PHYSICAL MODEL STUDIES ON THE EFFECT OF COASTAL VEGETATION ON WAVE ATTENUATION AND RUN-UP

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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MAY 2018

D E C L A R A T I O N

by the Ph.D. Research scholar

I hereby *declare* that the Research Thesis entitled "**Physical Model Studies on the Effect of Coastal Vegetation on Wave Attenuation and Run-up**" which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in the **Department of Applied Mechanics and Hydraulics** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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C E R T I F I C A T E

This is to *certify* that the Research Thesis entitled "**Physical Model Studies on the Effect of Coastal Vegetation on Wave Attenuation and Run-up**" submitted by **Beena Mary John** (Register Number: 135025 AM13F03) as the record of the research work carried out by her, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

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ACKNOWLEDGEMENTS

First and foremost, I would like to thank **God**; He has never ceased to show me His grace and mercy.

I will give thanks to you, Lord, with all my heart; I will tell of all your wonderful deeds. (Psalm 9:1)

I would like to express my deepest gratitude to my research guides, **Prof. Kiran G. Shirlal** and **Prof. Subba Rao**, Department of Applied Mechanics and Hydraulics, NITK, Surathkal for supervising my research work, and for all the valuable ideas, suggestions, comments and encouragement. Their guidance and support have been priceless. In addition to the subject of my research, I have learnt a lot from my esteemed guides, which will surely be useful in different stages of my life.

I offer my profound gratitude to my Research Progress Assessment Committee members, **Prof. Arkal Vittal Hegde** and **Prof. A. U. Ravishankar**, for their critical evaluation and useful suggestions during the progress of the work. I would also like to thank my Doctoral Thesis Assessment Committee members **Prof. S.A. Sannasiraj**, **Prof. R. Shivashankar**, **Dr. Manu** and **Prof. M.K. Nagaraj** for their valuable suggestions. Also, I wish to extend my gratitude to **Prof. G. S. Dwarakish** for his support and encouragement, and to **Dr. Rajasekaran C**, Department of Civil Engineering, NITK for his valuable suggestions.

I am greatly indebted to the former Heads of Department, **Prof. Subba Rao** and Prof. **G. S. Dwarakish**, and the present Head of the Department, **Prof. A. Mahesha** for granting me the permission to use the laboratory and computing facilities for the completion of this work.

I would like to express my gratitude to the former Director of NITK, Surathkal, **Prof. Swapan Bhattacharya**, the former Director In-charge **Prof. K. N. Lokesh** and present Director **Prof. Karanam Uma Maheshwar Rao** for granting me the permission to use the institutional infrastructure facilities.

I sincerely acknowledge the help and support rendered by the faculty, staff and research scholars of the Department of Applied Mechanics & Hydraulics. I take this opportunity to thank **Mr. Jagadish** and **Mr. Seetharam**, and their supporting staff **Mr. Ananda Devadiga**, **Mr. Gopalakrishna**, **Mr. Harisha**, **Mr. Anil Kumar**, **Mr. Padmanabha**, **Mr. Niranjan** and **Ms. Ashwini**, for their help in fabricating and placing the models. I also thank **Mr. Balakrishna** for his help in solving the computer snags during my research.

I sincerely thank all my teachers and mentors, especially **Dr. D.D. Ebenezer**, Scientist 'G' and Associate Director (Transducers and Materials), NPOL, DRDO, for kindling interest in pursuing research. I also wish to thank my co-research scholars and post-graduate students: **Nawin**, **Mohit**, **Arun**, **Jithin, Sachin** and **Chetan** for all the help and encouragement during this period of research.

I express my sincere gratitude to my family for their constant support and encouragement. I thank my dear parents **Chev. M. Johny** and **Mrs. Z Elizabeth** for all the care, love and for all the sacrifices to shape my life. Also, I express my thanks to my sister **Teena** and brother-in-law, **Sajith** for their valuable prayers, help and support. I greatly acknowledge the support and prayers of my father-in-law **Mr. V.T. Thomas**, mother-in-law **Mrs. Licikutty Thomas**, sister-in-law **Shruthi** and her family.

Last but not the least, I owe thanks to a very special person and my unbelievably supportive husband, **Arun** for his continued and unfailing love, support and understanding during the course of this research. I greatly value his contribution in making this thesis a reality.

Beena Mary John

ABSTRACT

High rates of population growth, rapid urbanization along the coastal zone, rising sea levels and coastal flooding due to global warming and climate change represents some of the trends that affect the world at large. With an unprecedented rise in the frequency of natural calamities like cyclones, storm surges and tsunamis and the losses from such extreme events reaching an all-time high, it becomes a prime necessity to devise measures to defend our coasts. Evidences of coastal ecosystems in reducing the impacts of cyclones and tsunamis in Kendrapara (Odisha), Pichavaram (Tamil Nadu) and in other places, paved the way for researchers and administrators to realize that coastal habitats have an important role to play in risk reduction.

A series of experiments are conducted in a two-dimensional monochromatic wave flume on 1:30 scaled models of different types of vegetation. To investigate the wave attenuation and beach inundation characteristics, the simulated vegetation models are subjected to incident waves of heights 0.08 m to 0.16 m and periods 1.4 s to 2 s, in water depths of 0.40 m and 0.45 m.

The very first set of experimental runs conducted on submerged simulated vegetation, namely, seagrass and rigid vegetation reveals the dependence of wave height attenuation and beach inundation on meadow width and relative plant height. The vegetated meadow progressively interferes with the wave particle orbital velocities as the wave propagates through the meadow. The percentage reduction in wave heights ranges from 53.25% to 41.61% for the submerged seagrass model of width 2 m and from 62.65% to 46.71% for the submerged rigid vegetation model of width 2 m, for the highest relative plant height, $h_s/d = 0.525$. Further, the beach inundation measured in terms of relative run-up (R_u/H_i) varies from 0.861 to 0.534 and from 0.840 to 0.498, for the above two models with increase in wave steepness parameter, H_i/gT^2.

The effect of height of emergence of the vegetation on wave height attenuation and further run-up on the beach is studied with emergent vegetation models of varying plant densities. For the emergent trunk model of width 2 m, and plant density, N = 107 trunks/m^2, the percentage reduction in wave heights ranges from 39.47% to 33.83%;

whereas, the relative wave run-up, R_u/H_i varies from 0.871 to 0.628, for h_s/d = 1.25. As the plant density increases to 107 trunks/m^2 and 300 roots/m^2, for the emergent trunk model with roots of width 2 m, the percentage reduction in wave heights ranges from 66.27% to 50.90% and R_u/H_i varies from 0.840 to 0.512, for h_s/d = 1.25.

The capability of individual habitats like seagrasses, coral reefs and mangroves as a natural barrier has been a topic of research interest since late 1900s. But it is still uncertain how these individual habitats complement each other in containing the brunt of these disasters and therefore tests are conducted with simulated heterogeneous vegetated models and their influence on wave attenuation. For the submerged heterogeneous model of width 4 m, the percentage reduction in wave heights varies from 67.50% to 51.25% and R_u/H_i ranges from 0.737 to 0.435, for h_s/d = 0.525. The emergent heterogeneous model of width 4m and the compound heterogeneous model of width 6 m shows a variation of percentage reduction in wave heights from 70.00% to 52.50% and from 70.00% to 58.75%, respectively.

Finally, experimental runs to test the effect of fragmented vegetated meadows on wave decay is taken up by introducing gaps in the vegetated meadow which may alter its hydrodynamics. For the fragmented heterogeneous vegetation model, the percentage reduction in wave heights increases with increase in gap width parameter, w_{gap}/w from 0.125 to 0.375. The performance of all the vegetation types on wave decay is compared and based upon the results of this study, the optimum configuration of vegetated meadow, namely, fragmented heterogeneous vegetation model with the highest gap width parameter (w_{gap}/w) of 0.375 is selected as the best model with highest percentage reduction in wave heights ranging from 76.25% to 66.88% and lowest values of R_u/H_i ranging from 0.498 to 0.254, for h_s/d = 1.25.

Keywords: Coastal vegetation, meadow width, relative plant height, plant density, heterogeneity, fragmentation, gap width parameter, wave attenuation, wave run-up, coastal protection.

CONTENTS

LIST OF PLATES

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

d	Depth of water in the wave flume
E	Energy per unit surface area
g	Acceleration due to gravity
h_s	Length of stem/leaf
H	Wave height
H_i	Incident wave height in front of the meadow
H_x	Wave height at location *'x'* within the meadow
L	Wave length
T	Wave period
w	Meadow width
w_{gap}	Gap between vegetation meadows
ρ	Density of water
h_s/d	Relative plant height
H_x/H_i	Relative wave height
H_i/gT^2	Wave steepness
w/L	Meadow width parameter
w_{gap}/w	Gap width parameter

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Coastal populations around the world are at a greater risk of damage from coastal hazards due to the unprecedented rise of global climate change characterized by sea-level rise, longer and frequent droughts and floods, heightened cyclonic and storm surge activities. The vulnerability of coastal areas to sea level rise increase with the increase in population and development along the coast. The narrow fringe of vegetated coastal habitats extending from the upper intertidal zone to about 40 m in depth along the shores of all continents mainly acts as a buffer for the impacts of rising sea levels and wave action.

Coastlines are dynamic systems which are vulnerable to strong winds, storm surges, tsunamis, cyclones and erosion. Conventional structures such as breakwaters, seawalls and jetties are used to dissipate and reflect wave energy. However, the near-shore hydrodynamics and regional sediment transport characteristics might get altered by the use of such artificial hard engineering structures. The losses from natural disasters like the 2004 Indian Ocean tsunami, Hurricane Katrina, and others have reached an all-time high, and the decision-makers now realize that coastal habitats have an important role to play in risk reduction. Coastal forests, which are ecologically sustainable and cost effective, acts as a natural barrier to reduce the fury of storm surges and tsunamis. Coastal vegetation is a form of "green infrastructure" that can serve almost the same function as that of "grey infrastructure"; their human engineered counterparts made of concrete and steel.

The Indian Ocean tsunami that hit the Indian coast on 26 December 2004 has raised concern on coastal vulnerability and consequently, measures to protect our coasts has become a prime concern. Newspaper reports have shown that some of the villages which were behind the mangrove and shelter bed plantations in southern Tamilnadu suffered considerably less damage as the intensity of the tsunami was weakened by these natural barriers.

Coastal vegetation aids in shoreline protection by damping the incoming waves and dissipating the energy. Wave attenuation by vegetation is a function of vegetation characteristics, wave conditions, and the water depth. The vegetation characteristics include stem density, leaf structure, geometry, stiffness and the wave conditions include wave period, wave height, water depth and direction. Mork (1996) carried out field investigations on a kelp plant species in Hustadvika, Norway and established that damping of waves is caused by the energy loss through work done on the plants.

The mechanism of wave attenuation through vegetation is still not fully understood. The variability of wave damping is very large and it is difficult to define a generalized behaviour of the “plant-induced dissipation” as wave attenuation depends on the characteristics of the plant (geometry, buoyancy, density, stiffness, degrees of freedom and spatial configuration) as well as wave parameters (mainly wave height, period and direction). Also, the structure of the plant field changes with time as it is exposed to the physical forcing of wave action and water flow (Mendez and Losada, 2004), and therefore the interaction between the fluid and vegetation is dynamic. The distribution of plants in a natural wetland is random, and their stem diameter and height also varies. Individual plant characteristics vary along the length of the plant and also changes with different stages of its life cycle. All these factors account for the fact that the interaction between waves and vegetation is complex.

This thesis presents the findings of a detailed physical model study conducted on different types of simulated vegetation models of submerged and emergent types, flexible and rigid types, combinations of vegetation types as well as fragmented vegetation types and their effect on wave attenuation and subsequent beach inundation. The conventional methods of coastal protection as well as the sustainable methods of shoreline protection, which is the focus of attention in recent times is briefly introduced, along with the mechanism of wave attenuation by vegetation as well as its role in controlling coastal flooding in the upcoming sections.

1.2 COASTAL PROTECTION MEASURES

Since time immemorial, man has been fascinated by the oceans and have settled near coasts. Even in the present times, humankind is aware of the wide array of services and opportunities provided by the coasts and is therefore the most preferred regions of human settlements. Coastal regions, are therefore home to a large and growing proportion of the world's population.

The coastal zone, represented by a dynamic natural system, occupies less than a quarter of the earth's land surface; yet these regions are associated with large and growing concentrations of human population (Small and Nicholls, 2003). The concentration of human settlements along the coastal regions throughout the world is an outcome of the richness and diversity of natural resources in these regions. This zone comprises of different coastal ecosystems of distinctive plants and animal communities which provide both direct and indirect services to humans.

As human population has grown and the power of technology has expanded, the scope and nature of the modification of their environment has changed drastically (Vitousek et al., 1997). The increased concentration of human settlements near the coasts have led to the evolution of coastal ecosystems as one of the most impacted and altered ecosystems on a global scale. The looming threat of increased intensity of storms and cyclones due to global climate change and predictions of rise in sea levels instills a sense of serious thought in the mind of administrators and decision makers to devise measures to protect our coasts.

Man has continuously evolved methods to keep his settlements protected from the onslaught of the advancing sea. Inspired by nature's own defense mechanism, man has come up with a variety of methods and techniques for coastal protection (Charlier and De Meyer, 2000). The comparison of nature's coastal protection methods to man's counterparts in the form of: shore rock to seawall, islands of rocks to breakwaters, natural headlands to large breakwaters, rocky outcrops perpendicular to the shore to groins, sediment transport mechanisms to artificial nourishment from land sources is quite interesting (Bruun, 1972). Traditionally, the protection of the coastal area from flooding, erosion, storm surges, cyclones and tsunamis is approached from an engineering perspective.

Structural shore protection methods or hard structures such as breakwaters, groins and jetties can reduce the energy of waves, but can also redirect it so that the erosion problem may simply move to another area. A steep beach or retaining wall allows waves to crash into the shore, thereby increasing erosion drastically; whereas, a gradual, gentle slope of the shoreline can absorb the energy of waves to a large extent. The deep roots of mangroves which grow on estuarine regions and other beach vegetation like casuarinas helps in binding the earth together. In marshes, swamps and creeks, the canopy of trees provides a rich cover which shields the soil surface from the impact of falling rain and thus reduces runoff.

Hard methods of coastal protection including massive constructions was prevalent during the 19th and 20th centuries, but alternative approaches harnessed from nature or natural resources have gained acceptance in the recent past (Charlier et al., 2005). Non-structural shore protection measure is cost efficient, aesthetically pleasing, environmentally friendly, and sustainable and are therefore gaining acceptance as opposed to the commonly used “hard” or structural methods. Beaches with wide and gentle slopes characterized by dunes stabilized with plants acts as nature’s first line of defense against erosion due to action of high waves and storm surges. Seagrasses with its root and leaf system acts as the next line of defense and provides protection in the shallow inshore areas. This can proceed to woody, emergent aquatic plants which successively protect woody trees, which are best suited for upper shoreline stabilization. These green shoreline guardians act as an ecosystem engineering species capable of protecting the coastline in a sustainable way, as opposed to their grey coastal resilient counterparts.

1.3 SUSTAINABLE SHORELINE PROTECTION

The concept of certain species that modify, maintain and create habitats by structuring the physical and biological components of their environment was put forward by Jones et al. (1994). Also, the utilization of ecosystem engineering species for achieving civil-engineering objectives or the facilitation of multiple use of limited space in coastal protection is focused upon by Borsje et al. (2011). The world's oceans are home to an abundance of important habitats ranging from coral reefs, and kelp forests to mangrove forests and salt marshes. Plate 1.1 shows the photographs of different types of sustainable shoreline protection ecosystems.

The contribution of coral reefs to coastal risk reduction and adaptation is partly explained in studies conducted by Hardy et al. (1991), Lowe et al. (2005), Harris and Vila-Concejo (2013) and Ferrario et al. (2014). The physics of wave energy reflection, dissipation and transmission on coral reefs is of importance.

Kelps are highly productive seaweeds which dominates the shallow rocky, temperate latitude coastlines of the world (Duggins et al., 1989; Steneck et al., 2002). These forests are capable of altering the local oceanography by wave surge dampening, thus shading the sea floor with their canopy. A few of the studies attempted on the role of kelp forests on wave attenuation include Jackson (1984), Anderson et al. (1996), Mork (1996) and Rosman et al. (2013).

Sustainable aquaculture practices such as mussel and oyster farming have the capability of protecting the shorelines by wave attenuation and reduction of velocities through the farm. Studies conducted by Gibbs et al. (1991), Brinkman et al. (2002) and Plew et al. (2005) reveals this fact.

Seagrasses, a type of marine plant that have roots, leaves and underground stems, form extensive beds or meadows in shallow coastal waters with sandy or muddy bottoms. Previous studies to establish the attenuation of waves due to seagrasses include wave flume studies on artificial and live vegetation. Detailed field investigations also revealed flow reduction at different levels of the canopy and turbulence attenuation by the vegetation. The orbital velocity of waves is significantly attenuated by the seagrass leaves.

(a)

(b)

(c)

(d)

(e)

(f)

Plate 1.1 Photographs of different types of sustainable shoreline protection ecosystems a) coral reefs in Micronesia (Photo courtesy: TNC) b) kelp forests c) mussel farms in Primorsko, Bulgaria, CC BY 2.0 (Photo by Vasil Raev) d) Rising sea levels inundating San Francisco wetlands (Source: NOAA) e) seagrass and f) mangroves

Mangroves play a major role in safeguarding communities from natural disasters along the tropical coastal zones. The trunks, leaves, root systems, and pneumatophores of mangroves are capable of providing additional drag against wave energy (Mazda et al. 2006). Factors within the forest itself that likely determine the wave attenuation include the specific characteristics of the species (e.g., presence of pneumatophores or complex prop root systems), the density of the forest, and the diameter of the tree stems (Ewel et al. 1998; Alongi 2008). Studies on the economic valuation of mangroves have estimated coastal protection to be a major portion of their total value (Marois and Mitsch, 2015).

Another principal technique used for beach restoration and protection from storm and damage caused by flooding is beach nourishment, wherein, sand is pumped from offshore “borrow sites” onto the existing beaches which leads to widening of the beaches (Plate 2.1 a). This technique is generally considered as an environment-friendly and sustainable method of coastal protection. But this can also create new issues regarding cumulative, long-term losses in borrow areas and appropriate human actions in fill areas (Nordstrom, 2005).

(a)

(b)

Plate 1.2 a) Rainbow method for transferring nourishment material ashore (Source: Courtesy of Dredging International) b) Dune vegetation in Mangaluru

Vegetation plays yet another significant role in protecting the beach from erosion. Sand dunes, formed by accumulation of sand by wind and wave action, acts as a natural barrier against waves and storms by protecting inland houses and property. Dunes get destroyed due to storms, erosion of shorelines and human interference. Vegetation on the dune helps in restoration of the dune, with the leaves acting as collectors for blowing sand and its roots helping in trapping and stabilizing the sand, which leads to the formation of a stronger dune system resilient to erosion (Plate 1.2 b).

1.4 MECHANISM OF WAVE ATTENUATION BY VEGETATION

Ocean waves are propagating energy in waveform through orbital motion of water particles. The energy of a wave is related to the square of its height (Dean and Dalrymple, 2001) as

$$E = \frac{1}{8}\rho g H^2 \tag{1.1}$$

where, E is the energy per unit surface area (J/m^2), ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2) and H is the wave height (m). Eq. (1) holds well within the limits of the small-amplitude wave theory.

As the waves propagate towards the shore and encounters shallower water, the wavelength and hence, the wave speed decreases as a result of shoaling. As the waves slow down, the wave energy and correspondingly the wave height increases in order to maintain the total amount of energy flux which is due to the resulting friction between the water particles and the seabed causing energy loss (Schwartz, 2005). Meanwhile, the presence of vegetation meadow near the surface can attenuate the wave energy further as they offer frictional resistance to particle movement and cause wave breaking.

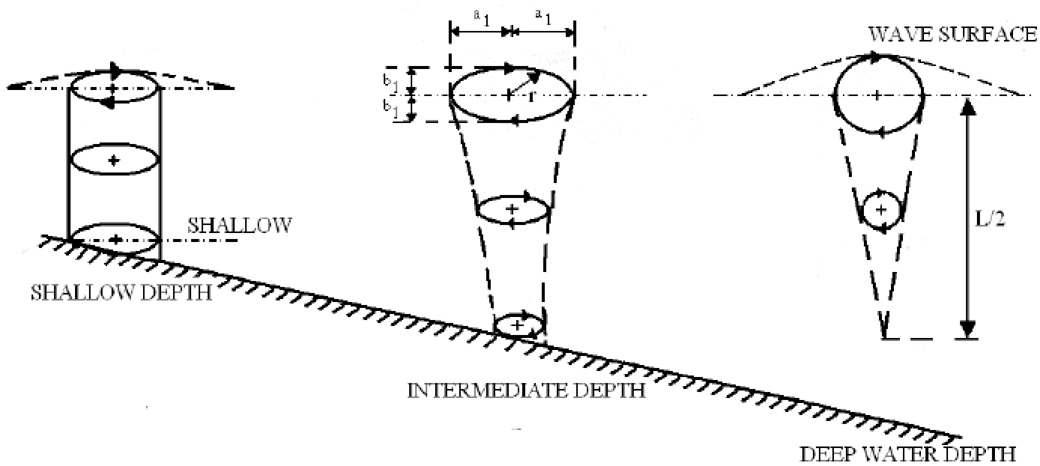


Fig. 1.1 Water particle displacements (Deo, 2007)

Vegetation penetrates through the layers of varying particle orbital velocities and causes a distortion in the wave orbital velocities, resulting in an increase in turbulence and loss of energy and consequently, wave breaking. The vegetated meadow progressively interferes with the wave particle orbital velocities as the wave progresses through the meadow. Since the wave horizontal particle velocities, *u(z)* are highest near the crest of the wave, with velocities decreasing towards the bed (depending on water depth and wave period) (Dean and Dalrymple, 1991), the height of the vegetation plays a pivotal role in wave dissipation (Fig. 1.1). As the height of stem/vegetation increases, the wave height attenuation also increases. As the stem height approaches the surface of water, the highest velocities are impeded, which leads to a greater drag and a consequent increase in wave energy dissipation. As the stems become submerged, only the lower particle orbital velocities are distorted, resulting in reduced drag and consequently lesser wave attenuation, while wave energy of the upper layers will pass over the vegetation meadow undisturbed (Anderson et al., 2011).

1.5 ROLE OF VEGETATION IN CONTROLLING COASTAL FLOODING

Coastal flooding or inundation associated with storm events, tsunamis and sea-level rise over a span of years, poses a significant threat to lives and livelihoods of coastal communities. The factors responsible for increased coastal flooding include global sea-level rise, land subsidence in coastal and deltaic regions, human activities, climate change factors which may lead to increased storm surge heights (Ward et al., 2011) and submarine earthquakes and landslides which can trigger tsunamis, resulting in inundation of several kilometres (Mimura et al., 2011). Plate 1.3 depicts a coast affected by a devastating hurricane leading to a storm surge.

Shibayama et al. (2008) performed field surveys in the southwest region of Bangladesh, affected by Cyclone Sidr in 2007. Measurements of inundation heights along the areas affected by the cyclone revealed that dikes on the coast could reduce the damages caused to the area behind. In this study, the run-up heights along rivers, its tributaries and waterways were considered and the results showed that the inundation heights along the Baleshwar river and the Burishwar river were relatively high compared to those observed on the coast of Kuwakata.

Plate 1.3 Powerful winds from Hurricane Irma leading to storm surges and massive flooding across Florida, United States in September 2017

Wave run up (R_u) is defined as the landward extent of wave uprush measured vertically from the still water level (SWL). The presence of submerged and emergent vegetation leads to wave height attenuation due to its extensive canopy, shoot, stem and root system which interferes with the particle orbital velocities. This consequently leads to a decreased extent of inundation on the beach.

Kakinuma et al. (2012) and Mori et al. (2012) conducted post-tsunami field surveys along the Tohoku region, Japan after the 2011 Tohoku Tsunami. The inundation and run-up heights were measured using a laser range finder with a reflection prism, real-time kinematic (RTK) GPS receiver with a cellular transmitter, and total stations, along the regions affected by the onslaught of this tsunami. The studies showed that the inundation heights were generally larger at bay heads, as well as promontory tips, except several points, which were sheltered by a peninsula or had a tapering area. The distribution of inundation heights in inland areas revealed that the tsunamis had reached inland, far away from the sea, along valleys and rivers.

1.6 ORGANIZATION OF THE THESIS

The introduction to the thesis and an overview of the relationship between human settlements and the coastal environment, the value of coastal ecosystems in protecting and sustaining life and the measures of coastal protection is presented in Chapter 1. The mechanism of wave attenuation by vegetation as well as its role in controlling coastal flooding is also described, and the organization description of the thesis is presented.

An overview of the current state of knowledge on the role of vegetation in coastal protection, the formulation of the research problem and the objectives of the present study is presented in Chapter 2.

The materials and methods of the present experimental investigation which includes model scale selection, the test models, the experimental set-up and the range of experimental parameters is described in detail in Chapter 3.

Chapter 4 includes the results obtained from experiments conducted on submerged vegetation models with special emphasis on the meadow width parameter and the relative plant heights.

The results of experiments conducted on emergent vegetation models of varying meadow width parameter, relative plant height and plant density and their influence on wave attenuation is presented in Chapter 5.

The role of heterogeneous vegetation models of different combinations of vegetation types in wave height attenuation and subsequent uprush on the beach is analysed and presented in Chapter 6.

An attempt to model the presence of open gaps in the forest cover, by introducing gaps of varying widths between portions of the vegetated meadow is carried out and the effect of this fragmentation in the vegetated meadow with respect to wave height attenuation and run up on the beach slope is discussed in Chapter 7.

Finally, the conclusions drawn from the findings of this physical model study conducted with the aid of simulated vegetation models on wave attenuation and run-up is summarized in Chapter 8. The limitations of the present study and indications of future directions from this study is also presented here.

CHAPTER 2

CURRENT STATE OF KNOWLEDGE

2.1 GENERAL

Coastal vegetation has been advocated as an efficient natural barrier following several recent coastal disasters like the 1999 Odisha cyclone, the Boxing day Indian Ocean tsunami in 2004, the 2007 Cyclone Sidr which struck the southern Bangladesh coast, the Phailin Cyclone which hit the Odisha coast in 2013, wherein reports of intact coastal vegetation did play a significant role in protecting the hamlets behind the shelterbeds. It is well known from investigations conducted worldwide that coastal forests, being a porous medium cannot fully prevent inland flooding and inundation associated with storm surges, but can certainly reduce the impacts of waves and currents. Interest in the scientific understanding of the interaction between waves and vegetation took shape during the late 1900s. Pioneering works conducted by Asano et al. (1992) and Kobayashi et al. (1993) revealed the exponential decay of waves as a result of its interaction with vegetation, which followed from works carried out by Rogers (1986) and Jenkins (1987) on a novel approach of using artificial seaweeds for shoreline protection.

2.2 STUDIES ON THE EFFECT OF COASTAL HABITATS ON WAVE ACTIVITY

Coastal habitats which includes submerged seaweeds (macroalgae), seagrasses and coral reefs, as well as partially emerged habitats like mangroves and saltmarshes occupy a narrow fringe which ranges from the upper intertidal zone to about 40 m depth, along the shores of all continents (Duarte et al., 2013). Among the many coastal habitat types, seagrasses and mangroves are selected in this study as natural defenses against coastal hazards like cyclones, storm surges and tsunamis. A detailed review of literature of studies related to wave attenuation and coastal protection functions of different coastal habitats is discussed in this section.

One of the earliest known works in the field of coastal habitats used in coastal protection is by Price et al. (1969), wherein it was attempted to discover whether an offshore artificial seaweed field could help in promoting an onshore transport of bed material, which could consequently lead to build-up of beaches. Experimental runs conducted in a wave tank using artificial polypropylene "pony tails" representing seaweeds revealed that this artificial bed contributed in increasing the net drift of water towards the shore, which helped in the build-up of beach levels. The strands of the artificial seaweeds were 0.055 mm in diameter and 3 inches in length. The model was subjected to waves of height 3 inches and a period of 1.33 seconds. Fig. 2.1 depicts the model beach in this study, with and without the placement of seaweed. It is seen that the effect of the seaweed was to transfer material from the off-shore sea bed towards the shore, which could cause an increase in beach levels. A theoretical hydrodynamic model was also proposed with predictions of increased wave attenuation and shoreward mass-transport.

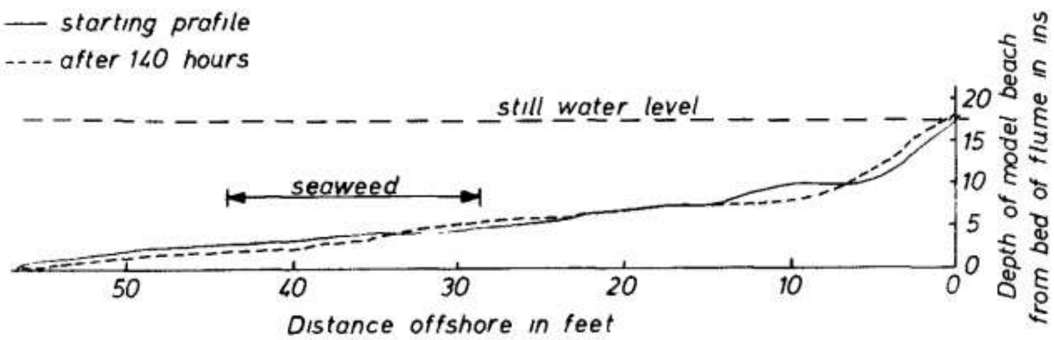


Fig. 2.1 Model beach with and without seaweed (Price et al.,1969)

Kelp, a type of macroalgae, which grows on hard rock and stone, can reduce the wave and current energies propagating through them. Some of the early works which confirmed this fact include studies on the effect of kelp forest on coastal currents (Jackson and Winant, 1983), internal wave attenuation by coastal kelp stands (Jackson, 1984) and theoretical work on the ocean engineering aspects of coastal kelp farming (Dalrymple et al., 1982; Dubi and Torum, 1995).

Dalrymple et al. (1982) studied interaction between waves and a kelp farm and developed a wave height attenuation formula of the form:

$$\frac{a(x)}{a_0} = \left(\frac{1}{1+\alpha_d x}\right) \tag{2.1}$$

where, a is the local wave amplitude, and $a = a_0$ at $x = 0$,

$$\alpha_d = \frac{2C_D}{3\pi}\left(\frac{d_k}{b}\right)\left(\frac{a_0}{b}\right)\left[\sinh^3 kd + 3\sinh kd\right]\left[\frac{4k}{3\sinh kd(\sinh 2kh + 2kh)}\right] \tag{2.2}$$

in which only the real part of the wave number *k* is used, C_D is the drag coefficient assumed constant over depth, d_k is the plant diameter, *d* is the height of the plant above the bottom, *b* is the spacing between the plants, *h* is the water depth and α_d is the damping factor.

Water waves propagating through large stands of seaweeds, pockets of mud in a sandy bottom, or submerged and emergent trees lose energy, which results in smaller wave heights (Dalrymple et al. 1984). The results shown here are for the case in which the damping is a result of local energy losses due to a cluster of cylinders, which represents a dense stand of giant kelp (*Macrocystus pyrifera*).

Asano et al. (1992) presented an analytical solution for water waves propagating over submerged vegetation and showed that the local wave amplitude decays exponentially as:

$$a(x) = a_0 e^{-k_i x} \tag{2.3}$$

where, k_i is the damping rate of the wave height with distance and $a = a_0$ at $x = 0$.

Kobayashi et al. (1993) formulated the vertically two-dimensional problem of small-amplitude waves propagating over submerged vegetation without lateral boundaries using continuity and linearized momentum equations for the regions above and within the vegetation and developed an analytical solution for the small amplitude monochromatic wave whose height decays exponentially as given by:

$$H = H_0 \exp(-k_i x) \tag{2.4}$$

where, H_0 is the wave height at x=0, and k_i is the exponential decay coefficient.

Wave attenuation by kelp forests in shallow waters has been substantiated by field investigations at Hustadvika, Norway, at a site strongly exposed to waves from the open ocean (Mork, 1996). The average stipe length in the kelp forest was 1.6 m, with frond area 0.8 m^2 and plant density of 25 large kelp plants per square meter. Investigations to evaluate the reduction of wave energy from the outer part to the inner part of a kelp belt was conducted. Under the influence of a pronounced swell, which is considered as a plane sine wave travelling in the direction from outer to inner station from the North, the swell energy was observed to be reduced by 60-75%.

The role of seagrasses and mangrove ecosystems in controlling wave activity is of interest in the present study and therefore, the related studies are presented in the following sub-sections.

2.2.1 Role of seagrasses

Seagrasses are marine angiosperms (flowering plants) that have roots, stems and leaves; and are known to perform a variety of functions within ecosystems, and have both economic and ecological value. These meadows are capable of suppressing sediment resuspension and enhancing deposition (Ward et al., 1984); and are among the most productive and economically valuable ecosystems (Zieman and Wetzel, 1980). They offer food, habitat and spawning area for many commercial and recreational fishery species, and to countless number of invertebrates. Seagrass meadows also help dampen the effects of strong currents, stabilise ocean sediments, filter pollutants from river run-off and prevent harmful build-up of sediments from reaching coral reefs. Studies conducted on the examination of depth limit of various seagrass communities revealed that seagrasses may extend from mean sea level down to a depth of 90 m (Duarte, 1991).

Gambi et al. (1990) studied flow speed reduction by Zostera marina L. (eelgrass) in a seawater flume of dimensions 10 m x 2 m x 3 m, with the seagrass bed occupying 20 percent of the width of the flume. The *Zostera marina* bed of length 100 cm, with canopy height of nearly 11 cm and plant density of 1200 shoots/m^2, was placed in the center of the flume, and tested in water depths varying from 22 cm to 25 cm. It was shown that depending on the shoot density, water speed was 2 to 10 times lower under the canopy than upstream of the seagrass bed.

The wave height reduction over vegetated seabed using four species of seagrass, *Halodule wrightii*, *Syringodium filiforme*, *Thalassia testudinum* and *Zostera marina* was studied by Fonseca and Cahalan (1992), in a 6.1 m long wave flume. They were evaluated for their ability to reduce wave energy under various combinations of shoot density and water depths over a 1 m test section. The change in wave height through the test section was recorded under each combination of water depth, density and species. Plant densities were chosen for each species to reflect field conditions. Wave height attenuation was found between 20% and 76% over the 1 m length when the plants were occupying the entire water depth. Percent wave energy reduction per meter of seagrass bed equaled 40% when the length of these seagrasses was similar to the water depth. *S. filiforme*, the near – cylindrical species showed a significant effect on the percent energy reduction with density.

Studies on the hydrodynamics of flow through seagrass canopies was conducted by Koch (1994), with emphasis on interactions between the hydrodynamics of *Thalassia testudinum* and *Cymodocea nodosa* seagrass beds and its biological, physical and geochemical parameters. High resolution speed and wave time series recorded in situ outside and within beds of the seagrass *Thalassia testudinum* revelaed that canopies of this species were efficient in attenuating turbulent energy at frequencies in which most of the wave energy is concentrated (0.06 to 0.9 Hz), while generating turbulent energy at higher frequencies (0.9 Hz). Additionally, the interaction between the water column above the canopy and a densely populated seagrass bed in a tide-dominated environment was reduced when compared to a less dense canopy in a wave-dominated environment, which may be attributed to the shoot biomass or the low blade flapping frequency in the tide-dominated environment when compared to the higher frequencies in the wave-dominated environment.

Ciraolo et al. (2006) carried out experimental research in a laboratory flume by reproducing *Posidonia oceanica* by assembling plastic strips. For reproducing a shallow water situation which is common in lagoons, the leaf length of the model was kept larger than the flow depth. Very low velocities were observed in the vegetated layer and much higher velocities in the upper flow layer. The flow rate in the vegetated layer was a small percentage of that of the total flow. Results indicate the hydraulic behaviour of the plants with variation in the Reynolds number of flow and the ratio between the leaf length and the flow depth.

Augustin et al. (2009) conducted laboratory experiments to measure wave attenuation resulting from synthetic emergent and nearly emergent wetland vegetation under a range of wave conditions and plant stem densities. Experiments were conducted in a shallow-water wave basin of length 30.5 m. Stems were held constant at a length (l_s) of 0.3 m. Two separate water depth conditions, the first with vegetation under emergent conditions (h = 0.3 m) and the other with vegetation under near-emergent conditions (h = 0.4 m) were analyzed. The experiments showed that emergent conditions resulted in a higher amount of wave attenuation compared to near-emergent conditions. Emergent conditions are most prevalent in marsh and wetland systems during regular tidal conditions and during initial inundation by storm surge. Emergent conditions are expected to result in a higher amount of wave attenuation because the plant stem occupies the entire depth of the water column, unlike near-emergent conditions where the plant stem does not impede the top portion of the water column where orbital velocities are greatest. Near-emergent plant conditions are important when the wetland becomes inundated by storm surge, or in the case of subaquatic vegetation. The wave height decay followed the same trends for all the experimental cases and appeared to be most dependent on the ratio of stem length to water depth and stem density.

Stratigaki et al. (2011) conducted experiments in a large-scale facility for the measurement of wave attenuation, transmission and energy dissipation over artificial *Posidonia oceanica*. The effects of submergence ratio corresponding to the seagrass height divided by water depth, and seagrass density as the number of stems per square metre on the above characteristics were investigated. Measurements of wave height at different locations along the vegetation meadow indicate the wave attenuation along the *Posidonia oceanica* for three different submergence ratios and two seagrass densities. For the higher seagrass density, the wave height reduction just behind the meadow is approximately 35% for the highest submergence ratio and decreases to 20% for the lowest submergence ratio. With increase of submergence ratio, there is an increase in horizontal velocities above the canopy because of higher interaction between waves and moving plants, while the opposite is observed within the canopy

Koftis et al. (2012) conducted an experimental study to evaluate the effects of Posidonia oceanica meadows on wave induced velocities and wave height damping. Assuming that drag forces account for the energy loss over the vegetated field, it was shown that the results for wave height attenuation are in good agreement with the analytical expression found in literature, of the form $(1/1 + \beta x)$ where x is the distance from the meadow boundary and β depends on wave and plant characteristics. An empirical relationship for the drag coefficient related to the Reynolds number is also proposed. The wave orbital horizontal and vertical velocities inside the meadow and just above the flume bed were found to be significantly decreased.

To investigate the effect of hydrodynamic forcing due to vegetation which affects the wave attenuation, mimics of seagrasses that varied in blade stiffness, shoot density and leaf length were used by Paul et al. (2012). Wave attenuation characteristics in the absence and presence of a tidal current was measured and results indicated that wave attenuation was positively correlated with blade stiffness and for a given wave in shallow water, attenuation is dependent on a combination of shoot density and leaf length. The presence of a tidal current strongly reduced the wave-attenuating capacity of seagrass mimics, and this reduction was most pronounced at high shoot densities. The stiff material used in this experiment to model blades did not bend significantly, and its motion was described as the back and forth movement of a cantilever. The flexible material, however, did bend under waves as well as under combined waves and currents and showed a whip-like motion when it moved against the direction of wave propagation. This whip-like motion was equally apparent in the presence and absence of a current, but with a smaller excursion when a current was present. The presence of an underlying current led to a reduction in wave attenuation for all the mimic meadows under investigation.

Infantes et al. (2012) conducted field investigations on a *Posidonia oceanica* seagrass meadow in Cala Millor, Spain, using acoustic doppler velocimeters (ADVs). It was observed that the root mean squared wave height (H_{rms}) reduced by 50%, for incident waves of height 1.1 m while propagating over a *P. oceanica* meadow of 1000 m width in a water depth of 8 m. The seagrass meadow consisted of seagrasses with mean shoot length 0.8 ± 0.1 m and shoot density of 600 shoots/m^2.

Luhar et al. (2013) reports the findings of a field campaign designed to study wave-induced flows within a meadow of *Posidonia oceanica* at water depth 9m. This paper provides the first field measurements of this wave-induced streaming through submerged canopies of vegetation. During periods of high wave activity, streaming flows with magnitudes as high as 20% of the near-bed oscillatory velocity were measured within the meadow.

An experimental study to examined the impact of blade motion on wave decay by concurrently recording blade posture during a wave cycle and measuring wave decay over a model seagrass meadow conducted by Luhar et al. (2017), revealed that blade flexibility led to lowering of drag and wave decay relative to theoretical predictions for rigid, upright blades. Greater blade motion leads to smaller relative velocities, reducing drag and wave energy dissipation.

2.2.2 Role of mangroves

Mangrove ecosystems are important habitats, especially in developing countries, and play a key role in human sustainability and livelihoods (Alongi, 2002), being heavily used traditionally for food, timber, fuel, and medicine (Saenger, 2002). These tidal forests are often important nursery grounds and breeding sites for birds, mammals, fish, crustaceans, shellfish, and reptiles; a renewable resource of wood; and sites for accumulation of sediment, nutrients, and contaminants (Twilley, 1995; Kathiresan and

Bingham, 2001; Manson et al., 2005). It is also believed that mangroves offer protection from waves, tidal bores, and tsunamis, and can dampen shoreline erosion (Mazda et al., 2007; Alongi, 2008). Studies related to the role of mangroves in wave attenuation and coastal protection is discussed below.

A theoretical model for propagation of wind-induced random surface waves through non-uniform mangrove forest of arbitrary depth was developed by Vo-Luong and Massel (2008). In this predictive model, water depth was considered as an arbitrary function of distance in the mangrove forest and mangrove species varied at different locations in terms of forest density, root dimensions and mangrove forest biological composition. The numerical calculations revealed that most of the energy dissipated within the mangrove forest was mainly due to wave breaking and wave–trunk interaction. The effect of wave breaking played an important role on wave attenuation in a sparse forest. However, it was smaller compared to the effect of wave–trunk interactions in denser forest. The results of numerical calculations for wave height, wave spectrum and wave-induced velocities as well as for the coefficients of transmission and reflection prove that most of the energy is dissipated within mangrove forest at a relatively small distance. Energy dissipation varies from species to species and depends on the density of mangroves and spectral characteristics of the incident waves and bottom topography.

In a comparative study on the extent of damage caused by two cyclones (Paul, 2009), namely, Cyclone Gorky in 1991 and Cyclone Sidr in 2007, both Category IV cyclones of similar severity, which hit the southwestern and southeastern coast of Bangladesh, respectively, the fatalities were significantly lower with 3,406 deaths due to Cyclone Sidr than with 140,000 fatalities due to Cyclone Gorky. The fewer casualties for the latter cyclone was attributed to a number of factors, such as duration of the storm and storm surge, landfall time and site, varied coastal ecology, and coastal embankment. The Sundarbans, the world's largest mangrove forest, along the southwestern coast of Bangladesh, served as a buffer, bore the brunt of Cyclone Sidr, thus saving residents near this area from more disastrous consequences. The thick growth of mangrove trees successfully reduced the intensity of both the wind and the storm surge.

Another study which investigated the damage caused by the 2004 Indian Ocean tsunami to mangroves at Pakarang Cape in Pang Nga Province, Thailand by Yanagisawa et al., 2009, found that approximately 70% of the mangrove forest was destroyed by the tsunami. Specifically, it was found that the survival rate of mangroves increased with increasing stem diameter and that 72% of Rhizophora trees with a 25–30 cm stem diameter survived the tsunami impact, whereas only 19% with a 15–20 cm stem diameter survived the damaging effect of the tsunami. Results of the numerical model revealed that a mangrove forest of Rhizophora sp. with a density of 0.2 trees m^2 and a stem diameter of 15 cm in a 400 m wide area can reduce the tsunami inundation depth by 30% when the incident wave is assumed to have a 3.0 m inundation depth and a wave period of 30 min at the shoreline. However, 50% of the mangrove forest is destroyed by a 4.5 m tsunami inundation depth, and most of the mangrove forest is destroyed by a tsunami inundation depth greater than 6 m. The reduction effect of tsunami inundation depth decreased when the tsunami inundation depth exceeded 3 m, and was mostly lost when the tsunami inundation depth exceeded 6 m.

Bao (2011) analyzes wave attenuation with data from 32 mangrove plots of six dominant species located in two coastal regions of Vietnam. To examine the relationship between wave height and cross shore distances to the forest, regression models were applied to the wave height data measured at different distances from edge to the centre of the mangrove stand. The result showed that the wave height decays exponentially with the distance and this reduction is explained by the dense network of trunks, branches and roots of the mangroves which increases the bed roughness causing more friction and dissipating more wave energy.

Laboratory experiments on the effectiveness of mangroves to reduce tsunami energy were performed by Husrin et al., 2012. A complex tree structure of Rhizophora sp. was parameterized using the stiff structure assumption (root system and trunk) for different submerged root volume ratios and frontal tree areas. The damping performance of the mangrove forest with mangrove models of complex roots with different densities was determined from laboratory tests performed synchronously in a twin-wave flumes (with and without the forest model in 1 and 2 m-wide wave flumes, respectively) for varying incident heights of solitary wave (0.04 m, 0.08 m, 0.12 m, 0.16 m and 0.20 m), water depth (0.465 m, 0.515 m, 0.565 m and 0.615 m) and forest width (0.75 m, 1.5 m, 2.25 m and 3.0 m). The flow velocities, surface elevations and hydraulic forces due to the model were measured and it was observed that the highest wave energy reduction by forest model was achieved for breaking waves propagating over the widest forest model of width 3 m.

Hortsman et. al. (2012) conducted field studies in the east coast of southern Thailand at two specific locations which remained unaffected after the 2004 Indian ocean tsunami because of the tip of Sumatra (Banda Aceh) and the islets sheltering this location from the incoming waves from the Indian ocean. The study transect consisted of mangrove species: *Avicennia sp.*, *Sonnerata sp.* And *Rhizophora sp.* Wave attenuation has been studied along two contrasting transects with different elevation and vegetation characteristics and different orientations towards the Andaman Sea. Along the Kantang transect, which is mostly exposed to swell waves, vegetation densities increased from 4.5 to 9.3% along the transect and on average 63% of the incident wave energy was attenuated over a distance of 246 m. Along the Palian transect, mostly exposed to sea waves instead, vegetation increased from 4.3 to 19% and 72% of the incident wave energy was attenuated over this 98 m transect.

Das and Crepin (2013) devised a theoretical model of wind protection by mangroves and calibrated and applied this model using data from the 1999 cyclone in the Odisha region of India. This model predicted and quantified the actual level of damage and showed that mangroves reduced wind damage to houses. According to this study, the wind protection value of mangroves in reducing house damage amounted to approximately US$177 per hectare at 1999 prices.

The relation between vegetation densities, wave attenuation rates, sediment characteristics and sedimentation rates in mangroves was studied by Horstman et al. (2014), in the southern Andaman region of Thailand. The generalized total wave attenuation rates increased from 0.002 m^{-1} in the sparsely vegetated forest fringes with *Avicennia* and *Sonneratia* and upto 0.012 m^{-1} in the dense Rhizophora vegetation.. The total wave attenuation rates integrate effects of shoaling and energy losses due to various bio-physical interactions within the mangrove ecosystem.

A three-dimensional numerical approach based on IHFOAM to study the interaction of tsunami waves with mangrove forest is presented in Maza et al. (2015). As a first approximation, the problem is modelled by means of solitary waves impinging on emergent rigid cylinders. The simulations are validated against laboratory experiments for wave damping. Large differences are found in the forces exerted on the vegetation for uniform and random distributions. Generalizations obtained from uniform arrangements could lead to underestimation of wave-exerted forces, especially for low dense configurations.

Parvathy and Bhaskaran (2017) conducted studies on the wave damping characteristics of mangroves on varying seabed slopes. Sensitivity experiments to analyze the wave attenuation over mangroves with different sea-bottom slopes using a third-generation wave model is conducted, which exposes the sensitivity of wave attenuation characteristics to different beach slopes. The total percentage energy reduction for waves reaching the shoreline after propagating through mangroves on mild slope (1:80, 1:40) is observed to be 93%–98%, nearly 84% for 1:20 slope, and 67% for steep slope (1:10). The study reveals that the wave height decays exponentially for the mild slope, but as the degree of bottom steepness increases, the wave height reduction becomes gradual, and this can be attributed to the water depth variation, shoaling, breaking, and reflection characteristics associated with different slopes, in the presence of mangroves.

2.2.3 Role of saltmarshes

Neumeier and Ciavola (2004) presented detailed field investigations of the water flow in a *Spartina maritime* salt-marsh in Southern Portugal. It was shown that the flow depends on the vegetation density at each level of the canopy. The upward increase of horizontal velocity is roughly linear when the canopy is partially emergent or is only slightly submerged. When the canopy is well submerged, there is a drastic reduction in flow, with a slow, nearly constant velocity of 1.0 – 1.5 cm/s in the denser part of the canopy and a faster, logarithmic shaped velocity profile above. This dampening effect of vegetation aids in sedimentation.

Neumeier and Amos (2006) investigated the processes of turbulence attenuation by collecting wave-dominated turbulence profiles with unidirectional flow on a *Spartina anglica* salt-marsh in east England. The vertical variations of turbulence and damping of orbital velocities of waves is evaluated by comparing measured values and theoretical predicted values. The results indicate that the orbital velocities of waves were significantly attenuated (10% - 20%) by the vegetation and turbulence reduction favours settling of sediments.

Jadhav and Chen (2012) analyzed field data on wave attenuation by coastal marshes in a high energy environment produced by a tropical storm in a wet land with *Spartina alterniflora* in Terrebonne Bay (Louisiana). Wave height decay rates were estimated along a 28m long transect over a 2-day period. The wave height reduction due to vegetation per unit length of the wave propagation is quantified as

$$r = \frac{H - H_o}{H_o(\Delta x)} \times 100 \tag{2.5}$$

where H_0 is the incoming and H is the outgoing wave height along the measurement transect of length Δx. The linear spatial wave height reduction rate increased from 1.5% to 4% /m as incident wave height decreased.

Maza et al. (2012) used a Navier-Stokes (NS) model called IH-2VOF to minimize the number of predefined assumptions for wave propagation and the non-linear interactions between waves and plants and also to explore the possibility to improve existing turbulence models to consider wave interaction with vegetation. The IH-2VOF model has been validated using large scale experiments carried out by Stratigaki et al. (2011). The model has shown a high degree of accordance between the laboratory data and the numerical predictions in free surface evolution. Numerical predictions of the velocity field have been compared both over and inside the vegetation, showing also a high degree of accordance.

Blackmar et al. (2014) carried out physical model experiments to evaluate random wave attenuation through two types of synthetic vegetation (the first type of vegetation had 25 stems per plant and the second type had 5 stems per plant). The experiment was performed with two peak periods, three water depths, and two stem densities. Each combination of wave conditions was evaluated for the following four different cases: Case A with no vegetation; Cases B and C with short and long specimens, respectively; and Case D with mixed vegetation. The three water depths in the experiment were chosen to evaluate the wave height attenuation under various submergence ratios. These experiments were also modeled in the numerical model FUNWAVE to evaluate the model's ability to predict wave height attenuation in heterogeneous vegetation. FUNWAVE is a phase-resolved model for studying wave propagation based on Boussinesq-type equations. The numerical attenuation followed the same trends as the measured data, with an average RMSE of 0.017.

Large-scale laboratory flume studies by Anderson and Smith (2014) to study the wave attenuation by flexible, salt marsh vegetation, *Spartina alterniflora,* represented by polyolefin tubing, by documenting its interactions, revealed that the wave attenuation appeared to be most dependent on stem density and the ratio of stem length to water depth.

2.3 DYNAMICALLY HETEROGENOUS SEASCAPES ON COASTAL PROTECTION

The use of individual habitats to protect the coast against specific wave forcing conditions might be compared to the use of traditional hard structures which are mono-functional. This might also lead to an underutilization of the exact potential of other habitats present on the seascape. Indeed, this approach overlooks the fact that natural systems can help protect coasts from a host of hazards that occur under different forcing conditions (Guannel et al., 2016). By combining the benefits of structurally different natural ecosystems on a seascape in providing more ecosystem services, it can also supply higher levels of protection by progressively moderating the impacts of hydrodynamic processes. Since different marine ecosystems, such as seagrasses, coral reefs, salt marshes and mangroves are well connected to each other by various biological, chemical and physical processes (Grober-Dunsmore et al., 2009), they often co-exist as spatially and dynamically heterogenous seascapes (Barbier and Lee, 2014).

The positive interactions between habitats is increasingly acknowledged in contemporary ecology (Thomsen et al., 2010), but studies related to how these habitats complementing each other functions as a coastal protection option is scanty. In one of the studies conducted by Ysebaert et al. (2011), the wave attenuation characteristics of two salt marsh macrophytes, *Spartina alterniflora* and *Scirpus mariqueter* that co-occurs in the pioneer zone of the Yangtze estuary, China were studied using field investigations. The results from this study revealed that vegetation reduced the wave heights up to 80% over less than 50 m of vegetated meadow. Owing to a higher standing biomass of *Spartina alterniflora*, the hydrodynamic energy from the waves were reduced to a larger extent when compared to that of *Scirpus mariqueter*.

2.4 FRAGMENTED VEGETATION AND ITS ROLE IN COASTAL PROTECTION

Over the last decades, marine ecosystems all around the world have been facing impacts of human activities at various extents (Halpern et al. 2008; Jorda et al. 2012; Abadie et al., 2016). This anthropogenic impact creates bare patches that are not easily recolonized. Patchiness, represented by the presence of open gaps in the forest cover is a common phenomenon in natural habitats. The fragmentation of vegetated meadows leads to the formation of a complex seascape (Abadie et. al., 2015) which may alter the hydrodynamics of the submerged or emergent vegetated canopies.

Sim et al. (2011) investigated experimentally the effects of layered coastal vegetation on long wave (solitary wave) propagation. This layering vegetation was represented by an open gap in a patch of vegetation that was perpendicular to the flow direction. Solitary waves with different heights were used to simulate the leading tsunami waves. It was noted that the presence of a parallel open gap between the mangrove models played no significant role in dissipating wave energy and is also true for when it comes to reflecting waves.

Allaoui et al. (2015) conducted laboratory experiments to investigate the effect of longitudinal gaps within canopies exposed to a wave field. In rigid submerged and emergent vegetation, wave velocities were reduced compared to the case without vegetation. Flexible canopies also attenuated waves, but this attenuation was lower than for rigid canopies. The presence of the gap modified the mean current associated with the waves in both the gap and the lateral vegetation. A gap within a canopy of 5% solid plant fraction did not show differences in the wave attenuation between the gap and the lateral vegetation. In contrast, gaps within canopies of 10% solid plant fraction resulted in large differences between the gap and the lateral vegetation. In all the experiments, the effect of a gap within a canopy reduced the wave attenuation within the lateral vegetation adjacent to the gap when compared with a canopy without a gap.

In yet another study, Allaoui et al. (2016), investigated the effect of a single transversal gap within a canopy (i.e. a gap oriented perpendicular to the wave direction) on hydrodynamics, which was compared to fully vegetated canopies (i.e. no gaps) and also to bare sediment. The wave velocity increased with gap width for the two canopy densities studied (2.5% and 10% solid plant fraction) reaching wave velocities found over bare sediments. The turbulent kinetic energy (TKE) within the gap also increased, but was more attenuated by the adjacent vegetation than the wave velocity. As expected, denser canopies produced a greater attenuation of both the wave velocity and the turbulent kinetic energy within an adjacent gap, compared to sparse canopies.

2.5 SAND-BASED SOLUTIONS FOR COASTAL PROTECTION

Sand-based solutions for coastal protection generally includes the sustainable use of sand-based methods for reducing the impacts of high wave activity, storm surges and sea-level rise. The major sand-based solutions for coastal protection include ‘dune care’, ‘beach nourishment’ and the use of sand-filled geotextiles for the strengthening of dunes.

A dune is a mound or ridge of sediment with its axis, or crest, parallel to the shoreline. Dune building/replenishment involves nurturing existing or artificial sand dunes, focusing on methods to enhance the dunes by planting and the use of fencing to prevent trampling.

Dunes have three general vegetation zones based on soil salinity, elevation, sand texture, wind velocity, temperature and human interference. In addition, these zones can intergrade and sharp distinctions between zones are usually absent. The foreshore and face of the fore dune supports creeping sand-binders such as *Ipomoea pes caprae* and *Spinifex littoreus* along with *Cyperus rotundus* in the upper portion (Plate 2.1). Over the fore dune crest and back dune, which is also exposed to winds and salt spray, shrubs and a few sand-binding creepers and herbaceous plants such as Aerva sp, *Calotropis sp, Crotalaria spp, Cissus sp, Sida acuta, Vitex negundo, Lantana sp, Clerodendrum inerme, Ipomoea pes caprae, Opuntia sp, Scaevola taccada; Salvadora persica, Pandanus tectorius, Terminalia catappa, Calophyllum innophyllum, Thespesia populnea, Pongamia pinnata, Cocos nucifera* are the most common vegetation found. The inner back dune is vegetated by a number of trees and shrubs like Palmyrah (*Borassus flabellifer*), Cashew (*Anacarduium oxydentrum*), *Pandanus sp., Calophyllum inophyllum* etc, which occur either in pure stands or as mixed vegetation. Local tree species like *Tamarindus indica*, *Erythrina indica*, *Hibiscus tiliaceous* have the ability to survive in dune systems but are mostly restricted to landward slopes of rear dunes (ADB-IND TA 8652).

Ipomoea pescaprae

Spinifex littoreus

Sesuvium portulacastrum

Chrysopogon zizanioides

Cynodon dactylon

Launaea sarmentosa

Saccharum sp *Canavalia maritima* *Cassia tora*

Plate 2.1 Some of the common vegetation on the beach - sand dune system in India (Source: ADB-IND)

Beach nourishment, a soft alternative to hard coastal defenses, involves bringing new sand to the beach and nearshore zone. It is the process of dumping or pumping sand from elsewhere onto an eroding shoreline that has a sediment deficiency, to create a new beach or to rebuild the same beach at a width that could provide storm protection or the desired recreational beach (Davison et al, 1992). Plate 2.2 shows the pumping of sand water as part of beach nourishment.

Plate 2.2 Dredge-21, a vessel of the Dredging Corporation of India pumps sand water as part of beach nourishment (Source: The Hindu, Photo Credit: K R Deepak)

2.6 VEGETATION SUITABLE FOR INDIAN COAST

Due to the heightened awareness of environmental issues over the last decade, the use of vegetation for erosion control and slope stabilization, commonly known as 'bioengineering' has become popular. Along the Indian coast, erosion is more prominent towards the south western coasts of Karnataka and Kerala. Karnataka coast has more number of sand dune vegetation species. This could be attributed to the larger beach widths, compared to Kerala. Over 60% of Kerala's shoreline is threatened by erosion (Mallik, 1987). Kerala coast is protected mostly by hard structures such as sea walls (Nayak, 2005) and therefore has a low number of sand dune species.

After the December 2004 Indian Ocean tsunami, it was seen that the profusely vegetated stretches of Tamil Nadu such as Pichavaram and Muthupet displayed an exceptional resilience by dissipating high waves. Field measurements confirmed that only the frontal Casuarina woodland strip, ranging from 0 to 25 m, was stripped of leaf cover (Mascarenhas and Jayakumar, 2008). Villages behind the coastal forests remained intact and the Casuarina plantations helped dissipate violent waves. Coastal vegetation thus played an essential role as efficient biological buffers (Rodrigues et.al, 2011). Even though casuarinas performed exceptionally as natural wave breakers in the wake of tsunami, the same cannot be applied to storm surge events which may last for several hours or even days. Erosion of sand is observed wherever high waves recurrently lash the base of casuarina trees as these plants are known to bear a shallow root system and easily uproot with strong wind and beach erosion (Schmid et.al, 1993).

Although herbs cover the dune in most places, tall hinterland trees such as *Cocos nucifera* and *Casuarina equisetifolia* are routinely seen along the frontal dune along Goa and Tamil Nadu coast which represents a mixed disposition of floral species (Rodrigues et.al, 2011). The main reason could be attributed to lack of management initiatives and haphazard plantation programs. Improper selection of plant species in different areas of the beach/dune, and inadequate planning generates a potentially high environmental stress on the coast (Martinez et. al, 2006).

Casuarina (Casuarina equisetifolia L), commonly known has the Australian pine, is one of the dominant exotic species of trees planted along the Indian coast as a bioshield under various initiatives of coastal shelterbelt schemes, since 1920s (Das and Sandhu, 2014). This work also presents a comparative study of the role of casuarina, an exotic species and of mangroves and cashew forests, which is an indigenous species, and also questions the policy of promoting casuarina monoculture in mangrove habitats. Even though casuarinas performed exceptionally well as natural wave breakers in the wake of the tsunami (Santiago-Fandiño et al., 2016), there are evidences of easy uprooting of casuarinas with strong winds and beach erosion due to its shallow root system (Schmid et al., 2008).

Rodrigues et al (2011), in their work proposed a succession of coastal sand dune vegetation species landward from the dune, which is expected to form a functional buffer zone. This would comprise of pioneer shallow rooted herbs such as *Sesuvium portulacastrum* and *Ipomoea pescaprae* on the frontal dune, followed by herbs and medium-rooted shrubs on the mid-shore zone, followed by deep rooted coastal sand dune species of taller shrubs and trees such as *Anacardium occidentale*, *Ziziphus spp*. and *Cocos nucifera*.

The complex root structure of seagrass beds secures and stabilizes sediments providing essential shoreline protection and reduction of coastal erosion from extreme storm events. The leaves act as a trap for suspended materials that are brought to the seagrass meadows with the currents. (Björk et al. 2008). Seagrasses may thus reduce coastal erosion, especially following heavy winds, rains and floods. Another physical benefit of seagrasses is their ability to attenuate waves, thereby offering some degree of protection from erosion. The major seagrass species found in India are *Cymodocea rotundata* (locality: Gulf of Mannar), *Cymodocea serrulata* (locality: Palk Bay), *Enhalus koenigi* (locality: Gulf of Mannar), *and Halophila ovate* (locality: Palk Bay).

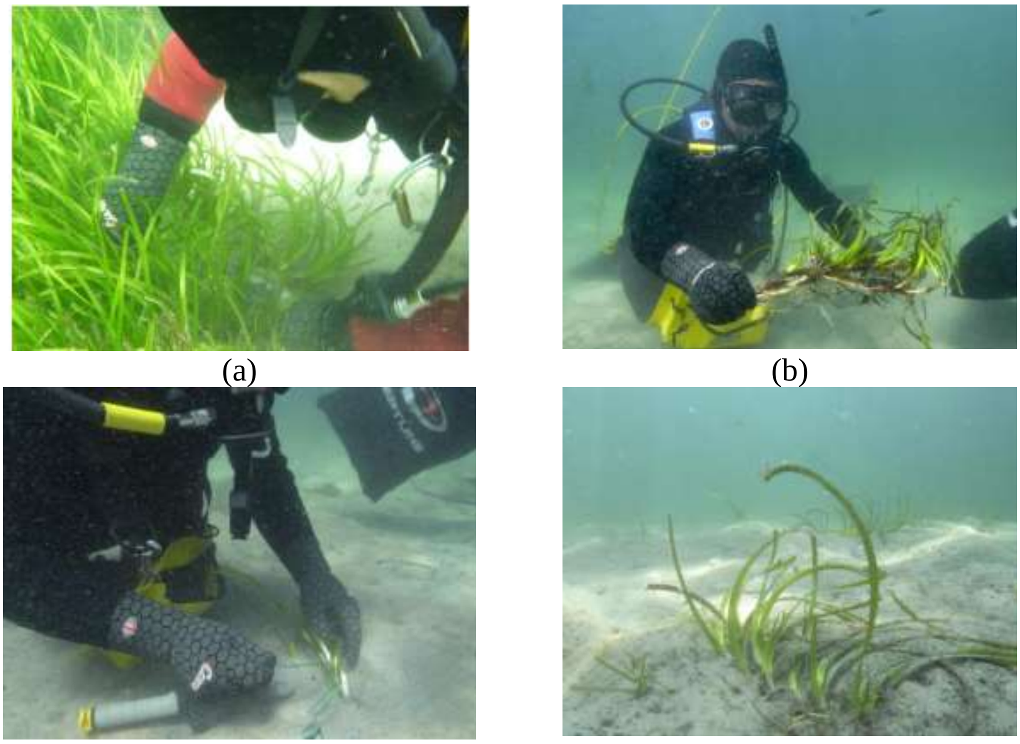
The 2004 Indian Ocean which wreaked devastation across the Indian Ocean coastline, including the south eastern coast of India marked a critical turning point for the scientists and administrators in India. The vulnerability of coasts to sudden catastrophic events gained importance and measures to protect our coastline has become a prime concern. Kathiresan and Rajendran (2005), in their study of tsunami-hit regions reported that agricultural fields suffered enormous loss due to intrusion of seawater in regions not protected by mangroves and other coastal vegetation; and reiterates that mangroves prevent the entry of seawater inland, thus protecting the underground water systems essential for drinking water supply. Post tsunami reconnaissance investigations along the most affected coastal stretches of India revealed that the thick forest of interwoven mangrove vegetation along the backwater canals of Pichavaram decelerated the gush of tsunami shoreward, thus greatly protecting the hamlet from the impact of tsunami (NIO, 2005). Jayakumar et al (2005) carried out a post tsunami survey to ascertain the inundation limits at different locations along the tsunami affected coastline. It was observed that the inundation values were lower at places where the coast is protected by dunes. However, the inundation values were higher wherever openings were found in dunes, as these openings provided a gateway for the water mass to travel through them to the hinterland. With reference to the Tamil Nadu coast (South East of Indian Peninsula), field observations with relevant measurements revealed that sand dunes and casaurina forests could aid in dissipating powerful waves (Mascarenhas and Jayakumar, 2008). The soft measures of coastal protection thus gained importance in India during the post tsunami years. Some of the early experimental works which shot up from this need was conducted in the 72 m long, 2 m wide and 2.7 m deep wave flume at the Department of Ocean Engineering, Indian Institute of Technology Madras, India by Sundar et al. (2011) and Lakshmanan et al. (2012).

