarding wave action and related failure mechanisms of protection measures is of utmost important.

When armor units are installed in coastal embankment, presence of that structure will alter the flow pattern in its immediate neighbourhood, resulting in one or more of the following phenomena:

1. Formation of lee-wake vortices behind the structure.
2. Generation of wave turbulence.
3. Occurrence of reflection, diffraction and dissipated of waves energy.
4. Occurrence of wave breaking.

These phenomena results in dissipating wave energy and increased armor stability. Present study deals with the investigation of stability of the armor units used in shore protection work. Usually stability of armor units depends on wave height (H), water depth (h), thickness of armor units, number of armor units, density of armor units, placement pattern of armor units and as well as different conditions of filter layer.

In this study, a set of experiments will be carried out to evaluate the stability of armor units by using C.C. block, tetrapod and X-block used in shore protection work. A total twenty-four experimental runs will be carried out to compare the performance of armor units and to check the physical stability of armor units. To investigate the water surface profile wave heights, will be measured at five locations. Still water depth (h) will be kept 50 cm for all runs. By varying the frequency of wave paddle wave period will be varied. Test runs will be carried out for four different wave periods.

1.2 Objective

With the background stated above the specific objectives of this study are as follows:

(1) To conduct experimental investigation and evaluate the physical stability of revetment and falling apron consist of C.C. block, tetrapod and X-block used as armor units in shore protection structure.

(2) To compare the performance of different types of armor units under various wave condition.

1.3 Scope of study

The present study deals with an investigation of the performance on various type of armor unit used in coastal bank protection work. Performance of a hydraulic structure for armor units can be examined in this point of view. Finer sand and coarser sand are used for preparation of granular filter layer. Considering 1:4 fixed slope to examine hydraulic behaviour of armor unit. Geotextile and stone chips are also used on the revetment.

In this study, the effectiveness of armor unit work against wave action has been studied through laboratory experiment.

1.4 Organization of the thesis

The subject matter of this report has been arranged in five chapters. First chapter provides a background with rationale the study, objectives, scope of study and organization of this report. In Second chapter reviews of formulae and previous work in the same laboratory have been provided. The detailed descriptions of the laboratory experiments and data collection techniques and methodology have been included in the third chapter. In chapter four analyses of data with results have been discussed and this chapter is titles as "Data analysis result and result". Finally ‘conclusions and recommendation’ have been presented in chapter five.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Coastal bank erosion has been the subject of research for a long time. Current practice the design of bank protection work, different types of armor units and hydraulic aspects involved in the stability of bank protection structure are briefly discussed in this chapter. Types of failure of coastal bank, associated reasons, countermeasures and other relevant feature are also discussed.

2.2 Wave

A wave is the common terms for any periodic fluctuation in water height, velocity or pressure. Surface waves normally derive their energy from the winds. Waves have potential energy in the form of their surface displacement and kinetic energy in the motion of the water particles. Waves transmit this energy as they propagate.

Ocean wave generation:

When the wind is blowing on the sea, the surface exerts the gravitational force on the bottom layer of the wind. This, in turn, exerts the pull on the layer above it until it reaches the top-most layer. With the gravitational pull being different at each layer, the wind moves at a different speed. The top-most layer tumbles, forming a circular motion. This creates a downward pressure at the front and upward pressure at the rear of the surface, causing a wave.

Five factors influence the formation of wind wave:

i. Wind speed
ii. Distance of open water that the wind has blown over (called the fetch)
iii. Width of area affected by fetch
iv. Time duration the wind has blown over a given area
v. Water depth

All of these factors work together to determine the size of wind waves. The greater each of the variables, the larger the waves. Waves are characterized by (Fig 2.1):

i. Wave height
ii. Wave length
iii. Wave period
iv. Wave propagation direction.

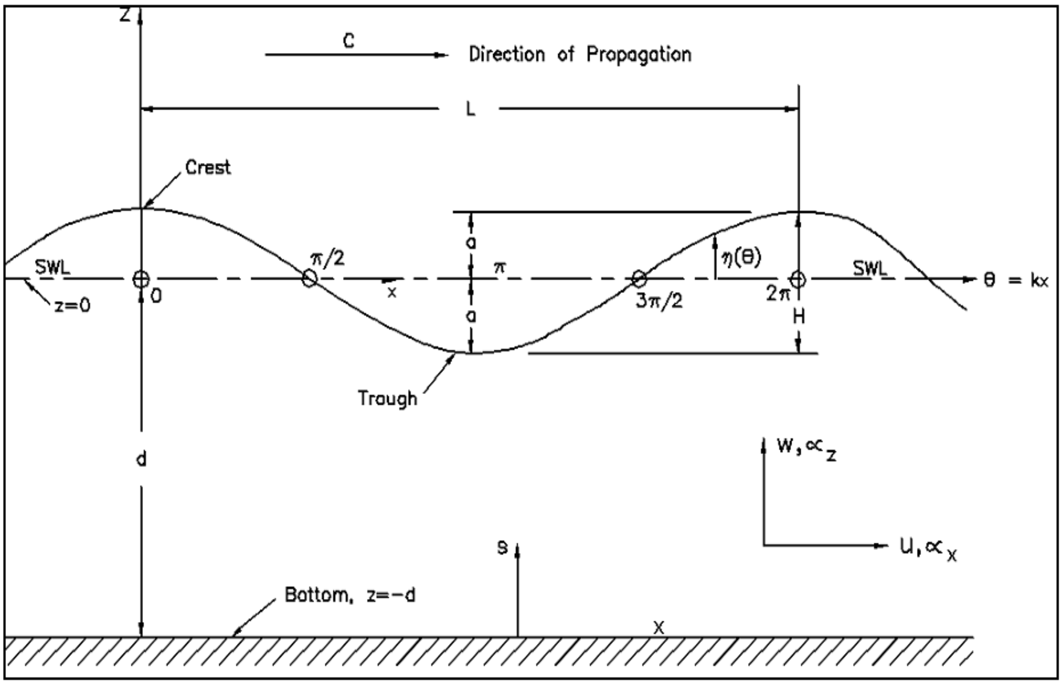


Fig 2.1: Definition sketch of wave

Wave height (H) is the vertical distance from the crest of a wave (the highest position of a wave) to the trough of the wave (the lowest position of the wave). For a given wind speed, many different wave lengths are produced and for each wave length many different wave heights are developed. The general relationship is that higher waves tend to have longer wave length (lower frequencies).

Wave length (L) is the horizontal distance from one wave crest to the next wave crest or the distance from one wave trough to the next wave trough. Although difficult to measure at sea, this parameter may be measured on aerial photograph.

Wave period (T) is the time, usually measured in seconds, that it takes for a complete wave cycle (crest to crest or trough to trough) to pass a given fixed point. It depends upon the speed of movement of the wave across the surface. It is the one characteristics of a wave that remains constant at all times, no matter what changes occur in height or length.

Other wave parameters include $\omega = 2\pi/T$ which is the angular or radian frequency, the wave number $k = 2\pi/L$, the phase velocity or wave celerity $C = L/T = \omega/k$, the wave steepness $\varepsilon = H/L$, the relative depth h/L and the relative wave height H/h. These are the most common parameters encountered in coastal practice. Wave motion can be defined in terms of dimensionless parameters such as H/L, H/h and h/L. The speed at which a wave form propagates is termed the phase velocity or wave celerity C. Since the distance travelled by a wave during one wave period is equal to one wave length, wave celerity can be related to the wave period and length by

$$C = \frac{L}{T} \tag{2.1}$$

An expression relating wave celerity to wavelength and water depth can be given as

$$C = \sqrt{\frac{gL}{2\pi} tanh\left(\frac{2\pi h}{L}\right)} \tag{2.2}$$

The equation below is termed as dispersion relation since it has been indicated that waves with different periods travel at different speeds. For a situation where more than one wave is present, the longer period wave will travel faster.

$$C = \frac{gT}{2\pi} tanh\left(\frac{2\pi h}{L}\right) \tag{2.3}$$

From Equation 2.2 and 2.3 an expression for wavelength as a function of depth and wave period may be obtained as

$$L = \frac{gT^2}{2\pi} tanh\left(\frac{2\pi h}{L}\right) = \frac{gT}{2\pi} tanh(kh) \tag{2.4}$$

To use Eq. 2.4 there involves some difficulty since the unknown L appears on both sides of the equation. Tabulated values of d/L and d/L_0 (SPM 1984) where L_0 is the deepwater wavelength may be used to simplify the solution of this Equation.

$$L_0 = \frac{gT^2}{2\pi} \tag{2.5}$$

2.2.1 Wave Classification

Ocean waves can be classified in various ways. One classification uses the forces which generate the waves. In ascending order of wave lengths we have:

1. Meteorological forcing (wind, air pressure); sea and swell belong to this category.
2. Earthquakes; they generate tsunamis, which are shallow water or long waves.
3. Tides (astronomical forcing); they are always shallow water or long waves.

Another classification is based on the frequency spectrum representation of all oceanic waves and distinguishes between capillary waves, gravity waves, long period waves, tides and trans tidal waves (Fig 2.2).

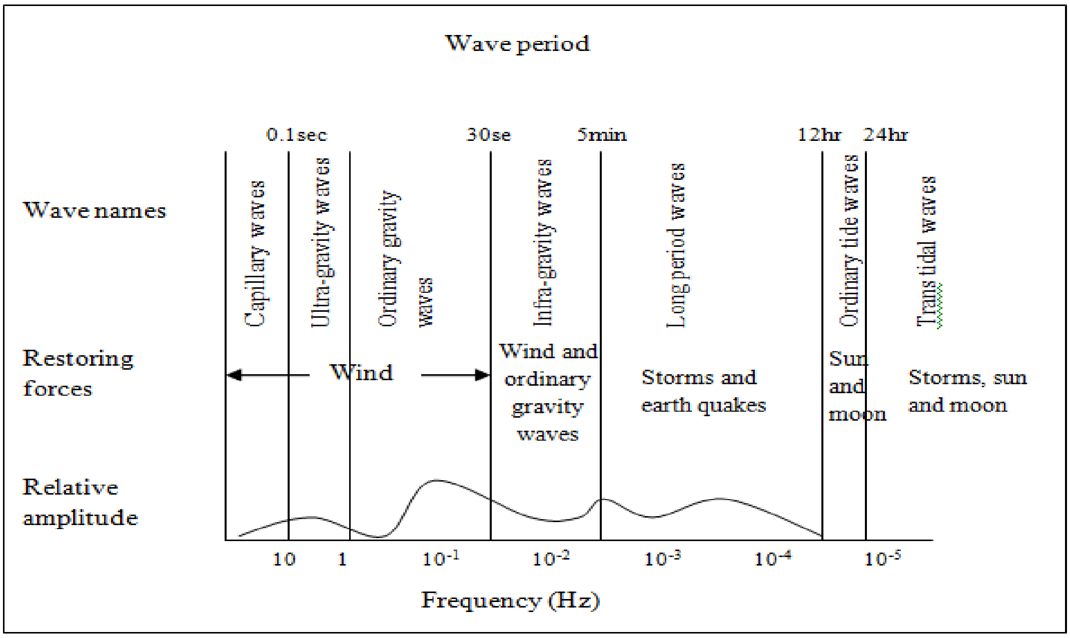


Fig 2.2: Classification of ocean waves according to wave period

Waves are classified in various ways. Ocean waves have a very wide range of periods. The energy of waves of fixed period is proportional to Hz, as shown in the Fig 2.2. This displays the predominant types of waves in the ocean, the names of the various waves for each period range, and the agents generating these waves. The Fig 2.2 shows that waves of the greatest energy concentration are wind waves. Wind waves are generated and developed by wind action stated above and their wave period is normally less than 10 to 15 sec, while heights of as much as 34 m have been reported. Swells consist of wind-generated waves that have traveled out of their generating area.

Usually, the most concentrated change that occurs to waves as they propagate forward takes place when they interact with a variety of structures, including beaches. When wave arrive at a structure, be floating or fixed, they will undergo some degree of reflection and dissipation. Moored floating structures allow a significant portion of the transmitted wave energy to directly pass the structure, but a component of the transmitted energy is produced by wave regeneration by the moving structures. Wave run-up and overtopping of stone-mound breakwaters will cause wave transmission and regeneration of waves on the lee side and energy may be transmitted through the structure if it is sufficiently permeable. Wave transmission is accomplished by direct transmission of waves over the submerged solid stone mound structures. There is a decrease in the transmitted energy owing to reflection and dissipation of some of the incident wave energy.

2.3 General Considerations for shoreline protection

A precondition for a successful shoreline restoration project is that all the parties involved have some understanding of the coastal morphological processes. They are then in a position to understand why the present situation has developed and why certain solutions will work and others will not.

The following should be considered in connection with shoreline protection and management projects:

1. Consider the coastal area as a dynamic natural landscape. Make only interventions in the coastal processes and in the coastal landscape if the interests of the society are more important than preserving the natural coastal resource.

2. Appoint special sections of the coast for natural development.
3. Demolish inexpedient old protection schemes and re-establish the natural coastal landscape where possible.
4. Minimize the use of coastal protection schemes, give high priority to the quality of the coast resource, and concentrate on shore protection.
5. Preserve the natural variation in the coastal landscapes.
6. Restrict new development/housing close to the coastline in the open uninhabited coastal landscape. Allow only such facilities, which require access to the sea.
7. Maintain and improve the public access to and along the beach, legally as well as in practice.
8. Reduce pollution and enhance sustainable utilization of coastal waters.

This leads to the practical guidelines for shore protection in connection with coast protection, shore protection and shore restoration projects.

2.4 Bank protection works

Protection of bank is the part and parcel of coastal engineering. Constructions having the primary function of preserving the profile of a watercourse within certain boundaries are known as bank and bed protection works. The principle behind these structures is to retain the bed and bank materials.

Function of bank protection works

The main function of bank protection works are-

i. To guide the coastal flow, and
ii. To prevent erosion of existing bank line.

Some additional functions of bank protection works are-

i. Preservation of ecological values,
ii. Preservation of recreational and landscape functions,
iii. Provision of visual guidance to navigation,
iv. A hydraulic function concerning the roughness of the profile and
v. Provision of a safe and expeditious passage of flood flow.

Classification

The various kinds of protective works can be broadly classified into two groups, those are

i. Direct protection
ii. Indirect protection

Direct protection

These works are done directly on the banks such as-

- Slope protection of coastal bank and upper bank and
- Toe protection of lower bank

As such works continuously cover a certain length of banks, they are called 'continuous protection'. Commonly seen direct protection works are banks protected against erosion by revetment or by maintain the existing bank line for economic or other human interest.

Indirect protection

These works are not constructed directly on the banks but in front of them in order to reduce the erosive force of the current either by-

- Repelling groynes- deflected the current form banks.
- Sediment or permeable groynes- allows water to pass but not sediment.

Some typical bank protection structures are:

i. Groynes
ii. Longitudinal dikes
iii. Revetment and riprap
iv. Cross dikes tying in longitudinal structure to the bank to divide the closed off channel space.
v. Sills to stabilize the bottom of the regularized river according to a corresponding longitudinal slope.
vi. Closures to cut of secondary channels
vii. Bed load traps

Selection of revetment types

The type of revetment to be used depends upon the cost of materials and upon considerations of durability, safety and appearance. In many circumstances, attention is concentrated in Bangladesh on stone riprap because of its following advantage:

It is flexible and is not impaired by slight movement of the resulting from settlement.

i. Local damage can be repaired easily.
ii. No special equipment or construction practices are necessary.
iii. Appearance is normal.
iv. Vegetation will often grow through the rocks.
v. Additional thickness can be provided at the toe offset possible scour.

Design of coastal revetment, seawalls, and bulkheads by U.S army corps of engineers (1996) endowed with vast methodologies, consideration and design concerning various armor units such as tetrapod, tribar, coreloc, X-block etc. Design of revetment by K.W. Pliarczyk (1998) provided necessary guidelines for the design perspective with concrete cube blocks. Internet base references of delta marine consultants presented an overview of the delta design by X-block armor unit.

2.5 Coastal protection in Bangladesh

The coast of Bangladesh is approximately 710 km long. A series of coastal polder were constructed between mid–sixties and mid seventies in order to limit saline water intrusion and thus improve conditions for agriculture and support an increasing population. While successful in achieving that objective, especially since large scale polder construction began in about 1960, this has had morphological consequences like increased sedimentation and drainage congestion, which tend to underline the benefits. Series of devastating cyclones damaged several polders since 1985 and at several places embankments were breached.

In 1963 a continuous embankment was constructed over a distance of 15 km extended northwards from Karnaphuli River with crest level of 6.7 km and seaward slope was 1.5. Since 1980, it was extended northward by some 3.5 km. the embankment has been damaged on numerous occasions by high tide monsoon waves and cyclonic storms. Due to coastal erosion the most severe damage occurs at south Patenga. Several attempts have been made in the past to protect the embankment against wave erosion including stone armor, steel slag, and brickwork and placed concrete blocks of various thicknesses.

2.6 Coastal structure for shore protection

Coastal structures are used in coastal defence schemes with the objective of preventing shoreline erosion and flooding of the hinterland. Other objectives include sheltering of harbour basins and harbour entrances against waves, stabilization of navigation channels at inlets, and protection of water intakes and outfall.

Various types of coastal structures with sea dike, sea wall, revetments, bulkhead, groins, breakwaters etc.

Sea dike: An artificial earthen wall often meant to prevent flooding of the hinterland like revetments but without or hardly any beach in front of the structure. Sea dikes are onshore structures with the principal function of protecting low-laying areas against flooding. Sea dikes are usually built as a mound of fine material like sand and clay with a gentle seaward slope in order to reduce the wave run up and the erodible effect of the waves. The surface of the dike is armoured with grass, asphalt, stones, or concrete slabs. Fig 2.3 shows that coastal bank protection is done by sea dike.

Fig 2.3 Sea dike

Sea wall: Sea wall are onshore structure with the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind due to storm surges and waves. Sea walls range from vertical face structures such as massive gravity concrete walls, tied walls using steel or concrete pilling, and stone- filled cribwork to sloping structures with typical surfaces being reinforced concrete slabs, concrete armor units, or stone rubble. A seawall is constructed at the coastline, at the foot of possible cliffs or dunes. A seawall is typically a sloping concrete structure; it can be smooth, stepped-faced or curved-faced.

A seawall can also be built as a rubble-mound structure, as a block seawall, steel or wooden structure (Fig 2.4). The common characteristic is that the structure is designed to withstand severe wave action and storm surge. A rubble-mound revetment often protects the foot of such non-flexible seawalls. A rubble-mound seawall bears a great similarity to a rubble-mound revetment; however a revetment is often used as a supplement to a seawall or as a stand-alone structure at less exposed locations. An exposed dike, which has been strengthened to resist wave action, is sometimes referred to as a seawall.

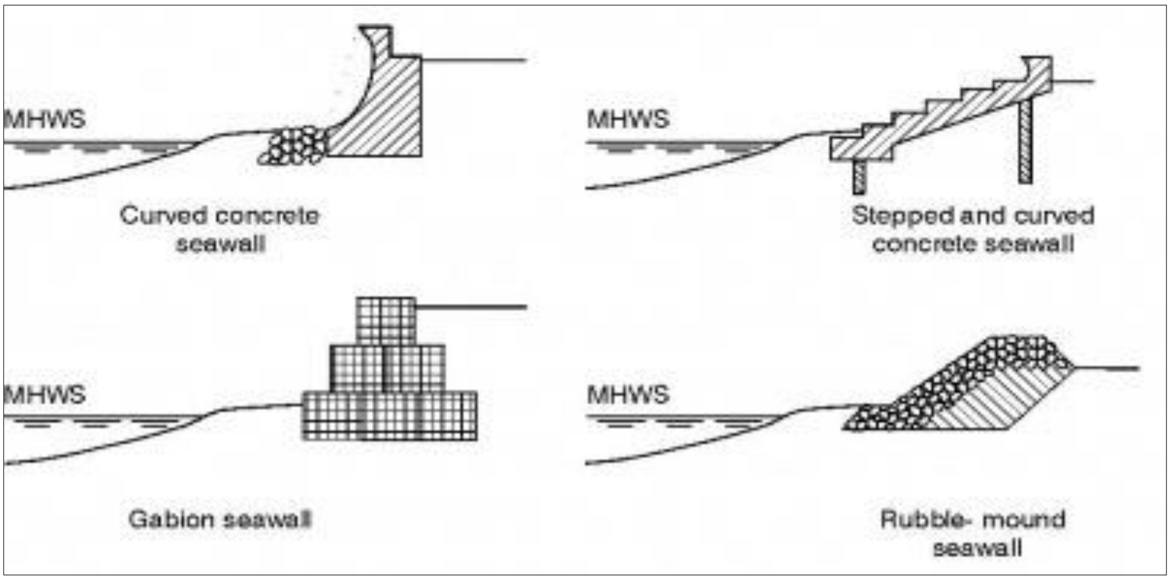


Fig 2.4 Different types of seawall structures.

The nearly vertical seawall, which was mainly used in the past, had the unfortunate function of reflecting some of the wave energy, whereby the erosion was aggravated, resulting in accelerated disappearance of the beach. However, all kinds of seawalls involve beach degradation as they are used at locations where the coast is exposed to erosion. The seawall will fix the location of the coastline, but it will not arrest the ongoing erosion in the coastal profile. On the contrary, it will to a varying degree, accelerate the erosion. It is quite normal that the beach disappears in front of a seawall, and it will most often be necessary, after some years, to strengthen the foot of the seawall with a rubble revetment. A seawall will decrease the release of sediments from the section it protects and will have a negative impact on the sediment budget along adjacent shorelines. Views of sloping and curved seawalls are shown in Fig 2.6.

Fig 2.6 Seawalls

A seawall is a massive structure, which protects the coast against erosion and flooding. Seawalls are often used at locations off exposed city fronts, where good protection was needed and where space was scarce. Promenades have often been constructed on top of these seawalls. They are also used along other less inhabited coasts, where combined coast protection and sea defence is urgently needed. Seawalls are primarily used at exposed coasts, but they are also used at moderately exposed coasts.

Revetments: Revetments are on shore structure with principal function of protecting shorelines from erosion. Revetment structure typically consists of a cladding of stone concrete, or asphalt to armor sloping natural shoreline profiles. A revetment is a facing of stone, concrete units or slabs, etc., built to protect a scarp, the foot of a cliff or a dune, a dike or a seawall against erosion by wave action, storm surge and currents. A revetment is, just as a seawall, a shore parallel structure. The main difference is that it is more sloping than a seawall. A revetment has a distinct slope (e.g. 1:2 or 1:4), while a seawall is often almost vertical, the surface of a revetment might be either smooth or rough (a seawall is mostly smooth) and that the height of a revetment does not necessarily fill the total height difference between beach and mainland (a seawall often covers the total height difference). Revetments are always made as sloping structures and are very often constructed as permeable structures using natural stones or concrete blocks (Fig 2.7), thereby enhancing gwave energy absorption and minimizing reflection and wave run-up.

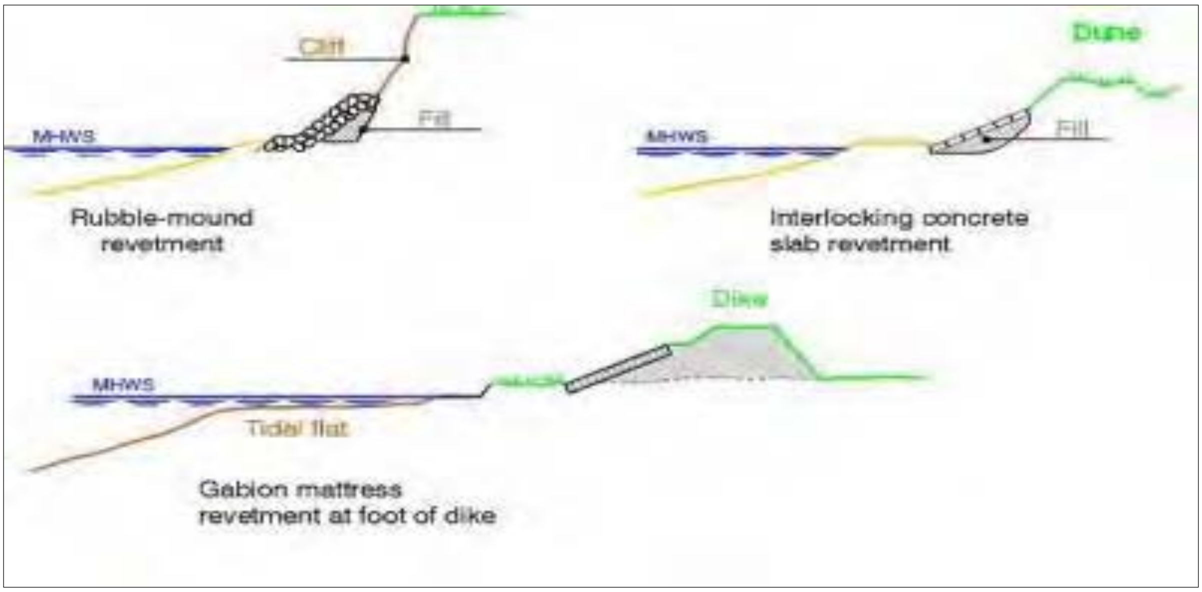


Fig 2.7 Different types of revetments

However, revetments can also consist of different kinds of concrete slabs, some of them permeable and interlocking. In this way their functionality is increased in terms of absorption and strength. Revetments can also consist of sand-filled geotextile fabric bags, mattresses and tubes. Such structures must be protected against UV-light to avoid weathering of the fabric. Sand-bagging is often used as emergency protection. Geotextile fabric revetments are fragile against mechanical impact and vandalism, and their appearance is not natural. Revetment design is shown in Fig 2.8.

