Investigations of wave-induced turbulent structures in vegetated flows

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INVESTIGATIONS OF WAVE-INDUCED TURBULENT STRUCTURES IN VEGETATED FLOWS

A Thesis
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by
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B.S. in Civil Engineering, Jadavpur University, 2009
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Dedicated to my parents for the immense sacrifices they made for me through the toughest of times...

To Dr. Koustuv Debnath, who has been much more than a mentor and provided me inspirations that has lead me here..

To my friends at LSU who have stuck by me throughout my graduate career and with whom I’ll share many a bitter-sweet memories throughout my life..
Acknowledgments

The very first person whom I would like to thank is my adviser Dr. Heather D. Smith who has been the most instrumental in guiding me throughout this work. I am ever indebted to her for being immensely patient with me and for providing me the opportunity of a lifetime to work in such a prestigious project. I owe my entire graduate career to her and cannot possibly express in these few words the importance of her contribution in my professional development. I would also like to thank Dr. Qin Jim Chen and Dr. Clinton S. Wilson, who were much more than just committee members. Their constant help and guidance created a very positive environment without which this work would not have been possible.

My acknowledgments can never be complete without the mention of Dr. Dan Cox and Dr. Dennis A. Albert whose help and guidance at OSU were extremely insightful and made even the most difficult of problems seem very easy. I would also like to thank the National Science Foundation whose Environmental, Sustainability and Climate Program funded this project through Grant 0828549, the Louisiana Board of Regents, the Louisiana Water Resources Research Institute and the LSU Office of Sponsored Research for providing financial aid for this research. Last but not least I would like to thank my lab-mates at LSU and OSU - Getnet B. Agegnehu, Hyung Doug Yoon, and all others who made this work possible.
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Abstract

The role of coastal vegetation in mitigating shoreline erosion by damping of incoming waves and the resultant effect on sediment transport is a critical area of coastal management research. However our understanding of the underlying hydrodynamic processes is limited. Laboratory flume experiments were conducted where a naturally grown emergent vegetation channel and a vegetation-less sand channel were exposed to regular waves. Wave height data was collected using wave gauges located at various points along the channel in the direction of oncoming waves. Acoustic Doppler Velocimeters (ADVs) placed at various depths in the water column measured wave orbital velocity signatures.

This thesis investigates the wave-damping phenomenon of the vegetation and attempts to quantify it using the wave attenuation factor. Variation of plant drag coefficient with distance in the vegetation field as well as dependence with Reynolds number, Keulegan Carpenter number and the Viscous Frequency Parameter $\beta$ are investigated. Horizontal and vertical orbital velocity signals from ADV measurements were analyzed and variation of turbulent kinetic energy with depth has been presented. Comparisons with Linear and Stokes Wave Theory predicted values, calculated using wave height data from wave gauges, were made to understand the turbulence generated by the vegetation bed under wave action. Frequency analysis of the power spectra
of wave orbital velocities was used to separate the wave and turbulent portions from the total component of the velocity and has been separately studied to understand the depth variation of the turbulent structures.

Wave attenuation factor decreased with increasing distance in the vegetation field while the drag coefficient remained almost constant after a couple of meters. The drag coefficient decreased with both Reynolds number and Keulegan Carpenter number. The observed orbital velocities were less than the wave theory predicted values with the horizontal component showing a zone of decreased attenuation in the mid-depth region, while the vertical velocities showed greater attenuation near the free surface. This work advances the existing knowledge base of vegetative wave attenuation and turbulence studies involving emergent vegetation canopies under regular wave action by employing natural vegetation effects in the laboratory environment as an unique feature of the experiment.
Chapter 1