Sundar et al. (2011), from IIT Madras, India, in their detailed experimental investigations studied the effect of vegetation in reducing the wave run up and the variation of pressure on a wall fronted by different arrangements of vegetation, by varying the vegetative parameters such as diameter of stem, spacing between the stems, width of the green belt and their rigidity. Lakshmanan et al. (2012) presented the variation of forces on a model building mounted over a slope, positioned at different distances from the vegetation belt and subjected to the action of Cnoidal waves as a function of flow and vegetation parameters. The authors also studied the hydro elastic interaction of flow with vegetal stems and the resulting wave run-up on beach slopes (Naorayanan et al., 2012).

2.7 CONSERVATION AND RESTORATION TECHNIQUES OF COASTAL VEGETATION

The distribution of seagrasses is greatly influenced by factors such as the depth of light penetration, salinity conditions, nutrient status and wave energy (Ganassin and Gibbs, 2008). Various anthropogenic activities such as dredging, reclamation, pollution and land management practices have led to alteration of seagrass meadows (Williams and Meehan, 2004). Owing to the slow process of natural recovery of seagrass species from such disturbances, various techniques for accelerating the recovery of seagrass beds has gained importance. Such techniques include use of seeds and seedlings for rehabilitation, transplantation of seagrass from a donor bed to a nearby location or manual planting of seagrass sprigs; and use of natural substrates to facilitate restoration of seagrass meadows, suitable in moderate wave energy environments (Wear et al, 2006).

The manual transplanting technique involves harvesting seagrass transplant material from the donor meadows. The rhizome sprigs are harvested by the divers and stored in seawater for transiting to the transplantation site. The divers then break the seagrass into sections and prepares sprigs, which varies from 3 shoots per sprig to > 10 shoots per sprig. Plate 2.3 (a to d) shows the steps involved in manual transplanting of seagrasses.



(a) (b) (c) (d)

Plate 2.3 a) diver harvesting seagrass from meadow edge, b) seagrass sprig prior to transplanting, c) diver transplanting sprig using metal peg and d) transplanted sprig (Source: BMT Oceanica and Halsall Photography)

Transplanting Eelgrass Remotely with Frame Systems" (TERFS') is a technique wherein shoots of seagrasses are attached to rubber-coated weighted wire frames with biodegradable ties. This provides protection from uprooting. The frames are deployed from a small boat, and the eelgrass rhizomes are pressed onto the substrate. The new transplants are held in place by the frame. After a month, when the eelgrass shoots have rooted, the frame is removed (Short et al., 2002).

Another recent method of dispersing seagrass seeds is the Buoy-Deployed Seeding System (BuDS), wherein, mature reproductive shoots of *Zostera marina* L. are collected during the second week of seed release. These shoots are stocked into mesh bags, which are deployed from the shore by suspending from buoys. As the seeds gets ripened, they are released from the bags naturally, fall to the bottom and germinates to form a meadow under each buoy (Pickerell et al., 2005). Photographs of the BuDS method of dispersing seagrass seeds is shown in Plate 2.4.

(a) (b) (c)

Plate 2.4 Buoy Deployed Seeding (BuDS) of seagrass: a) Filling mesh bags with standardized measure of reproductive shoots b) Transporting stocked nets to the planting site c) Attaching stocked net to buoy (Pickerell et al., 2005)

The planting techniques for the mangrove species *Avicennia officianalis* consists of collecting the propagules from the base of trees and is directly planted into sheltered areas by 'dibbling', where the propagule is pushed gently into the soft sediment. Another technique involves raising the propagules in nursery beds. The seedlings are raised for about 1-2 months, then gently pulled out of the ground and are transported to various afforestation sites (Saenger and Siddiqi, 1993).

The need for mangrove nurseries gained importance when studies proved that the rate of survival of nursery-raised mangrove saplings is grater when compared to direct dibbling of mangrove propagules/seeds. The chemical reaction accompanied with the sprouting of seeds emits a gaseous smell which attracts crabs the crabs. The crabs feed on the hypocotyl (stem of a germinating seedling, found below the cotyledons) which damages the sprouting seeds. Therefore, nursery-raised saplings are preferred for mangrove restoration. Such saplings have a well-established root system, since they are maintained for 8-9 months in the nursery under simulated conditions, before being transplanted in the degraded areas. The requirements for a mangrove nursery site are: areas with periodic inundation, access to good quality salt and fresh water, pumps for pumping saline water from the creeks for the saplings, access to road/creek to mobilize transport and labour to the planting sites and good quality propagation stock (Ravishankar and Ramasubramanian, 2004). Plate 2.5 displays a mangrove nursery at Naupal, Odisha.

(a)

(b)

Plate 2.5 a) Mangrove nursery at Naupal, Odisha b) Farmers monitoring the mangrove nursery (Source: Regional Centre For Development Cooperation, Odisha)

2.8 SUMMARY OF LITERATURE REVIEW

The literature provides sufficient evidences about the capacity of coastal ecosystems, especially coastal vegetation, to supply coastal protection services. It is clear from the previous works that science is strongly advancing to evaluate the hydrodynamic processes, the vegetation and wave parameters, as well as the efficiency that affects the defense service provided. However, there are still uncertainties in the characterization and quantification of the protection offered by vegetation, which demands greater attention from science if it is to be applied as a real adaptation option (Ondiviela et al., 2014).

Owing to the random distribution of vegetation in a natural wetland, the variation of plant characteristics and the dynamic interaction between the fluid and vegetation, it becomes difficult to model the interaction between waves and vegetation using purely theoretical or numerical methods which may involve many assumptions. A field study may prove to be costly owing to the complex nature of the problem. Therefore, physical model studies with simulated vegetation models of different types and under various wave conditions would be a good option to examine and analyze the wave damping effect of vegetation.

2.9 NECESSITY AND RELEVANCE OF THE PRESENT STUDY

The literature showcases that within any coastal ecosystem, there exists a complex interaction between waves and vegetation. With regard to the hydrodynamics, not only does water flow affects vegetation and vice-versa but vegetation and water flow may interact in highly coupled, nonlinear ways (Koftis and Prinos, 2011). The variability of wave attenuation is very large and it is difficult to define a generalized behaviour of the "plant-induced dissipation" as wave attenuation depends on the characteristics of the plant as well as wave parameters. Though several theoretical, experimental and field studies were carried out, the mechanism of wave attenuation due to vegetation is still not fully explained. The study of literature showed that no comprehensive physical modelling was undertaken to quantify the effects of vegetation types on wave attenuation. Hence, it is decided to experimentally investigate the effect of different types and combinations of vegetation on wave attenuation and to arrive at the optimum variety of vegetation which offers maximum protection against coastal inundation.

2.10 OBJECTIVES OF THE STUDY

The present study is intended to demonstrate the effectiveness of coastal vegetation in protecting the shoreline with the aid of physical model studies on simulated vegetation, to quantify the extent of wave attenuation and run-up. More specifically, the objectives of the proposed investigation are to:

1. Conduct laboratory flume experiments with different types of simulated vegetation with varying vegetal parameters acted upon by varying wave climate and to determine the extent of wave height attenuation.

2. Determine the dependence of wave height attenuation on relative plant height, plant density and meadow width.

3. Demonstrate the effect of heterogeneity and fragmentation in vegetated meadows and its subsequent influence on wave decay.

4. Investigate the extent of wave run-up on a mild beach slope due to monochromatic waves propagating through the model vegetation.

5. Compare the performance of different vegetation types and selection of the optimum configuration of vegetation meadow among the test models.

CHAPTER 3

MATERIALS AND METHODS OF EXPERIMENTAL STUDY

3.1 GENERAL

Even though there are a lot of studies on wave damping due to vegetation, developing a generalized method to quantify this behavior is difficult since vegetation shows a large variability across the world. The present work deals with a comprehensive study on wave attenuation due to simulated vegetation in well-controlled laboratory conditions with different combinations and arrangements of simulated submerged as well as emergent types of vegetation under different wave conditions and vegetation stem densities.

3.2 SIMILITUDE CRITERIA AND MODEL SCALE SELECTION

Physical model studies undoubtedly play a pivotal role in the domain of coastal engineering because they provide the closest representation of wave-structure interaction in coastal structures. Physical models are scaled representations of a physical system (Hughes, 1993), which allows simulation of complex physical phenomena without a mathematical or theoretical simplification of the governing process.

Modelling of coastal engineering solutions to protect shorelines is a difficult problem which involves complex interaction of waves and the structure. Such problems have been conventionally addressed through large scale field studies combined with mathematical and numerical modelling. Even though mathematical models have helped us in better understanding of the complex wave-structure interaction problems, they are inevitably subjected to simplifications and use of empirical coefficients derived from limited input data. Physical model studies allow the reproduction of complex physical phenomena within controlled laboratory conditions. They also provide a ‘snapshot’ and instant analysis of complex physical processes involved in the propagation of waves and in the interaction with the coastal structures (Reis et al., 2014).

The basis of all physical modelling is similitude of the model and prototype. Deviations between model and prototype results are due to scale and model effects. Incorrect reproduction of ratios between forces in the model leads to scale effects whereas, differences between prototype and model because of deviations in wave kinematics, wave recording methods, methods of wave analysis, geometrical differences etc leads to model effects (Burcharth et al., 2009). This study deals with surface waves and therefore the scaling is in accordance with the Froude scaling law. For wave motion studies, the gravity effect is predominant in the prototype. The flow is turbulent, and hence viscous and surface tension effects are negligible in the prototype if the flow velocity is reasonably small. In such cases a Froude similitude is selected.

Similitude, in the present study is achieved by the method of dimensional analysis. The non-dimensional parameters of the complex wave interaction phenomenon decides the similitude achieved between the model and the prototype. By taking into account the wave climate off Mangaluru coast, the similitude criteria in the present study is achieved by considering the non-dimensional parameter, wave steepness H_i/gT^2 as given in Table 3.1. Using the existing facilities of the two-dimensional wave flume in the Department of Applied Mechanics, National Institute of Technology Karnataka, regular waves of heights ranging from 0.03 m to 0.24 m and periods ranging from 1s to 3 s can be produced.

Table 3.1 Wave parameters of Prototype and Model

Wave Parameters	H_i (m)	T (s)	H_i/gT^2
Prototype	1 to 5.4	8 to 12	0.00070 to 0.0086
Model	0.030 to 0.24	1.0 to 3.0	0.00033 to 00244

3.3 WAVE CLIMATE

The present study takes into consideration the wave climate off the Mangalore coast as given by the KREC Study Team (1994). The maximum recorded wave height off Mangalore coast during the monsoon period is about 4.5 m. The wave height hardly exceeds 1 m during fair weather season. The predominant wave period is in the range 8 s to 11 s. Wave periods up to 15 s are observed occasionally during the fair-weather season.

3.4 EXPERIMENTAL SETUP

3.4.1 Details of wave flume

Experiments with simulated vegetation are conducted in a two-dimensional wave flume of the Marine Structures Laboratory of the Department of Applied Mechanics and Hydraulics, National Institute of Technology Karnataka, Surathkal, India. The wave flume is 50 m long, 0.71 m wide and 1.1 m deep and has a 6.3 m long, 1.5 m wide and 1.4 m deep wave generating chamber at one end and a built-in beach of slope 1:12 at the other end. The wave generating chamber has a bottom hinged flap controlled by an induction motor (11 kW at 1450 rpm), which in turn is regulated by an inverter drive (0-50 Hz) rotating in a speed range of 0-155 rpm. A flywheel and a bar chain link the motor with the flap. Regular waves of heights 0.08 m to 0.24 m and periods 0.8 sec to 4.0 sec in a maximum water depth of 0.5 m can be generated with this facility. Fig. 3.1 gives a schematic diagram of the experimental setup. The schematic representation of experimental set-up for other models are depicted in Figs. 3.18 to 3.21, at the end of this chapter.

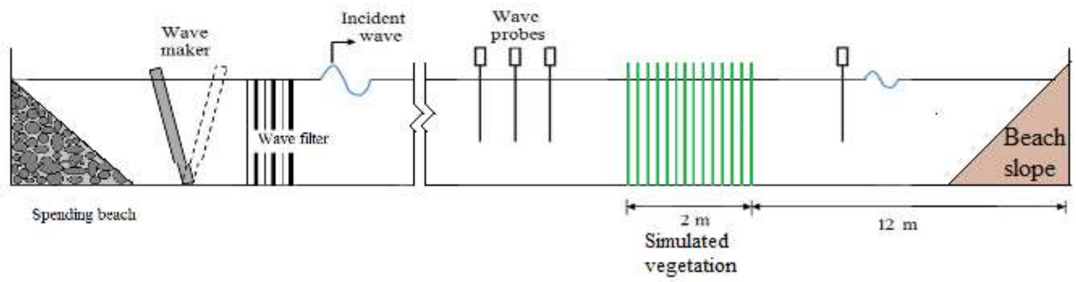


Fig. 3.1 Schematic experimental set-up

3.4.2 Wave probes

Capacitance-type wave probes are used to measure the water surface elevation (as shown in Plate 3.2 at the end of this chapter). The accuracy of measurements using wave probes is 0.001 m. Probes are used to record the incident and transmitted wave characteristics. The recorded analog data is converted into digital data and is stored in digital form by a software controlled A/D converter. The spacing of probes and decomposition of incident wave characteristics from superposed waves is accomplished using the three-probe method suggested by Isaacson (1991).

3.4.3 Data acquisition system

The water surface elevations are acquired using the capacitance type wave probes along with its amplification units and the computer data acquisition. The variation of capacitance between water and the copper conductor is a measure of the wave height. This variation is sensed by the circuit inside the electronic unit. The converted digital signals are modified to get physical wave signals using the calibration constant of the wave probe. These modified signals are analyzed using the software provided by EMCON, Kochi. From the digitized transmitted wave form, equivalent wave height is calculated by a software program. The wave probes are calibrated before and after each session. The wave surface elevations measured using the probes are checked manually by using well marked strips of graph paper pasted on the glass panel of the flume. The data acquisition system and the wave generating system is depicted in Plates 3.3 to 3.4, at the end of this chapter.

3.4.4 Calibration of test facilities

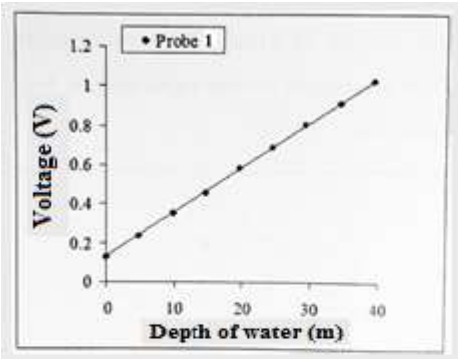
Calibration of instruments and experimental setup was undertaken frequently to check and ensure accuracy, precision and reproducibility. The method of calibration of each component is given below.

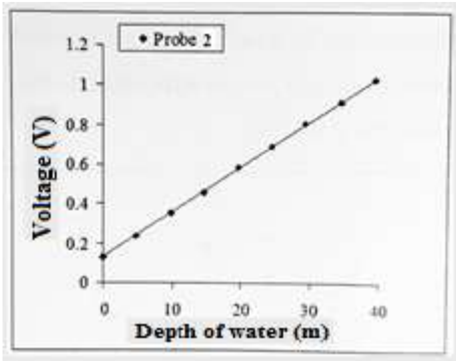
3.4.4.1 Wave flume

The relationship between frequency of the inverter and wave period; and eccentricity and wave height for a particular water depth is evaluated. Waves of height (H) ranging from 0.08 m to 0.16 m with varying time periods (T) from 1.4 to 2.2 seconds for different water depths were required for the experiment. By changing frequency through the inverter drive, the desired wave period is generated and by changing the eccentricity of bar chain on the flywheel, wave height for a particular wave period is produced.

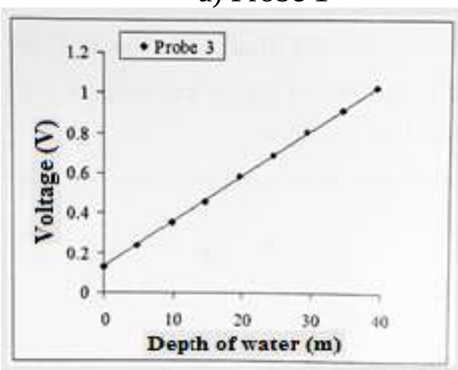
3.4.4.2 Wave probes

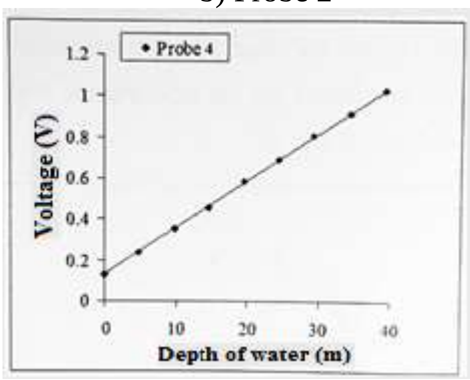
The wave probe is a simple and reliable instrument for measuring rapidly changing water levels in physical model studies. The output of the probes originally calibrated by the manufacturer is expected to show minor variations depending on the salinity and temperature of the water used in the flume studies. Hence, probes are subjected to static immersion tests and the relationship between the water level and the output voltage is determined and recorded.





a) Probe 1 b) Probe 2





c) Probe 3 d) Probe 4

Fig. 3.2 Calibration of wave probes

Fig. 3.2 shows the variation of voltage with water level. Calibration of probes is carried out daily before and after the experiments. The free surface of water is considered as zero mark in x axis and the probe will be moved from the bottom tip to the top tip inside the water to record the change in voltage.

3.5 TEST MODELS OF SIMULATED VEGETATION

3.5.1 Selection of model material

In order to replicate the original vegetation in the field, a suitable material for the model is selected based upon the Young's modulus of natural vegetation. This is a measure of stiffness of the elastic material and is used to characterize the material property. The value of Young's modulus for seagrass is in the range 0.4 GPa to 0.8 GPa (Folkard, 2005), and that for common timber is in the range 10.05 GPa to 15 GPa (Table 3.2 and 3.3). To cover this range of E, a reference value of 0.8 GPa and 20 GPa is assumed for the seagrass and the rigid vegetation respectively for the field condition. A model scale of 1:30 is adopted in this experiment to scale down the prototype values. This would mean that the value of Young's modulus of the model material should be about 0.026 GPa and 0.667 GPa respectively. A material corresponding to this value is quite difficult to be identified for this type of vegetation model. Therefore, the stiffness property, EI is modelled as a single parameter, instead of separately modelling Young's modulus, E and the second moment of area, I. Thus, the appropriate material chosen for simulating seagrass leaves and the rigid vegetation trunks for this study is polyethylene, with an E value of about 0.6 GPa and nylon with an E value of about 3 GPa, respectively. Accordingly, the prototype dimensions of seagrass leaves as well as the diameter of the rigid vegetal stems are fixed.

Mangrove tree trunks could be characterized similar to cantilever beams, for which the mechanical characteristics may be brought in through the resonance frequency of the first mode of vibration, namely the natural frequency of the vegetal stems (Noarayanan, 2009). The resonance frequencies are denoted as f_j (with j = 1, 2, 3,..., n,where f_1 is the fundamental or base natural frequency and f_2,.., n are higher modes of natural frequencies). For a linear and homogeneous beam, f_j depends upon the beam's length *l*, mass per unit length *m*, second moment of inertia *I*, modulus of elasticity *E*, as well as a dimensionless parameter λ_j which in turn is a function of beam geometry and the boundary conditions under which it is tested. The mathematical relationship between the resonance frequency and the above variables may be written as (Timoshenko and Gere 1961),

$$f_j = \frac{\lambda_j^2}{2\pi}\left(\frac{EI}{ml^4}\right)^{0.5} \quad (3.1)$$

The above parameter characterizes the height, mass (including leaf density) and the moment of inertia of a tree. Herein, the beam length *l* is taken to be the height of the vegetal stem.

3.5.2 Submerged models

3.5.2.1 Submerged seagrass model

A 1:30 scaled simulated *Enhalus acoroides* model (Fig. 3.3) with 0.21 m long leaves and 0.01 m high stipes is prepared from 0.0001 m thick polyethylene plastic sheets.

(a) (b)

Fig. 3.3 (a) Seagrass model; (b) Natural *Enhalus acoroides* (*Photo courtesy:* http://www.seagrasswatch.org**)**

Each simulated seagrass plant is composed of 4 to 5 polyethylene leaves and is attached to 1 m x 0.7 m x 0.02 m slabs in a staggered distribution. Two such 1 m long slabs are placed consecutively along the length of the flume to form a 2 m long seagrass meadow. Tests are conducted for the seagrass model of 1 m width as well as for the seagrass model of 2 m width. Polyethylene sheets with a density of 800 kg/m^3 and a modulus of elasticity of 0.6 GPa, which is comparable to the average values measured for natural *E. acoroides* is selected for modelling the simulated seagrass leaves, as discussed in section 3.5. The dimensions of the seagrass leaves are in the range of 0.5 to 1.5 m. The length of the model vegetation (h_s) is fixed in the range of 0.15 m to 0.27 m, by employing the Froude model law of scaling of stiffness property.

Table 3.2 Properties of natural and simulated seagrass.

Item	**Natural (*Enhalus acoroides*)**	**Simulated seagrass (polyethylene)**
Modulus of Elasticity	0.8 GPa	0.6 GPa
Density	800-1020 kg/m3	800 kg/m3
Thickness of leaf	0.003 m	0.0001 m
Width of leaf	0.03 m	0.004 m
Plant density	150 shoots/m^2	10000 shoots/m^2

The simulated plants have 0.01 m high stipe and 0.21 m long leaves. Each simulated plant is composed of 4 to 5 leaves and are attached to 1 m x 0.73 m slabs in a staggered distribution representing a full-scale plant density of 10,000 plants / m^2. A 0.02 m thick slab is made of plaster of Paris. The preparation of the model is done in two steps. Initially fabrication of the iron frame is carried out and consequently the plastic seagrass plant model is fixed using plaster of Paris slurry filled in the iron frame. This iron frame filled with plaster of Paris acts as a slab of size 1 m x 0.73 m x 0.02 m. The height of the model seagrass is 0.21 m. Likewise; two concrete slabs of base size 1 m x 0.73 m and 0.02 m thickness is prepared to check the effect of wave damping by changing the meadow width from 1 m to 2 m. A schematic representation of the arrangement of the seagrass model is illustrated in Fig. 3.4.

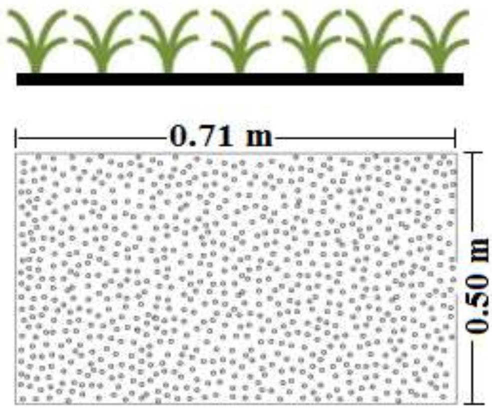


Fig. 3.4 Schematic representation of arrangement of the seagrass model (side and top view)

3.5.2.2 Submerged rigid vegetation model

Nylon rods of 0.21 m length and 0.01 m diameter is used to prepare a 1:30 scaled submerged *Avicennia officianalis* pneumatophore model, which is represented as submerged rigid vegetation model (Fig. 3.5). Tests are conducted for the submerged rigid vegetation model of 1 m width as well as for that of 2 m width. The nylon rod has a modulus of elasticity of 3 GPa, whereas the modulus of elasticity of the prototype is around 20 GPa. Since the stiffness property is modeled herein, an E value of 3 GPa for the model is accounted for by varying the moment of inertia of the material. The length of the simulated vegetation is fixed as 0.25 m. The diameter of the model rigid vegetation is fixed in the range of 0.009 m to 0.010 m, by employing the Froude model law of scaling of stiffness property.

(a)

(b)

Fig. 3.5 (a) Model and (b) Prototype of rigid vegetation (Photo courtesy: http://images.fineartamerica.com)

Table 3.3 Properties of natural and simulated rigid trunk

Item	**Natural (*Avicennia officianalis*)**	**Simulated rigid vegetation (polyethylene)**
Modulus of Elasticity	20 GPa	3 GPa
Height of trunk	7.5 m	0.21 m
Diameter of trunk	0.43 m	0.01 m
Trunk spacing	1.5 m	0.05 m

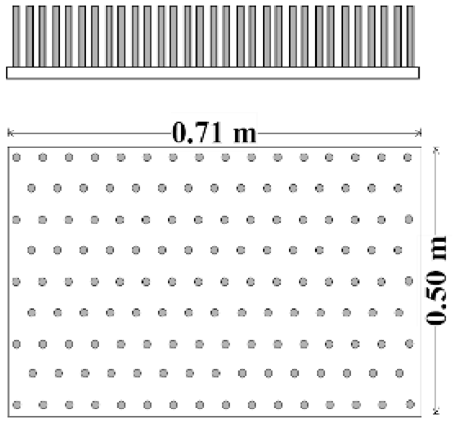


Fig. 3.6 Construction details of the submerged rigid vegetation model (side and top view)

The model is prepared using 10 mm diameter nylon rods which is cut into 0.25 m length. The projected height of the nylon rods above the slab is 0.21 m. The nylon rods are inserted into the 0.04 m thick concrete slab. The nylon rods are fixed to the 0.5 m x 0.73 m x 0.04 m concrete slab using a strong adhesive called Araldite. Four such concrete slabs with nylon rods fixed to them are prepared which is used to conduct the test runs. A schematic representation of the construction details of the rigid vegetation model is illustrated in Fig. 3.6.

3.5.3 Emergent models

3.5.3.1 Emergent trunk model

The emergent trunk model is made of nylon rods of diameter 0.016 m respectively. To study the hydro-elastic interaction of the flow with the vegetal stem, coastal vegetation in real-world is reproduced in laboratory conditions with the key parameter, the Young’s modulus, E. Common timber has an E value in the range from 10.05 to 15GPa. Mangrove has maximum E values of 20.03 GPa (Vallam et al., 2011)

By adopting a model scale of 1:30 to scale down the prototype values and by modelling the stiffness property, EI as a single parameter, the appropriate material chosen for the vegetation trunks for this study is nylon with an E value of about 3 GPa. Accordingly, the diameter of the vegetal stems are fixed. The emergent trunk model used for the experiments is depicted in Fig. 3.7.

(a) (b)

Fig. 3.7 (a) Emergent trunk model; (b) Natural mangrove trunks (*Photo courtesy: http://cnx.org/*)

The emergent trunk model is constructed by fixing rigid nylon rods in holes drilled in 1 m x 0.73 m x 0.04 m concrete slabs. The rods are 0.016 m in diameter and length 0.50 m. The trunk density, represented by the number of trunks per square meter area for the model is 107 trunks/m^2. The construction details of the arrangement of the emergent trunk model is illustrated in Fig. 3.8.

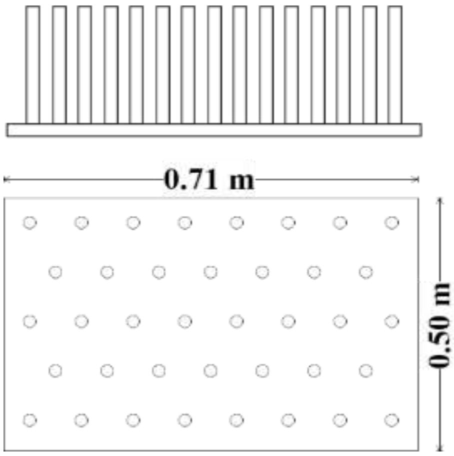


Fig. 3.8 Construction details of the emergent trunk model (side and top view)

3.5.3.2 Emergent trunk model with roots

Mangroves are characterized by a very complex three-dimensional tree structure with randomly distributed roots and branches. The parameterization approach adopted in this study is from Strusinska-Correia et al. (2013), wherein, the porotype tree is replaced by a model tree of stiff trunk structure with roots. The emergent trunk model is made of nylon rods of diameter 0.016 m. The roots for the model consists of nylon rods of diameter 0.010 and 0.006 m placed around the trunk as shown in 3.10. The prototype tree dimensions adopted for this study and the photo of model setup for the emergent trunks with roots is depicted in Fig. 3.9.

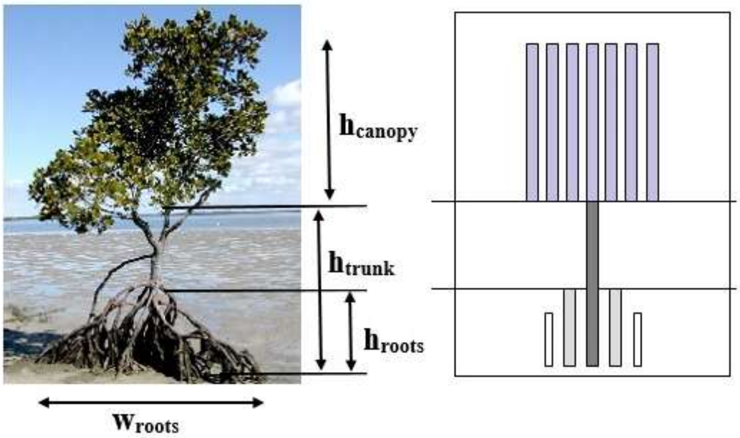


Fig. 3.9 Prototype tree dimensions adopted, according to stiff tree structure assumption –h_{trunk}= 15 m, h_{roots} = 6.3 m, 4.8 m, w_{roots} = 3 m (Duke et al., 2010)

(a) (b)

Fig. 3.10 Photo of model setup to study wave attenuation over an emergent trunk model with roots a) Side view b) Top view

The emergent trunk model with roots is constructed by fixing rigid nylon rods in holes drilled in 1 m x 0.73 m x 0.04 m concrete slabs. The trunks are 0.016 m in diameter and length 0.50 m. The roots are 0.010 m in diameter and length 0.25 m for Root Type I and 0.006 m in diameter and length 0.21 m for Root Type II. The density of trunks, root type I and root type II is 107 trunks/m^2, 300 $roots_1/m^2$ and 300 $roots_2/m^2$ respectively.

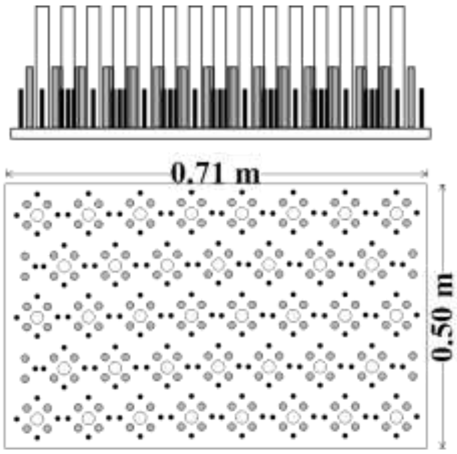


Fig. 3.11 Construction details of the emergent trunk model with roots (side and top view)

3.5.4 Heterogeneous models

3.5.4.1 Submerged heterogeneous model

The submerged heterogeneous model comprises of a 2 m wide seagrass meadow followed by a 2 m wide rigid vegetation meadow (rigid in the sense that the vegetation considered here is a submerged stem which may vibrate under the influence of passing waves, but this is very much less compared to the swaying motion of the seagrass leaves or kelp fronds).

(a) (b)

Fig. 3.12 Photo of model setup to study wave attenuation over a submerged heterogeneous vegetation model a) Side view b) Top view

The submerged simulated seagrass is prepared from 0.1 mm thick polyethylene plastic sheets, whereas the submerged rigid plant model is made of nylon rods of diameter 0.010 m as discussed in section 3.5.2.1 and 3.5.2.2.

3.5.4.2 Emergent heterogeneous model

The emergent heterogeneous model comprises of a submerged rigid vegetation meadow of width 2 m followed by an emergent trunk model with roots of width 2 m.

Fig. 3.13 Photo of model setup to study wave attenuation over a emergent heterogeneous model (top view)

3.5.4.3 Compound heterogeneous model

The test model is a compound heterogeneous model comprising of a 2 m wide seagrass meadow followed by a 2 m wide rigid vegetation meadow and a 2 m wide emergent trunk model with roots. The submerged simulated seagrass is prepared from 0.1 mm thick polyethylene plastic sheets, whereas the submerged rigid plant model is made of nylon rods of diameter 0.010 m, as discussed in section 3.5.2. A 1:30 scaled emerged *Avicennia officianalis* model with 0.50 m long trunk is prepared from 0.016 m diameter nylon rods, as described in section 3.5.3.

Fig. 3.14 Photo of model setup to study wave attenuation over a compound heterogeneous model (top view)

3.5.5 Fragmented models

Coastal forests or vegetated habitats are vulnerable to impacts of climate change scenarios and increased anthropogenic activities. Patchiness, represented by the presence of open gaps in the forest cover is a common phenomenon in natural habitats. Therefore, gaps of varying widths (w_{gap}) are introduced between portions of the vegetated meadow to elucidate the effect of fragmentation in the vegetated meadow with respect to wave height attenuation and run up on the beach slope. The gap width parameter, given by w_{gap}/w, is of interest while analyzing the results. The fragmented vegetation models are represented by a) fragmented emergent trunks with roots, and b) fragmented compound heterogeneous vegetation model.

3.5.5.1 Fragmented emergent trunk model with roots

The test model is a fragmented emergent trunk model with roots, with varying gap widths (w_{gap}), as depicted in Fig. 3.15. This represents the introduction of transverse gaps between clusters of vegetation, with each cluster of vegetation represented by 0.50 m of vegetated meadow.

Fig. 3.15 Photo of model setup to study wave attenuation over fragmented emergent trunk model with roots

3.5.5.2 Fragmented compound heterogeneous model

In order to find the effect of fragmentation in the compound heterogenous models, gaps of varying widths are introduced after each type of vegetation, as represented in Fig. 3.16. The gap width parameter, given by w_{gap}/w, is of interest while analyzing the results.

Fig. 3.16 Photo of model setup to study wave attenuation over a fragmented compound heterogeneous model

The model preparation, placing of the model in the flume bed and the wave propagation through the simulated vegetation model are represented by Plates. 3.5 to 3.8, at the end of this chapter.

3.6 METHODOLOGY

To achieve the objectives mentioned in section 2.10, the general methodology adopted for the present research work is explained in this section and the flow chart of methodology is depicted in Fig. 3.17.

Literature survey and collection of information:

A comprehensive review and analysis of the effectiveness of coastal vegetation in wave attenuation is carried out based on available knowledge related to characteristics of coastal vegetation, seasonal information of wave parameters and existing models and methods to describe the vegetation- wave interaction.

Problem formulation:

Interaction between waves and vegetation is very complex and literature showed that there is little work done on wave attenuation due to different types of vegetation. In order to fill up this knowledge gap, a comprehensive experimental study to examine and analyze the wave damping effect of submerged sea grasses, submerged rigid vegetation, emergent tree trunks and various combinations of vegetation is formulated.

Physical modelling:

Froude's similitude criteria with 1:30 scaled dimensions are used for physical modelling of vegetation for different still water levels and wave characteristics. The most important parameters of the coastal vegetation – geometry and stiffness of the vegetation leaves, stem/trunk and roots, and the plant density is deduced.

Model testing and observations:

The vegetation model is subjected to waves of varying characteristics. The influence of various vegetation parameters and types of vegetation on wave attenuation and run-up characteristics is undertaken.

Experimental technique:

Experiments are conducted in a two-dimensional wave flume generating monochromatic waves. Using different vegetation models, the data collected for varying water depths and periods include the incident wave heights, wave heights at different locations along the vegetation model and at positions of fragmentation in vegetation, and the wave run-up characteristics.

Analysis of results:

The damping performance of different types of simulated vegetation subjected to waves of varying climate is analyzed and selection of the best model is attempted.

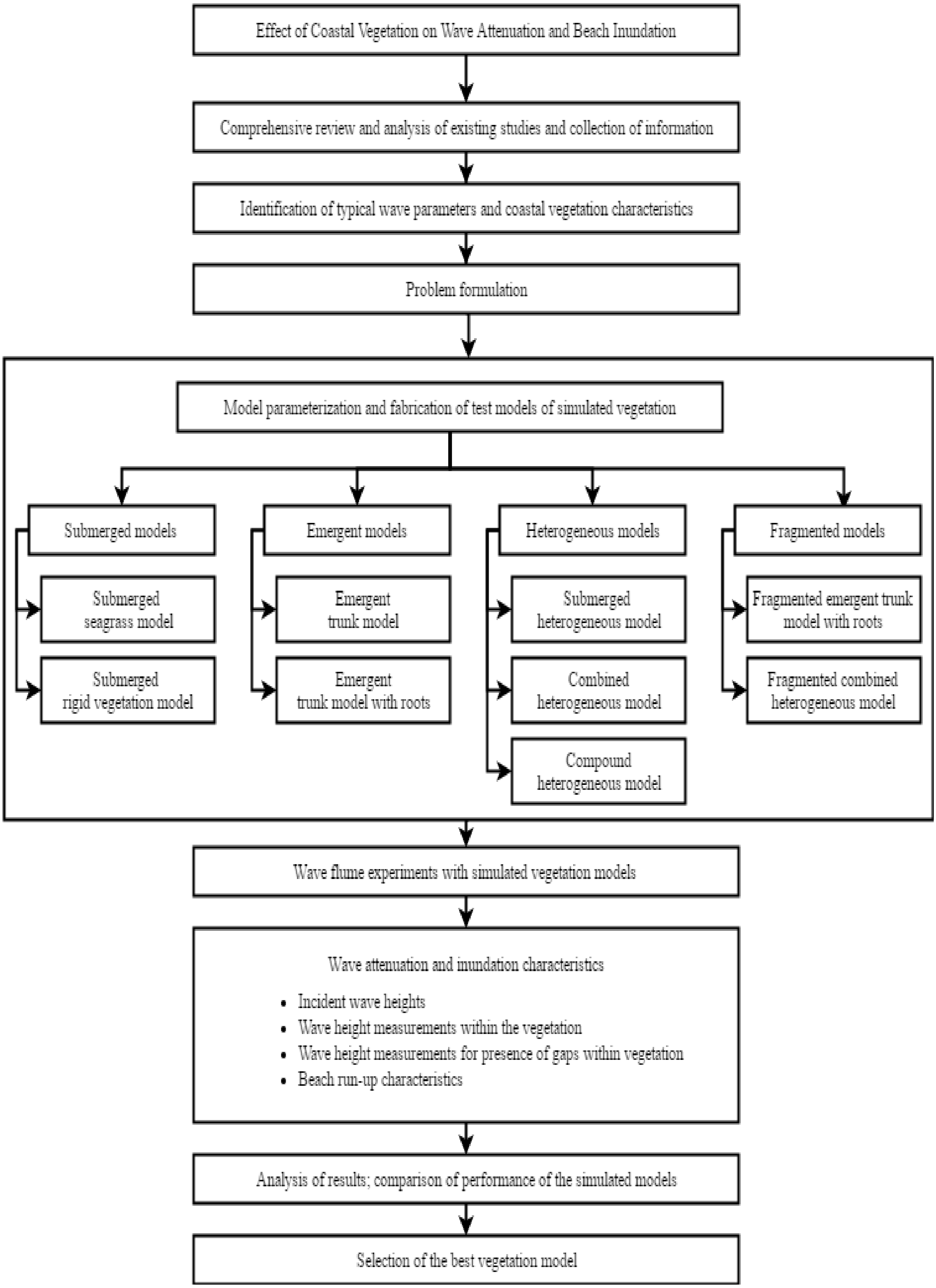


Fig. 3.17 Flowchart of methodology showing various phases of the research study

3.7 TEST CONDITIONS

The present experimental study is carried with the following test conditions:

1. The seabed is rigid and horizontal and it is assumed that the sediment movement does not interfere with the wave motion.
2. The waves generated in each burst is periodic and monochromatic.
3. Waves are generated in short burst of 5 waves.
4. Between wave burst there are brief intervals to allow wave energy to dampen.
5. Secondary waves generated during the tests are not considered.
6. The density difference between fresh water and seawater is not considered.

3.8 RANGE OF EXPERIMENTAL PARAMETERS

The range of experimental parameters is selected at an earlier stage of the physical model investigations on the effect of simulated vegetation on wave damping. The parameters related to wave conditions as well as the vegetation characteristics are described in Table 3.2.

Table 3.4 Vegetation characteristics and experimental conditions.

Simulated plant type	Vegetation model characteristics		Wave height (m)	Wave period, T (s)	Water depth, d (m)	Relative plant height (h_s/d)
Seagrass	Modulus of Elasticity	0.6 GPa	0.08, 0.10, 0.12, 0.14, 0.16	1.4, 1.6, 1.8, 2	0.40, 0.45	0.525, 0.47
	Thickness of leaf	0.0001 m				
	Length of leaf	0.21 m				
	Width of leaf	0.004 m				
	Plant density	10000 shoots/m^2				
Rigid vegetation	Modulus of Elasticity	3 GPa	0.08, 0.10, 0.12, 0.14, 0.16	1.4, 1.6, 1.8, 2	0.40, 0.45	0.525, 0.47
	Length of rod	0.21 m				
	Diameter of rod	0.010 m				
	Density	394 plants/m^2				
Emergent trunk model	Modulus of Elasticity	3 GPa	0.08, 0.10, 0.12, 0.14, 0.16	1.4, 1.6, 1.8, 2	0.40, 0.45	1.25, 1.11
	Length of trunk	0.5 m				
	Diameter of trunk	0.016 m				
	Density	107 trunks/m^2				
Emergent trunk model with roots	Modulus of Elasticity	3 GPa	0.08, 0.10, 0.12, 0.14, 0.16	1.4, 1.6, 1.8, 2	0.40, 0.45	1.25, 1.11; 0.525, 0.47; 0.4, 0.36
	Length of trunk	0.5 m				
	Diameter of trunk	0.016 m				
	Density of trunks	107 trunks/m^2				
	Length of Root 1	0.21 m				
	Diameter of Root 1	0.010 m				
	Density of Roots I	300 roots$_1$/m^2				
	Length of Root 2	0.16 m				
	Diameter of Root 2	0.006 m				
	Density of Roots 2	300 roots$_2$/m^2				

3.9 SUMMARY OF MODEL STUDY

The test models designed as submerged, emergent, heterogeneous and fragmented simulated vegetation are tested for wave height attenuation and run-up characteristics when subjected to varying wave heights and wave periods in a water depth of 0.40 m and 0.45 m. The test sections are subjected to normal attack of waves of characteristics as described in Table.3.2. The incident wave height (H_i) and the wave heights at different locations within the meadow (H_x) are recorded during the study. Correspondingly, the relative wave heights (H_x/H_i) are obtained from the experimental runs. The wave attenuation is represented by the percentage wave height reduction, which is calculated as $\left(1-\frac{H_x}{H_i}\right)$. The increase in wave height attenuation leads to a decreased wave run-up on the beach slope. The relative wave run-up (R_u/H) is the extent of inundation on the beach.

The wave flume is filled with ordinary tap water to the required depth. The flume is calibrated before the start of experiments to produce the incident waves of different combinations of wave height and wave periods. The models are then tested for wave height attenuation in water depths (d) of 0.40 m and 0.45 m with varying waves of heights (H) of 0.08 m to 0.16 m, with an increment of 0.02 m and wave periods (T) of 1.4 s to 2 s. A comparative analysis of the performance of different types of vegetation of varying densities and meadow widths is undertaken.

3.10 SOURCES OF ERRORS AND PRECAUTIONS EXERCISED

The following sources are identified which may cause error in the experimental study.

1. Error in linear dimensions: The model is constructed with an accuracy of linear dimensions up to ±1.0 mm, which may contribute errors in between 0.2% to 0.3%.

2. Error in wave height measurement: The least count of the wave probe is 1.0 mm and may contribute to an error of 2% to 6% in the incident wave height.

3. Error due to change in water level: The water level is checked at the 2 mm of the required level.

The following precautions are taken for minimizing the errors:

1. The model is constructed, as per the standard procedure, with a largest possible model with a scale of 1:30.

2. The depth of water in the flume is maintained exactly at the required level and was continuously monitored. Average variation of 2 mm was found after a full day of model testing. Any drop in the water level of more than 2 mm was immediately corrected.

3. Before the commencement of the experiments, calibration of flume and wave probes without the placement of model were undertaken to determine the proper wave height to assign to a specific combination of generator stroke and wave period. The wave heights to be used in the test runs are obtained during calibration. This will exclude the losses due to interference of flume bed and side walls and therefore, eliminates these error sources.

4. Waves were run in short bursts of five during the tests. Between wave bursts there will be brief interval to allow reflected wave energy to dampen out.

5. All the wave characteristics were measured with more iterations.

Similar exercise was repeated for wave run-up measurements as well.

3.11 PHOTOS OF EXPERIMENTAL SET-UP AND MODELS

Plate 3.1 View of wave flume with the simulated vegetation placed on the flume bed

Plate 3.2 Arrangement of wave probes for data acquisition

Plate 3.3 Data acqusition system

Plate 3.4 Wave generating system (clockwise from top left: motor, flap type wave paddle, invertor drive, wave filter)

Plate 3.5 Preparation of the base slab

Plate 3.6 Fixing the simulated vegetation model on to the base slab

Plate 3.7 Simulated vegetation model placed on the flume bed

Plate 3.8 Selected snapshots of wave propagation through simulated vegetation

Plate 3.9 Wave run-up along the beach slope

3.12 SCHEMATIC REPRESENTATION OF EXPERIMENTAL SET-UP FOR VARIOUS MODELS

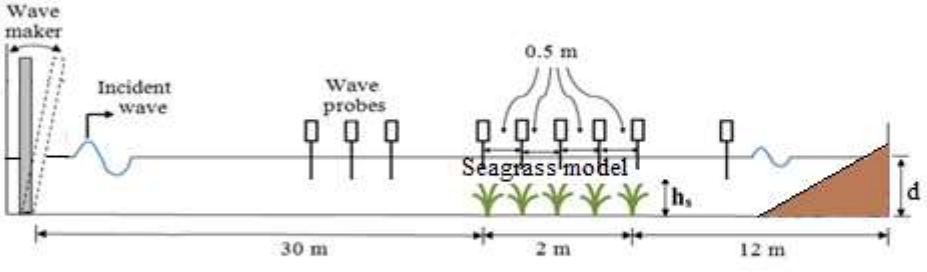


Fig. 3.18 Schematic representation of experimental set-up for submerged seagrass model

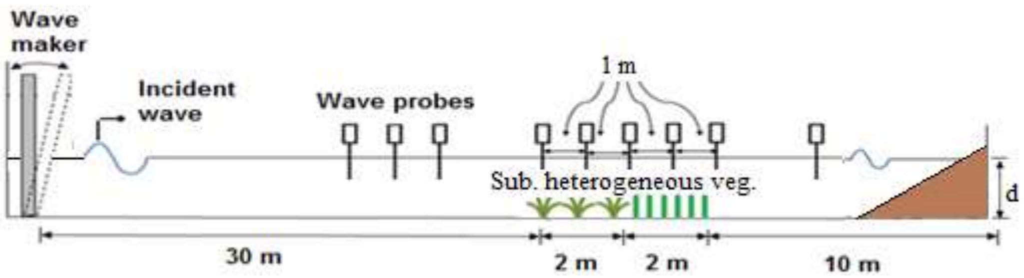


Fig. 3.19 Schematic representation of experimental set-up for submerged heterogeneous model

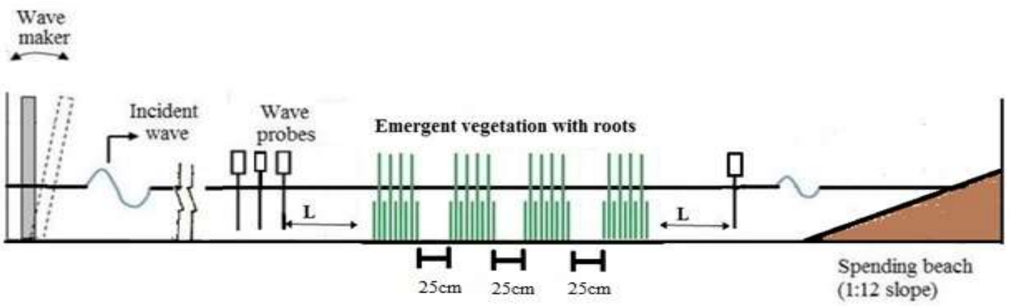


Fig. 3.20 Schematic representation of experimental set-up for fragmented emergent trunk model with roots

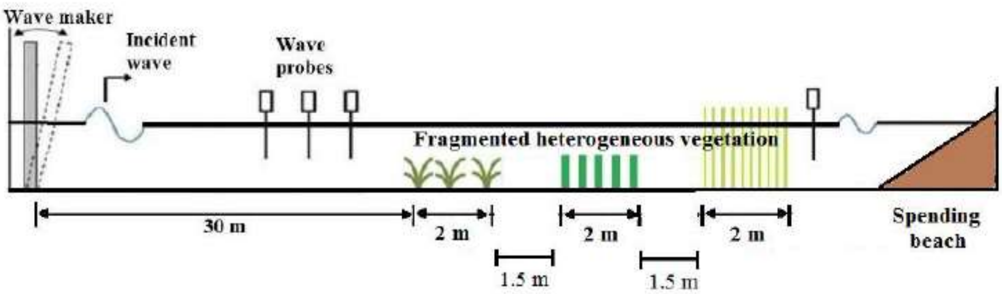


Fig. 3.21 Schematic representation of experimental set-up for fragmented compound heterogeneous vegetation model

CHAPTER 4

INVESTIGATIONS ON SUBMERGED VEGETATION MODELS

4.1 GENERAL

The experiments are conducted on submerged vegetation models namely, submerged seagrass meadow and submerged rigid vegetation meadow for varying meadow widths. The effect of various sea state parameters on vegetation characteristics like the relative plant height (h_s/d), the meadow width parameter (w/L) and plant density (N) on wave attenuation, and the subsequent run-up characteristics corresponding to the submerged vegetation models is analyzed. After the completion of experiments, the results obtained are analyzed to know the efficacy of the different submerged vegetation models in attenuating waves and run-up. In this chapter, the variation of measured wave height at locations within the submerged vegetation models with respect to the percentage meadow width and the variation of wave run up over the beach slope with respect to wave steepness parameter is being discussed in detail.

It is seen that the wave height decreases exponentially as it propagates through the vegetation models. Vegetation causes wave attenuation because it acts as an obstacle for the wave propagation. This dissipates a significant portion of the energy of the waves, thereby reducing the wave height. This leads to a decreased wave run-up, represented by the relative run up (R_u/H_i).

4.2 STUDIES ON SUBMERGED SEAGRASS MEADOW

A 1:30 scaled submerged seagrass model is placed on the horizontal part of the flume bed at 30 m away from the wave flap. The model is subjected to monochromatic waves of height varying from 0.08 m to 0.16 m at an interval of 0.02 m. Results of experiments conducted with submerged seagrass of varying meadow widths are presented in this section.

4.2.1 Wave height attenuation

The width of the seagrass meadow plays a major role in attenuating the wave heights passing through the meadow. Experiments are therefore conducted with varying meadow widths to observe this effect. During the test runs, it is observed that the leaves of the seagrass tend to sway back and forth as the wave passes through the width of the meadow as shown in Plate 4.1. Interestingly, the seagrass meadow does contribute significantly to the reduction in wave heights as the wave passes through the meadow. This is because vegetation is capable of penetrating the layers of varying particle orbital velocities, which further causes an alteration in the wave orbital velocities, which subsequently results in an increased turbulence and loss of energy. The wave height decreases exponentially as it propagates through the meadow.

(a)

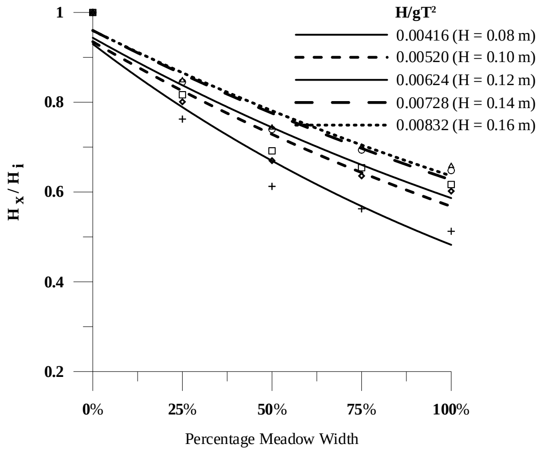
(b)

Plate 4.1 Snapshots of wave propagation along the seagrass meadow a) side view b) top view

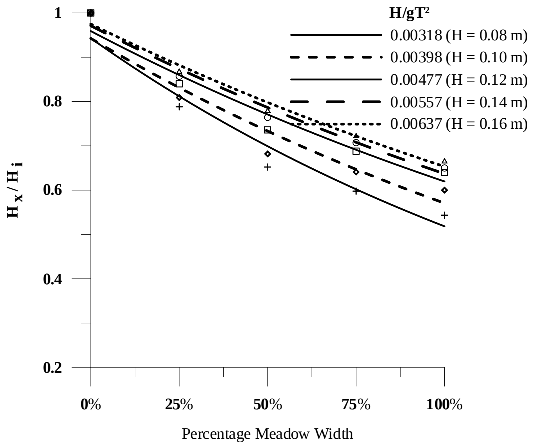
4.2.1.1 For relative plant height, $h_s/d = 0.525$; meadow width = 1 m.

In this section, results are presented for the case of wave attenuation through a submerged seagrass meadow of width 1 m and relative plant height, $h_s/d = 0.525$. Fig. 4.1 exhibits the influence of submerged seagrass meadow on waves of varying heights, ranging from 0.08 m to 0.16 m, propagating over it, while wave periods vary from 1.4 s to 2 s.

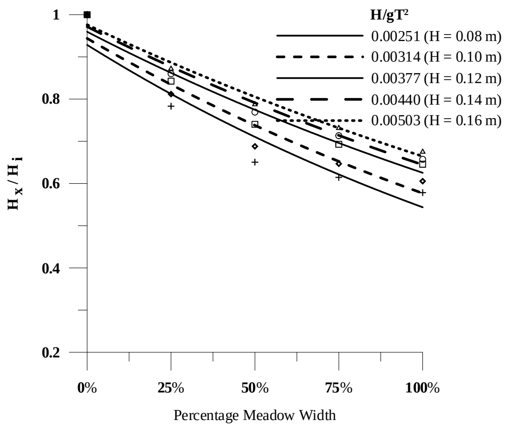
For a given wave period, say T = 1.4 s (refer Fig. 4.1 a), the wave transmission, represented by the relative wave height within the meadow (H_x/H_i) decreases as the waves travel along the meadow. The wave transmission is smallest for the smaller wave heights (say, 0.08 m) and increases with increasing wave heights. This means that the percentage wave height attenuation i.e, $\left(1-\frac{Hx}{Hi}\right)x100$, is largest for the smallest wave and vice versa. to the propagating waves (Zhao and Chen, 2013).



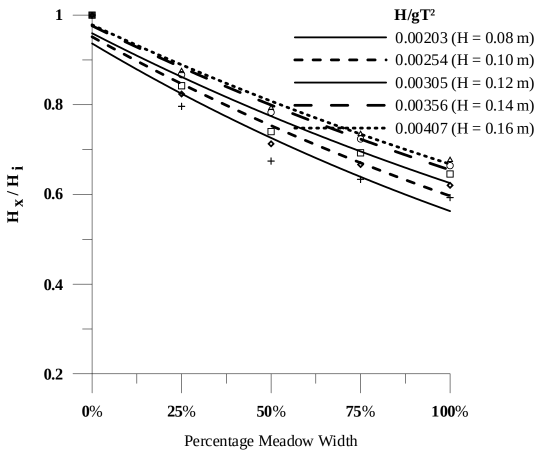
(a) for w/L = 0.418, T = 1.4 s



(b) for w/L = 0.357, T = 1.6 s



(c) for w/L = 0.305, T = 1.8 s



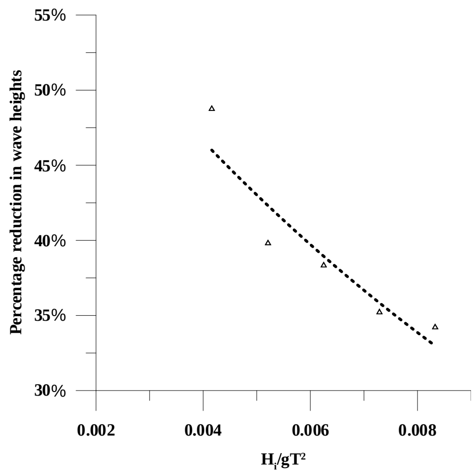
(d) for w/L = 0.270, T = 2 s.

Fig. 4.1 Relative wave heights at locations within the model for $h_s/d = 0.525$; w = 1 m

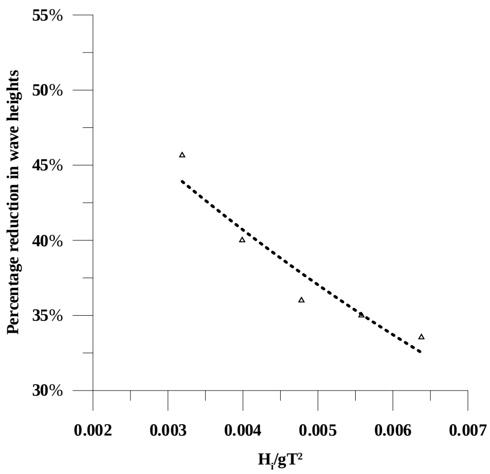
The submerged seagrass is effective in restraining the smaller wave heights effectively than the larger wave heights as the smaller waves have relatively smaller energy and the seagrass leaves can provide increased resistance for the smaller waves, causing increased attenuation. Steeper waves with higher energy can set the seagrass leaves to swaying and bending motion, so that it develops into a flat bed, offering very little resistance to the propagating waves. Further, the bent seagrass leaves reduce the vegetation-induced resistance

Similar behavior is exhibited for other wave periods of 1.6 s to 2 s as illustrated in Fig. 4.1-b to d. Fig. 4.1 (a) displays the relative percentage wave height at the exit point, $\left(\frac{H_{exit}}{H_i}\right)$ of the meadow which varies from 51.25% to 59.30% for an incident wave of height 0.08 m, corresponding to a range of wave periods from 1.4 s to 2 s. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 60.19% to 62.04%, from 61.67% to 64.57%, from 64.79% to 66.43% and from 64.79% to 67.68%, respectively, as illustrated in Fig. 4.1 (b to d).

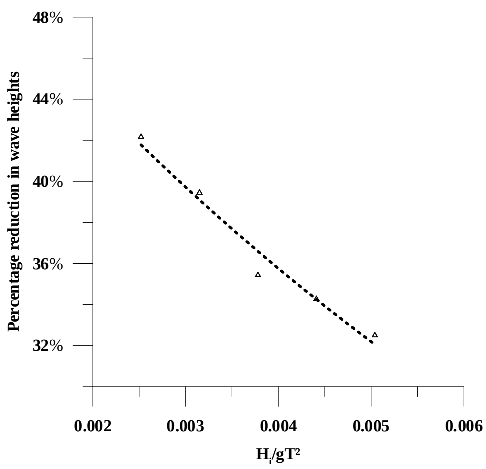
Interestingly, it is observed that as the wave steepness, H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 48.75% to 34.21%, which reveals that the wave height attenuation for steeper waves is less and that the smallest wave heights accounts for the maximum wave height reduction. This may be attributed to the fact that since they have less energy, the seagrass leaves are capable of more efficient wave reduction. Similarly, the percentage wave reduction varies from 45.65% to 33.54%, 42.17% to 32.50% and from 40.70% to 32.32% for increasing wave steepness, 0.00318 to 0.00637, 0.00251 to 0.00503 and 0.00203 to 0.00407, respectively, as indicated in Fig. 4.2. It is also seen that as the wave period increases, wave transmission too increases while wave height attenuation reduces. This clearly shows that the effectiveness of seagrass in containing wave heights reduces as wave period increases (Bradley and Houser, 2009; Suzuki et al., 2011).



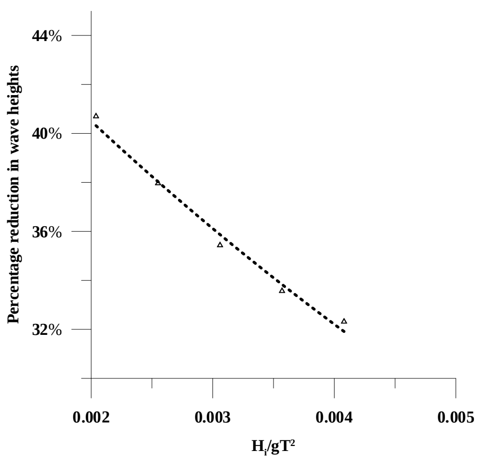
(a) for w/L = 0.418, T = 1.4 s



(b) for w/L = 0.357, T = 1.6 s



(c) for w/L = 0.305, T = 1.8 s

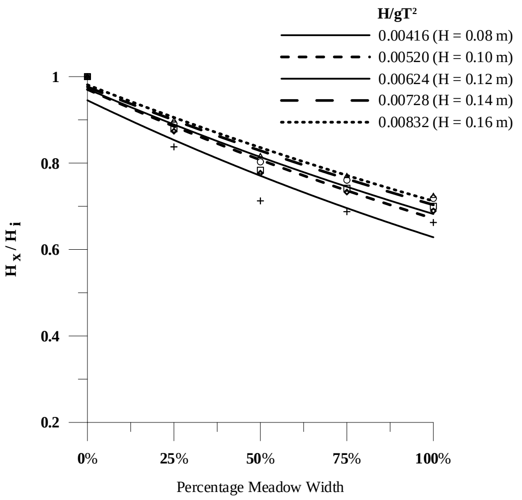


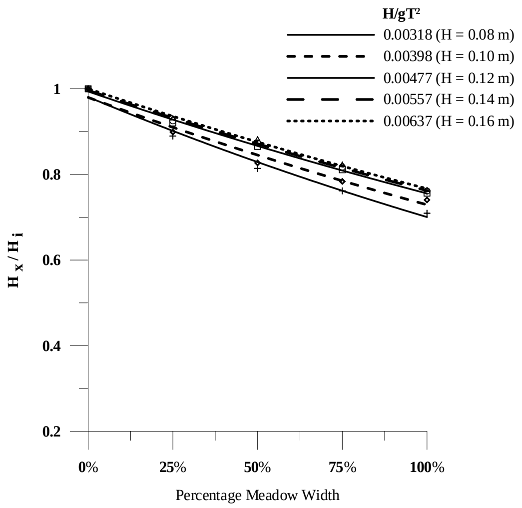
(d) for w/L = 0.270, T = 2 s

Fig. 4.2 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.525; w = 1 m

4.2.1.2 For relative plant height, $h_s/d = 0.47$; meadow width = 1 m.

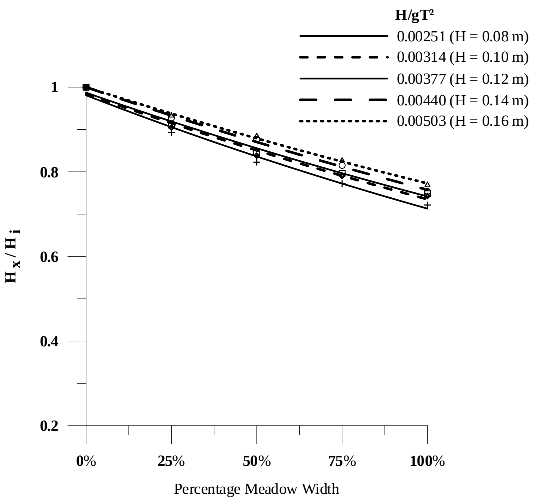
The variation of wave heights at different locations within the simulated seagrass meadow with relative plant height, $h_s/d = 0.47$ when subjected to waves of heights ranging from 0.08 m to 0.16, and periods from 1.4 s to 2 s is shown in Fig. 4.3 (a to d). The relative percentage wave height at the exit point, $\left(\frac{H_{exit}}{H_i}\right)$ of the meadow varies from 66.25% to 72.84%, from 68.93% to 74.29%, from 70.00% to 75.61%, from 71.83% to 76.26% and from 72.37% to 78.21% for incident waves of heights 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, corresponding to a range of wave periods from 1.4 s to 2 s.