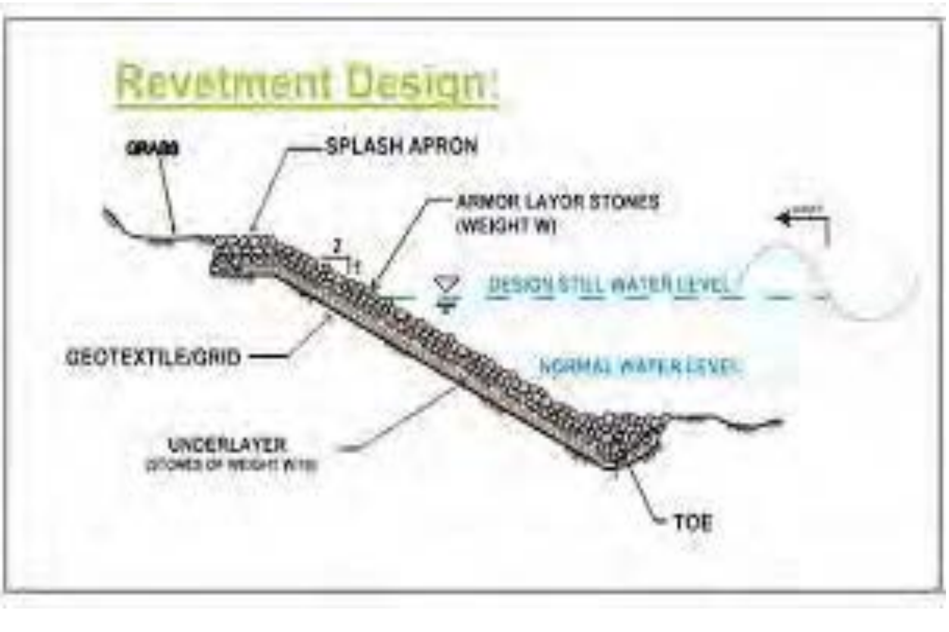


Fig 2.8 Design of revetment

Bulkhead: Bulkhead is the term of structures primarily intended to retain or prevent of sliding of the land, whereas protecting the hinterland against flooding and wave action is a secondary importance. Bulkheads are built as soil retaining structures, and in most cases as a vertical wall anchored with tie rods. A bulkhead (Fig 2.9) is a structure or partition used to retain or prevent sliding of the land. A secondary purpose is to protect the coast against

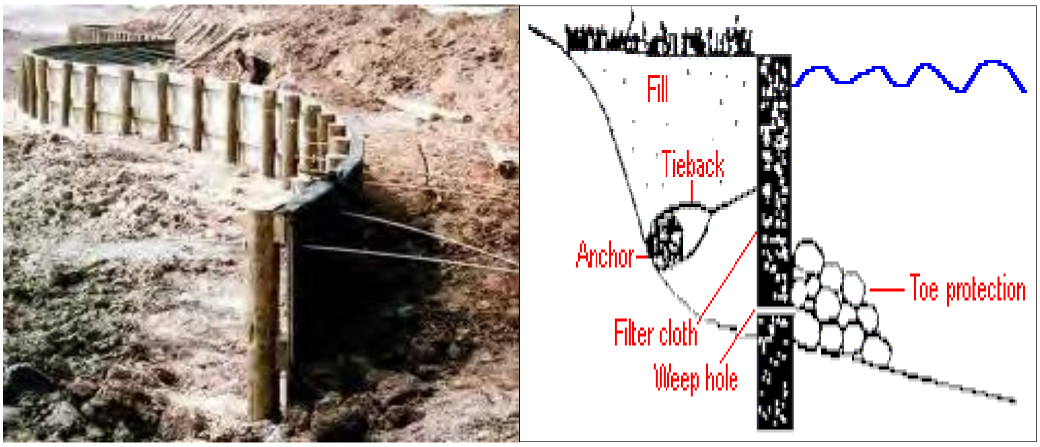


Fig 2.9 Bulkhead.

damage from wave action. Construction materials commonly used include wood pilings, commercially developed vinyl products, large boulders stacked to form a wall, or a seawall built of concrete or another hard substance.

Groins: Groins are built to stabilize a stretch of natural or artificially nourished beach against erosion that is due primarily to a net long shore loss of beach material. Groins function only when long shore transport occurs. Groins are narrow structures, usually straight and perpendicular to the pre project shore line. In most cases, groins are sheet-pile or rubble-mound construction. Groin is a coastal structure constructed perpendicular to the coastline from the shore into the sea to trap long shore sediment transport or control long shore currents. This type of structure is easy to construct from a variety of materials such as wood, rock or bamboo and is normally used on sandy coasts. Fig 2.10 shows some photo views of groin. They from a cross-shore barrier that traps sand that moves along shore, thereby increasing the width of the beach on the upstream side. Thus they function best on beaches with a predominant along shore transport direction. Some disadvantages of groins are:

- Induces local scour at the toes of the structure.
- Causes erosion down drift; requires regular maintenance.

- Typically more than one structure is required.

Fig 2.10 shows some photo views of groin.

Breakwater: Breakwaters are wave energy barriers designed to protect the land or near shore area behind them from the direct attack of waves. Breakwaters have traditionally been used only for harbor protection and navigational purposes; but in recent years, designs of shore-parallel segmented breakwaters have been used for shore protection purposes. Segmented breakwaters can be used to provide protection over longer sections of shoreline than is generally managed through the use of bulkheads or revetments. Wave energy is able to pass through the breakwater gaps, allowing for the maintenance of some level of longshore sediment transport, as well as mixing and flushing of the sheltered waters behind the structures. The dissipation of wave energy allows drift material to be deposited behind the breakwater. This accumulation of material protects the shore and may also extend the beach. The amount of deposition depends on the site characteristics and the design of the breakwater.

Breakwaters are built to reduce wave action in an area in the lee of the structure. Wave action is reduced through a combination of reflection and dissipation of incoming wave energy. Breakwaters can be classified into two main types: sloping front and vertical structures. Sloping front structure are in most cases rubble mound structures armoured with rock or concrete armor units, with or without wave wall super structures. Vertical-fornt structures are most cases constructed of either sand filled concrete caissons or stacked massive concrete blocks placed on a rubble stone bedding layer. Fig 2.11 shows some photo views of breakwater.

Fig 2.11 shows some photo views of breakwater.

Sea dikes, sea walls and revetments are armoured in the sea side slopes to be reinforced compromising wave loading, run up, down rush etc. Sea dikes are principally armoured by asphalt, grass or concrete slabs where as for sea walls and revetments it may include with typical surfaces being reinforced concrete slabs, concrete armor units, or stone rubble.

2.7 Armor unit used as a cover layer

Armor unit may be defined as a type of block that used in bank protection work. That is arm type block and it has arm or leg. When wave height is very high in that case C.C. blocks are not effective for bank protection work then armor units like tetrapods, X-blocks etc are an effective measure. In Bangladesh it is a new concept. It is widely used in japan or other developed country.

Armor unit to be used in coastal structures can be divided by

- Massive or blocky- Cubes including grooved types, parallelepiped block
- Bulky – Accropode, Core loc, Haro, Seabee
- Slender- Tetrapod, Dolos
- Multi-hole cubes- Shed, Cob

Various types of armor units are shown in Fig 2.12

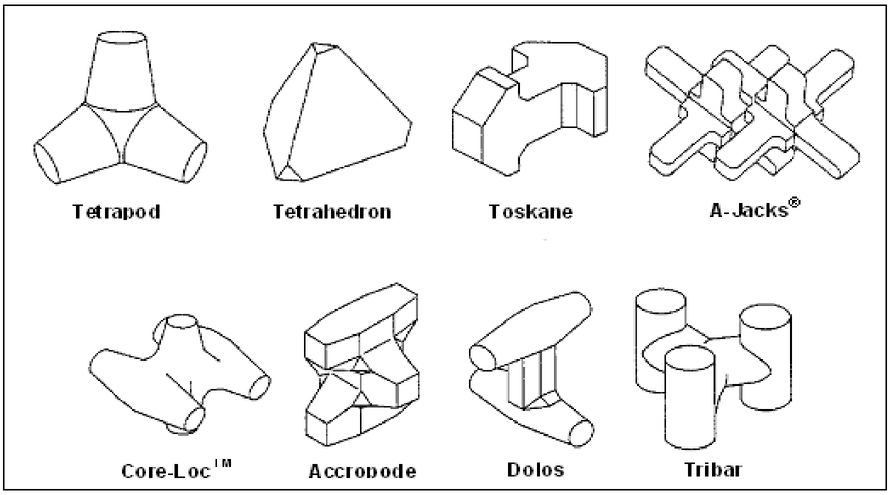


Fig 2.12: Different types of armor units.

The three different types of armor units (tetrapod, x-block and concrete cube block) used in this study are described in detail below.

2.7.1 TETRAPODS

The tetrapod is no longer entirely a new-comer in the field of marine construction. The sea water intake of the Roches Noires thermic power station at Casablanca, North Africa, the first structure for which tetrapods were used, was constructed nearly four years ago. However, it is of interest to recall the ideas. High stimulated the invention of this new type of protection.

Fig 2.13: Dice for manufacturing Tetrapod

The following remark made by engineers specializing in marine work undoubtedly points to the origin of this inventions "The rectangular or cubic artificial blocks normally used are nearly always less stable than natural rocks of the same unit weight, and of random shape, used under the same conditions." This fact, observed after systematic studies and comparisons and both confirmed and amplified by scale model tests, obviously constituted a real challenge to the science of engineering. To take up the challenge, it was sufficient to state clearly the questions what would be the best form for an artificial protecting block? It was also necessary to have the tools needed to make a practical study of the different block shapes under consideration. These conditions were fulfilled in the Neyrpic Hydraulics Laboratory. It was obviously impossible to test a series of chosen shapes in a haphazard manner. On the contrary, one of the first steps taken by the laboratory technicians was to establish a list of the properties desired in the new block. Dice for manufacturing tetrapod are shown in (Fig.2.13). A brief review of these properties is given below.

2.7.1.1 CHARACTERISTICS OF THE TETRAPOD

(i) PERMEABILITY

Protecting revetments for marine structures should not be impervious because of the possible occurrence of internal pressures which may cause considerable disturbance to the structure. Systematic tests, made during the study of the Mers-el-Kebir naval base, have shown that an impervious revetment could be lifted almost bodily by internal pressures, even when the revetment is constructed of 400-ton blocks. In addition, a permeable revetment is desirable in order to absorb incidental swell and thus reduce wave overtopping and reflection. These two occurrences may constitute a considerable drawback to navigation and use of the harbor. Besides, waves overtopping a structure may attack its more or less unprotected inner slope and in this way, cause a part of or even the whole structure to collapse. A new block must therefore permit construction of a pervious facing and the pervious ness obtained must not be reduced or eliminated by subsequent alterations which may be caused by sea action against the structure. This condition, therefore, eliminates blocks which may provide a continuous facing and consequently, the ideal block should have as few large plane surfaces as possible.

(ii) ROUGBNESS

It is desirable for a marine structure revetment to have a rough surface so that it can dissipate the energy of incidental waves and slow down the water masses which tend to rise along the facing and to pass over the structure. The "friction" of water against the mound is thus increased. On the other hand, it is of advantage to increase "internal friction" of the mound by promoting the interlocking of the blocks of which it is made. These results can be obtained with blocks having projections which will ensure both a rough external facing and satisfactory interlocking of the blocks.

(iii) RESISTANCE

Finally the block must have maximum resistance, and therefore, the study was passed on to one of the laboratory's experts on the resistance of materials. It seemed difficult to satisfy all of these conditions. However, after various preliminary studies the outline took shape a sort of sea monster with four tentacles which was patented under the name "tetrapod" (Fig.2.14).

Hydraulic tests were made to check the properties of the new block and perfect its design; in this respect one of the essential points was to find the most suitable proportion between the length of the four prongs and the size of the body. The prongs could not be too short because the blocks would then not interlock properly and the revetment would be less stable, they could not be too long because then they would be too fragile. The correct design was finally established.

Once these general proportions were found, further details were settled by considering not only the resistance and hydraulic problems but also the ease of manufacture of the tetrapod casting forms. The result was to give prongs the shape of a truncated cone, of which angle was determined so as to favour the wedging effect during the first settling movements they make after they are placed into position. The tetrapod with four equidistant prongs, gives, to our knowledge, the best combination of those qualities required for a block used to protect marine structures.

A revetment constructed of tetrapods is pervious, and therefore, on the one hand there is no risk whatever of under-pressure and on the other, wave energy is satisfactorily absorbed and overtopping is reduced, in addition the block projections provide the revetment with the required roughness.

Fig 2.14: A tetrapod

But before deciding that the tetrapod was the perfect answer, the block in its final shape was again the subject of other experiments. Tests of resistance were made. Sample blocks of several weights were coast in concrete, reinforced or not, and of several mixes, and then tested for resistance to shocks (fig. 2.15).

Fig 2.15: A four tone tetrapod after 3 ft. fall

Then followed systematic scale model tests were performed in the behaviour of the blocks when they undergo prolonged attack by the sea. The tetrapod came through all of these tests in a completely satisfactory manner and it was shown to have some great advantages over other blocks in current use; i.e,

(i) The same degree of stability can be achieved with smaller unit weights and steeper facings;
(ii) The structures can be built lower because overtopping is reduced;
(iii) Maintenance and repairs are relatively easy as is the case of pell-mell construction

Once these advantages of the tetrapod were established on scale models, it was deemed possible to use them in actual construction.

(iv) USE OP TETRAPODS

There are obviously several ways in which tetrapods may be used for building new structures, or for strengthening and repairing existing ones. In each case where tetrapods are used it is necessary to make a special study, and just as it should be done for any large marine project, it is often helpful to make a scale model study, as this will give the best solution from both technical and economical points of view.

Nevertheless, by referring to experience acquired from many scale model studies, it is possible to specify the most frequently recommended and particularly favourable designs, in fact, two of these are in the majority the "mound" and the "double layer". A mound of tetrapods is generally used when a vertical structure is to be protected by placing against its seaward face a fill of natural or artificial rocks having a sufficient weight to resist wave action (Fig.2.16).

This fill must satisfy several requirements:

(i) It protects the wall against any direct wave attack which may endanger its stability;

(ii) It reduces overtopping;

(iii) It reduces wave reflections.

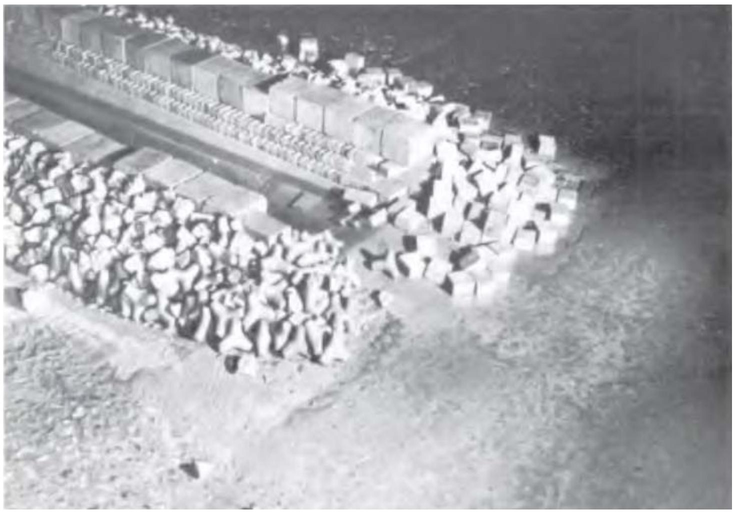


Fig 2.16: Comparative study between a tetrapod mound and classic blocks used for protecting structure.

If the water at the structure is not too deep, it is often desirable to design this protection in the form of a mound composed completely of tetrapods. This type of construction provides the maximum use of the tetrapods properties, i.e. high stability is obtained, although the seaward slope is very steep (about 1:1). Despite this slope, the mounds have low reflected coefficient because they are pervious and round. To avoid "slaps" against the upper part of the wall, a slight berm is often provided at the upper part of the tetrapod mound. The berm obviously increases the volume of the mound a small amount.

When large water depths are reached, the mound, whose volume increases roughly as the square of the depth, would become too expensive if it was made entirely of tetrapods. The alternative is therefore a core of natural rocks and a revetment of tetrapods. The best design of this revetment is the "double layer" previously mentioned. The part of the core laying directly under the facing should be constructed of rocks having a unit weight not less than l/10 of that of the tetrapods in order that these rocks may not pass through the gaps. This foundation cannot have a slope as steep as 1:1, because this would be destroyed by any sea disturbance occurring before the tetrapods are placed into position. Thus it is necessary to give a gentler slope to the facing; this will increase the volume, and consequently the expense, but as against this, the method will allow tetrapods to be replaced by small, less expensive natural rocks and will finally result in an economy in comparison to a complete mound of tetrapods. On such a foundation the double layer is built as follows:

a. A first layer of tetrapods is laid down so that three prongs rest on the mound with the fourth pointing outward. This disposition is not strict but simply indicates the general orientation of the tetrapods in the first layer.

b. The second layer is then laid down pointing in the opposite direction to the first, i.e., with one prong directed inward. Tetrapods in the second layer have a natural tendency to settle in this manner, but they are, of course, still less regularly placed than the first because these rest on a relatively plane foundation.

c. When the second layer has been laid down, there is a rather compact revetment which has few processes open for additional tetrapods. Thus it is difficult to add a few more tetrapods, which would in any case be useless or even harmful. Scale model tests have shown that such additional tetrapods are the first to be, torn away by wave action when this peaches the limit of resistance of the facing.

Therefore, the only way to increase the thickness of the revetment would be by constructing a second "double layer". But then the first becomes useless and it is not advisable to use such a method because the upper "double layer” will then rest on a less even and more expensive base than that made of small rocks.

The "double layer" revetment therefore constitutes a well adapted constructional method. It has even better stability than a mound of tetrapods. This can be explained by the fact that tetrapods in a mound are placed quite haphazardly, while those in the "double layer" although largely laid down at random, nevertheless have a general rational organization because of this tetrapods on the surface offer the smallest possible hold to lifting forces and have the maximum points of contact with those in the second layer.

When the double layer is used, thickness of the revetment varies with the unit weight of the tetrapods (Table 2.l). For a given revetment surface, the required quantity of these blocks at a determined unit weight is almost constant. As a first approximation, the percentage of space in a mound of tetrapods is approximately 50 percent or a little higher. The quantity of tetrapods required to fill a given volume can thus be calculated both easily and quickly.

Table 2.1: Characteristics for use of tetrapods in double layers

Unit weight T	50	40	32	25	16	12.5	8	4	2	1	0.5	0.25
Volume m^3	20	16	12.5	10	6.3	5	3.2	1.6	0.8	0.4	0.2	0.1
Height of Tetrapod mm	4155	3860	3550	3300	2830	2620	2260	1790	1420	1130	900	710
Thickness of double layer mm	5600	5200	4900	4500	3800	3500	3000	2400	1900	1500	1200	950
Quantity On 100 m^2	14	16	19	22	30	35	47	47	120	190	300	470

Density of concrete = 2.5
T (tonne) = 0.984, long ton= 1.102 U.S. ton. m^3 =35.314 cu. ft.; mm = 0.039 inch; m^2 =10.764 sq. ft.

In very deep water it is not necessary to construct a protection of tetrapods down to the sea-bed. In such cases, the toe of the facing rests on a rock footing built up to a certain level (Fig. 2.17). This level obviously depends on the amplitude of waves which attack the structure concerned and on the unit weight of the rocks available. Another equally important question is to establish the height above sea level to which the tetrapod protection must be built. This height also depends on the wave amplitude and on the amount of overtopping which can be allowed.

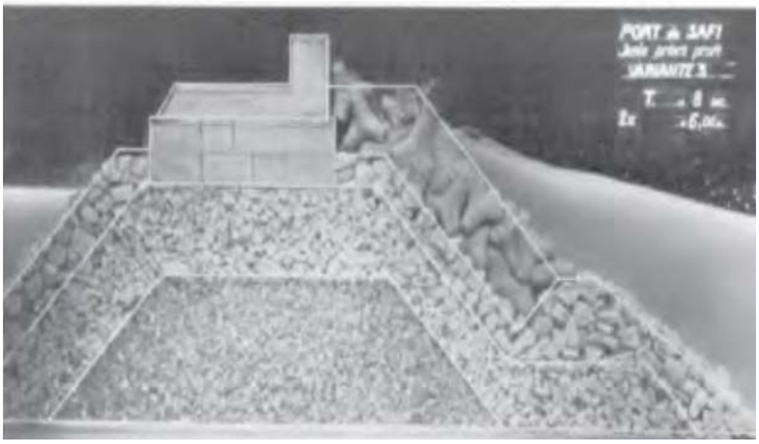


Fig 2.17: Study in a wave channel for a revetment made of a double layer of tetrapod.

Systematic studies are now in progress and it will soon be possible to give rapidly a rough estimate for any project. However, it will always be of value to make a scale model study of a projected structure in order to find the most economical and the most technically satisfactory solution.

In particular, the most important question is to decide the proper unit weight for tetrapods so that they can resist waves of certain amplitude with a given slope. The Neyrpic Hydraulios Laboratory has made a series of tests to find the necessary rules for determination of the unit weights necessary. These tests do not as yet cover all possible oases because a really complete series of tests is very long and expensive to conduct. The results obtained to date nevertheless allow useful conclusions in a great many problems. Shore protection by using Tetrapod are shown in (Fig.2.18).

Fig 2.18: Shore protection by Tetrapod.

Several structures using tetrapods already have been built are in the course of construction. Tetrapods have produced the results expected of them and experience has shown that they have the qualities anticipated. For instance, the first structure for which tetrapods were used, the sea-water intake for the Roches Hoires thermic power station at Casablanca, Jforth Africa, has withstood four hard winters. The 15-ton tetrapods protecting the pier-heads have not moved, although they are exposed to formidable Atlantic waves when photographs taken at two or three years interval are examined, all the blocks above low water mark are seen to be in their original position. In all the cases studied to date, tetrapods have proved themselves more efficient and economical than ordinary rectangular or cubic blocks. They have undoubtedly enabled marine construction engineers to widen their field of activity, because the tetrapod offers a new answer to the problem of protecting structures in the sea.

2.7.2 X-block

The armor unit, called the X-block is a simple, robust and reliable armor unit. It has considerable structural integrity as an individual element and has great hydraulic in the armor layer. Casting position the X-block is straight forward and very cost effective. A special toe unit X-base has been developed for use with X-block armor. This toe unit provide to be more stable than a conventional rock toe. Shore line protected by using X-block is shown in (Fig.2.19).

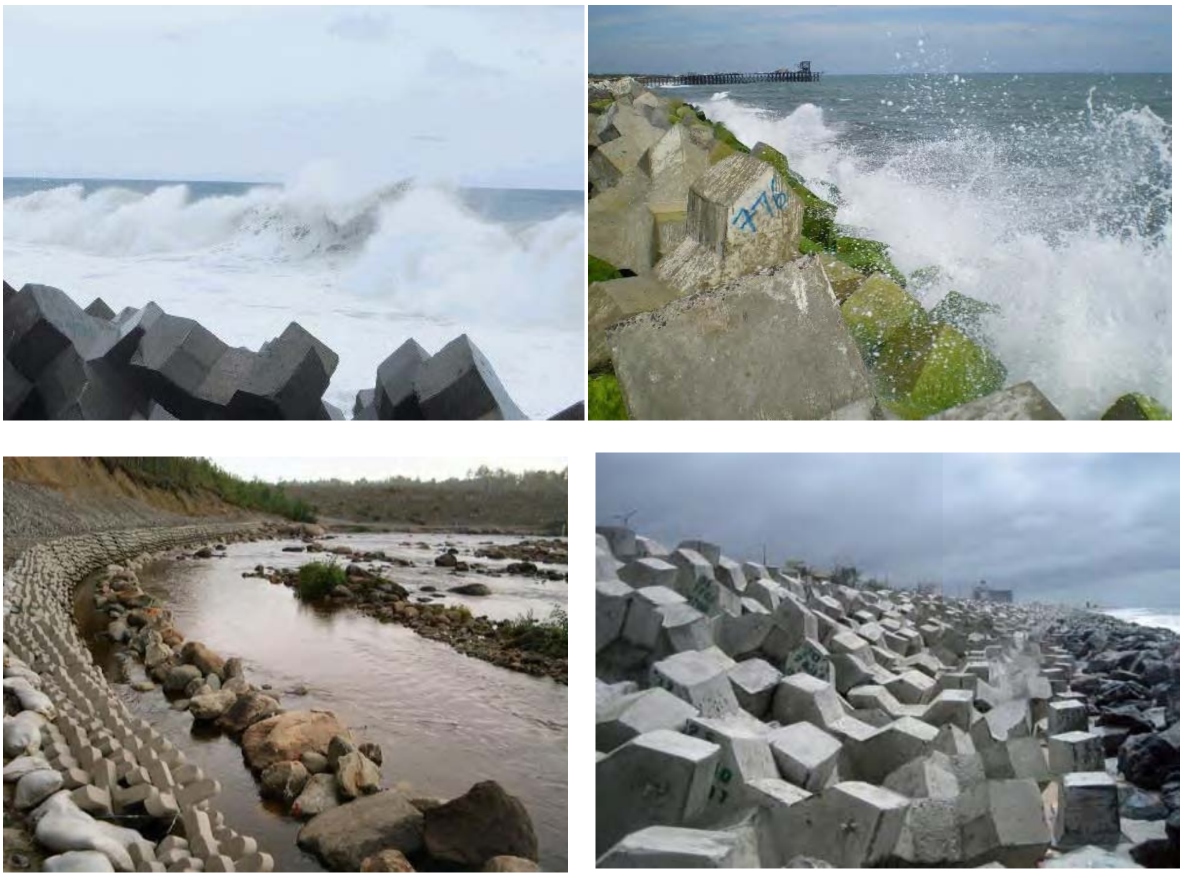


Fig 2.19: Shore protection by X-Block.

Applications:

A high stability cost effective concrete armour unit available in various sizes suitable for marine and riverine applications such as:

(i) breakwaters & reefs
(ii) harbours & inlets
(iii) river bank and shoreline revetments
(iv) toe-scour protection
(v) bridge pier scour protection

Rocla is the Australian licensee for the manufacture and marketing of X-block high stability concrete armour units. X-blocks are precast concrete armour units designed to:

(i) Protect waterfront structures subject to severe wave action and high flows.
(ii) Provide high stability using single layer construction in order to reduce construction costs.
(iii) Interlock into a flexible, highly permeable matrix.
(iv) Maximize dissipation of wave energy.
(v) Have a patented two-piece construction allowing X-bloc to be easily transported flat on pallets from a remote point of manufacture for assembly and installation on site.
(vi) Use a simple steel mould construction that allows fast flat-bed casting and de-moulding.

Concrete armour units are used for coastal applications typically in areas with rough wave climates or where insufficient quality and/ or size of available quarry stone are available. X-block can be manufactured in various size armour units and are installed either in a uniform or random pattern. X-block has been rigorously tested at Oregon manly Hydraulics Laboratory in terms of performance and stability – stability coefficient Kd has determined and can vary from a minimum of 25 for single units up to 100+ for nested units.