Introduction

1.1 Coastal Land Loss in Louisiana

A United Nations Environmental Programme (UNEP, 2006) study estimates that nearly a third of the world’s population resides in or near coastal ecosystems and in small islands. Yet we are witnessing a steady degradation of coastal wetlands throughout the world due to both anthropogenic and natural causes. The State of Louisiana possesses more than 3 million acres of wetlands, a 37% share of the nation’s total and faces its own share of challenges against wetland erosion and subsidence (CPRA Louisiana, 2007). It is a hard fact that 90% of the nation’s coastal land loss occurred in Louisiana between 1932 and 2010 (Couvillion et al., 2011). The continued loss not only affects the fragile ecosystem which houses diverse species of flora and fauna, many of them unique to the region, but also has far reaching commercial impacts. The fishing industry is projected to lose by the year 2050 a staggering $37 billion (LADNR, 1999) as a direct result of coastal land loss.
There are a number of natural causes (Day et al., 2007) that have lead to wetland loss in the region. Powerful hurricanes like Katrina and Rita regularly erode marshes and bring excess saltwater into the wetlands. Increase in rates of global sea level rise averaging 2 mm/yr and the natural avulsion of the Mississippi River Delta system have further contributed to the degradation. Subsidence, which is the phenomenon of sinking of wetlands due to geological movement of deposits along fault lines and the compaction of loosely deposited sediments is another major natural cause of wetland loss.

Among anthropogenic factors, the presence of river-control structures like dams and levees (Kesel et al., 1992) along the Mississippi River contribute the highest losses. Since the 1920’s large scale structures like the Old River Control Structure were constructed to alleviate flooding problems along the banks. The control structures were instrumental in an immediate and massive reduction in the sedimentary load which used to form new coastal land at the river mouth and adjacent plains. Moreover, flood control levees built since the early 1900s along the lower reaches of the Mississippi River effectively isolated the river from the adjacent deltaic plains and starved the wetlands of their much needed sediment supply (Barras et al., 1994). Fresh river water which previously helped to reduce marsh salinity and provide nutrients was no longer available and resulted in the breakup and dispersal of large amounts of nutrient-starved marshlands. The sinking of wetlands coupled with a lack of sediment supply has resulted in the loss of nearly 4900 square kilometers of wetlands (Day et al., 2007) over the last century. As subsidence increases, the sea reaches inland and wave erosion occurs at the exposed wetland fringes leading to further degradation. Land loss trends since the 1950’s indicate that over 20,000 square miles of land in coastal Louisiana will have been lost to the sea between the years
1.2 Advantages of Coastal Vegetation

Traditionally, the engineering solutions for shoreline protection typically dealt with the construction of conventional civil engineering structures such as breakwaters, jetties and sea-walls to dissipate and reflect wave energy. However these artificial and rigid structures cause significant change in near-shore hydrodynamics and alter regional sediment transport characteristics which often leads to further erosion. Globally, the steady occurrence of natural disasters like the 2004 Indian Ocean Tsunami, Hurricane Katrina, and others have only bolstered the dire need for an ecologically sustainable, cost effective and natural alternative to shoreline protection. Coastal vegetation comes up as an excellent candidate for this purpose (Danielsen et al., 2005; Kathiresan and Rajendran, 2005; Barbier et al., 2008). Thus recent research in coastal engineering has been directed to the understanding and utilization of more non-intrusive forms of shore protection such as vegetation barriers, which protects the shoreline, especially in estuarine wave conditions, while simultaneously providing habitat for a multitude of aquatic and amphibious animals and plants. Infact the turbulent vortices generated by the flow-vegetation interaction act as vehicles of exchange for nutrients and manifests biological processes such as dispersion of fish larva. Aquatic vegetation has been found to help regulate water quality by exchange of nutrients and large stretches of wetlands play a vital role in reducing flood heights by acting as natural reservoirs of water and by helping to reduce the speed of flooding also reduce erosion. Recreational benefits offered by wetlands have economic consequences for the state and promotes eco-tourism. Moreover, the root structures of coastal vegetation helps in binding the soil and aids in the storage of sediments (Dean, 1978). Also dead plants increase organic
content in the soil providing a nutrient rich bed for crabs and oysters to thrive on. The added soil mass may help in further accretion of sediments and thus offset the sea level rise to some extent.

1.3 Background and Literature Review

For over the last half a century several researchers have worked to understand how wetland plants shape coastal geomorphology (Redfield, 1965; Chapman, 1974). The hypothesis that coastal marshes have the capacity to protect shoreline areas from storm and erosion damage was formally introduced to the coastal engineering community in 1971 in the wake of a devastating storm on the Bangladesh coast (Fosberg, 1971). Quantifying coastal wetlands’ efficiency in protecting shorelines is critical to estimate a cost benefit ratio between wetland degradation and the value of restoration (Barbier, 2007). Since wetland protection has the potential to be a low cost alternative to barrier construction, the protection and restoration of coastal wetlands can be a much more economically sustainable choice for rural areas in reducing storm damage (Halpern et al., 2007; Costanza et al., 2008). Quantifying wave attenuation forms the first step of such a cost benefit analysis.