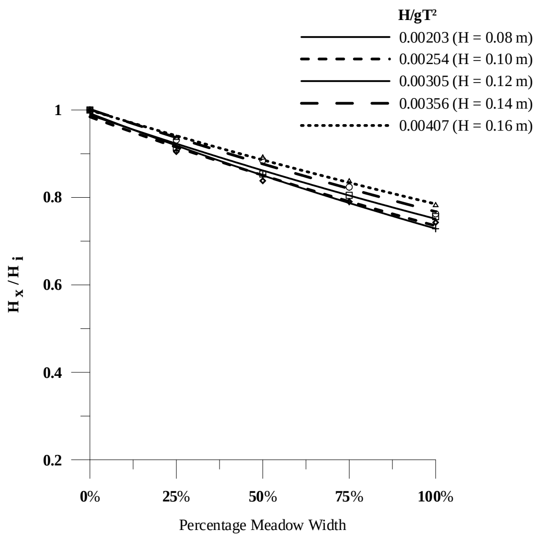




(a) for w/L = 0.401, T = 1.4 s

(b) for w/L = 0.348, T = 1.6 s



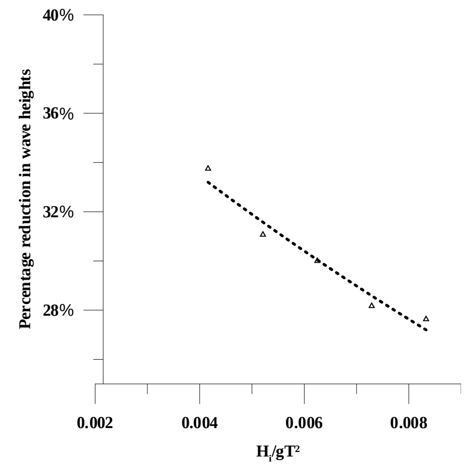


(c) for w/L = 0.291, T = 1.8 s

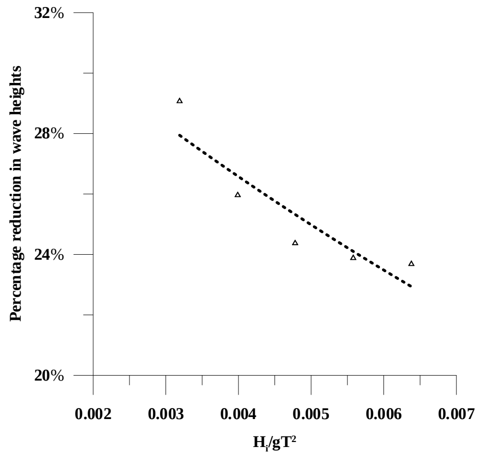
(d) for w/L = 0.257, T = 2 s.

Fig. 4.3 Relative wave heights at locations within the model for h_s/d = 0.47; w = 1 m

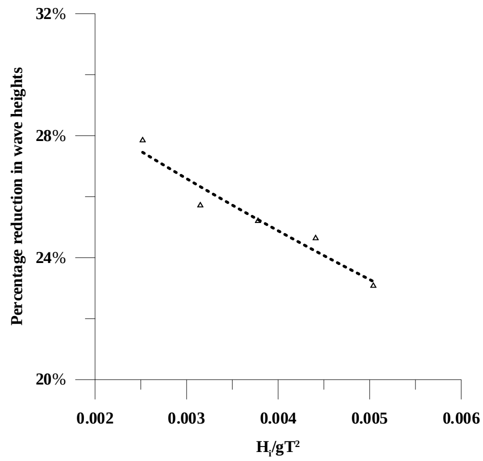
It is observed that for the above case, for w/L = 0.401, T = 1.4 s, as H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 33.75% to 27.63%. A similar trend of decrease in wave height reduction from 29.07% to 23.68%, 27.85% to 23.08% and 27.16% to 21.79% is observed for the cases corresponding to w/L = 0.348, T = 1.6 s; w/L = 0.291, T = 1.8 s and w/L = 0.257, T = 2 s, respectively (refer Fig. 4.4 (a to d)).



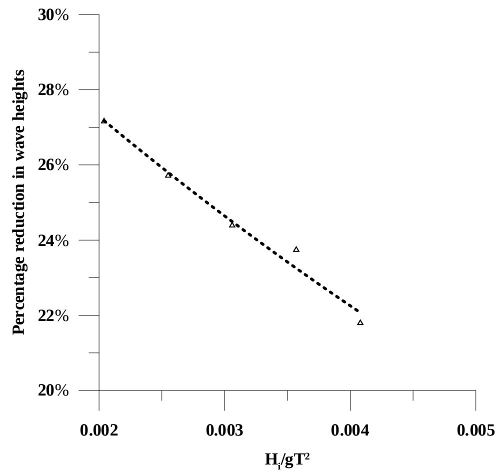
(a) for w/L = 0.401, T = 1.4 s



(b) for w/L = 0.348, T = 1.6 s



(c) for w/L = 0.291, T = 1.8 s



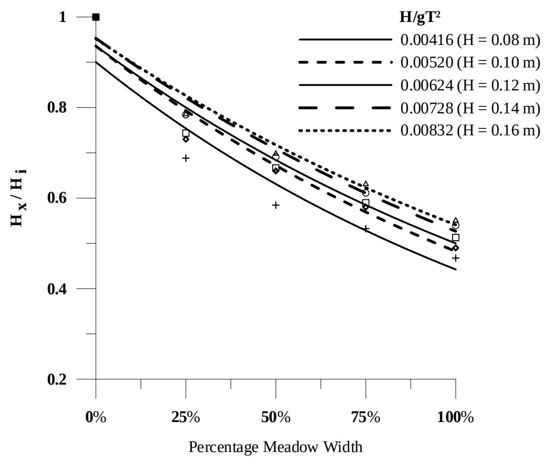
(d) for w/L = 0.257, T = 2 s

Fig. 4.4 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.47; w = 1 m

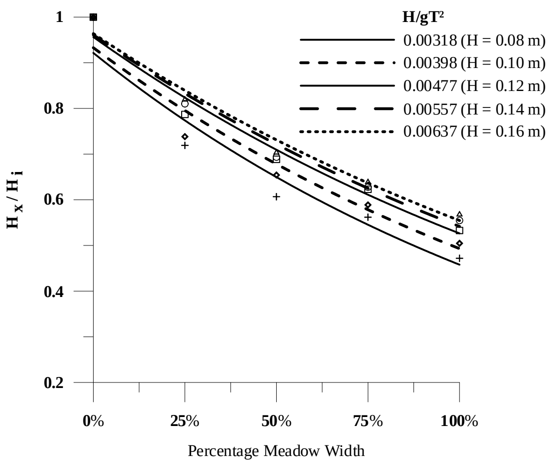
4.2.1.3 For relative plant height, h_s/d = 0.525; meadow width = 2 m.

Fig. 4.5 (a-d) illustrates the measured wave heights at locations within the 2 m wide artificial seagrass meadow with relative plant height, h_s/d = 0.525 corresponding to different wave periods, T = 1.4 s to 2 s. Fig. 4.5 (a) indicates that the relative percentage wave height at the exit point of the meadow is varies from 46.75% to 48.19% for an incident wave of height 0.08 m. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 49.00% to 51.43%, from 51.28% to 54.03%, from 53.96% to 56.43% and from 55.03% to 58.39%, respectively, as illustrated in Fig. 4.5 (b to d).

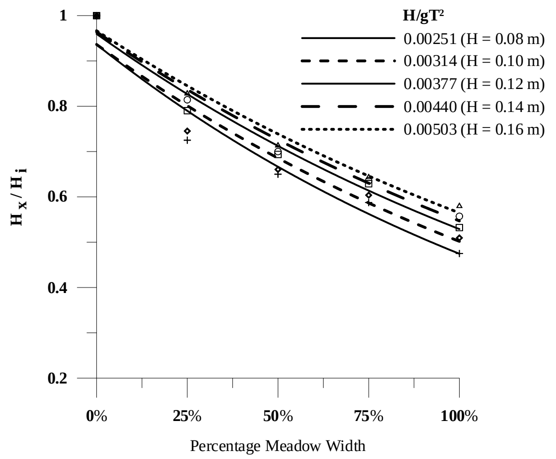
Variations in percentage reduction in wave heights from 53.25% to 44.97%, 52.81% to 43.23%, 52.50% to 42.04% and from 51.81% to 41.61% is observed for this model with T = 1.4 s, w/L = 0.836 and H_i/gT^2 = 0.00416 to 0.00832, w/L = 0.714, T = 1.6 s, H_i/gT^2 from 0.00318 to 0.00637; w/L = 0.612, T = 1.8 s, H_i/gT^2 from 0.00251 to 0.00503 and w/L = 0.541, T = 2 s, H_i/gT^2 from 0.00203 to 0.00407, respectively (Figs. 4.6 b to d).



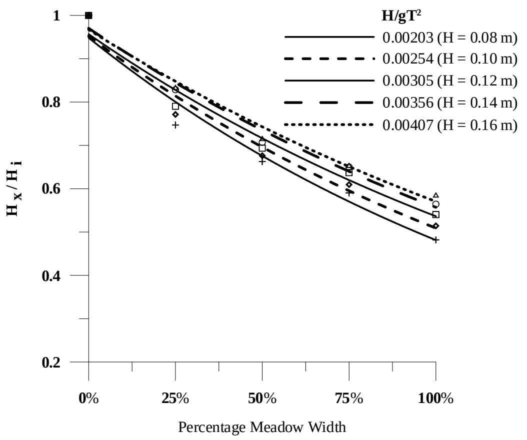
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



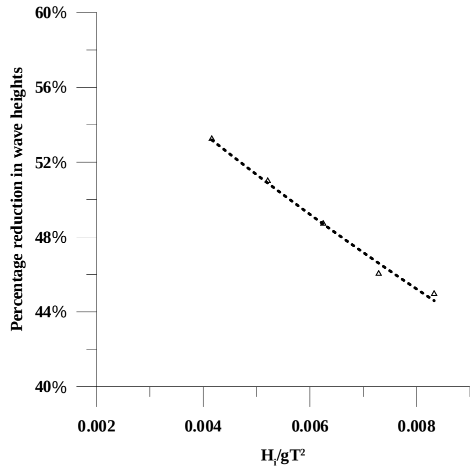
(c) for w/L = 0.612, T = 1.8 s



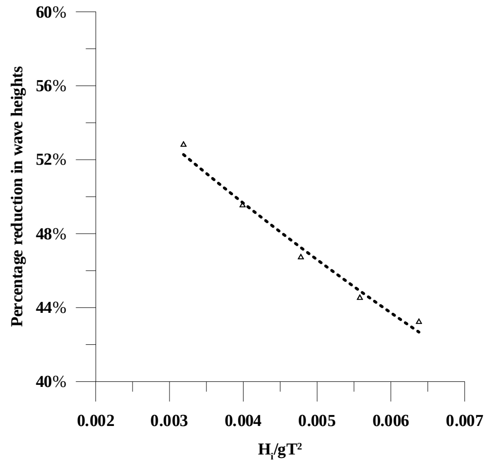
(d) for w/L = 0.541, T = 2 s

Fig. 4.5 Relative wave heights at locations within the model for h_s/d = 0.525; w = 2 m

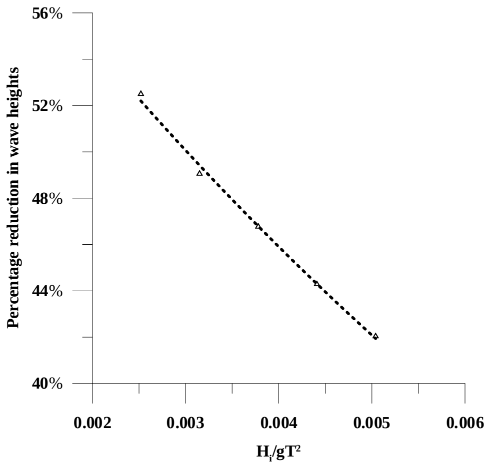
A comparison between the percentage wave height reduction of the submerged seagrass model of width 1 m (discussed in section 4.2.1.1) and of width 2 m, discussed here, strongly suggests that the width of the meadow and the meadow width parameter (w/L) plays a significant role in wave height attenuation. For a given relative plant height, h_s/d = 0.525 and wave period, T = 1.4 s, as w/L increases from 0.418 to 0.836, there is an observed increase in percentage wave height reduction ranging from 48.75% - 34.21% to 53.25% - 44.97% when the meadow width increases from 1m to 2m for the submerged seagrass model.



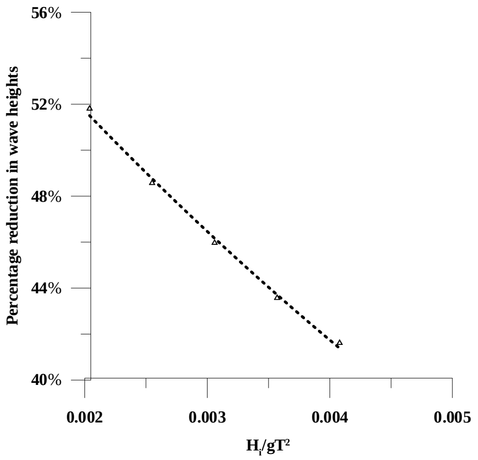
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s



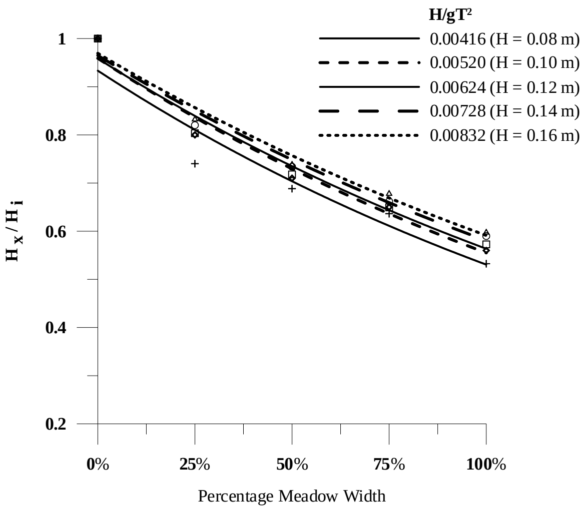
(d) for w/L = 0.541, T = 2 s

Fig. 4.6 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.525; w = 2 m

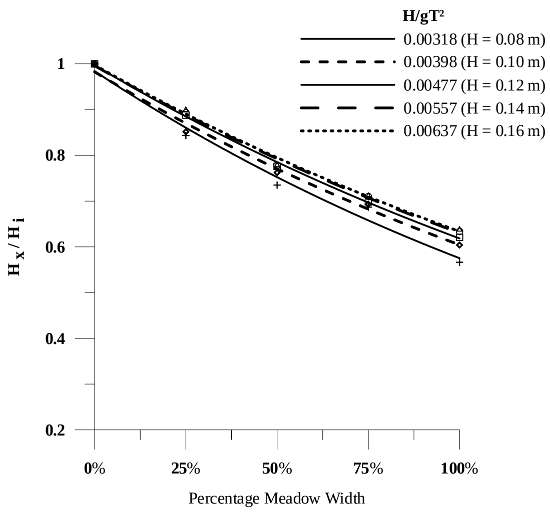
4.2.1.4 For relative plant height, h_s/d = 0.47; meadow width = 2 m.

The relative wave heights at locations within the 2 m wide seagrass meadow with relative plant height, h_s/d = 0.47 corresponding to different wave periods and meadow width parameters is depicted in Fig. 4.7 (a to d). As the relative plant height decreases from 1.25 to 1.11, the relative percentage wave height at the exit point of the meadow,

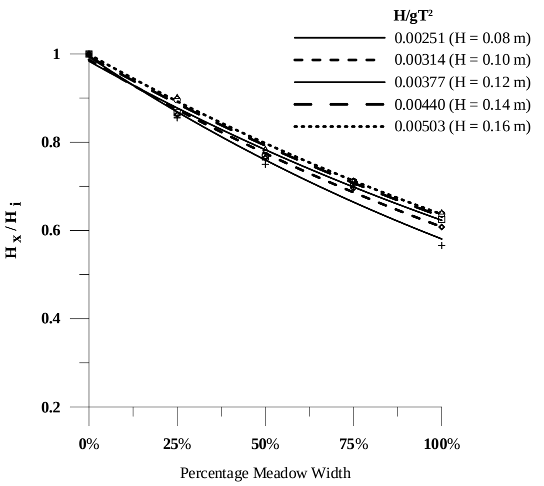
$\left(\frac{H_{exit}}{H_i}\right)$ varies from 53.25% to 57.69% for an incident wave of height 0.08 m, corresponding to a range of wave periods from 1.4 s to 2 s. Further variations of the relative percentage wave heights at exit of the meadow is observed to be from 56.00% to 60.78%, from 57.26% to 62.50%, from 58.99% to 63.97% and from 59.73% to 64.71% for incident wave heights of 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as depicted in Fig. 4.7 (a to d).



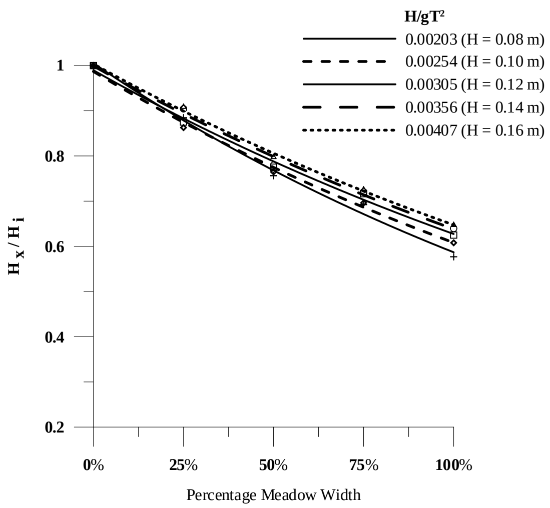
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



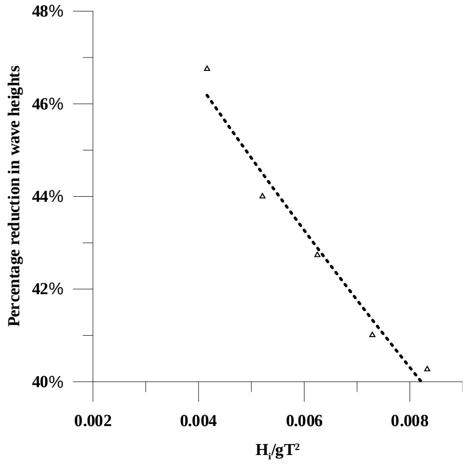
(c) for w/L = 0.583, T = 1.8 s



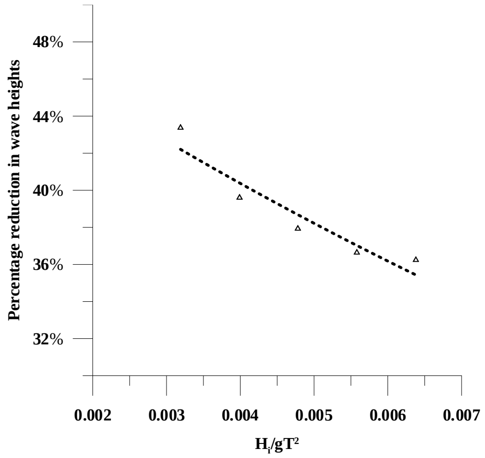
(d) for w/L = 0.515, T = 2 s

Fig. 4.7 Relative wave heights at locations within the model for h_s/d = 0.47; w = 2 m

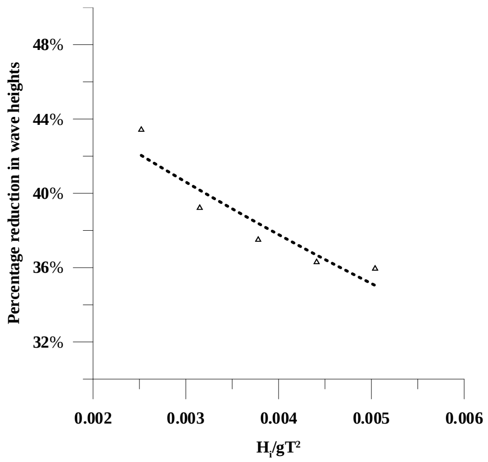
Fig. 4.8 (a to d) displays the variation of percentage wave height reduction from 46.75% to 40.27%, 43.37% to 36.24%, 43.42% to 35.95% and 42.31% to 35.29% for w/L = 0.804, T = 1.4 s, H_i/gT^2 = 0.00416 to 0.00832; w/L = 0.696, T = 1.6 s, H_i/gT^2 = 0.00318 to 0.00637; w/L = 0.583, T = 1.8 s, H_i/gT^2 = 0.00251 to 0.00503; and w/L = 0.515, T = 2 s, H_i/gT^2 = 0.00203 to 0.00407, respectively. The above results also conform to the fact that the percentage wave height reduction increases as the meadow width parameter increases from 0.401 to 0.804 for the same relative plant height (h_s/d = 0.47), corresponding to wave period, T = 1.4 s. Similar observations are recorded for the complete set of wave periods and incident wave heights.



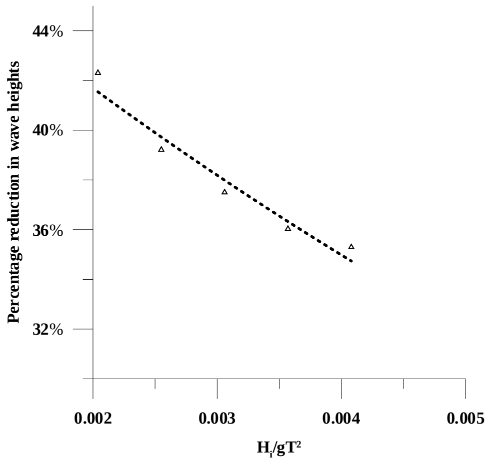
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s



(d) for w/L = 0.515, T = 2 s

Fig. 4.8 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.47; w = 2 m

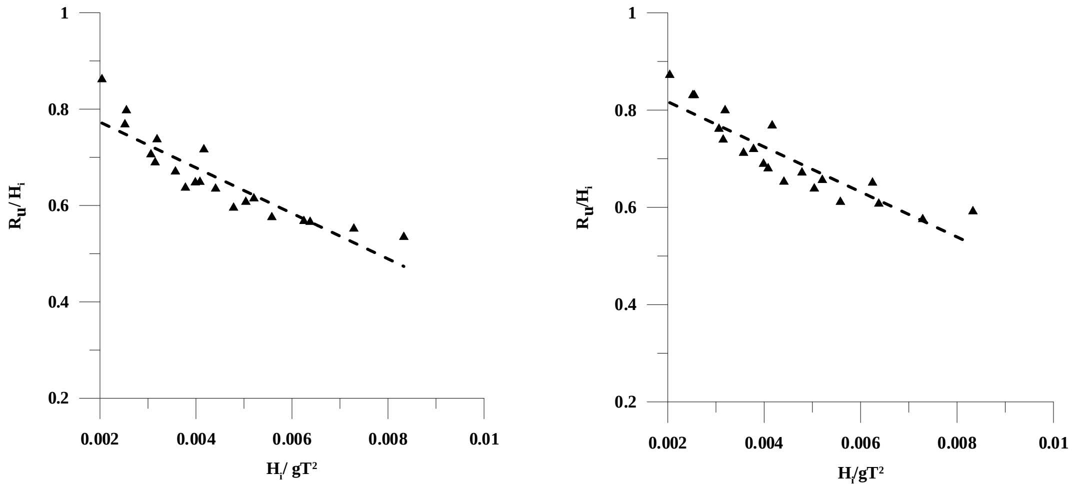
4.2.2 Effect of wave steepness on wave run-up

Measurements of wave run-up on the beach due to the submerged seagrass meadow reveals the extent of run-up on the beach slope. It is observed that the relative wave run-up (R_u/H_i) decreases with an increase in wave steepness parameter (H_i/gT^2).

Fig. 4.9 (a-b) gives a representative illustration of the variation of wave run up over the beach slope with an increase in wave steepness for the submerged seagrass model of width 2 m, corresponding to relative plant heights, h_s/d = 0.525, 0.47 and wave periods, T = 1.4 s to 2 s.

For the case of the submerged seagrass model of width 2 m (h_s/d = 0.525) subjected to waves of incident wave heights ranging from 0.08 m to 0.16 m and periods, T = 1.4 s to 2 s, as the wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00503, R_u/H_i decreases from 0.862 to 0.535, as is evident from Fig. 4.9 (a). Similarly, for the same model of relative plant height, h_s/d = 0.47, as the wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00503, R_u/H_i decreases from 0.872 to 0.575, as depicted in Fig. 4.9 (b).

These results can correspondingly be associated with the percentage reduction in wave heights for the submerged seagrass model of width 2 m, discussed in sections 4.2.1.3 and 4.2.1.4. The percentage reduction in wave heights varies from 53.25% to 41.61% for h_s/d = 0.525; whereas it varies from 46.75% to 35.29% for h_s/d = 0.47, corresponding to wave periods, T = 1.4 s to 2 s. It is therefore worth noting that as the percentage reduction in wave heights increases, there is a decreased extent of run-up on the beach slope. It is seen that for h_s/d = 0.525, the percentage reduction in wave heights varies from 53.25% to 41.61%, with R_u/H_i ranging from 0.862 to 0.535; and for h_s/d = 0.47, the percentage reduction in wave heights varies from 46.75% to 35.29%, with R_u/H_i ranging from 0.872 to 0.575.



(a) for $h_s/d = 0.525$ (b) for $h_s/d = 0.47$

Fig. 4.9 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d)

4.3 STUDIES ON SUBMERGED RIGID VEGETATION

A 1:30 scale submerged rigid vegetation model, placed on the horizontal part of the flume bed at 30 m away from the wave flap, is subjected to monochromatic waves of height varying from 0.08 m to 0.16 m at an interval of 0.02 m. Results of experiments regarding wave height attenuation and beach run-up for varying meadow widths is presented in this section.

4.3.1 Wave height attenuation

Results of variation in relative wave heights at locations within the rigid submerged vegetation model with respect to the relative plant height, meadow width and varying periods is presented in this section. The vegetation considered here is a submerged stem which may vibrate under the influence of propagating waves, but this is very much less compared to the swaying motion of the seagrass leaves or kelp fronds. During the course of the test runs, it was seen that the vegetation stems do not move with wave action, owing to the stiffness of the stem which controls the vegetation motion. This might be the reason for the increased reduction in wave heights along the vegetated meadow when compared to that along the seagrass meadow. The snapshots of wave propagation along the rigid submerged vegetation model is displayed in Plate 4.2.

(a) (b)

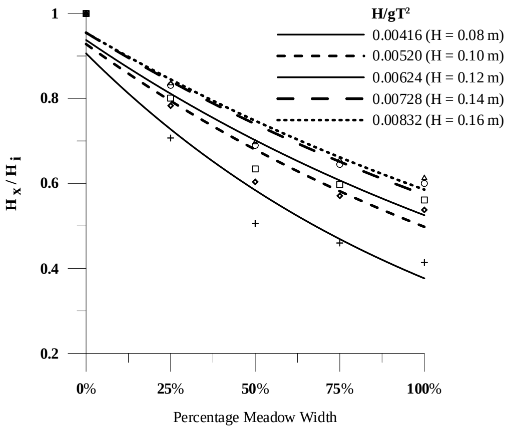
Plate 4.2 Snapshots of wave propagation along the submerged rigid vegetation a) side view b) top view

4.3.1.1 For relative plant height, h_s/d = 0.525; meadow width = 1 m.

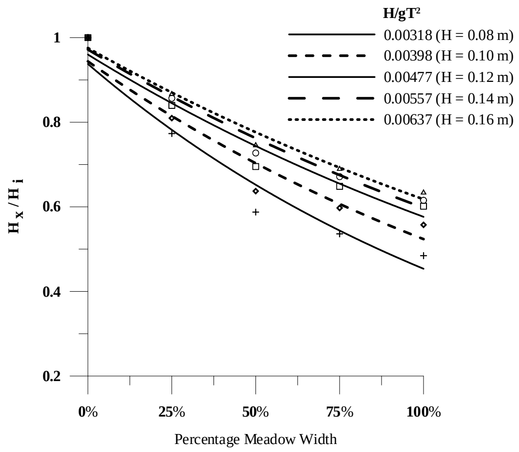
Results are presented for the case of wave attenuation through a submerged rigid vegetation model of width 1 m and relative plant height, h_s/d = 0.525. The effect of the submerged rigid vegetation on waves of varying parameters, with incident wave heights ranging from 0.08 m to 0.16 m, and wave periods from 1.4 s to 2 s is clearly brought out.

As in the case of the submerged seagrass, the submerged rigid vegetation is also capable of providing resistance to smaller wave heights effectively than for the larger wave heights, since the smaller waves have relatively smaller energy for which the submerged stems can provide increased resistance. The relative percentage wave height at the exit point of the model varies from 41.38% to 52.75%, from 53.77% to 57.66%, from 56.10% to 60.77%, from 60.00% to 63.01% and from 61.29% to 64.67% corresponding to incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as illustrated in Fig. 4.10 (a to d)

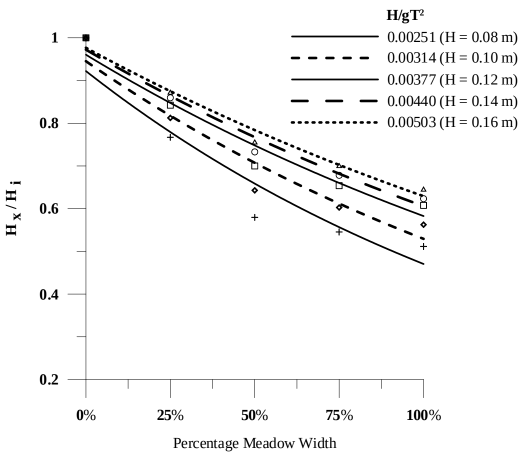
The results shown in Fig. 4.11 (a to d) indicate that as the wave steepness, H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 58.62% to 38.71% for the submerged rigid vegetation model. This reveals that the wave height attenuation for steeper waves is less and that the smallest wave heights accounts for the maximum wave height reduction. Similarly, the percentage wave reduction varies from 51.55% to 36.65%, 48.86% to 35.58% and from 47.25% to 35.33% for increasing wave steepness, 0.00318 to 0.00637, 0.00251 to 0.00503 and 0.00203 to 0.00407 respectively. It is also evident from the above results that the capability of the submerged vegetation in attenuating waves decreases as the wave period increases.



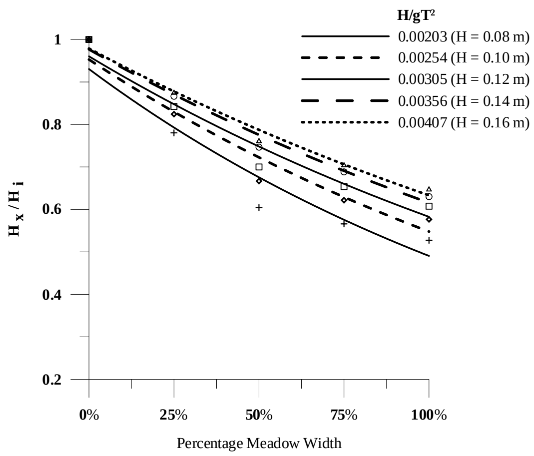
(a) for w/L = 0.418, T = 1.4 s



(b) for w/L = 0.357, T = 1.6 s

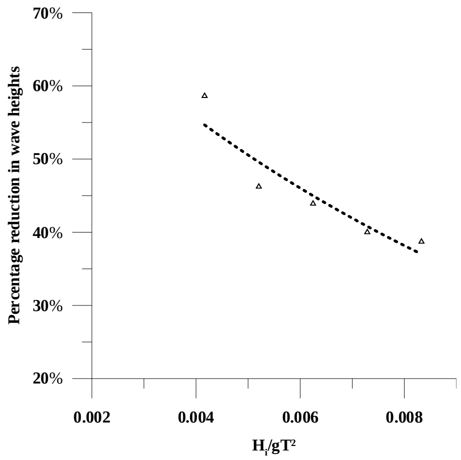


(c) for w/L = 0.305, T = 1.8 s

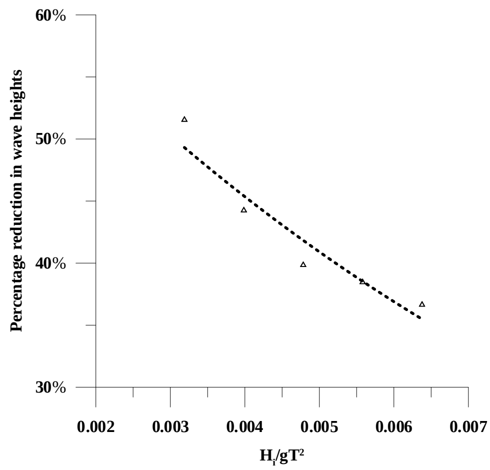


(d) for w/L = 0.270, T = 2 s

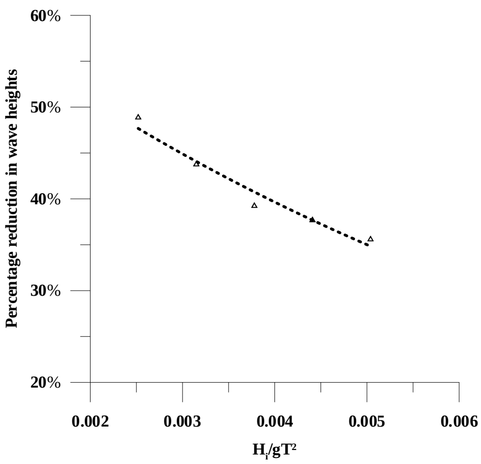
Fig. 4.10 Relative wave heights at locations within the model for h_s/d = 0.525; w = 1 m



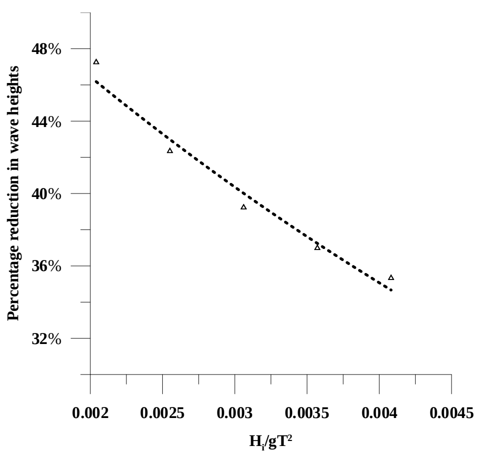
(a) for w/L = 0.418, T = 1.4 s



(b) for w/L = 0.357, T = 1.6 s



(c) for w/L = 0.305, T = 1.8 s



(d) for w/L = 0.270, T = 2 s

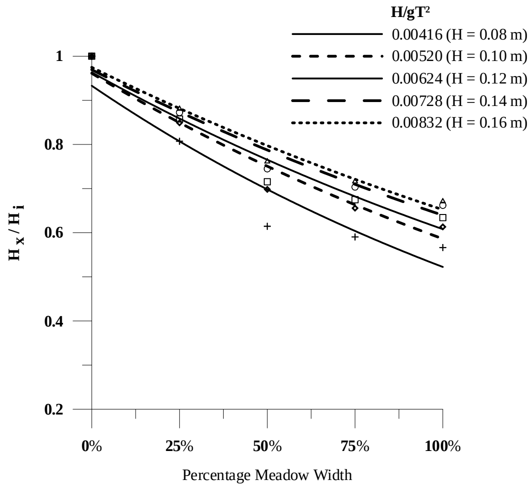
Fig. 4.11 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.525; w = 1 m

4.3.1.2 For relative plant height, h_s/d = 0.47; meadow width = 1 m.

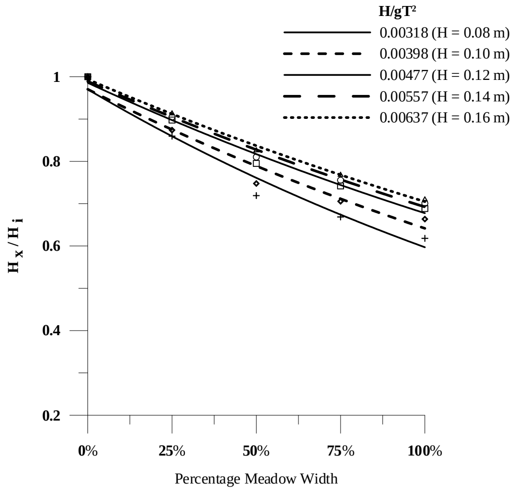
Fig. 4.12 (a to d) illustrates the variation of relative wave heights at locations within the submerged rigid vegetation model of 1 m meadow width and relative plant height, h_s/d = 0.47, when subjected to waves of heights and periods ranging from 0.08 m to 0.16, and from 1.4 s to 2 s, respectively.

For a given wave period, T = 1.4 s, the percentage wave height reduction corresponds to 43.37%, 38.68%, 36.59%, 33.79% and 32.90% for incident waves of heights 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m respectively (Fig. 4.13 a). For w/L = 0.401, T = 1.4

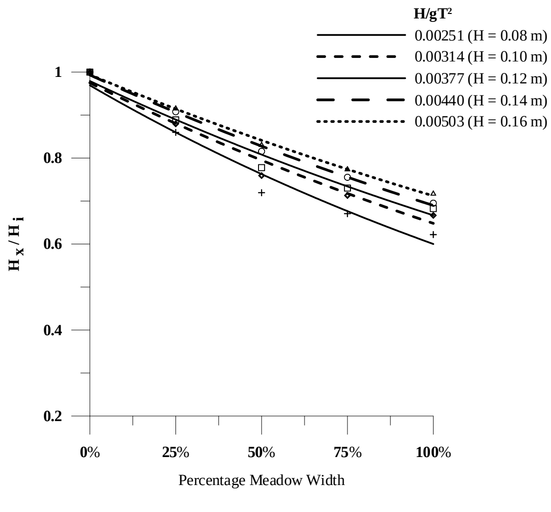
s, as H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 43.37% to 32.90%. Similarly, for the cases corresponding to w/L = 0.348, T = 1.6 s; w/L = 0.291, T = 1.8 s and w/L = 0.257, T = 2 s, the percentage reduction in wave heights ranges from 38.20% to 29.03%, 37.80% to 28.30% and from 36.90% to 27.04%, respectively (Fig. 4.13 b to d).



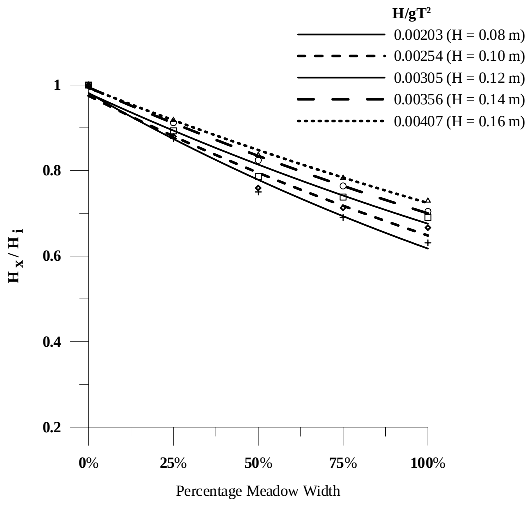
(a) for w/L = 0.401, T = 1.4 s



(b) for w/L = 0.348, T = 1.6 s

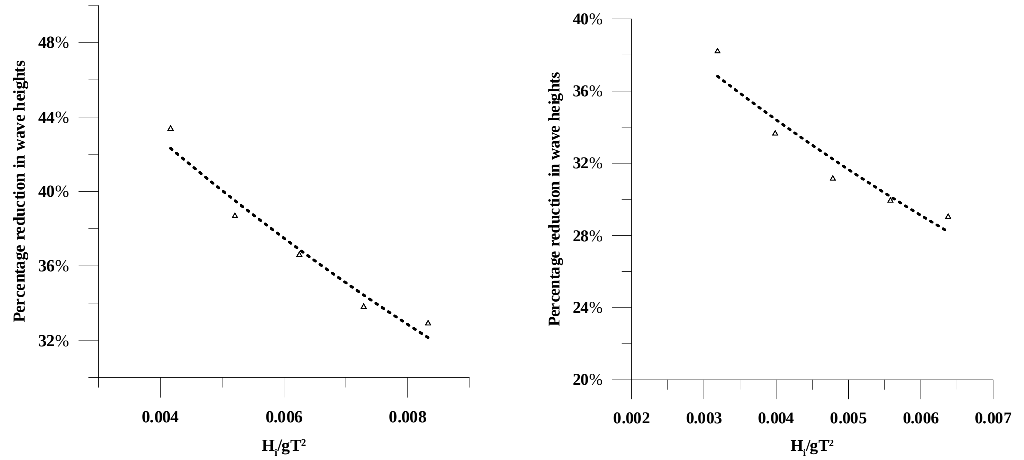


(c) for w/L = 0.291, T = 1.8 s

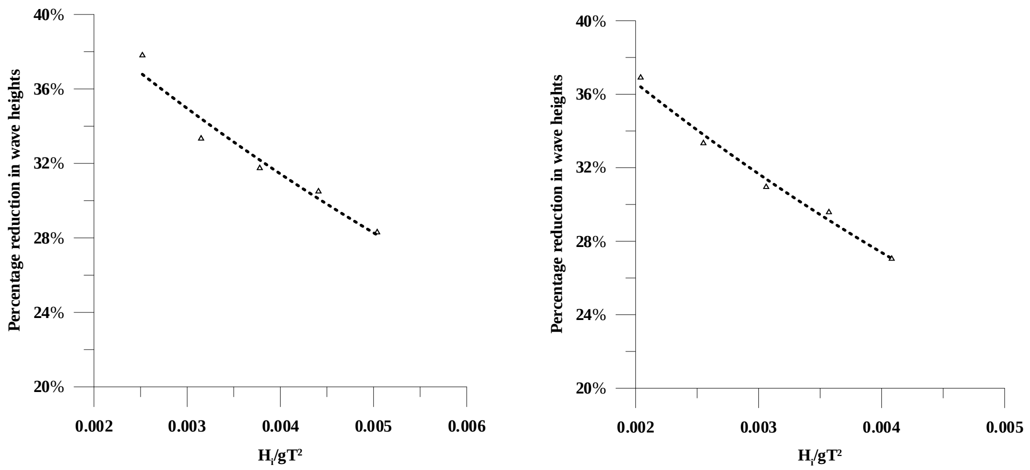


(d) for w/L = 0.257, T = 2 s

Fig. 4.12 Relative wave heights at locations within the model for h_s/d = 0.47; w = 1 m



(a) for w/L = 0.401, T = 1.4 s (b) for w/L = 0.348, T = 1.6 s

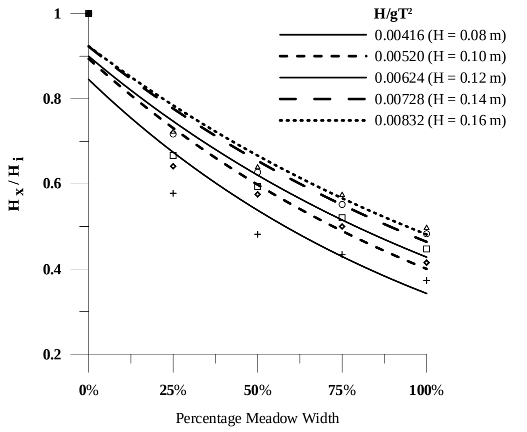


(c) for w/L = 0.291, T = 1.8 s (d) for w/L = 0.257, T = 2 s

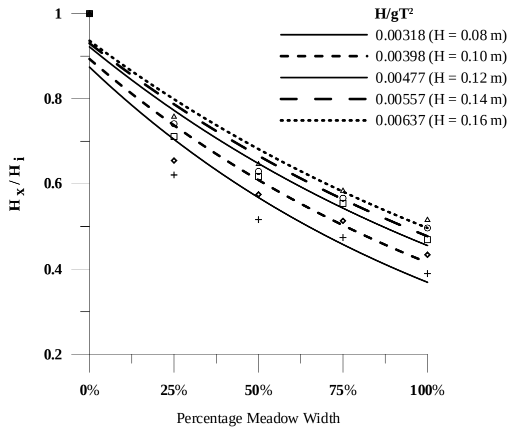
Fig. 4.13 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.47; w = 1 m

4.3.1.3 For relative plant height, h_s/d = 0.525; meadow width = 2 m.

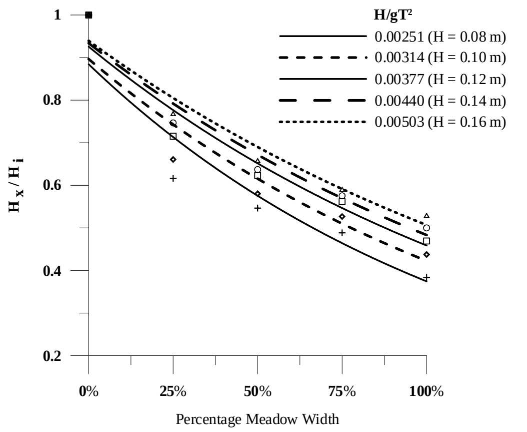
The influence of increase in meadow width parameter, w/L on wave attenuation for the submerged seagrass model is discussed in section 4.2.1.3. This section presents the results of wave attenuation due to a submerged rigid vegetation model of width 2 m (w/L ranging from 0.836 to 0.541), corresponding to a relative plant height, h_s/d = 0.525. Fig. 4.14 (a to d) depicts the relative wave heights at different locations along the rigid submerged model of width 2 m, for a relative plant height, h_s/d = 0.525 subjected to waves of varying heights and periods.



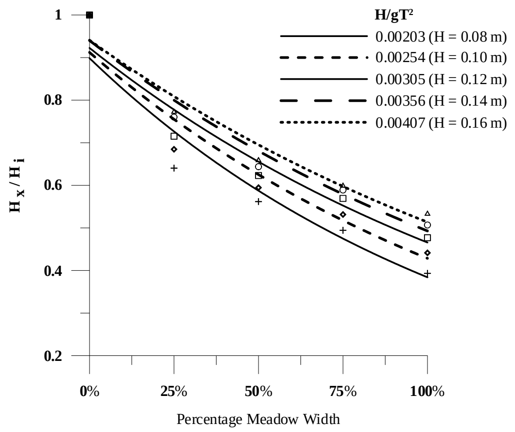
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



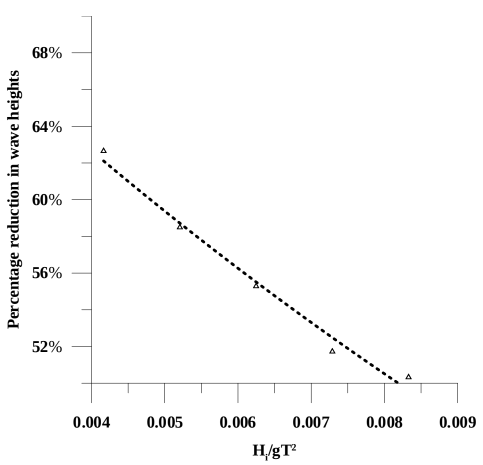
(c) for w/L = 0.612, T = 1.8 s

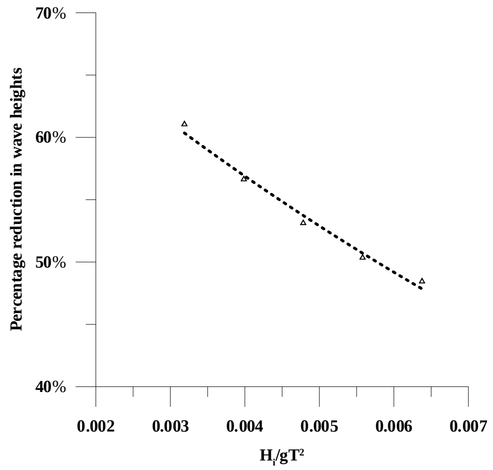


(d) for w/L = 0.541, T = 2 s

Fig. 4.14 Relative wave heights at locations within the model for h_s/d = 0.525; w = 2 m

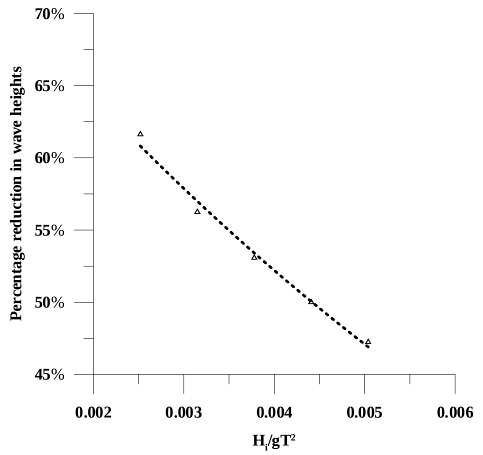
The percentage reduction in wave heights is observed to be 62.65% for an incident wave of height 0.08 m. Further, the percentage reduction in wave heights for incident waves of heights 0.10 m, 0.12 m, 0.14 m and 0.16 m corresponds to 58.49%, 55.28%, 51.72% and 50.32% respectively for T = 1.4 s, w/L = 0.836 and H_i/gT^2 = 0.00416 to 0.00832 (Fig. 4.15 a). Similarly, the percentage wave height reduction varies from 61.05% to 48.45%, 61.63% to 47.24% and 60.67% to 46.71% for w/L = 0.714, T = 1.6 s, H_i/gT^2 = 0.00318 to 0.00637; w/L = 0.612, T = 1.8 s, H_i/gT^2 = 0.00251 to 0.00503; and w/L = 0.541, T = 2 s, H_i/gT^2 = 0.00203 to 0.00407, respectively, as illustrated in Fig. 4.15 (b-d). A comparison of the percentage wave height reduction discussed in this section with that presented in section 4.3.1.1 highlights that meadow width parameter (w/L) plays a critical role in wave attenuation through vegetated meadows.

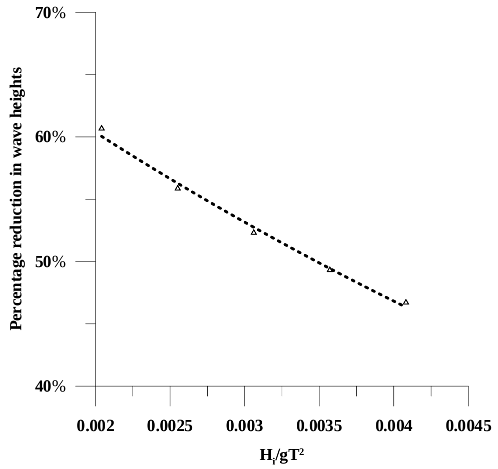




(a) for w/L = 0.836, T = 1.4 s

(b) for w/L = 0.714, T = 1.6 s





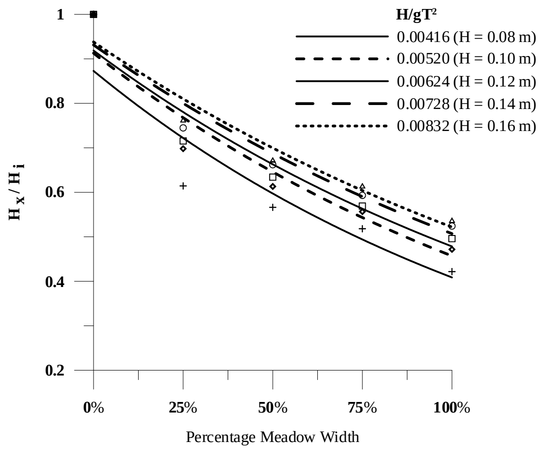
(c) for w/L = 0.612, T = 1.8 s

(d) for w/L = 0.541, T = 2 s

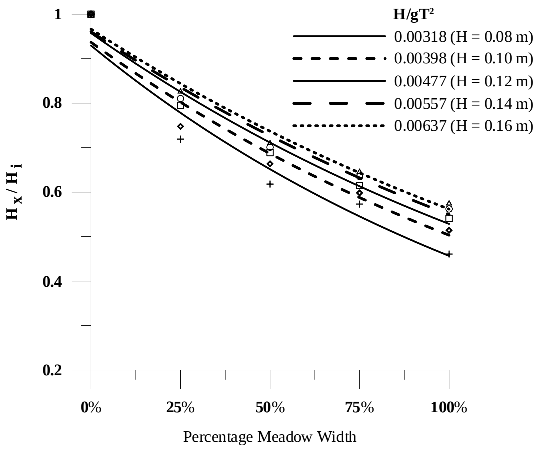
Fig. 4.15 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 0.525$; w = 2 m

4.3.1.4 For relative plant height, $h_s/d = 0.47$; meadow width = 2 m.

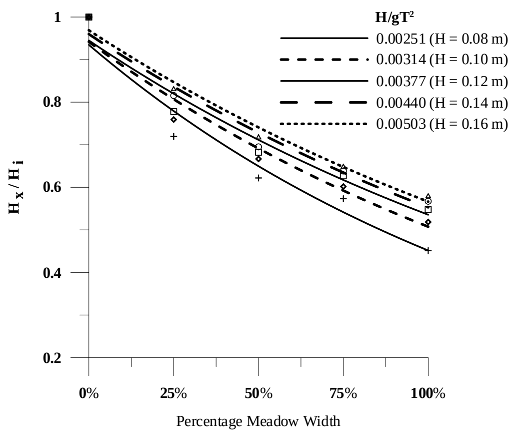
Fig. 4.16 (a-d) depicts the relative wave heights at different locations along the rigid submerged vegetation model of width 2 m, for a relative plant height, $h_s/d = 0.47$ subjected to waves of varying heights and periods.



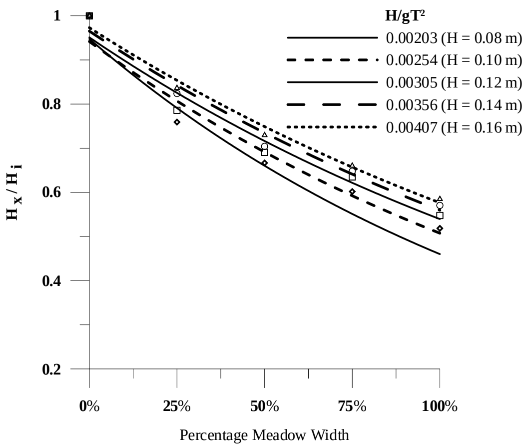
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



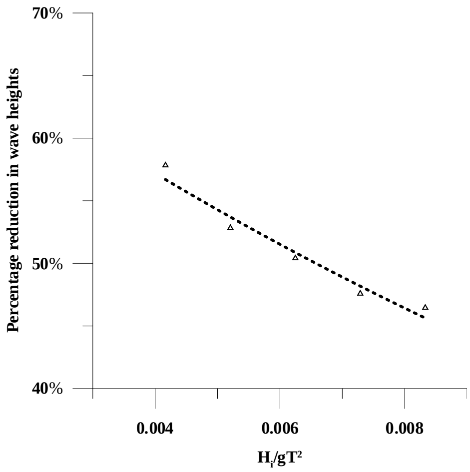
(c) for w/L = 0.583, T = 1.8 s



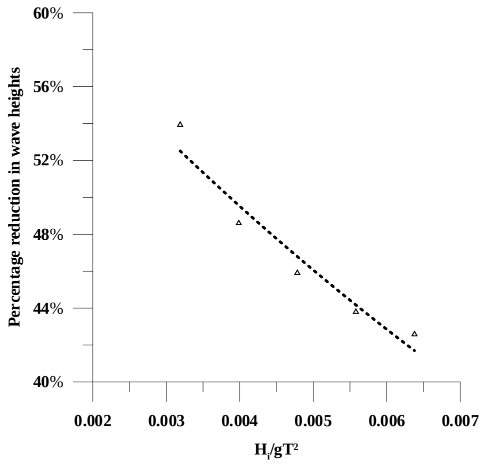
(d) for w/L = 0.515, T = 2 s

Fig. 4.16 Relative wave heights at locations within the model for $h_s/d = 0.47$; w = 2 m

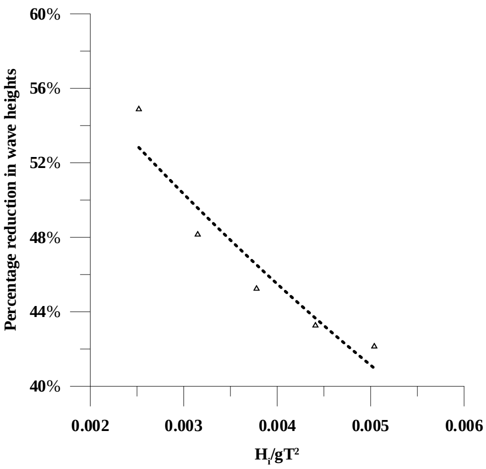
For w/L = 0.804, T = 1.4 s, as H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 57.83% to 46.45%, as seen in Fig. 4.17 a. A similar trend of decrease in wave height reduction from 53.93% to 42.58%, 54.88% to 42.14% and 53.57% to 41.51% is observed for the cases corresponding to w/L = 0.696, T = 1.6 s; w/L = 0.583, T = 1.8 s and w/L = 0.515, T = 2 s, respectively (Fig. 4.17 b to d). These results also support the fact that wave attenuation decreases as wave periods increase along a constant water depth.



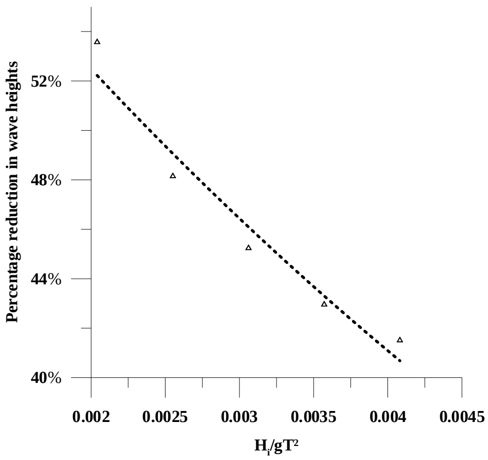
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s



(d) for w/L = 0.515, T = 2 s

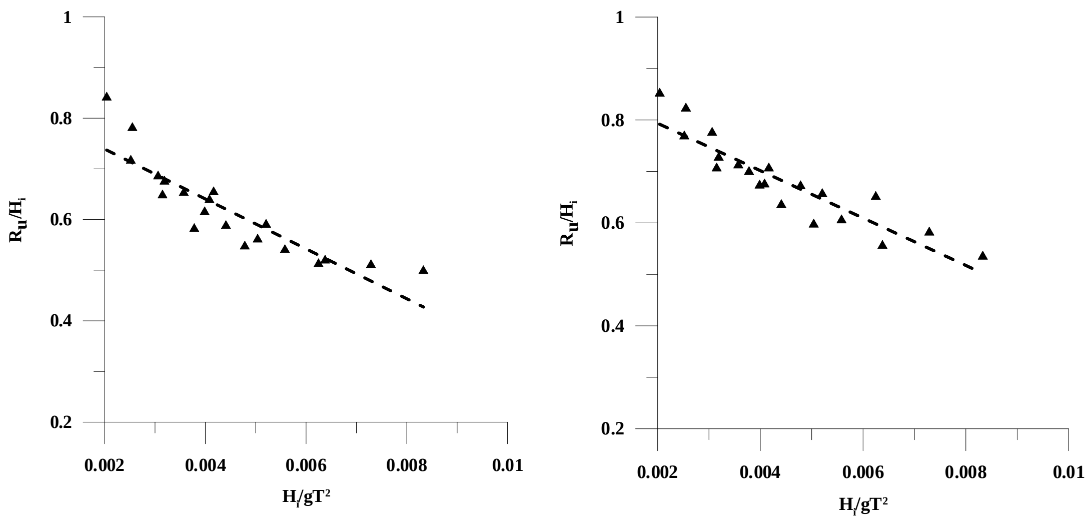
Fig. 4.17 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.47; w = 2 m

4.3.2 Effect of wave steepness on run-up

As discussed in section 4.2.3, the relative wave run-up (R_u/H_i) decreases with an increase in wave steepness parameter (H_i/gT^2). The variation of wave run up over the beach slope with an increase in wave steepness for the submerged rigid vegetation model of width 2 m, corresponding to relative plant heights, h_s/d = 0.525, 0.47 and wave periods, T = 1.4 s to 2 s is illustrated in Fig. 4.18 (a to b).

As the wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00503, R_u/H_i decreases from 0.841 to 0.498 for the case of submerged rigid vegetation model of width 2 m (h_s/d = 0.525) subjected to waves of incident wave heights ranging from 0.08

m to 0.16 m and periods, T = 1.4 s to 2 s (Fig. 4.18 a). Similarly, for the same model of relative plant height, $h_s/d = 0.47$, as the wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00503, R_u/H_i decreases from 0.851 to 0.535, as depicted in Fig. 4.18 (b). These results when compared with the percentage reduction in wave heights discussed in sections 4.3.1.3 and 4.3.1.4, strongly suggests that as the percentage reduction in wave heights increases, there is a decreased extent of run-up on the beach slope.



(a) for $h_s/d = 0.525$ (b) $h_s/d = 0.47$

Fig. 4.18 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d)

For $h_s/d = 0.525$, the percentage reduction in wave heights varies from 62.65% to 46.71%, with R_u/H_i ranging from 0.841 to 0.498; and for $h_s/d = 0.47$, the percentage reduction in wave heights varies from 57.83% to 41.51%, with R_u/H_i ranging from 0.851 to 0.535, for the submerged rigid vegetation meadow of width 2 m (w/L = 0.836 to 0.541; 0.804 to 0.515).

4.4 COMPARISON OF PERFORMANCE OF SUBMERGED VEGETATION MODELS

The results from the studies conducted on submerged vegetated models, namely, seagrass meadow and rigid vegetation model, presented in section 4.2 and 4.3 explains the fact that the incident wave characteristics as well as the vegetation parameters like material property, its geometry, relative plant height (h_s/d) and meadow width parameter (w/L) plays a key role in wave height attenuation and the corresponding extent of run-up on the beach.

It is observed that the wave heights decay exponentially as the wave propagates through the submerged vegetation models and the steeper waves, represented by a higher value of H_i/gT^2, exhibits lower wave attenuation for the simulated submerged models. As the relative plant height (h_s/d) increases from 0.47 to 0.525 (11.7%) or from 1.11 to 1.25 (12.6%), the submerged seagrass model of width 1 m and 2 m shows increased efficiency in wave height reduction varying from 33.75% to 21.79% and from 46.75% to 35.29%, respectively, for the higher relative plant height condition (h_s/d = 0.525). The same trend follows for the submerged rigid vegetation as well, with the percentage wave height reduction varying from 58.62% to 35.33%, for the model of width 1 m and from 62.65% to 46.71%, for the model of width 2 m.

Among the submerged vegetation models, the submerged rigid vegetation model of 2 m width shows maximum reduction in wave heights for both the cases with h_s/d = 0.525 and h_s/d = 0.47. The percentage wave height reduction for the submerged rigid vegetation of width 2 m for h_s/d = 0.525 ranges from 62.65% to 46.71%, for the entire set of incident wave characteristics, with the subsequent wave run-up on the beach (R_u/H_i) varying from 0.841 to 0.498, as wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00503. The same model with relative plant height, h_s/d = 0.47, exhibits smaller percentage wave height reduction values in the range 57.83% to 41.51%, with R_u/H_i varying from 0.851 to 0.535, as wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00503. The results clearly show that there is significant reduction in wave heights when simulated seagrass is substituted with rigid submerged vegetation.

4.5 KEY FINDINGS AND SUMMARY

The results of experimental runs on the submerged vegetation models to determine the wave height attenuation and the corresponding run-up on the beach slope presented in this chapter suggests that the meadow width parameter (w/L), relative plant height, (h_s/d), and wave steepness parameter (H_i/gT^2) play a significant in governing the wave attenuation characteristics. The results are interpreted in terms of relative wave heights at locations within the vegetation model (H_x/H_i), percentage reduction in wave heights $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$, and the corresponding beach inundation expressed in terms of relative wave run up (R_u/H_i) on the beach.

The key findings of this study on submerged vegetation models are:

4.5.1 Conclusions for submerged seagrass model

1. The percentage wave height at exit point of a 1 m wide (w/L = 0.418-0.270 for h_s/d = 0.525; 0.401-0.257 for h_s/d = 0.47) meadow varies from 51.25% - 67.68% and from 66.25% - 78.21%, respectively; whereas the percentage wave height reduction for the same case varies from 48.75% - 32.32% and from 33.75% - 21.79% for h_s/d of 0.525 and 0.47, respectively.
2. For a 2 m wide model, the percentage wave height at exit point of a 2 m wide (w/L = 0.836-0.541 for h_s/d = 0.525; 0.804-0.515 for h_s/d = 0.47) meadow varies from 46.75% - 58.39% and from 53.25% - 64.71% for h_s/d of 0.525 and 0.47, respectively; whereas the percentage wave height reduction varies from 53.25% - 41.61% and from 46.75% - 35.29% for h_s/d of 0.525 and 0.47, respectively for the same model.
3. For the submerged seagrass model of width 2 m, as wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.862 to 0.535 (h_s/d = 0.525) and from 0.872 to 0.575 (h_s/d = 0.47).

4.5.2 Conclusions for submerged rigid vegetation model

1. The percentage wave height at exit point of a 1 m wide (w/L = 0.418-0.270 for h_s/d = 0.525; 0.401-0.257 for h_s/d = 0.47) meadow varies from 41.38% - 64.67% and from 56.63% - 72.96% for h_s/d of 0.525 and 0.47, respectively; whereas the percentage wave height reduction for the same case varies from 58.62% - 35.33% and from 43.37% - 27.04% for h_s/d of 0.525 and 0.47, respectively for the submerged rigid vegetation model.
2. For a 2 m wide model, the percentage wave height at exit point of a 2 m wide (w/L = 0.836-0.541 for h_s/d = 0.525; 0.804-0.515 for h_s/d = 0.47) meadow varies from 37.35% - 53.29% and from 42.17% - 58.49% for h_s/d of 0.525 and 0.47, respectively; whereas the percentage wave height reduction varies from 62.65% - 46.71% and from 57.83% - 41.51% for h_s/d of 0.525 and 0.47, respectively for the same model.
3. For the submerged rigid vegetation model of width 2 m, as wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.841 to 0.498 (h_s/d =1.25) and from 0.851 to 0.535 (h_s/d =1.11).

The optimum meadow width (w), relative plant height (h_s/d) and plant density (N) which gives the maximum wave attenuation and minimum run-up on the beach slope corresponds to the submerged rigid vegetation model of width, w = 2 m, relative plant height, h_s/d = 0.525; wherein, the percentage reduction of wave height varies from 62.65% to 46.71% and wave run-up on the beach ranges between 0.841 to 0.498, when compared to the results of the same submerged seagrass meadow, where the percentage wave height reduction varies from 53.25% to 41.61% and wave run-up on the beach ranges between 0.862 to 0.535.