(i) Product Features & Benefits

(i) Flume-tested at Oregon State Uni – proven high stability units with stability coefficient K_d range 25 -100

(ii) Units interlock with each other to form a flexible, highly permeable matrix

(iii) A nested structure has a 60% VOID space providing maximum energy dissipation

(iv) Available in mass range 36 kg up to 20 T

(v) Manufactured in a two piece unit to facilitate easy transport to site

X-block concrete armour units are high stability concrete armour units that are used in river, lake, and coastal applications to control erosion, stabilize shorelines, and provide habitat. In coastal applications X-block concrete armour units are typically used for reefs, revetments, breakwaters, and jetties and may also be used to provide habitat. The size of units in coastal applications ranges from less than 1 meter to over 4 meters in length. The units may be wet cast at a pre-cast yard or produced on site. X-block concrete armour units may be fabricated using flat forms and grouting two halves together or using 3D single pour forms. Using flat forms may result in a significant decrease in fabrication costs and production time. A-Jacks concrete armour units are placed in a layer that is one armour unit thick. They may be installed in random, bundle, or uniform placement patterns. Uniform corresponds to a special placement in which the units weave together into an extremely stable geometry. Bundle placement is a uniform group of 4 to 20 X-block concrete armour units that are assembled onshore and placed as a group using a lifting frame. This is an efficient placement method that also provides near uniform installation. Table 3.2 is shown that X-bloc concrete armour units sizes

Table 3.2 X-bloc concrete armour units sizes

Wave height	Random placement			Bundle			Uniformly placement		
H m	W (t)	V(m^3)	C (m)	W (t)	V (m^3)	C (m)	W (t)	V (m^3)	C (m)
1	0.04	0.02	0.54	0.03	0.01	0.50	0.03	0.01	0.46
2	0.33	0.14	1.08	0.27	0.11	1.00	0.21	0.09	0.93
3	1.12	0.47	1.61	0.89	0.37	1.50	0.72	0.30	1.39
4	2.65	1.10	2.15	2.12	0.88	2.00	1.70	0.71	1.85
5	5.18	2.16	2.69	4.14	1.73	2.50	3.31	1.38	2.32
6	8.95	3.73	3.23	7.16	2.89	3.00	5.73	2.39	2.78
7	14.21	5.92	3.76	11.37	4.74	3.49	9.09	3.79	3.24
8	21.21	8.84	4.30	16.97	7.07	3.99	13.57	5.66	3.71
9	30.20	12.58	4.84	24.16	10.07	4.49	19.33	8.05	4.17
10	41.43	17.26	5.38	33.14	13.81	4.99	26.51	11.05	4.63

(γ_{cc} = 2.4 t/m^3, r = 1/5.2, m = 1.5H:1V)

(ii) Model study

X-block concrete armour units have been extensively tested in 2D wave flumes and 3D model basins in Australia, Indonesia, and the United States. These studies have the examined influence of wave conditions, structure slope, placement method, packing coefficient, and waist ratio on hydraulic stability. Tests were conducted at the Manly Hydraulics Laboratory in NSW using irregular waves on a slope of 1.5H: 1V. The Manly report is available upon request. A model study are shown in (Fig.2.20).

Fig 2.20: After 1000 waves for random placement**.** After 1000 waves for bundle placement**.**

Cost benefits of the X-bloc

X-block is the most economical single layer armour unit. The average saving yielded by incorporation of X-block units [less concrete needed] is up to 15% compared to other single layer armour units. The difference is due to the high stability coefficient of the X-block units and the low packing-density required, both of which result in a lower concrete demand. As there are no specific requirements on the orientation of the individual units to achieve good interlocking, the placement of the units is straightforward reducing both construction time and overall cost. Fig 2.21 shows the costs of different types of armor units in percentages.

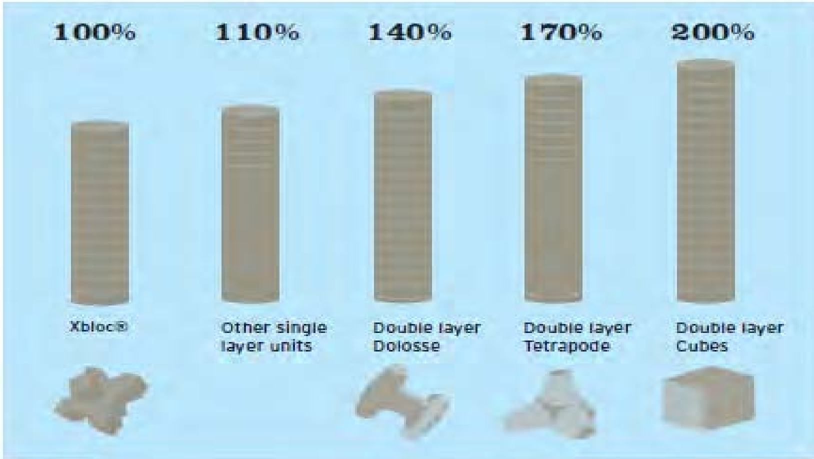


Fig 2.21 costs of different types of armor units in percentages

Hydraulic stability of X-block

- **Excellent hydraulic stability:**

i. For concept design a Kd value [stability coefficient in the Hudson formula] of 16 [trunk section] and 13 [head section] should be applied.
ii. The stability coefficient of the X-block is the same for breaking and non-breaking waves.
iii. X-block has a safety margin of at least 20 % without damage to the armour layer.

- **Automatic interlocking:**

i. X-block units naturally find a stable position on the slope.
ii. Self repairing of the X-block armour layer after damage is enhanced by automatic interlocking.
iii. The X-block unit is simple to place as no specific orientation of the individual units is required.

- **Low wave overtopping:**

i. The highly porous armour layer minimises wave overtopping

2.7.3 Concrete cube block

Blocks are popular revetment material having numerous shapes and types. The blocks can be interlocking pieces or held together by grouting, cables, clips, pins, or other devices. The blocks can be placed either randomly, uniformly or staggerdly on the revetment. Analysis of block stability is a difficult task due to the complexity of breaking waves impinging upon an inclined surface that is supported by flexible porous material. C.C. block placement pattern are shown in (Fig.2.22 & 2.23).

In coastal defence work the placed block revetment are widely used in world. Before deriving the formula of stability of revetment blocks one must have understanding about the system involved in a revetment. A filter is placed 0n the subsoil. The blocks are placed on this filter layer. Normally the blocks placed in a way that the revetment has a flat surface. In this way force the forces parallel to the slope caused by wave attack are minimized. Sometimes rough surface is created to minimize wave run-up. The water movement in the filter and revetment system of this type is normally decisive for the stability of revetment the pressure difference in the plane of perpendicular to the revetment, caused by wave attack, lead to some general design principles. Performance of uniformly placed C.C. block was better than randomly or staggerdly placed C.C. block. Because wave breaking are caused on it easily and wave energy was reduced after breaking wave height.

General Empirical formula from pilarczyk (1989)

$$\frac{H_s}{\Delta_m D} \leq \frac{\psi_u \varphi cos\alpha}{\xi_z^b}$$

Where,

H_s = Significant wave height

D = Thickness of the cover layer

ψ_u= System determines stability upgrading factor

φ = Stability factor for incipient motion.

ξ_z^b = Breaker parameter = 1.25 T_z $H_s^{-0.5}$tanα

T_z= Average wave period

Δ_m=Relative density of a system of unit

b = Exponent related to the interaction process between waves and revetment

α = angle of slope

Fig 2.22 C.C. block uniformly place with double layer toe protection.

Fig 2.23 Shore protection by C.C. block stagger placement

2.8 Filter

Filter layers are required for the stability of bank protection works. The main function of a filter-layer in bed and bank protection is the retention of bed and base material, without the generation of unacceptable excess pore water pressures. This means that the construction should transmit water it life time, without the loss of any base material. The filter may also function as soil reinforcement.

2.8.1 Function

The principal functions of a filter layers are as follows:

(i) To prevent the migration of sub-soil particles out of bank slope.

(ii) To allow, at the same time, movement of water through the filter.

In addition the following are also carried out:

(i) To separate the cover layer from the sub-soil
(ii) To provide drainage zone parallel to the slope of bank protection works.
(iii) To act as soil reinforcement.
(iv) To protect the sub-soil from erosion when water flows over its surface parallel to the slope.
(v) To dissipate the energy of internal flow in the sub-soil caused by wave and current action.

2.8.2 Types of filter

Filter is used in bank protection works can be broadly classified in two groups;

- Granular filter
- Fibre filter

Example of granular filter is:

(i) Layers of slag or gravel (loose grains)
(ii) Sand asphalt (bonded grains)
(iii) Filter mattress stones (packed stone)

Fibre filter may be composed of:

(i) Synthetic materials – geotextile
(ii) Natural materials- the classical willow matting

Fibre materials are commonly referred to as 'Geotextiles'. By definition: Geotextiles are permeable textiles made from artificial or natural fibres in conjuction with soil or rocks as an integral part of man made project. Based on their composition geotextiles can be subdivided into:

(i) Woven
(ii) Staple fibre and continuous filament non-wovens
(iii) Thread- structure mats and strip mats
(iv) Gauges
(v) Grids
(vi) Knitted

However, geotextile cab be simply classified into-

(i) Woven geotextile
(ii) Non woven geotextiles

The choice of materials and construction depends on the properties required. In addition the boundary conditions related to the type of work and methods of execution must be taken into account.

2.8.3 Diversified use of geotextiles in bank protection work

Use of Geotextile is increasing in civil engineering. Their growth during the past 15 years has been remarkable. They are frequently employed as filter membranes and as the interface between differently graded layers. They are used in armouring the soil in foundations and lopes, as membrane to prevent seepage or to protect the environment against pollution from a dump area.

Geotextile are used as bed protection and can be loaded with-

(i) Concrete blocks (block mattress)
(ii) Bituminous bound crushed stone and sand (fix tone mattress)
(iii) Geotextiles tubes filled with gravel (gravel-sausage mattress)
(iv) Gavel bags- for special filter requirements.

In addition to a filter, geotextile can fulfil the following function:

(i) Erosion control
(ii) Reinforcement
(iii) Drainage
(iv) In embankment/ soil reinforcement
(v) Special application in bank protection work

2.8.4 Advantage of Geotextile

The benefits of using geotextiles are manifold. The numerous advantages can be summiarized as follows:

- Geotextiles have high tensile strength and durability
- Geotextiles have high thermal insulation value
- It is good in resilience and has low specific gravity
- Geotextiles increase the stability of structure by acting as a separation layer and preventing their mixing of two layers lying above and below
- It release excess pore pressure build up in the sub soil, thereby geotextile favour filtration and drainage and ensures stability
- Geotextiles are easy to maintain
- It is erosion resistant
- Enables better construction quality control
- It increases the performance life of the base material as a load distribution layer and preserves its integrity
- Geotextiles increase resistive forces
- It is suitable to saline water
- It is cost effective and in many case cost saving. Reduces the cost of facing or revetment structures
- It acts as a shock-absorbing layer and reduces vibration. This increases the working life of many structure
- It protected the embankment body inhibiting soil loss
- For certain structures, its presence reduces active forces
- Geotextiles are relatively easy in construction
- Geotextiles require less area. And so is highly suitable for urban protection structure
- It is resistant to Moth. Fungus, and bacterial attack
- It is chemically inert

2.8.5 Advantage of Granular Filter

In general, loose granular filters can have the following advantages:

(i) Element are very durable

(ii) There is a good surface contact between the layers above and below.

(iii) The layer easy to repair.

2.8.6 Design of Granular Filter

The design of granular filters depends on the particle size of subsoil. The filter criterion relates the grading of the filter to that of the subsoil.

The layers of granular filter have to be designed in successively coarse layers proceeding outward from underlying finest soil. The first layer should hold the subsoil, while each following layer has to be able to hold the underlying layer. The outer layer must also be stable under the prevailing hydraulic loads. Granular filter design rules may be summarized as:

A) According to the US Bureau of Reclamation:

- For sand with U<5:
  D_{50}<(5to10)*d_{50}
- For sand with U>5:
  D_{15}<(12to 40)*d_{15}
  And D50< (12to58)*d_{50}

B) According to US crops of Engineers

- $D_{15} < 5d_{85}$
- $D_{15} < 20d_{15}$
- $D_{15} < 25d_{50}$

C) According to Pilarczyk(1990)

- D_{15} < (4 to 5)*d_{85} (Stability crition)
- D_{15} <(4 to 5)*d_{15} (permeability crition)
- D_{50} <2 5d_{50} (segregation criterion)
- $U = \frac{D_{50}}{D_{10}} < 10$ (no migration)
- $U = \frac{D_{50}}{D_{10}} > 20$ (Migration)

Where,

U = Co-efficient of Uniformity = $\frac{D_{60}}{D_{10}}$

d_x= particle size of sub soil from a grain size distribution plot at X% finer by mass (mm)

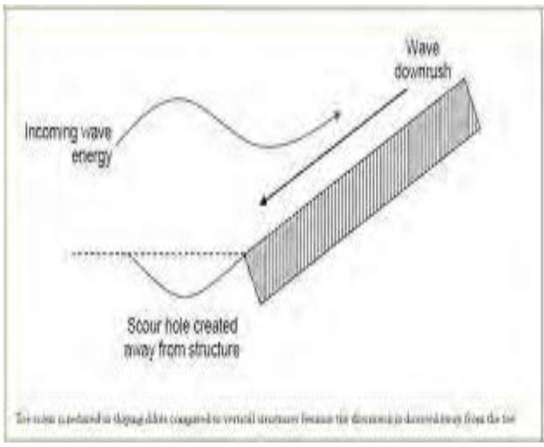
D_x= Particle size of filter material from a grain size distribution plot at X% finer by mass (mm)

Filter material does not contain size > 65mm and not more than 5% with size < 0.074mm. The lower factor in the above equation corresponds to strong cyclic flow conditions and the higher ones to steady flow conditions. In all cases, the grading curve of the filter should be approximately parallel to that of the sub soil.

2.9 Failure of coastal structure

Failure: Damage that result in structure performance and functionality below the minimum anticipated by design. Thus, partial collapse of a structure may be classified as damage. Provided the structure still serves its original purpose at or above the minimum expected level. For example, subsidence of a break water protecting a harbour would be considered a failure if it resulted in wave height with in the harbour that exceed operational criteria. Conversely, partial collapse of a rubble-mound jetty head might be classified as damage if resulting impacts to navigation and dredging requirement are minimal or with in acceptable limits. Coastal project elements fail for one or more of the following reasons:

- Deign failure occurs when either the structure as a whole, including its foundation, or individual structure components cannot with stand load conditions with in the design criteria. Design failure also occurs when the structure does not perform as anticipated.
- Load exceedance failure occurs because anticipated design load conditions were exceeded.
- Construction failure arises due to incorrect or bad construction or construction materials.
- Deterioration failure is the result of structure deterioration and lack of project maintenance.



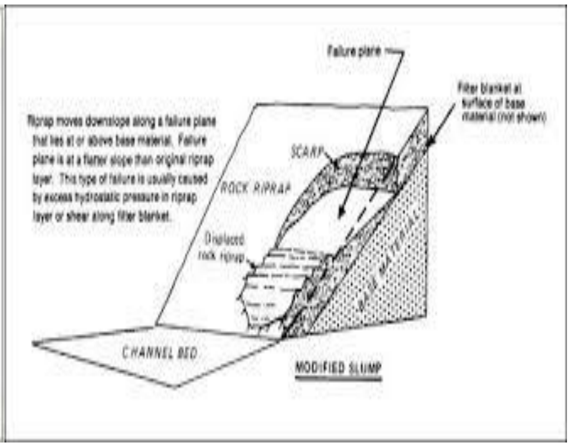


Fig 2.24 Failure of coastal structure by combined effect.

New or innovative coastal project design concepts are more susceptible to design failure due to lack of previous experience with similar designs. In these situations, allowances should for unknown design effects. And critical project elements should be extensively tested using laboratory or numerical model techniques before finalizing the design. Practically all projects accept some level of failure probability associated with exceedance of design load conditions, but failure probability increases at project sites where little prototype data exist on which to base the design. These cases may require a conservative factor of safety. Fig 2.24 shows that failure of coastal structure by combined effect.

Typical failure modes for revetment are

(i) Back scour failure due to overtopping
(ii) Toe erosion failure of rubble slope
(iii) Failure of sheet pile toe wall
(iv) Push out of slab elements due uplift pressure

2.10 Review of past studies

Many experimental and theoretical studies were done for determining the efficiency and stability of armor units. The design of C.C. block revetment in Bangladesh is done with Hudson (1961) formula and Pilarczyk (1990) formula for wave protection in Bangladesh. Mass, thickness and number of armor units per area require for a shore protection project are determined by 'shore protection manual1984'.the most widely used measure of armor stability is developed by Hudson(1961).

Wave runup, transmission and reflection for structures armored with core-loc were investigated by Melito and Melby (2002). Wave induced runup and wave transmission due to over topping are important variables in coastal structure design. Wave runup and transmitted wave heights are measured for a wide range of wave, water level and structure conditions in order to develop predictive tools for core-loc layer response. Bruce et.al. (2009) studied the overtopping performance of different armor units for rubble mound breakwaters. It was a small scale physical model tests to establish the influence of armor type and configuration on overtopping. Rufin et.al. (1996) developed the estimation method of stable weight of spherical armor unit used in submerged wide crown breakwater. The armor stone was idealized as a sphere and the stability of a spherical armor unit analyzed in relation to the active wave force method of placement, type and direction of movement, and physical quantities affecting the stability of spherical armor units.

Melby(2005) concluded that breakwater and revetment armor stability equations are based on the concept that the maximum wave force causing armor instability is proportional to the maximum wave momentum flux near the structure toe. This concept introduces a more physics based first principles approach to estimation of armor stability. Cevik et. al.(2005) conducted experiments to find out stability for structures armored with core-loc. It is found that conventional two layer system of various armor units such as tetrapod, dolos and tribar have been commonly used. Oever et. Al. (2006) investigated the theoretical and experimental study on the placement of x-bloc armor units. They described the relation of placement method to the selection of the stability coefficient (K_d) used in determining the weight of armor units.

Masum, S. (2002) was concluded that the effectiveness of riprop protect structures with soil reinforcement under wave action. Nandi, B. (2002) was conducted that a study on the stability of C.C. blocks revetment material against wave attack. Choudhary, N.H. (2011) was studied investigation on the failure in protective work along marine drive road in cox's bazaar. Womera S.A. (2011) investigated the interaction between waves and rectangular submerged impermeable breakwater. To predict the investigation, a two-dimensional numerical model based on the SOLA-VOF method was proposed there. Also a two- -dimensional laboratory experiment had been carried out and found that for any particular wave period the relative structure height and the relative structure width were the important parameters for the reduction of incident wave height. Akter A. (2013) was studied that Experimental study on hydrodynamic performance of vertical thick porous breakwater.

From the above point of view an experimental investigation on the performance of armor unit against wave action is undertaken. Experiments are design to study the effect of compaction, filter and placement of armor unit, stability slope, subsoil condition and toe stability. In general, the experiments are conducted with the common field conditions available in Bangladesh, so that the results of this investigation can facilitate sustainable design of bank protection works.

CHAPTER 3

EXPERIMENTAL SETUP AND METHODOLOGY

3.1 Introduction

The experimental runs have been carried out to evaluate the effectiveness of different types of armor units in the Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering of Bangladesh University of Engineering and Technology, Dhaka. Experimental methods of this study have been described in this chapter.

3.2 Laboratory Equipments

For collection of necessary data the following components were used for experiment runs.

(i) Laboratory flume
(ii) Wave height meter
(iii) Data acquisition system

3.2.1 Laboratory Flume

The flume used for experimental runs is 21.34 m long, 0.76 m wide and 0.74 m deep. The side walls are made of glass and bed is painted by water resistance colour as shown in (Fig. 3.1).

Fig. 3.1: Wave flume

In the flume wave generator was set at one end and at other end bank slope was prepared. It consists of a reservoir and a stilling chamber. The stilling chamber is located behind the wave generator. This chamber is approximately 3.0 m in length. The bed of the flume was kept horizontal and section of the flume section is rectangular. The flume is supported on an elevated steel truss. Laboratory flume height is limited to carry out runs in a large scale experiment. To generate a highest possible wave height rubber pads were attached such that water can not be flush out from the flume. Flume was set and ensured in such a condition that there was no leakage.

3.2.2 Wave Generator

The generator has a motor and paddle with two vertical limbs as shown in (Fig. 3.2). Waves are generated by rotating paddle. Wave period of generated waves can be altered by rotating its rotational speed and wave height can be altered by changing the arm of paddle. Rotational speed can be altered from 20 rpm to 120 rpm and paddle arm can be altered from 25 mm to 320 mm.

During movement of paddle two displacements were observed. One is rotational displacement and another is vertical displacement. By adjusting vertical limbs these two types of displacements were adjusted.

Fig 3.2: Wave paddle with generator

3.2.3 Wire Screens to reduce wave reflection

Several screens were set to reduce wave reflections. Screens were made of coarse wire mesh. They were placed in front of wave generator as shown in (Fig. 3.3).

Numbers of screen and spacing have been determined by trial and error method. Screens were kept at approximately 5 cm apart from each other. In this study finally 15 screens have been used to reduce reflections. When the crests of wave generator were seen in a straight line from side view reflection of the wave was considered to be reduced at the minimum.

Fig 3.3: Screen for wave re-reflection control

3.2.4 Setting of wave generator

To set the wave generator at a certain wave period, the flume needs to be emptied before setting the wave generator. Then the mean position of wave paddle was marked by a permanent marker on the glass. For doing this, the cooling fan cover of the driving motor was being removed and the fan was being rotated by hand until the wave paddle was vertical. This was checked by a sprit level. Then a line was drawn along the paddle which indicated the mean position of wave paddle.

Four different wave periods were used in this experiment. Those were 1.5, 1.6, 1.8, and 2.0 sec water level was kept constant at 50 cm for all the runs. For setting the wave periods there are some calculation which has to be done every time. Suppose when wave period was 1.5 sec-

So, T= 1.5 sec, H= 50 cm

Then, $\frac{\omega^2}{g} = (\frac{2\pi}{T})^2 * \frac{h}{g} = \frac{4\pi^2}{1.5^2} * \frac{50}{980} = 0.895$

From the graph (Appendix A), it found e =0.53 and f = 0.63 so, e + f = 0.53+0.63 = 1.16.

$\frac{e+f}{f} = \frac{1.16}{0.63} = \frac{1.16*100}{0.63*100} = \frac{116}{63} = 1.84$

So we found that the ratio was 1.84. Now, it was the time to adjust the cradle arm. When the cradle was vertical, there was rotational motion. So, the arm was set in such position that $\frac{e+f}{f} = 1.84$. By, taking the measurement from mean line, arm was set in desirable position. Then, the flume was again filled and experiment was done for wave period 1.5 sec. similarly the experiment was done for 1.6, 1.8 and 2.0 sec. For wave periods 1.6, 1.8 and 2.0 sec the $\frac{e+f}{f}$ ratio was 1.69, 1.48 and 1.36 respectively.

3.3 Methodology

3.3.1 Bank slope preparation

At first a wooden support is placed at the end of the channel. It is 76cm height, 74 cm width and 4 cm thick. It acts as a support system, to retain the sand on their desire positions. Two types of sand are used to prepare the slope. One is coarse sand and other is finer sand. Properties of the sand is

Finer sand: Fineness modules (F.M) = 1.41 D_{15} = 0.17 D_{50} =0.3 D_{85} =0.47

Coarse sand: Fineness modules (F.M) = 2.1 D_{15} = 0.29 D_{50} = 0.42 D_{85} = 0.6

From the gradation curve get these values. Gradation curve as shown (Appendix A)

Compact finer sand is laid in first layer for prepared the slope that is 62 cm height. Then 4 cm thickness of coarse sand lay over the finer sand. Then 1.5 mm thickness geotextile is placed on the coarse sand layer. Finally, 3 cm thick stone chips are placed over the geotextile (filter condition-1). In filter condition-2 stone chips were not used over the geotextile, armor units are directly placed on it. Some photographs are shown in (Fig.3.4) for slope preparation in the wave flume.

Fig 3.4 Some photographs of slope preparation

Properties of Getextile

Thickness of geotextile (TS15) is used for the present study. Table 3.1 shows properties of geotextile. This fiber filter is found to satisfy the retention criterion and the permeability criterion, based on the particle size distribution of the back fill material. A piece of geotextile is laid on the compacted sand to act as filter. Properties of the geotextile filter are given below. Geotextile used as a filter layer are shown in (Fig.3.5).

Table 3.1: Properties of geotextile

Filter type	Tensile strength kN/m	CBR puncture N	Vertical permeability m/sec	Thickness at 2 kbp mm
TS15	7.5	1175	$3X10^{-3}$	1.5

Fig 3.5: Geotextile used as a filter layer

Properties of Stone chips

The lowest size stone chips are select in the present study. Size of the stone chips are (1/4) or 0.25 inch downgraded. Stone chips acts as filter material. Stone chips are placed over the geotextile are shown in (Fig.3.6).

Fig 3.6 stone chips on filter layer.

Details design of granular filter

Details design of filter condition-1 and 2 are shown in (Fig.3.7 &3.8).