Wave attenuation depends on plant stem density, geometry, spatial extent, flexibility, buoyancy as well as water depth, wave period, and wave height. The simplest way of quantifying damping of waves is due to the energy loss through work done on the plants and was established by Mork (1996) who studied a kelp plant species and proposed a simple, linear model on the assumption that rotational and dissipative effects are important in the canopy level and friction due to shear stresses and form drag are important in the lower layer of the vegetation. Wave energy dissipation rates ranged around 30% per meter of vegetation channel and
the highest amount of attenuation occurred during low tide when water levels were low. The most prevalent method of quantifying wave damping is relating the decay in wave energy, expressed as a function of wave height, to the vegetation drag. A way to achieve this is using the conservation of wave energy approach, which accounts for vegetation effect as an energy dissipation term (Dalrymple et al., 1984). This theory uses linear wave theory and assumes that waves are propagating over a flat bottom. The other limitation of this theory is that vegetative plants are assumed to behave as an array of slender, vertical, rigid cylinders. The advantage of this model is that it can be applied to both emergent and submerged vegetations. Mendez and Losada (2004) extended the theory of Dalrymple et al. (1984) to an empirical model for wave damping and wave breaking over variable depth vegetation fields. Also this model was the first to use both monochromatic and random waves, consider wave breaking, and include a parameter which can be calibrated depending upon the plant type. As in Dalrymple et al. (1984), even though swaying motion is neglected, the drag coefficient can be adjusted so that the model can be applied to flexible plants.

Some researchers (Kobayashi et al., 1993) have also used the conservation of momentum approach to include random wave cases. In this type of model, the fundamental assumption is that the force acting on the plant is distributed over depth and is a function of the linear drag force. Wave attenuation coefficients were determined by Kobayashi et al. (1993) through a regression analysis by fitting values to experimental data. Lima et al. (2006), based on laboratory flume experiments using constant length, flexible nylon rope stretches, developed a finite-difference numerical model, which once calibrated gave satisfactory results for the hydrodynamic force time series, velocities and positions of stems.
The final step for all these methods involve deriving a solution for the exponential decay in wave height through the vegetation field. However in spite of all these sophisticated models the variety of wetland plants is extensive and trying to find a universal method for modeling the behavior of plant dissipation is practically impossible (Mendez and Losada, 2002). The vast majority of vegetation flow studies focus on a single species of vegetation localized in a particular region. Thus, despite there being a rich repertoire of research works, there has been some doubt among the scientific community towards the ability of coastal wetlands to attenuate waves and protect coastal communities from storm damage. The year 2005 saw Hurricanes Katrina and Rita ravage the Louisiana coast and triggered the same concern over reduced shore-line protection due to salt marsh habitat loss and degradation (Day et al., 2007; Stokstad, 2005; Feagin, 2008). Feagin et al. (2009) compared erosion under small waves (below 10 cm) with and without vegetation in a small-scale laboratory water flume and from plots at the edge of a rapidly eroding salt marsh concluded that commonly available salt marsh vegetations do not significantly reduce erosion along a wetland edge. In order to answer these doubts there is an imperative need to understand the underlying hydrodynamic process behind wave attenuation by vegetation.