CHAPTER 5

INVESTIGATIONS ON EMERGED VEGETATION MODELS

5.1 GENERAL

In the earlier chapter, it was observed that specific configurations of submerged seagrass and rigid vegetation meadow was quite effective in restraining wave attenuation and beach inundation. The presence of vegetation near the surface can attenuate the wave energy further as they increasingly interfere in the wave field propagating above and offer frictional resistance to particle movement causing wave breaking. Vegetation penetrates through the layers of varying particle orbital velocities and causes a distortion in the wave orbital velocities, resulting in an increase in turbulence and loss of energy. The vegetated meadow progressively interferes with the wave particle orbital velocities as the wave propagates through the meadow. Since the wave horizontal particle velocities, *u(z)* are highest near the crest of the wave, with velocities decreasing towards the bed (depending on water depth and wave period) (Dean and Dalrymple, 1991), the height of the vegetation plays a pivotal role in wave dissipation. As the height of stem or vegetation increases, the wave height attenuation also increases. As the stem height approaches the surface of water, the highest velocities are impeded, which leads to a greater drag and a consequent increase in wave energy dissipation.

This chapter showcases the effect of height of vegetation or the height of emergence of the stem, experiments are conducted with emergent vegetation models placed on the horizontal flume bed. The variation of measured wave height at locations within the emergent vegetation models with respect to the percentage meadow width and the extent of inundation over the beach slope with respect to wave steepness parameter are illustrated through various graphs.

5.2 STUDIES ON EMERGENT TRUNK MODEL

A 1:30 scaled emergent trunk model with vegetation characteristics as displayed in Table 3.4, is placed on the horizontal flume bed at 30 m away from the wave flap. Results of experiments conducted with this model subjected to waves of varying heights and periods are presented in this section.

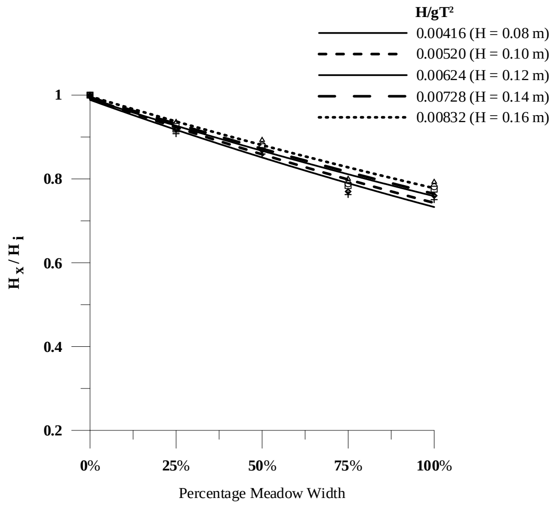
5.2.1 Wave height attenuation

Vegetation causes wave attenuation because it acts as an obstacle for the wave propagation. The kinematics of water particles are intercepted by the vegetation resulting in large amount of turbulence. This turbulence gives rise to energy dissipation, thereby reducing the wave height. Moreover, the height of the vegetation plays a pivotal role in wave height reduction. A visual examination of the test run indicates that as the wave propagates through the vegetated meadow, the presence of emergent trunks which interferes with the particle orbital velocities at the surface and further along the depth causes increased turbulence. Despite this turbulence owing to the emergence of the trunk, this model exhibits decreased reduction in wave height. This observation may be due to the role of plant density wherein the trunks interfere with the waves causing attenuation; while some energy passes through the gap between the emergent trunks.

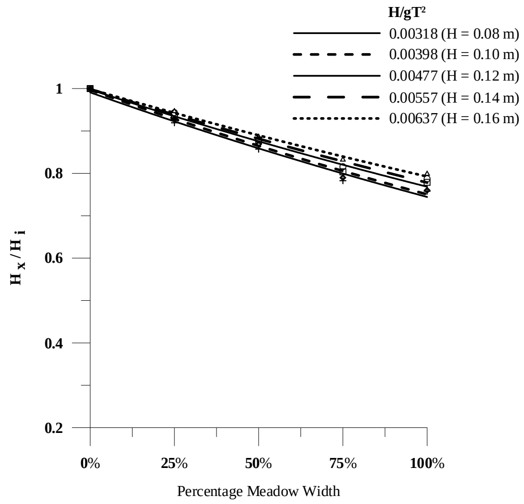
(a) (b)

Plate 5.1 Snapshots of wave propagation along the emergent trunk model a) side view b) top view

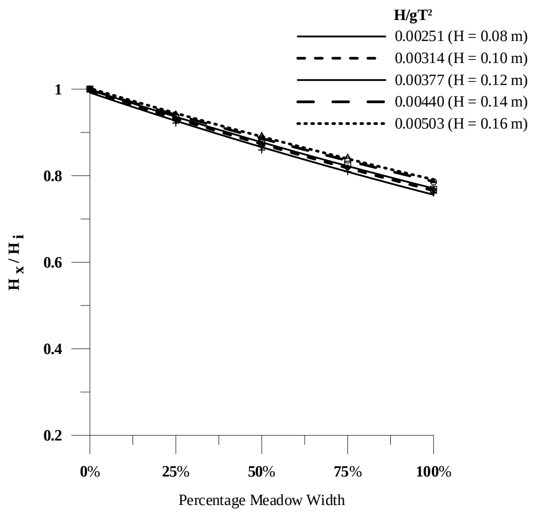
5.2.1.1 Relative plant height, h_s/d = 1.25; meadow width, w = 1 m.



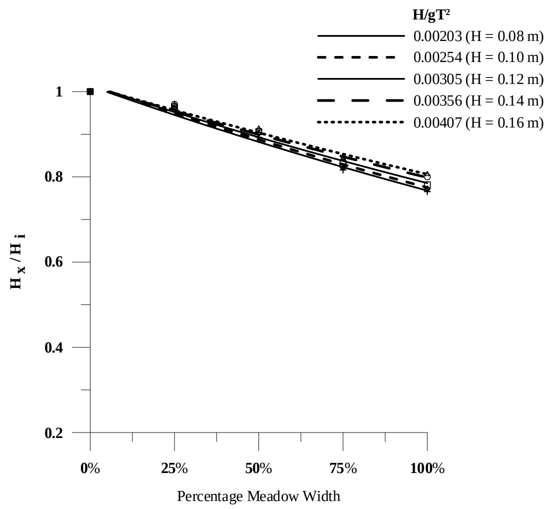
(a) for w/L = 0.418, T = 1.4 s



(b) for w/L = 0.357, T = 1.6 s



(c) for w/L = 0.305, T = 1.8 s



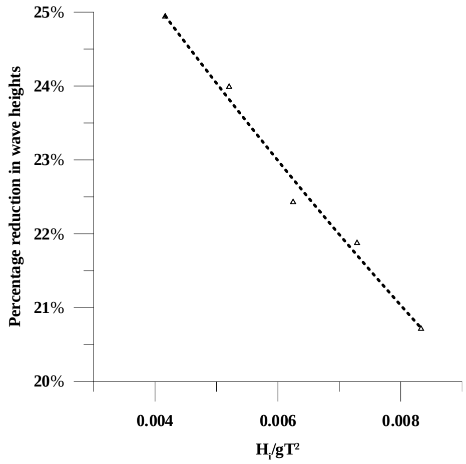
(d) for w/L = 0.270, T = 2 s

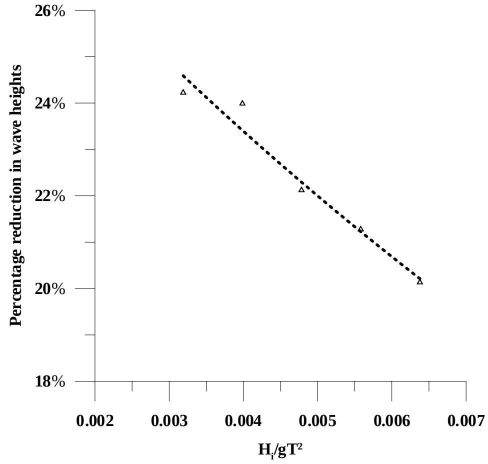
Fig. 5.1 Relative wave heights at locations within the model for h_s/d = 1.25; w = 1 m

Results are presented for the case of wave attenuation through an emergent trunk model of width 1 m and relative plant height, h_s/d = 1.25. The relative wave heights at locations within the model, $\left(\frac{H_x}{H_i}\right)$ is plotted against the percentage meadow width to visualize the wave height attenuation due to the emergent trunk model of width 1 m, when subjected to waves of varying heights and periods, as seen in Fig. 5.1 (a to d).

It is seen from Fig. 5.1 (a) that the relative percentage wave height at the exit point, $\left(\frac{H_{exit}}{H_i}\right)$ of the meadow is varies from 75.06% to 76.53% for an incident wave of height 0.08 m, corresponding to a range of wave periods from 1.4 s to 2 s. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 76.01% to 77.15%, from 77.57% to 78.14%, from 78.13% to 80.03% and from 79.29% to 80.60%, respectively, as illustrated in Fig. 5.1 (b to d). The influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction, $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$ for the emergent trunk model is depicted in Fig. 5.2 (a to d). It is noted from Fig. 5.2 (a) that there is a decrease in wave height reduction from 24.94% to 20.71% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 0.418, T = 1.4 s). This strengthens the observation that as the waves get steeper, there is a marked reduction in wave height attenuation.

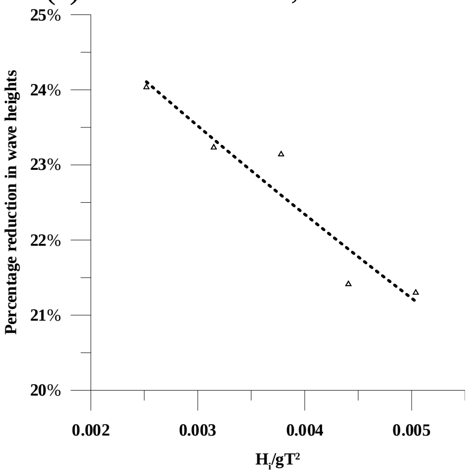
Waves with smaller wave heights displays maximum reduction; whereas as the wave height increases, the attenuation decreases, owing to the porosity of the vegetated meadow and stiffness of the trunks. Further, the percentage wave reduction varies from 24.22% to 20.13%, 24.03% to 21.30% and from 23.47% to 19.40% for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 0.357, T = 1.6 s), 0.00251 to 0.00503 (w/L = 0.305, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 0.270, T = 2 s), respectively, as illustrated in Fig. 5.2 (b to d). It is also observed that when the waves propagate through the emergent trunk model, the reduction in wave heights is gradual and therefore, the effect of different wave heights and wave steepness is less pronounced as seen in Fig. 5.1 and 5.2 (a to d), when compared to a wider spread demonstrated in the results corresponding to the submerged vegetation models. This is attributed to the presence of large gaps in the model owing to the reduced plant density (N = 107 trunks/m^2). The degree of interference of the trunks is less i.e, the trunks are not capable of penetrating the particle orbital velocities to a greater extent and therefore the transmission is higher, which leads to a decreased wave height reduction.

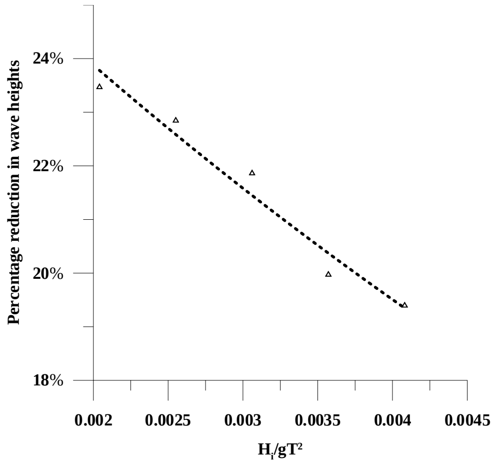




(a) for w/L = 0.418, T = 1.4 s

(b) for w/L = 0.357, T = 1.6 s





(c) for w/L = 0.305, T = 1.8 s

(d) for w/L = 0.270, T = 2 s

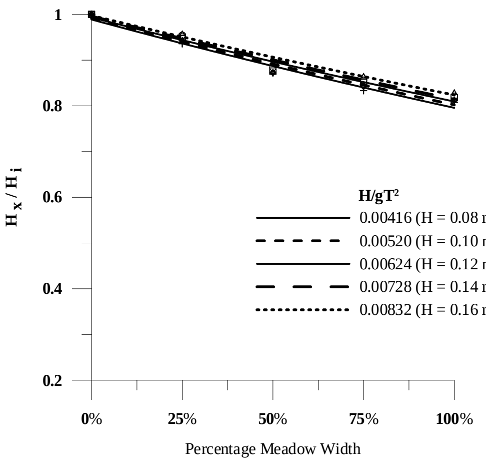
Fig. 5.2 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w = 1 m

5.2.1.2 Relative plant height, h_s/d = 1.11; meadow width, w = 1 m

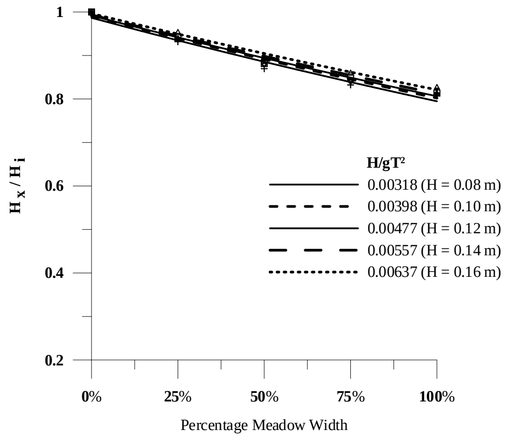
The effect of reduction in relative plant height (h_s/d) from 1.25 to 1.11 due to increase in water depth from 0.40 m to 0.45 m on wave height attenuation of emergent trunk model of 1 m width is discussed in this section.

Fig. 5.3 (a to d) illustrates the relative wave heights at locations within the emergent trunk model of width 1 m. The relative percentage wave height at the exit point,

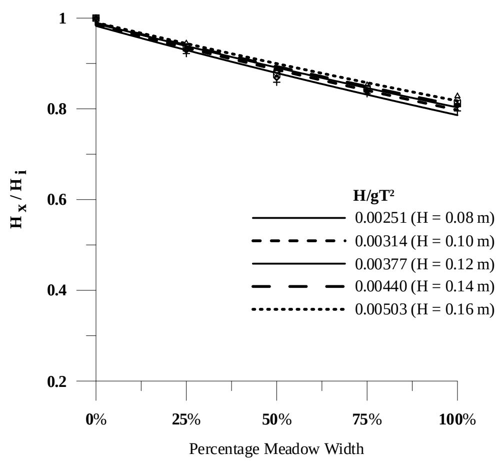
$\left(\frac{H_{exit}}{H_i}\right)$ of the meadow varies from 80.77% to 84.15%, from 81.24% to 83.50%, from 81.82% to 85.21%, from 82.11% to 84.29% and from 82.86% to 85.28% for incident waves of heights 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, corresponding to a range of wave periods from 1.4 s to 2 s.



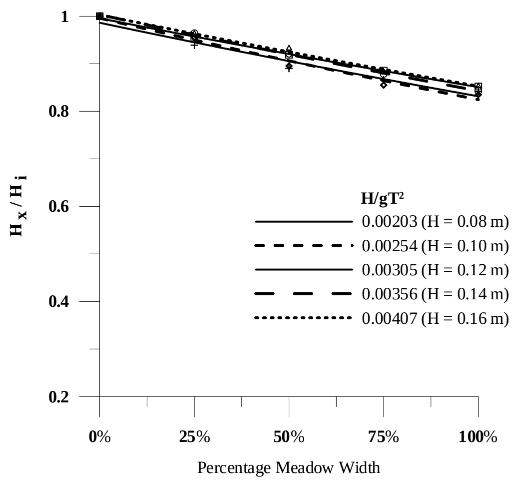
(a) for w/L = 0.401, T = 1.4 s



(b) for w/L = 0.348, T = 1.6 s



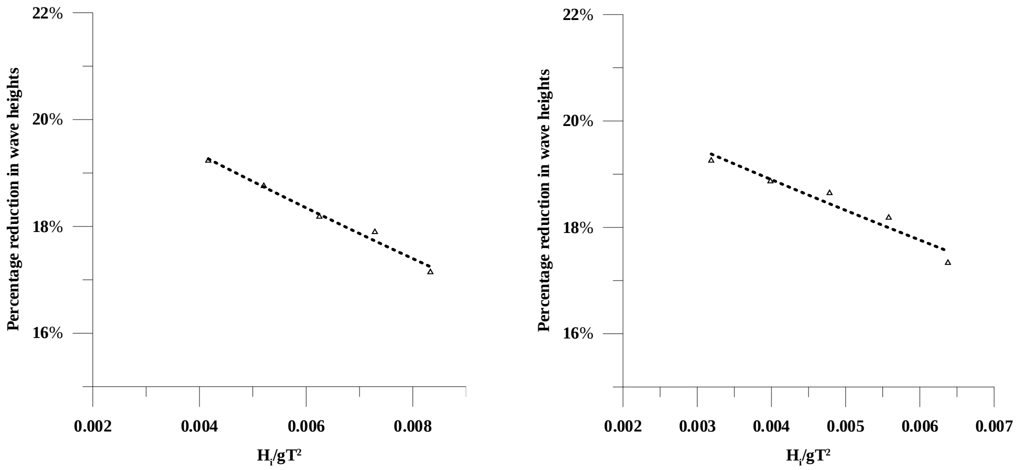
(c) for w/L = 0.291, T = 1.8 s



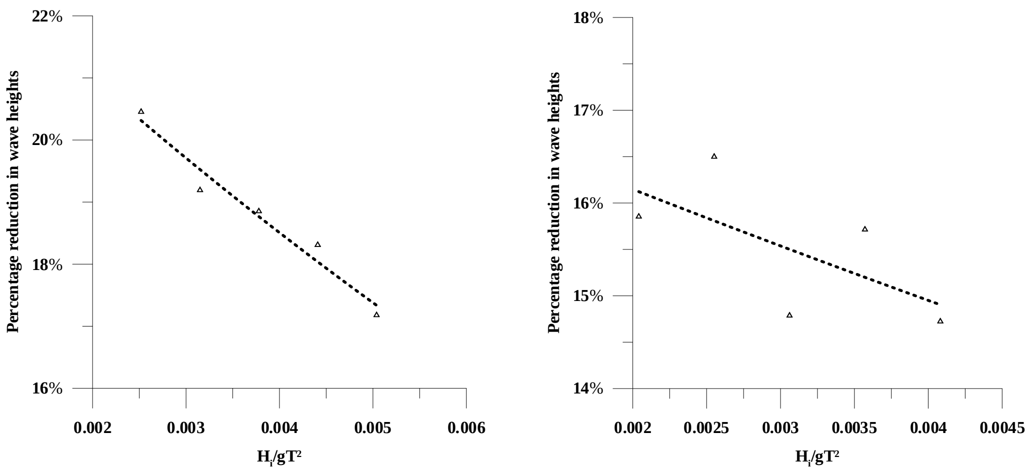
(d) for w/L = 0.257, T = 2 s

Fig. 5.3 Relative wave heights at locations within the model for h_s/d = 1.11; w = 1 m

Fig. 5.4 (a) depicts the percentage reduction in wave heights, $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$ for increasing wave steepness, which varies from 19.23% to 17.14% for wave steepness parameter, H_i/gT^2 ranging from 0.00416 to 0.00832 (w/L = 0.401, T = 1.4 s).



(a) for w/L = 0.401, T = 1.4 s (b) for w/L = 0.348, T = 1.6 s

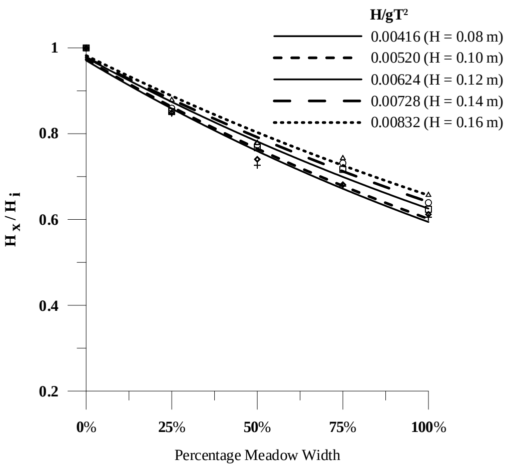


(c) for w/L = 0.291, T = 1.8 s (d) for w/L = 0.257, T = 2 s

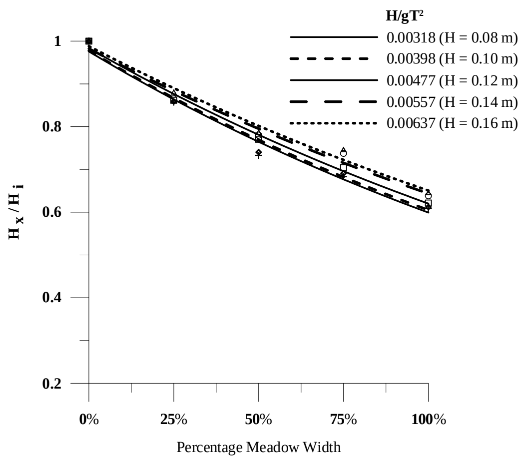
Fig. 5.4 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w = 1 m

Correspondingly, for w/L = 0.348, T = 1.6 s, H_i/gT^2 = 0.00318 to 0.00637; w/L = 0.291, T = 1.8 s, H_i/gT^2 = 0.00251 to 0.00503 and w/L = 0.257, T = 2 s, H_i/gT^2 = 0.00203 to 0.00407, the percentage reduction in wave height varies from 19.25% to 17.33%, 20.45% to 17.18% and from 15.85% to 14.72%, respectively Fig. 5.4 (b to d). The results in this section justifies the fact that wave height attenuation decreases as the relative plant height (h_s/d) changes from 1.25 to 1.11. For h_s/d = 1.25, since the depth of water is lower, as the wave passes along the width of the model, the trunks successfully interfere with the waves and the entire distribution of energy field is interfered. This results in increased wave height attenuation when compared to the case of $h_s/d = 1.11$ wherein, the increased gap between the wave and the height of trunks leads to ease in passage of wave energy. As the degree of interference is less, the wave passes effortlessly which results in reduced wave height attenuation. From the above results, it is also noted that there exists an inverse relationship between wave period and wave attenuation.

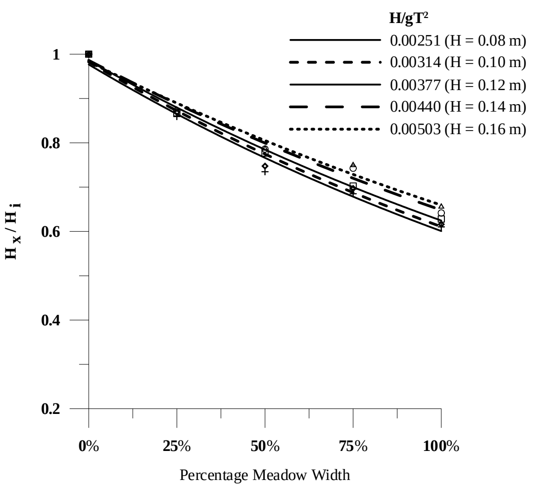
5.2.1.3 Relative plant height, $h_s/d = 1.25$; meadow width, w = 2 m



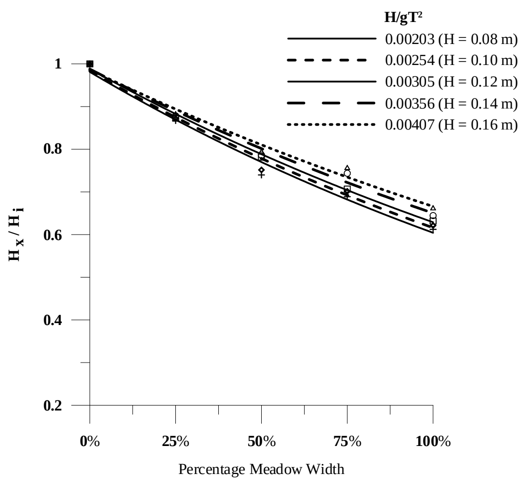
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s

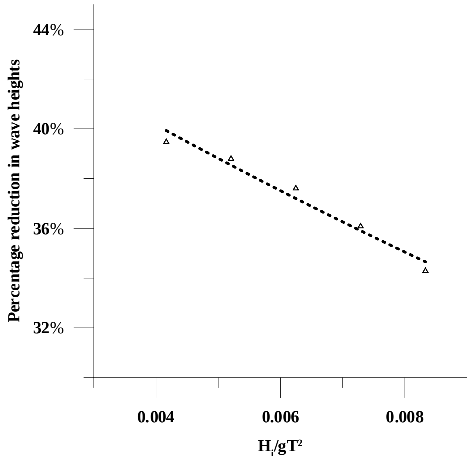


(d) for w/L = 0.541, T = 2 s

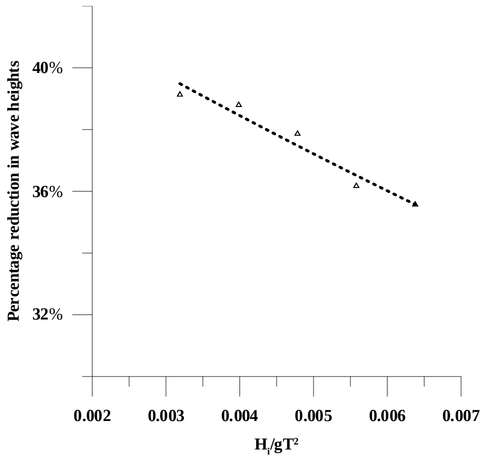
Fig. 5.5 Relative wave heights at locations within the model for $h_s/d = 1.25$; w = 2 m

The influence of increase in meadow width parameter (w/L) from 0.418 to 0.836, 0.357 to 0.714, 0.305 to 0.612 and 0.207 to 0.541, corresponding to wave periods, T = 1.4 s, 1.6 s, 1.8 s and 2 s, respectively on wave height attenuation is discussed in this section. Fig. 5.5 (a) indicates that the relative percentage wave height at the exit point, $\left(\frac{H_{exit}}{H_i}\right)$ of the meadow is varies from 60.53% to 61.22% for an incident wave of height 0.08 m. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 61.20% to 62.12%, from 62.39% to 63.18%, from 63.92% to 64.45% and from 65.71% to 66.12%, respectively, as illustrated in Fig. 5.5 (b to d).

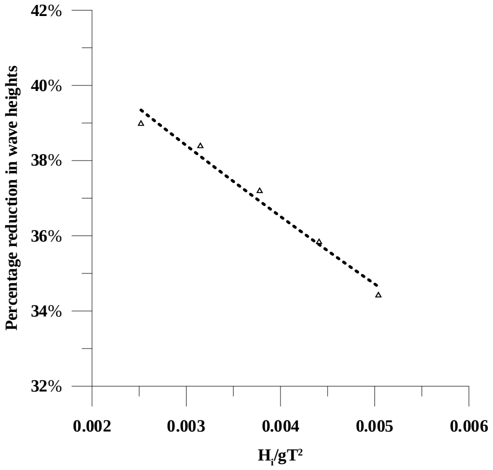
Fig. 5.6 (a to d) exhibits the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction, $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$ for the emergent trunk model of width 2 m. The percentage wave height reduction varies from 39.47% to 34.29% for T = 1.4 s, w/L = 0.836 and H_i/gT^2 = 0.00416 to 0.00832, as clearly observed in Fig. 5.6 (a). Similar variations in percentage reduction in wave heights from 39.13% to 35.57%, 38.98% to 34.42% and from 38.78% to 33.88% is observed for the same model with w/L = 0.714, T = 1.6 s, H_i/gT^2 from 0.00318 to 0.00637; w/L = 0.612, T = 1.8 s, H_i/gT^2 from 0.00251 to 0.00503 and w/L = 0.541, T = 2 s, H_i/gT^2 from 0.00203 to 0.00407, respectively (Figs. 5.6 a-d). It is therefore evident from the comparison of results between this section and that of section 5.2.1.1, that there is considerable increase in wave height attenuation with increase in meadow width parameter.



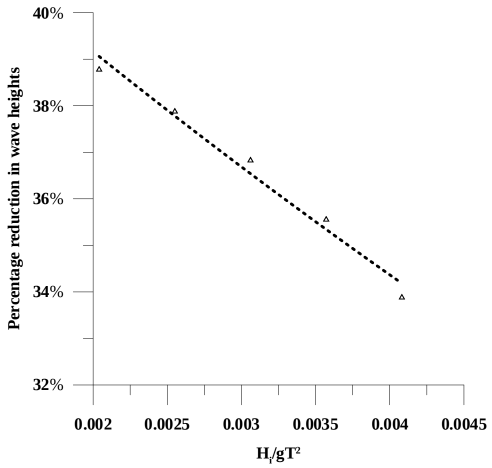
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s

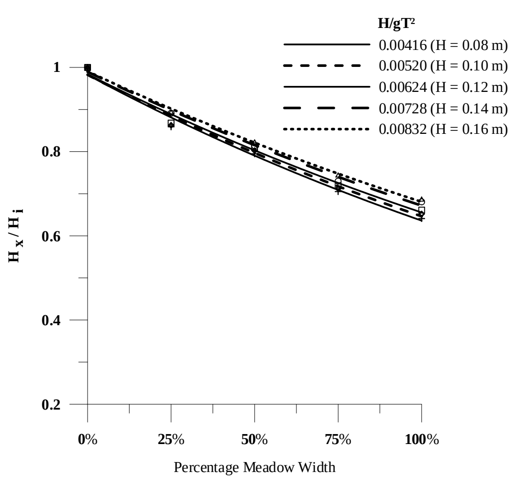


(d) for w/L = 0.541, T = 2 s

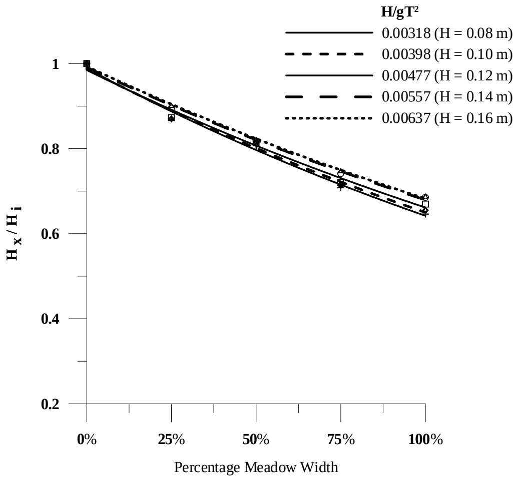
Fig. 5.6 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w = 2 m

5.2.1.4 Relative plant height, h_s/d = 1.11; meadow width, w = 2 m

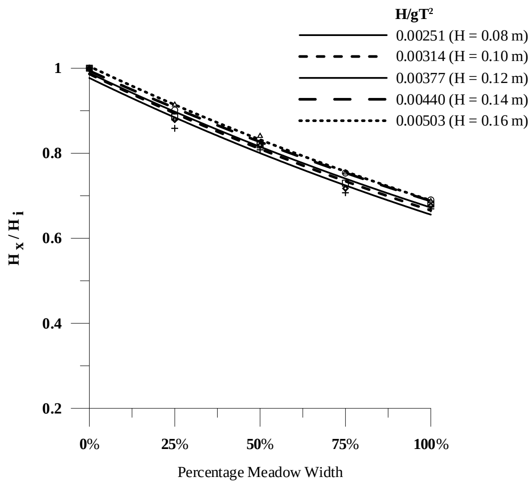
As the relative plant height decreases from 1.25 to 1.11, the relative percentage wave height at the exit point of the meadow, $\left(\frac{H_{exit}}{H_i}\right)$ varies from 64.10% to 67.07% for an incident wave of height 0.08 m, corresponding to a range of wave periods from 1.4 s to 2 s.



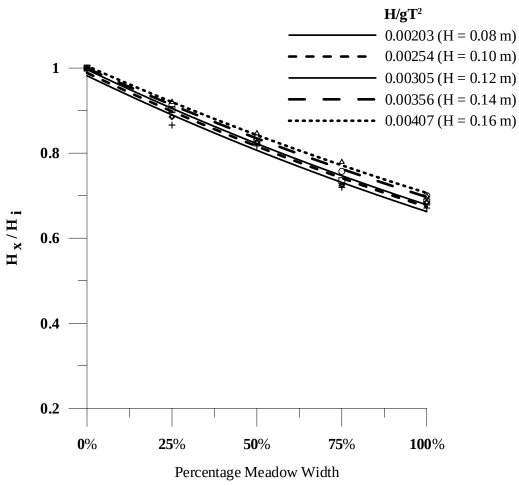
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



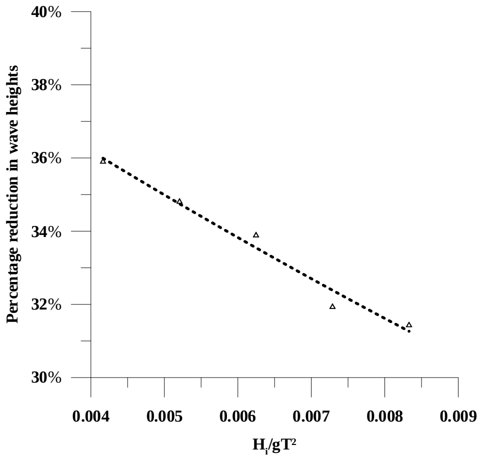
(c) for w/L = 0.583, T = 1.8 s



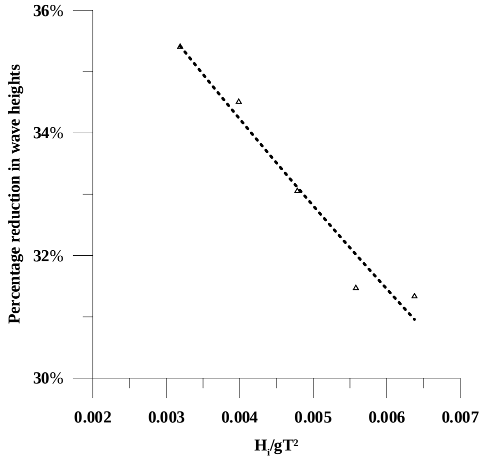
(d) for w/L = 0.515, T = 2 s

Fig. 5.7 Relative wave heights at locations within the model for h_s/d = 1.11; w = 2 m

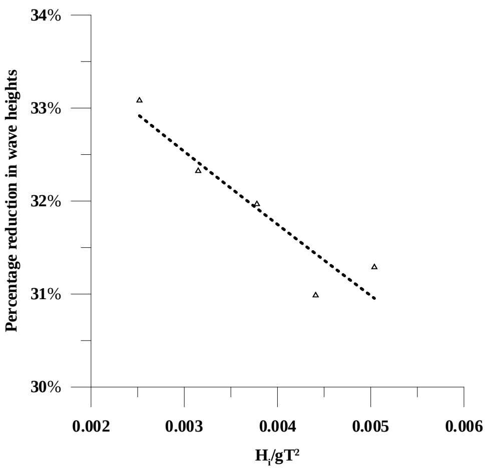
Further variations of the relative percentage wave heights at exit of the meadow is observed to be from 65.20% to 67.40%, from 66.12% to 67.67%, from 68.07% to 68.57% and from 68.57% to 69.33% for incident wave heights of 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as depicted in Fig. 5.7 (a to d).



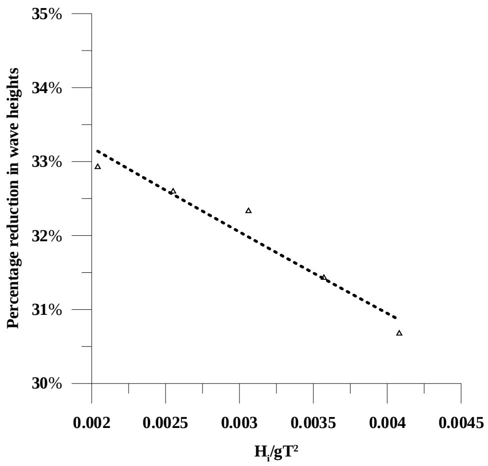
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s



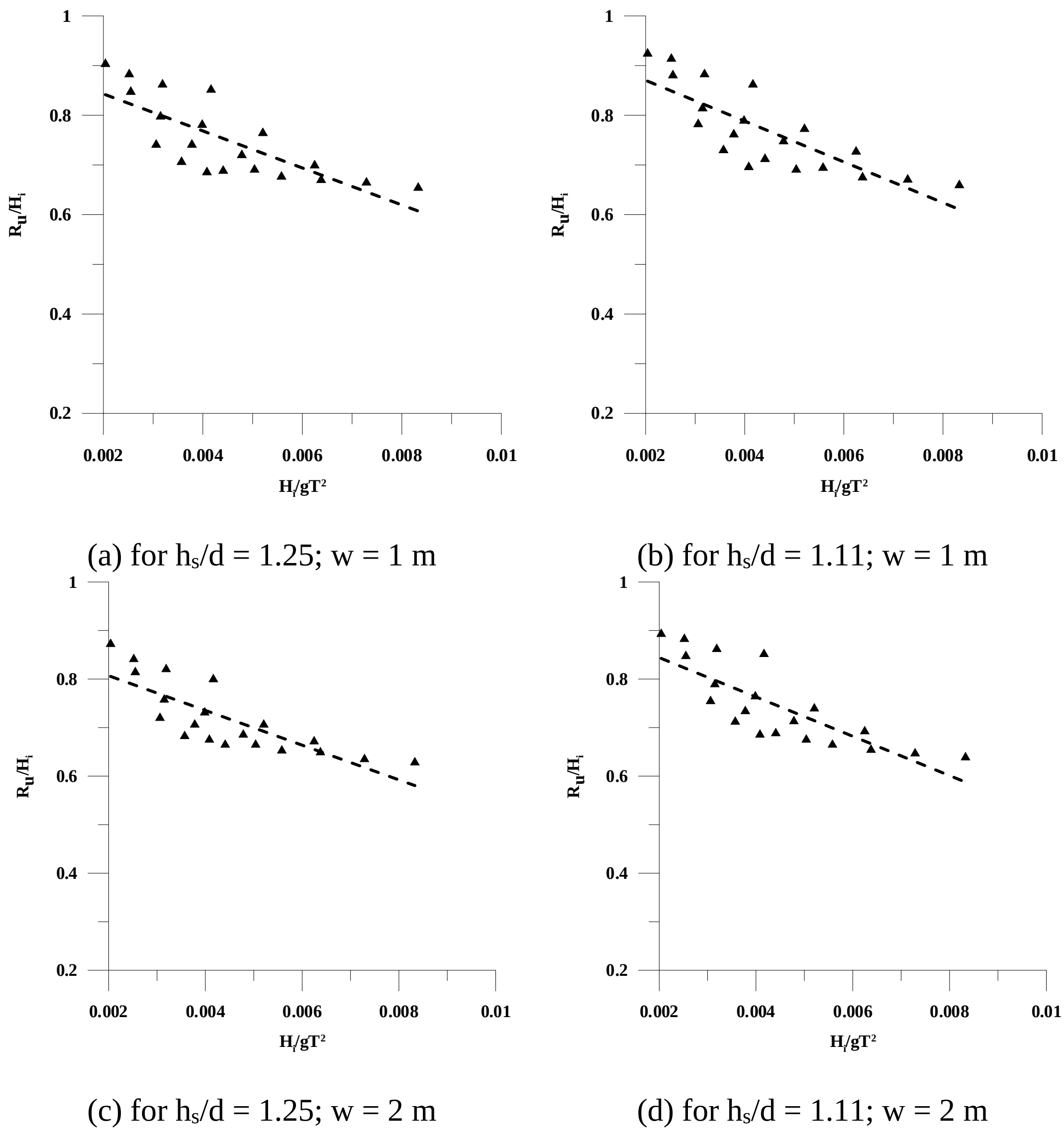
(d) for w/L = 0.515, T = 2 s

Fig. 5.8 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w = 2 m

Fig. 5.8 (a to d) shows that the percentage wave height reduction varies from 35.90% to 31.43%, 35.40% to 31.33%, 33.08% to 31.29% and 32.93% to 30.67% for w/L = 0.804, T = 1.4 s, H_i/gT^2 = 0.00416 to 0.00832; w/L = 0.696, T = 1.6 s H_i/gT^2 = 0.00318 to 0.00637; w/L = 0.583, T = 1.8 s, H_i/gT^2 = 0.00251 to 0.00503; and w/L = 0.515, T = 2 s, H_i/gT^2 = 0.00203 to 0.00407, respectively. The above results also solidify the fact that the percentage wave height reduction increases as the meadow width parameter increases from 0.401 to 0.804, 0.348 to 0.696, 0.291 to 0.583 and from 0.257 to 0.515 for the same relative plant height (h_s/d = 0.47), corresponding to wave periods, T = 1.4 s, 1.6 s, 1.8 s and 2 s.

5.2.2 Effect of wave steepness on run-up

The percentage reduction in wave heights for the emergent trunk model of width 1 m, for h_s/d = 1.25, ranges from 24.94% to 19.40%, respectively for entire set of incident wave parameters. The corresponding wave run-up measurements on the beach slope ranges from 0.903 to 0.653, as shown in Fig. 5.9 (a).



(a) for h_s/d = 1.25; w = 1 m

(b) for h_s/d = 1.11; w = 1 m

(c) for h_s/d = 1.25; w = 2 m

(d) for h_s/d = 1.11; w = 2 m

Fig. 5.9 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d)

However, as the relative plant height, h_s/d decreases to 1.11, the wave run-up on the beach slope ranges from 0.923 to 0.659, as in Fig. 5.9 (b).

The percentage reduction in wave heights for the emergent trunk model of width 2 m, for h_s/d = 1.25, ranges from 39.47% to 33.88% for entire set of incident wave parameters. The corresponding wave run-up measurements on the beach slope ranges from 0.871 to 0.628 (Fig. 5.9-c). It is therefore noted that the relative wave run-up (R_u/H) decreases with an increase in wave steepness parameter (H_i/gT^2). Correspondingly, as the water depth increases and the relative plant height (h_s/d) decreases to 1.11, the extent of inundation on the beach represented by the wave run-up (R_u/H_i) decreases from 0.893 to 0.638 for an increase in wave steepness parameter (H_i/gT^2) from 0.00203 to 0.00833, as illustrated in Fig. 5.10 (c to d). The percentage reduction in wave heights for the same is observed to be in the range 35.90% to 30.67%. The extent of inundation on the beach is therefore observed as a consequence of the extent of attenuation of wave heights.

5.3 STUDIES ON EMERGENT TRUNK MODEL WITH ROOTS

A 1:30 scaled emergent trunk model with roots, placed on the horizontal part of the flume bed at 30 m away from the wave flap, is subjected to monochromatic waves of height varying from 0.08 m to 0.16 m at an interval of 0.02 m. Results of experiments conducted with emergent trunk model with roots of varying meadow widths is presented in this section.

5.3.1 Wave height attenuation

Results of variation in relative wave heights at locations within the emergent trunk model with roots with respect to the relative plant height, meadow width and varying periods is presented in this section. During the course of the test runs, it was seen that the trunks of the emergent trunk model with roots vibrates with wave action, whereas the vibrations observed for the roots of different geometries as indicated in Table 3.2 is negligible when compared to that of the trunks, owing to the variation in stiffness of the trunk and the roots. This model shows an increased reduction in wave heights when compared to the results presented for the model described in section 5.2. The presence of a root system in this model results in a higher plant density (N) of 107 trunks/m^2, 300 $roots_1/m^2$, 300 $roots_2/m^2$, when compared to the emergent trunk model with a plant density of 107 trunks/m^2 results in an increased turbulence observed along the vegetated meadow, which might be the reason for the increased reduction in wave heights along the model described in this section. The snapshots of wave propagation along the rigid submerged vegetation model is displayed in Plate 5.2.

(a)

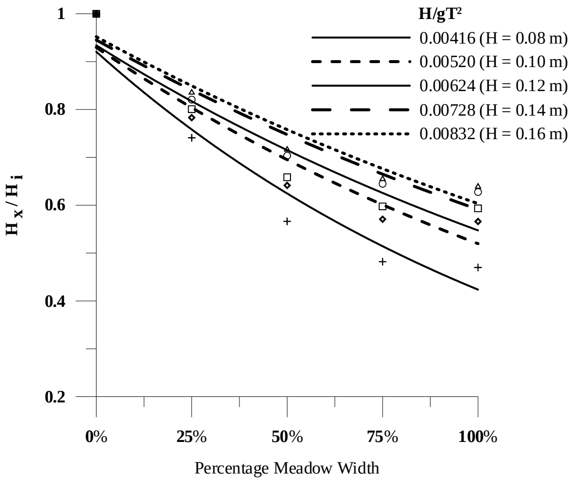
(b)

Plate 5.2 Snapshots of wave propagation along the emergent trunk model with roots a) side view b) top view

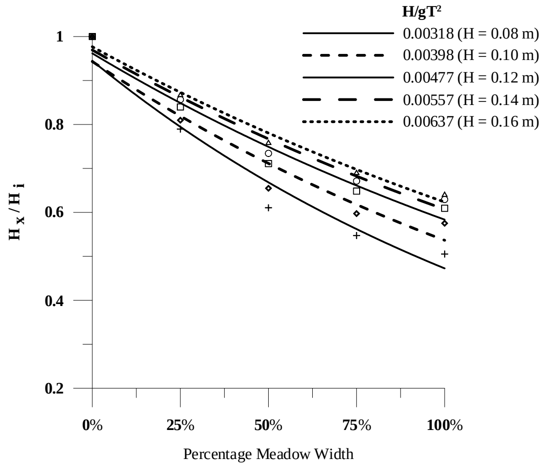
5.3.1.1 Relative plant height, h_s/d = 1.25; meadow width, w = 1 m

The presence of roots in the 'emergent trunk model with roots' leads to an increase in wave height attenuation because of the increase in plant density characterized by a trunk density of 107 trunks/m^2, along with a root density of 300 $roots_1/m^2$, 300 $roots_2/m^2$ (with relative root height of 0.525, 0.4), when compared to a 'trunk model without roots' (trunk density = 107 trunks/m^2).

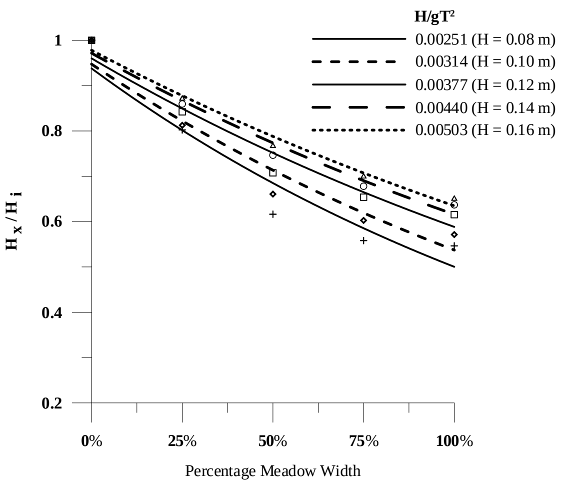
Analysis of relative wave heights at locations within the emergent trunk model with roots and at the exit of the model reveals that there is an exponential decay in wave heights as it propagates along the model. The relative percentage wave height at the exit point, $\left(\frac{H_{exit}}{H_i}\right)$ of the meadow is varies from 46.99% to 55.06%, from 56.60% to 58.56%, from 59.35% to 62.31%, from 62.76% to 64.38% and from 63.87% to 65.27% corresponding to incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as illustrated in Fig. 5.10 (a to d)



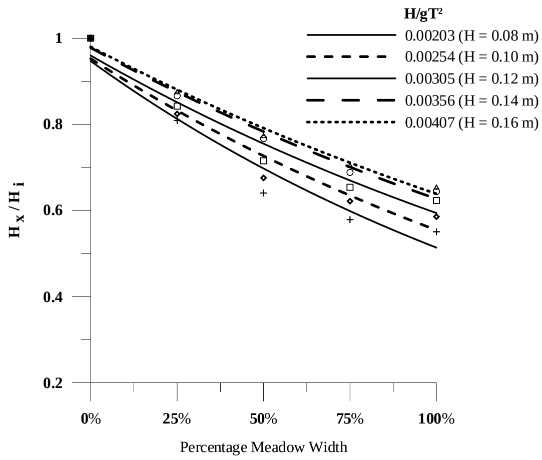
(a) for w/L = 0.418, T = 1.4 s



(b) for w/L = 0.357, T = 1.6 s



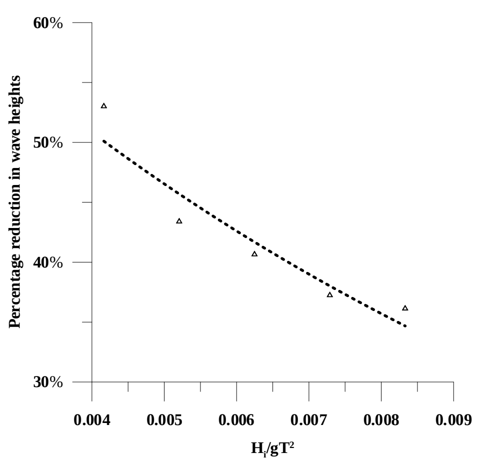
(c) for w/L = 0.305, T = 1.8 s



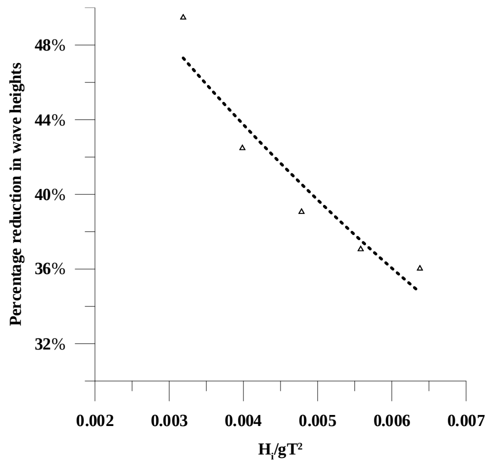
(d) for w/L = 0.270, T = 2 s

Fig. 5.10 Relative wave heights at locations within the model for $h_s/d = 1.25$; w = 1 m

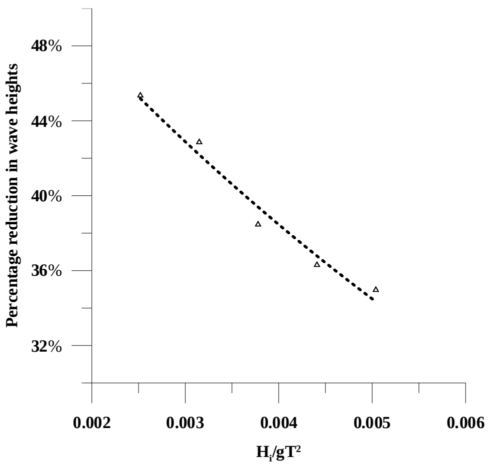
The percentage reduction in wave heights for an emergent trunk model with roots is 53.01% to 34.73% when compared to a reduction of 24.94% to 19.40% for the case of the same model without roots and of the same meadow width parameter (w/L = 0.418-0.207), for relative plant height, $h_s/d = 1.25$.



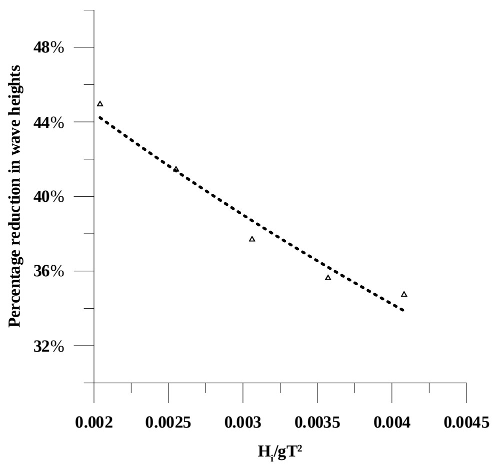
(a) for w/L = 0.418, T = 1.4 s



(b) for w/L = 0.357, T = 1.6 s



(c) for w/L = 0.305, T = 1.8 s

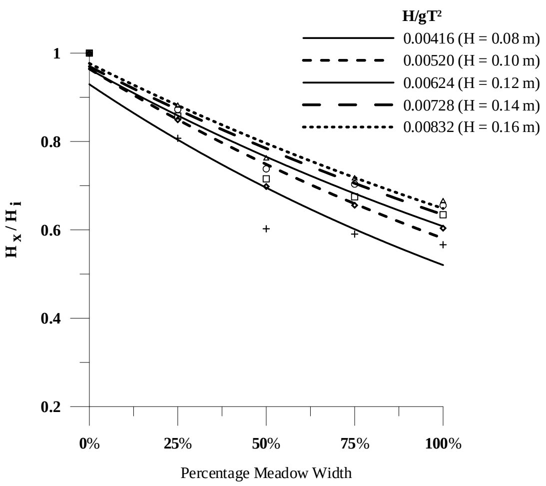


(d) for w/L = 0.270, T = 2 s

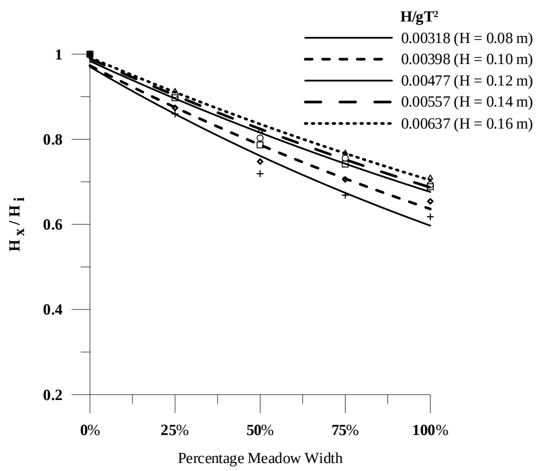
Fig. 5.11 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w = 1 m

The results also indicate the capability of the emergent trunk model with roots in attenuating waves decreases as the wave period increases i.e, as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832, 0.00318 to 0.00637, 0.00251 to 0.00503 and from 0.00203 to 0.00407, percentage reduction in wave heights, $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$ varies from 53.01% to 36.13%, 49.47% to 36.02%, 45.35% to 34.97% and from 44.94% to 34.73%, respectively (Fig. 5.11 a to d).

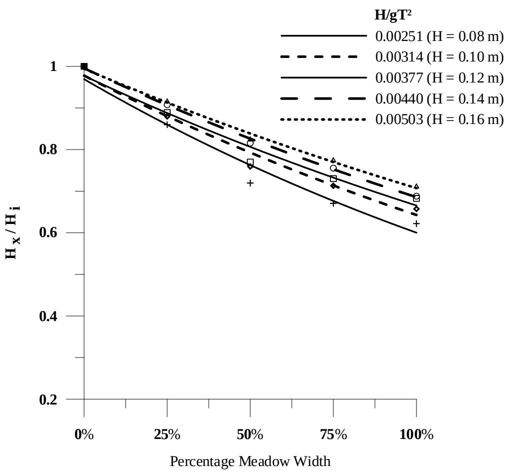
5.3.1.2 Relative plant height, h_s/d = 1.11; meadow width, w = 1 m



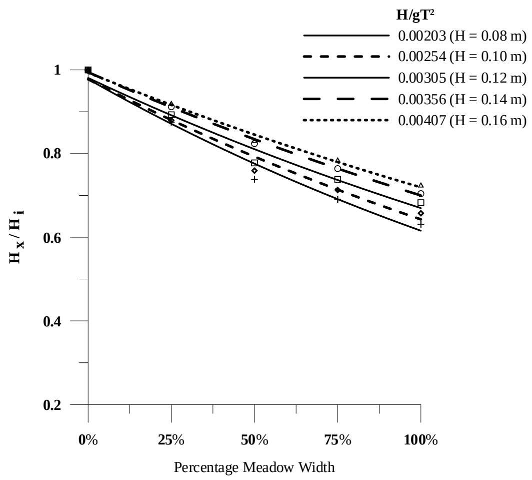
(a) for w/L = 0.401, T = 1.4 s



(b) for w/L = 0.348, T = 1.6 s



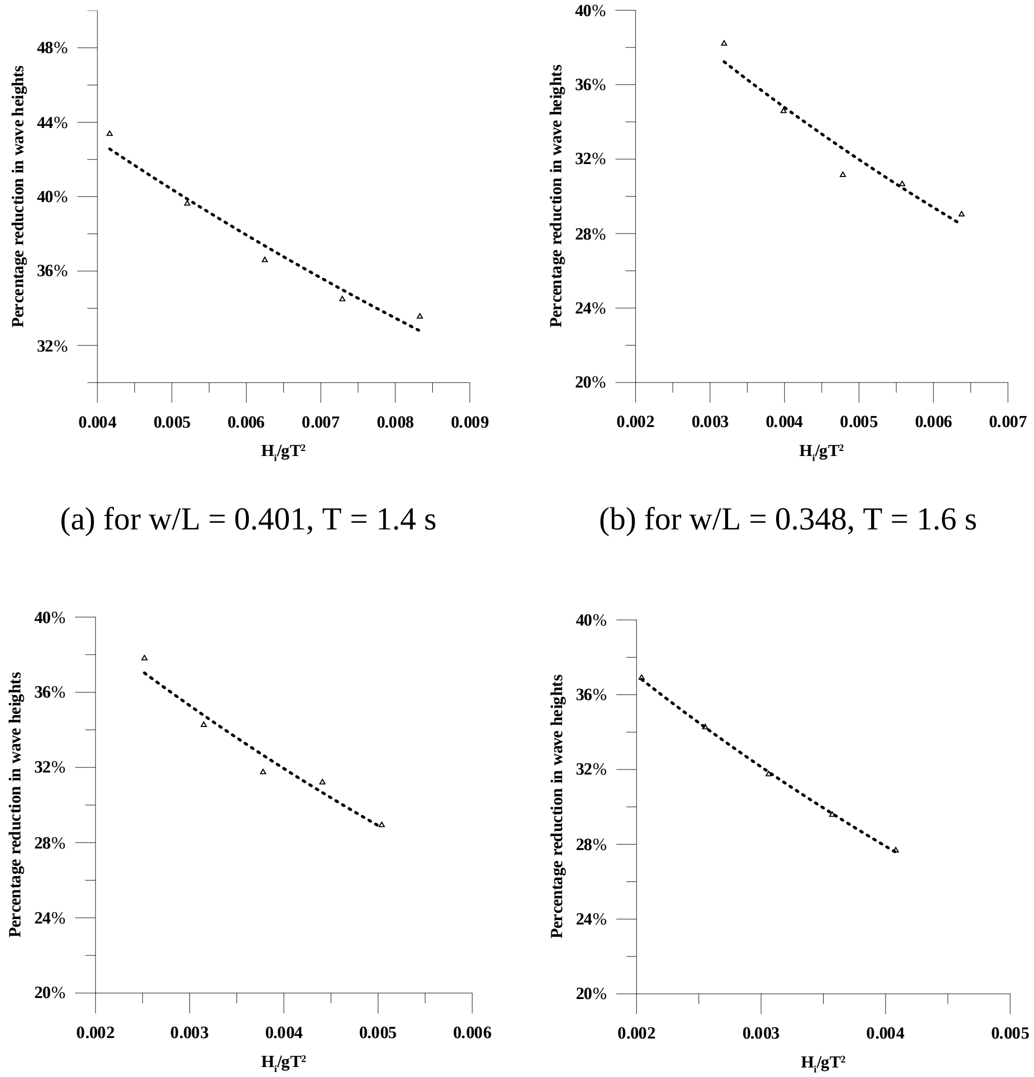
(c) for w/L = 0.291, T = 1.8 s



(d) for w/L = 0.257, T = 2 s

Fig. 5.12 Relative wave heights at locations within the model for h_s/d = 1.11; w = 1 m

For the emergent trunk model with roots of 1 m width and relative plant height, h_s/d = 1.11, the relative percentage wave height at the exit point, $\left(\frac{H_{exit}}{H_i}\right)$ of the meadow is varies from 56.63% to 63.10%, from 60.38% to 65.74%, from 63.41% to 68.25%, from 65.52% to 70.42% and from 66.45% to 72.33% for incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as seen in Fig. 5.12 (a to d).



(a) for w/L = 0.401, T = 1.4 s (b) for w/L = 0.348, T = 1.6 s

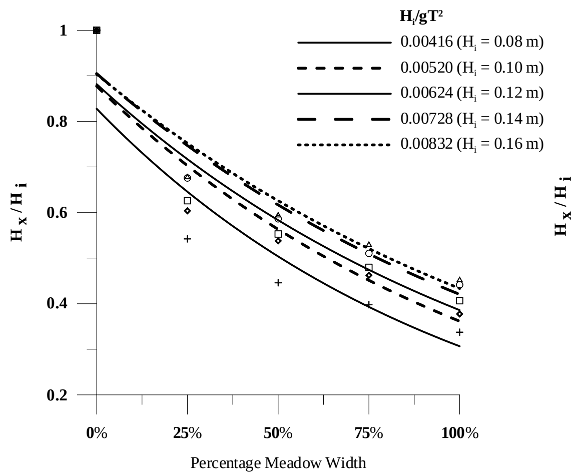
(c) for w/L = 0.291, T = 1.8 s (d) for w/L = 0.257, T = 2 s

Fig. 5.13 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 1.11$; w = 1 m

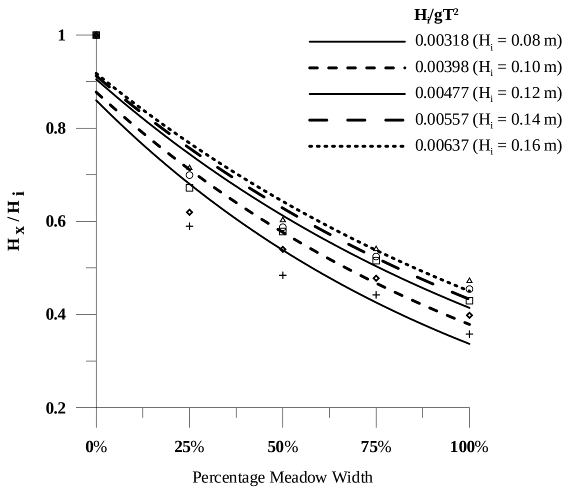
However, the percentage reduction in wave heights, $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$ varies from 43.37% to 33.55%, 38.20% to 29.03%, 37.80% to 28.93% and from 36.90% to 27.67%, respectively (Fig. 5.13 a to d), as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832, 0.00318 to 0.00637, 0.00251 to 0.00503 and from 0.00203 to 0.00407. Comparing these results with that presented in section 5.3.1.1 indicates that there is a direct relationship between wave height attenuation and decrease in relative plant height.

5.3.1.3 Relative plant height, h_s/d = 1.25; meadow width, w = 2 m

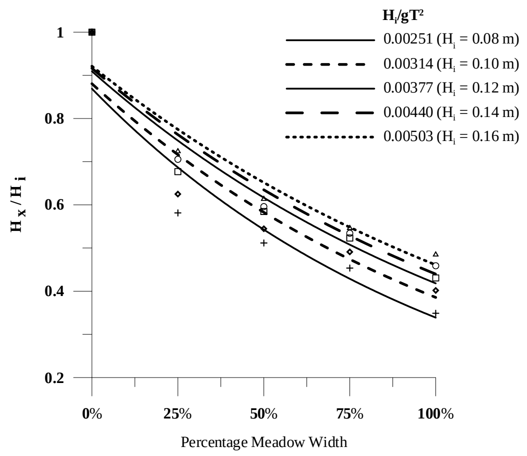
The measured wave heights at locations within the emergent trunk model with roots of increased meadow width of 2 m with h_s/d = 1.25, corresponding to different wave periods is illustrated in Fig. 5.14 (a to d).



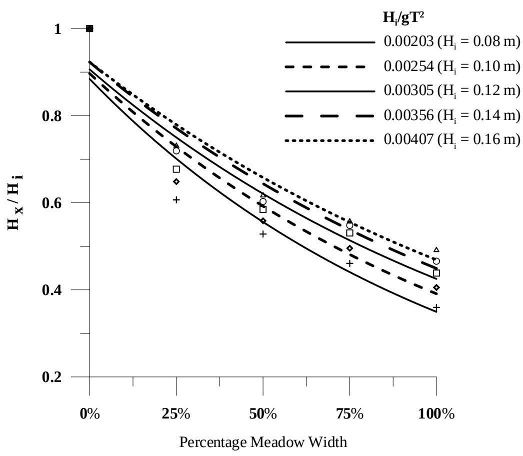
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



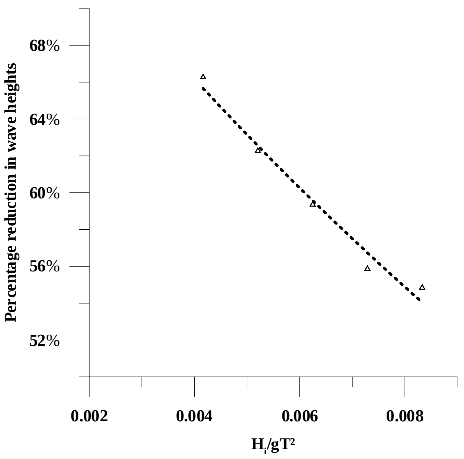
(c) for w/L = 0.612, T = 1.8 s



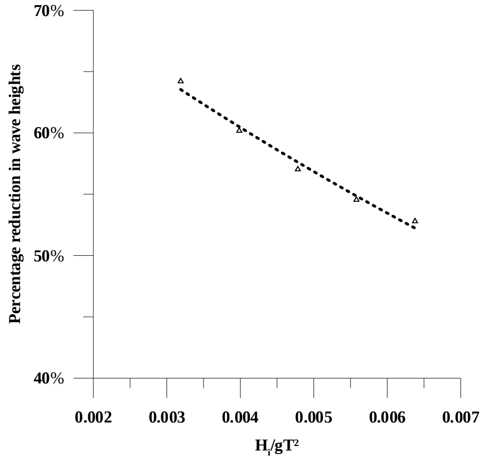
(d) for w/L = 0.541, T = 2 s

Fig. 5.14 Relative wave heights at locations within the model for h_s/d = 1.25; w = 2 m

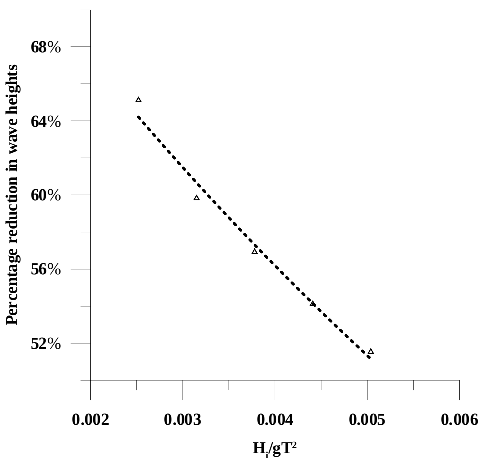
The increase in meadow width parameter (w/L) from 0.418-0.207 to 0.836-0.541 accounts for the increase in wave height attenuation.