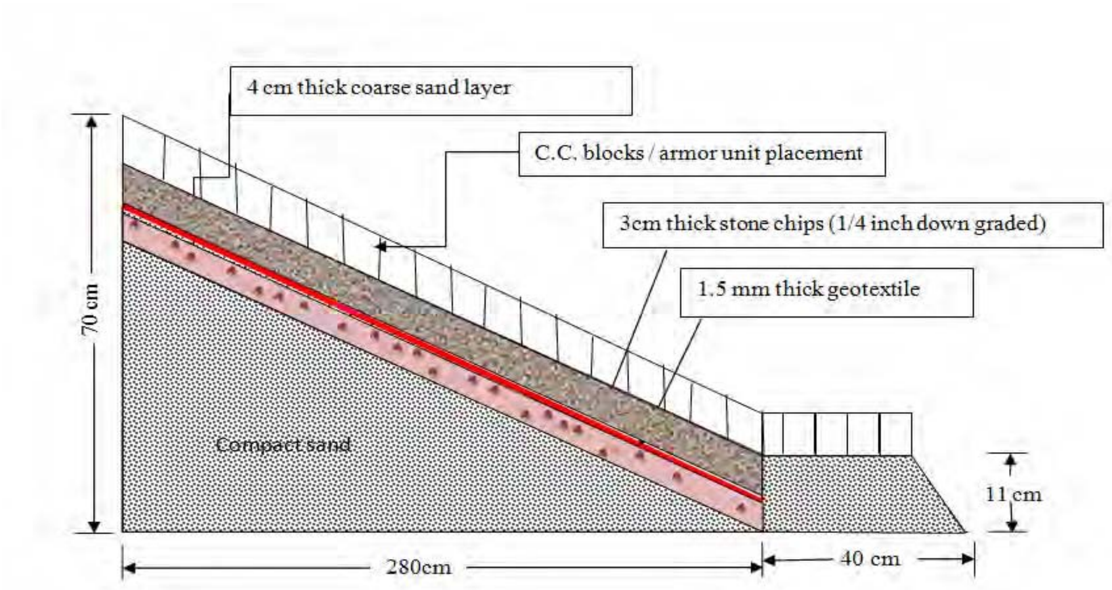


Fig.3.7: Detail design of revetment with toe protection and filter layer (condition-1)

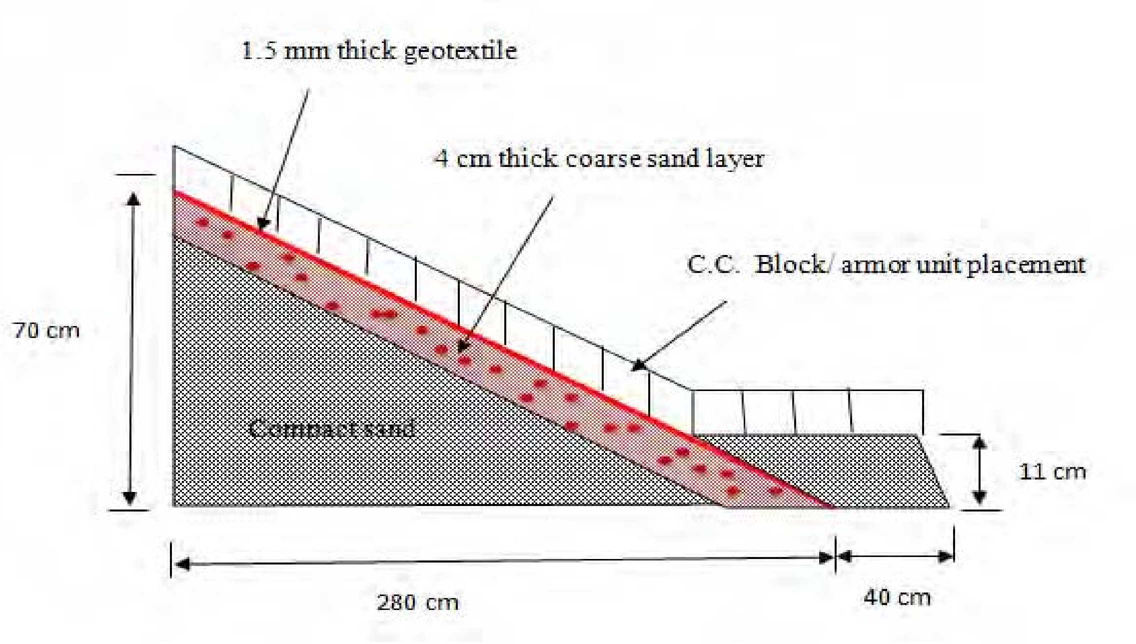


Fig.3.8: Detail design of revetment with toe protection and filter layer (condition-2)

3.3.2 Design of Tetrapod

Mass, thickness and number of armor units per area required for a shore protection work are determined by following equation referred from "shore protection manual 1984"

Mass: The most widely used measure of armor stability is that developed by Hudson (1961). Thus,

$$W = \frac{w_r H^3}{g K_d (s-1)^3 3\cot\theta} \text{ ------------------------------ (1)}$$

Where

w_r = Unit weight of concrete

H = Design wave height,

θ = Slope of the structure

W = require mass of individual armor unit

K_d = Stability coefficient

S_r =Specific gravity of armor unit =$\frac{Wr}{Ww}$

W_w = Unit weight of water

Thickness: The thickness of an armor layer can be determined by

$$r = nk(\frac{W}{w_r} g)^{\frac{1}{3}} \text{ --- (2)}$$

Where

r = layer of thickness in meter

n = number of armor units that would fit within the layer thickness

k = layer coefficient

Number of armor units: The placing density, number of armor units (N_r) for a given surface area in square feet (A), is

$$\frac{N_r}{A} = nk(1 - \frac{p}{100})(\frac{w_r}{Wg})^{\frac{2}{3}} \text{ -- (3)}$$

Where

P = average porosity of the cover layer. Now considering that the 3m wave height as a prototype then scale down on (1:20) ratio. Then calculated wave height is H_s=15cm. wave period for 2s and slope is 1:4. Using the above equations detailed armor units to be used in laboratory experiment is as below.

Armor unit design:

For tetrapod, by considering, H = 15 cm, slope (cotθ) = 3, W_r=23.5 kN/m^3, K_d= 7, W_w=10.05 kN/m^3, S_r =2.24, k=1.04. P=50, & n=2. Now from equation (1)

Mass of individual armor unit, W=0.2019 kg.

Table 3.3 and 3.4 shows the values to be consider for evaluating mass, thickness and number of armor unit per area required (wave breaking condition) referred from 'Design of Coastal Revetments, Seawalls and Bulkheads' (1995) and Melby j.a Turk G.F. (1997)

Table 3.2: Values for determining mass of armor unit

Armor units	**n**	**Placement**	**Slope (cotθ)**	**k_d**
Tetrapod	2	Random	1.5 to 3.0	7
Tripod	2	Random	1.5 to 3.0	9
Tripod	1	Uniform	1.5 to 3.0	12
Dolos	2	Random	2.0 to 3.0	15
Coreloc	1	Random	1.33 to 2.0	16

N.B: n equals the number of equivalent spherical diameters corresponding to the median stone weight that would fit within the layer thicknes.

Table 3.3: layer coefficients and porosity for various armor units.

Armor units	**n**	**Placement**	**k_Δ**	**P%**
Tetrapod	2	Random	1.04	50
Tripod	2	Random	1.02	54
Tripod	1	Uniform	1.13	47
Dolos	2	Random	0.94	56
Coreloc	1	Random	1.6	66

Making procedure of tetrapod in laboratory

The diameter of a single leg of the tetrapod is calculated to find out the desired cylindrical shape of the dice. The selected dia. at bottom is 15 mm, at top is 36 mm and the height of the tetrapod is 42 mm. Then mobile and grees lay on the inner side of the dice. So that it can be removed easily after hardening the mortar paste. Cement and sand are mixed properly by 1:4 ratios. After mixing, dice are filled with mortar paste and mortar filled dice are laid on the plane surface. Three dice are joined at 120^0 angle with each other's and one dice is placed on the upper face of the previously joined dice. After hardening the mortar paste the dice was removed the dice and then the tetrapod got submerged in water for curing. The fig.3.9 shows some photographs of making tetrapod in the laboratory.

Fig 3.9: Some photographs of tetrapod preparation

3.3.3 Design of X-Block

By considering that, H=15 cm, slope (cotθ) = 2, W_r=23.5 kN/m^3, K_d= 16, W_w=10.05 kN/m^3, S_r =2.24, k=1.60. P=66, & n=1.Now from equation (1)

Mass of individual armor unit, W=0.1325 kg.

Making procedure of X-block in laboratory

At first desire size of X-block dice is calculated. The dice of X-block is made in such a way that it can be easily opened after casting. In this study, 65 mm width, 65 mm length and 18 mm thick wooden dice are chosen. Then 20 mm X 20 mm square hole was made on the wooden dice. Then mobile and grees lay on the inner side of the dice so that it can be removed easily after hardening the mortar paste. Cement and sand are mixed properly 1:4 ratios. After mixing, dice are filled with mortar paste. Mortar filled dice are laid on the plane surface. Four square wooden block placed on upper surface of dice and filled with the mortar paste. After hardening, wooden dice were removed and then the X-block got submerged in water for curing. The fig 3.10 shows some photographs of making X-block in the laboratory. Design weight of Tetrapod and X-block are shown in (Fig3.11).

Fig 3.10: Some photographs of X-block preparation

Fig 3.11: Weight of tetrapod and x-block is found same as its design weight

3.4 Experimental setup

The experiment has been carried out on a 21.3 m long, 76 cm wide and 74 cm deep rectangular wave flume at Hydraulic and River Engineering Laboratory of BUET. Water is allowed to enter the flume by pipes from the main water supply system. In the wave flume artificial wave has been generated by wave paddle. The frequency of the wave paddle is set before every run which is related to the desired wave height and wave period. A set of experiment has been carried out using C.C. block, Tetrapod and X-block used as armor units in shore protection.

The experiment is performed in a rectangular two-dimensional wave flume as mentioned before. The detail experimental set up is shown in fig.3.12.

L_1, L_2, L_3, L_4, L_5 are location for wave height measurement

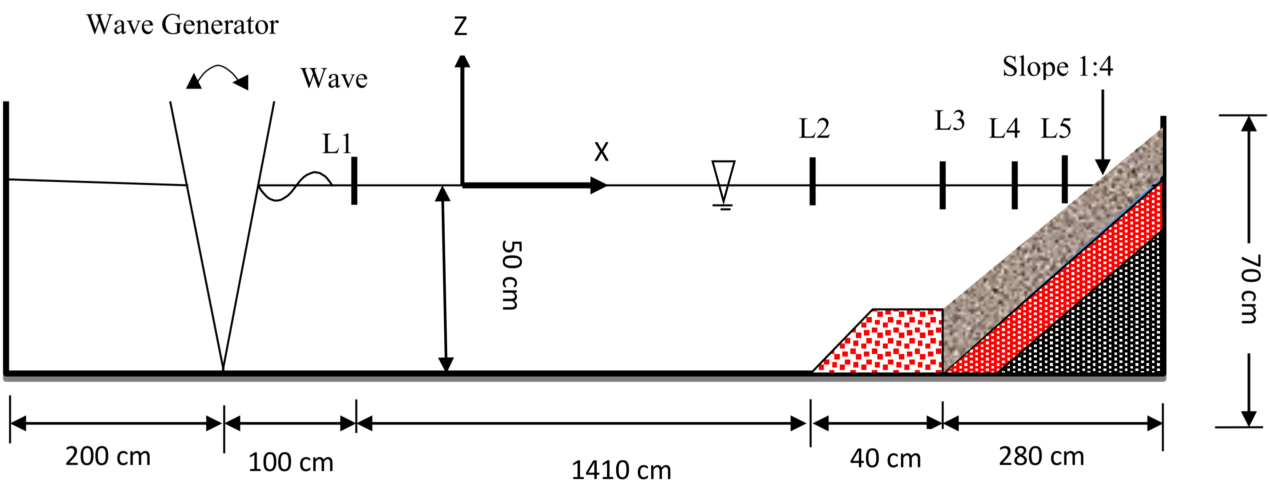


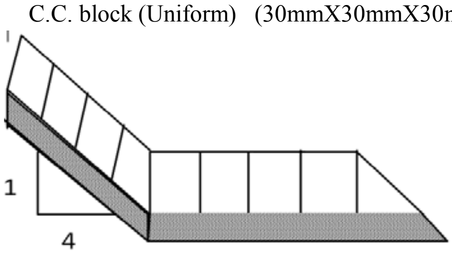
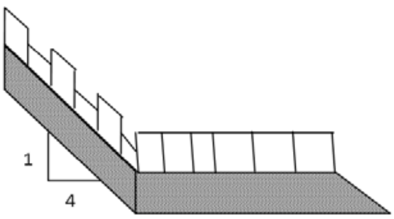
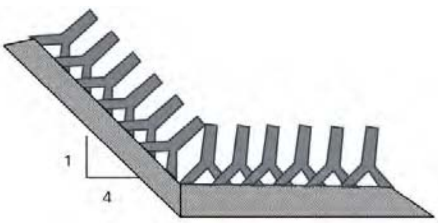
Fig 3.12: Detail experiment set up

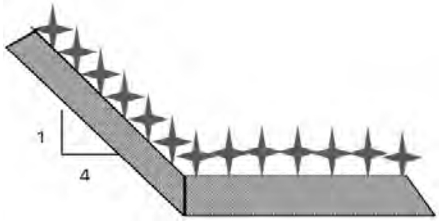
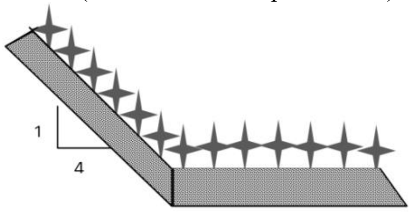
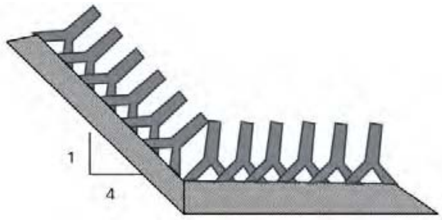
3.5 Experimental Run

A total twenty four experimental runs have been carried out in the laboratory for six different conditions. i. e When C.C. block uniformly placed, C.C. block staggerdly placed, tetrapod, X-block placed in filter condition-1, Tetrapod and X-block placed in filter condition-2. Each condition contains 4 runs corresponding to wave periods of 1.5 sec, 1.6 sec, 1.8 sec and 2.0 sec. Run conditions are given below in the Table 3.4

To investigate the water surface profile, wave heights are measured at five different locations. Five measuring tape were placed at five locations on the glass surface of the flume to measure the water level at five desire points. The station 1 is placed at 100 cm, station 2 at 1510 cm, station 3 at 1550 cm from wave generator, station 4 at wave breaking location and station 5 is at wave height after breaking these are shown in Fig.3.12.

Table 3.4: Experimental Run conditions

Run no	Armor type	Wave period	Water depth
1	C.C. block (Uniform) (30mmX30mmX30mm) 	1.5	50 cm
		1.6	
3		1.8	
4		2.0	
5	C.C. block (Staggered) (3oX30X30)mm, (3oX30X45)mm 	1.5	50 cm
6		1.6	
7		1.8	
8		2.0	
9	Tetrapod 	1.5	50 cm
10		1.6	
11		1.8	
12		2.0	

13	X-block 	1.5	50 cm
14		1.6	
15		1.8	
16		2.0	
17	X-block (without stone chips on filter) 	1.5	50 cm
18		1.6	
19		1.8	
20		2.0	
21	Tetrapod (without stone chips on filter) 	1.5	50 cm
22		1.6	
23		1.8	
24		2.0	

3.6 Data Acquisition

Data acquisition is the most essential part of the experiment. The runs were carried out for four different wave periods with six different conditions for each of the wave periods. Still water depth was at 50 cm for all the experimental runs. For every run wave paddle was changed to set the desired wave period. The frequency of the wave period was set before every run which was related to the desired wave height and wave period by the method which has been discussed in article 3.2.4. Five locations were selected for investing the water surface variations. Water level was measured at five different locations at 5 seconds interval for 60 seconds. The Fig 3.14 shows some photo views of data acquisition during the laboratory experiment.

To draw the water surface profile at any particular time, it is necessary to start the collection of data at each position simultaneously. This is done by starting the data acquisition at every position when the incident wave reaches the crest. Still photographs and video recordings are taken during each run. Some photographs that were taken during the experimental runs are given below:

Fig 3.13: photo views data acquisition

CHAPTER 4

EXPERIMENTAL DATA ANALYSIS AND RESULTS

4.1 Introduction

In this study, Experimental data has analysed to evaluate the efficiency of armor units. From laboratory wave flume, all the data that were recorded at different wave measuring location is being analysed to evaluate the efficiency of armor units. Different parameters have been considered to evaluate the armor stability such as wave height (H), water depth (h), thickness of armor units, number of armor units, density of armor units, placement pattern of armor units and as well as different conditions of filter layer.

1.2 Effect of armor units on water level variation

1.2.1 Revetment with C.C. block (uniformly distribution)

In this section, effects of armor units on water level variations are shown for four different wave periods. Incident wave height (H_i) is measured at location (L1) and wave height after breaking (H_b) is also measured at location (L5) for different time periods.

The Fig. 4.1, Fig 4.2, Fig 4.3 and Fig 4.4 represent the variation of water surface with Time for T=1.5, 1.6, 1.8, and 2.0 sec respectively when C.C. blocks were uniformly placed on the revetment. The Fig. 4.1 shows that the wave height reduction for the wave period of 1.5 sec and it is found that the wave is reduced by 36%. The Fig. 4.2 shows that the wave height reduction for the wave period of 1.6 sec and it is found that the wave height is reduced by 50%. The Fig. 4.3 shows that the wave height reduction for the wave period of 1.8 sec and it is found that the wave height is reduced by 50%. From the Fig. 4.4 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

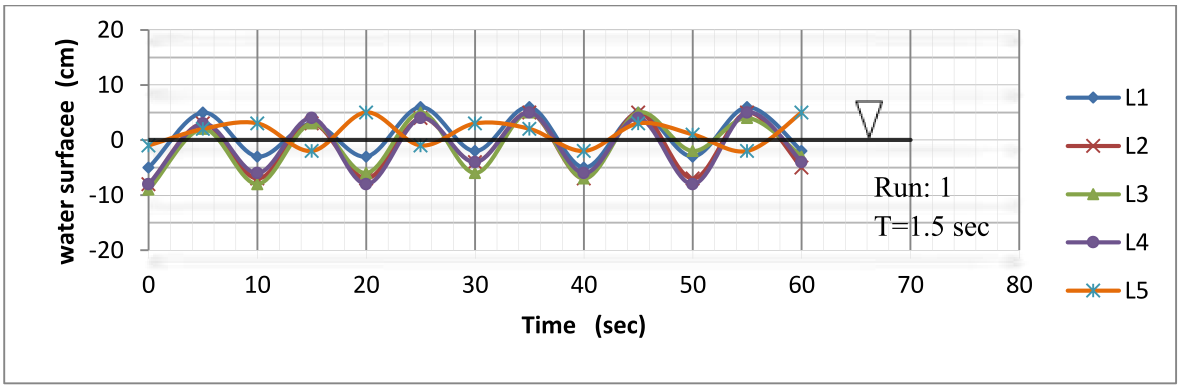


Fig. 4.1: Water level variation with time at various locations.

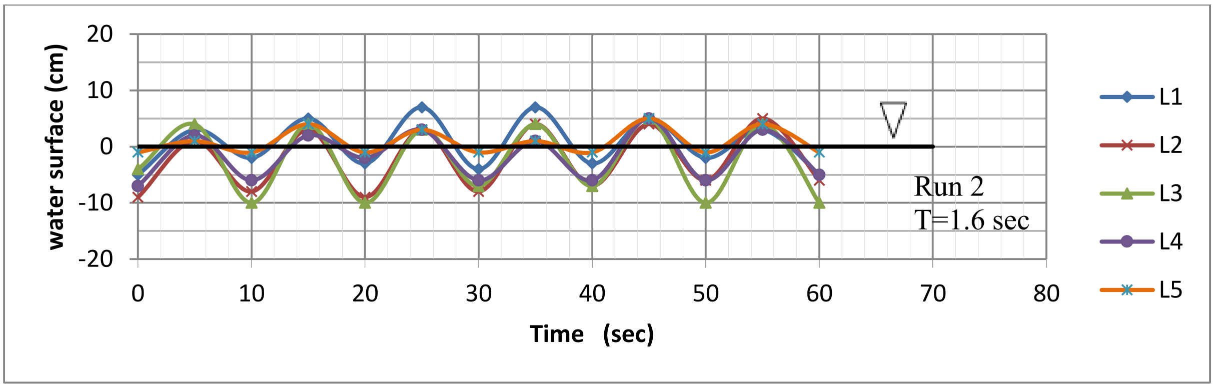


Fig. 4.2: Water level variation with time at various locations.

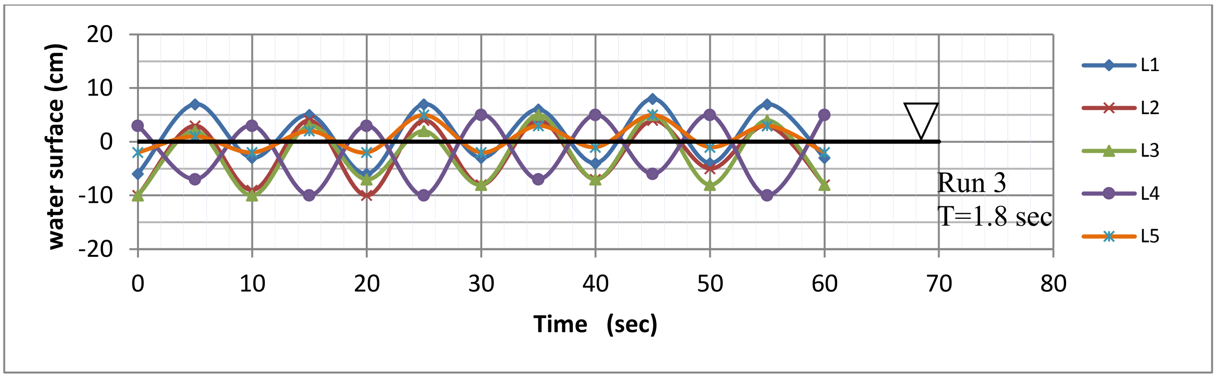


Fig. 4.3: Water level variation with time at various locations.

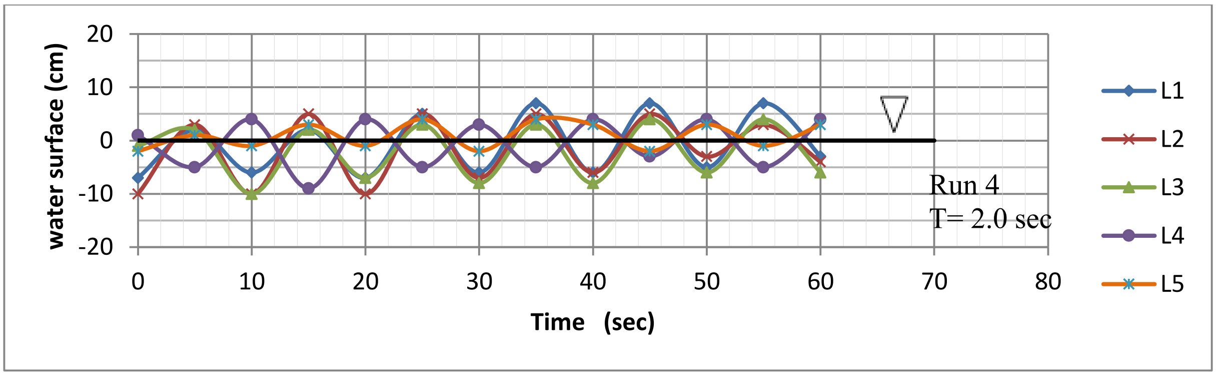


Fig. 4.4: Water level variation with time at various locations.

1.2.2 Revetment with C.C. block (staggerdly distribution)

The Fig. 4.5, Fig. 4.6, Fig. 4.7 and Fig. 4.8 represent the variation of water surface with Time for T=1.5, 1.6, 1.8, and 2.0 sec respectively when C.C. blocks were staggerdly placed on the revetment. The Fig. 4.5 shows that the wave height reduction for the wave period of 1.5 sec and from this Fig. it is found that the wave height reduced by 54%. The Fig. 4.6 shows that the wave height reduction for the wave period of 1.6 sec and it is found that the wave height reduced by 50%. The Fig. 4.7 shows that the wave height reduction for the wave period of

1.8 sec and it is found that the wave height reduced by 40%. From the Fig. 4.8 it is found that the wave height is reduced by 42% for wave period of 2.0 sec.