Vegetation aids in the reduction of energy of incoming waves by turbulent dissipation, commonly called damping. In their field experiment with Spartina anglica salt marshes in eastern England, Neumeier and Amos (2006) found that in wave dominated environments, significant attenuation of wave orbital velocity occurs in the denser part of the salt marsh canopy resulting in an effective reduction of 20-35% of the turbulent kinetic energy (TKE). It is known that at low stem densities, the drag locally enhances turbulence, causing increased shear stress
and potential scour of the bed (Nepf, 1999; Bouma et al., 2009). However, under stem densities characteristic of a typical marsh canopy, vegetation reduces turbulence, slows water velocity, and diminishes shear stress near the bed (Li and Amos, 1995; Nepf, 1999). The decreased near bed excursion velocity may lead to decreased shear stresses and in turn decreased bed erosion. Comparisons between vegetated and unvegetated sites indicate that marsh vegetation indeed reduces near-bed water velocity (Neumeier and Ciavola, 2004). Further the dense canopy of stems in a naturally vegetated wetland themselves provide physical obstruction to sediment fluxes and trap sediment which in turn settles downward easily due to low vertical wave orbital excursions. The increased accumulation of sediments can aid in the building of the shoreline upward and accrete the marsh profile in the offshore direction, while keeping an increasing profile over the rising ocean levels. There is active research going on to ascertain the influence of vegetation in reducing storm surges as sea level rise magnifies storm surge levels and causes increased wave heights. Any benefit that coastal vegetation can offer in the reduction of either storm surge or waves or both can thus be of extreme scientific relevance. While a considerable number of researchers have worked to quantify the influence of canopy structure in mono-directional current flows in field environments (Li and Amos, 1995; Leonard and Reed, 2002) and in the laboratory with artificial vegetation (Nepf, 1999; Nepf and Vivoni, 2000), studies in exclusively wave-dominated environments are limited. Koch and Gust (1999) noticed for sea-grass in the field that the vegetation flaps with the wave forcing, producing barriers between the flow and the lower part of the vegetation over part of the wave cycle and an open structure as the wave reverses. This open structure is thought to be an avenue of sediment exchange, but the exact mechanism is unknown. The uncertainty is primarily due to the increased difficulty in getting accurate field measurements of wave forcing within the canopy and also in part due to the dif-
difficulty in reproducing a natural canopy in the laboratory flume. Existing work using artificial, rigid to moderately flexible vegetation (Augustin et al., 2009) in waves is a first attempt to understand the mechanism. However only a study of a fully natural vegetation canopy can possibly encompass the effects of the structural variety offered by a natural system and can attempt to properly simulate the complex flapping mechanism, which undoubtedly plays a significant role in turbulent dissipation and wave attenuation.

The present research is an attempt to investigate the phenomenon of wave attenuation by coastal vegetation through large scale laboratory experiments involving a natural vegetated canopy and provides insights into the mechanism of wave attenuation by studying the vertical variation of turbulence structures. A range of offshore regular wave heights ($H_0$) varying from 5 to 15 centimeters (cm) and time periods ($T$) from 1 to 3 seconds (s) has been looked into. Among these cases, Acoustic Doppler Velocimeter (ADV) measurements were obtained for one particular offshore wave case of $H_0$=15 cm and $T$=1.5 s period at various depths and at different locations inside the vegetated field as well as in an unvegetated sand channel in order to understand the unique turbulence signatures generated inside the vegetated field. The following four chapters contain respectively detailed description of the experiment, methods of data analysis, results and discussions and conclusions and scope for future work.
Chapter 2

Description of the Experiment

2.1 Experiment Layout

The wave experiments were performed at the Oregon State University O. H. Hindsdale Wave Research Laboratory (HWRL) in the large-scale wave flume in the summer of 2010. The wave flume, the largest of its type in North America, is 104 m (342 feet) long, 3.7 m (12 feet) wide and 4.6 m (15 feet) deep. An upgraded programmable hydraulic ram wave-maker capable of generating regular and random waves with maximum significant wave heights of 1.5 m (5 feet) was used for generating the waves in this experiment.

Four partitioned channels (Fig.2.1), each measuring 10 m in length and 63.5 cm in width were constructed parallel to each other and extended in the shoreward direction. The channel walls were made of plywood with squares having sides equal to 10 cm painted on a white background. This was meant to create an easy to read rectangular scaling system from which measurements like distance between two points on the channel, deviation of plants stems etc.
could be easily observed. In addition, the top surface of the partition walls had graduations made at every 0.5 m so that the distances of Wave Gauges (WG) and Acoustic Doppler Velocimeters (ADVs) from the beginning of the channel could be easily determined during the experiment. The waves originated at a distance of 57.94 m offshore from the point where the beds started.