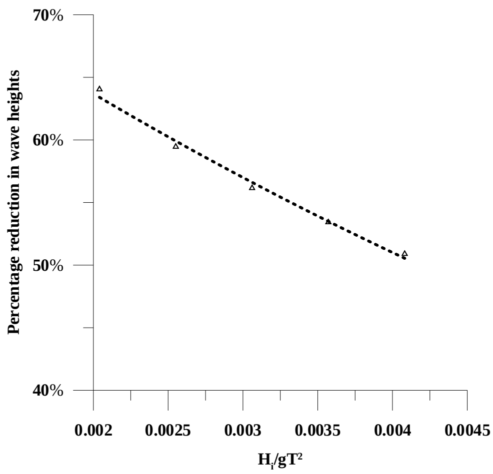
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s

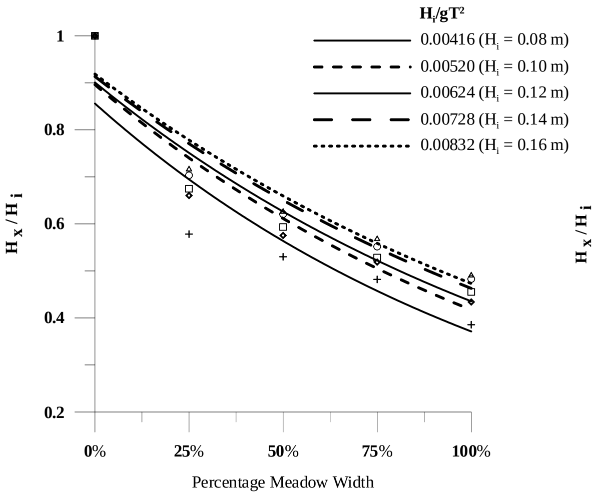


(d) for w/L = 0.541, T = 2 s

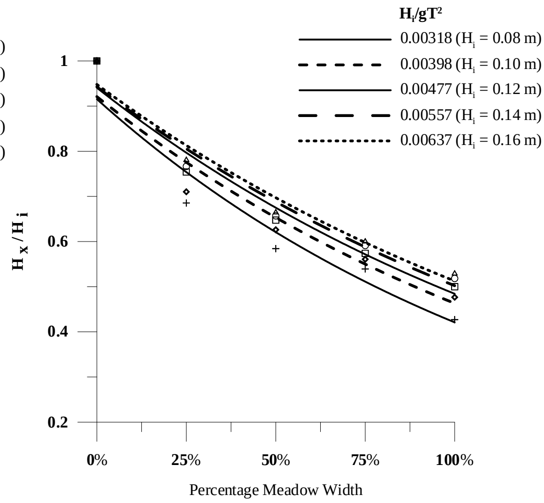
Fig. 5.15 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w = 2 m

The percentage wave height reduction varies from 66.27% to 54.84%, 64.21% to 52.80%, 65.12% to 51.53% and 64.04% to 50.90% for w/L = 0.836, T = 1.4 s, H_i/gT^2 = 0.00416 to 0.00832; w/L = 0.714, T = 1.6 s, H_i/gT^2 = 0.00318 to 0.00637; w/L = 0.612, T = 1.8 s, H_i/gT^2 = 0.00251 to 0.00503; and w/L = 0.541, T = 2 s, H_i/gT^2 = 0.00203 to 0.00407, respectively, as illustrated in Fig. 5.15 (a to d). A comparison of the percentage wave height reduction discussed in this section with that presented in section 5.3.1.1 shows the importance of meadow width parameter (w/L) in wave height attenuation.

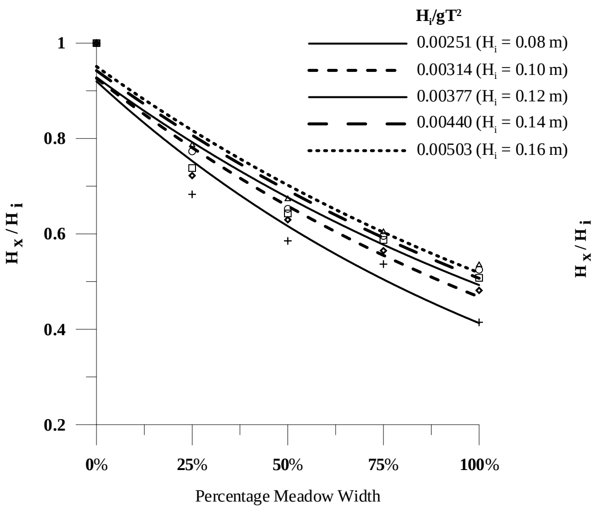
5.3.1.4 Relative plant height, h_s/d = 1.11; meadow width, w = 2 m



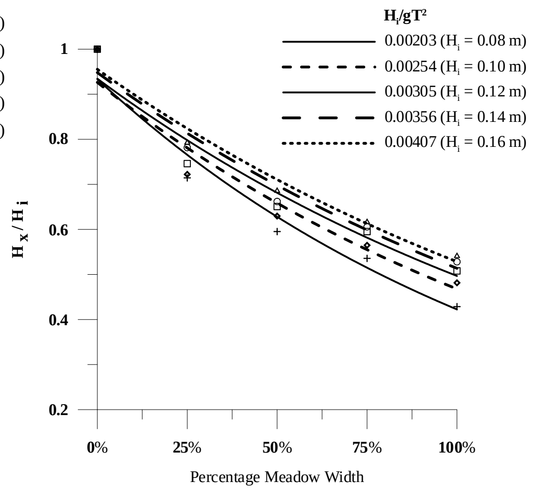
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s

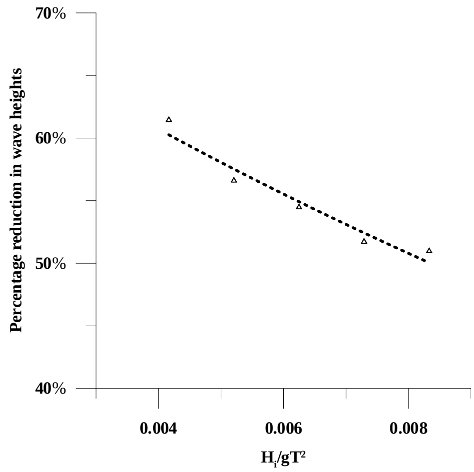


(d) for w/L = 0.515, T = 2 s

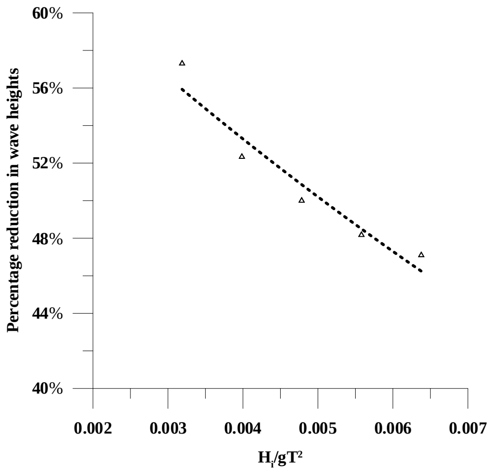
Fig. 5.16 Relative wave heights at locations within the model for h_s/d = 1.11; w = 2 m

Fig. 5.16 (a to d) depicts the relative wave heights at different locations along the rigid emergent trunk model with roots of width 2 m, for a relative plant height, h_s/d = 0.47 subjected to waves of varying heights and periods.

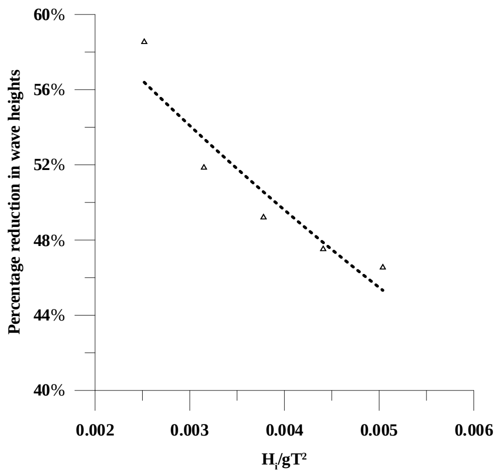
For w/L = 0.804, T = 1.4 s, as H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 61.45% to 50.97%, as seen in Fig. 5.17 (a). A similar trend of decrease in wave height reduction from 57.30% to 47.10%, 58.54% to 46.54% and 57.14% to 45.91% is observed for the cases corresponding to w/L = 0.696, T = 1.6 s; w/L = 0.583, T = 1.8 s and w/L = 0.515, T = 2 s, respectively (Fig. 5.17 b to d). These results also support the fact that wave attenuation decreases as wave periods increase along a constant water depth.



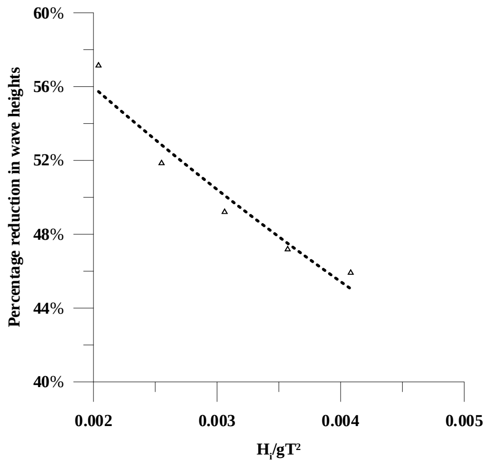
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s

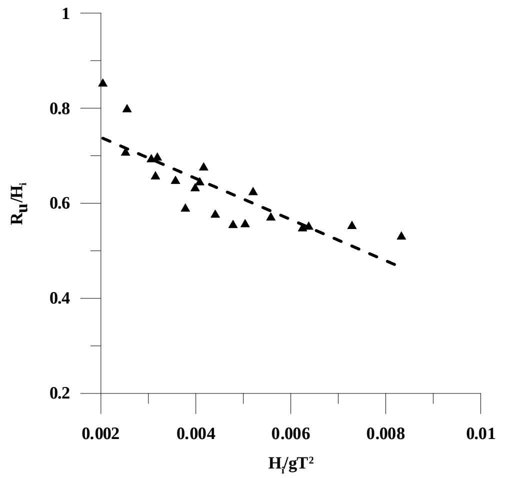


(d) for w/L = 0.515, T = 2 s

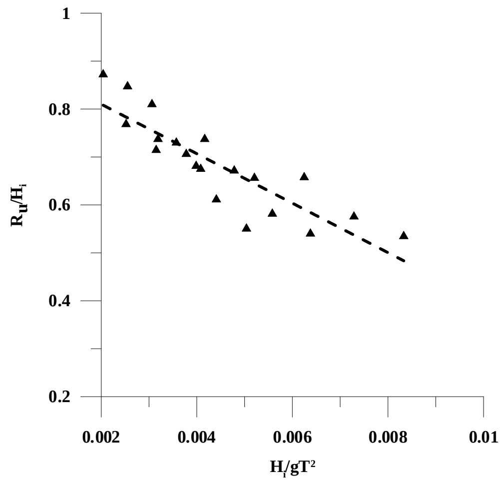
Fig. 5.17 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w = 2 m

5.3.2 Effect of wave steepness on run-up

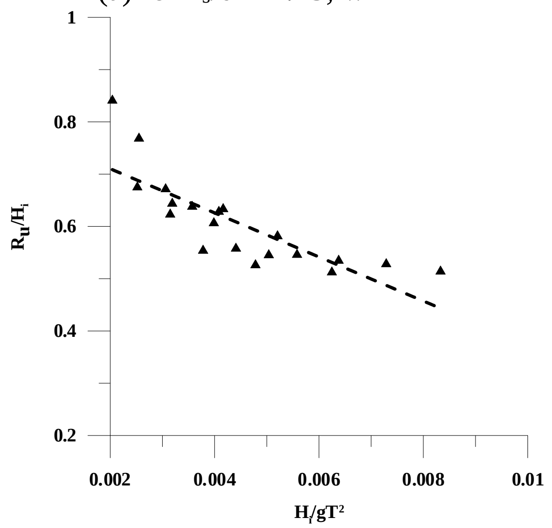
The variation of wave run up over the beach slope with an increase in wave steepness for the emergent trunk model with roots of width 1 m and 2 m, corresponding to relative plant heights, h_s/d = 1.25, 1.11 and wave periods, T = 1.4 s to 2 s is illustrated in Fig. 5.18 (a to d).



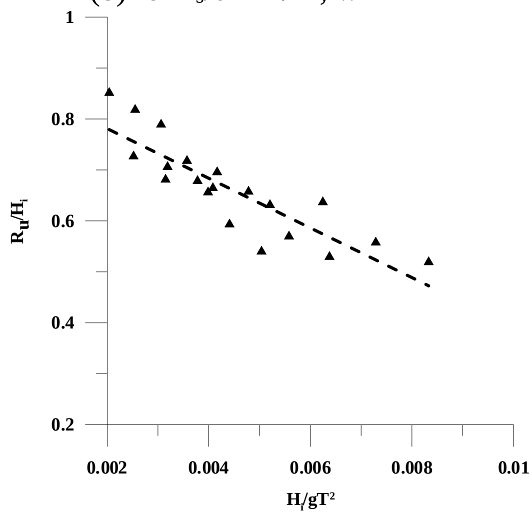
(a) for h_s/d = 1.25; w = 1 m



(b) for h_s/d = 1.11; w = 1 m



(c) for h_s/d = 1.25; w = 2 m



(d) for h_s/d = 1.11; w = 2 m

Fig. 5.18 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d)

As the wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00832, R_u/H_i decreases from 0.851 to 0.529 for the case of emergent trunk model with roots of width 1 m (h_s/d = 1.25), whereas, it varies from 0.841 to 0.512 for the same model of width 2 m, subjected to waves of incident wave heights ranging from 0.08 m to 0.16 m and periods, T = 1.4 to 2 s (Fig. 5.18). Similarly, for the same model of relative plant height, h_s/d = 1.11, as the wave steepness parameter (H_i/gT^2) increases from 0.00203 to

0.00832, R_u/H_i decreases from 0.851 to 0.519 and for the model of width 2 m, as depicted in Fig. 5.18 (d). These results when compared with the percentage reduction in wave heights discussed in sections 5.3.1.3 and 5.3.1.4, strongly suggests that as the percentage reduction in wave heights increases, there is a decreased extent of inundation on the beach slope.

5.4 COMPARISON OF PERFORMANCE OF EMERGENT VEGETATION MODELS

The results from the studies conducted on emergent vegetated models, namely, emergent trunk model and the emergent trunk model with roots, discussed in section 5.2 and 5.3 explains the fact that the incident wave characteristics as well as the vegetation parameters plays a key role in wave height attenuation and the corresponding wave run-up on the beach.

A comparison of results discussed in chapter 4 and the present chapter reveals that the submerged rigid vegetation model shows increased wave height attenuation, when compared with the emergent trunk model, both having meadow width equal to 2 m. Regardless of the emergence of the vegetation which should ideally provide increased attenuation, the emergent trunk model does not perform well in terms of wave height attenuation when compared to the submerged rigid vegetation model. This can be attributed to the role of plant density (N) in wave attenuation. For the 2 m wide submerged rigid vegetation model (N = 394 plants/m^2), the percentage reduction in wave heights varies from 62.65% to 46.71% for the case of higher relative plant height (h_s/d = 0.525) and from 57.83% to 41.51% for h_s/d = 0.47; whereas, for the emergent trunk model (N = 107 plants/m^2) of width 2 m, it varies from 39.47% to 33.88% for h_s/d = 1.25 and from 35.90% to 30.67% for h_s/d = 1.11. The emergent trunk model with roots (N = 107 trunks/m^2, 300 $roots_1/m^2$, 300 $roots_2/m^2$) shows a higher wave height attenuation, with percentage reduction in wave heights varying from 66.27% to 50.90% for h_s/d = 1.25 and from 61.45% to 45.91% for h_s/d = 1.11.

The results of submerged rigid vegetation model and the emergent trunk model with roots are comparable. The increased wave height attenuation for the model discussed in section 5.3, is attributed to the presence of submerged roots along with the emergent trunks. It is observed that for a higher relative plant height, owing to the relatively higher emergence of plant stems/trunks, its effect on wave attenuation is more pronounced because the stems effectively penetrate the layers of varying particle orbital velocities.

Among the emergent vegetation models, the emergent trunk model with roots of 2 m width shows maximum reduction in wave heights for both the cases with $h_s/d = 1.25$ and $h_s/d = 1.11$. The percentage wave height reduction for the emergent trunk model with roots of width 2 m for $h_s/d = 1.25$ ranges from 66.27% to 50.90%, for the entire set of incident wave characteristics, with the subsequent wave run-up on the beach (R_u/H_i) varying from 0.841 to 0.512, as wave steepness parameter (H_i/gT^2) increases from 0.00204 to 0.00832. The same model with relative plant height, $h_s/d = 1.11$, exhibits smaller percentage wave height reduction values in the range 61.45% to 45.91%, with R_u/H_i varying from 0.851 to 0.519, as wave steepness parameter (H_i/gT^2) increases from 0.00204 to 0.00832. The results clearly show that there is significant reduction in wave heights for the emergent trunk model with roots, which is attributed to the presence of submerged roots along with the emergent trunks.

5.5 KEY FINDINGS AND SUMMARY

The results of experimental runs on emergent vegetation models, namely, emergent trunk model and emergent trunk model with roots to determine the wave height attenuation and the corresponding run-up on beach slope presented in this chapter suggests that the meadow width parameter (w/L), relative plant height, (h_s/d), plant density (N) and wave steepness parameter (H_i/gT^2) are pivotal in governing the wave attenuation characteristics. The results are interpreted in terms of relative wave heights at locations within the vegetation model (H_x/H_i), percentage reduction in wave heights

$\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$, and the corresponding beach inundation expressed in terms of relative wave run up (R_u/H_i) on the beach.

The key findings of this study on emergent vegetation models are:

5.5.1 Conclusions for emergent trunk model

1. The percentage wave height at exit point of a 1 m wide (w/L = 0.418-0.270 for h_s/d = 1.25; 0.401-0.257 for h_s/d = 1.11) meadow varies from 75.06% - 80.60% and from 80.77% - 85.28% for h_s/d of 1.25 and 1.11, respectively; whereas the percentage wave height reduction for the same case varies from 29.94% - 19.40% and from 19.23% - 14.72% for h_s/d of 1.25 and 1.11, respectively for the emergent trunk model of plant density, N = 107 trunks/m^2.
2. For a 2 m wide model, the percentage wave height at exit point of a 2 m wide (w/L = 0.836-0.541 for h_s/d = 1.25; 0.804-0.515 for h_s/d = 1.11) meadow varies from 60.53% - 66.12% and from 64.10% - 69.33% for h_s/d of 1.25 and 1.11, respectively; whereas the percentage wave height reduction varies from 39.47% - 33.88% and from 35.90% - 30.67% for h_s/d of 1.25 and 1.11, respectively for the same model.
3. As wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.903 to 0.653 (h_s/d =1.25) and from 0.923 to 0.659 (h_s/d =1.11) for the emergent trunk model of width 1 m.
4. For the emergent trunk model of width 2 m, as wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.872 to 0.628 (h_s/d =1.25) and from 0.893 to 0.638 (h_s/d =1.11).

5.5.2 Conclusions for emergent trunk model with roots

1. The percentage wave height at exit point of a 1 m wide (w/L = 0.418-0.270 for h_s/d = 1.25; 0.401-0.257 for h_s/d = 1.11) meadow varies from 46.99% - 65.27% and from 56.63% - 72.33% for h_s/d of 1.25 and 1.11, respectively; whereas the percentage wave height reduction for the same case varies from 53.01% -

34.73% and from 43.37% - 27.67% for h_s/d of 1.25 and 1.11, respectively for the emergent trunk model with roots of plant density, N = 107 trunks/m^2, 300 $roots_1/m^2$, 300 $roots_2/m^2$.

2. For a 2 m wide model, the percentage wave height at exit point of a 2 m wide (w/L = 0.836-0.541 for h_s/d = 1.25; 0.804-0.515 for h_s/d = 1.11) meadow varies from 33.73% - 49.10% and from 38.55% - 54.09% for h_s/d of 1.25 and 1.11, respectively; whereas the percentage wave height reduction varies from 66.27% - 50.90% and from 61.45% - 45.91% for h_s/d of 1.25 and 1.11, respectively for the same model.
3. As wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.851 to 0.529 (h_s/d =1.25) and from 0.871 to 0.534 (h_s/d =1.11) for the emergent trunk model with roots of width 1 m.
4. For the emergent trunk model with roots of width 2 m, as wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.841 to 0.512 (h_s/d =1.25) and from 0.851 to 0.519 (h_s/d =1.11).

The optimum meadow width (w), relative plant height (h_s/d) and plant density (N) which gives the maximum wave attenuation and minimum run-up on the beach slope corresponds to the emergent trunk model with roots of meadow width, w = 2 m, relative plant height, h_s/d = 1.25 and plant density, N = 107 trunks/m^2, 300 $roots_1/m^2$, 300 $roots_2/m^2$; wherein, the percentage reduction of wave height varies from 66.27% to 50.90% and wave run-up on the beach ranges between 0.841 to 0.512, when compared to the results of the same emergent trunk model, without roots, where the percentage wave height reduction varies from 39.47% to 33.88% and wave run-up on the beach ranges between 0.872 to 0.628. The results of this experimental study on emergent trunk model with roots of meadow width 2 m which shows an increased percentage reduction of wave height varies from 66.27% to 50.90% highlights the capability of mangrove trees which thrive in the open coastal environment in wave attenuation and in reducing the wave impact on the beach.

CHAPTER 6

INVESTIGATIONS ON HETEROGENEOUS VEGETATION MODELS

6.1 GENERAL

The effectiveness of submerged and emergent vegetation models on wave height attenuation and the subsequent wave run-up on the beach slope was studied and discussed in detail in chapters 4 and 5, which revealed the influence of vegetation height heterogeneity on wave attenuation.

Coastal vegetation shows a large variability of species composition across the globe. Apart from the ability of individual natural habitats such as seagrasses, coral reefs, salt marshes and mangroves to protect the shoreline against the fury of intense wave activity and storm surges, it is still uncertain how these habitats can complement each other in containing these impacts on the shoreline (Guannel et al., 2016). Since these marine ecosystems are well connected to each other by various biological, chemical and physical processes (Grober-Dunsmore et al., 2009), they often co-exist as spatially and dynamically heterogenous seascapes (Barbier and Lee, 2014). Therefore, it is of interest to experimentally analyze the wave height attenuation and the subsequent wave run-up on the beach due to heterogeneous vegetation models of different combinations of vegetation types.

The experiments are conducted on heterogeneous vegetation models namely, submerged heterogeneous model, emergent heterogeneous model and compound heterogeneous model for varying wave conditions. The selection of meadow width for the heterogeneous model is based upon the experimental results obtained for the individual vegetation models discussed in chapters 4 and 5, wherein, the effect of varying meadow widths on wave height attenuation and its subsequent influence on beach run-up is discussed in detail. The results of the previous chapters indicate that the meadow width of 2 m is more effective in wave attenuation than that of 1 m, and therefore, the maximum width of the individual plant model (2 m) is selected for the heterogeneous vegetation models. Another important parameter having a prominent role in wave height attenuation and subsequent inundation on the beach is the plant density (N). This chapter discusses the effect of emergent vegetation models of varying plant densities on wave attenuation and subsequent wave run-up. The variation of measured wave height at locations (H_x/H_i) within the heterogeneous vegetation models with respect to the percentage meadow width, the influence of wave steepness (H_i/gT^2) on percentage wave height reduction $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$ and the subsequent wave run-up on the beach, measured in terms of wave run-up (R_u/H_i) is discussed in this chapter; with emphasis on the effect of relative plant height (h_s/d), the meadow width parameter (w/L) and plant density (N).

6.2 STUDIES ON SUBMERGED HETEROGENEOUS MODEL

A 1:30 scaled submerged heterogeneous model, comprising of a 2 m wide seagrass meadow followed by a 2 m wide rigid vegetation meadow placed on the flume bed is subjected to waves of height varying from 0.08 m to 0.16 m at an interval of 0.02 m and periods ranging from 1.4 s to 2 s, at an interval of 0.2 s. Results of experiments conducted with this model of relative plant heights 0.525 and 0.47 are presented in this section.

6.2.1 Wave height attenuation

Results presented in the previous chapters 4 and 5 displayed the role of height of vegetation, represented by the relative plant height (h_s/d) and the meadow width parameter (w/L) in wave height attenuation and subsequent inundation on the beach, due to individual vegetation models of submerged and emergent types. In order to quantify the effect of individual coastal habitats complementing each other in containing storm surges and wave activity, results of experiments conducted with a combination of submerged seagrass and rigid vegetation are presented in this section. During the course of the test runs, it is seen that the seagrass leaves are subjected to continuous back and forth motion as the wave passes over this section, whereas, the motion of stems in rigid vegetation is negligible as the wave further propagates, which is attributed to the characteristics of the vegetation, mainly the stiffness. Snapshots of model set up to study the wave attenuation over the submerged heterogeneous model is displayed in Plate 6.1.

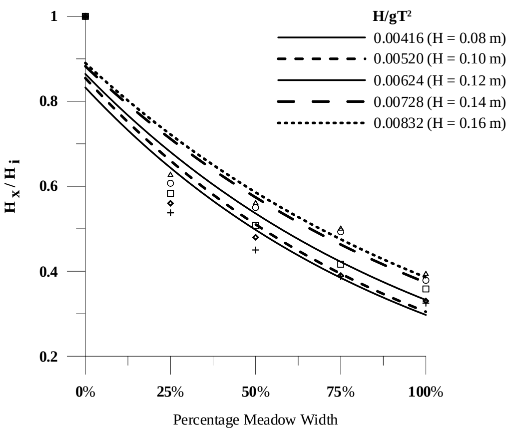
(a) (b)

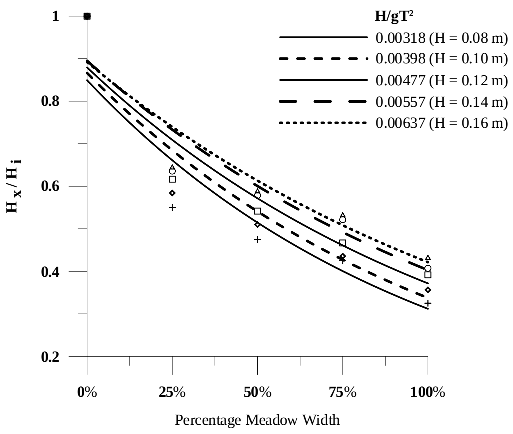
Plate 6.1 Snapshots of model setup to study wave attenuation over a submerged heterogeneous vegetation model a) side view b) top view

6.2.1.1 Relative plant height, $h_s/d = 0.525$; meadow width, w = 4 m

In this section, results are presented for the case of waves propagating through a submerged heterogeneous model of width 4 m and relative plant height, $h_s/d = 0.525$. A plot of relative wave heights at locations within the model, $\left(\frac{H_x}{H_i}\right)$ and percentage meadow width, illustrated in Fig. 6.1 (a to d) explains the reduction in wave heights as waves of varying heights and periods propagates along this model.

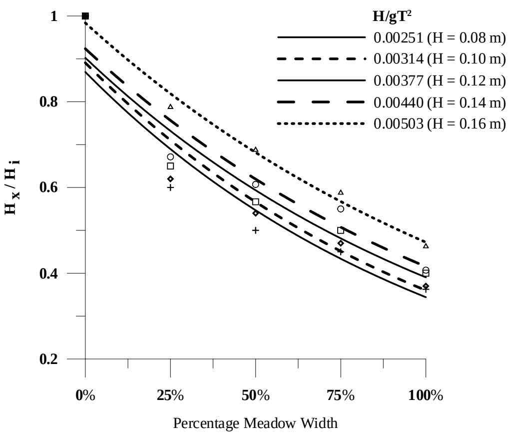
As illustrated in Fig. 6.1 (a-d), the relative percentage wave height at the exit point, of the meadow varies from 32.50% to 37.50% for an incident wave of height 0.08 m. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 33.00% to 39.00%, from 35.83% to 43.33%, from 37.86% to 45.71% and from 39.33% to 48.75%.

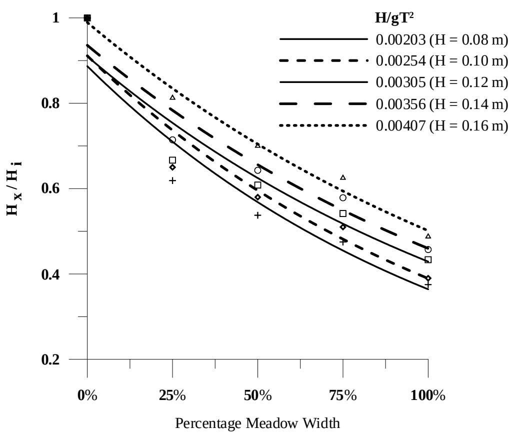




(a) for w/L = 1.672, T = 1.4 s

(b) for w/L = 1.428, T = 1.6 s



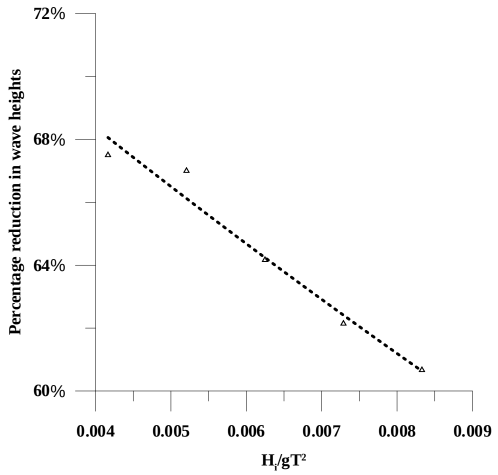


(c) for w/L = 1.223, T = 1.8 s

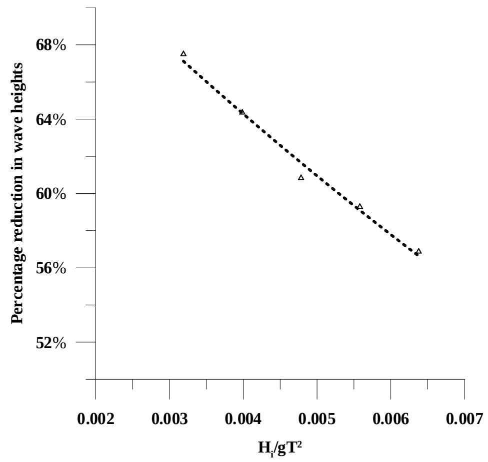
(d) for w/L = 1.082, T = 2 s

Fig. 6.1 Relative wave heights at locations within the model for h_s/d = 0.525; w = 4 m

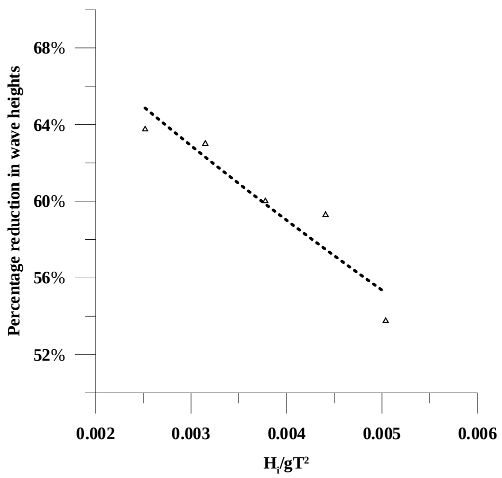
Fig. 6.2 (a to d) depicts the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction, wherein it is noted that there is a decrease in wave height reduction from 67.50% to 60.67% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 1.672, T = 1.4 s), from 67.50% to 56.88%, 63.75% to 53.75% and from 62.50% to 51.25% for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 1.428, T = 1.6 s), 0.00251 to 0.00503 (w/L = 1.223, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 1.082, T = 2 s), respectively. It is clear from the above results that the heterogenous submerged model exhibits increased wave height reduction when compared to the individual submerged models namely, seagrass and rigid vegetation of width 2 m each, as discussed in sections 4.2.1.3 and 4.3.1.3. This wave height reduction is obvious predominantly due to the presence of a seagrass meadow followed by a rigid vegetation bed which aids in increased attenuation. The presence of the initial bed of seagrass of width 2 m penetrates the layers of varying particle orbital velocities, causing an alteration in the wave orbital velocities, which subsequently results in an increased turbulence and loss of energy and thereby reduction in wave heights. The wave when further propagates along the rigid vegetation meadow undergoes further reduction in wave heights due to the increased stiffness of stems which controls the vegetation motion leading to increased wave attenuation.



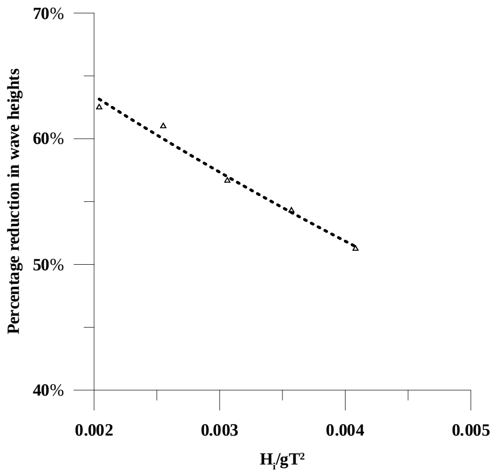
(a) for w/L = 1.672, T = 1.4 s



(b) for w/L = 1.428, T = 1.6 s



(c) for w/L = 1.223, T = 1.8 s



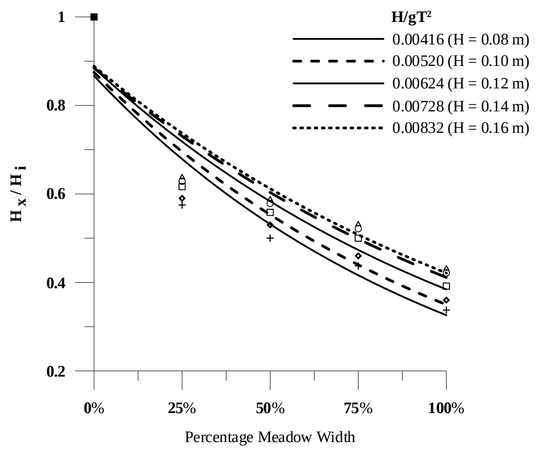
(d) for w/L = 1.082, T = 2 s

Fig. 6.2 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.525; w = 4 m

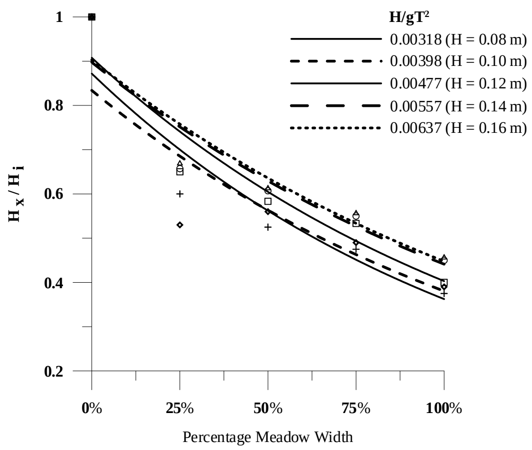
6.2.1.2 For relative plant height, h_s/d = 0.47; meadow width, w = 4 m

This section describes the wave reduction along a submerged heterogenous vegetation model due to the effect of reduction in relative plant height (h_s/d) from 0.525 to 0.47, as the water depth increases from 0.40 m to 0.45 m.

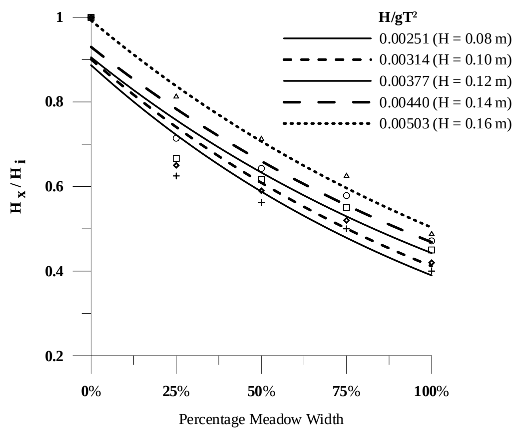
Fig. 6.3 (a to d) illustrates the relative wave heights at locations within the submerged heterogeneous model of width 4 m. For incident waves of heights 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, the relative percentage wave height at the exit point, of the meadow varies from 33.75% to 42.50%, from 36.00% to 45.00%, from 39.17% to 48.33%, from 42.14% to 50.00% and from 43.13% to 51.88%, respectively, corresponding to a range of wave periods from 1.4 s to 2 s.



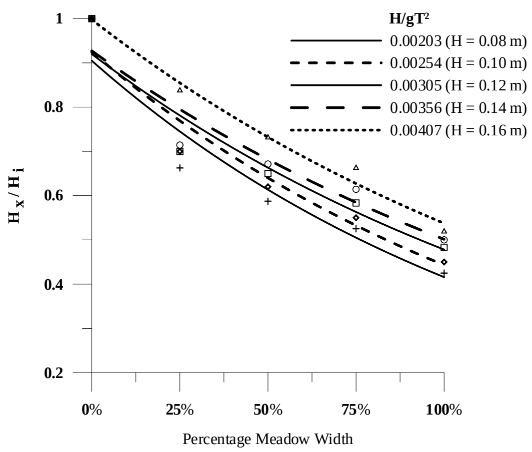
(a) for w/L = 1.607, T = 1.4 s



(b) for w/L = 1.393, T = 1.6 s



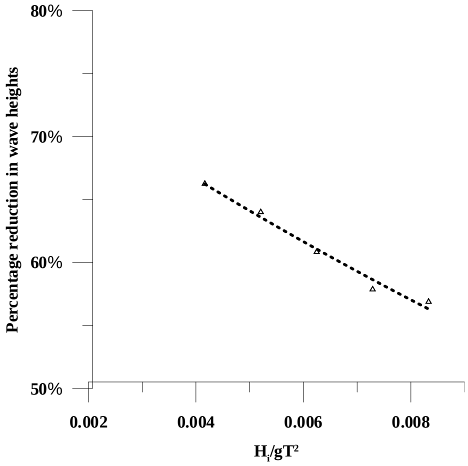
(c) for w/L = 1.167, T = 1.8 s



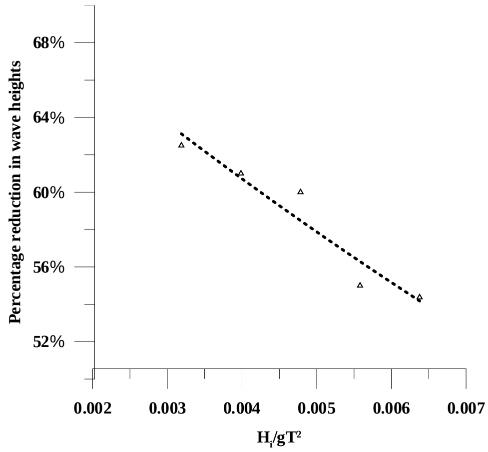
(d) for w/L = 1.031, T = 2 s

Fig. 6.3 Relative wave heights at locations within the model for h_s/d = 0.47; w = 4 m

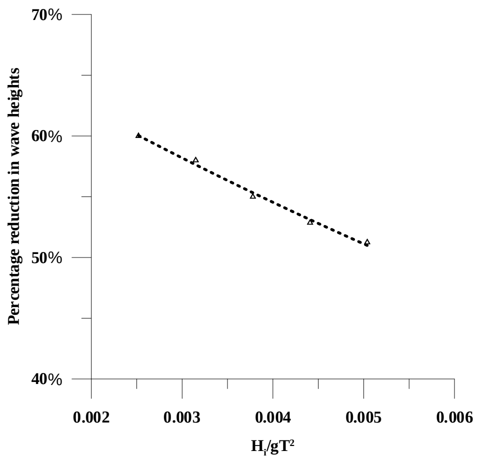
Fig. 6.4 (a) illustrates the percentage reduction in wave heights, for increasing wave steepness, which varies from 66.25% to 56.88% for wave steepness parameter, H_i/gT^2 ranging from 0.00416 to 0.00832 (w/L = 1.607, T = 1.4 s).



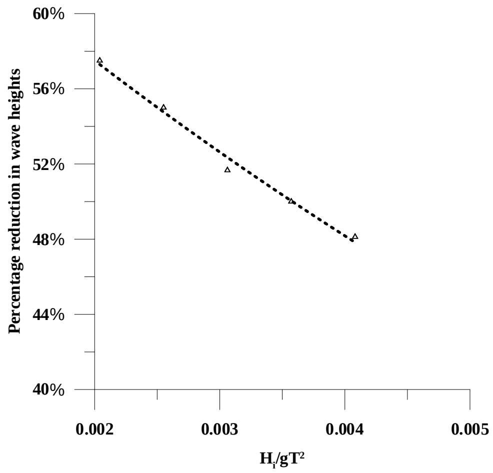
(a) for w/L = 1.607, T = 1.4 s



(b) for w/L = 1.393, T = 1.6 s



(c) for w/L = 1.167, T = 1.8 s

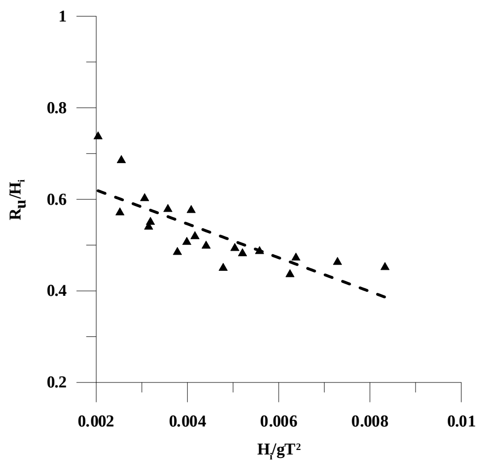


(d) for w/L = 1.031, T = 2 s

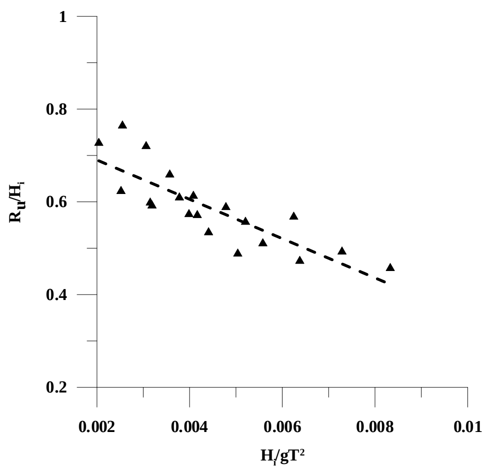
Fig. 6.4 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 0.47; w = 4 m

Correspondingly, for w/L = 1.393, T = 1.6 s, H_i/gT^2 = 0.00318 to 0.00637; w/L = 1.167, T = 1.8 s, H_i/gT^2 = 0.00251 to 0.00503 and w/L = 1.031, T = 2 s, H_i/gT^2 = 0.00203 to 0.00407, the percentage reduction in wave height varies from 62.50% to 54.38%, 60.00% to 51.25% and from 57.50% to 48.13%, respectively Fig. 6.4 (b to d). The results in this section justifies the fact that wave height attenuation decreases as the relative plant height (h_s/d) changes from 0.525 to 0.47. For h_s/d = 0.525, since the depth of water is lower, as the wave passes along the width of the heterogeneous model, the leaves/stems successfully interfere with the particle orbital velocities resulting in increased wave attenuation when compared to the case of h_s/d = 0.47. As the degree of interference is less, the wave passes effortlessly which results in reduced wave height attenuation. From the above results, it is also noted that there exists an inverse relationship between wave period and wave attenuation.

6.2.2 Effect of wave steepness on run-up



(a) for h_s/d = 0.525



(b) for h_s/d = 0.47

Fig. 6.5 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d)

The extent of run-up on the beach slope, measured as wave run-up on the beach for the submerged heterogeneous model (h_s/d = 0.525) varies from 0.519 to 0.436 (for w/L = 1.672; T = 1.4 s), from 0.550 to 0.450 (for w/L = 1.428; T = 1.6 s), from 0.571 to 0.484 (for w/L = 1.223; T = 1.8 s) and from 0.737 to 0.576 (for w/L = 1.082; T = 2 s), whereas it varies from 0.571 to 0.457 (for w/L = 1.607; T = 1.4 s), 0.592 to 0.472 (for w/L = 1.393; T = 1.6 s), 0.623 to 0.488 (for w/L = 1.167; T = 1.8 s) and 0.764 to 0.612 (for w/L = 1.031; T = 2 s), as the water depth increases to 0.45 m (relative plant height, h_s/d = 0.47).

The percentage reduction in wave heights for the submerged heterogeneous model of width 4 m, for h_s/d = 0.525, ranges from 67.50% to 51.25% for entire set of incident wave parameters. The corresponding wave run-up measurements (R_u/H_i) on the beach slope ranges from 0.737 to 0.436, for an increase in wave steepness parameter (H_i/gT^2) from 0.00203 to 0.00833, as depicted in Fig. 6.5 (a). It is therefore noted that the relative wave run-up (R_u/H_i) decreases with an increase in wave steepness parameter (H_i/gT^2); whereas, the relative wave run-up (R_u/H_i) varies from 0.764 to 0.457 for h_s/d = 0.47 (as in Fig. 6.5 (b)), corresponding to a percentage wave height reduction ranging from 66.25% to 48.13%. The results presented in this section shows that the extent of run-up on the beach is as a result of the extent of attenuation of wave heights.

6.3 STUDIES ON EMERGENT HETEROGENEOUS MODEL

A 1:30 scale emergent heterogeneous model, placed on the horizontal flume bed at 30 m away from the wave flap, is subjected to waves of heights varying from 0.08 m to 0.16 m at an interval of 0.02 m and periods 1.4 s to 2 s. Results of experiments conducted with this model is presented below.

6.3.1 Wave height attenuation

As discussed in the earlier chapter on emergent vegetation models, the presence of vegetation near the surface attenuates the wave energy further as they increasingly interfere in the wave field propagating above and offer frictional resistance to particle movement. The importance of height of the vegetation in wave dissipation is discussed in detail in section 5.1. Further to the discussion in section 6.1 about different coastal habitats complementing each other leading to increased wave energy dissipation as well as the role of emergent vegetation to contain wave activity (chapter 5), it is intended to test an emergent heterogeneous model subjected to waves of varying heights and periods. The emergent heterogeneous model consists of a submerged rigid vegetation of width 2 m, followed by an emergent trunk model with roots of width 2 m, placed on the flume bed. In this model, the emergent trunk model with roots is preferred over the emergent trunk model because of the fact that the former model performs better with respect to wave height attenuation and subsequent beach run-up, as discussed in Chapter 5. This chapter showcases the variation of measured wave height at locations within the emergent heterogeneous models with respect to the percentage meadow width and the extent of inundation over the beach slope with respect to wave steepness parameter. The propagation of wave along the emergent heterogeneous model is depicted in Plate 6.2.

(a) (b)

Plate 6.2 Snapshots of wave propagation along the emergent heterogeneous model a) side view b) top view

6.3.1.1 For relative plant height, $h_s/d = 1.25$; meadow width, $w = 4$ m

The presence of trunks and roots in the emergent vegetation model along with the submerged rigid vegetation model leads to an increase in wave height attenuation because of the variation in plant density as well as in plant heights.

Analysis of relative wave heights at locations within the emergent heterogeneous model reveals the same trend of exponential decay in wave heights as it propagates along the model, discussed in the previous chapters. The relative percentage wave height at the exit point of the meadow varies from 30.00% to 35.00%, 31.00% to 37.00%, 34.17% to 40.83%, 36.43% to 43.57% and from 38.00% to 47.50% corresponding to incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as illustrated in Fig. 6.6 (a to d)

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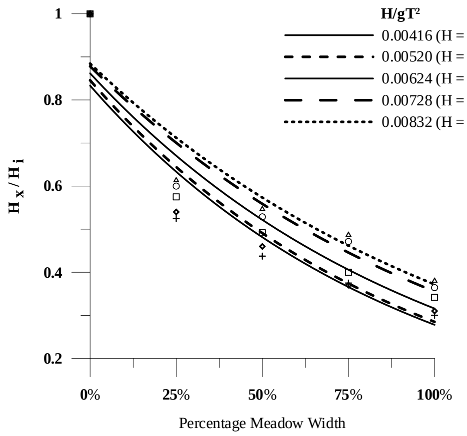
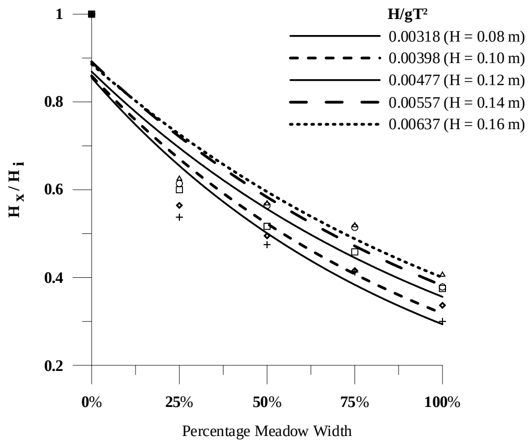
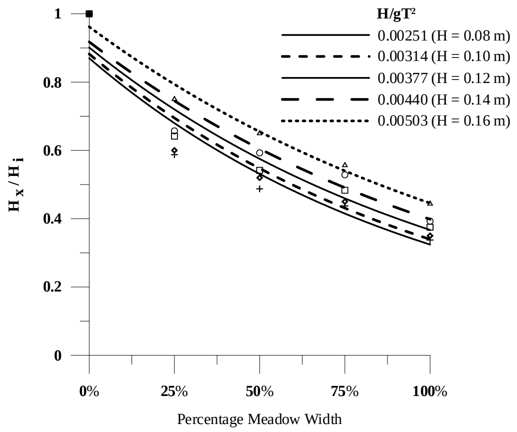


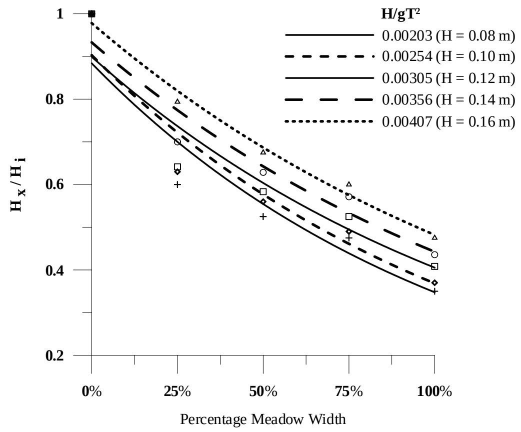
(a) for w/L = 1.672, T = 1.4 s



(b) for w/L = 1.428, T = 1.6 s



(c) for w/L = 1.223, T = 1.8 s

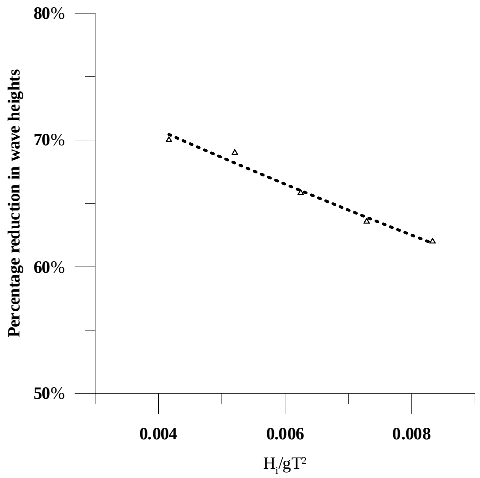


(d) for w/L = 1.082, T = 2 s

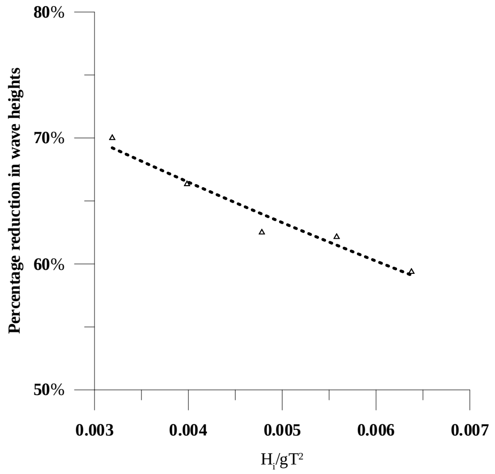
Fig. 6.6 Relative wave heights at locations within the model for h_s/d = 1.25; w = 4 m

The percentage reduction in wave heights for an emergent heterogeneous model is 70.00% to 52.50% when compared to a reduction of 67.50% to 51.25% for the case of the submerged heterogeneous model of same meadow width parameter (w/L = 1.672-1.082), for relative plant heights (h_s/d) 1.25 and 0.525 respectively. The above results confirm the fact that the wave height reduction is higher for the emergent heterogeneous model, since the emergence of the trunks provides an increased interference in the wave field. As the wave passes along the submerged heterogeneous model, there is reduction in wave heights, but as it propagates through the emergent heterogeneous model, the increased turbulence owing to the emergence of the trunk along with the presence of roots leads to an increase in wave height reduction.

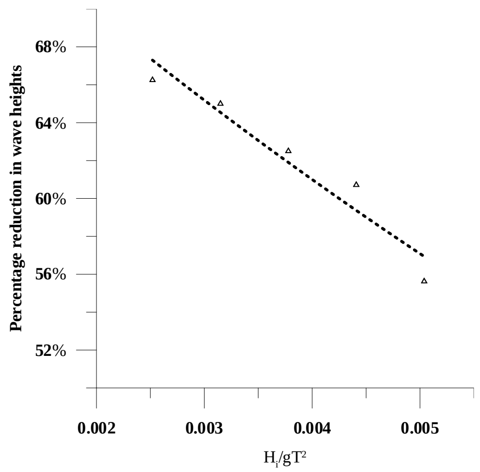
Fig. 6.7 (a to d) illustrated that as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832, 0.00318 to 0.00637, 0.00251 to 0.00503 and from 0.00203 to 0.00407, percentage reduction in wave heights varies from 70.00% to 62.00%, 70.00% to 59.38%, 66.25% to 55.63% and from 65.00% to 52.50%, respectively.



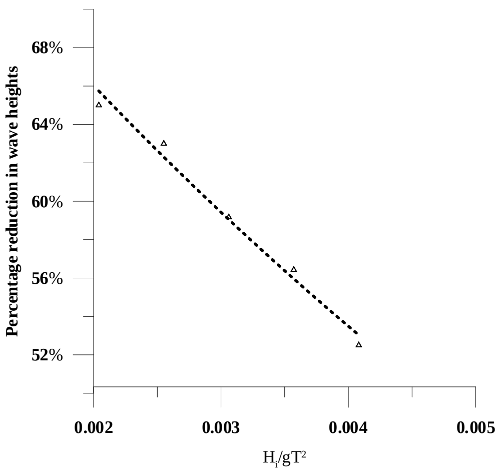
(a) for w/L = 1.672, T = 1.4 s



(b) for w/L = 1.428, T = 1.6 s



(c) for w/L = 1.223, T = 1.8 s



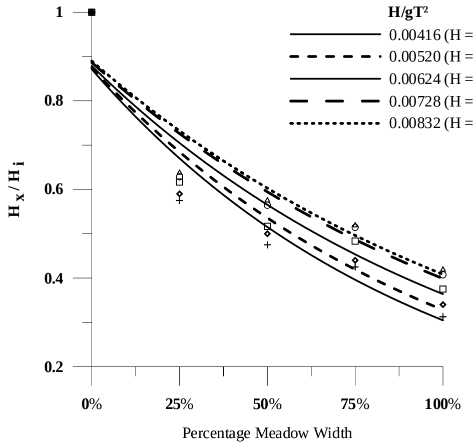
(d) for w/L = 1.082, T = 2 s

Fig. 6.7 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w = 4 m

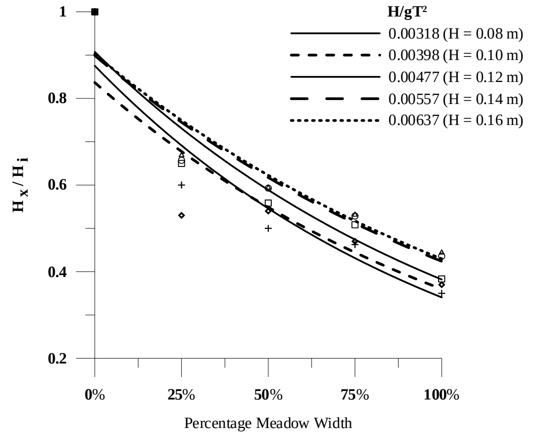
6.3.1.2 For relative plant height, h_s/d = 1.11; meadow width, w = 4 m

Fig. 6.8 (a to d) depicts the relative wave heights at different locations along the emergent heterogeneous model of width 4 m, for a relative plant height, h_s/d = 1.11 subjected to waves of varying heights and periods.

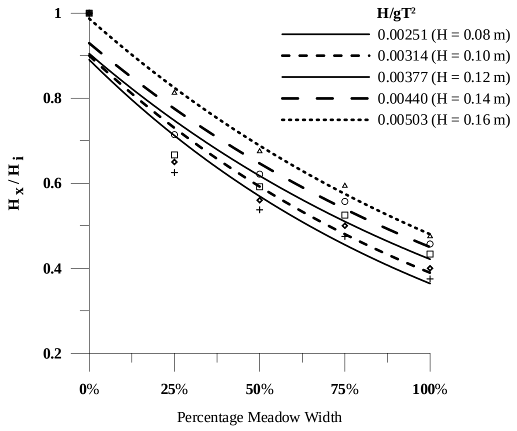
From the plots of relative wave heights at locations within the model illustrated in Fig. 6.8 (a to d), the relative percentage wave height at the exit point, of the meadow varies from 31.25% to 40.00%, 34.00% to 43.00%, 37.50% to 46.67%, 40.71% to 48.57% and from 41.88% to 50.63% corresponding to incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as illustrated in Fig. 6.8 (a to d).



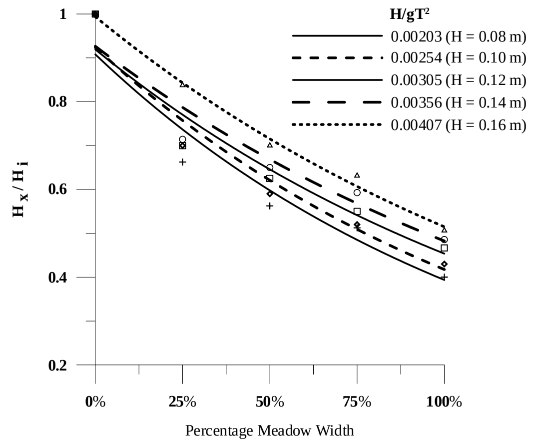
(a) for w/L = 1.607, T = 1.4 s



(b) for w/L = 1.393, T = 1.6 s



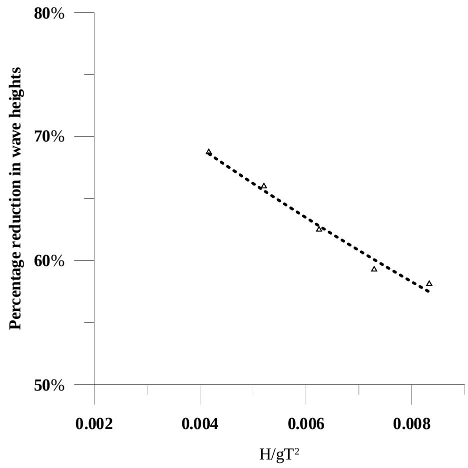
(c) for w/L = 1.167, T = 1.8 s

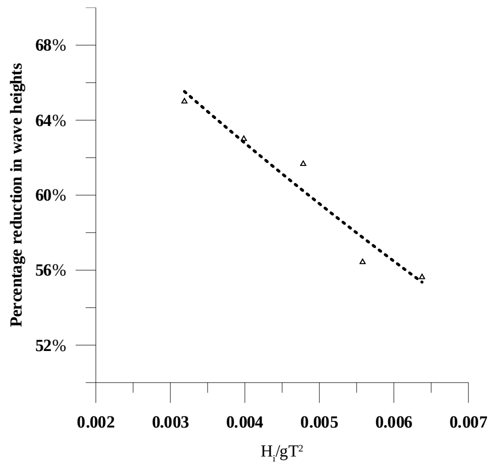


(d) for w/L = 1.031, T = 2 s

Fig. 6.8. Relative wave heights at locations within the model for $h_s/d = 1.11$; w = 4 m

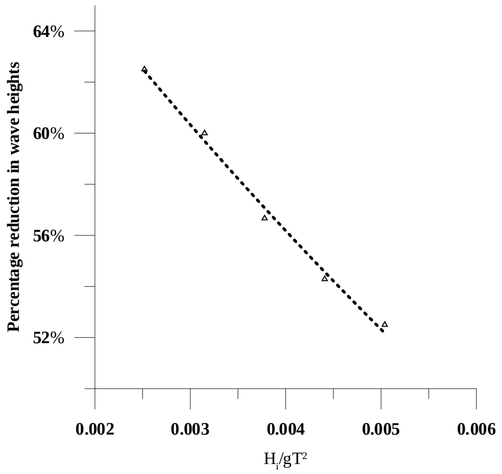
For w/L = 1.607, T = 1.4 s, as H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 68.75% to 58.13%, as seen in Fig. 6.9 (a). A similar trend of decrease in wave height reduction from 65.00% to 55.63%, 62.50% to 52.50% and 60.00% to 49.38% is observed for the cases corresponding to w/L = 1.393, T = 1.6 s; w/L = 1.167, T = 1.8 s and w/L = 1.031, T = 2 s, respectively (Fig. 6.9 b to d).

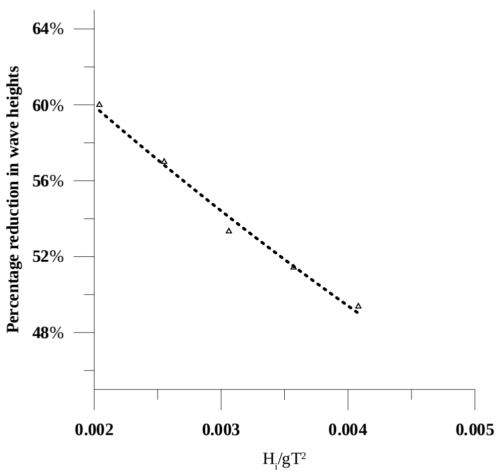




(a) for w/L = 1.607, T = 1.4 s

(b) for w/L = 1.393, T = 1.6 s





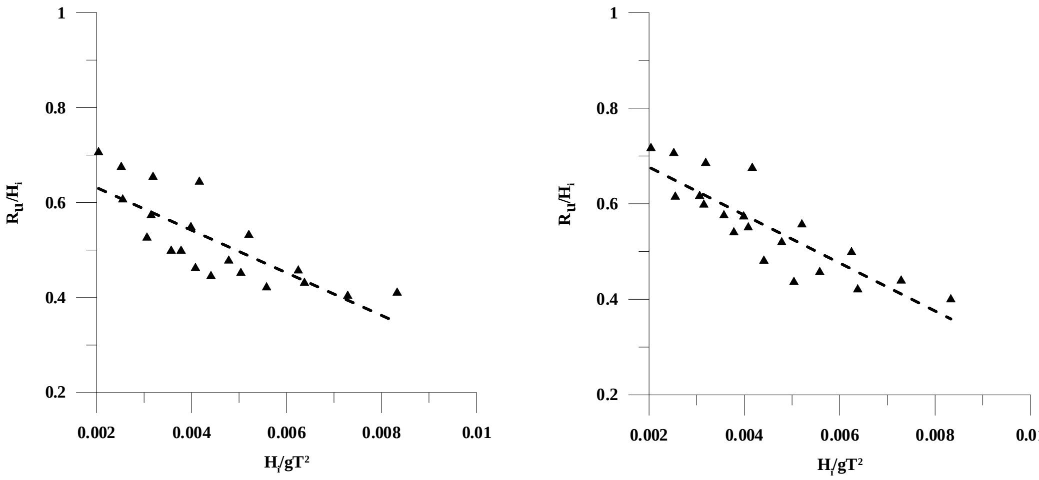
(c) for w/L = 1.167, T = 1.8 s

(d) for w/L = 1.031, T = 2 s

Fig. 6.9 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w = 4 m

6.3.2 Effect of wave steepness on run-up

The extent of inundation on the beach slope, expressed in terms of wave run up over the beach slope, with an increase in wave steepness for the emergent heterogeneous model of width 4 m, corresponding to relative plant heights, h_s/d = 1.25, 1.11 and wave periods, T = 1.4 s to 2 s is illustrated in Fig. 6.10 (a to b).