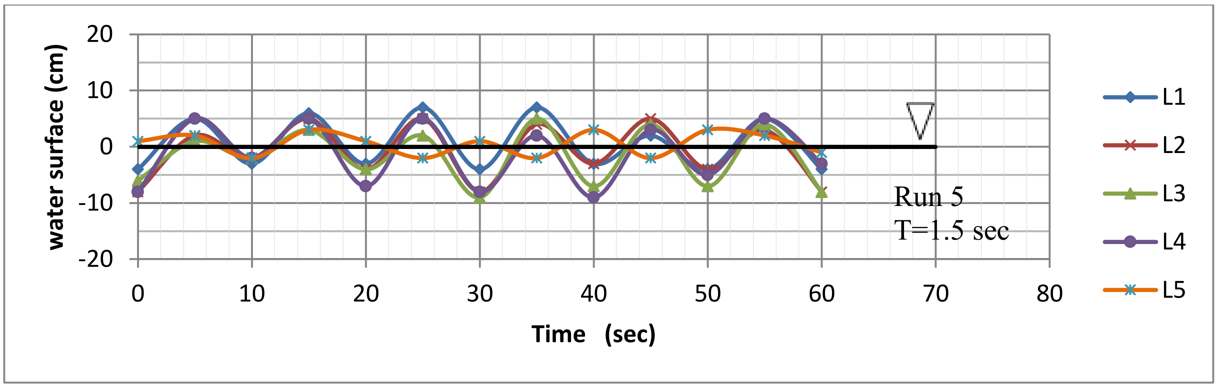


Fig. 4.5: Water level variation with time at various locations

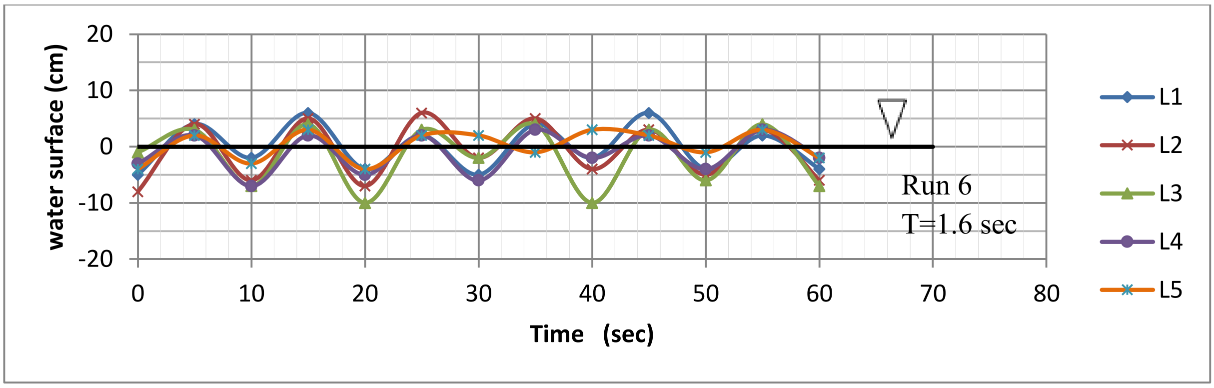


Fig. 4.6: Water level variation with time at various locations

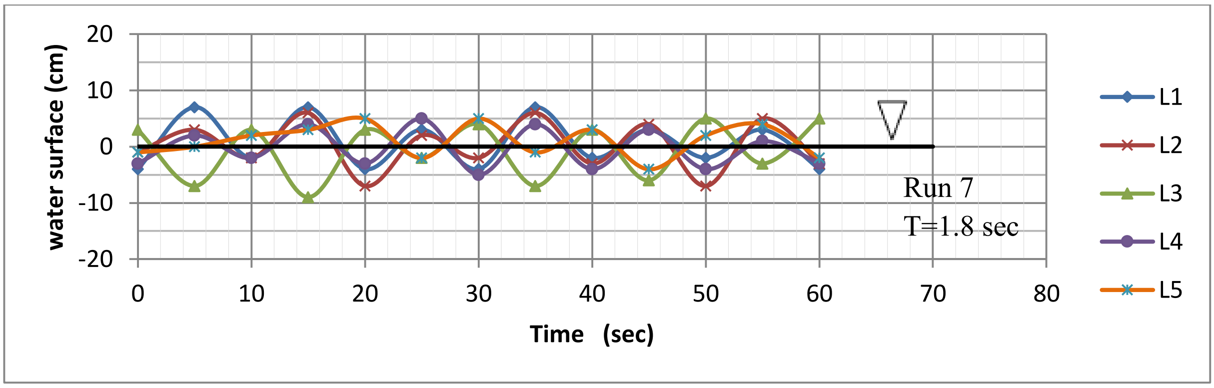


Fig. 4.7: Water level variation with time at various locations

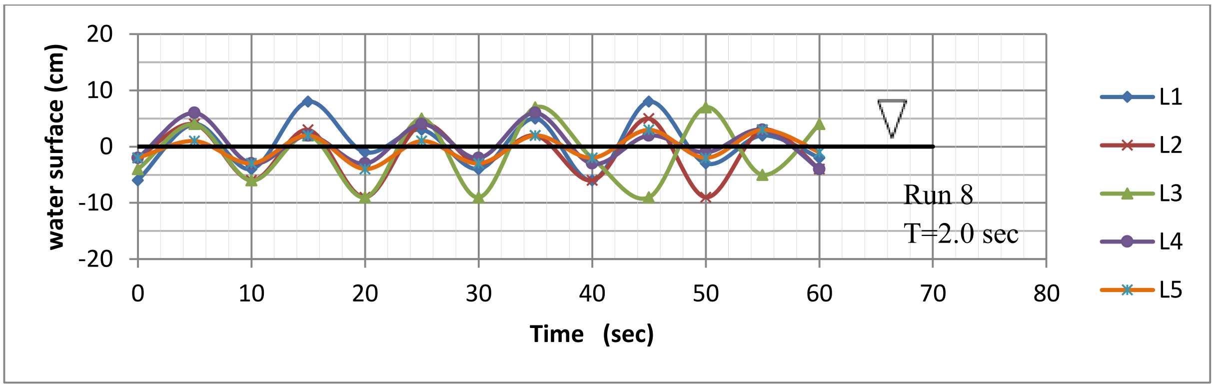


Fig. 4.8: Water level variation with time at various locations

1.2.3 Revetment with Tetrapod (filter condition 1)

The Fig.4.9, Fig. 4.10, Fig. 4.11 and Fig. 4.12 represent the variation of water surface with Time for T=1.5, 1.6, 1.8, and 2.0 sec respectively when tetrapods were placed on the revetment in filter condition-1. The Fig. 4.9 shows that the wave height reduction for the wave period of 1.5 sec. and from this Fig. it is found that the wave height reduced by 54%. The Fig. 4.10 shows that wave height reduction for the wave period of 1.6 sec. and it is found that the wave height reduced by 50%. The Fig. 4.11 shows that the wave height reduction for the wave period of 1.8 sec. and it is found that wave reduced by 46%. From the Fig. 4.12 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

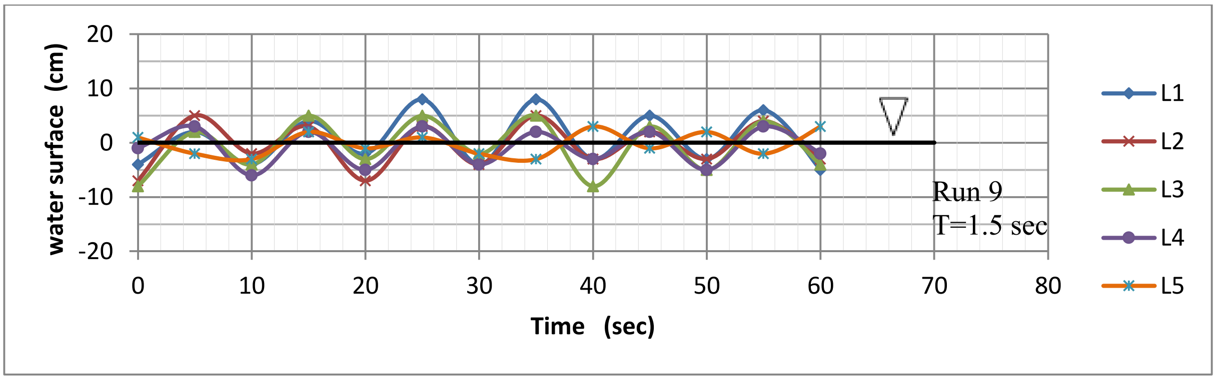


Fig. 4.9: Water level variation with time at various locations

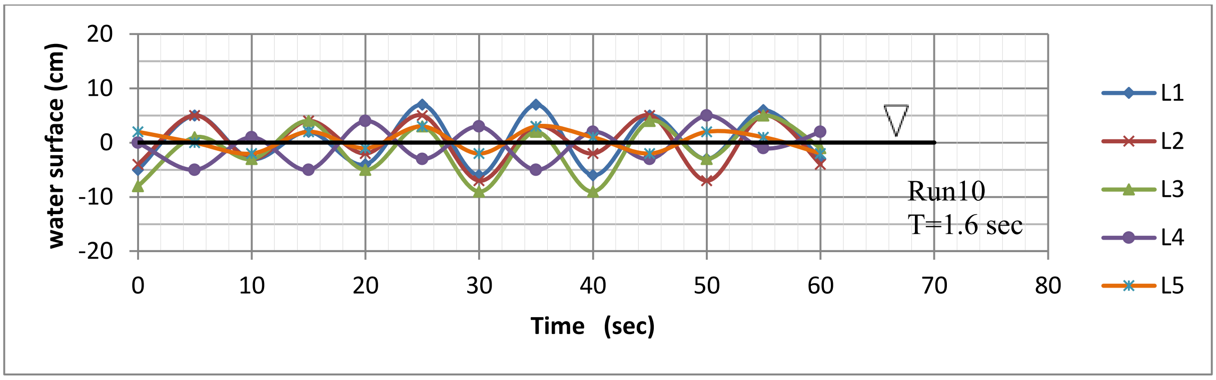


Fig. 4.10: Water level variation with time at various locations

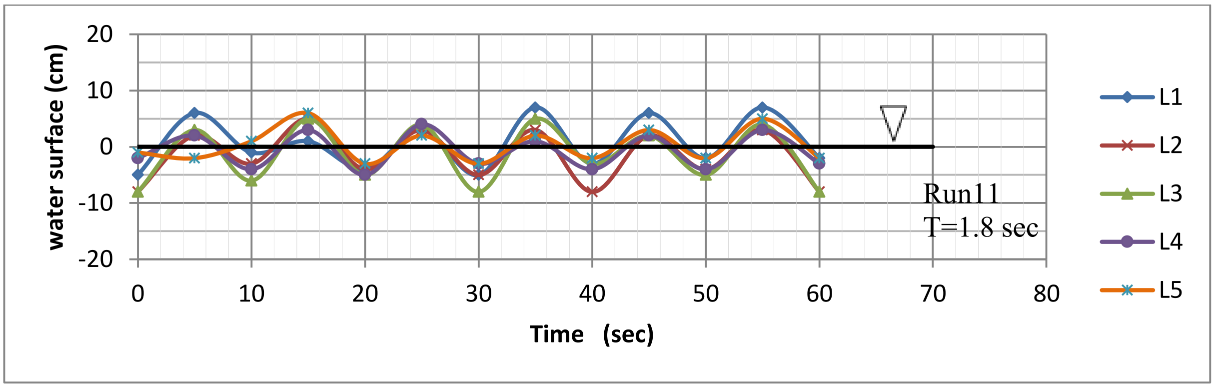


Fig. 4.11: Water level variation with time at various locations

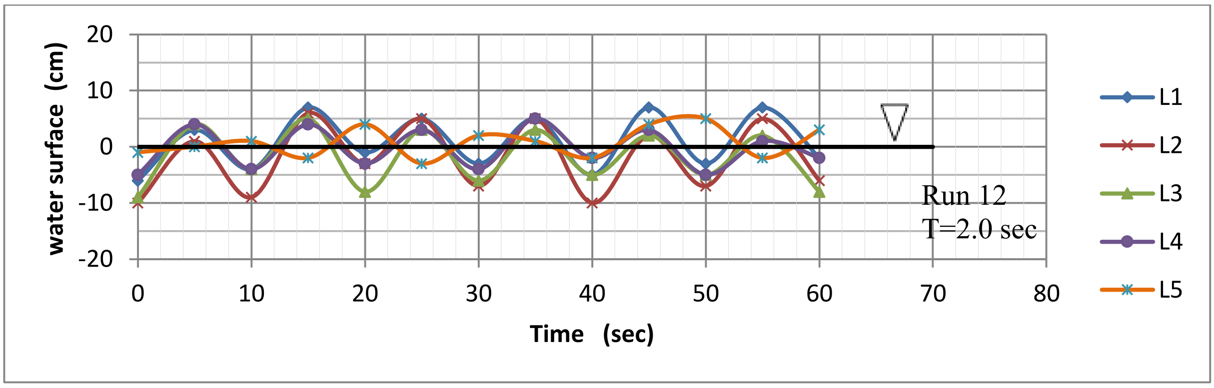


Fig. 4.12: Water level variation with time at various locations

1.2.4 Revetment with X-block (filter condition 1)

The Fig. 4.13, Fig. 4.14, Fig. 4.15 and Fig. 4.16 represent the variation of water surface with Time for T=1.5, 1.6, 1.8, and 2.0 sec, respectively when X-blocks were placed on the revetment in filter condition-1. The Fig. 4.13 shows that wave height reduction for the wave period of 1.5 sec. and from this Fig. it is found that wave reduced by 54%. The Fig. 4.14 shows that the wave height reduction for the wave period of 1.6 sec and it is found that the wave height reduced by 50%. The Fig. 4.15 shows that the wave height reduction for the wave period of 1.8 sec and it is found that wave reduced by 46%. From the Fig. 4.16 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

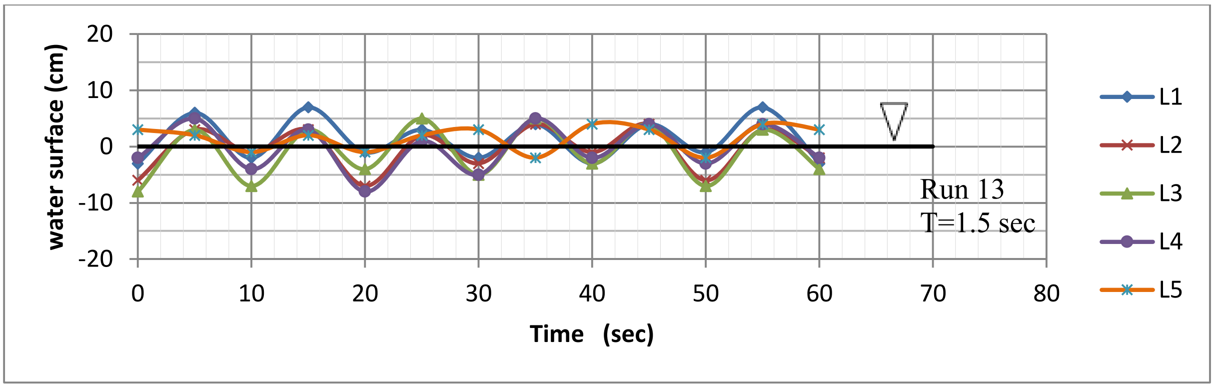


Fig. 4.13: Water level variation with time at various locations

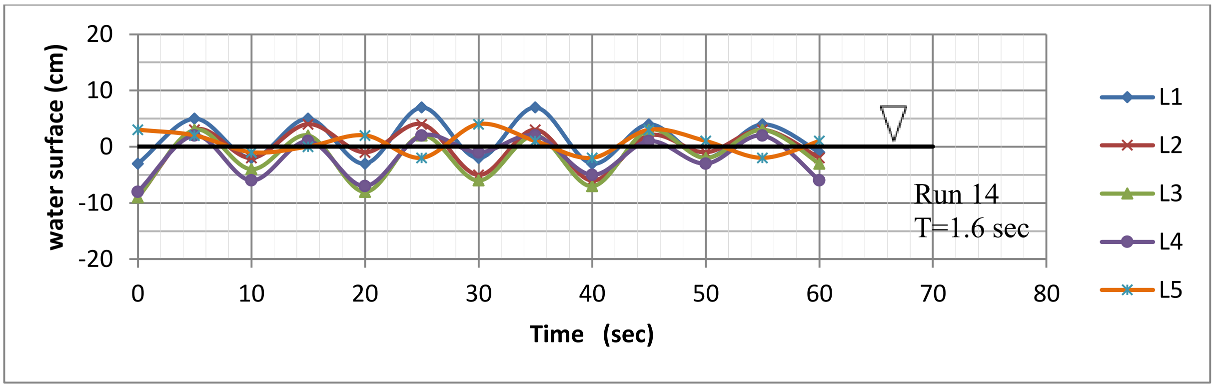


Fig. 4.14: Water level variation with time at various locations

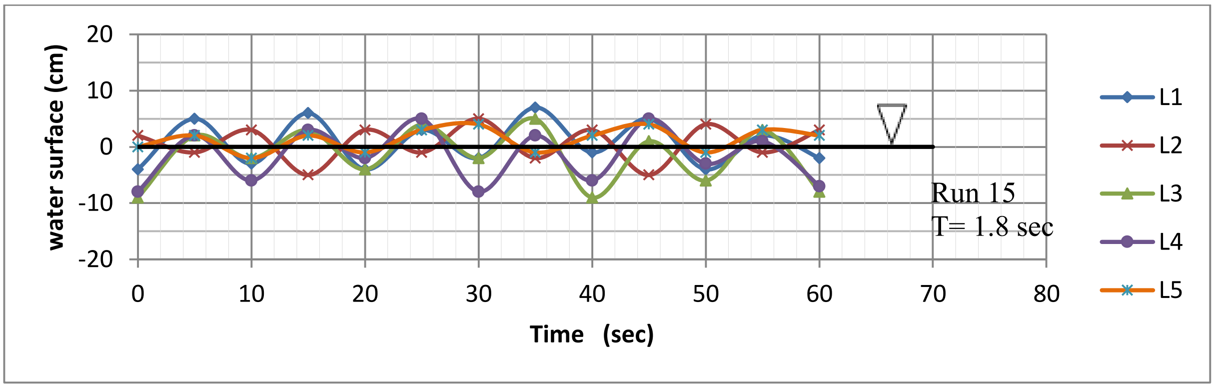


Fig. 4.15: Water level variation with time at various locations

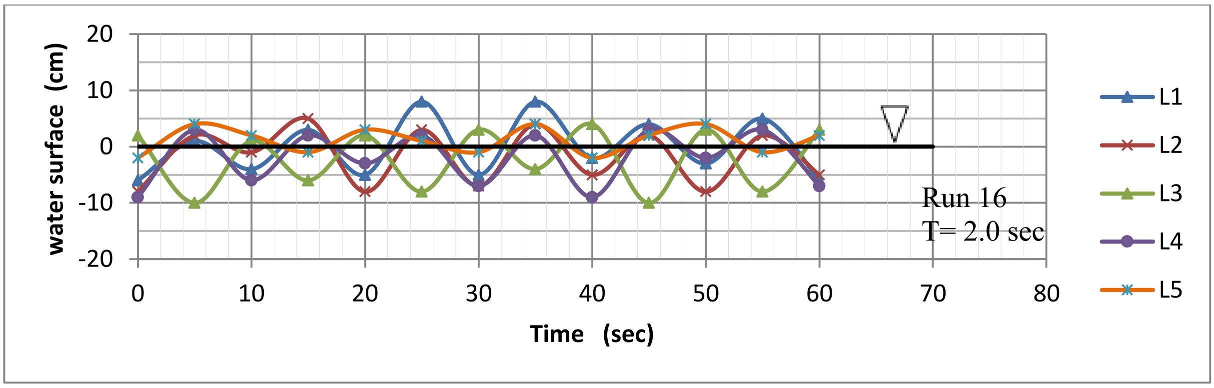


Fig. 4.16: Water level variation with time at various locations

1.2.5 Revetment with X-block (filter condition 2)

The Fig. 4.17, Fig. 4.18, Fig. 4.19 and Fig. 4.20 represent the variation of water surface with Time for T=1.5, 1.6, 1.8, and 2.0 sec, respectively when X-blocks were placed on the revetment in filter condition-2. The Fig. 4.17 shows that the wave height reduction for the wave period of 1.5 sec and from this Fig. it is found that the wave height reduced by 54%. The Fig. 4.18 shows that the wave height reduction for the wave period of 1.6 sec and it is found that the wave height reduced by 50%. The Fig. 4.19 shows that the wave height reduction for the wave period of 1.8 sec and it is found that the wave height reduced by 46%. From the Fig. 4.20 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

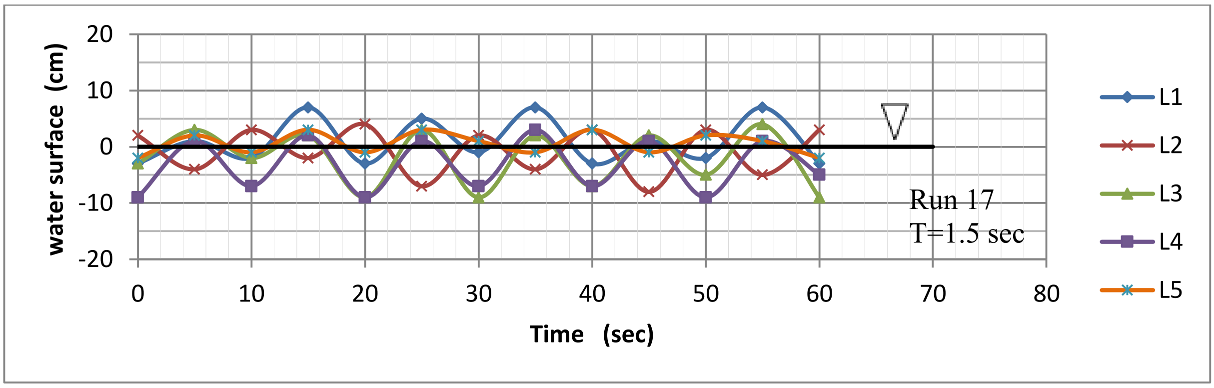


Fig. 4.17: Water level variation with time at various locations

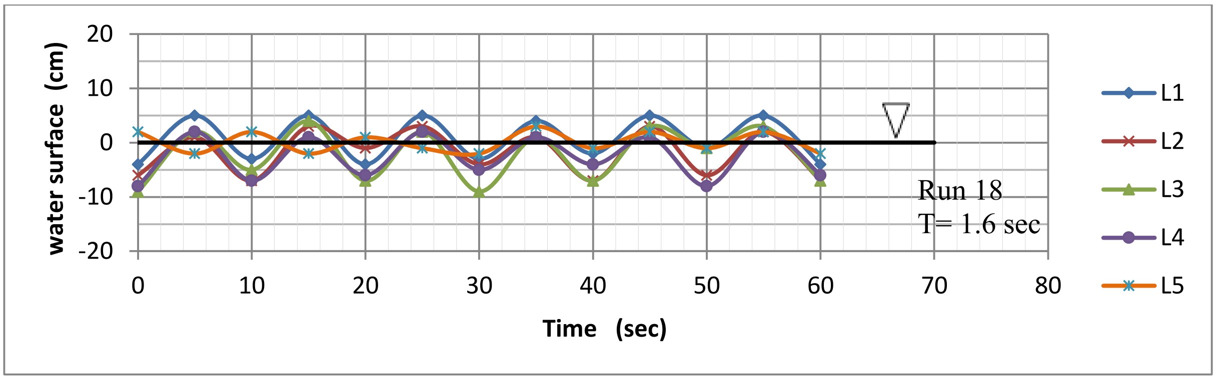


Fig. 4.18: Water level variation with time at various locations

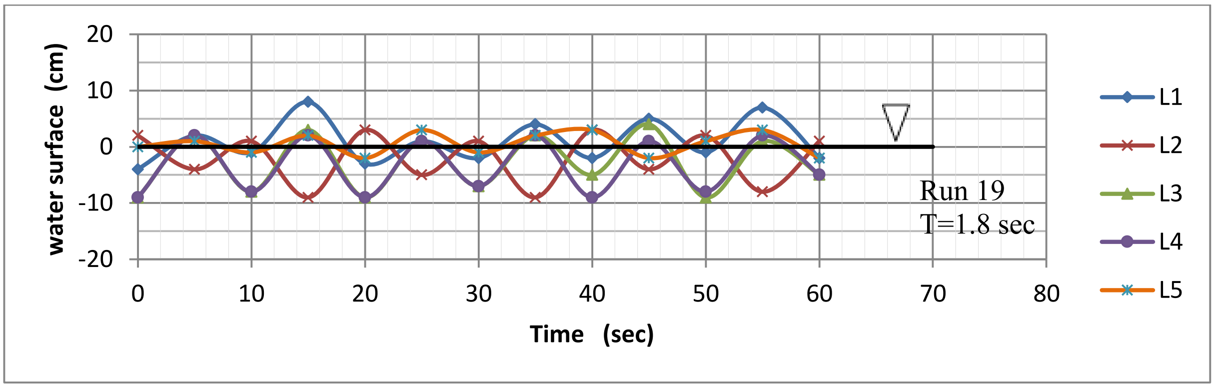


Fig. 4.19: Water level variation with time at various locations

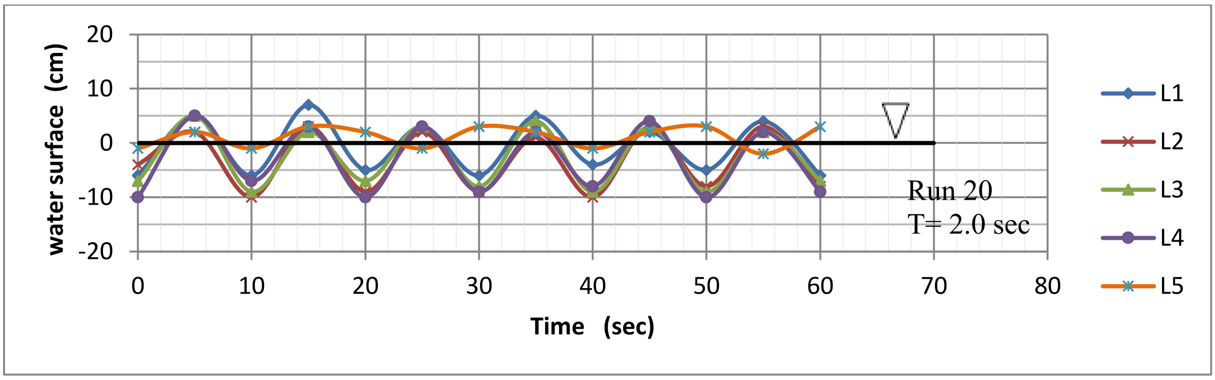


Fig. 4.20: Water level variation with time at various locations

1.2.6 Revetment with Tetrapod (filter condition 2)

The Fig. 4.21, Fig. 4.22, Fig. 4.23 and Fig. 4.24 represent the variation of water surface with Time for T=1.5, 1.6, 1.8, and 2.0 sec respectively when tetrapods were placed on the revetment in filter condition-2. The Fig. 4.21 shows that the wave height reduction for the wave period of 1.5 sec and from this Fig. it is found that the wave height reduced by 54%. The Fig. 4.22 shows that the wave height reduction for the wave period of 1.6 sec. and it is found that the wave height reduced by 58%. The Fig. 4.23 shows that the wave height reduction for the wave period of 1.8 sec. and it is found that the wave height reduced by 53%.

From the Fig. 4.24 it is found that the wave height is reduced by 57% for wave period of 2.0 sec.