![Test Channels. Camera is facing the offshore direction](image)

**Figure 2.1:** Test Channels. Camera is facing the offshore direction

In order to run the tests at the desired water depth, a reinforced concrete slab was placed at an elevated height above the flume floor and the test channels were constructed on top of this raised concrete platform. Thus a 1:12 concrete slope (elevation view Fig. 2.2), imitating the natural slope of a beach allowed waves to shoal up to the desired depth, before entering the constructed channels A, B, C and D (plan view Fig. 2.2). Channel A was the sand channel, channel B and D were vegetation channels with similar vegetation densities and channel C, the restoration channel, had a significantly lesser vegetation density.
Figure 2.2: Experimental Setup within the Large Wave Flume. Figure not to scale.

A specific vegetation species *Schoeneplectus pungens* or three-square bulrush, which grows fairly commonly in intertidal wetlands throughout the United States, was used for this experiment. It is a perennial species with the stem having a triangular cross-section for most of the upper part with a circular cross-section at the base. The vegetation used in the experiment was harvested from young natural bulrush beds in Tillamook Bay of Oregon in the late spring of 2009. The bulrush stems with their root system still intact were cut out in blocks from the inner estuarine regions experiencing low to moderate wave forcing similar to what was simu-
lated in the laboratory. These were then placed in the specially constructed channel boxes and care was taken to sustain their growth throughout the winter of 2009 in the laboratory, under Dr. Dennis A. Albert’s\textsuperscript{1} supervision and expertise. The purpose of this exercise was to mimic the field conditions in the best possible way.

Sampling studies were conducted at the end of the experiments in which vegetation stems were cut out from the last 30 cm of each channel (i.e. from an area 63.5 x 30 sq.cm. at the back of the channel) and the total number of stems were noted in order to get an estimate of vegetation density. The length and mean diameter of these stems were also recorded. The length results indicate the vegetation heights in channel D ranged mostly between 50-70 cm with approximately 66% of the stems having heights within this height range. The water depth was 40 cm and thus predominantly emergent conditions prevailed. Wave damping mats, made of horse hair were placed at the end of the flume (Fig. 2.3a) to absorb the wave energy and prevent the reflection of waves from the back end. Horse hair padding were also placed in between the plywood making up the partition walls (Fig. 2.3b) in order to prevent reflection and diffraction of wave energy from the wall ends facing the oncoming waves. A series of WGs, one in each channel were fixed at the beginning of each channel (position marked as 0m in elevation view of Fig. 2.2) and recorded water surface elevations for each trial. A movable wheel-mounted platform had resistive type WGs attached to its offshore end and ADVs (Nortek) attached to its onshore end (elevation Fig. 2.2). The data presented in this thesis compares the observations in Channel A with those in Channel D, and these will henceforth be referred throughout the thesis as ‘Sand Channel’ and ‘Vegetation Channel’ respectively.

\textsuperscript{1}Dr. Dennis Albert is currently an Assistant Professor/Senior Research Ecologist in the Department of Horticulture at Oregon State University. He has over twenty years experience in the field of ecology and has worked extensively on the Great Lakes ecosystem. (http://hort.oregonstate.edu/faculty-staff/albert)
2.2 Experimental Conditions

Table 2.1 (R-Regular waves, I-Irregular Waves) summarises the various types of experiments that were conducted as part of the study at HWRL. The present thesis examines the results from regular wave trials for the Wave Attenuation and Velocity Kinematics experiments and Table 2.2 represents the set of 12 experiments whose results will follow in the next chapters. WGs placed at the wavemaker ram location ensured quality control of these offshore parameters throughout the experiments. For Experiments 1 to 5 the movable WG locations were varied from 0.5 m to 2.0 m at 0.5 m intervals, from 2 m to 5 m at 1 m intervals and from 5 m to 9 m at 2 m intervals, giving a total of 9 study points in the shoreward direction in both sand and vegetation channel. Wave conditions in Experiment 2c ($H_0=15$ cm and $T=1.5$ s) was selected for turbulence data analysis and a separate experiment (Experiment 6) with these wave conditions was conducted. For Experiment 6 the ADVs were positioned at 2.9 m, 3.0 m and 3.1 m with
<table>
<thead>
<tr>
<th>Objective</th>
<th># Trials</th>
<th>( H_0 )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>(cm)</td>
<td>(s)</td>
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<tr>
<td>Wave Attenuation</td>
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<td>I:2.0,3.0</td>
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<tr>
<td>Velocity Kinematics</td>
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<td>R:1.5,2.0,2.5,3.0</td>
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<td></td>
<td>(28%)</td>
<td>I:20</td>
<td>I:2.0,3.0</td>
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<td></td>
<td>(2%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment Introduction in Canopy</td>
<td>9</td>
<td>I:20</td>
<td>I:3.0</td>
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<tr>
<td></td>
<td>(3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Survivability</td>
<td>21</td>
<td>R:25,30,45</td>
<td>R:2.0,3.0</td>
</tr>
<tr>
<td></td>
<td>(6%)</td>
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**Table 2.1:** Summary of Experiments Conducted (adapted from Yoon et al. (2011))