(a) for $h_s/d = 1.25$ (b) for $h_s/d = 1.11$

Fig. 6.10 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d)

As the wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00832, R_u/H_i decreases from 0.706 to 0.403 for the case of emergent heterogeneous model of width 4 m ($h_s/d = 1.25$), whereas, it varies from 0.716 to 0.400 for the same model of $h_s/d = 1.11$, subjected to waves of incident wave heights ranging from 0.08 m to 0.16 m and periods, T = 1.4 to 2 s (Fig. 6.10). These results when compared with the percentage reduction in wave heights discussed in sections 6.3.1.1 and 6.3.1.2, strongly suggests that as the percentage reduction in wave heights increases, there is a wave run-up on the beach slope. The increased reduction of wave run-up over the beach slope for the emergent heterogeneous model when compared to the submerged heterogeneous model discussed in section 6.2 is attributed to the presence of emergent trunks and roots in this model which causes increased wave height attenuation and subsequent reduction in wave run-up.

6.4 STUDIES ON COMPOUND HETEROGENEOUS MODEL

A 1:30 scaled compound heterogeneous model, comprising of a submerged seagrass model, submerged rigid vegetation and emergent trunk model with roots, placed in order (termed as the compound heterogeneous model) on the flume bed, is subjected to waves of height varying from 0.08 m to 0.16 m at an interval of 0.02 m. Results of experiments conducted with the compound heterogeneous model of varying relative plant heights are presented in this section.

6.4.1 Wave height attenuation

It is revealed from the previous chapters that the width of the meadow, the height of emergence of vegetation and the plant density plays a pivotal role in attenuating the wave heights passing through the meadow. In this section, the model subjected to the test runs is a compound heterogeneous model, which consists of both submerged (seagrass and rigid vegetation) as well as emergent (emergent trunk model with roots) models. Therefore, this model satisfies both increase in width of meadow (6 m), variation in vegetation heights as well as varying plant densities.

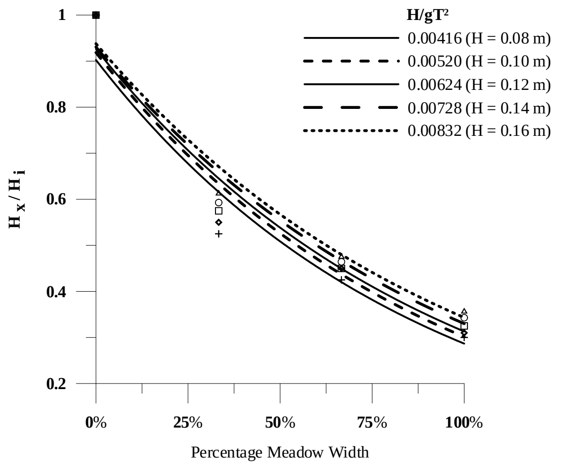
(a) (b)

Plate 6.3 Snapshots of model setup to study wave attenuation over a compound heterogeneous vegetation model a) side view b) top view

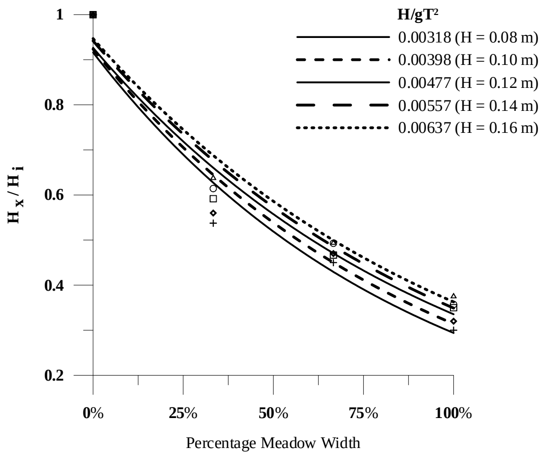
The selection of width of meadow of this particular model is based upon the performance of the models of varying widths discussed in the previous chapters 4 and 5 as well as the previous sections 6.2 and 6.3. Therefore, experiments are conducted with this compound model of selected width of 6 m, to observe the changes in wave heights as the wave propagates along the model. Plate 6.3 depicts the propagation of wave along the compound heterogeneous model.

6.4.1.1 For relative plant height, h_s/d = 1.25; meadow width, w = 6 m

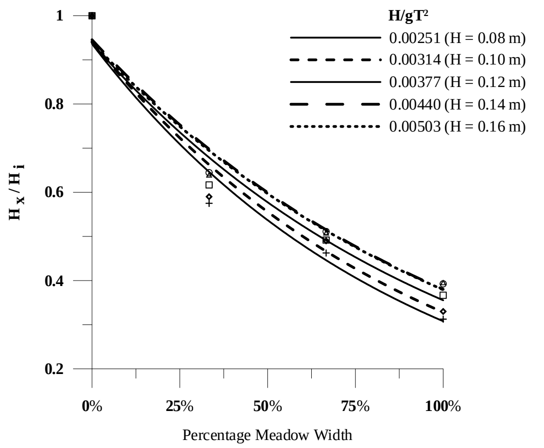
Fig. 6.11 (a) indicates that the relative percentage wave height at the exit point, $\left(\frac{H_{exit}}{H_i}\right)$ of the meadow is varies from 30.00% to 32.50% for an incident wave of height 0.08 m. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 31.00% to 36.00%, from 32.50% to 39.17%, from 34.29% to 40.00% and from 35.63% to 41.25%, respectively, as illustrated in Fig. 6.11 (b to d).



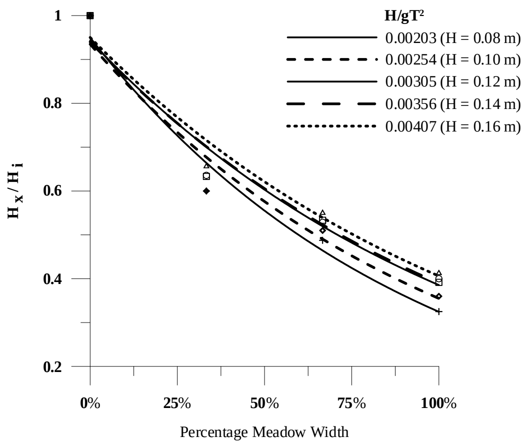
(a) for w/L = 2.508, T = 1.4 s



(b) for w/L = 2.142, T = 1.6 s



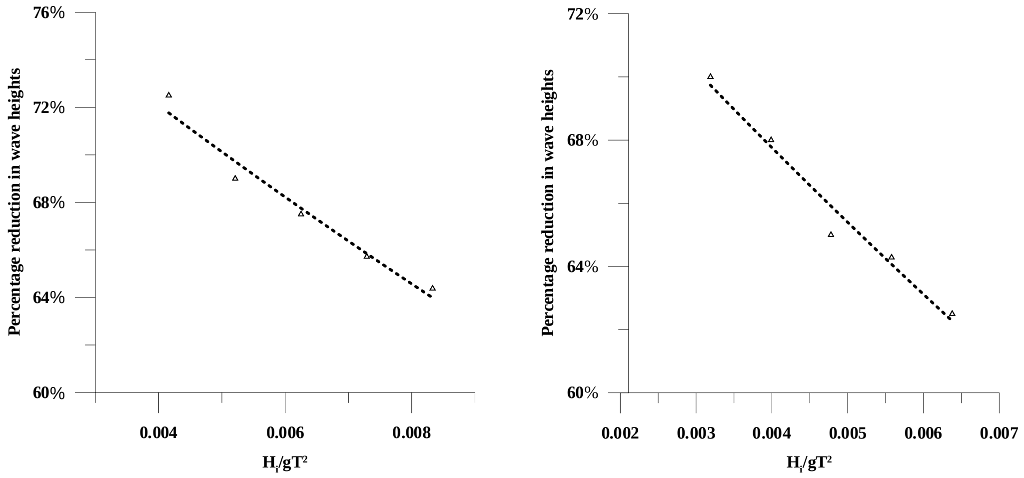
(c) for w/L = 1.835, T = 1.8 s



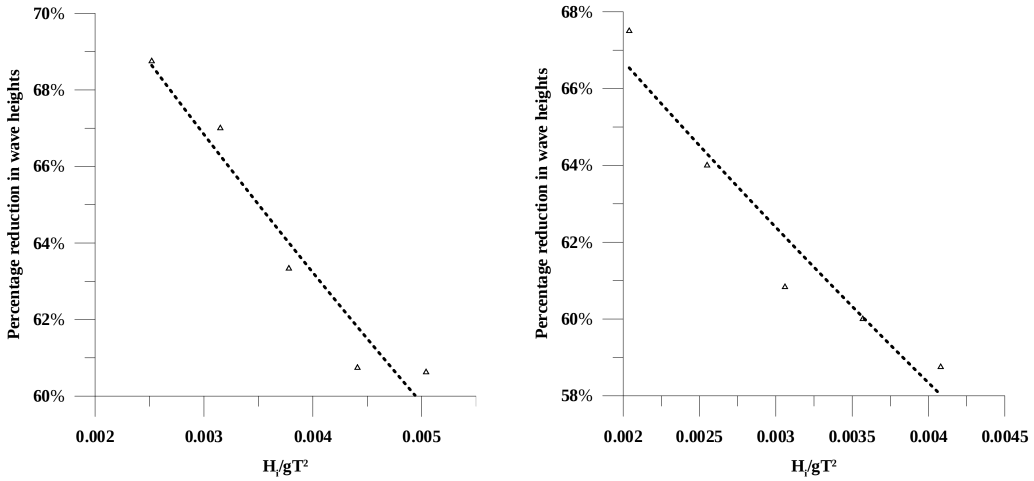
(d) for w/L = 1.623, T = 2 s

Fig. 6.11 Relative wave heights at locations within the model for h_s/d = 1.25; w = 6 m

In this complex model consisting of three types of simulated vegetation, as the wave passes over the seagrass meadow, the wave height decreases due to the interference of the seagrass leaves with the wave field. As the wave further propagates along the rigid submerged model as well as the emergent trunk model with roots, the wave height further decreases owing to the increased resistance provided by the submerged stems and the increased turbulence created by the emergent trunks.



(a) for w/L = 2.508, T = 1.4 s (b) for w/L = 2.142, T = 1.6 s



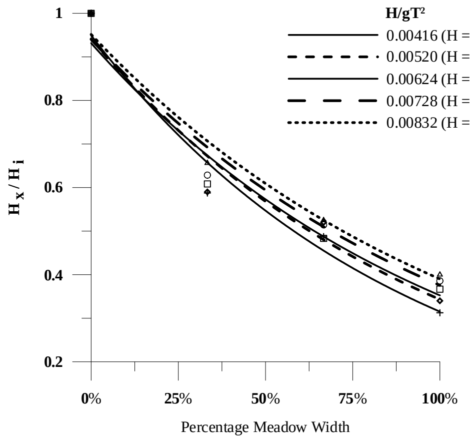
(c) for w/L = 1.835, T = 1.8 s (d) for w/L = 1.623, T = 2 s

Fig. 6.12 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w = 6 m

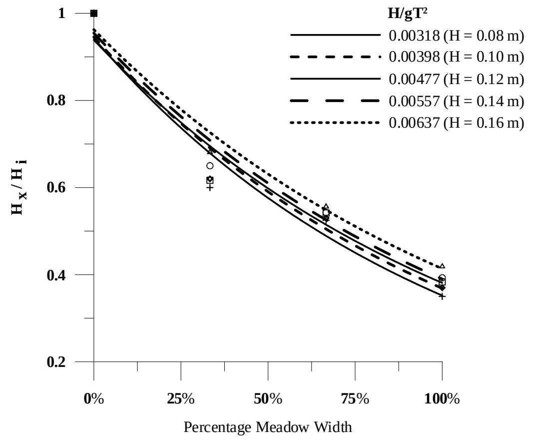
Fig. 6.12 (a to d) exhibits the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction, for this model. The percentage wave height reduction varies from 70.00% to 64.38% for T = 1.4 s, w/L = 2.508 and H_i/gT^2 =

0.00416 to 0.00832, as clearly observed in Fig. 6.12 (a). Similar variations in percentage reduction in wave heights from 70.00% to 62.50%, 68.75% to 60.63% and from 67.50% to 58.75% is observed for the same model with w/L = 2.142, T = 1.6 s, H_i/gT^2 from 0.00318 to 0.00637; w/L = 1.835, T = 1.8 s, H_i/gT^2 from 0.00251 to 0.00503 and w/L = 1.623, T = 2 s, H_i/gT^2 from 0.00203 to 0.00407, respectively (Figs. 6.12 a-d).

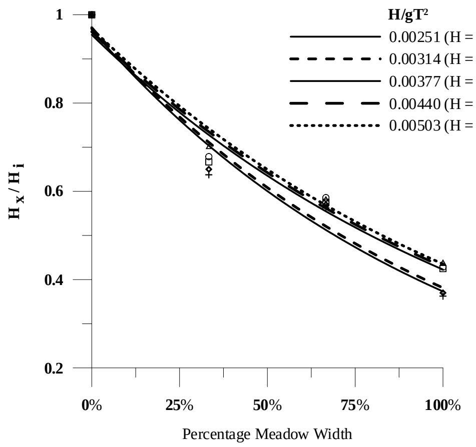
6.4.1.2 For relative plant height, h_s/d = 1.11; meadow width, w = 6 m



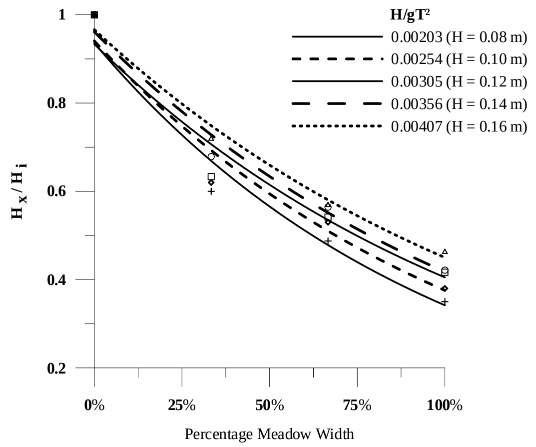
(a) for w/L = 2.411, T = 1.4 s



(b) for w/L = 2.089, T = 1.6 s



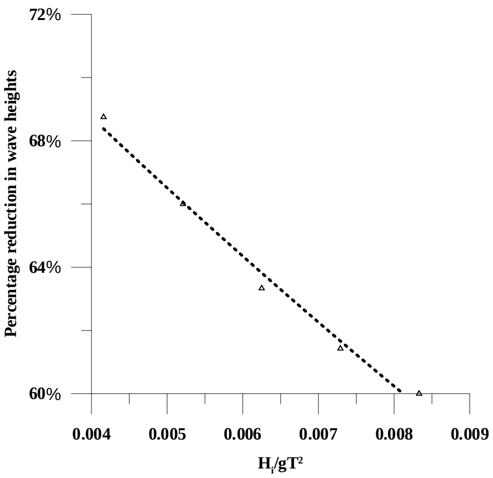
(c) for w/L = 1.750, T = 1.8 s



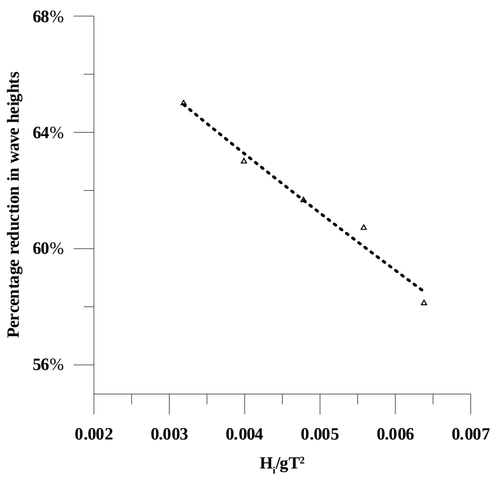
(d) for w/L = 1.546, T = 2 s

Fig. 6.13 Relative wave heights at locations within the model for h_s/d = 1.11; w = 6 m

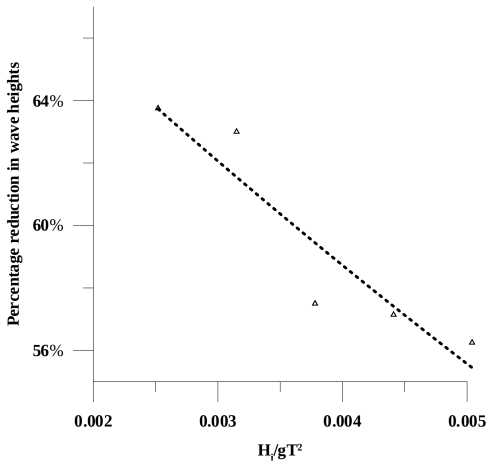
The effect of reduction in relative plant height (h_s/d) from 1.25 to 1.11 due to increase in water depth from 0.40 m to 0.45 m on wave height attenuation of compound heterogeneous model of 6 m width is discussed in this section. Fig. 6.13 (a to d) illustrates the relative wave heights at locations within this model of width 6 m. The relative percentage wave height at the exit point of the meadow varies from 31.25% to 35.00%, from 34.00% to 38.00%, from 36.67% to 41.67%, from 38.57% to 42.14% and from 40.00% to 46.25% for incident waves of heights 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, corresponding to a range of wave periods from 1.4 s to 2 s.



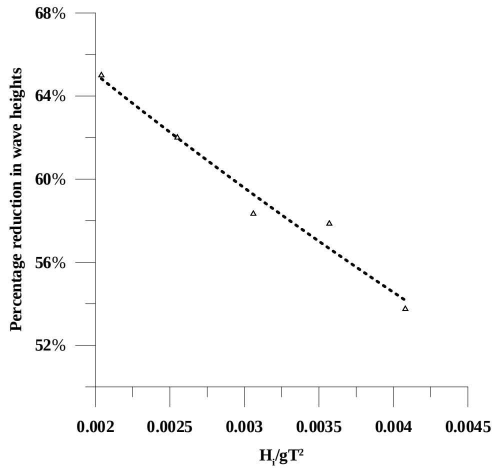
(a) for w/L = 2.411, T = 1.4 s



(b) for w/L = 2.089, T = 1.6 s



(c) for w/L = 1.750, T = 1.8 s



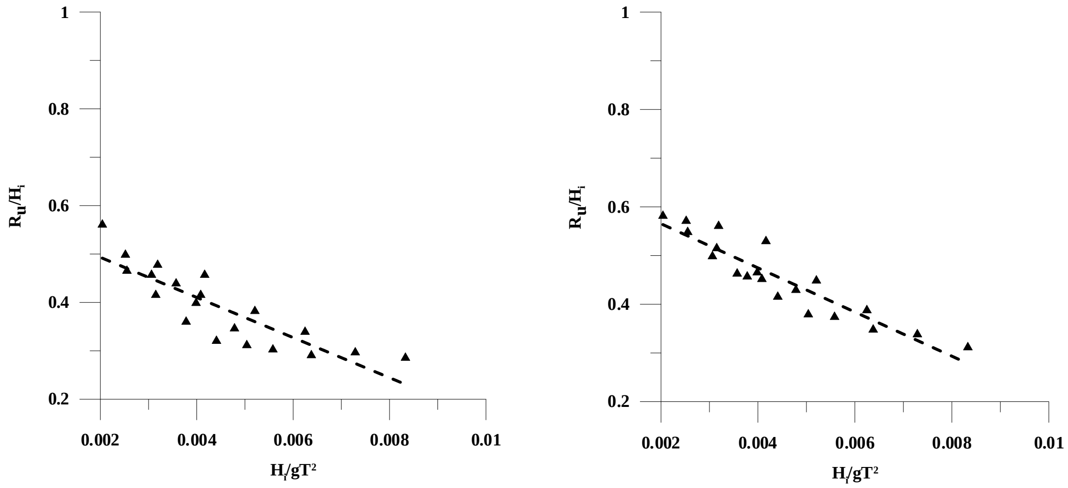
(d) for w/L = 1.546, T = 2 s

Fig. 6.14 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w = 6 m

Fig. 6.14 (a) depicts the percentage reduction in wave heights for increasing wave steepness, which varies from 68.75% to 60.00% for wave steepness parameter, H/gT^2 ranging from 0.00416 to 0.00832 (w/L = 2.411, T = 1.4 s). Correspondingly, for w/L = 2.089, T = 1.6 s, H_i/gT^2 = 0.00318 to 0.00637; w/L = 1.750, T = 1.8 s, H_i/gT^2 = 0.00251 to 0.00503 and w/L = 1.546, T = 2 s, H_i/gT^2 = 0.00203 to 0.00407, the percentage reduction in wave height varies from 65.00% to 58.13%, 63.75% to 56.25% and from 65.00% to 53.75%, respectively, as in Fig. 6.14 (b to d). The results in this section justifies the fact that wave height attenuation decreases as the relative plant height (h_s/d) changes from 1.25 to 1.11. For h_s/d = 1.25, since the depth of water is lower, as the wave passes along the width of the model, the trunks successfully interfere with the waves and the entire distribution of energy field is interfered. This results in increased wave height attenuation when compared to the case of h_s/d = 1.11. As the degree of interference is less, owing to decreased relative plant height, the wave passes effortlessly which results in reduced wave height attenuation. From the above results, it is also noted that there exists an inverse relationship between wave period and wave attenuation.

6.4.2 Effect of wave steepness on beach run-up

The variation of wave run up over the beach slope with an increase in wave steepness for the compound heterogeneous model of width 6 m, corresponding to relative plant heights, h_s/d = 1.25, 1.11 and wave periods, T = 1.4 s to 2 s is illustrated in Fig. 6.15 (a & b).



(a) for h_s/d = 1.25 (b) for h_s/d = 1.11

Fig. 6.15 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d)

As the wave steepness parameter (H_i/gT^2) increases from 0.00203 to 0.00832, R_u/H_i decreases from 0.561 to 0.285 for the case of compound heterogeneous model of width 6 m (h_s/d = 1.25), wherein, the percentage reduction in wave heights varies from 72.50% to 58.75%, as discussed in section 6.4.1.1. However, the relative wave run-up on the beach varies from 0.581 to 0.311 for the same model of relative plant height, h_s/d = 1.11, subjected to waves of incident wave heights ranging from 0.08 m to 0.16 m and periods, T = 1.4 to 2 s, as in Fig. 6.15 (b); for which the percentage reduction in wave heights varies from 68.75% to 53.75%, as in section 6.4.1.2.

6.5 COMPARISON OF PERFORMANCE OF HETEROGENEOUS VEGETATION MODELS

The results from the studies conducted on heterogeneous vegetation models, namely, submerged heterogeneous model, emergent heterogeneous model and the compound heterogeneous model, discussed in section 6.2, 6.3 and 6.4 highlights the role of wave characteristics and vegetation characteristics in dissipating wave energy and thus the wave run-up on the beach.

A comparison of results displayed in section 6.2, 6.3 and 6.4 reveals that the compound heterogeneous model of width 6 m displays increased attenuation in wave heights and the corresponding extent of inundation on the beach. For a relative plant height, h_s/d = 1.25; the percentage reduction in wave heights for the submerged heterogeneous model varies from 67.50% to 51.25%, taking into consideration the entire range of test conditions. However, this varies from 70.00% to 52.50% for the emergent heterogeneous model. The results indicate that the submerged heterogeneous model shows less reduction in wave heights when compared to the emergent heterogeneous model, which consists of the rigid submerged vegetation, along with the emergent trunk model with roots. The stiffness of the stem as well as the trunk of the model discussed in section 6.3 results in a higher impact on the wave height attenuation pattern, whereas the swaying and bending motion of the seagrass meadow in the model discussed in section 6.2 alters the hydrodynamics of the wave action to a lesser extent when compared to the emergent heterogeneous model. The height of emergence of the emergent heterogeneous model does play a very crucial role in attenuating the waves.

The emergent trunk, along with the roots can provide increased interference in the wave field by altering the particle orbital velocities along the water depth considered. The percentage reduction in wave heights for the compound heterogeneous model varies from 70.00% to 58.75%. This increased reduction in wave heights may be characterized by the presence of all three types of vegetation, viz., submerged seagrass, submerged rigid vegetation and the emergent trunk with roots. This compound heterogeneous model, owing to its increased width of meadow of 6 m also plays a substantial role in wave height attenuation (the role of meadow width parameter has been discussed in detail in chapters 4 and 5).

The same pattern is observed among the heterogeneous models of $h_s/d = 1.11$, but with a reduction in the percentage wave height reductions, which is attributed to the increase in depth of water. The values of percentage reduction in wave heights varies from 66.25% to 48.13%, 68.75% to 49.38% and from 68.75% to 53.75% for the submerged heterogeneous model, emergent heterogeneous model and the compound heterogeneous model, respectively.

The results of submerged heterogeneous model and the emergent heterogeneous model is comparable, with the emergent heterogeneous model showing increased reduction in wave heights; whereas, the results of the compound heterogeneous model shows maximum reduction in wave heights (72.50% to 58.75% for $h_s/d = 1.25$), mainly characterized by the increase in meadow width parameter as well as the height of emergence of the trunk, which leads to effective penetration of the layers of varying particle orbital velocities. A comparison between the results presented in this chapter and results of the field study on the capability of coral reefs, seagrasses and mangroves in protecting coastal regions, by Guannel et. al., 2016, wherein mangroves are capable of systematically reducing wave heights by more than 70% reveals a comparable wave height attenuation for heterogeneous vegetation models. The results from this study indicates that together, live corals and seagrasses provide more protection benefits than either of these habitats alone. Therefore, the findings from this study reveals that the compound heterogeneous model consisting of seagrass meadow, rigid submerged model as well as the emergent trunk model with roots shows the maximum reduction in wave heights and subsequent reduction in wave run-up. But, the facilitation of interaction between the three prototype species depends upon many other ecological factors. Bruno et. al. (2003), discusses the minimal requirements of ecosystems in close proximity connected by flows of energy, materials and organisms so as to enable landscape-scale positive interactions among the species. However, the interactions between species in the above terms have not been considered in this study which focuses only on the effect of heterogeneous plant communities on wave height attenuation as well as its influence on wave run-up.

A comparison of the extent of inundation on the beach slope, measured in terms of R_u/H, plotted against the wave steepness parameter H_i/gT^2, varying from 0.00203 to 0.00832 shows that the relative wave run up varies from 0.737 to 0.436, from 0.706 to 0.403 and from 0.561 to 0.285 for the submerged, emergent and compound heterogeneous models respectively, for h_s/d = 0.525, 1.25; whereas it varies from 0.764 to 0.457, from 0.716 to 0.400 and from 0.581 to 0.311 the same models (h_s/d = 0.47, 1.11), respectively.

6.6 KEY FINDINGS AND SUMMARY

The results of the test run on heterogeneous vegetation models, namely, submerged heterogeneous model, emergent heterogeneous model and compound heterogeneous model to determine the extent of wave attenuation and the subsequent wave run-up on beach slope presented in this chapter suggests that the meadow width parameter (w/L), relative plant height, (h_s/d) and wave steepness parameter (H_i/gT^2) plays a critical role in governing the attenuation characteristics. The results are interpreted in terms of relative wave heights at locations within the heterogeneous models, percentage reduction in wave heights, and the corresponding wave run-up expressed in terms of relative wave run up on the beach. The results presented in this chapter reveals that the compound heterogeneous model is capable of attenuating the waves to a higher extent when compared to the submerged and emergent heterogeneous models, owing to the combined effect of increase in meadow width parameter and the height of emergence of the trunks.

The key findings of this study on heterogeneous vegetation models is listed below:

6.6.1 Submerged heterogeneous model

1. The percentage wave height at exit point of a 4 m wide (w/L = 1.672-1.082 for h_s/d = 0.525; 1.607-1.031 for h_s/d = 0.471) submerged heterogeneous model varies from 32.50% - 48.75% and from 33.75% - 51.88% for h_s/d of 1.25 and 1.11, respectively.
2. The percentage wave height reduction for the same case varies from 67.50% - 51.25% and from 66.25% - 48.13% for h_s/d of 1.25 and 1.11, respectively for the submerged heterogeneous model.
3. As wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H varies from 0.737 to 0.436 (h_s/d =0.525) and from 0.764 to 0.457 (h_s/d =0.47) for the submerged heterogeneous model of width 4 m.

6.6.2 Emergent heterogeneous model

1. The percentage wave height at exit point of a 4 m wide (w/L = 1.672-1.082 for h_s/d = 1.25; 1.607-1.031 for h_s/d = 1.11) model varies from 30.00% - 47.50% and from 31.25% - 50.63% for h_s/d of 1.25 and 1.11, respectively.
2. For the same model, the percentage wave height reduction varies from 70.00% - 52.50% and from 68.75% - 49.38% for h_s/d of 1.25 and 1.11, respectively.
3. As wave steepness, H/gT^2 increases from 0.00204 to 0.00832, R_u/H varies from 0.706 to 0.403 (h_s/d =1.25) and from 0.716 to 0.400 (h_s/d =1.11) for this model.

6.6.3 Compound heterogeneous model

1. For the compound heterogeneous model of width 6 m, the percentage wave height at exit point varies from 30.00% - 41.25% and from 31.25% - 46.25% for h_s/d of 1.25 (w/L = 2.508-1.623) and 1.11 (w/L = 2.411-1.546), respectively.
2. This model also displays a percentage wave reduction varying from 72.50% - 58.75% and from 68.75% - 53.75% for h_s/d of 1.25 and 1.11, respectively.

3. R_u/H varies from 0.561 to 0.285 (h_s/d =1.25) and from 0.581 to 0.311 (h_s/d =1.11) for this model, as the wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832

Among the heterogeneous models, the optimum meadow width (w) and relative plant height (h_s/d) which gives the maximum wave attenuation and minimum wave run-up on the beach slope corresponds to the compound heterogeneous model of meadow width, w = 6 m and relative plant height, h_s/d = 1.25; wherein, the percentage reduction of wave height varies from 72.50% to 58.75% and wave run-up on the beach ranges between 0.561 to 0.285, when compared to the results of the submerged and emergent heterogeneous models, where the percentage wave height reduction varies from 67.50% to 51.25% and from 70.00% to 52.50% and wave run-up on the beach ranges between 0.737 to 0.436 and from 0.706 to 0.403, respectively for h_s/d = 0.525, 1.25.

CHAPTER 7

STUDIES ON FRAGMENTED VEGETATION MODELS

7.1 GENERAL

Coastal vegetation spread over vast expanses as continuous homogeneous meadows may occasionally be broken by vegetation-free gaps or patches due to impacts of climate change scenarios, extreme wave activity, increased anthropogenic activities and/or natural causes.

The fragmentation of vegetated meadows leads to the formation of a complex seascape (Abadie et. al., 2016) which may alter the hydrodynamics of the submerged or emergent vegetated canopies. In this chapter, the effect of fragmentation in vegetation meadows by introducing gaps of varying widths on wave attenuation and subsequent wave run-up is discussed in detail. This chapter is divided into two sections. The first section deals with studies conducted on fragmented emergent trunk model with roots, with gaps introduced alternatively between each quarter width of the vegetation model. The second section focuses on gaps of varying widths introduced in a heterogeneous compound vegetated meadow and its influence on wave attenuation and beach inundation.

The selection of model for studying the effect of gaps in vegetation on wave attenuation and subsequent beach inundation is based upon the experimental results obtained for the individual vegetation models discussed in chapters 4 and 5, as well as the heterogeneous vegetation models discussed in chapter 6. The focus of the present chapter is mainly related to the effect of fragmentation in vegetation, and therefore emphasizes on the effect of varying gap widths (w_{gap}) on wave attenuation. In this study, the concept of fragmentation in vegetation is brought out by introducing gaps between parts of the vegetation, in the test meadow. The actual meadow width (w) for the emergent trunk model with roots, discussed in section 7.2 is 2 m; and for the compound heterogeneous model, discussed in section 7.3, is 6 m. Gaps of varying widths (w_{gap}) are introduced and the influence of gap width parameter (w_{gap}/w) and its role in controlling wave heights and subsequent wave run-up is discussed in detail. The variation of measured wave height at locations (H_x/H_i) within the fragmented vegetation models with respect to the percentage meadow width, the influence of wave steepness (H_i/gT^2) on percentage wave height reduction $\left\{\left[1-\left(\frac{H_{exit}}{H_i}\right)\right]x100\right\}$ and the subsequent run-up on the beach, measured in terms of wave run-up (R_u/H_i) is discussed in this chapter; with emphasis on the effect of gap width parameter (w_{gap}/w), relative plant height (h_s/d) and the meadow width parameter (w/L).

7.2 STUDIES ON FRAGMENTED EMERGENT TRUNK MODEL WITH ROOTS

A 1:30 scaled emergent trunk model with roots of 2 m, with gaps introduced alternatively between each quarter width of the model, that is, 0.50 m is placed on the horizontal part of the flume bed. The model is subjected to monochromatic waves of height varying from 0.08 m to 0.16 m at an interval of 0.02 m. Results of experiments conducted with the emergent trunk model with roots of width 2 m, with gaps of varying widths (w_{gap}) of 0.25 m, 0.50 m, 0.75 m and 1 m are presented in this section.

7.2.1 Wave height attenuation

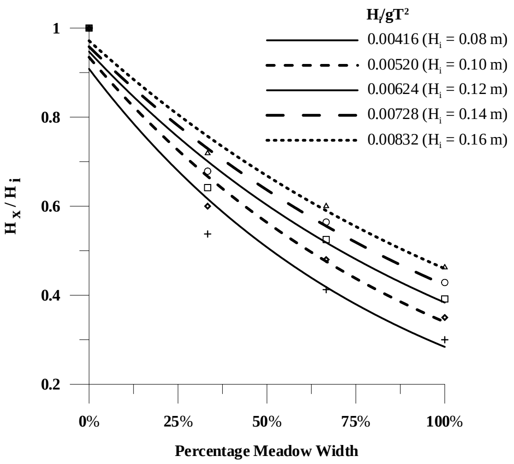
The role of relative plant height (h_s/d), meadow width parameter (w/L), plant density (N) and type of vegetation given by individual vegetation models as well as heterogeneous vegetation models in wave height attenuation and subsequent wave run-up on the beach is presented in chapters 4, 5 and 6. This section discusses the effect of transverse gaps present in vegetated meadows on wave height attenuation. Experiments are therefore conducted with gaps of varying widths (w_{gap}) to observe its effect on wave attenuation. It is observed that the wave height decreases as it propagates through the fragmented vegetation meadow. Snapshots of model set up to study the wave attenuation over the fragmented emergent trunk model with roots is displayed in Plate 7.1

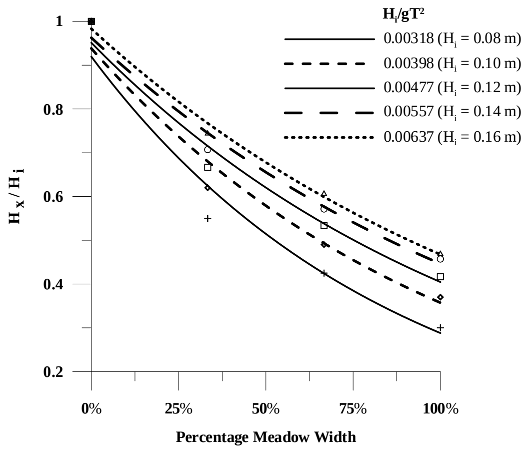
Plate 7.1 Snapshots of model setup to study wave attenuation over a fragmented emergent trunk model with roots a) Side view b) Top view

7.2.1.1 Relative plant height, $h_s/d = 1.25$; gap width parameter, $w_{gap}/w = 0.125$

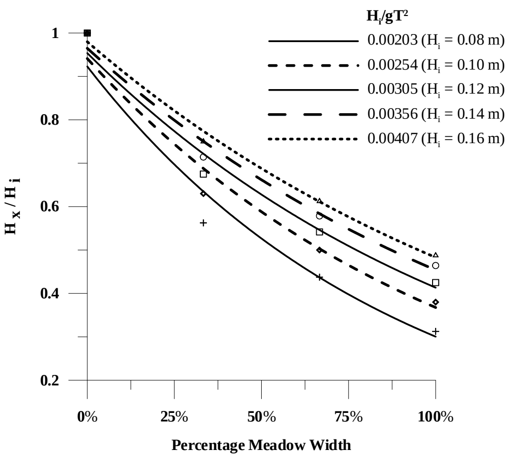
In this section, results are presented for the case of waves propagating through a fragmented emergent trunk model with roots of relative plant height, $h_s/d = 1.25$. This model consists of four sections of the emergent trunk model with roots, each of width 0.50 m, which adds up to form the base model of width 2 m. Gaps of width (w_{gap}) 0.25 m is introduced alternately between the four sections of the base model. A plot of relative wave heights at locations within the model, $\left(\frac{H_x}{H_i}\right)$ and percentage meadow width for varying incident wave conditions is illustrated in Fig. 7.1 (a to d). The relative percentage wave height at the exit point of the meadow varies from 30.00% to 32.50% for an incident wave of height 0.08 m. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 35.00% to 39.00%, from 39.17% to 43.33%, from 42.86% to 47.14% and from 46.25% to 50.63%, (refer Fig. 7.1 (a to d)).



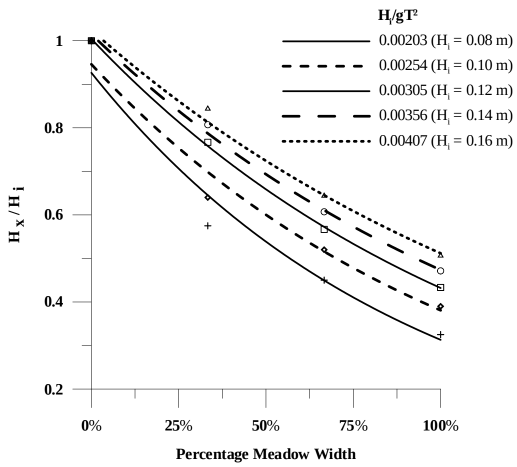
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



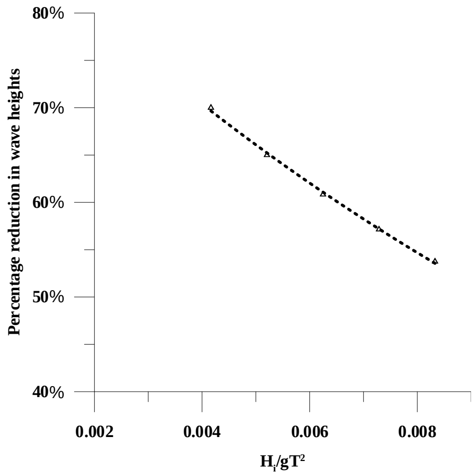
(c) for w/L = 0.612, T = 1.8 s



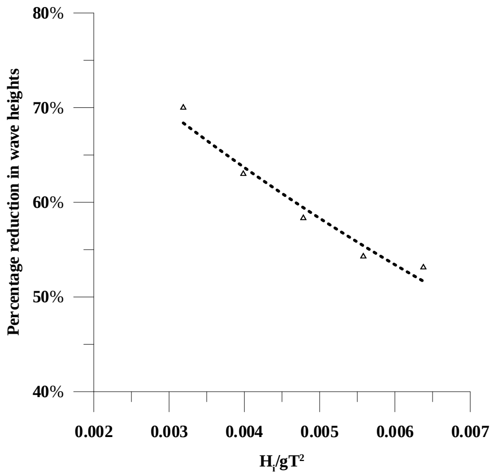
(d) for w/L = 0.541, T = 2 s

Fig. 7.1 Relative wave heights at locations within the model for $h_s/d = 1.25$; $w_{gap}/w = 0.125$

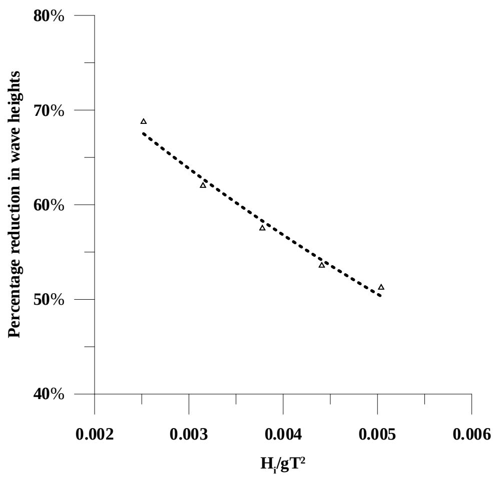
Fig. 7.2 (a to d) depicts the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction. It is noted that there is a decrease in wave height reduction from 70.00% to 53.75% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 0.836, T = 1.4 s), from 70.00% to 53.13%, 68.75% to 51.25% and from 67.50% to 49.38% for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 0.714, T = 1.6 s), 0.00251 to 0.00503 (w/L = 0.612, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 0.541, T = 2 s), respectively. It is also noted that as the wave period, T increases from 1.4 s to 2 s, there is a decrease in percentage wave height reduction from 70.00% to 53.75%, corresponding to T = 1.4 s and from 67.50% to 49.38% for T = 2 s, which indicates that the effectiveness of the fragmented emergent trunk model with roots in attenuating wave heights decreases as the wave period increases.



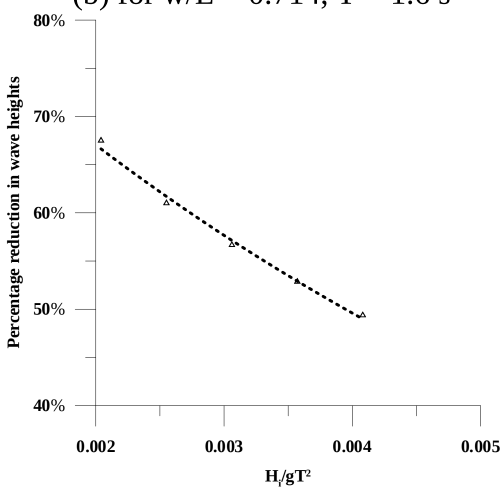
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s



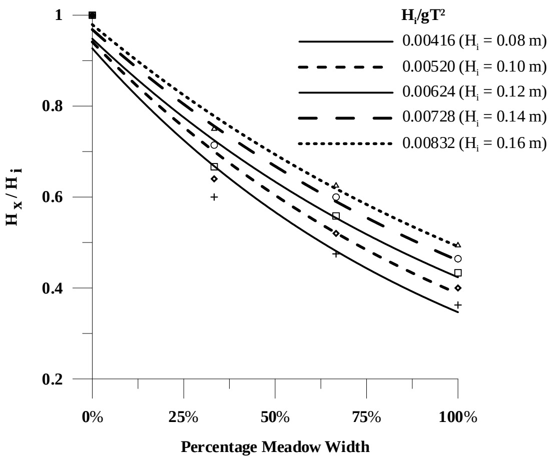
(d) for w/L = 0.541, T = 2 s

Fig. 7.2 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w_{gap}/w = 0.125

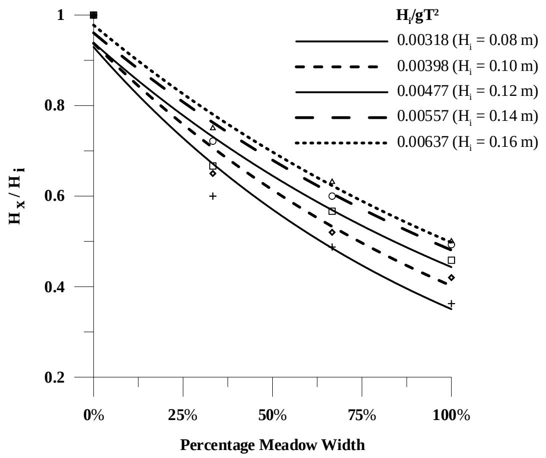
As the wave propagates through the initial stretch of vegetation, the trunks of the model interfere with the particle orbital velocities which leads to a decrease in wave heights. As the propagating wave encounters a gap, that is, a zone free of vegetation, there is no significant decrease in wave heights, which again gets attenuated while it passes through the next stretch of vegetation. This continues as the wave propagates along the vegetated meadow with gaps. It is evident from the above results that the fragmented emergent trunk model with roots exhibits a slight increase in wave height reduction when compared to the individual emergent trunk model with roots of width 2 m, discussed in section 5.3.1.3, which may be attributed predominantly to the increase in total meadow width from 2 m to 2.75 m.

7.2.1.2 Relative plant height, h_s/d = 1.11; gap width parameter, w_{gap}/w = 0.125

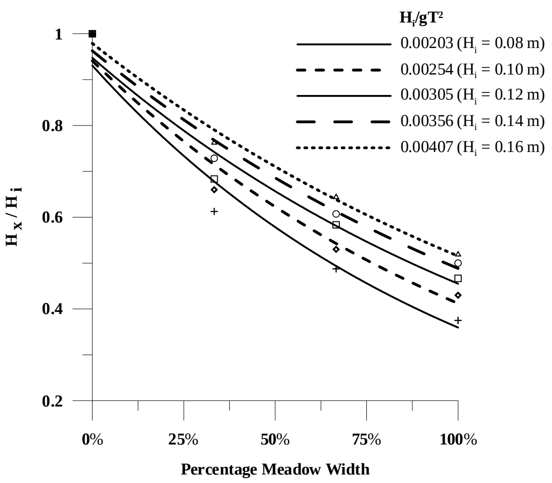
The wave reduction along the fragmented emergent trunk model with roots due to the effect of reduction in relative plant height (h_s/d) from 1.25 to 1.11, as the water depth increases from 0.40 m to 0.45 m is discussed in this section.



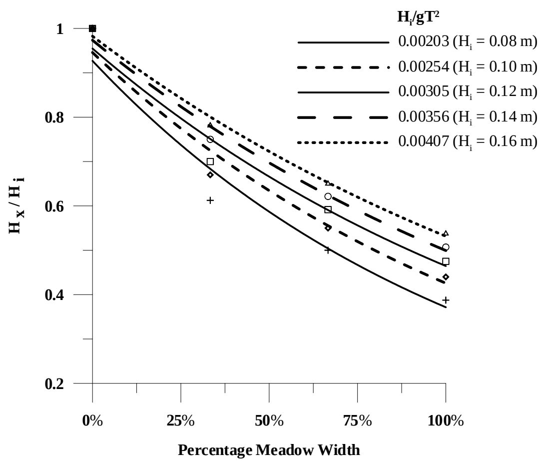
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



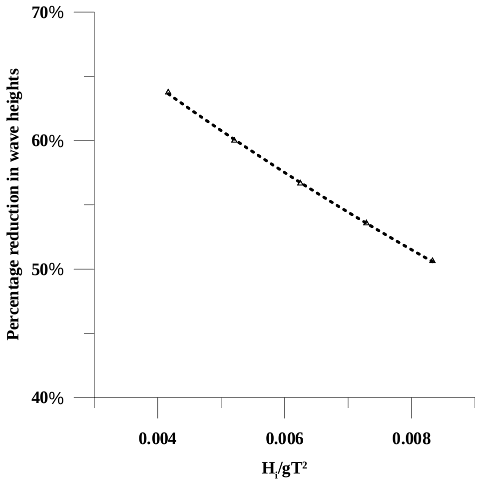
(c) for w/L = 0.583, T = 1.8 s



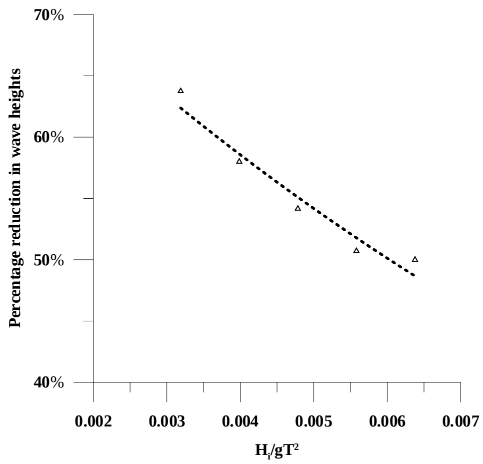
(d) for w/L = 0.515, T = 2 s

Fig. 7.3 Relative wave heights at locations within the model for h_s/d = 1.11; w_{gap}/w = 0.125

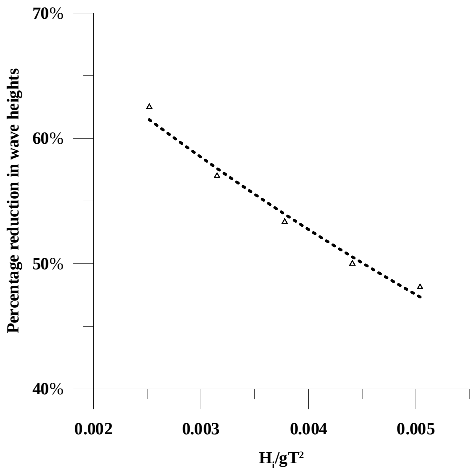
Fig. 7.3 (a to d) illustrates the relative wave heights at locations within the model versus the percentage meadow width for varying incident wave conditions for the fragmented emergent trunk model with roots with gap width parameter, w_{gap}/w = 0.125 and relative plant height, h_s/d = 1.11. The relative percentage wave height at the exit point of the meadow varies from 36.25% to 38.75% for an incident wave of height 0.08 m. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 40.00% to 44.00%, from 43.33% to 47.50%, from 46.43% to 50.71% and from 49.38% to 53.75%.



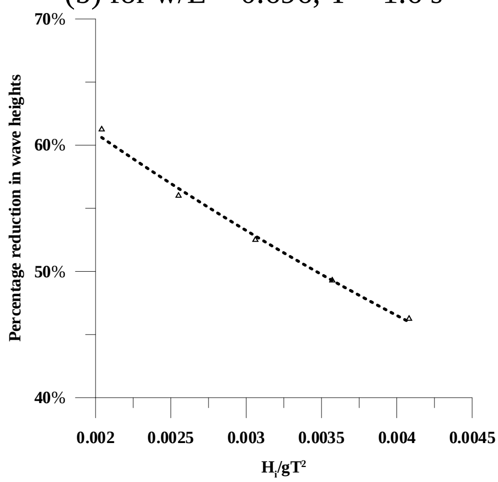
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s

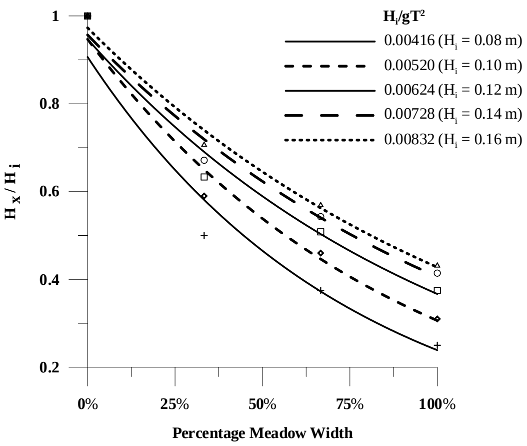


(d) for w/L = 0.515, T = 2 s

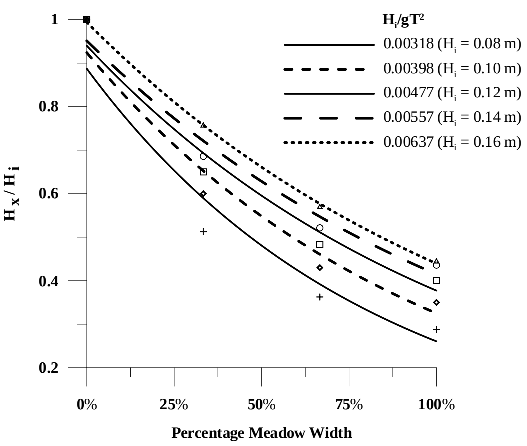
Fig. 7.4 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w_{gap}/w = 0.125

The percentage reduction in wave height varies from 63.75% to 50.63% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 0.804, T = 1.4 s). Correspondingly, for w/L = 0.696, T = 1.6 s, H/gT^2 = 0.00318 to 0.00637; w/L = 0.583, T = 1.8 s, H/gT^2 = 0.00251 to 0.00503 and w/L = 0.515, T = 2 s, H/gT^2 = 0.00203 to 0.00407, the percentage reduction in wave height varies from 63.75% to 50.00%, 62.50% to 48.13% and from 61.25% to 46.25%, respectively Fig. 7.4 (b to d). As the relative plant height (h_s/d) changes from 1.25 to 1.11, the reduction in wave heights decreases. As the depth of water is more, the degree of interference is less and therefore the wave passes effortlessly which results in reduced wave height attenuation.

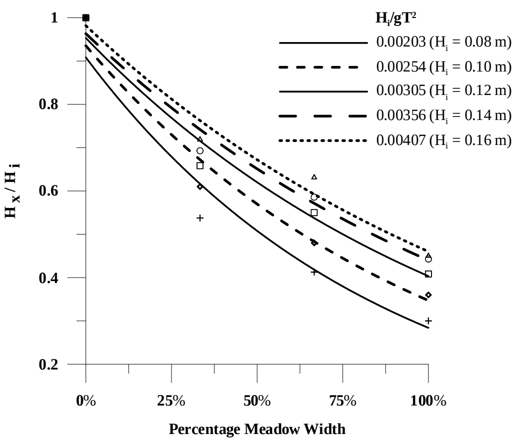
7.2.1.3 Relative plant height, h_s/d = 1.25; gap width parameter, w_{gap}/w = 0.25



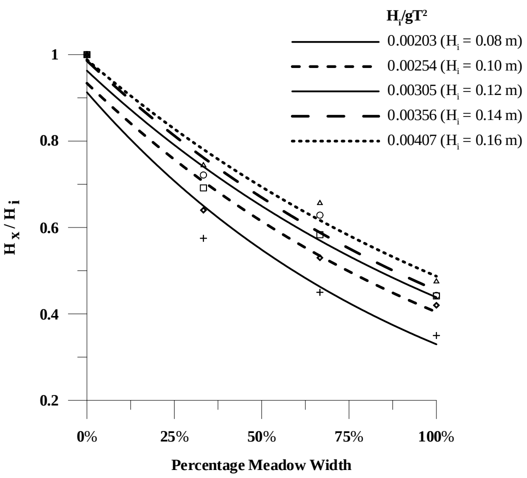
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s

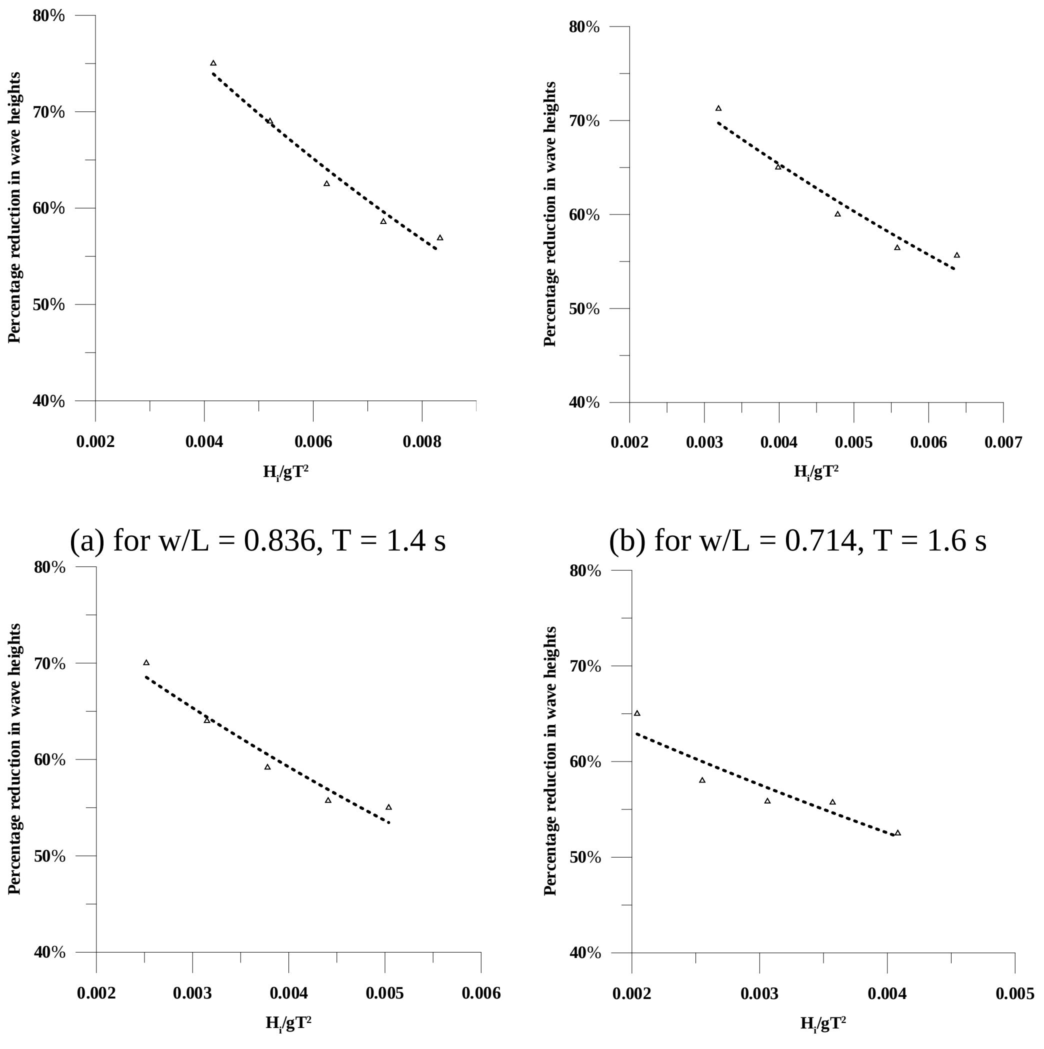


(d) for w/L = 0.541, T = 2 s

Fig. 7.5 Relative wave heights at locations within the model for h_s/d = 1.25; w_{gap}/w = 0.25

As the gap width parameter (w_{gap}/w) increases from 0.125 to 0.25 (100% increase), with an increase in gap width (w_{gap}) from 0.25 m to 0.50 m, the changes in wave height attenuation is described using the following results.

The relative wave heights at locations within the fragmented emergent trunk model with roots for h_s/d = 1.25 and w_{gap}/w = 0.25 is illustrated in Fig. 7.5 (a to d). The relative percentage wave height at the exit point of the meadow varies from 25.00% to 35.00%, from 31.00% to 42.00%, from 37.50% to 44.17%, from 41.43% to 44.29% and from 43.13% to 47.50% for incident waves of heights 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, corresponding to a range of wave periods from 1.4 s to 2 s.



(a) for w/L = 0.836, T = 1.4 s (b) for w/L = 0.714, T = 1.6 s

(c) for w/L = 0.612, T = 1.8 s (d) for w/L = 0.541, T = 2 s

Fig. 7.6 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w_{gap}/w = 0.25

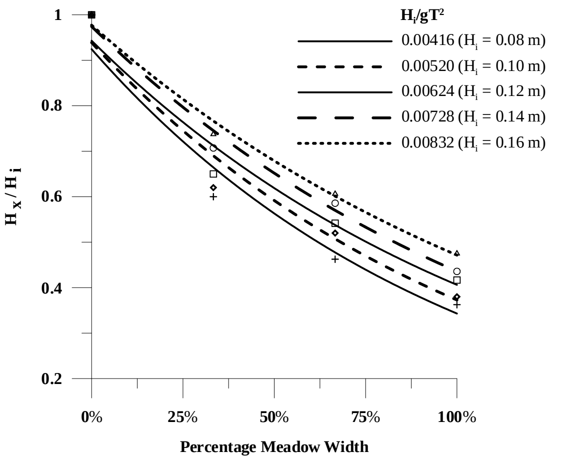
Fig. 7.6 (a to d) depicts the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction. It is observed that there is a decrease in wave height reduction from 75.00% to 56.88% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 0.836, T = 1.4 s), from 71.25% to 55.63%, 70.00% to 55.00% and from 65.00% to 52.50% for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 0.714, T = 1.6 s), 0.00251 to 0.00503 (w/L = 0.612, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 0.541, T = 2 s), respectively.

The above results indicate higher values of percentage wave reduction when compared to that discussed in section 7.2.1.1 for the same model with gap width parameter, w_{gap}/w = 0.125. The increased percentage wave reduction might be attributed to the increase in total meadow width from 2.75 to 3.5 m. As the wave travels along the first stretch of vegetation model, there is decrease in wave heights. As the wave propagates further and reaches the zone free of vegetation i.e., when it encounters a gap, there is no significant decrease in wave heights, which again gets attenuated while it passes through the next stretch of vegetation. This phenomenon gets repeated as the wave propagates through the next stretches of vegetation as well as the gaps, which leads to an increase in wave height attenuation when compared to the previous case where the total width of the model is less.

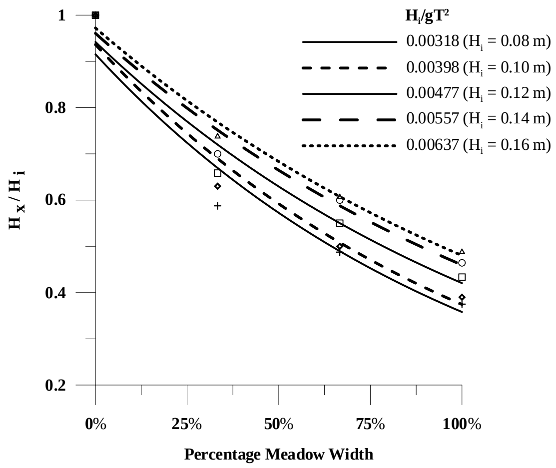
7.2.1.4 Relative plant height, h_s/d = 1.11; gap width parameter, w_{gap}/w = 0.25

The decrease in relative plant height (h_s/d) from 1.25 to 1.11 leads to a decrease in wave attenuation as discussed in section 7.2.1.2, due to an increase in water depth from 0.40 m to 0.45 m.

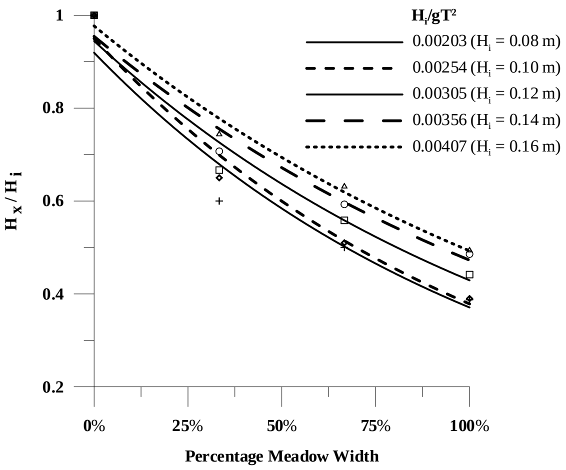
The relative percentage wave height at the exit point, of the meadow is varies from 36.25% to 40.00%, from 38.00% to 42.00%, from 41.67% to 45.83%, from 43.57% to 49.29% and from 47.50% to 51.25% corresponding to incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively, as illustrated in Fig. 7.7 (a to d).