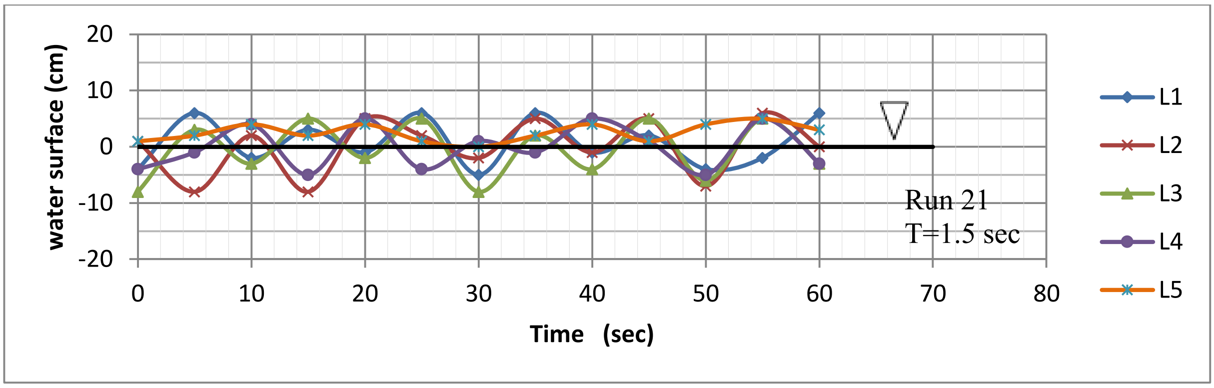


Fig. 4.21: Water level variation with time at various locations

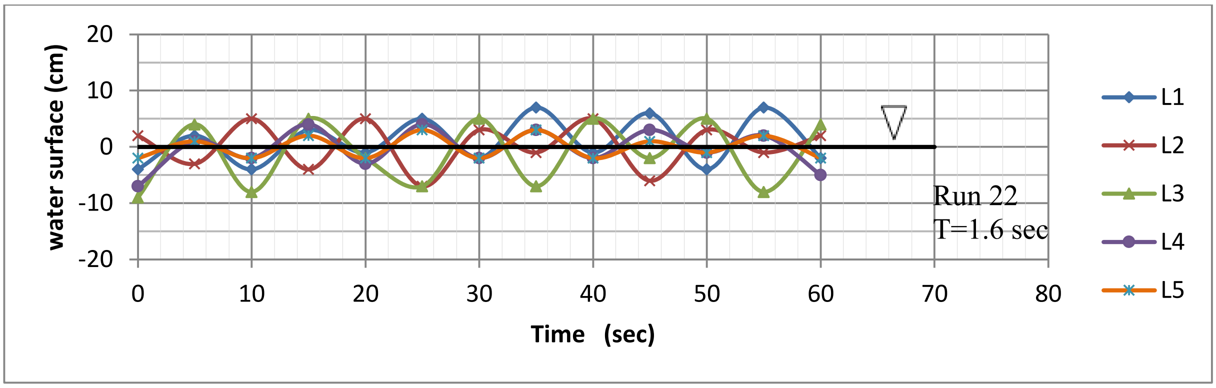


Fig. 4.22: Water level variation with time at various locations

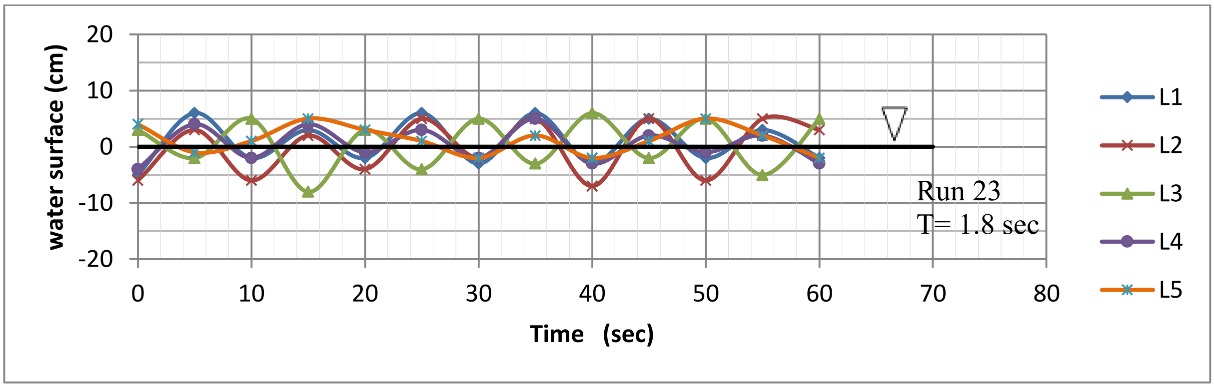


Fig. 4.23: Water level variation with time at various locations

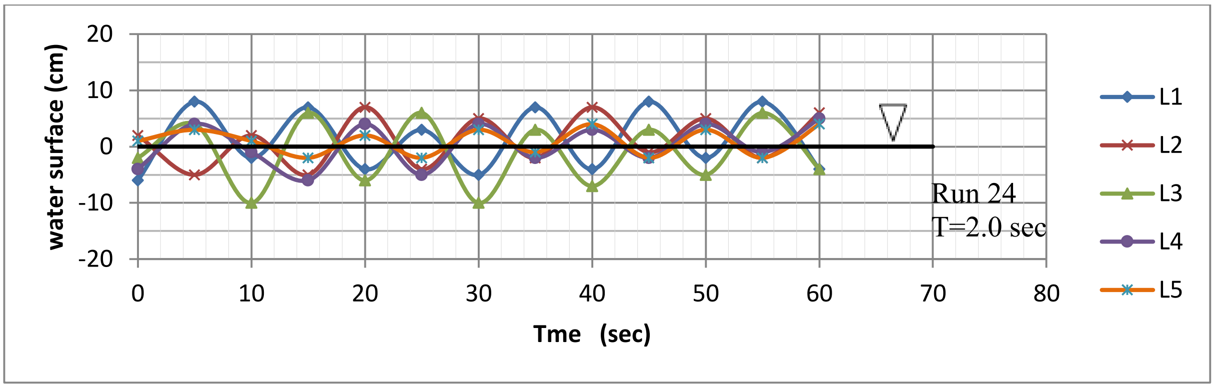


Fig. 4.24: Water level variation with time at various locations

1.3 water surface profile

The figure ranges from Fig. 4.25 to Fig, 4.48 shows the variation of water surface elevation with distance. The high energy of incident wave is reduced by various types of armor units installed on the revetment. In these graph the Water surface profiles are plotted at 20 sec interval for 60 sec for wave periods (T= 1.5, 1.6, 1.8 and 2.0 sec).

1.3.1 Revetment with C.C. block (uniformly placement)

The variations of water surface elevation with distance are represented by the Fig. 4.25 to Fig. 4.28 for wave periods of 1.5, 1.6, 1.8, and 2.0 sec and wave height reductions are also shown in these figures at different wave measuring locations. The Fig. 4.25 shows that the wave height reduced by 36% for the wave period of 1.5 sec. The Fig. 4.26 shows that the wave height reduction for the wave period of 1.6 sec and it is found that the wave height reduced by 50%. The Fig. 4.27 shows that the wave height reduction for the wave period of 1.8 sec and it is found that the wave height reduced by 50%. From the Fig. 4.28 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

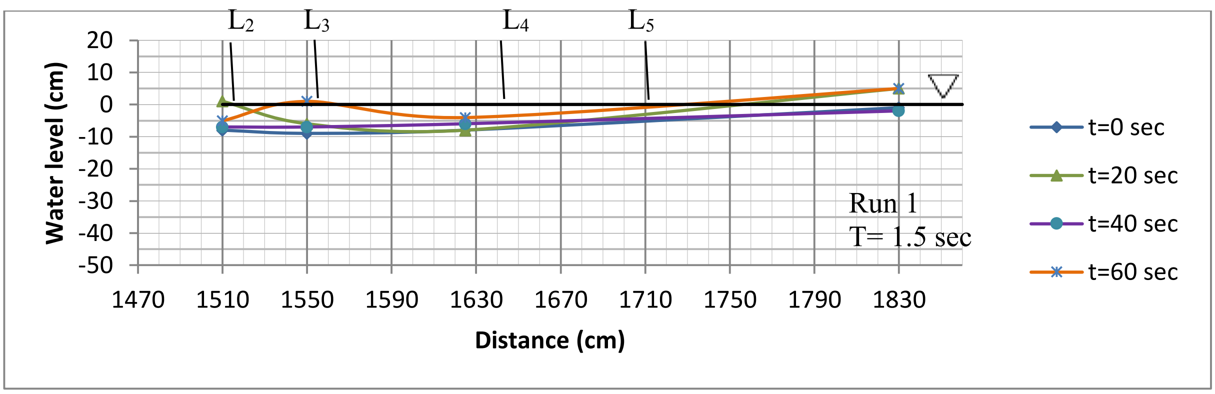


Fig. 4.25 Variation of water level with distance for different time interval

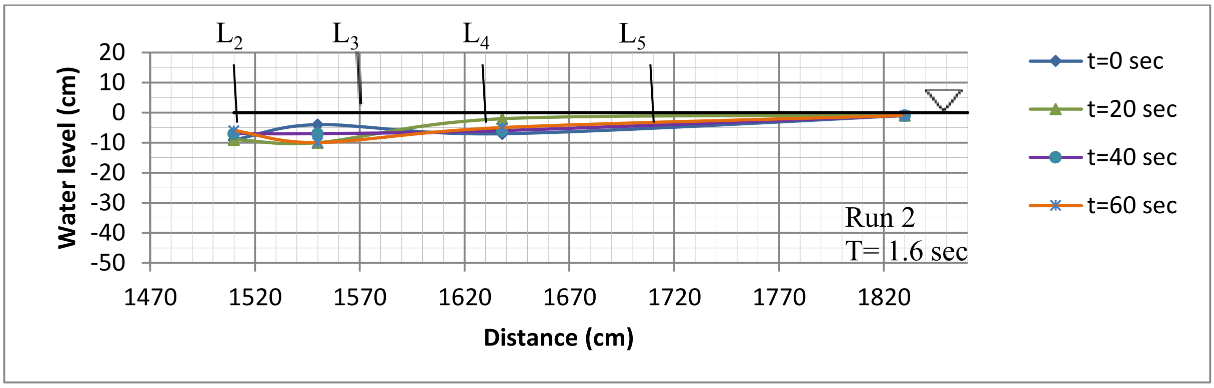


Fig. 4.26 Variation of water level with distance for different time interval

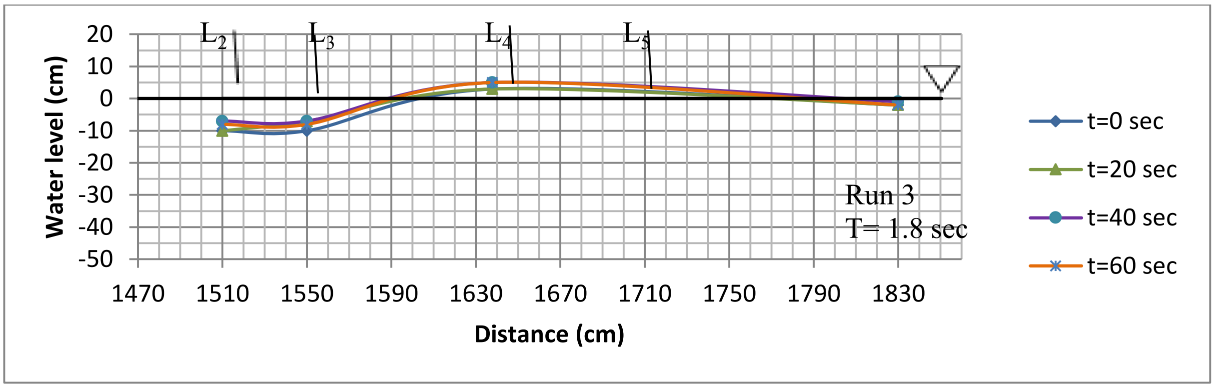


Fig. 4.27 Variation of water level with distance for different time interval

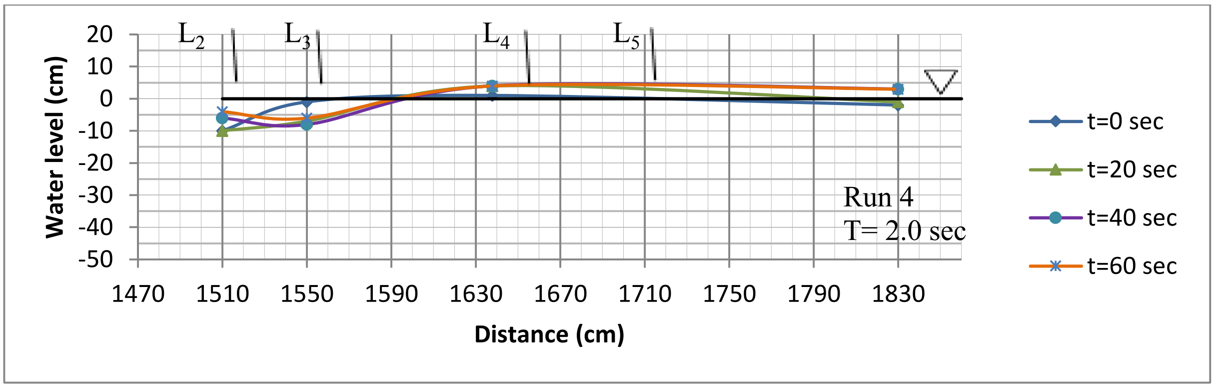


Fig. 4.28 Variation of water level with distance for different time interval

4.3.2 Revetment with C.C. block (stagger placement)

The Fig 4.29 to Fig 4.32 represent the variation of water surface with Distance for wave periods of 1.5, 1.6, 1.8, and 2.0 sec and wave height reductions are also shown at different wave measuring location. The Fig. 4.29 shows that the wave height reduction for the wave period of 1.5 sec and it is found that the wave height reduced by 54%. The Fig. 4.30 shows that the wave height reduction for the wave period of 1.6 sec and it is found that wave height reduced by 50%. The Fig. 4.31 shows that the wave height reduction for the wave period of 1.8 sec and it is found that wave height reduced by 40%. From the Fig. 4.32 it is found that the wave height is reduced by 42% for wave period of 2.0 sec.

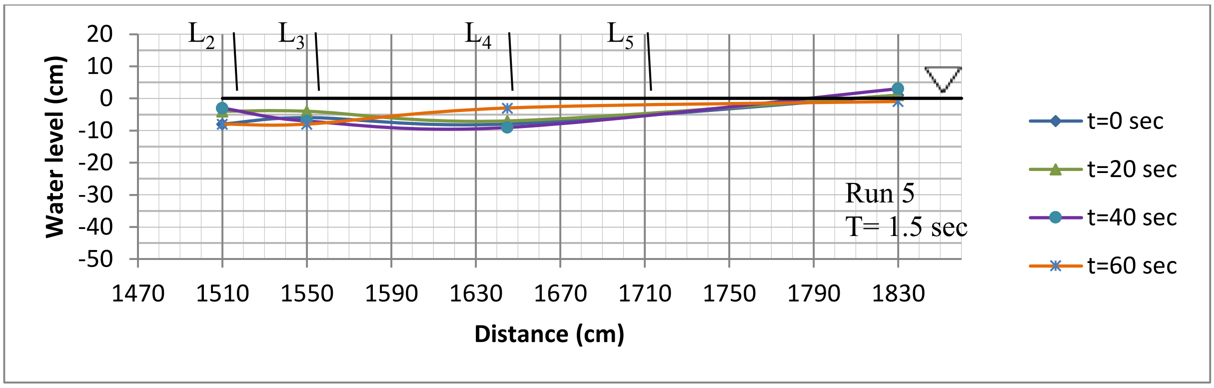


Fig. 4.29 Variation of water level with distance for different time interval

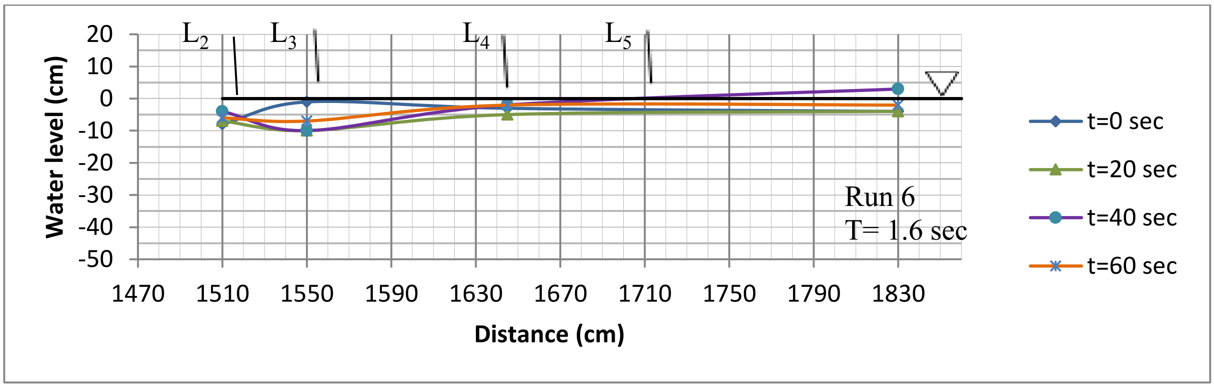


Fig. 4.30 Variation of water level with distance for different time interval

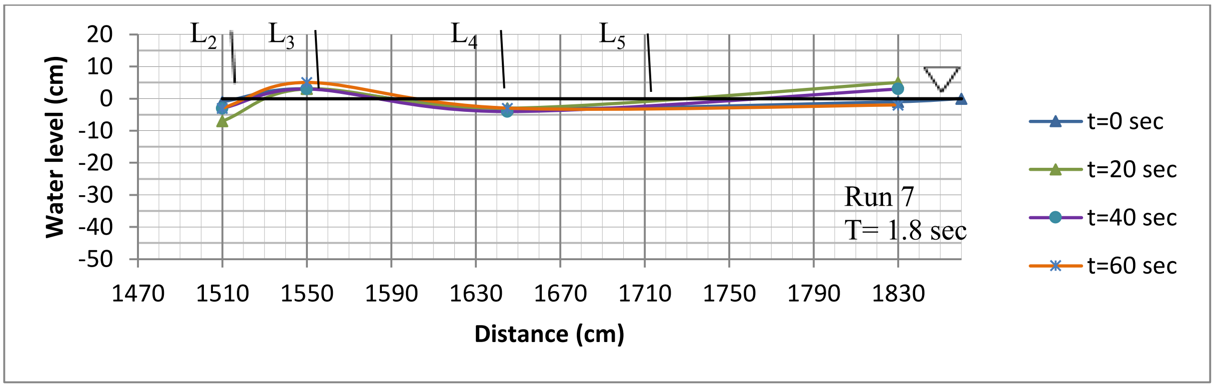


Fig. 4.31 Variation of water level with distance for different time interval

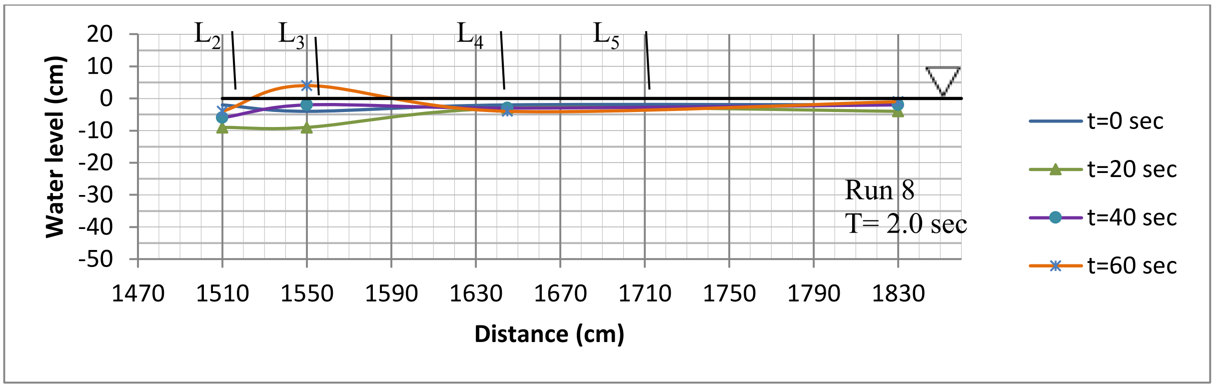


Fig. 4.32 Variation of water level with distance for different time interval

4.3.3 Revetment with Tetrapod (filter condition 1)

The Fig. 4.33 to Fig. 4.36 represent the variation of water surface with Distance for wave periods of 1.5, 1.6, 1.8, and 2.0 sec and wave height reduction are also shown in these figures at different wave measuring location. The Fig. 4.33 shows that the wave height reduction for the wave period of 1.5 sec and it is found that wave height reduced by 54%. The Fig. 4.34 shows that the wave height reduction for the wave period of 1.6 sec and it is found that wave height reduced by 50%. The Fig. 4.35 shows that the wave height reduction for the wave period of 1.8 sec and it is found that wave height reduced by 46%. From the Fig. 4.36 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

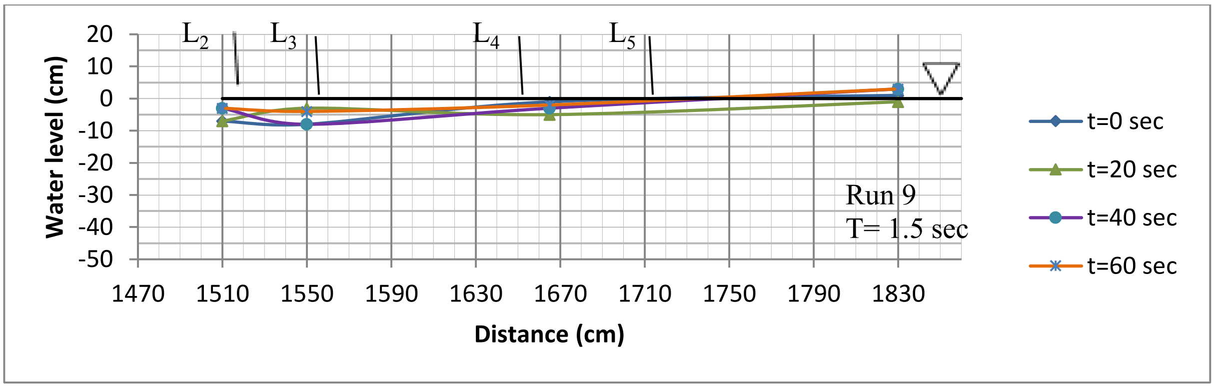


Fig. 4.33 Variation of water level with distance for different time interval

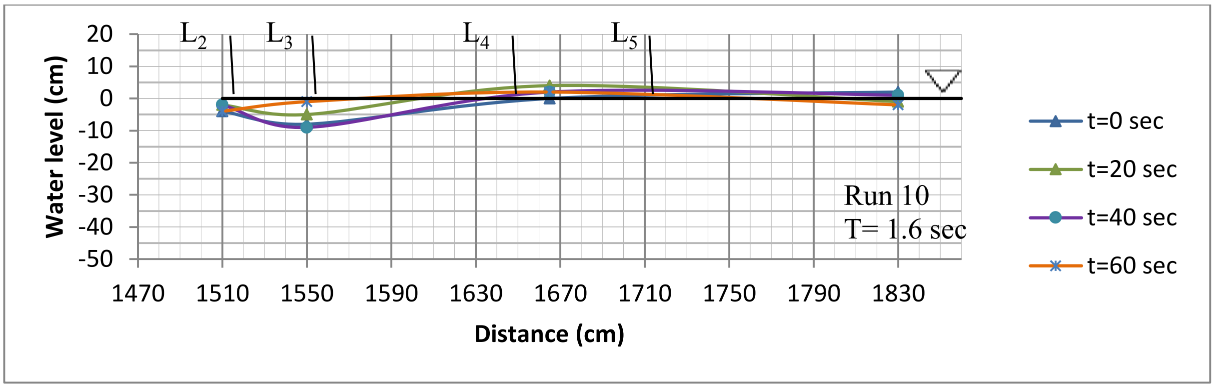


Fig. 4.34 Variation of water level with distance for different time interval

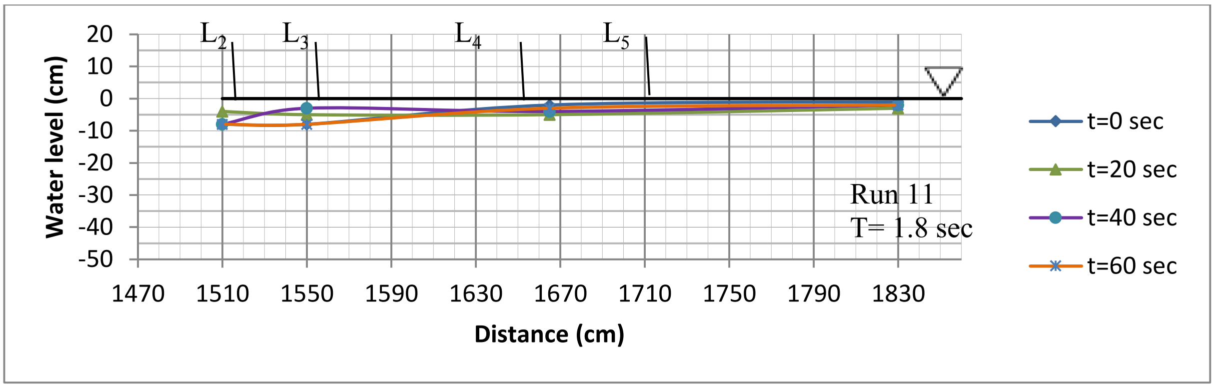


Fig. 4.35 Variation of water level with distance for different time interval

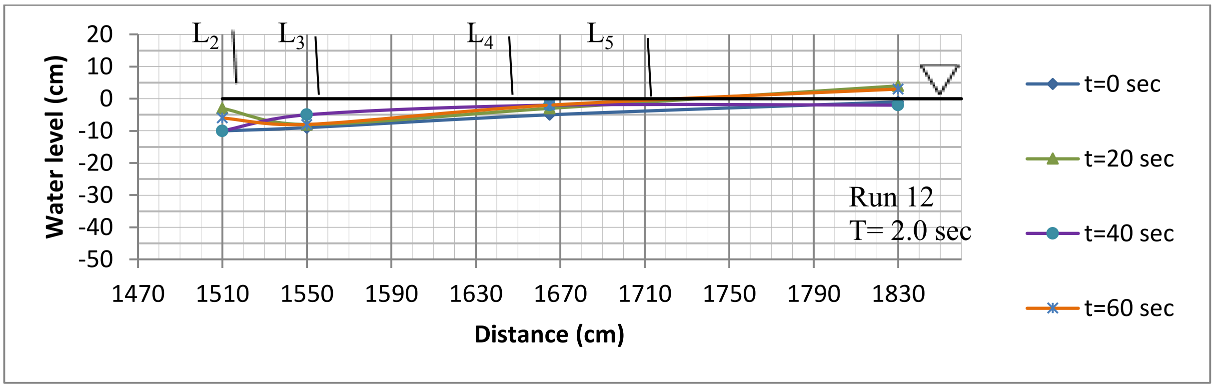


Fig. 4.36 Variation of water level with distance for different time interval

4.3.4 Revetment with X-block (filter condition 1)

The Fig 4.37 to Fig 4.40 represents the variation of water surface with Distance for T=1.5, 1.6, 1.8, and 2.0 sec and wave height reduction are also shown at different wave measuring locations. The Fig. 4.37 shows that the wave height reduction for the wave period of 1.5 sec and it is found that wave height reduced by 54%. The Fig. 4.38 shows that the wave height reduction for the wave period of 1.6 sec and it is found that wave height reduced by 50%. The Fig. 4.39 shows that the wave height reduction for the wave period of 1.8 sec and it is found that wave height reduced by 46%. From the Fig. 4.40 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