WGAs at 1.1 m, 1.2 m and 1.3 m into the channels (Fig. 2.2) respectively. The vegetation in close proximity of the ADV probe had to be cropped to prevent stray plant stems interfering with the acoustic signal (Fig. 2.5). For each of these ADV positions the vertical positions of the ADVs were varied from 12.4 cm below the free water surface down to 34.4 cm at 2 cm increments in the sand channel (Channel A Fig. 2.4) and from 12.4 cm from the free water surface down to 28.4 cm at 2 cm increments in the vegetation channel (Channel D Fig. 2.4).

Depth measurements \((h)\) conducted at the three ADV locations at the end of the experiments are given in Table 2.3. It was seen that the sand channel was about 6 cm deeper than the vegetation channel. This was the reason, as will be seen later for the slightly higher wave...
<table>
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<th>Expt. No.</th>
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<th>$H_0$</th>
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<td>(s)</td>
<td>(cm)</td>
<td></td>
</tr>
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<td>WG only</td>
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<tr>
<td>2c</td>
<td>1.5</td>
<td>15.0</td>
<td>WG only</td>
</tr>
<tr>
<td>3a</td>
<td>2.0</td>
<td>5.0</td>
<td>WG only</td>
</tr>
<tr>
<td>3b</td>
<td>2.0</td>
<td>10.0</td>
<td>WG only</td>
</tr>
<tr>
<td>3c</td>
<td>2.0</td>
<td>15.0</td>
<td>WG only</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>15.0</td>
<td>WG only</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>15.0</td>
<td>WG only</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>15.0</td>
<td>WG &amp; ADV</td>
</tr>
</tbody>
</table>

**Table 2.2:** Wave Cases Analyzed

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Channel</th>
<th>$h_{2.9m}$</th>
<th>$h_{3.0m}$</th>
<th>$h_{3.1m}$</th>
<th>$h_{mean}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Sand</td>
<td>42.5</td>
<td>42.9</td>
<td>43.0</td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td>Vegetation</td>
<td>36.3</td>
<td>37.2</td>
<td>37.1</td>
<td>36.9</td>
</tr>
</tbody>
</table>

**Table 2.3:** Channel Depths at the 3 ADV Locations

heights being recorded in the vegetation channel than in the sand channel. The depth difference is also the reason why care should be taken before results from the sand channel and the veg-
etation channel are compared side by side as the wave structure at any given distance from the channel beds will have different characteristics in the two channels.

Figure 2.4: Channel cross-section showing ADV positions. Figure not to scale.

Figure 2.5: Vegetation cropped around ADV probe
Chapter 3

Data Analysis

3.1 Data Acquisition and Collection Procedures

The four wave gauges, one in each channel as shown in Fig. 3.1 were calibrated to obtain a relationship between the voltage output signal from the probe and the water surface elevation. For the ADV, the sampling volume was located at 6 cm in front of the central receiver. Seeding material was regularly flushed in the channels in the locality of the ADV probes to maintain clean signals. Both WGs and ADVs had the same frequency of 50 Hz. Waves were run in bursts of 2 minutes for Experiments 1 to 5 and in bursts of 1 minute for Experiment 6, so that the time series window had at least 40 complete waves of data. It took approximately 60 s for the first wave to reach the 0 m mark at the beginning of the channel.