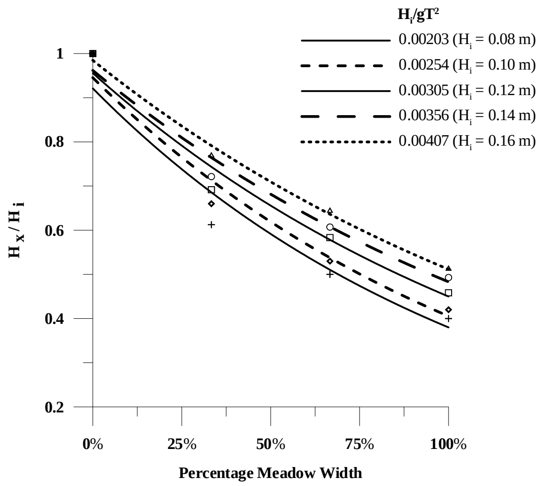
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



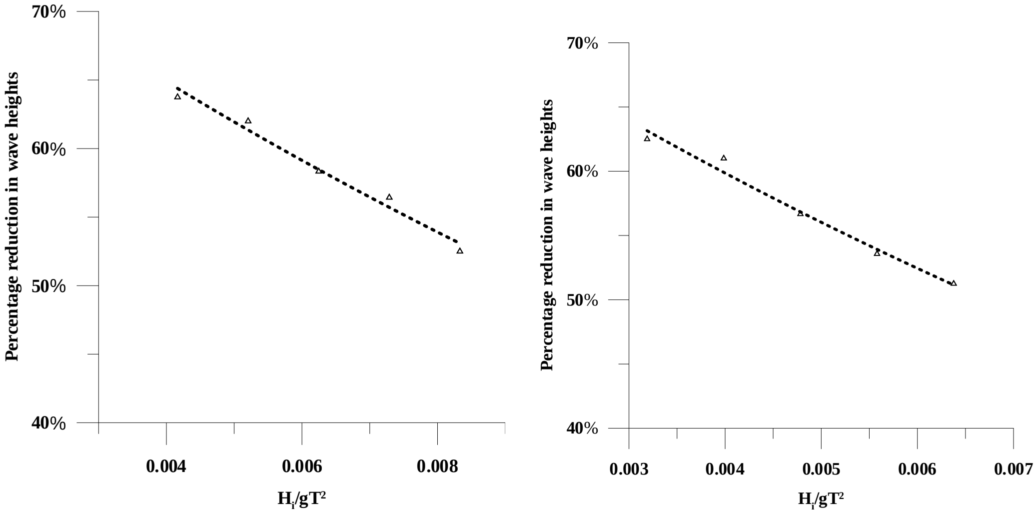
(c) for w/L = 0.583, T = 1.8 s



(d) for w/L = 0.515, T = 2 s

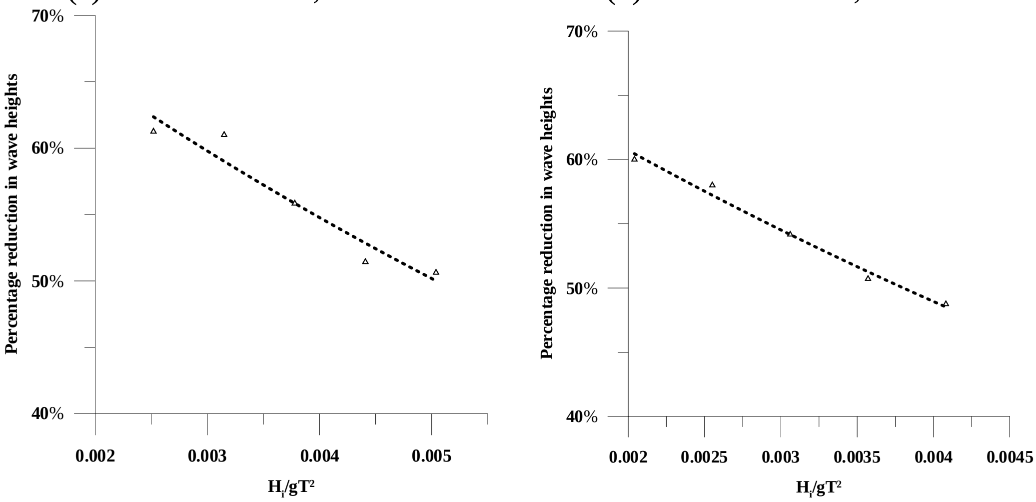
Fig. 7.7 Relative wave heights at locations within the model for h_s/d = 1.11; w_{gap}/w = 0.25

The percentage reduction in wave heights for the fragmented emergent trunk model with roots (h_s/d = 1.11; w_{gap}/w = 0.25) is illustrated with the help of Fig. 7.8 (a to d), which shows the influence of increasing wave steepness parameter on percentage wave height reduction. Fig. 7.8 (a to d) shows that as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832, 0.00318 to 0.00637, 0.00251 to 0.00503 and from 0.00203 to 0.00407, the percentage reduction in wave heights varies from 63.75% to 52.50%, 62.50% to 51.25%, 61.25% to 50.63% and from 60.00% to 48.75%, respectively



(a) for w/L = 0.804, T = 1.4 s

(b) for w/L = 0.696, T = 1.6 s



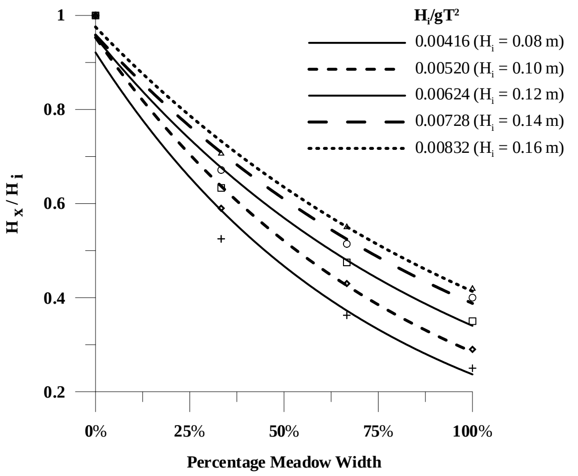
(c) for w/L = 0.583, T = 1.8 s

(d) for w/L = 0.515, T = 2 s

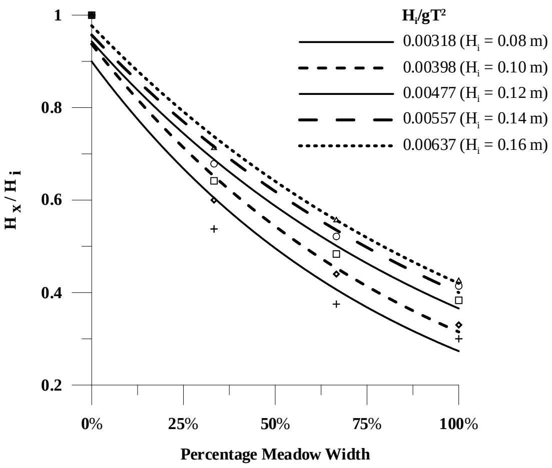
Fig. 7.8 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w_{gap}/w = 0.25

7.2.1.5 Relative plant height, h_s/d = 1.25; gap width parameter, w_{gap}/w = 0.375

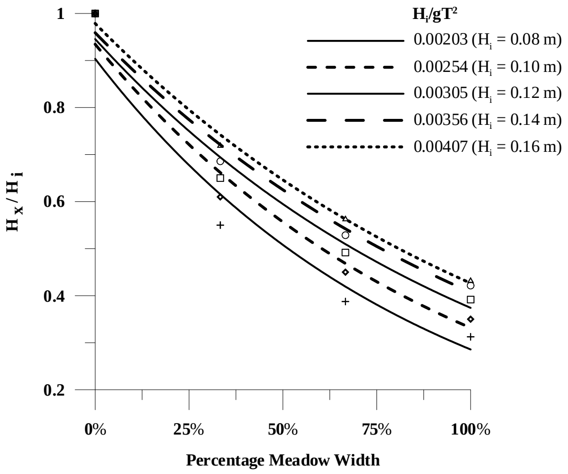
As the gap width (w_{gap}) further increases from 0.50 to 0.75 (50 %), i.e., an increase in gap width parameter (w_{gap}/w) from 0.25 to 0.375, it is observed that there is an increased reduction in wave heights, owing to the increase in total meadow width from 3.5 m to 4.25 m. Due to the increased gap width of 0.75 m when compared to gap widths equal to 0.25 m and 0.50 m, discussed in the previous sections, an increased attenuation in wave heights is observed.



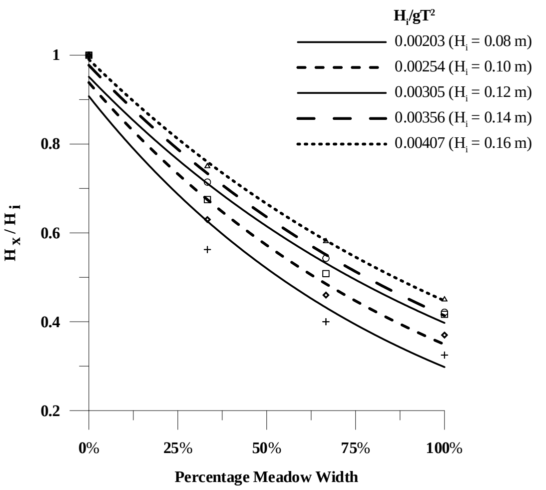
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



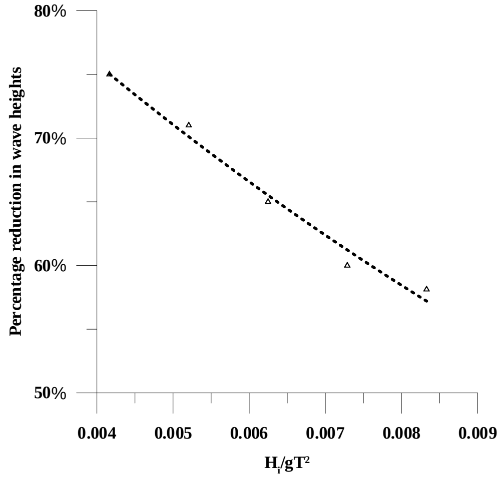
(c) for w/L = 0.612, T = 1.8 s



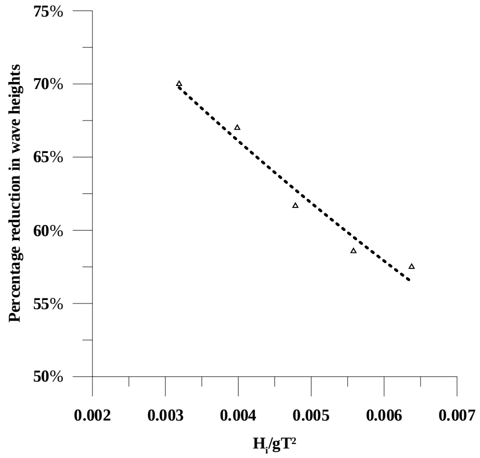
(d) for w/L = 0.541, T = 2 s

Fig. 7.9 Relative wave heights at locations within the model for h_s/d = 1.25; w_{gap}/w = 0.375

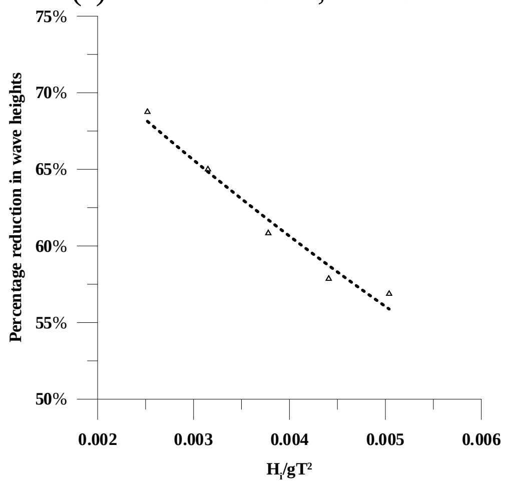
The percentage wave height at the exit point of the meadow is ranges from 25.00% to 32.50% for an incident wave of height 0.08 m. Further, the percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 29.00% to 37.00%, 35.00% to 41.67%, 40.00% to 42.14% and 41.88% to 45.00% respectively (Fig. 7.9 (a to d)).



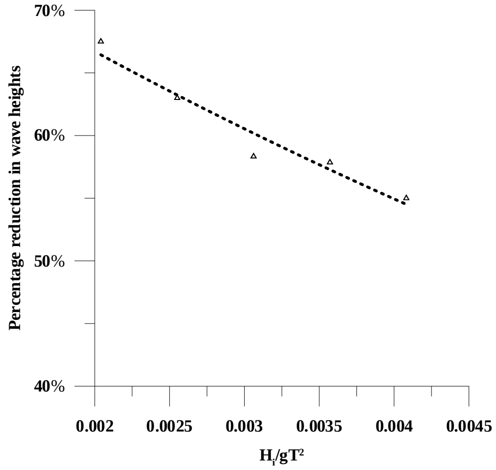
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s



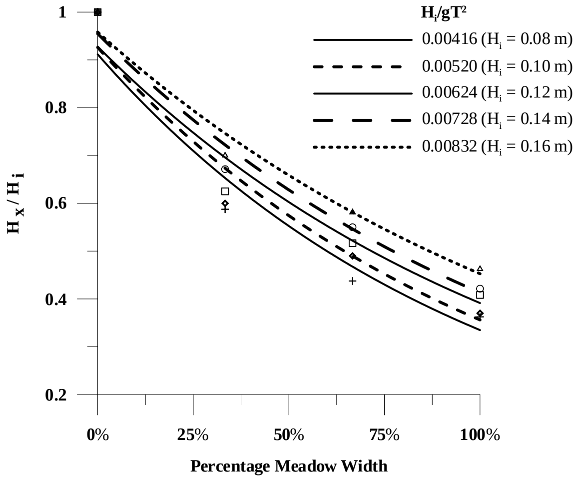
(d) for w/L = 0.541, T = 2 s

Fig. 7.10 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 1.25$; $w_{gap}/w = 0.375$

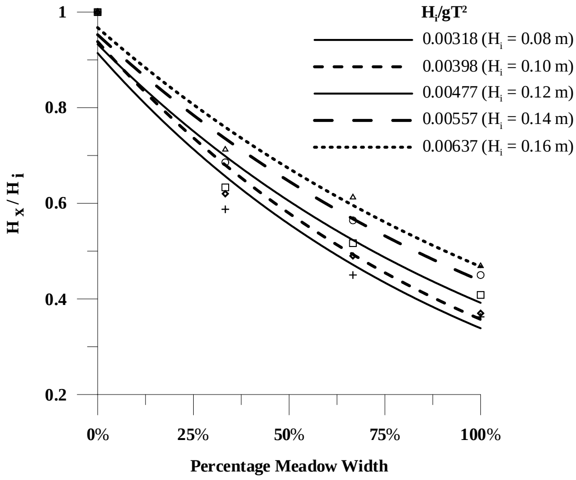
Fig. 7.10 (a to d) depicts the influence of wave steepness on percentage wave height reduction for the fragmented emergent trunk model with roots of $h_s/d = 1.25$; $w_{gap}/w = 0.375$. As the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832, 0.00318 to 0.00637, 0.00251 to 0.00503 and from 0.00203 to 0.00407, percentage reduction in wave heights varies from 75.00% to 58.13%, 70.00% to 57.50%, 68.75% to 56.88% and from 67.50% to 55.00%, respectively.

7.2.1.6 Relative plant height, h_s/d = 1.11; gap width parameter, w_{gap}/w = 0.375

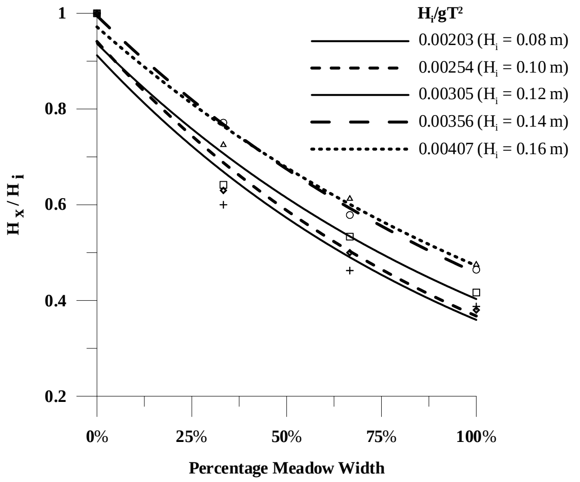
The influence of relative plant height (h_s/d) on wave attenuation for the fragmented emergent trunk model with roots of gap width parameter, w_{gap}/w = 0.375 is discussed in this section.



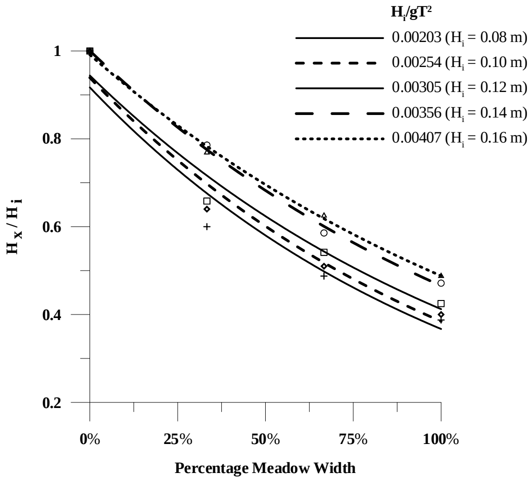
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s

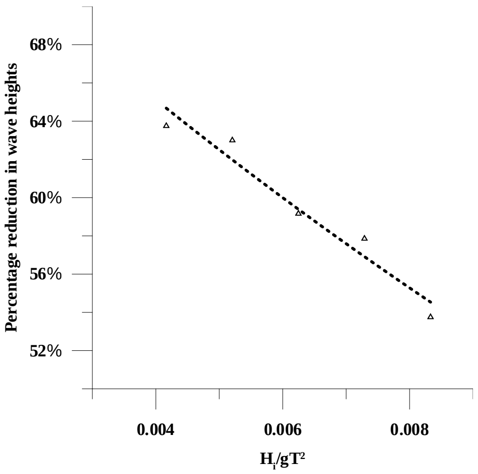


(d) for w/L = 0.515, T = 2 s

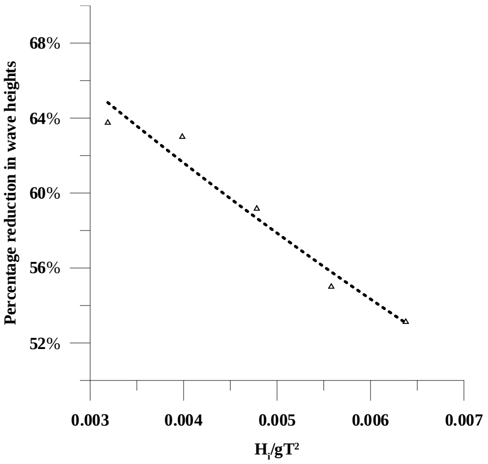
Fig. 7.11 Relative wave heights at locations within the model for h_s/d = 1.11; w_{gap}/w = 0.375

The percentage wave height at the exit point of the meadow varies from 36.25% to 38.75% for an incident wave of height 0.08 m. Further, the percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m varies from

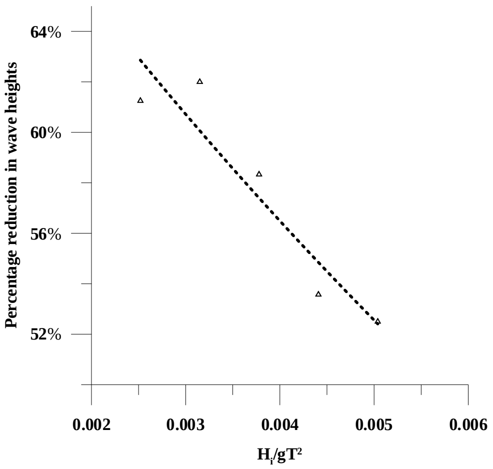
37.00% to 40.00%, 40.83% to 42.50%, 42.14% to 47.14% and from 46.25% to 48.75% respectively (Fig. 7.11 (a to d)).



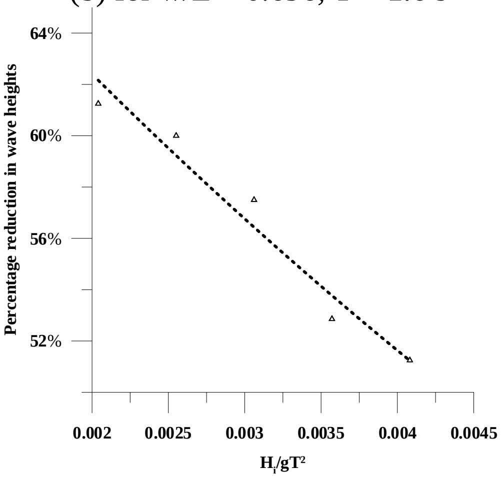
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s



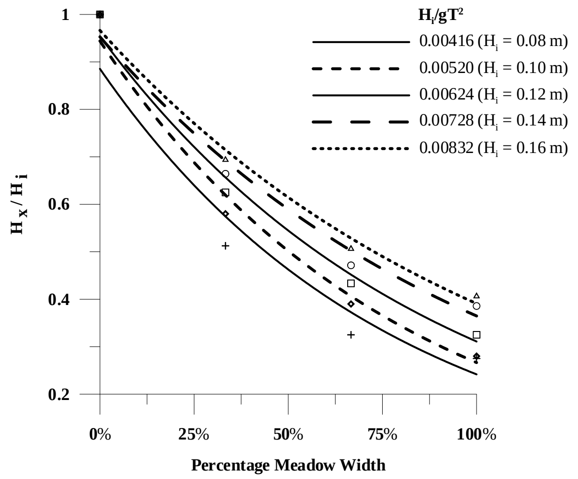
(d) for w/L = 0.515, T = 2 s

Fig. 7.12 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w_{gap}/w = 0.375

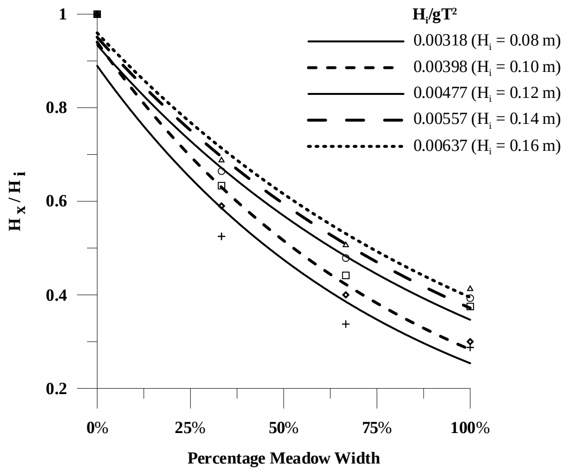
Plots of wave steepness parameter versus percentage reduction in wave heights depicted in Fig. 7.12 (a to d) shows that as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832, 0.00318 to 0.00637, 0.00251 to 0.00503 and from 0.00203 to 0.00407, percentage reduction in wave heights varies from 63.75% to 53.75%, 63.75% to 53.13%, 61.25% to 52.50% and from 61.25% to 51.25%, respectively.

7.2.1.7 Relative plant height, h_s/d = 1.25; gap width parameter, w_{gap}/w = 0.5

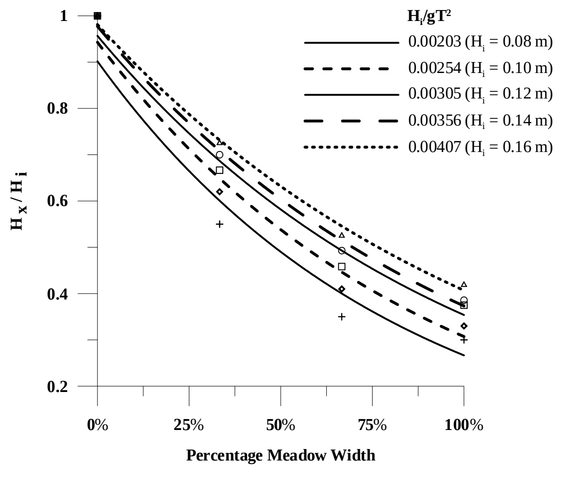
As the gap width (w_{gap}) increases from 0.75 m to 1 m (33.33%), i.e., an increase in gap width parameter (w_{gap}/w) from 0.375 to 0.5, it is observed that there is a considerable increase in wave height attenuation when compared to the fragmented emergent trunk model with roots of gap width parameter (w_{gap}/w) 0.125, discussed in sections 7.2.1.1 and 7.2.1.2. This increase in wave attenuation, attributed to the increase in meadow width to 5 m is described with results presented below.



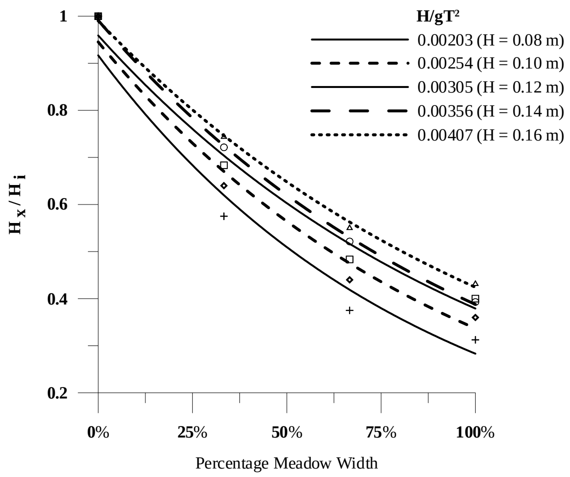
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s

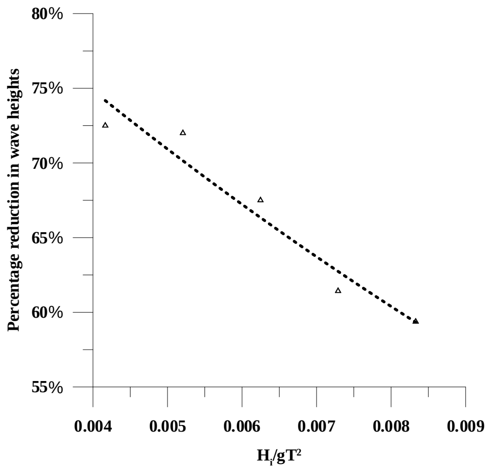


(d) for w/L = 0.541, T = 2 s

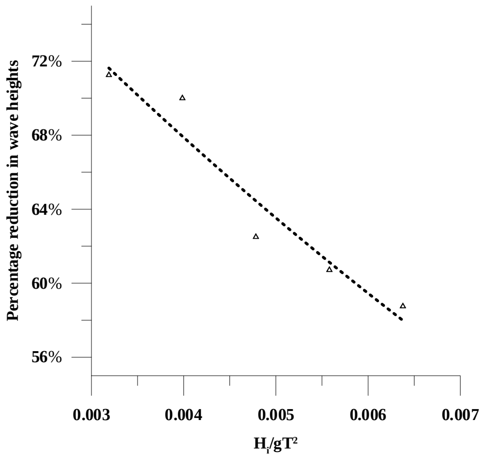
Fig. 7.13 Relative wave heights at locations within the model for h_s/d = 1.25; w_{gap}/w = 0.5

Fig. 7.13 (a to d) illustrates the measured wave heights at locations within the fragmented emergent trunk model with roots (h_s/d = 1.25; w_{gap}/w = 0.5) corresponding to different wave heights and periods. It is seen that the relative percentage wave height at the exit point of this model varies from 27.50% to 31.25%, 28.00% to 36.00%, 32.50% to 40.00%, 38.57% to 39.29% and from 40.63% to 43.13% corresponding to incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively.

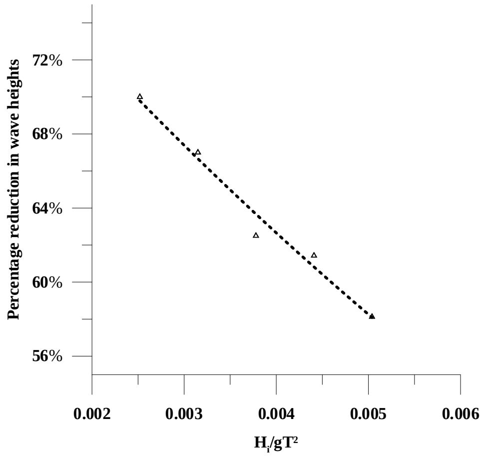
As the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832, 0.00318 to 0.00637, 0.00251 to 0.00503 and from 0.00203 to 0.00407, the percentage reduction in wave heights varies from 72.50% to 59.38%, 71.25% to 58.75%, 70.00% to 58.13% and from 68.75% to 56.88%, respectively (Fig. 7.14 (a to d)).



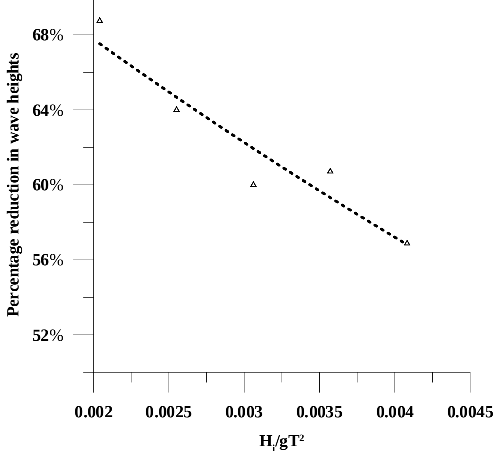
(a) for w/L = 0.836, T = 1.4 s



(b) for w/L = 0.714, T = 1.6 s



(c) for w/L = 0.612, T = 1.8 s

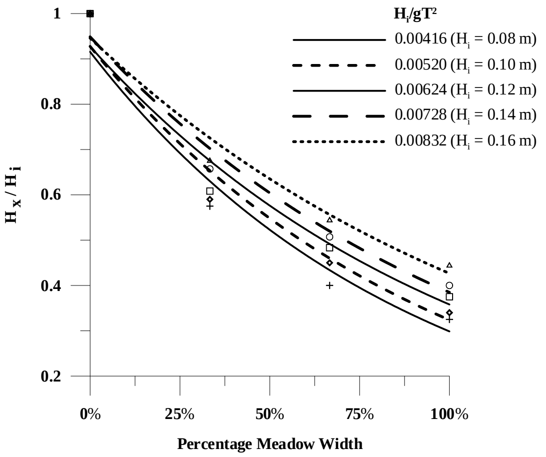


(d) for w/L = 0.541, T = 2 s

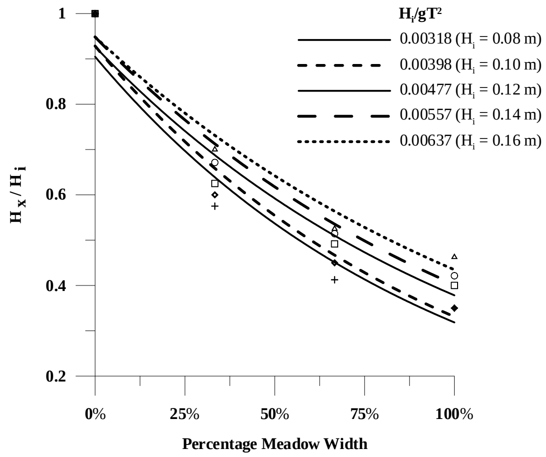
Fig. 7.14 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 1.25$; $w_{gap}/w = 0.5$

7.2.1.8 Relative plant height, $h_s/d = 1.11$; gap width parameter, $w_{gap}/w = 0.5$

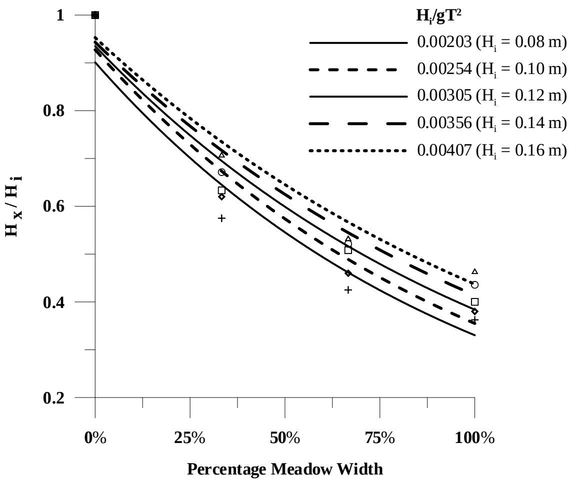
From the plots of relative wave heights at locations within the fragmented emergent trunk model with roots of gap width parameter (w_{gap}/w) 0.5 illustrated in Fig. 7.15 (a to d), it is observed that the relative percentage wave height at the exit point of the meadow varies from 32.50% to 38.75%, 34.00% to 39.00%, 37.50% to 40.00%, 40.00% to 45.00% and from 44.38% to 47.50% corresponding to incident wave heights of 0.08 m, 0.10 m, 0.12 m, 0.14 m and 0.16 m, respectively.



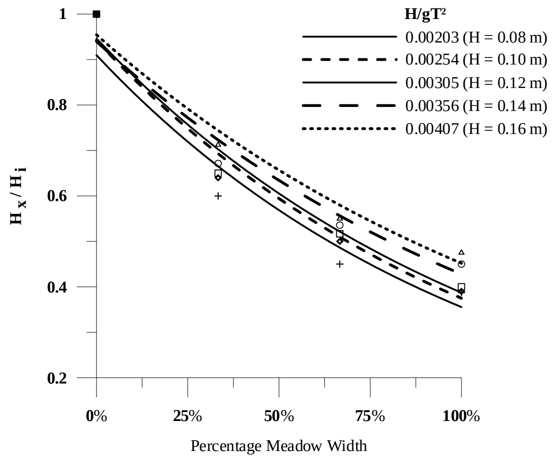
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



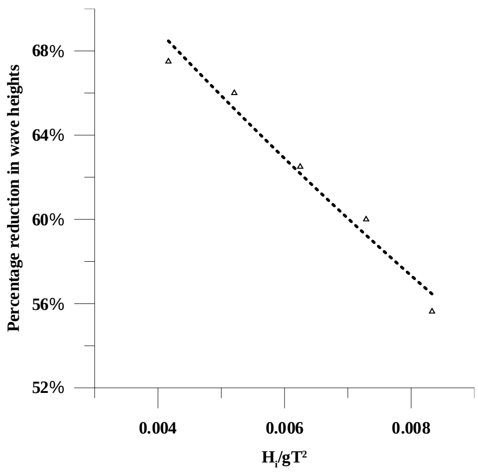
(c) for w/L = 0.583, T = 1.8 s



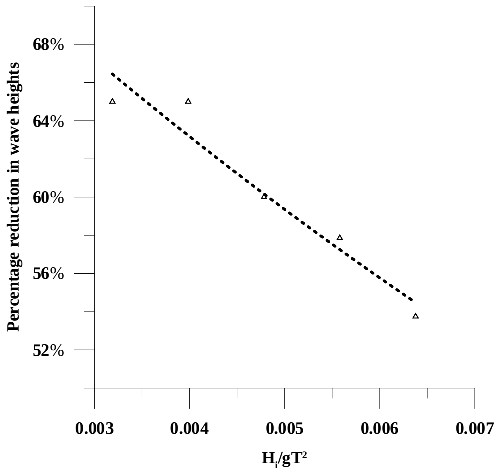
(d) for w/L = 0.515, T = 2 s

Fig. 7.15 Relative wave heights at locations within the model for $h_s/d = 1.11$; $w_{gap}/w = 0.5$

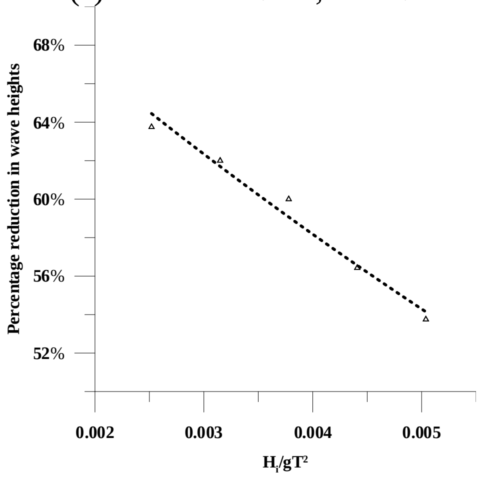
For w/L = 0.804, T = 1.4 s, as H_i/gT^2 increases from 0.00416 to 0.00832, there is a decrease in wave height reduction from 67.50% to 55.63%, as seen in Fig. 7.16 (a). A similar trend of decrease in wave height reduction from 65.00% to 53.75%, 63.75% to 53.75% and 61.25% to 52.50% is observed for the cases corresponding to w/L = 0.696, T = 1.6 s; w/L = 0.583, T = 1.8 s and w/L = 0.515, T = 2 s, respectively (Fig. 7.16 b to d). The pattern of wave height reduction shows that as the relative plant height (h_s/d) decreases from 1.25 to 1.11, there is a decrease in wave attenuation. This is attributed to the decrease in the degree of interference due to the submergence of the emergent trunks, when waves of higher wave heights pass through the model.



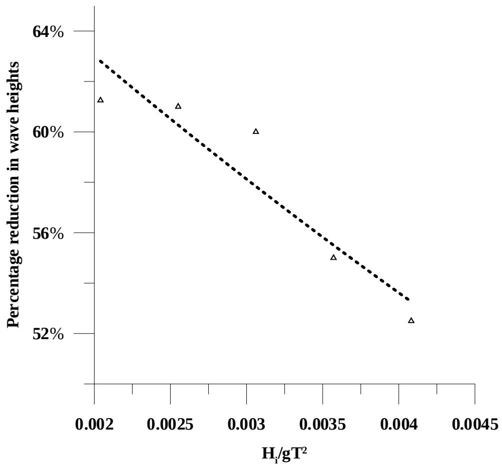
(a) for w/L = 0.804, T = 1.4 s



(b) for w/L = 0.696, T = 1.6 s



(c) for w/L = 0.583, T = 1.8 s



(d) for w/L = 0.515, T = 2 s

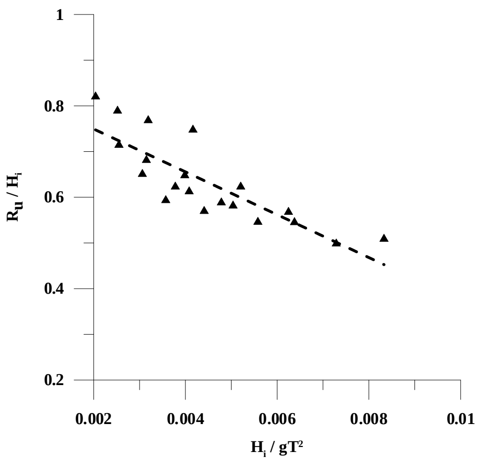
Fig. 7.16 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 1.11$; $w_{gap}/w = 0.5$

7.2.2 Effect of wave steepness on run-up

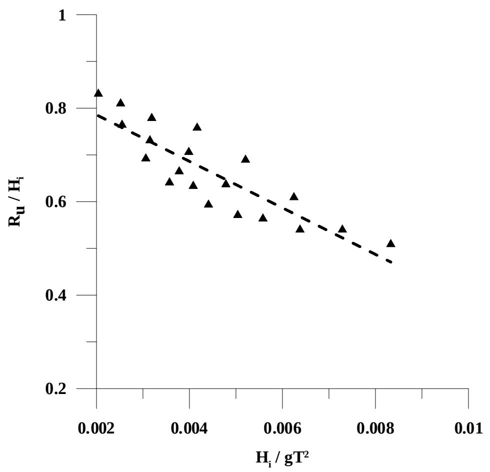
Wave run-up over a beach determines the extent to which ocean waves acts on the shore. The extent of inundation due to wave activity is determined based on this important parameter called wave run up. The effect of wave steepness parameter (H_i/gT^2) on relative wave run-up (R_u/H_i) for the fragmented emergent trunk model with roots is discussed in this section.

The extent of run-up on the beach slope, measured as wave run-up (R_u/H_i) on the beach for the fragmented emergent trunk model with roots (h_s/d = 1.25; w_{gap}/w = 0.125) varies from 0.820 to 0.498 (for w/L = 0.836 to 0.541), wherein the percentage reduction in wave heights ranges from 70.00% to 49.38%. Also, for the same model with h_s/d = 1.11; w_{gap}/w = 0.125, the wave run-up (R_u/H_i) on the beach varies from 0.830 to 0.508 (for w/L = 0.804 to 0.515), as depicted in Fig. 7.17 (a to b).

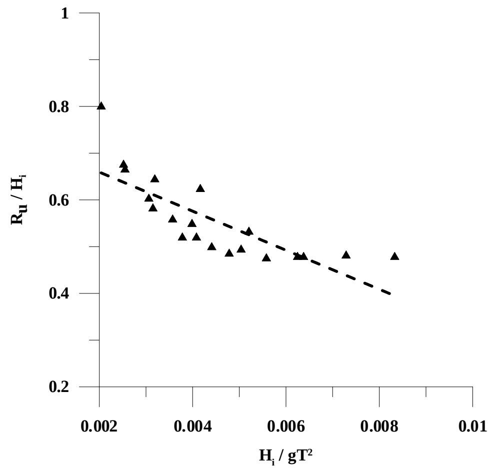
For the same model with h_s/d = 1.25; w_{gap}/w = 0.25, it is observed from Fig. 7.17 (c to d) that the wave run-up (R_u/H_i) varies from 0.799 to 0.474 (for w/L = 0.836 to 0.541) and from 0.809 to 0.480 (w/L = 0.804 to 0.515) for h_s/d = 1.11; w_{gap}/w = 0.25. The corresponding percentage reduction in wave heights ranges from 75.00% to 52.50% (h_s/d = 1.25; w_{gap}/w = 0.25) and from 63.75% to 48.75% (h_s/d = 1.11; w_{gap}/w = 0.25).



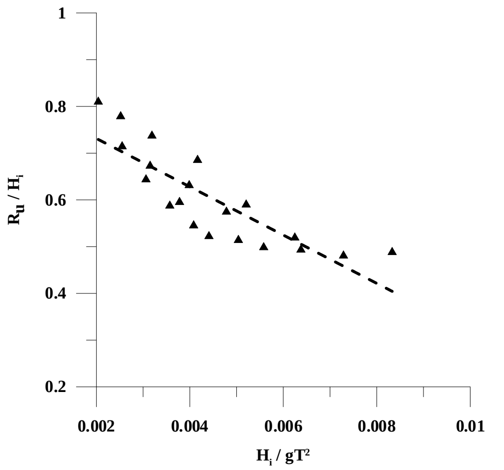
(a) for h_s/d = 1.25; w_{gap}/w = 0.125



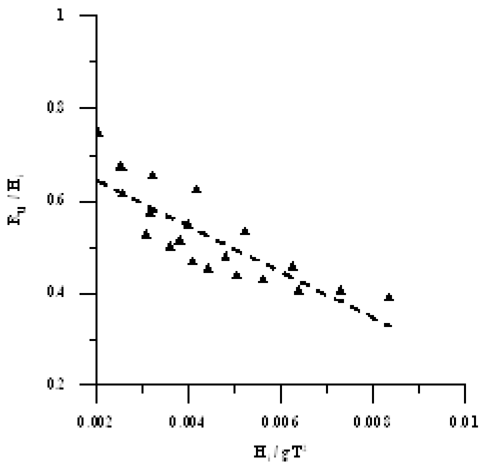
(b) for h_s/d = 1.11; w_{gap}/w = 0.125



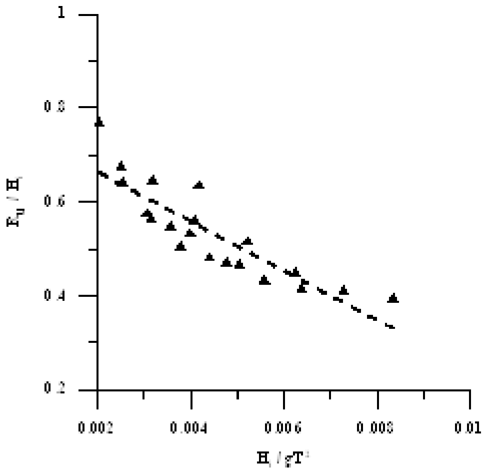
(c) for $h_s/d = 1.25$; $w_{gap}/w = 0.25$



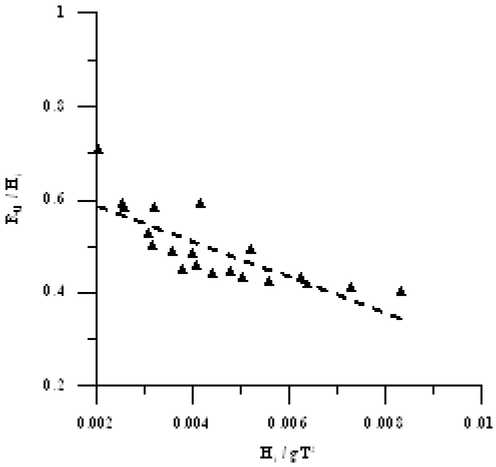
(d) for $h_s/d = 1.11$; $w_{gap}/w = 0.25$



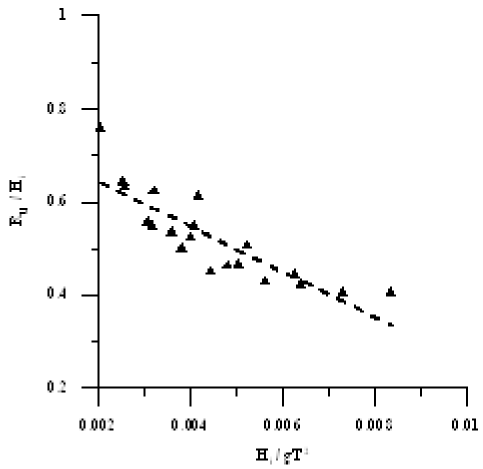
(e) for $h_s/d = 1.25$; $w_{gap}/w = 0.375$



(f) for $h_s/d = 1.11$; $w_{gap}/w = 0.375$



(g) for $h_s/d = 1.25$; $w_{gap}/w = 0.5$



(h) for $h_s/d = 1.11$; $w_{gap}/w = 0.5$

Fig. 7.17 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d) and gap width parameters (w_{gap}/w)

Fig. 7.17 (e) depicts the effect of wave steepness parameter (H_i/gT^2) on wave run-up (R_u/H_i) for the fragmented emergent trunk model with roots with relative plant height, h_s/d = 1.25 and gap width parameter, w_{gap}/w = 0.375. It is seen that the wave run-up on the beach varies from 0.779 to 0.467 for a variation of percentage reduction in wave heights from 75.00% to 55.00%. Fig. 7.17 (f) illustrates the decrease in wave run-up with increasing wave steepness, i.e., R_u/H_i varies from 0.789 to 0.467 for h_s/d = 1.11 and w_{gap}/w = 0.375; wherein, the percentage reduction in wave heights ranges from 63.75% to 51.25%.

For the fragmented emergent trunk model with roots with relative plant height, h_s/d = 1.25 and gap width parameter, w_{gap}/w = 0.5, it is seen that the wave run-up on the beach varies from 0.747 to 0.457, with corresponding variation of percentage reduction in wave heights from 72.50% to 56.88% (Fig. 7.17 (g)). It is seen from Fig. 7.17 (h) that R_u/H_i varies from 0.768 to 0.450 for h_s/d = 1.11 and w_{gap}/w = 0.5; wherein, the percentage reduction in wave heights ranges from 67.50% to 52.50%. The results presented in this section shows that the extent of wave run-up on the beach is as a result of the extent of attenuation of wave heights.

7.3 STUDIES ON FRAGMENTED COMPOUND HETEROGENEOUS MODEL

A 1:30 scaled fragmented compound heterogeneous model, comprising of a submerged seagrass model, submerged rigid vegetation and emergent trunk model with roots, with gaps of varying widths between the individual models, placed in order, on the flume bed, is subjected to waves of height varying from 0.08 m to 0.16 m at an interval of 0.02 m. Results of experiments conducted with the fragmented compound heterogeneous model of varying gap widths and relative plant heights are presented in this section.

7.3.1 Wave height attenuation

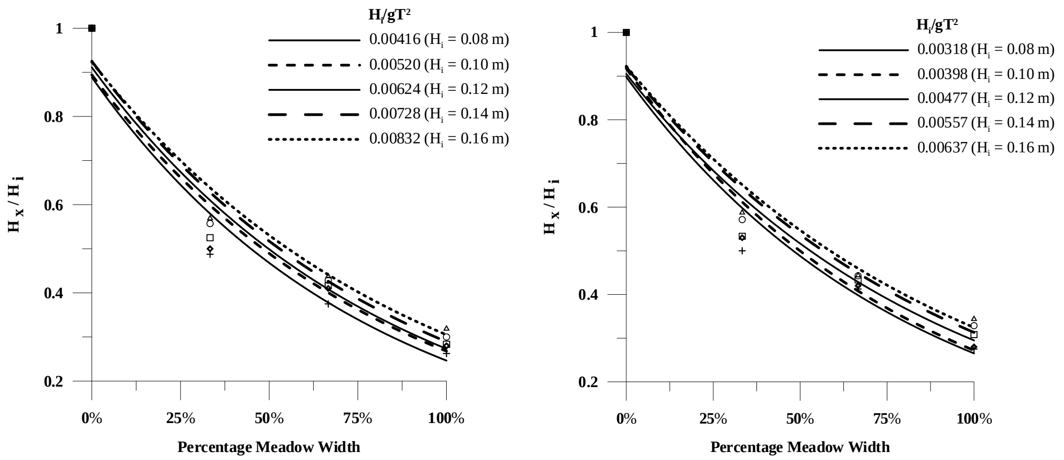
As an extension of the attempt to study the effect of heterogeneous plant communities on wave height attenuation discussed in section 6.4 of chapter 6, the influence of fragmentation is also included in this section to draw possible conclusions with regard to wave attenuation due to a fragmented compound heterogeneous model. Therefore, experiments are conducted with this fragmented compound heterogeneous model of base width 6 m, and with varying gap widths to observe the changes in wave heights as the wave propagates along the model. Plate 7.2 depicts the propagation of wave along the fragmented compound heterogeneous model.

Plate 7.2 Snapshots of model setup to study wave attenuation over a fragmented compound heterogeneous model.

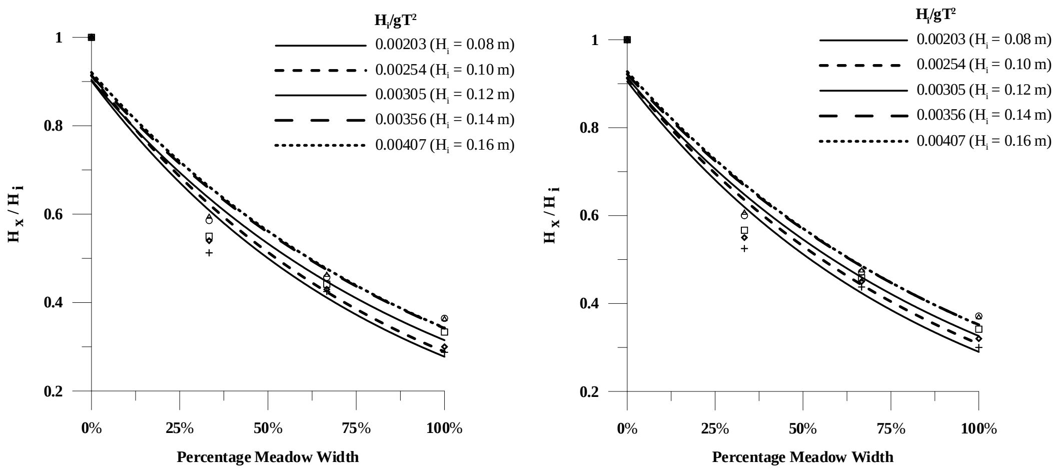
7.3.1.1 Relative plant height, $h_s/d = 1.25$; gap width parameter, $w_{gap}/w = 0.125$

In this section, results are presented for the case of waves propagating through a fragmented compound heterogeneous model of relative plant height, $h_s/d = 1.25$. This model consists of three sections, namely, submerged seagrass model, submerged rigid vegetation model and emergent trunk model with roots, each of width 2 m, which adds up to form the base model of width 6 m. Gaps of width (w_{gap}) 0.75 m is introduced alternately between the three sections of the base model, which leads to an increase in total meadow width from 6 m to 7.5 m. A plot of relative wave heights at locations within the model, $\left(\frac{H_x}{H_i}\right)$ and percentage meadow width for varying incident wave conditions is illustrated in Fig. 7.18 (a to d). The relative percentage wave height at the exit point of the meadow varies from 26.25% to 30.00% for an incident wave of height 0.08 m. Further, the relative percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 30.00% to 34.00%, from 30.83%

to 35.83%, from 32.14% to 37.86% and from 33.13% to 38.13%, (refer Fig. 7.18 (a to d)).



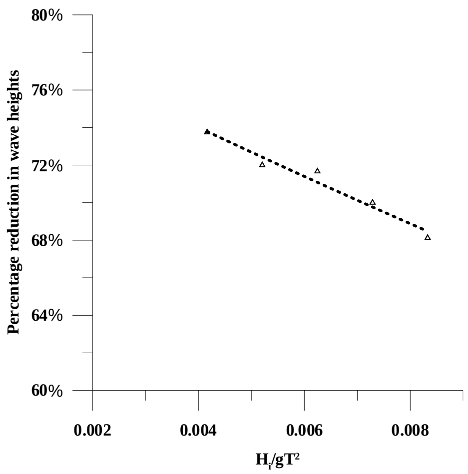
(a) for w/L = 2.508, T = 1.4 s (b) for w/L = 2.142, T = 1.6 s



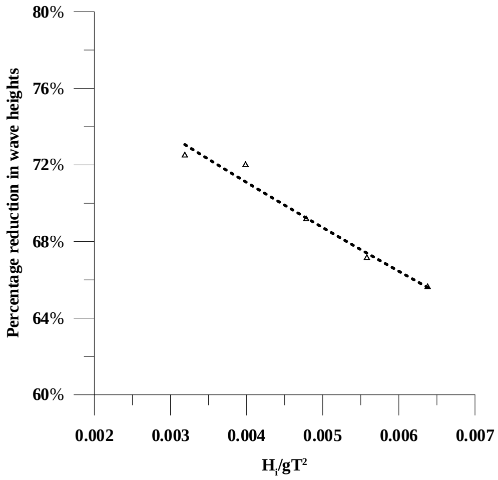
(c) for w/L = 1.835, T = 1.8 s (d) for w/L = 1.623, T = 2 s

Fig. 7.18 Relative wave heights at locations within the model for h_s/d = 1.25; w_{gap}/w = 0.125

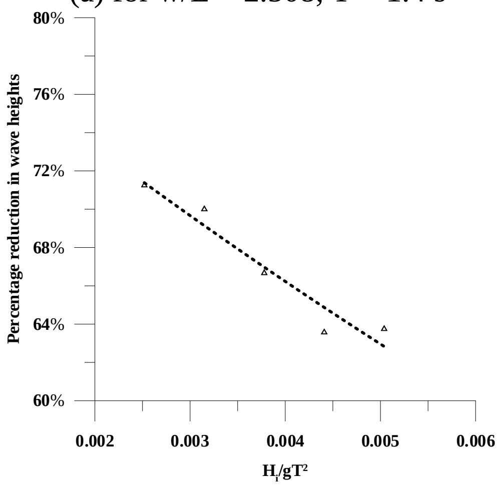
Fig. 7.19 (a to d) depicts the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction. It is noted that there is a decrease in wave height reduction from 73.75% to 66.88% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 2.508, T = 1.4 s), from 71.25% to 65.00%, 71.25% to 63.13% and from 70.00% to 61.88% for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 2.142, T = 1.6 s), 0.00251 to 0.00503 (w/L = 1.835, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 1.623, T = 2 s), respectively.



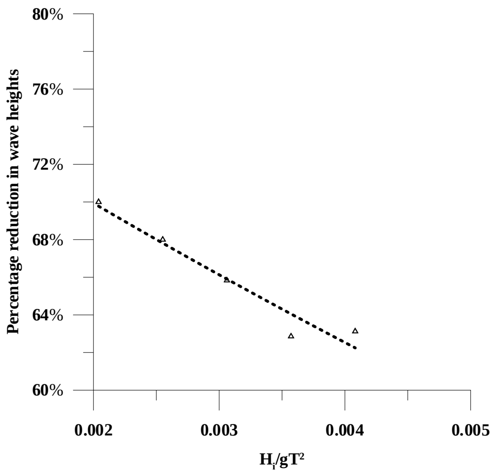
(a) for w/L = 2.508, T = 1.4 s



(b) for w/L = 2.142, T = 1.6 s



(c) for w/L = 1.835, T = 1.8 s



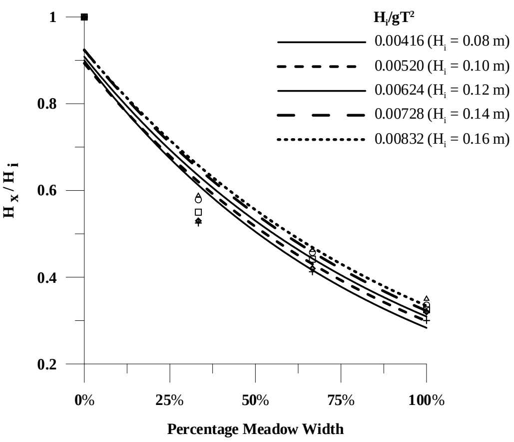
(d) for w/L = 1.623, T = 2 s

Fig. 7.19 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 1.25$; $w_{gap}/w = 0.125$

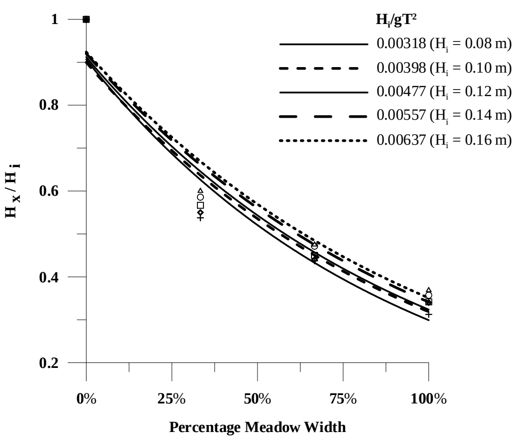
As the wave propagates through the initial stretch of submerged seagrass, the leaves of the seagrass interfere with the particle orbital velocities which leads to a decrease in wave heights. As the propagating wave further encounters a gap, that is, a zone free of vegetation, there is no significant decrease in wave heights, but as it passes through the next stretch of submerged rigid vegetation, the wave heights again get attenuated. The wave again encounters a zone free of vegetation, which again does not contribute much in attenuating wave heights, but as it still further passes over the emergent trunk model with roots, there is a significant reduction of wave heights. This is due to the presence of emergent trunks as well as the roots of the model which interferes with the particle orbital velocities, and an increased turbulence is observed which leads to an increased wave height attenuation. It is evident from the above results that the fragmented compound heterogeneous vegetation exhibits increased wave height reduction when compared to the fragmented models discussed in section 7.2. This increased wave height attenuation for the present model is predominantly due to the presence of three individual plant models, which helps in forming a heterogeneous model, as well as due to the increase in meadow width from 2 m, for the models discussed in sections 7.2, to 7.5 m.

7.3.1.2 Relative plant height, $h_s/d = 1.11$; gap width parameter, $w_{gap}/w = 0.125$

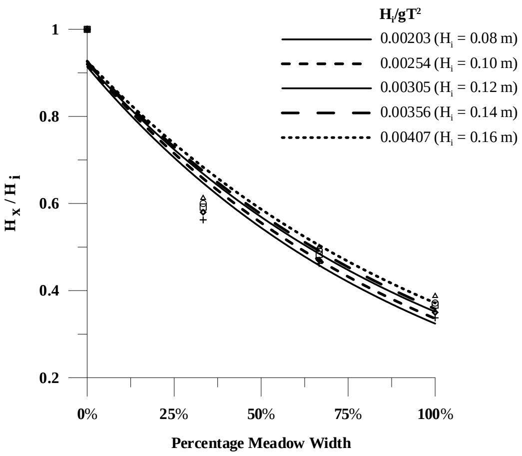
The variation of wave heights at different locations within the fragmented compound heterogeneous model with h_s/d of 1.11 corresponding to different wave periods is shown in Fig. 7.20 (a to d). The relative percentage wave height at the exit point of the meadow varies from 31.25% to 36.25% for an incident wave of height 0.08 m. For incident waves of heights 0.10 m, 0.12 m, 0.14 m and 0.16 m, the relative percentage wave heights at exit ranges from 34.00% to 39.00%, from 35.00% to 40.00%, from 35.71% to 41.43% and from 36.25% to 42.50%.



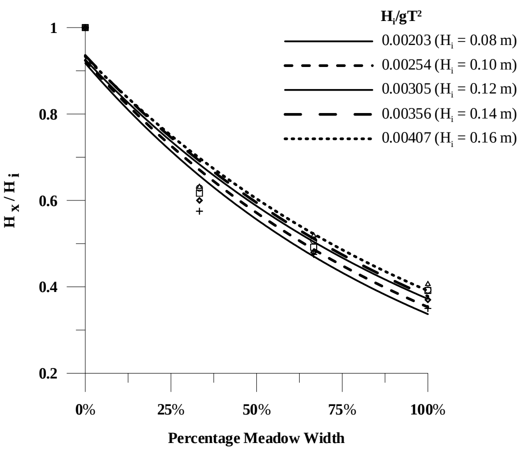
(a) for w/L = 2.411, T = 1.4 s



(b) for w/L = 2.089, T = 1.6 s



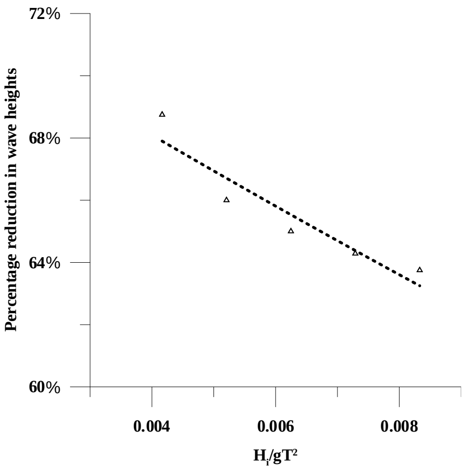
(c) for w/L = 1.750, T = 1.8 s



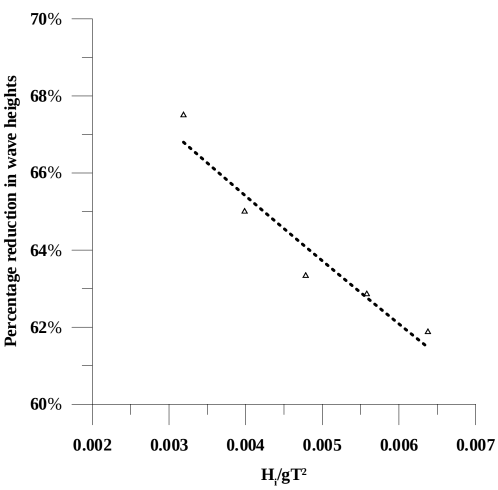
(d) for w/L = 1.546, T = 2 s

Fig. 7.20 Relative wave heights at locations within the model for $h_s/d = 1.11$; $w_{gap}/w = 0.125$

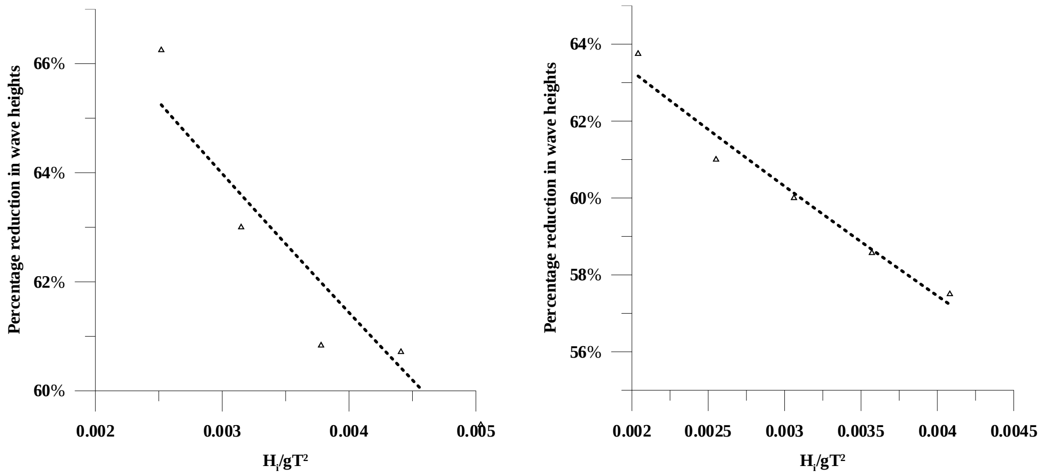
Also, Fig. 7.21 (a to d) depicts the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction. It is noted that there is a decrease in wave height reduction from 68.75% to 63.75% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 2.411, T = 1.4 s), from 67.50% to 61.88%, 66.25% to 59.38% and from 63.75% to 57.50% for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 2.089, T = 1.6 s), 0.00251 to 0.00503 (w/L = 1.750, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 1.546, T = 2 s), respectively.



(a) for w/L = 2.411, T = 1.4 s



(b) for w/L = 2.089, T = 1.6 s



(c) for w/L = 1.750, T = 1.8 s (d) for w/L = 1.546, T = 2 s

Fig. 7.21 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w_{gap}/w = 0.125

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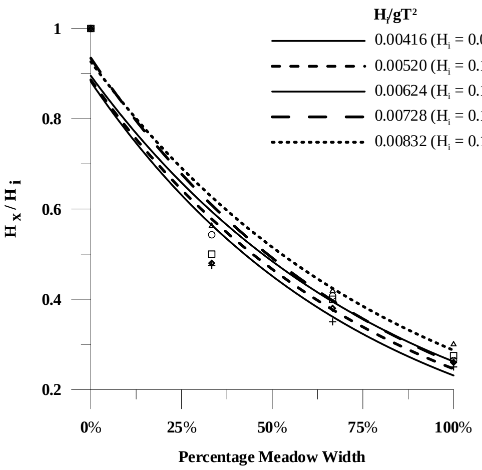
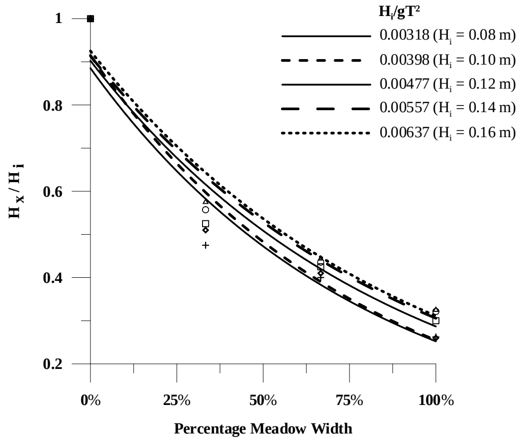
7.3.1.3 Relative plant height, h_s/d = 1.25; gap width parameter, w_{gap}/w = 0.25

Fig. 7.22 illustrates the measured wave heights at locations within the 6 m wide compound heterogeneous model with gaps of width 1.5 m between each of the individual vegetation sections with h_s/d of 1.25 corresponding to different wave conditions.

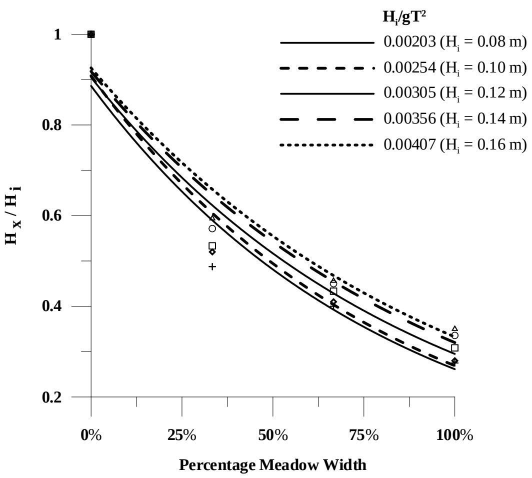
The percentage wave height at the exit point of the model varies from 25.00% to 28.75% for an incident wave of height 0.08 m. Further, the percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m correspondingly ranges from 26.00% to 30.00%, 27.50% to 31.67%, 26.43% to 34.29% and 30.00% to 35.63% respectively.