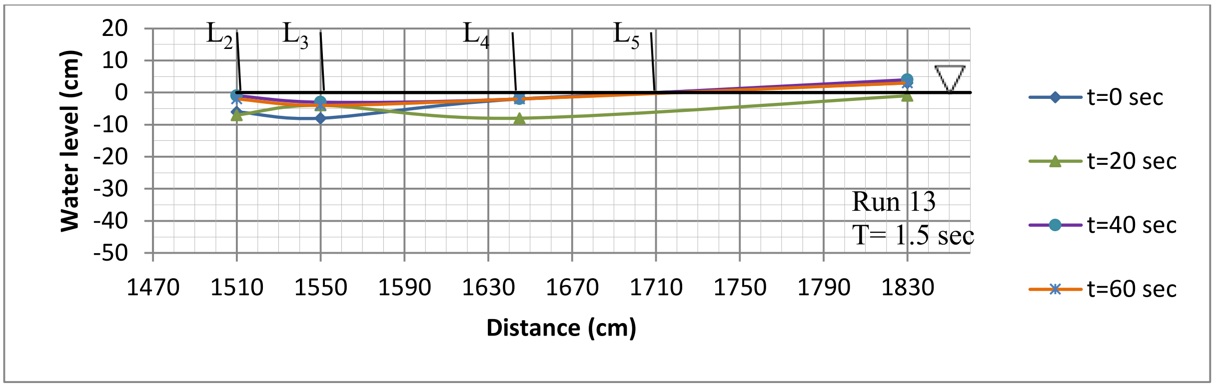


Fig. 4.37 Variation of water level with distance for different time interval

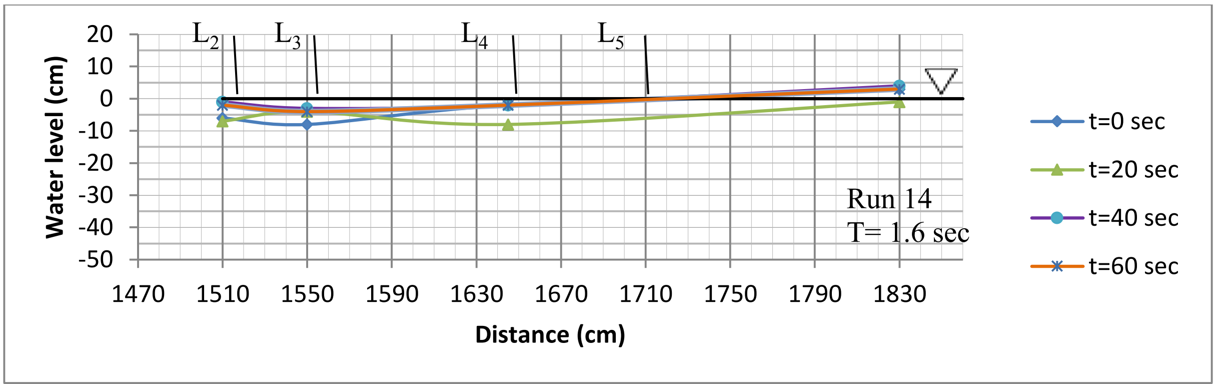


Fig. 4.38 Variation of water level with distance for different time interval

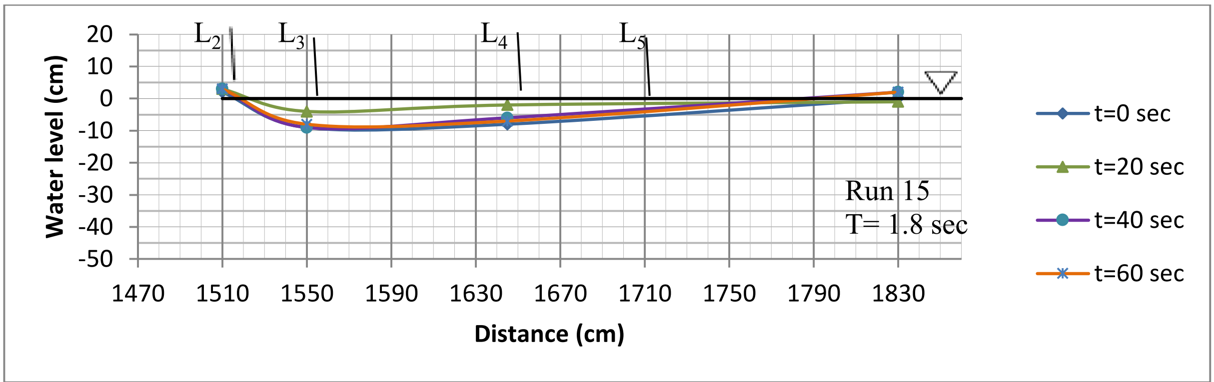


Fig. 4.39 Variation of water level with distance for different time interval

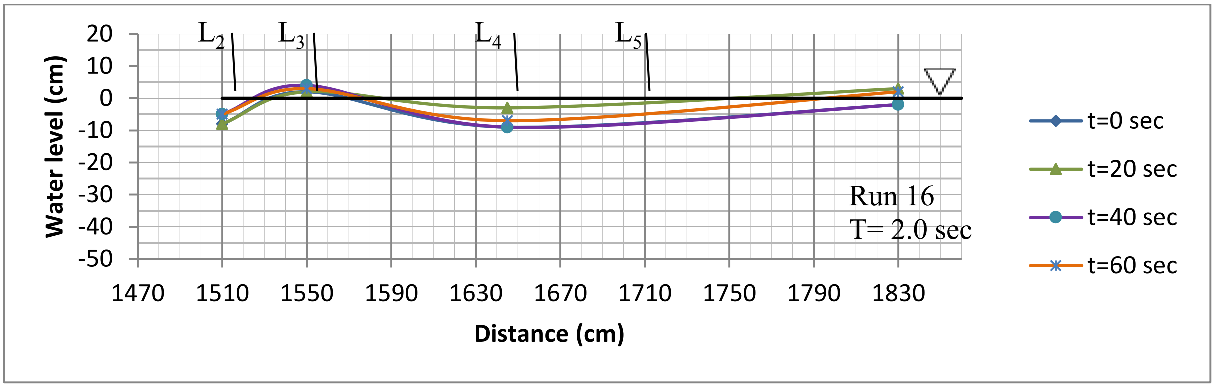


Fig. 4.40 Variation of water level with distance for different time interval

4.3.5 Revetment with X-block (filter condition 2)

The Fig. 4.41, Fig. 4.42, Fig. 4.43 and Fig 4.44 represent the variation of water surface with Distance for T=1.5, 1.6, 1.8, and 2.0 sec and the wave height reduction are also shown at different wave measuring locations. The Fig. 4.41 shows that the wave height reduction for the wave period of 1.5 sec and it is found that wave height reduced by 54%. The Fig. 4.42 shows that wave height reduction for the wave period T=1.6 sec and it is found that wave height reduced by 50%. The Fig. 4.43 shows that the wave height reduction for the wave period of 1.8 sec and it is found that wave height reduced by 46%. From the Fig. 4.44 it is found that the wave height is reduced by 50% for wave period of 2.0 sec.

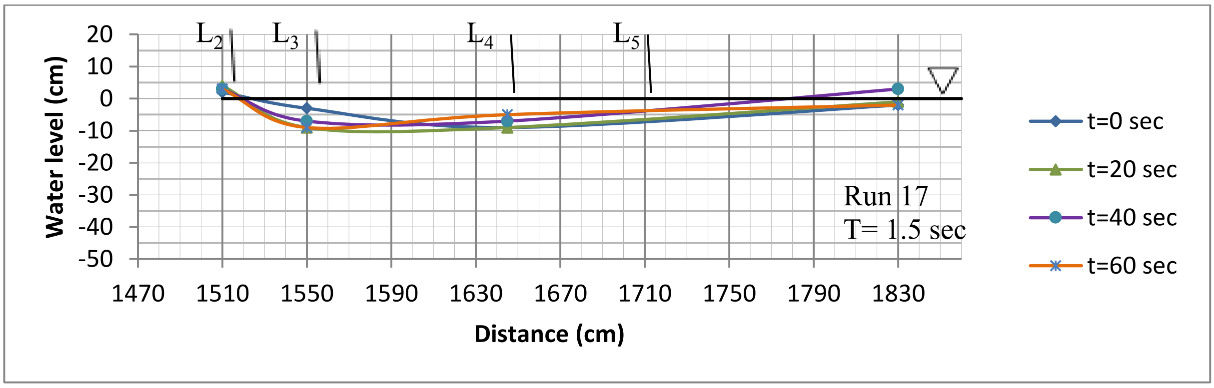


Fig. 4.41 Variation of water level with distance for different time interval

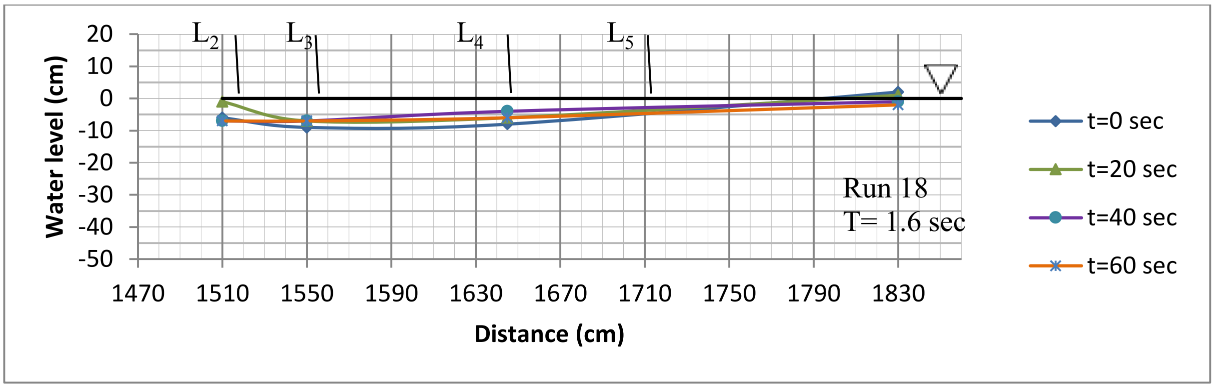


Fig. 4.42 Variation of water level with distance for different time interval

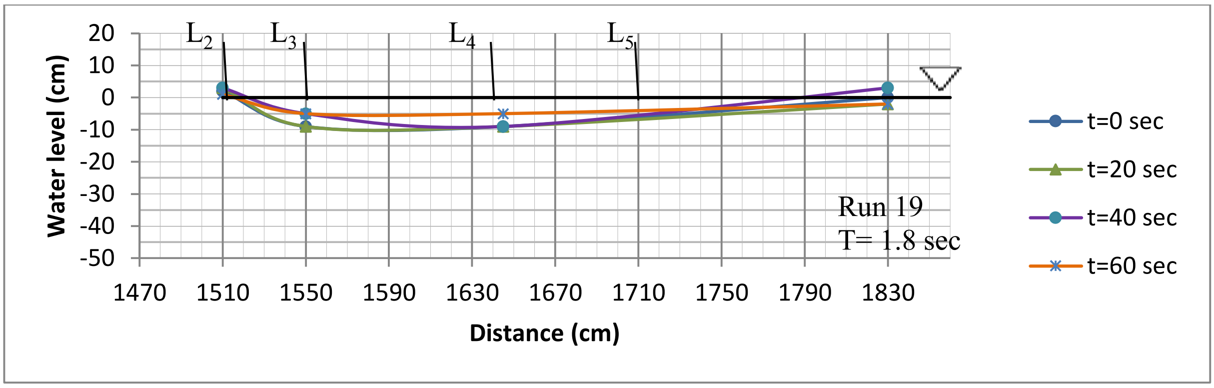


Fig. 4.43 Variation of water level with distance for different time interval

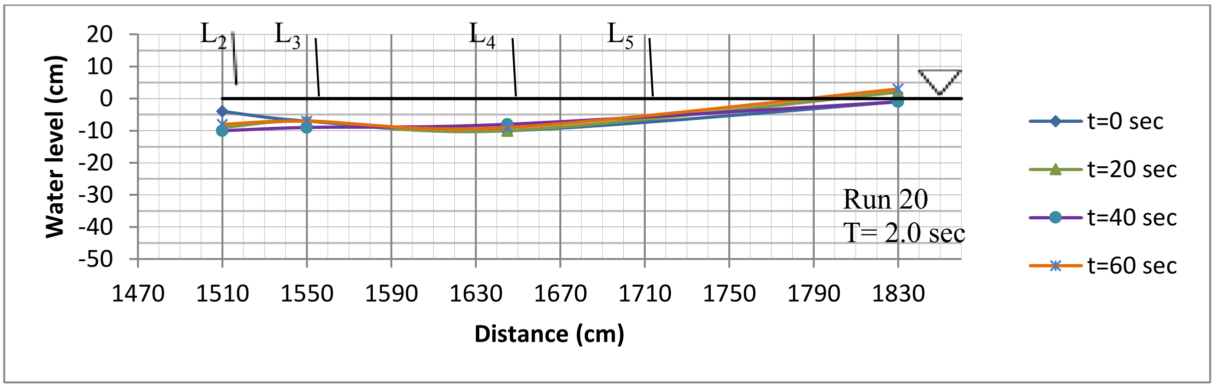


Fig. 4.44 Variation of water level with distance for different time interval

4.3.6 Revetment with tetrapod (filter condition 2)

The Fig. 4.45, Fig 4.46, Fig 4.47 and Fig. 4.48 represent the variation of water surface elevation with Distance for T=1.5, 1.6, 1.8, and 2.0 sec and wave height reduction are also shown at different wave measuring locations. The Fig. 4.45 shows that the wave height reduction for the wave period of 1.5 sec and it is found that wave height reduced by 54%. The Fig. 4.46 shows that the wave height reduction for the wave period of 1.6 sec and it is found that wave height reduced by 58%. The Fig. 4.47 shows that the wave height reduction for the wave period of 1.8 sec and it is found that wave height reduced by 53%. From the Fig. 4.48 it is found that the wave height is reduced by 57% for wave period of 2.0 sec.

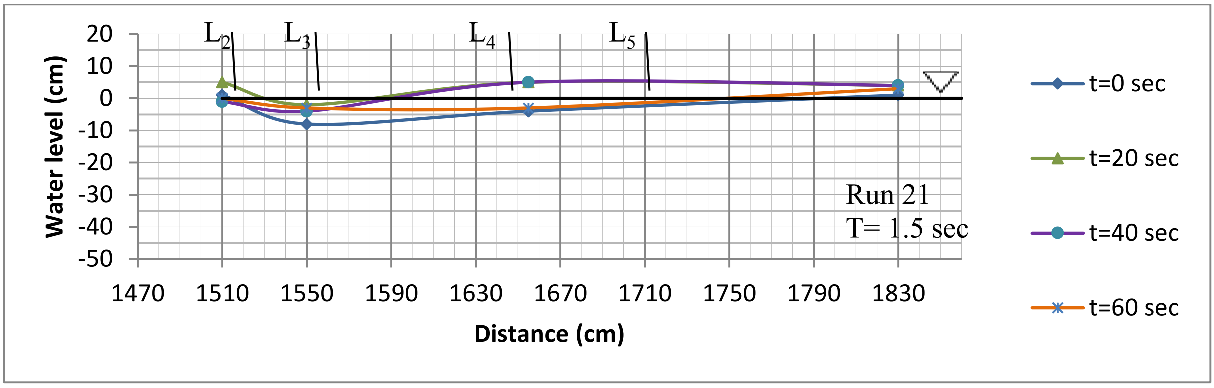


Fig. 4.45 Variation of water level with distance for different time interval

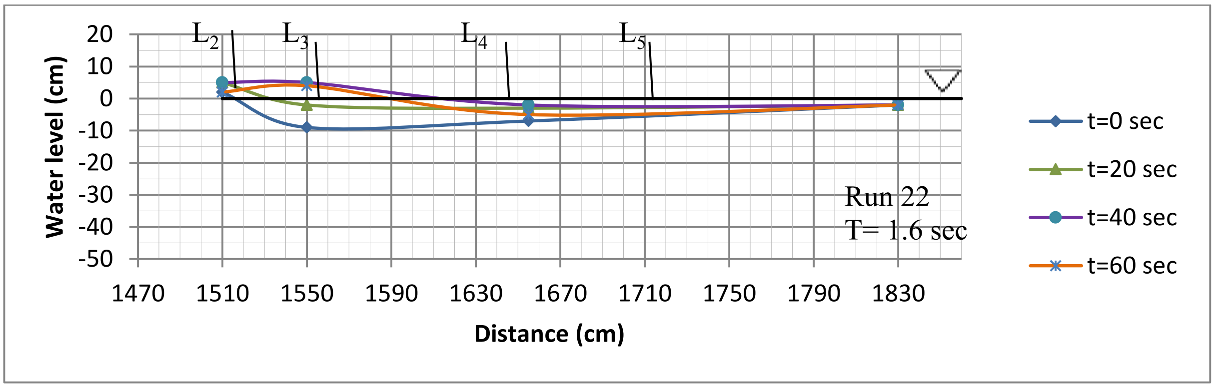


Fig. 4.46 Variation of water level with distance for different time interval

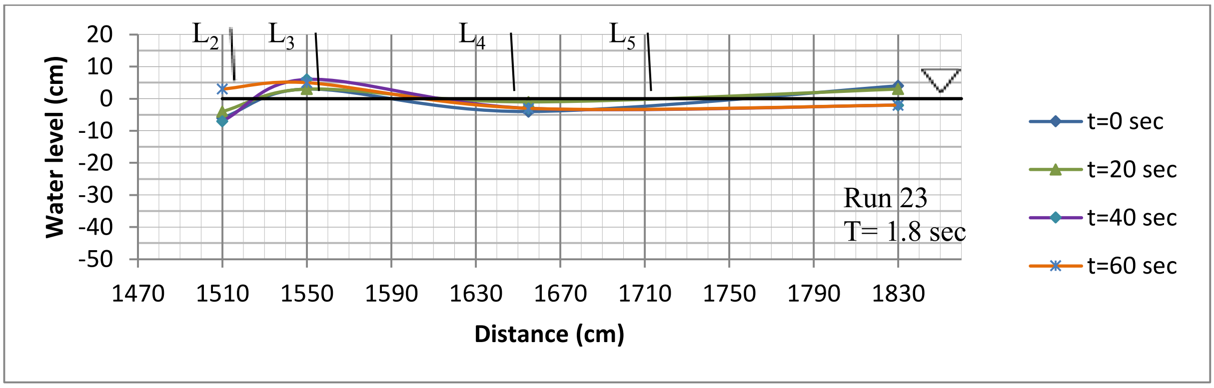


Fig. 4.47 Variation of water level with distance for different time interval

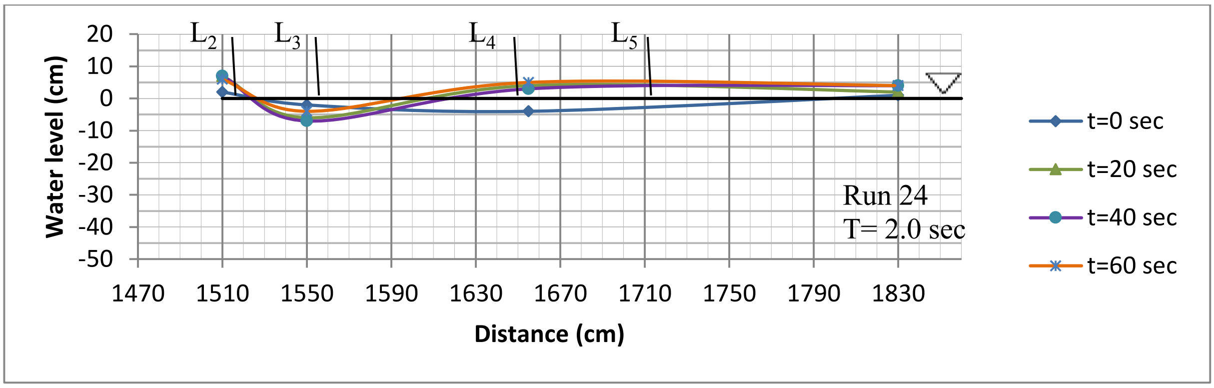


Fig. 4.48 Variation of water level with distance for different time interval

4.4 Effectiveness of armor unit placed on coastal revetment

Stability of armor unit is very important in shore protection revetment. Based on the analysis of laboratory data, the effectiveness of various types of armor units has been evaluated and presented in this article. To understand the performance of different types of armor units, these are discussed separately in six cases as below:

Case 1: Revetment with Uniformly Placed C.C. Block (Filter Condition-1).

Case 2: Revetment with Staggeredly Placed C.C. Block (Filter Condition-1).

Case 3: Revetment with Tetrapod (Filter Condition-1).

Case 4: Revetment with X-Block (Filter Condition-1).

Case 5: Revetment with X-Block (Filter Condition-2).

Case 6: Revetment with Tetrapod (Filter Condition-2).

Case 1: Revetment with Uniformly Placed C.C. Block (Filter Condition-1)

In this case, revetment was constructed by placing the C.C. block (30 cm X 30 cm X 30 cm) over the filter layer (filter condition-1) having 1:4 slopes. Toe protection was constructed as shown in Fig. 3.7. Four experimental runs were conducted for four wave conditions with T=1.5, 1.6, 1.8 and 2.0 sec which generated the incident wave height is 11cm, 12cm, 14 cm and 14 cm respectively.

For T=1.5 sec the incident wave height (H_i) is 11 cm and wave breaking location is measured (over the slope) 115 cm away from the wave measuring location L2 towards the shore. The wave height after breaking (H_b) is 7 cm which indicates that the damping of wave is 36%. The run duration was six minutes. No damage on sub-soil, toe, filter and cover layer was found after completion this run that is shown in Fig 4.49

Fig. 4.49 Revetment was stable after Run No. 1 (case-1, T=1.5sec)

For T=1.6 sec the incident wave height (H_i) is 12 cm and wave breaking location is measured (over the slope) 128 cm away from the wave measuring location L2 towards the shore. The wave height after breaking (H_b) is 6 cm which indicate that the damping of wave is 50%. The run duration was six minutes. Damage was occurred on cover layer about 30 cm X 8 cm area. It was started on shore side of the wave breaking location. No damage on sub-soil, toe and filter was found after completion this run that is shown in Fig.4.50

Fig. 4.50 Failure seen at the revetment after Run No 2 (case-1, T=1.6 sec)

For T=1.8 sec the incident wave height (H_i) is 14 cm and wave breaking location is measured (over the slope) 128 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 50%. The run duration was six minutes. Damage was occurred on cover layer about 30 cm X 12 cm area. It was started on shore side of the wave breaking location. Some C.C. block was subsided due to damage of filter. No change occurred at subsoil and toe was found after completion this run that is shown in Fig.4.51

Fig.4. 51 Failure seen at the revetment after Run No 3 (case-1, T=1.8 sec)

For T=2.0 sec the incident wave height (H_i) is 14 cm and wave breaking location is measured (over the slope) 128 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 50%. The run duration was six minutes. Damage was occurred on cover layer about 30 cm X 12 cm area. It was started on shore side of the wave breaking location. Some C.C. block was subsided due to damage of filter. Damage was also occurred at subsoil but no damage was found at toe after completion this run that is shown in Fig.4.52

Fig.4. 52 Failure seen at the revetment after Run No 4 (case-1, T=2.0 sec)

Case 2: Revetment with Staggeredly Placed C.C. Block (Filter Condition-1)

In this case, the revetment was constructed by satggeredly placed C.C. block (30 cm X 30 cm X 45 cm) over the filter layer (filter condition-1) having 1:4 slopes. Toe protection was constructed as shown in Fig. 3.7. Four experimental runs were conducted for four wave conditions with T=1.5, 1.6, 1.8 and 2.0 sec which generated the incident wave height is 11cm, 12 cm, 13 cm and 14 cm respectively.

For T=1.5 sec the incident wave height (H_i) is 11 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 5 cm which indicate that the damping of wave is 54%. The run duration was six minutes. No damage on sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.53.

Fig. 4.53 Revetment was stable after Run No 5 (case-2, T=1.5 sec)

For T=1.6 sec the incident wave height (H_i) is 12 cm, wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore.

Fig. 4.54 Revetment was stable after Run No 6 (case-2, T=1.6 sec)

Wave height after breaking (H_b) is 6 cm which indicate that the damping of wave is 50%. The run duration was six minutes. No damage on sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.54.

For T=1.8 sec the incident wave height (H_i) is 13 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 46%. The run duration was six minutes. Damage was occurred on cover layer about 70 cm X 30 cm area. It was started on shore side of the wave breaking location. Filter was also (stone chips were displaced) damaged but no change occurred at subsoil and toe was found after completion this run that as shown in Fig.4.55

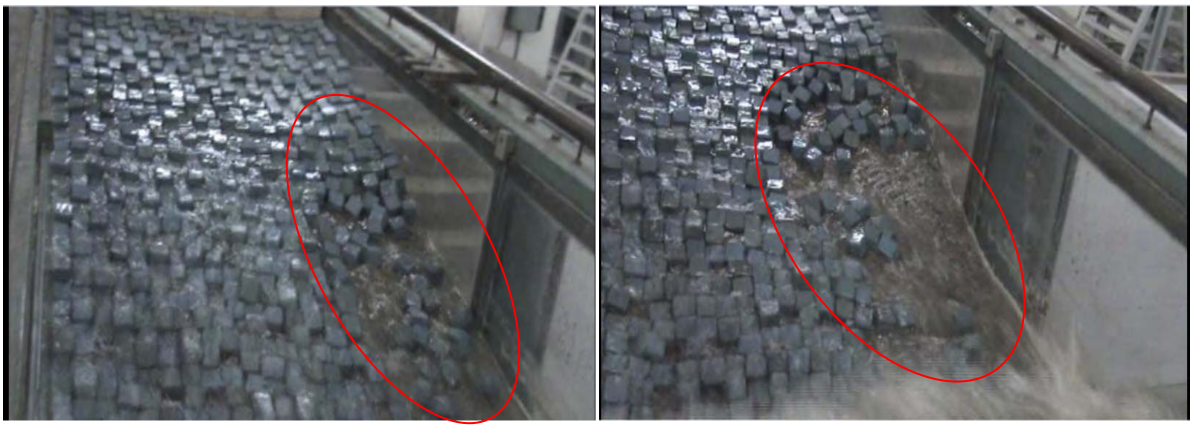


Fig. 4.55 Revetment was unstable after Run No 7 (case-2, T=1.8 sec)

For T=2.0 sec the incident wave height (H_i) is 14 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 8 cm which indicate that the damping of wave is 42%.

Fig. 4.56 Revetment was unstable after Run No 8 (case-2, T=2.0 sec)

The run duration was six minutes. Damage was occurred on cover layer about 150 cm X 45 cm area. It was started on shore side of the wave breaking location. Filter (stone chips were displaced) and subsoil was also damage but no change occurred at toe was found after completion this run that as shown in Fig.4.56.

Case 3: Revetment with Tetrapod (Filter Condition-1)

In this case, revetment was constructed by placing the tetrapod over the filter layer (filter condition-1) having 1:4 slopes. Toe protection was constructed as shown in Fig. 3.7. Four experimental runs were conducted for four wave conditions with T=1.5, 1.6, 1.8 and 2.0 sec which generated incident wave height of 11cm, 12cm, 13 cm and 14 cm respectively.

For T= 1.5 sec the incident wave height (H_i) is 11 cm and wave breaking location is (over the slope) 145 cm away from the wave measuring location L2 towards the shore.

Fig. 4.57 Revetment was stable after Run No 9 (case-3, T=1.5 sec)

Wave height after breaking (H_b) is 5 cm which indicate that the damping of wave is 54%. The run duration was six minutes. No damaged at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.57.

For T=1.6 sec the incident wave height (H_i) is 12 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 6 cm which indicate that the damping of wave is 50%. The run duration was six minutes. No damaged at sub-soil, toe, filter and cover layer was found after this run as shown in Fig.4.