3.2 Selection of Representative Data

To select a representative duration for the data analysis for the wave attenuation set of experiments (Experiments 1 to 5), the water surface elevation ($\eta$) time series at the 0 m mark
like in Fig. 3.2 (for Experiment 2c) as well as at all the other channel locations like in Fig. 3.3 (at 5 m into the channel) were investigated. It was found that the water surface elevations between 100 to 150 s (Figs. 3.4 (for 0 m) and 3.5 (at 5 m)) for Experiments 1 to 5 were free from end effects. Another consideration when selecting the representative interval was that the elevation recorded at the interior of the channels lagged with respect to that at the 0 m mark due to the time difference it took for the waves to reach from the 0 m mark to the point of interest. So the interval where the wave heights were fully grown was determined and selected for calculation of wave heights. For Experiment 6, the representative interval for elevation ($\eta$), horizontal ($u$), cross-channel ($v$) and vertical ($w$) velocities was similarly selected as 70 to 110 s based on the full time series data as in Fig. 3.6. Fig. 3.7 represents the data within the selected representative period.
Figure 3.2: Surface Elevation Time Series at 0 m for Experiment 2c
Figure 3.3: Surface Elevation Time Series at 5 m for Experiment 2c
Figure 3.4: Surface Elevation within the Representative Interval at 0 m for Experiment 2c
Figure 3.5: Surface Elevation within the Representative Interval at 5 m for Experiment 2c
Figure 3.6: Full Time Series Data for Experiment 6
Figure 3.7: Data within the Representative Interval for Experiment 6
3.3 De-Spiking and Time-Lagging the Data

Usually raw ADV data contains spikes representative of spurious noise in the system and needs to be properly eliminated. The method of Mori et al. (2007) was used to de-spike the ADV data. Figs. 3.6 and 3.7 show both the raw and despiked velocities in the horizontal and vertical directions. The missing data points after despiking were interpolated from the nearest neighbor points.

The fact that the peak of the wave crest did not align at the 0 m mark with the peak at of the wave crest recorded within any given point in the channel required that the wave gauge data at the x locations be properly time lagged, so that there was no initial phase shift between the data to be compared. This time lagging was done by calculating the correlation between two unlagged data series, computing the lag time between them and lagging the leading time series by that amount of time. Also for Experiment 6, the velocity time series from the ADV did not line up with one another from trial to trial, possibly due to the arbitrary starting position of the wave maker paddle at each trial and hence different initial temporal offset in the generated waves. Wave gauge as well as ADV time series were lagged with respect to a single trial, usually the first trial. Time lagging was also done between the sand and vegetation channels time series wherever needed.
Chapter 4

Results and Discussions

4.1 Wave Attenuation by Vegetation

Wave height decay by vegetation is quantified using the wave transmission coefficient \( K(x) \) which is defined as a function of wave height \( H(x) \) (Dalrymple et al., 1984) as

\[
K(x) = \frac{H(x)}{H(0)}
\]

where \( H(0) \) is the incident wave height at the channel entrance and \( x \) is the shoreward distance from the incident wave height location. As all the wave cases were regular waves \( H(x) \) and \( H(0) \) were both taken as mean wave heights calculated using a zero crossing method (Tucker and Pitt, 2001) from the water surface elevation time series at the WG location. While computing \( K \) using Eqn. 4.1.1, the water surface elevation time series at the \( x \) location was properly time-lagged with the same at the 0 m location so that the wave heights calculated from the representative interval at the two locations were comparable.
4.1.1 Effect of Time Period on Wave Attenuation

Using Eqn. 4.1.1, the wave transmission coefficients were calculated for the two channels for each of the wave cases and at each location of the WG cart. Fig. 4.1 shows the variation of $K$ with $x$ for a variety of wave cases from Experiments 1 to 3. Waves having the same mean wave heights but varying time periods are grouped together in different panels to study the effect of time period on wave attenuation. The topmost panel represents the cross-shore variation of attenuation for $H_0$=5 cm waves, the middle for $H_0$=10 cm cases and the bottom most panel for $H_0$=15 cm cases. A prevalent issue was that the $K$ values in the sand channel oscillated within a given range for more or less all the three time period waves, with the $T$=2.0 s wave showing the greatest variability. One reason for the increase in wave heights in the sand channel may have been due to standing waves generated as a result of reflection from the back of the channel. Though padding material was placed at the back, some waves were found to be reflected into the sand channel. This was not a problem in the vegetation channel as most of the waves had attenuated by the time they reached the back of the flume. In spite of the variability however the sand channel attenuation remained fairly constant while the vegetation channel showed an almost exponential decrease in attenuation. The attenuation curves for the vegetation channel show that the attenuation for the $T$=1.0 s wave is greater than the $T$=1.5 s and $T$=2.0 s waves for the $H_0$=5 cm case, the difference however diminishing as $H_0$ increased to 15 cm. This may be because the increased frequency of flapping causes increased stalk-fluid interaction and hence increased dissipation of vortices. However at higher wave height, since the orbital velocities are already higher the increased flapping may not create any added dissipation to the already existing highly turbulent shedding of vortices.
Figure 4.1: Effect of Time Period on Spatial Variation of Wave Attenuation
4.1.2 Effect of Wave Height on Wave Attenuation