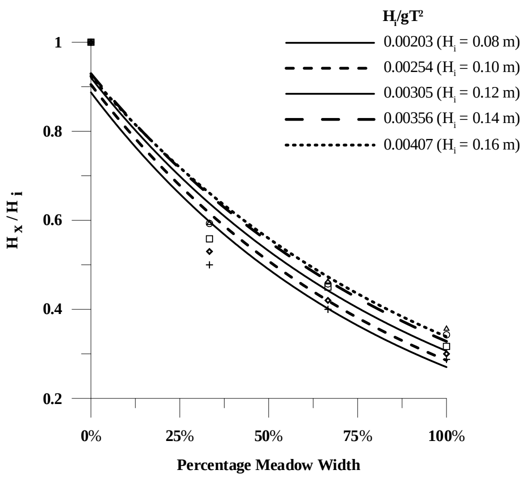
(a) for w/L = 2.508, T = 1.4 s



(b) for w/L = 2.142, T = 1.6 s



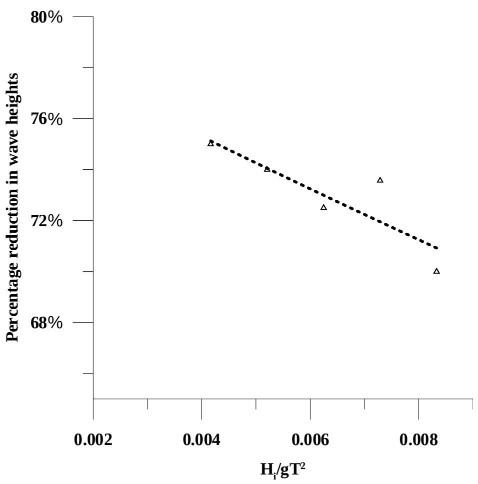
(c) for w/L = 1.835, T = 1.8 s



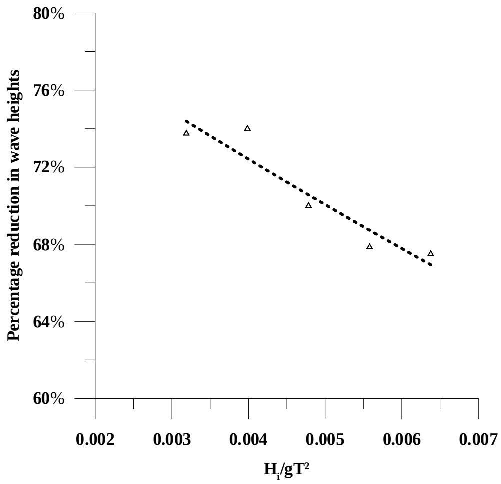
(d) for w/L = 1.623, T = 2 s

Fig. 7.22 Relative wave heights at locations within the model for h_s/d = 1.25; w_{gap}/w = 0.25

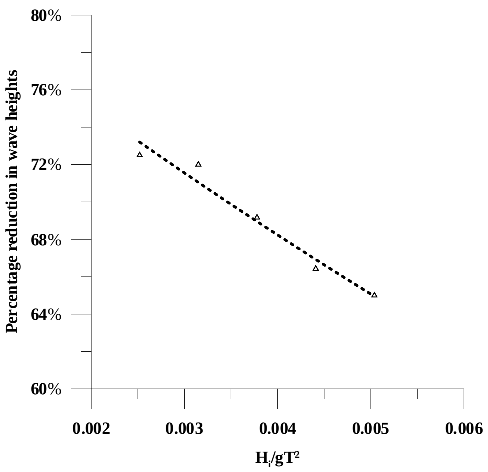
Fig. 7.23 (a to d) displays the effect of wave steepness parameter, H_i/gT^2 on percentage wave height reduction. A decrease in wave height reduction from 75.00% to 70.00% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 2.508, T = 1.4 s) is observed. Correspondingly, for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 2.142, T = 1.6 s), 0.00251 to 0.00503 (w/L = 1.835, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 1.623, T = 2 s), the percentage wave height reduction varies from 73.75% to 67.50%, 72.50% to 65.00% and from 71.25% to 64.38% respectively.



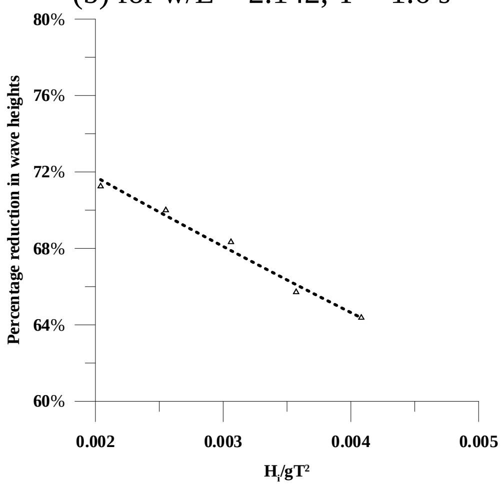
(a) for w/L = 2.508, T = 1.4 s



(b) for w/L = 2.142, T = 1.6 s



(c) for w/L = 1.835, T = 1.8 s



(d) for w/L = 1.623, T = 2 s

Fig. 7.23 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.25; w_{gap}/w = 0.25

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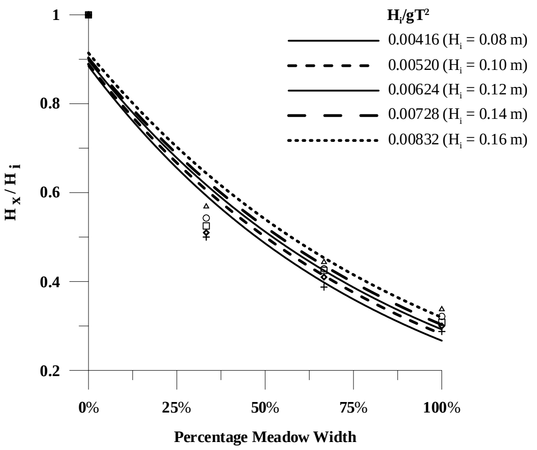
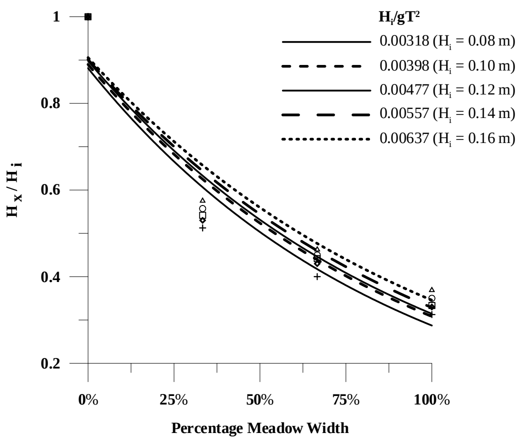
7.3.1.4 Relative plant height, h_s/d = 1.11; gap width parameter, w_{gap}/w = 0. 25

The measured wave heights at locations within the fragmented compound heterogeneous model with h_s/d of 1.11 of gap width parameter, w_{gap}/w = 0. 25, corresponding to different wave heights and periods is depicted in Fig. 7.24 (a to d).

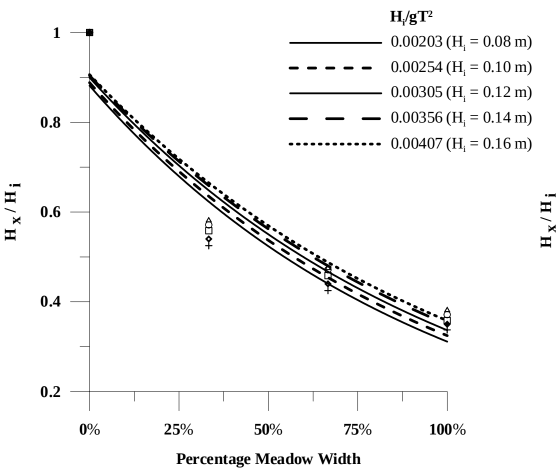
The percentage wave height at the exit point of the meadow varies from 28.75% to 35.00% for an incident wave of height 0.08 m. Further, the percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m correspondingly varies from 30.00% to 37.00%, 30.83% to 38.33%, 32.14% to 40.00% and 33.75% to 40.63% respectively.



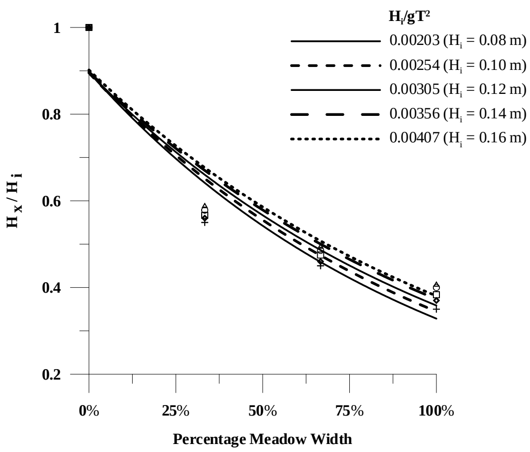
(a) for w/L = 2.411, T = 1.4 s



(b) for w/L = 2.089, T = 1.6 s



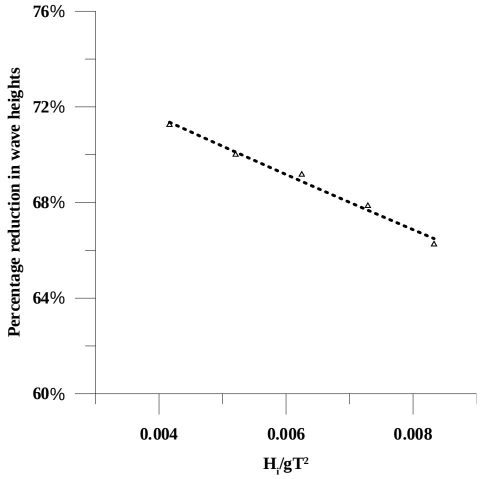
(c) for w/L = 1.750, T = 1.8 s

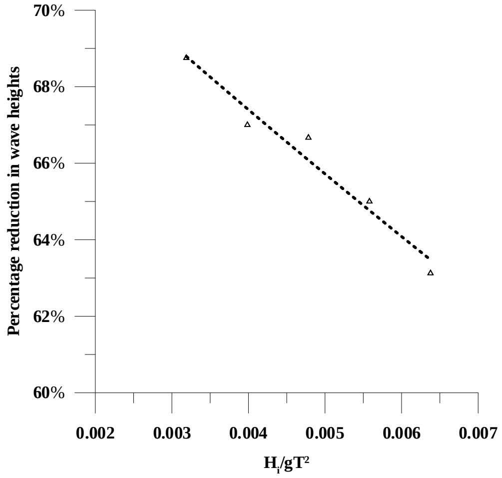


(d) for w/L = 1.546, T = 2 s

Fig. 7.24 Relative wave heights at locations within the model for h_s/d = 1.11; w_{gap}/w = 0.25

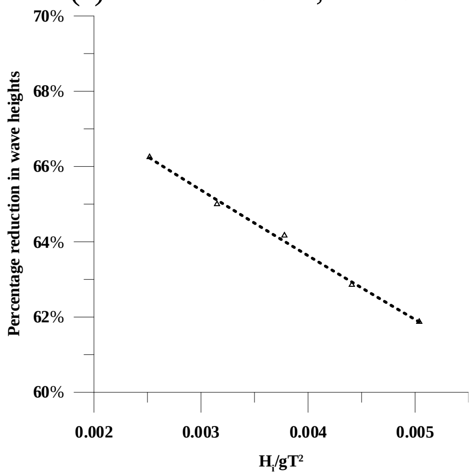
Fig. 7.25 (a to d) depicts the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction. It is noted that there is a decrease in wave height reduction from 71.25% to 66.25% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 2.411, T = 1.4 s). Further, the percentage wave height reduction varies from 68.75% to 63.13%, 66.25% to 61.88% and from 65.00% to 59.38%, for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 2.089, T = 1.6 s), 0.00251 to 0.00503 (w/L = 1.750, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 1.546, T = 2 s), respectively.

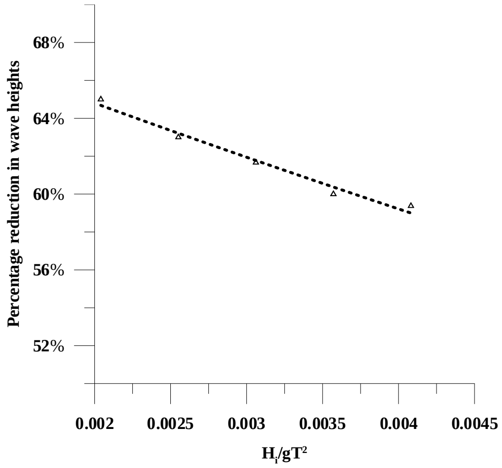




(a) for w/L = 2.411, T = 1.4 s

(b) for w/L = 2.089, T = 1.6 s





(c) for w/L = 1.750, T = 1.8 s

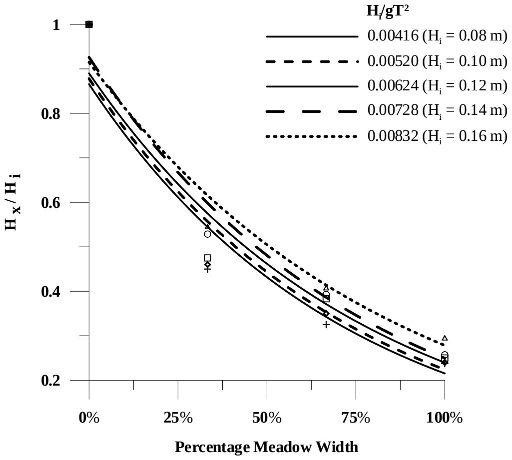
(d) for w/L = 1.546, T = 2 s

Fig. 7.25 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 1.11$; $w_{gap}/w = 0.25$

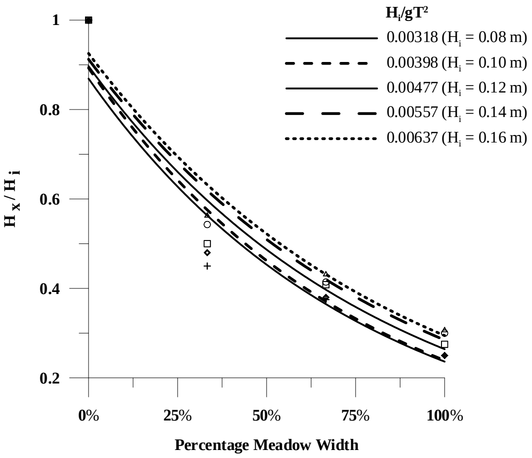
It is seen that the percentage wave height reduction is less when compared to that of the same model with $h_s/d = 1.25$, discussed in section 7.3.1.3 above. This is due to the fact that as the water depth increases and as the relative plant height is less, the effective interference between the vegetation and the particle orbital velocities are reduced when the model gets fully submerged at higher incident wave heights.

7.3.1.5 Relative plant height, $h_s/d = 1.25$; gap width parameter, $w_{gap}/w = 0.375$

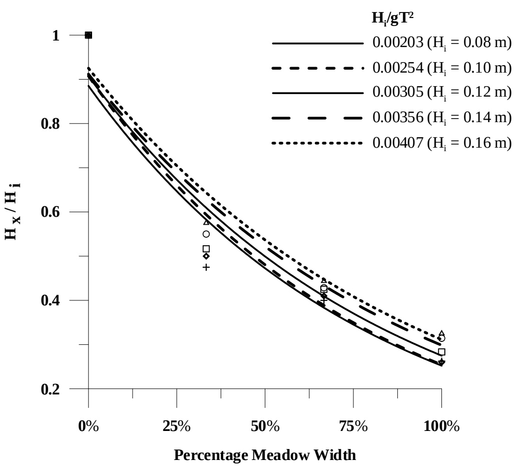
Fig. 7.26 illustrates the relative wave heights at locations within the fragmented compound heterogeneous model for $h_s/d = 1.25$; $w_{gap}/w = 0.375$, with gaps of width 2.25 m introduced between the individual vegetation models. For an incident wave of height 0.08 m, the percentage wave height at the exit point of the meadow varies from 23.75% to 27.50%. Further, the percentage wave heights at exit for incident wave of heights 0.10 m, 0.12 m, 0.14 m and 0.16 m ranges from 24.00% to 27.00%, 25.00% to 29.17%, 25.71% to 32.14% and 29.38% to 33.13% respectively.



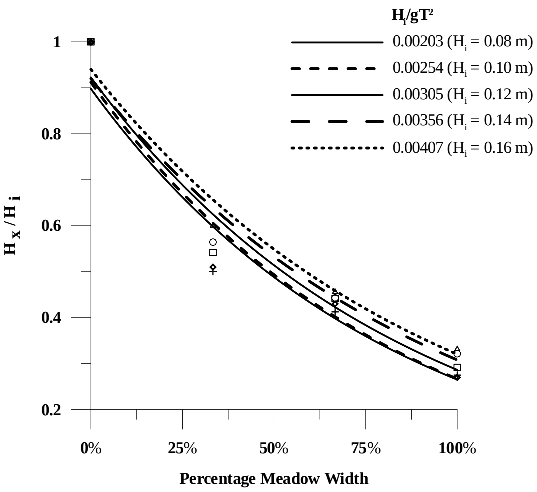
(a) for w/L = 2.508, T = 1.4 s



(b) for w/L = 2.142, T = 1.6 s



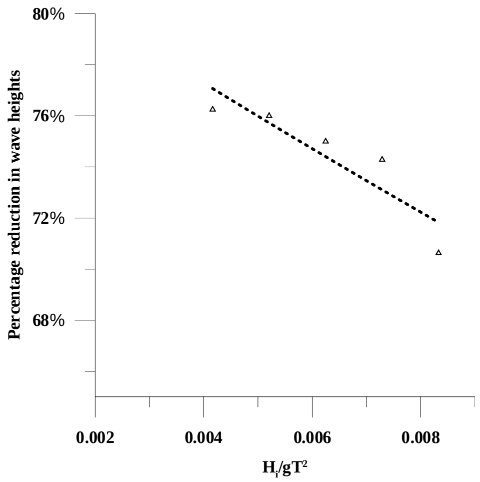
(c) for w/L = 1.835, T = 1.8 s



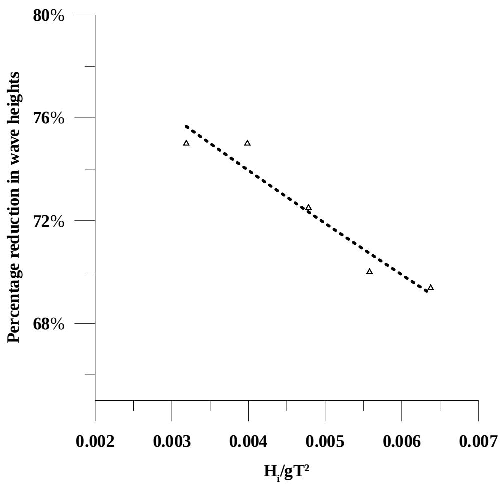
(d) for w/L = 1.623, T = 2 s

Fig. 7.26 Relative wave heights at locations within the model for $h_s/d = 1.25$; $w_{gap}/w = 0.375$

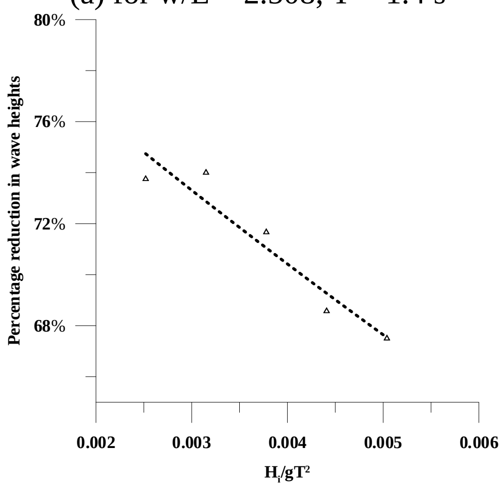
Fig. 7.27 (a to d) depicts the influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction.



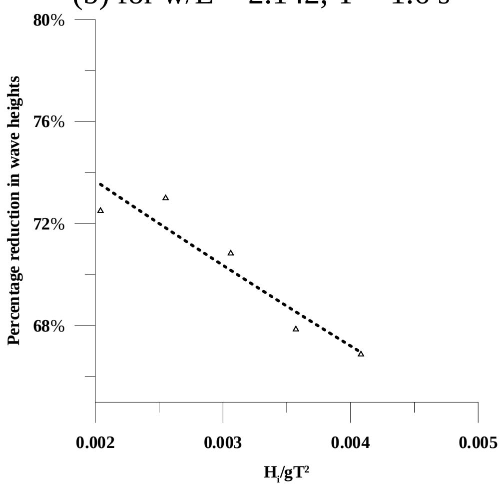
(a) for w/L = 2.508, T = 1.4 s



(b) for w/L = 2.142, T = 1.6 s



(c) for w/L = 1.835, T = 1.8 s



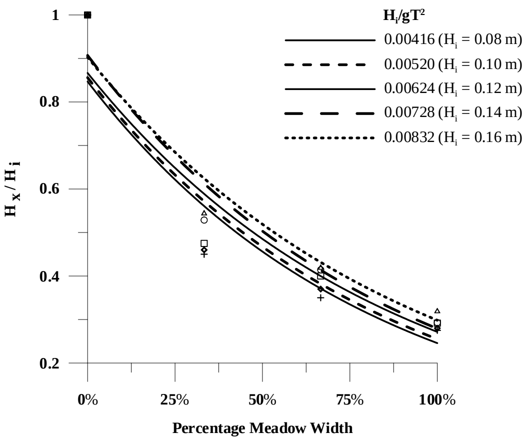
(d) for w/L = 1.623, T = 2 s

Fig. 7.27 Variation of percentage reduction in wave heights with H_i/gT^2 for $h_s/d = 1.25$; $w_{gap}/w = 0.375$

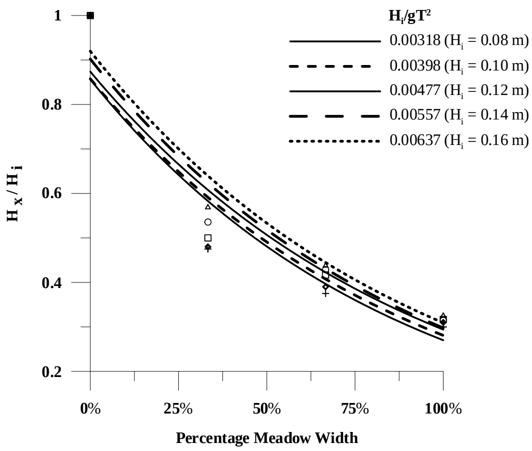
As the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 2.508, T = 1.4 s), it is noted that there is a decrease in wave height reduction from 76.25% to 70.63%. Similarly, for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 2.142, T = 1.6 s), 0.00251 to 0.00503 (w/L = 1.835, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 1.623, T = 2 s), the percentage reduction in wave heights ranges from 75.00% to 69.38%, 73.75% to 67.50% and from 72.50% to 66.88%, respectively.

7.3.1.6 Relative plant height, $h_s/d = 1.11$; gap width parameter, $w_{gap}/w = 0.375$

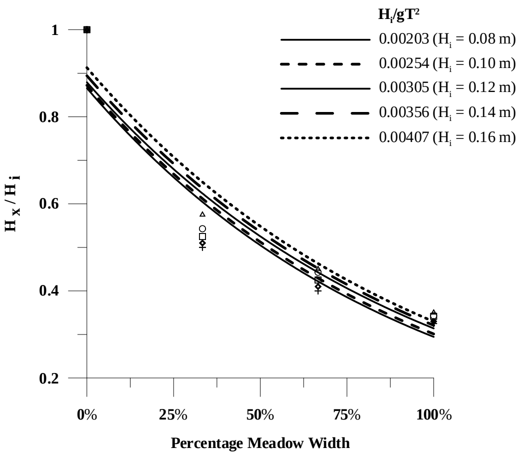
For the fragmented compound heterogeneous model, with $h_s/d = 1.11$ and $w_{gap}/w = 0.375$, the percentage wave height at the exit point of the model varies from 27.50% to 35.00% for an incident wave of height 0.08 m.



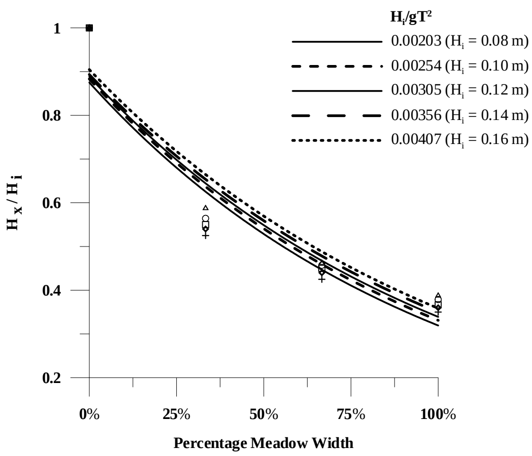
(a) for w/L = 2.411, T = 1.4 s



(b) for w/L = 2.089, T = 1.6 s



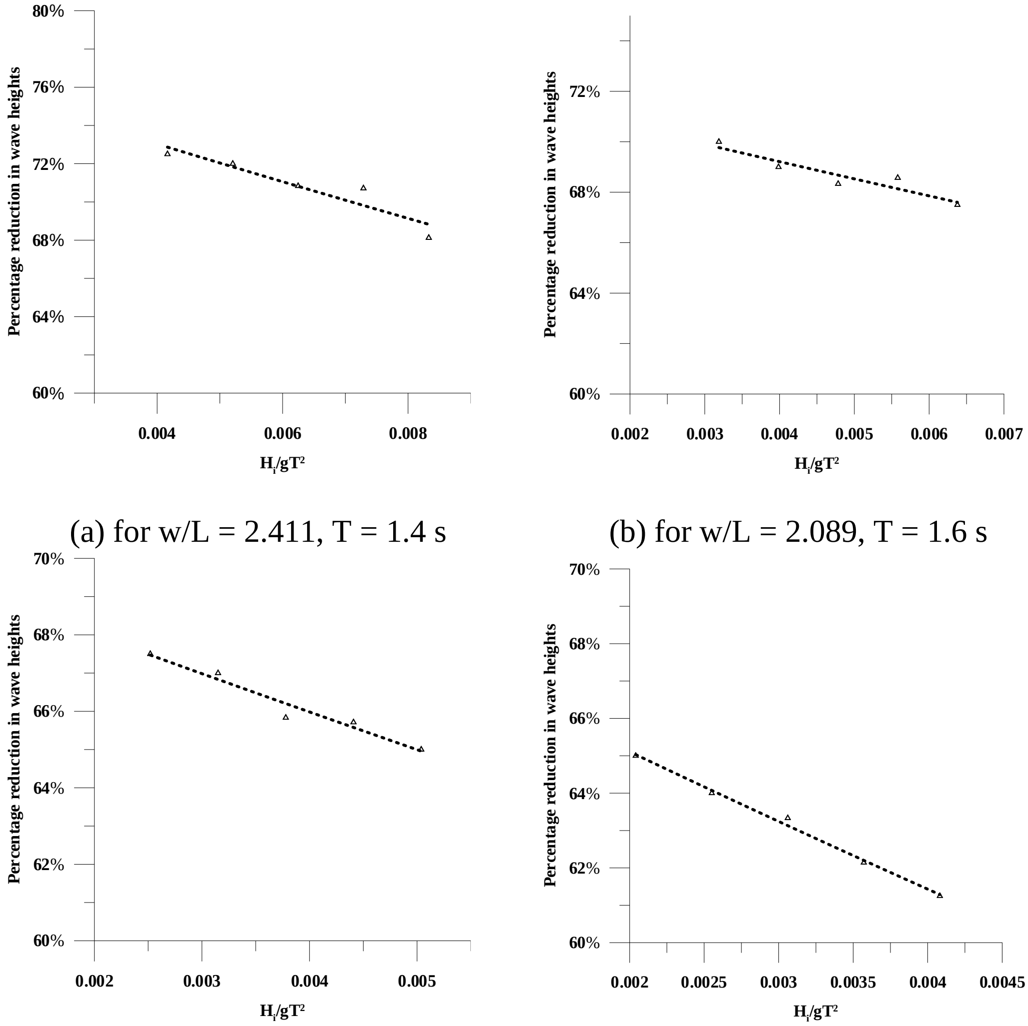
(c) for w/L = 1.750, T = 1.8 s



(d) for w/L = 1.546, T = 2 s

Fig. 7.28 Relative wave heights at locations within the model for $h_s/d = 1.11$; $w_{gap}/w = 0.375$

Further, the percentage wave heights at exit for an incident wave of height 0.10 m, 0.12 m, 0.14 m and 0.16 m varies from 28.00% to 36.00%, 29.17% to 36.67%, 29.29% to 37.86% and from 31.88% to 38.75% respectively (refer Fig. 7.28 (a to d)).



(a) for w/L = 2.411, T = 1.4 s (b) for w/L = 2.089, T = 1.6 s

(c) for w/L = 1.750, T = 1.8 s (d) for w/L = 1.546, T = 2 s

Fig. 7.29 Variation of percentage reduction in wave heights with H_i/gT^2 for h_s/d = 1.11; w_{gap}/w = 0.375

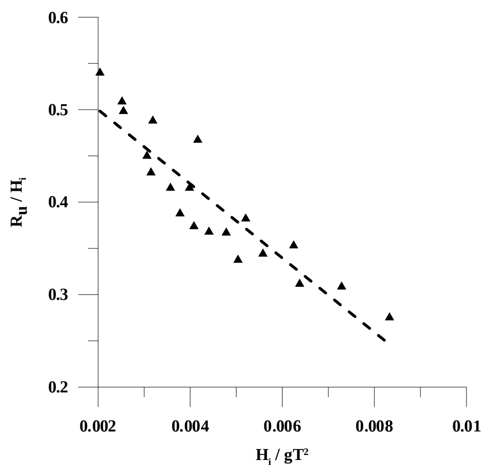
The influence of wave steepness parameter, H_i/gT^2 on percentage wave height reduction is illustrated in Fig. 7.29 (a to d). It is noted that there is a decrease in wave height reduction from 72.50% to 68.13% as the wave steepness parameter, H_i/gT^2 increases from 0.00416 to 0.00832 (w/L = 2.411, T = 1.4 s). The percentage wave height reduction varies from 70.00% to 67.50%, 67.50% to 65.00% and from 65.00% to 61.25% for wave steepness parameters ranging from 0.00318 to 0.00637 (w/L = 2.089, T = 1.6 s), 0.00251 to 0.00503 (w/L = 1.750, T = 1.8 s) and 0.00203 to 0.00407 (w/L = 1.546, T = 2 s), respectively.

7.3.2 Effect of wave steepness on run-up

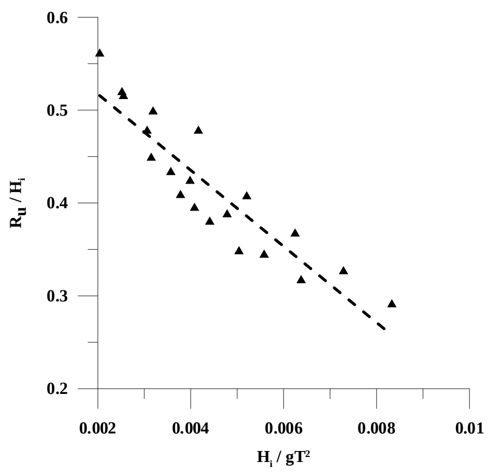
The effect of wave steepness parameter (H_i/gT^2) on relative wave run-up (R_u/H_i) for the fragmented compound heterogeneous model is discussed in this section.

The extent of inundation on the beach slope, measured as wave run-up (R_u/H_i) on the beach for the fragmented compound heterogeneous model ($h_s/d = 1.25$; $w_{gap}/w = 0.125$) varies from 0.540 to 0.275 (for w/L = 2.508 to 1.623), wherein the percentage reduction in wave heights ranges from 73.75% to 61.88%. Also, for the same model with $h_s/d = 1.11$; $w_{gap}/w = 0.125$, the wave run-up (R_u/H_i) on the beach varies from 0.561 to 0.291 (for w/L = 2.411 to 1.546), as depicted in Fig. 7.30 (a to b).

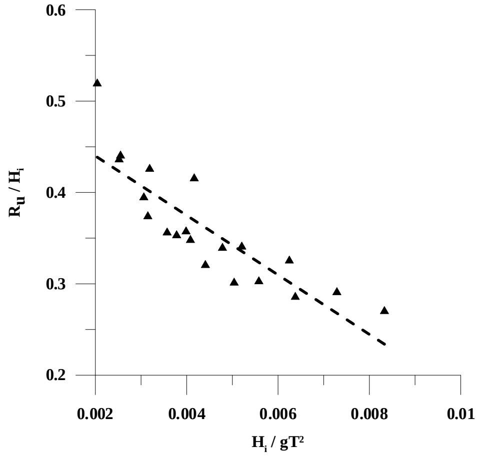
For the same model with $h_s/d = 1.25$; $w_{gap}/w = 0.25$, it is observed from Fig. 7.30 (c to d) that the wave run-up (R_u/H_i) varies from 0.519 to 0.270 (for w/L = 2.508 to 1.623) and from 0.540 to 0.275 (w/L = 2.411 to 1.546) for $h_s/d = 1.11$; $w_{gap}/w = 0.25$. The corresponding percentage reduction in wave heights ranges from 75.00% to 64.38% ($h_s/d = 1.25$; $w_{gap}/w = 0.25$) and from 71.25% to 59.38% ($h_s/d = 1.11$; $w_{gap}/w = 0.25$).



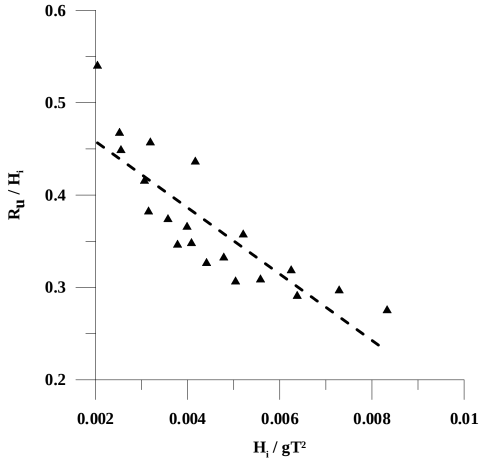
(a) for $h_s/d = 1.25$; $w_{gap}/w = 0.125$



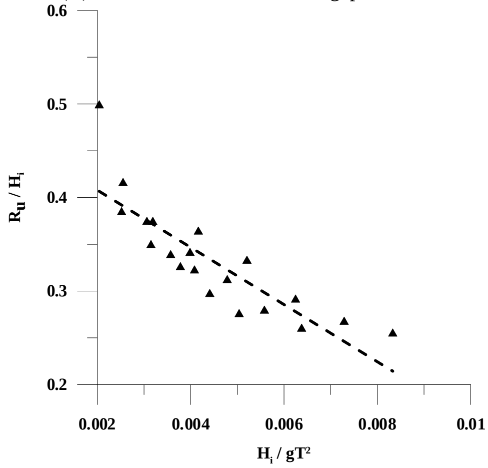
(b) for $h_s/d = 1.11$; $w_{gap}/w = 0.125$



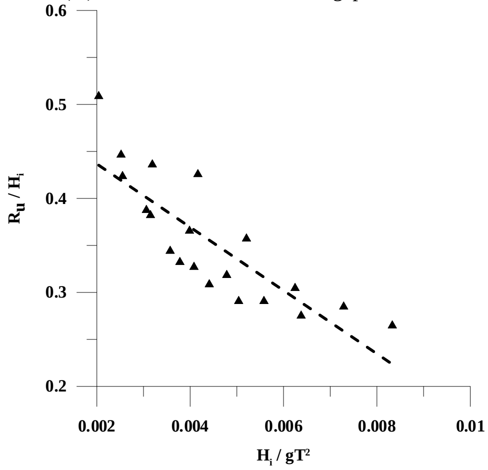
(c) for h_s/d = 1.25; w_{gap}/w = 0.25



(d) for h_s/d = 1.11; w_{gap}/w = 0.25



(e) for h_s/d = 1.25; w_{gap}/w = 0.375



(f) for h_s/d = 1.11; w_{gap}/w = 0.375

Fig. 7.30 Effect of wave steepness on wave run-up for varying relative plant heights (h_s/d) and gap width parameters (w_{gap}/w)

Fig. 7.30 (e) depicts the effect of wave steepness parameter (H_i/gT^2) on wave run-up (R_u/H_i) for the fragmented compound heterogeneous model with relative plant height, h_s/d = 1.25 and gap width parameter, w_{gap}/w = 0.375. It is seen that the wave run-up on the beach varies from 0.498 to 0.254 for a variation of percentage reduction in wave heights from 76.25% to 66.88%. Fig. 7.30 (f) illustrates the decrease in wave run-up with increasing wave steepness, i.e., R_u/H_i varies from 0.509 to 0.265 for h_s/d = 1.11 and w_{gap}/w = 0.375; wherein, the percentage reduction in wave heights ranges from 72.50% to 61.25%. The results reveal that the wave run-up on the beach is as a result of the extent of attenuation of wave heights.

7.4 COMPARISON OF PERFORMANCE OF FRAGMENTED VEGETATION MODELS

The results from the studies conducted on fragmented vegetation models, namely, fragmented emergent trunk model with roots and fragmented compound heterogeneous model, discussed in section 7.2 and 7.3 highlights the role of wave characteristics, vegetation characteristics as well as the presence of gaps in vegetation in dissipating wave energy and thus the inundation on the beach.

A comparison of results displayed in section 7.2 and 7.3 reveals that the fragmented compound heterogeneous model of width 6 m with gaps of width (w_{gap}) 2.25 m (gap width parameter, $w_{gap}/w = 0.375$) displays maximum attenuation of wave heights and the corresponding wave run-up on the beach. For a relative plant height, $h_s/d = 1.25$; the percentage reduction in wave heights for fragmented emergent trunk model with roots of maximum gap width parameter, $w_{gap}/w = 0.5$, varies from 72.50% to 56.88%, taking into consideration the entire range of test conditions. As the wave propagates through a stretch of vegetation, then through a zone of free vegetation and further through another stretch of vegetation, there is a decrease in wave heights as it propagates through the model.

The percentage reduction in wave heights for the fragmented compound heterogeneous model of maximum gap width parameter, $w_{gap}/w = 0.375$ and relative plant height, $h_s/d = 1.25$, varies from 76.25% to 66.88%. This increased reduction in wave heights may be characterized by the presence of all three types of vegetation, viz., submerged seagrass, submerged rigid vegetation and the emergent trunk with roots, in addition to the presence of gaps of maximum width of 2.25 m. This fragmented compound heterogeneous model, owing to its increased width of meadow of 6 m, along with alternate gaps of maximum gap width (w_{gap}) of 2.25 m, which leads to an increase in total meadow width (w) from 6 m to 10.5 m also plays a substantial role in wave height attenuation.

The same pattern is observed among the fragmented models of $h_s/d = 1.11$, but with a reduction in the percentage wave height reductions, which is attributed to the increase in depth of water. The values of percentage reduction in wave heights varies from 67.50% to 52.50%, and from 72.50% to 61.25% for the fragmented emergent trunk model with roots ($w_{gap}/w = 0.5$), and the fragmented compound heterogeneous model ($w_{gap}/w = 0.375$), respectively for $h_s/d = 1.11$.

The results of the fragmented compound heterogeneous model with highest gap width, $w_{gap} = 2.25$ m and gap width parameter, $w_{gap}/w = 0.375$, shows maximum reduction in wave heights (76.25% to 66.88% for $h_s/d = 1.25$), mainly characterized by the increase in total meadow width as well as the height of emergence of the model, which leads to effective penetration of the layers of varying particle orbital velocities. A comparison between the results presented in this chapter and results of the field study on the impact of anthropogenically created canopy gaps on wave attenuation in a seagrass meadow by Colomer et. al., 2017 reveals the influence of longitudinal gaps in the vegetation on the architectural characteristics of the adjacent meadow on wave attenuation. The results from this study indicates that the presence of gaps in the vegetated cover does not significantly increase the wave height attenuation, whereas it is the increase in meadow width that shows an increased reduction in wave heights, which is comparable to the conclusions of Colomer et. al. (2017) and El Allaoui et al. (2016).

A comparison of the extent of inundation on the beach slope, measured in terms of R_u/H_i, plotted against the wave steepness parameter H_i/gT^2, varying from 0.00203 to 0.00832 shows that the relative wave run up varies from 0.747 to 0.457 and from 0.498 to 0.254 for the emergent trunk model with roots and the fragmented compound heterogeneous models respectively, for highest gap widths of 1 m and 2.25 m, respectively, for $h_s/d = 1.25$. The values of R_u/H_i varies from 0.768 to 0.450 and from 0.509 to 0.265 for the same models, namely, the emergent trunk model with roots and the fragmented compound heterogeneous model, of highest gap widths and $h_s/d = 1.11$, respectively.

7.5 KEY FINDINGS AND SUMMARY

The results of the test runs conducted on fragmented vegetation models to determine the extent of wave attenuation and the subsequent inundation on beach slope presented in this chapter suggests that the meadow width parameter (w/L), relative plant height (h_s/d), gap width parameter (w_{gap}/w) and wave steepness parameter (H_i/gT^2) plays a critical role in governing the attenuation characteristics. The results are interpreted in terms of relative wave heights at locations within the fragmented models, percentage reduction in wave heights, and the corresponding wave run-up expressed in terms of relative wave run up on the beach. The results presented in this chapter reveals that the fragmented compound heterogeneous model is capable of attenuating the waves to a higher extent when compared to the fragmented emergent trunk model with roots, owing to the increase in meadow width and the height of emergence of vegetation.

The key findings of this study on fragmented vegetation models is listed below:

7.5.1 Fragmented emergent trunk model with roots

1. The percentage wave height at exit point of a 2 m wide emergent trunk model with roots with highest gap width (w_{gap}) of 1 m (w_{gap}/w = 0.5) (w/L = 0.836 - 0.541 for h_s/d = 1.25; 0.804 - 0.515 for h_s/d = 1.11) varies from 27.50% - 43.13% and from 32.50% - 47.50% for h_s/d of 1.25 and 1.11, respectively.
2. The percentage wave height reduction for the same case varies from 72.50% - 56.88% and from 67.50% - 52.50% for h_s/d of 1.25 and 1.11, respectively.
3. As wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.747 to 0.457 (h_s/d = 1.25) and from 0.768 to 0.450 (h_s/d = 1.11) for the emergent trunk model with roots, with highest gap width (w_{gap}) of 1 m and gap width parameter, w_{gap}/w = 0.5.

7.5.2 Fragmented compound heterogeneous model

1. For the fragmented compound heterogeneous model of width 6 m with highest gap width (w_{gap}) of 2.25 m and gap width parameter, w_{gap}/w = 0.375 (w/L = 2.508 – 1.623 for h_s/d = 1.25; 2.411 – 1.546 for h_s/d = 1.11), the percentage wave height at exit point varies from 23.75% - 33.13% and from 27.50% - 38.75% for h_s/d of 1.25 and 1.11, respectively.

2. This model also displays a percentage wave reduction varying from 76.25% - 66.88% and from 72.50% - 61.25% for h_s/d of 1.25 and 1.11, respectively.
3. R_u/H_i varies from 0.498 to 0.254 (h_s/d =1.25) and from 0.509 to 0.265 (h_s/d = 1.11) for this model, as the wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832.

Among the fragmented vegetation models, the optimum apparent meadow width and relative plant height (h_s/d) which gives the maximum wave attenuation and minimum wave run-up on the beach slope corresponds to the fragmented compound heterogeneous model of total meadow width, w = 10.5 m (out of which the actual vegetation meadow is only 6 m wide) and relative plant height, h_s/d = 1.25.

CHAPTER 8

CONCLUSIONS

8.1 BACKGROUND

The present scenario of global climate change and rise in sea levels has led to serious problems of erosion and increased intensity of storms and cyclones. This has paved the way for administrators and decision makers to consider sustainable implementation of coastal protection measures. Research has shown that sustainable shoreline buffers can also protect our coasts from increased wave activity and flooding. Significant importance is being given for such practices. Scientific evidence from physical model studies, numerical models and field investigations is needed to further create an awareness among the researchers and administrators in considering these options for shore protection. Further research in this field could lead to development of better practical solutions for various sites depending upon the geography and hydrodynamics of the coastal zone. Although there are many proven structural and non-structural shore protection measures, it is a well-known fact that there is no single quick or inexpensive method to protect the coast from nature’s forces. The future beckons for the powerful end-results of collaboration between engineers, researchers and conservationists in identifying the correct solutions to reduce the impacts of natural disasters on people and property. Hence, this study is attempted as a step towards quantifying wave attenuation and the subsequent extent of beach inundation due to different types of simulated vegetation of varying plant densities and meadow widths, acted upon by varying wave climate, tested in the experimental wave flume facility of Marine Structures Laboratory, Department of Applied Mechanics and Hydraulics, National Institute of Technology Karantaka, Surathkal. The key findings from the above study suggests a step forward into the experimentation and analysis of heterogeneity and fragmentation of vegetated meadows and their effect on wave attenuation and wave run-up on the beach, which led to the confirmation of the fact that vegetation has a definitive role in offering a good level of protection from wave activity, storm surges, cyclones and tsunamis. The detailed conclusions derived from the experiments conducted on different cases of simulated vegetation are presented in the following sections, whereas, a summary of these conclusions, along with the recommendations, limitations of this study and the scope for further research is included in the latter part of this chapter.

8.2 GENERAL CONCLUSIONS

The results of the test runs on different vegetation models, namely, submerged vegetation models, emergent vegetation models, heterogeneous vegetation models as well as fragmented vegetation models, to determine the extent of wave attenuation and the subsequent wave run-up on beach slope suggests that the meadow width parameter (w/L), relative plant height, (h_s/d), plant density (N) and wave steepness parameter (H_i/gT^2), gap width parameter (w_{gap}/w) and type of vegetation plays a critical role in governing the attenuation as well as run-up characteristics. The results, interpreted in terms of relative wave heights at locations within the various simulated vegetation models, percentage reduction in wave heights at the exit of the plant meadow, and the corresponding beach inundation expressed in terms of relative wave run up on the beach reveals the dependence of the above parameters on wave attenuation.

The key findings derived from the studies on different vegetation models is listed in the following sections:

8.3 CONCLUSIONS FOR SUBMERGED VEGETATION MODELS

The conclusions for the submerged vegetation models, namely, submerged seagrass and submerged rigid vegetation are presented below:

1. The percentage wave height at exit point of a 1 m wide (w/L = 0.418-0.270 for h_s/d = 0.525; 0.401-0.257 for h_s/d = 0.47) submerged seagrass model varies from 51.25% - 67.68% and from 66.25% - 78.21% for h_s/d of 0.525 and 0.47, respectively, whereas for the same model of width 2 m (w/L = 0.836-0.541 for h_s/d = 0.525; 0.803-0.515 for h_s/d = 0.47), the percentage

wave height at exit point of the meadow varies from 46.75% - 58.39% and from 53.25% - 64.71% for h_s/d of 0.525 and 0.47.

2. The percentage wave height reduction for the same seagrass model of width 1 m varies from 48.75% - 32.32% and from 33.75% - 21.79% for h_s/d of 0.525 and 0.47, respectively and from 53.25% - 41.61% and from 46.75% - 35.29% for the same model of width 2 m.
3. For the submerged rigid vegetation model of width 1 m, the percentage wave height at exit point of the meadow (w/L = 0.418-0.270 for h_s/d = 0.525; 0.401-0.257 for h_s/d = 0.47) varies from 41.38% - 64.67% and from 56.63% - 72.96% for h_s/d of 0.525 and 0.47, respectively. However, as the width of the same model is increased to 2 m (w/L = 0.836-0.541 for h_s/d = 0.525; 0.803-0.515 for h_s/d = 0.47), the percentage wave height at exit point of the meadow varies from 37.35% - 53.29% and from 42.17% - 58.49% for h_s/d of 0.525 and 0.47.
4. The variation of percentage wave height reduction ranges from 58.62% - 35.33% and from 43.37% - 27.04% for the submerged rigid vegetation model of width 1 m (w/L = 0.418-0.270 for h_s/d = 0.525; 0.401-0.257 for h_s/d = 0.47) and from 62.65% - 46.71% and from 57.83% - 41.51% for the same model of increased meadow width of 2 m (w/L = 0.836-0.541 for h_s/d = 0.525; 0.803-0.515 for h_s/d = 0.47) for h_s/d of 0.525 and 0.47, respectively.
5. As wave steepness, H_i/gT^2 increases from 0.00204 to 0.00832, R_u/H_i varies from 0.861 to 0.534 (h_s/d =0.525) and from 0.871 to 0.575 (h_s/d =0.47) for the submerged seagrass model of width 2 m. and from 0.840 to 0.498 for h_s/d =0.525, and from 0.851 to 0.534 for h_s/d =0.47.

8.4 CONCLUSIONS FOR EMERGENT VEGETATION MODELS

The conclusions for the emergent vegetation models, namely, emergent trunk model and emergent trunk model with roots are:

1. The percentage wave height at the exit point of a 1 m wide (w/L = 0.418-0.270 for h_s/d = 1.25; 0.401-0.257 for h_s/d = 1.11) emergent trunk model of plant density 107 trunks/m^2, varies from 75.06% - 80.60% and from 80.77%

- 85.28% for h_s/d of 1.25 and 1.11, respectively, whereas for the same model of width 2 m (w/L = 0.836-0.541 for h_s/d = 1.25; 0.803-0.515 for h_s/d = 1.11), the percentage wave height at exit point of the meadow varies from 60.53% - 66.12% and from 64.10% - 69.33% for h_s/d of 1.25 and 1.11.

2. The percentage wave height reduction for the same emergent trunk model of width 1 m varies from 24.94% - 19.40% and from 19.23% - 14.72% for h_s/d of 1.25 and 1.11, respectively and from 39.47% - 33.88% and from 35.90% - 30.67% for the same model of width 2 m.
3. As the plant density increases to 107 trunks/m^2 and 300 roots/m^2 each due to additional root system for the emergent trunk model with roots, the percentage wave height reduction increases when compared to the emergent trunk model.
4. For the emergent trunk model with roots of width 1 m, the percentage wave height at the exit point of the model (w/L = 0.418-0.270 for h_s/d = 1.25; 0.401-0.257 for h_s/d = 1.11) varies from 46.99% - 65.27% and from 56.63% - 72.33% for h_s/d of 1.25 and 1.11, respectively, whereas for the same model of width 2 m (w/L = 0.836-0.541 for h_s/d = 1.25; 0.803-0.515 for h_s/d = 1.11), the percentage wave height at exit point of the model varies from 33.73% - 49.10% and from 38.55% - 54.09% for h_s/d of 1.25 and 1.11.
5. The variation of percentage wave height reduction for the emergent trunk model with roots of width 1 m (w/L = 0.418-0.270 for h_s/d = 1.25; 0.401-0.257 for h_s/d = 1.11) ranges from 53.01% - 34.73% and from 43.37% - 27.67%, whereas, for the same model of width 2 m (w/L = 0.836-0.541 for h_s/d = 1.25; 0.803-0.515 for h_s/d = 1.11), the percentage wave height reduction varies from 66.27% - 50.90% and from 61.45% - 45.91%. for h_s/d of 0.525 and 0.47, respectively.
6. R_u/H_i varies from 0.871 to 0.628 (h_s/d =1.25) and from 0.892 to 0.638 (h_s/d = 1.11) for the emergent trunk model of width 2 m. and from 0.840 to 0.512 for h_s/d = 1.25, and from 0.851 to 0.519 for h_s/d = 1.11 for the emergent trunk model with roots of width 2 m, with increase in wave steepness parameter, H_i/gT^2 from 0.00204 to 0.00832.

8.5 CONCLUSIONS FOR HETEROGENEOUS VEGETATION MODELS

The conclusions for the heterogeneous vegetation models, namely, submerged heterogeneous model, emergent heterogeneous model and compound heterogeneous model are listed below:

1. For the submerged heterogeneous vegetation model of width 4 m, the percentage wave height at the exit point the model (w/L = 1.672-1.082 for h_s/d = 0.525; 1.607-1.030 for h_s/d = 0.47) varies from 32.50% - 48.75% and from 33.75% - 51.88% for h_s/d of 0.525 and 0.47, respectively, whereas for the emergent heterogeneous vegetation model of width 4 m (w/L = 1.672-1.082 for h_s/d = 1.25; 1.607-1.030 for h_s/d = 1.11), the percentage wave height at exit point of the meadow varies from 30.00% - 47.50% and from 31.25% - 50.63% for h_s/d of 1.25 and 1.11. However, for the compound heterogeneous model of width 6 m (w/L = 2.508-1.623 for h_s/d = 1.25; 2.411-1.546 for h_s/d = 1.11), the percentage wave height at exit point of the meadow varies from 30.00% - 41.25% and from 31.25% - 46.25% for h_s/d of 1.25 and 1.11.
2. The percentage wave height reduction for the same models, namely, submerged heterogeneous vegetation model of width 4 m (w/L = 1.672-1.082 for h_s/d = 0.525; 1.607-1.030 for h_s/d = 0.47) varies from 67.50% - 51.25% and from 66.25% - 48.13% for h_s/d of 1.25 and 1.11, respectively and for the emergent heterogeneous vegetation model of width 4 m (w/L = 1.672-1.082 for h_s/d = 1.25; 1.607-1.030 for h_s/d = 1.11), it varies from 70.00% - 52.50% and from 68.75% - 49.38%; whereas, for the compound heterogeneous model of width 6 m (w/L = 2.508-1.623 for h_s/d = 1.25; 2.411-1.546 for h_s/d = 1.11), the percentage wave height reduction ranges from 70.00% - 58.75% and from 68.75% - 53.75% for h_s/d of 1.25 and 1.11, respectively.
3. For the submerged heterogeneous vegetation model of width 4 m, R_u/H_i varies from 0.737 to 0.435 (h_s/d = 0.525) and from 0.764 to 0.456 (h_s/d = 0.47), with increase in wave steepness parameter, H_i/gT^2 from 0.00204 to 0.00832. However, for the emergent heterogeneous vegetation model of

width 4 m and the compound heterogeneous vegetation model of width 6 m, as the wave steepness parameter, H_i/gT^2 from 0.00204 to 0.00832, R_u/H_i varies from 0.705 to 0.403 (h_s/d =1.25) and from 0.716 to 0.399 (h_s/d = 1.11) for the former model and from 0.560 to 0.285 (h_s/d =1.25) and from 0.581 to 0.311 (h_s/d = 1.11) for the latter model.

8.6 CONCLUSIONS FOR FRAGMENTED VEGETATION MODELS

The conclusions drawn from the fragmented vegetation models, namely, fragmented emergent trunk model with roots and fragmented compound heterogeneous model are:

1. For the fragmented emergent trunk model with roots, of gap width parameter, w_{gap}/w = 0.125, the percentage wave height at exit point varies from 30.00% - 50.63% and from 36.25% - 53.75% for h_s/d of 1.25 (w/L = 0.836-0.541) and 1.11 (w/L = 0.803-0.515), respectively. For the same model of increasing gap width parameters, w_{gap}/w = 0.25, 0.375 and 0.5, the percentage wave height at exit point varies from 25.00% - 47.50% and from 36.25% - 51.25% for h_s/d of 1.25 (w/L = 0.836-0.541) and 1.11 (w/L = 0.803-0.515), 25.00% - 45.00% and from 36.25% - 48.75% for h_s/d of 1.25 (w/L = 0.836-0.541) and 1.11 (w/L = 0.803-0.515) and from 27.50% - 43.13% and from 32.50% - 47.50% for h_s/d of 1.25 (w/L = 0.836-0.541) and 1.11 (w/L = 0.803-0.515), respectively.
2. This model displays a percentage wave height reduction varying from 70.00% - 49.38% and from 63.75% - 46.25% for h_s/d of 1.25 and 1.11, respectively for w_{gap}/w = 0.125. Corresponding to increasing gap width parameters, w_{gap}/w = 0.25, 0.375 and 0.5, the percentage wave height reduction varies from 75.00% - 52.50% and from 63.75% - 48.75% for h_s/d of 1.25 and 1.11, 75.00% - 55.00% and from 63.75% - 51.25% for h_s/d of 1.25 and 1.11, and from 72.50% - 56.88% and from 67.50% - 52.50% for h_s/d of 1.25 and 1.11, respectively.

3. R_u/H_i varies from 0.820 to 0.498 (h_s/d = 1.25) and from 0.830 to 0.508 (h_s/d = 1.11), with increase in wave steepness parameter, H_i/gT^2 from 0.00204 to 0.00832 for the fragmented emergent trunk model with roots of gap width parameter, w_{gap}/w = 0.125. However, for the same model of increasing gap

width parameters, w_{gap}/w = 0.25, 0.375 and 0.5, as the wave steepness parameter, H_i/gT^2 from 0.00204 to 0.00832, R_u/H_i varies from 0.799 to 0.474 (h_s/d =1.25) and from 0.809 to 0.480 (h_s/d = 1.11); from 0.778 to 0.467 (h_s/d =1.25) and from 0.788 to 0.467 (h_s/d = 1.11) and from 0.747 to 0.456 (h_s/d =1.25) and from 0.768 to 0.449 (h_s/d = 1.11), respectively.

4. For the fragmented compound heterogeneous model of gap width parameter, w_{gap}/w = 0.125, the percentage wave height at exit point varies from 26.25% - 38.13% and from 31.25% - 42.50% for h_s/d of 1.25 (w/L = 0.836-0.541) and 1.11 (w/L = 0.803-0.515), respectively. For the same model of increasing gap width parameters, w_{gap}/w = 0.25 and 0.375, the percentage wave height at exit point varies from 25.00% - 35.63% and from 28.75% - 40.63% for h_s/d of 1.25 (w/L = 0.836-0.541) and 1.11 (w/L = 0.803-0.515), 23.75% - 33.13% and from 27.50% - 38.75% for h_s/d of 1.25 (w/L = 0.836-0.541) and 1.11 (w/L = 0.803-0.515), respectively.
5. The percentage wave height reduction for the above models, varies from 73.75% - 61.88% and from 68.75% - 57.50% for h_s/d of 1.25 and 1.11, respectively for w_{gap}/w = 0.125. Corresponding to increasing gap width parameters, w_{gap}/w = 0.25, 0.375, the percentage wave height reduction varies from 75.00% - 64.38% and from 71.25% - 59.38% for h_s/d of 1.25 and 1.11, and from 76.25% - 66.88% and from 72.50% - 61.25% for h_s/d of 1.25 and 1.11, respectively.

6. For the fragmented compound heterogeneous model of gap width parameter, w_{gap}/w = 0.125, R_u/H_i varies from 0.539 to 0.275 (h_s/d = 1.25) and from 0.560 to 0.290 (h_s/d = 1.11), with increase in wave steepness parameter, H_i/gT^2 from 0.00204 to 0.00832. However, for the same model of increasing gap width parameters, w_{gap}/w = 0.25 and 0.375, as the wave steepness parameter, H_i/gT^2 from 0.00204 to 0.00832, R_u/H_i varies from 0.519 to 0.269 (h_s/d =1.25) and from 0.539 to 0.275 (h_s/d = 1.11) for the former model and from 0.498 to 0.254 (h_s/d =1.25) and from 0.508 to 0.264 (h_s/d = 1.11) for the latter model.

Among the vegetation models tested in this study, the optimum meadow width (w) and relative plant height (h_s/d) which gives the maximum wave attenuation and minimum run-up on the beach slope corresponds to the fragmented compound heterogeneous model of total meadow width, w = 10.5 m, with actual vegetation occupying a width of 6 m and a gap width parameter (w_{gap}/w) of 0.375, relative plant height (h_s/d) of 1.25; wherein, the percentage reduction of wave height varies from 76.25% to 66.88% and wave run-up on the beach ranges between 0.498 to 0.254.

8.7 SUMMARY OF CONCLUSIONS

A summary of significant conclusions that can be drawn from the present study are listed below:

1. Wave heights decay exponentially as the wave propagates through the vegetation.
2. The important parameters that influence the wave height attenuation are: the relative plant height (h_s/d), meadow width parameter (w/L), wave steepness parameter (H_i/gT^2), plant density (N), gap width parameter (w_{gap}/w) and type of vegetation.
3. Steeper waves, represented by a higher value of H_i/gT^2, exhibits lower wave attenuation for all the simulated vegetation models.
4. The percentage reduction in wave heights for the various simulated models tested in this study varies from 21.79% to 76.25%.
5. As the relative plant height (h_s/d) increases from 0.47 to 0.525 (11.7%) or from 1.11 to 1.25 (12.6%), all the simulated vegetation models exhibit efficiency in wave height reduction varying from 32.32% to 76.25% for the higher relative plant height condition (h_s/d = 0.525 or 1.25), and from 21.79% to 72.50% for the lower relative plant height condition (h_s/d = 0.47 or 1.11).
6. As the plant density (N) increases from 107 trunks/m^2 (emergent trunk model) to 394 plants/m^2 (submerged rigid vegetation model) and to 107 trunks/m^2 and 300 roots/m^2 for Root Type I and 300 roots/m^2 for Root Type II (emergent trunk

model with roots), the model with higher plant density exhibits increased efficiency in wave height reduction. The percentage wave height reduction ranges from 61.45% - 45.91% for the emergent trunk model with roots of meadow width 2 m, for a lower relative plant height of 1.11, when compared to 66.27% - 50.90% for a higher relative plant height of 1.25.

7. As the meadow width increases from 1 m (seagrass meadow) to 6 m, there is a marked increase in wave height attenuation. The percentage reduction in wave heights varying from 76.25% to 66.88% is found to be the highest recorded for the fragmented compound heterogenous vegetation meadow of width 6 m, when compared to 48.75% to 32.32% for the submerged seagrass meadow of width 1 m, with both cases corresponding to a higher relative plant height.

8. The compound heterogeneous model of width 6 m (consisting of the seagrass meadow, rigid submerged model and the emergent trunk model with roots) exhibits a variation of percentage reduction in wave heights from 70.00% to 58.75% (for $h_s/d = 1.25$), when compared that of the individual emergent trunk model with roots of width 2 m which exhibits a percentage reduction in wave heights varying from 66.27% - 50.90%.

9. The fragmented compound heterogeneous model of total width 10.5 m exhibits highest percentage reduction in wave heights varying from 76.25% to 66.88% for $h_s/d = 1.25$, when compared to a variation of 72.50% to 58.75%, for the same model without the presence of gaps, namely, the compound heterogeneous model of width 6 m for the same relative plant height (h_s/d).

10. As the width of the meadow increases from 1 m to 10.5 m, it is observed that the relative wave run-up (R_u/H_i) varies from 0.861 to 0.534 for the submerged seagrass model of width 1 m and from 0.498 to 0.254 for the fragmented compound heterogeneous model of total width 10.5 m, for the model with a higher relative plant height (h_s/d).

11. The fragmented vegetation models of total meadow width 10.5 m and relative plant height, h_s/d = 1.25, gives the maximum wave attenuation (76.25% to 66.88%) and minimum run-up (0.498 to 0.254) on the selected beach slope.

8.8 RECOMMENDATIONS

Based upon the present research work, the recommendations for implementation of coastal protection using vegetation are listed below:

1. Vegetation indeed is a viable option for containing the wave action and subsequent flooding in low wave energy environments.

2. The implementation of coastal vegetation as a protection measure is highly site specific and therefore a pilot study to assess the feasibility of the restoration or afforestation of the vegetation type endemic to the region is recommended.

3. The findings from this study reveals that the percentage reduction of wave heights varies from 70.00% to 58.75% for the compound heterogeneous model consisting of the seagrass meadow, rigid submerged model and the emergent trunk model with roots (w = 6 m, h_s/d = 1.25), when compared to 66.27% - 50.90%, which represents the variation of percentage wave height reduction for the emergent trunk model with roots (w = 2 m, h_s/d = 1.25) exhibiting the highest wave attenuation among individual vegetation models. This suggests that there is a significant increase in wave attenuation for the heterogeneous plant model and therefore, restoration of different habitats complementing each other is recommended at possible locations.

8.9 LIMITATIONS OF THIS STUDY

The findings from this study provides an insight into the wave attenuation and beach run-up characteristics of simulated seagrasses and mangroves which may be helpful in the implementation of marine habitats as a natural barrier against coastal hazards. However, some of the limitations of this study are listed below:

1. Reproducing the dynamic similarity of vegetation in flumes is difficult because of varying plant structures. Therefore, the exact parameterization of plant characteristics which is linked to the structural integrity of vegetation is a major challenge.

2. The random variation of the standing plant biomass which includes varying vegetation heights, size of vegetation and age of vegetation is difficult to be modelled as different vegetation schemes in the laboratory.

8.10 SCOPE FOR FURTHER RESEARCH

The research findings of this study on coastal vegetation will surely help administrations, planners, researchers and academicians in looking forward to considering vegetation as a viable option for future coastal management and landscape planning. The coastal regions of the world are highly heterogeneous with respect to their physical, geomorphological, economic, biotic and climatic features. The type of solution for protection of a coastal region therefore depends on these factors and is of prime necessity that the solution for coastal protection for a region should consider the above factors. The future beckons for the use of sustainable natural buffers in coastal protection schemes. Some of the avenues of further research in this area could focus on the following:

1. The selected models could be used for a more detailed parameter study, thus extending the range of testing conditions.

2. Modelling of canopy effect of trees could be taken up to further extend to exact parameterization of coastal forests.

3. Studies on wave forced motion of vegetation stems and leaves could provide insight into the complex interaction between vegetation and waves.

4. Studies on the use of sustainable natural buffers in conjunction with the conventional structures for coastal protection could go a long way in devising solutions to protect our coasts.

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