Fig. 4.58 Revetment was stable after Run No 10 (case-3, T=1.6 sec)

For T=1.8 sec the incident wave height (H_i) is 13 cm and wave breaking location is (over the slope) 145 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 46%. The run duration was six minutes. No damaged at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.59.

Fig. 4.59 Revetment was stable after Run No 10 (case-3, T=1.8 sec)

For T=2.0 sec the incident wave height (H_i) is 14 cm and wave breaking location is (over the slope) 145 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 8 cm which indicate that the damping of wave is 45%. The run duration was six minutes. Filter was damaged (stone chips were displaced) in this run. Damage was started onshore side of wave breaking location. No damage at sub-soil, toe and cover layer was found after completion this run as shown in Fig.4.60

Fig. 4.60 Revetment was unstable after Run No 12 (case-3, T=2.0 sec)

Case 4: Revetment with X-Block (Filter Condition-1)

In this case, revetment was constructed by placing the X-block over the filter layer (filter condition-1) having 1:4 slopes. Toe protection was constructed as shown in Fig. 3.7. Four experimental runs were conducted for four wave conditions with T=1.5, 1.6, 1.8 and 2.0 sec which generated incident wave height of 11cm, 12cm, 13 cm and 14 cm respectively.

For T=1.5 sec the incident wave height (H_i) is 11 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height

Fig. 4.61 Revetment was stable after Run No 13 (case-4, T=1.5 sec)

after breaking (H_b) is 5 cm which indicate that the damping of wave is 54%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.61.

For T=1.6 sec the incident wave height (H_i) is 12 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 6 cm which indicate that the damping of wave is 50%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.62

Fig.4.62 Revetment was stable after Run No 14 (case-4, T=1.6 sec)

For T=1.8 sec the incident wave height (H_i) is 13 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 46%. The run duration was six minutes.

Fig.4.63 Revetment was unstable after Run No 15 (case-4, T=1.8 sec)

Filter was damaged (stone chips were displaced) in this run. Damage was started onshore side of wave breaking location but no damage at sub-soil, toe and cover layer was found after completion this run as shown in Fig.4.63.

For T=2.0 sec the incident wave height (H_i) is 14 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 50%. The run duration was six minutes. Filter was damaged (stone chips were displaced) in this run. Damage was started onshore side of wave breaking location. No damage at sub-soil, toe and cover layer was found after completion this run as shown in Fig.4.64.

Fig.4.64 Revetment was unstable after Run No 16 (case-4, T=2.0 sec)

Case 5: Revetment with X-block (Filter conditions-2)

In this case, revetment was constructed by placing the X-block over the filter layer (filter condition-2) having 1:4 slopes. Toe protection was constructed as shown in Fig. 3.8. Four experimental runs were conducted for four wave conditions with T=1.5, 1.6, 1.8 and 2.0 sec which generated incident wave height of 11cm, 12cm, 13 cm and 14 cm respectively.

For T=1.5 sec the incident wave height (H_i) is 11 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 5 cm which indicate that the damping of wave is 54%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.65.

Fig.4.65 Revetment was stable after Run No 17 (case-5, T=1.5 sec)

For T=1.6 sec the incident wave height (H_i) is 12 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 6 cm which indicate that the damping of wave is 50%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.66

Fig.4.66 Revetment was stable after Run No 18 (case-5, T=1.6 sec)

For T= 1.8 sec the incident wave height (H_i) is 13 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 46%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.67.

Fig.4.67 Revetment was stable after Run No 19 (case-5, T=1.8 sec)

For T= 2.0 sec the incident wave height (H_i) is 14 cm and wave breaking location is (over the slope) 135 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 7 cm which indicate that the damping of wave is 50%. The run duration was six minutes. Filter was damaged (sand was displaced) in this run. Damage was started onshore side of wave breaking location but no damage at sub-soil, toe and cover layer was found after completion this run as shown in Fig.4.

Fig.4.68 Revetment was unstable after Run No 20 (case-5, T=2.0 sec)

Case 6: Revetment with Tetrapod (Filter Condition-2)

In this case, revetment was constructed by placing the tetrapod over the filter layer (filter condition-2) having 1:4 slopes. Toe protection was constructed as shown in Fig. 3.8. Four experimental runs were conducted for four wave conditions with T=1.5, 1.6, 1.8 and 2.0 sec which generated incident wave height of 11cm, 12cm, 13 cm and 14 cm respectively.

For T= 1.5 sec the incident wave height (H_i) is 11 cm and wave breaking location is (over the slope) 145 cm away from the wave measuring location L2 towards the shore.

Fig.4.69 Revetment was stable after Run No 21 (case-6, T=1.5 sec)

Wave height after breaking (H_b) is 5 cm which indicate that the damping of wave is 54%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.69.

For T= 1.6 sec the incident wave height (H_i) is 12 cm and wave breaking location is (over the slope) 145 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 5 cm which indicate that the damping of wave is 58%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.70

Fig.4.70 Revetment was stable after Run No 22 (case-6, T=1.6 sec)

For T= 1.8 sec the incident wave height (H_i) is 13 cm and wave breaking location is (over the slope) 145 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 6 cm which indicate that the damping of wave is 53%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.71

Fig.4.71 Revetment was stable after Run No 23 (case-6, T=1.8 sec)

For T=2.0 sec the incident wave height (H_i) is 14 cm and wave breaking location is (over the slope) 145 cm away from the wave measuring location L2 towards the shore. Wave height after breaking (H_b) is 6 cm which indicate that the damping of wave is 57%. The run duration was six minutes. No damage at sub-soil, toe, filter and cover layer was found after completion this run as shown in Fig.4.72

Fig.4.72 Revetment was stable after Run No 24 (case-6, T=2.0 sec)

4.5 Comparison of effectiveness among different armor unit

4.5.1 Comparison between the performance of uniformly and Staggerredly placed C.C. block

C.C. block was placed on the slope in two ways, one is uniformly placed and other is staggeredly placed on the revetment. In this study, four wave periods (T= 1.5, 1.6, 1.8 and 2.0) sec are considered to evaluate stability of C.C. block. When C.C. block is uniformly placed on the revetment for wave period of 1.5 sec the incident wave height (H_i) is 11 cm and wave height after breaking (H_b) is found to be 7 cm hence wave reduction occurred as 36%. No damage was found on the revetment after completing the run. When C.C. block was staggerdly placed on the revetment for wave period of 1.5 sec, the incident wave height (H_i) is 11 cm and wave height after breaking (H_b) is found to be 5 cm, hence wave reduction occurred as 54%. Revetment was stable after completing the run. For T= 1.5 sec in both cases revetment was stable.

When C.C. block was uniformly placed on the revetment for the wave period of 1.6 sec, the incident wave height (H_i) is 12 cm and wave height after breaking (H_b) is 6 cm hence wave reduction occurred as 50%. After completing the run it was found that damage was occurred on the revetment and it started on shore side of the revetment but filter, subsoil and toe was stable. When C.C. block was staggerdly placed on the revetment for the wave periods of 1.6 sec, the incident wave height (H_i) is 12 cm and wave height after breaking (H_b) is 6 cm, hence wave reduction occurred as 50%. In this condition, no damage was occurred on the revetment after completing the run. For T=1.6 sec uniformly placed C.C. blocks unstable but staggerdly placed C.C. blocks was stable on the revetment.

When C.C. block was uniformly placed on the revetment for wave period of 1.8 sec, the incident wave height (H_i) is 14 cm and wave height after breaking (H_b) is 7 cm, hence wave reduction occurred as 50%. In this condition, damage was occurred on the revetment and it started on shore side of the wave breaking location. Some C.C. block was subsided due to damage on the filter. But subsoil and toe was stable. When C.C. block was staggerdly placed on the revetment for the wave period of 1.8 sec, incident wave height (H_i) is 13 cm and wave height after breaking (H_b) is 7 cm, hence wave reduction occurred as 46%. In this condition, damage was found on the revetment and it started on shore sided of the wave breaking location. But subsoil and toe was stable. After completing the run it was found that revetment was unstable in both cases for wave period of 1.8 sec.

When C.C. block was uniformly placed on the revetment for the wave period of 2.0 sec, the incident wave height (H_i) is 14 cm and wave height after breaking (H_b) is 7 cm, hence wave reduction occurred as 50%. In this condition, damage was found on the revetment and it was started on shore side of the wave breaking location. Some C.C. block was subsided due to damage on the filter. Subsoil was also damaged but toe remain stable after completing the run. When C.C. block was staggerdly placed on the revetment for wave period of 2.0 sec, the incident wave height (H_i) is 14 cm and wave height after breaking (H_b) is 8 cm, hence wave reduction occurred as 42%. In this condition, damage was occurred on the revetment and it was started on shore side of the wave breaking location. Subsoil and filter was damaged but toe remained stable after completing the run. After completing the run it was found that revetment was unstable in both cases for wave period of 2.0 sec.

From the above discussion, it was seen that for T=1.5 sec C.C. block was stable in both cases. For T=1.6 sec staggeredly placed C.C. block was stable but uniformly placed C.C. block was unstable. For T=1.8 sec and 2.0 sec in both cases C.C. block was unstable.

4.5.2 Comparison between the performance of Tetrapod and X-block (Filter Condition-1)

Tetrapods and X-blocks were placed on the revetment as a cover layer. When tetrapod was placed on the revetment for the wave period of 1.5 sec, the incident wave height (H_i) is 11 cm and wave height after breaking (H_b) is 5 cm, hence wave reduction occurred as 54.54%. After completing the run it was found that the revetment was stable. When X-block was placed on the revetment for wave period of 1.5 sec, the incident wave height (H_i) is 11 cm and wave height after breaking (H_b) is 5 cm, hence wave reduction occurred as 54%. In this condition no damage was found on the revetment after completing the run. For T= 1.5 sec in both cases revetment was stable.

When tetrapod was placed on the revetment for wave period of 1.6 sec, the incident wave height (H_i) is 12 cm and wave height after breaking (H_b) is 6 cm, hence wave reduction occurred as 50%. In this condition no damage was occurred at subsoil, filter, toe and cover layer. When X-block was placed on the revetment for the wave period of 1.6 sec, the incident wave height (H_i) is 12 cm and wave height after breaking (H_b) is 6 cm, hence wave reduction occurred as 50%. In this condition no damage was found at subsoil, filter, toe and cover layer after completing the run. For T= 1.6 sec in both cases revetment was stable.

When tetrapod was placed on the revetment for wave period of 1.8 sec, the incident wave height (H_i) is 13 cm and wave height after breaking (H_b) is 7 cm hence wave reduction occurred as 46%. In this condition no damage was occurred at subsoil, filter, toe and cover layer. When X-block was placed on the revetment for wave period of 1.8 sec, the incident wave height (H_i) is 13 cm and wave height after breaking (H_b) is 7 cm hence wave reduction occurred as 46%. In this condition damage was found on filter. Stone chips were displaced under the block. But subsoil and toe was remaining stable after completing the run. So, For T= 1.8 sec tetrapod was stable but X-block was unstable on the revetment.

When tetrapod was placed on the revetment for the wave period of 2.0 sec, the incident wave height (H_i) is 14 cm and wave height after breaking (H_b) is 7 cm hence wave reduction occurred as 50%. In this condition damage was occurred on filter, some stone chips were displaced under the tetrapod and damage started on shore side of wave breaking location. But subsoil, toe and cover layer was remained stable. When X-block was placed on the revetment for wave period of 2.0 sec, the incident wave height (H_i) is 14 cm and wave height after breaking (H_b) is 7 cm hence wave reduction occurred as 50%. In this condition damage was occurred on filter. Stone chips were displaced under X-block. But no damage was occurred at subsoil and toe. So, For T= 2.0 sec tetrapod and X-block was unstable on the revetment in filter condition-1.

From the above discussion it was seen that, performance of tetrapod and X-block was very good for wave period of 1.5 sec and 1.6 sec. In T=1.8 sec tetrapod was performed better than X-block in filter condition-1. But Performance of tetrapod and X-block was not good in wave period of 2.0 sec.

4.5.3 Comparison between the performance of Tetrapod and X-block (Filter condition-2)

In filter condition-2 stone chips were not used on the revetment as a filter material. Tetrapod and X-block was directly placed on Geotextile. When tetrapod was placed on the revetment for wave period of 1.5 sec, the incident wave height (H_i) is 11 cm and wave height after breaking (H_b) is 5 cm, hence wave reduction occurred as 54%. In this condition, it was found that the revetment was stable after completing the run. When X-block was placed on the revetment for wave period of 1.5 sec, the incident wave height (H_i) is 11 cm and wave height after breaking (H_b) is 5 cm, hence wave reduction occurred as 54%. In this condition, no damage was found on the revetment after completing the run. So, For T= 1.5 sec performance of tetrapod and X-block was very good in filter condition-2.

When tetrapod was placed on the revetment for wave period of 1.6 sec, the incident wave height (H_i) is 12 cm and wave height after breaking (H_b) is 5 cm, wave reduction occurred as 58%. In this condition no damage was occurred on the revetment. When X-block was placed on the revetment for wave period of 1.6 sec, the incident wave height (H_i) is 12 cm and wave height after breaking (H_b) is 6 cm, hence wave reduction occurred as 50%. In this condition no damage was found on the revetment after completing the run. So, For T= 1.6 sec performance of tetrapod and X-block was very good in filter condition-2.

When tetrapod was placed on the revetment for wave period of 1.8 sec, the incident wave height (H_i) is 13 cm and wave height after breaking (H_b) is 6 cm, wave reduction occurred as 58%. In this condition, no damage was occurred on the revetment. When X-block was placed on the revetment for wave period of 1.8 sec, the incident wave height (H_i) is 13 cm and wave height after breaking (H_b) is 7 cm, hence wave reduction occurred as 46%. In this condition, no damage was found on the revetment after completing the run. So, For T= 1.8 sec performance of tetrapod and X-block was very good in filter condition-2.

When tetrapod was placed on the revetment for wave period of 2.0 sec, the incident wave height (H_i) is 14 cm and wave height after breaking (H_b) is 6 cm, hence wave reduction occurred as 57%. In this condition, no damage was occurred on the revetment after completing the run. When X-block was placed on the revetment for wave period of 2.0 sec, the incident wave height (H_i) is 14 cm and wave height after breaking (H_b) is 7 cm, hence wave reduction occurred as 50%. In this condition damage was occurred on subsoil and it started on shore side of the wave breaking location. So, For T= 2.0 sec performance of tetrapod was better than X-block in filter condition-2.

From the above discussion, it was seen that the performance of tetrapod and X-block was very good on the revetment for wave periods 1.5, 1.6 and 1.8 sec. But For T= 2.0 sec performance of tetrapod was better than X-block in filter condition-2.

4.5.4 Comparison between the performance of tetrapod with filter condition 1 & 2

Difference between the filter condition 1 & 2 is that stone chips were used as a filter material for filter condition-1 and stone chips were not used as a filter material for filter condition-2.

Tetrapod was directly placed on geotextile in filter condition-2. Tetrapod was hollow type of armor units. So it can be placed on the revetment in two ways. In this study, tetrapod was placed on the revetment in two ways. For T=1.5 sec, the performance of tetrapod was very good in both filter condition. No damage was found at subsoil, filter, toe and cover layer on the revetment after completing the run.

For T=1.6 sec, the performance of tetrapod was very good in both filter condition. No damage was found at subsoil, filter, toe and cover layer on the revetment after completing the run.

For T=1.8 sec, the performance of tetrapod was very good in both filter condition. No damage was found at subsoil, filter, toe and cover layer on the revetment after completing the run.

For T=2.0 sec, the performance of tetrapod was not very good in filter condition-1. Stone chips were displaced on the revetment. Unstable condition created on the revetment but in filter condition-2 revetment was stable after completion the run.

From above discussion it was seen that the performance of tetrapod in filter condition-2 was better than filter condition-1.

4.5.5 Comparison between the performance of X-block with filter condition 1 & 2

Difference between the filter condition 1 & 2 is that stone chips were used as a filter material for filter condition-1 and stone chips were not used as a filter material for filter condition-2. X-block was directly placed on geotextile in filter condition-2. X-block was hollow type of armor units. So it can be placed on the revetment in two ways. In this study, X-block was placed on the revetment in two ways. For T=1.5 sec, the performance of X-block was very good in both filter condition. No damage was found at subsoil, filter, toe and cover layer on the revetment after completing the run.

For T=1.6 sec, the performance of X-block was very good in both filter condition. No damage was found at subsoil, filter, toe and cover layer on the revetment after completing the run.

For T=1.8 sec, the performance of X-block was not very good in filter condition-1. Stone chips were displaced on the revetment. Damaged was started onshore side of the wave breaking location. No damage was found on the subsoil, toe and cover layer on the revetment after completing the run. In filter condition-2 revetment was stable after completing the run in same wave period.

For T=2.0 sec performance of X-block was not good in both filter condition. In both filter conditions it was found that the revetment was unstable after completing the run.

From the above discussion it is seen that the performance of X-block is very good for wave period of 1.5 sec and 1.6 sec in both filter conditions. The performance of X-block in filter condition-2 is better than the filter condition-1 for wave period of 1.8 sec. For T=2.0 sec, it is found that revetment was unstable in both filter conditions.

4.5.6 Comparison among the Performance of C.C. Block (Uniformly and Staggered Place), X-block (Filter Condition 1&2) and Tetrapod (Filter Condition 1&2)

For T=1.5 sec, the performance of C.C. block (uniformly and staggered place), X-block (filter condition 1 & 2) and tetrapod (filter condition 1 & 2) was very good. No damage was found on the revetment after completing the run.

For T=1.6 sec, the performance of uniformly placed C.C. block was not good because damage was occurred on the revetment. But the performance of staggeredly placed C.C. block, X-block (filter condition 1& 2), tetrapod (filter condition 1&2) was very good. No damaged was found after completing the run.

For T= 1.8 sec, the performance C.C. block (uniformly placed and staggeredly placed) was not very good. Revetment was unstable in both cases after completing the run. Tetrapod was performed well in both filter condition (1 & 2) for same wave period. No damaged was found after completing the run. The performance of X-block was not well in filter condition-1 because revetment was unstable in wave period of 1.8 sec. But the performance of X-block was very good in filter condition-2 because revetment was stable after completing the run in same wave period.

For T=2.0 sec, the performance of C.C. block (uniformly placed & staggerdly placed) and X-block filter condition 1 & 2 for all cases the revetment was unstable. Damaged was found on the revetment after completing the run. Performance of tetrapod in filter condition-1 was not very good. Revetment was unstable after completing the run but in filter condition-2 performance of tetrapod was very good. No damaged was found on the revetment after completing the run.

From the above discussion it can be said that the performance of terrapod in filter condition-2 is better than any other types of blocks.

4.6 Summary of Test Scenario

In this study, a total of twenty four runs have been carried out to evaluate the stability of armor unit with six different run conditions for four wave periods. Only 12 run revetments remained stable out of 24 runs. The summaries of twenty four runs are shown in below:

Table 4.1 Summary of test scenarios

Run No	Protection Types	Wave Condition	Stability of Protection after 6 min Experimental Run
1	C.C. block uniformly placed on filter condition-1	T=1.5 sec H_i= 11 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
2	C.C. block uniformly placed on filter condition-1	T=1.6 sec H_i= 12 cm	Protection was unstable. Failure was occurred at cover layer. No failure was occurred at toe, subsoil and filter.
3	C.C. block uniformly placed on filter condition-1	T=1.8 sec H_i= 14 cm	Protection was unstable. Failure was occurred at cover layer and filter. Toe and subsoil was stable.
4	C.C. block uniformly placed on filter condition-1	T=2.0 sec H_i= 14 cm	Protection was unstable. Failure was occurred at cover layer, filter and subsoil but toe was stable.
5	C.C. block staggerdly placed on filter condition-1	T=1.5 sec H_i= 11 cm	Protection was stable. No failure was occurred at filter, toe, subsoil and cover layer.

6	C.C. block staggerdly placed on filter condition-1	T=1.6 sec H_i= 12 cm	Protection was stable. No failure was occurred at filter, toe, subsoil and cover layer.
7	C.C. block staggerdly placed on filter condition-1	T=1.8 sec H_i= 13 cm	Protection was unstable. Failure was occurred at cover layer and filter. Toe and subsoil was stable.
8	C.C. block staggerdly placed on filter condition-1	T=2.0 sec H_i= 14 cm	Protection was unstable. Failure was occurred at cover layer, filter and subsoil. Toe was stable.
9	Tetrapod placed on filter condition-1	T=1.5 sec H_i= 11 cm	Protection was stable. No failure was ocurred at filter, toe, subsoil and cover layer.
10	Tetrapod placed on filter condition-1	T=1.6 sec H_i= 12 cm	Protection was stable. No failure was occurred at filter, toe, subsoil and cover layer.
11	Tetrapod placed on filter condition-1	T=1.8 sec H_i= 13 cm	Protection was stable. No failure was occurred at filter, toe, subsoil and cover layer.
12	Tetrapod placed on filter condition-1	T=2.0 sec H_i= 14 cm	Protection was unstable. Failure occurred at filter. No failure occurred at toe, subsoil and cover layer.
13	X-block placed on filter condition-1	T=1.5 sec H_i= 11 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
14	X-block placed on filter condition-1	T=1.6 sec H_i= 12 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.

15	X-block placed on filter condition-1	T=1.8 sec H_i= 13 cm	Protection was unstable. Failure occurred at filter. No failure occurred at toe, subsoil and cover layer.
16	X-block placed on filter condition-1	T=2.0 sec H_i= 14 cm	Protection was unstable. Failure occurred at filter. No failure occurred at toe, subsoil and cover layer.
17	X-block placed on filter condition-2	T=1.5 sec H_i= 11 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
18	X-block placed on filter condition-2	T=1.6 sec H_i= 12 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
19	X-block placed on filter condition-2	T=1.8 sec H_i= 13 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
20	X-block placed on filter condition-2	T=2.0 sec H_i= 14 cm	Protection was unstable. Failure occurred at filter. No failure was seen at toe, subsoil and cover layer.
21	Tetrapod placed on filter condition-2	T=1.5 sec H_i= 11 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
22	Tetrapod placed on filter condition-2	T=1.6 sec H_i= 12 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
23	Tetrapod placed on filter condition-2	T=1.8 sec H_i= 13 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.
24	Tetrapod placed on filter condition-2	T=2.0 sec H_i= 14 cm	Protection was stable. No failure occurred at filter, toe, subsoil and cover layer.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.1 Introduction

Various type of armor units are used in coastal bank protection work. Detached, segmented, reef, floating and emerged breakwater are also used in coastal bank protections. The primary function of such structures is to intercept the incident waves and caused them to break. In this study, stability of armor units has been investigated experimentally in shore protection structure. In a two-dimensional wave flume, twenty four runs have been conducted with constant water depth, h=50 cm for different wave periods as T=1.5, 1.6, 1.8 and 2.0 sec respectively.

5.2 Conclusion

The performance of armor units has been evaluated experimentally in laboratory. By conducting details and rigorous experimental investigation and data analysis as presented in the previous chapter, the key findings of the study have been presented below:

(I) The performance of C.C. block has been examined in two ways, one is uniformly placed and other is staggerdly placed on the revetment for different wave periods. The performance of C.C. block (uniformly placed) was very good for T=1.5 sec, where incident wave height (H_i) =11 cm and wave reduction occurred as 36%. But for T= 1.6, 1.8 and 2.0 sec, where incident wave height (H_i) = 12 cm, 13 cm and 14 cm respectively, wave reduction occurred as 50% for all cases and revetment was unstable in these wave periods.

When C.C. block was staggerdly placed on the revetment, it performed well for T=1.5 and 1.6 sec, incident wave height (H_i) = 11 cm and 12 cm where wave reduction occurred as 54.54% and 50% respectively. But for T=1.8 sec and 2.0 sec, where incident wave height (H_i) = 14 cm and 14 cm and wave reduction occurred as 40% and 42% respectively, and revetment was unstable in these wave periods. So, The performance of staggerdly placed C.C. blocks was better than uniformly placed C.C. blocks in same wave conditions.

(II) X-block was placed as armor units on the revetment in two filter conditions. One is, stone chips were used (filter condition 1) on the revetment and another is, stone chips were not used (filter condition 2) on the revetment. When stone chips were used (filter condition 1) on the revetment, performance of X-block was well for T= 1.5 and 1.6 sec, incident wave height (H_i) = 11 cm and 12 cm where wave reduction occurred as 54% and 50% respectively. But for T=1.8 sec and 2.0 sec, where incident wave height (H_i) = 13 cm and 14 cm and wave reduction occurred as 46% and 50% respectively and revetment was unstable for these two wave periods.

When stone chips were not used (filter condition 2) on the revetment, performance of X-block was well for T= 1.5 sec, 1.6 sec, and 1.8 sec where incident wave height (H_i) = 11 cm, 12 cm and 13 cm and wave reduction occurred as 54%, 50% and 46% respectively. But for T= 2.0 sec, where incident wave height (H_i) = 14 cm and wave reduction occurred as 50%, and revetment was unstable in this wave period. So, The performance of X-block in filter condition-2 was better than filter condition-1 in same wave conditions.

(III) Tetrapod was placed as armor units on the revetment in two filter conditions. One is, stone chips were used (filter condition-1) on the revetment and another is, stone chips were not used (filter condition-2) on the revetment. When stone chips were used (filter condition-1) on the revetment, performance of tetrapod was well for T= 1.5 sec, 1.6 sec, and 1.8 sec where incident wave height (H_i) = 11 cm, 12 cm, and 13 cm and wave reduction occurred as 54%, 50% and 46% respectively. But for T= 2.0 sec stone chips were moved under the tetrapod. As a result revetment was unstable. Wave reduction occurred as 50% in this wave period.

When stone chips were not used (filter condition 2) on the revetment, performance of tetrapod was very good for T= 1.5, 1.6, 1.8 and 2.0 sec, where incident wave height (H_i) = 11 cm, 12 cm, 13 cm and 14 cm, wave reduction occurred as 54%, 58%, 53% and 57% respectively. Revetment was stable for all wave periods. So, The performance of tetrapod in filter codition-2 was better than filter codition-1 in same wave conditions.

So, from the above discussion it can be said that, the performance of tetrapod was better in filter condition 2 than any other types of blocks.

5.3 Recommendations for further study

In this study, effect of only the unidirectional regular waves on armor units has been investigated to assess the performance of the armor units for particular bank slope. For future studies, the following recommendations can therefore be made.

(I) Multi-directional irregular waves can be created from different wave generators simultaneously in a large wave basin and can be listed for different armor units.

(II) In this study, only the stability of C.C. block, tetrapod and X-blocks are examined other shape of the armor units stability can be also examined in the laboratory.

(III) Similar experimental studies may be conducted with different bank slopes.

(IV) The influence of wave periods (longer waves) can also be made for different slopes and block sizes.

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