Fig. 4.2 presents the same attenuation curves represented in Fig. 4.1 for the wave cases from Experiments 1 to 3 except that here the wave cases with the same wave periods are grouped together in the three panels, the topmost panel being for $T=1.0$ s, middle for $T=1.5$ s and bottom most for $T=2.0$ s. As was seen in the previous section the $K$ values in the sand channel oscillate in a regular fashion for all the wave runs and the common nature of the curves for all the time periods for the same wave height suggests even more that this is likely due to generation of standing waves from the back of the flume. The vegetation channel attenuation curves in general show an exponential decay trend as was seen before. The curves show almost no variation with wave height for $T=1.0$ s, indicating the previously discussed fact that the higher frequency of swaying allowed for higher dissipation with increased rate of vortex evolutions. However as the wave period increases the $H_0=5$ cm wave faces slightly lower attenuation possibly due to even greater turbulent dissipation of the higher wave orbital velocities resulting from higher wave heights.

Fig. 4.3 shows the variation of wave attenuation for a variety of waves with different time periods but a single deep water wave height of $H_0=15$ cm case. Here also it is seen that under the same wave energy condition the $T=1.0$ s waves have the highest dissipation reiterating the fact discussed before. In addition it can be seen that Fig. 4.3 presents two sets of trials of the same $T=2.0$ s wave, one labeled ‘fresh vegetation’ and the other as ‘old vegetation’. These two sets differed in that they were conducted over a week in between them, the ‘fresh vegetation’ trial-set is one that was conducted earlier and a separate series of wave experiments (whose results are not in the scope of this thesis) were run in between the week so that the vegetation
Figure 4.2: Effect of Wave Height on Spatial Variation of Wave Attenuation
Figure 4.3: Spatial Variation of Wave Attenuation for $H_0=15$cm cases

for the latter trial-set (‘old vegetation’) became less stiff, with the emergent portion of the stem laid flat across the water surface. This loss of stiffness is attributed to a combination of repeated exposure to wave forcing as well as the lack of natural light to sustain growth. Looking at the attenuation curves for the vegetation channel the fresh versus old effect can be seen in that for the old vegetation the attenuation decreased towards the front portion of the channel up to almost 7 m after which the attenuation increased slightly possibly due to the almost complete slanting of the stalks which increased the submerged portion of the above ground biomass, thereby increasing turbulence within the water column. However the difference between the two records were relatively minor compared to the variation with wave period.
4.2 Drag Coefficient Variations

Dalrymple et al. (1984), use a conservation of energy approach to equate the rate of wave energy decay in the shoreward direction to the energy dissipation due to work done on the plant stems by the waves. Using this approach and assuming linear wave theory holds, the drag coefficient can be related to the wave attenuation factor by,

\[
\alpha = \frac{g^2C_d dH(0)N[cosh^2(ks) + 2|sinh(ks)|]}{9\pi kC_G C^3 cosh^3(kh)}
\]  

(4.2.1)

where the factor \(\alpha\) occurs in the attenuation factor as,

\[
K = \frac{H(x)}{H(0)} = \frac{1}{1 + \alpha x}
\]  

(4.2.2)

Here, \(C_d\) is the drag coefficient for an individual plant stem, \(N\) is the plant stem density calculated as number of plants per unit area, \(d\) is the plant stem diameter, \(s\) is the submerged height of plants and for our case is equal to the depth \(h\) as all experiments were conducted in emergent conditions, \(k = 2\pi/L\) is the wave number, \(L\) being the wavelength calculated iteratively using the dispersion relationship \(L_0 = L\tanh(kh), L_0 = gT^2/2\pi\) being the deep-water wavelength, \(g\) the acceleration due to gravity, \(C_G = nC\) is wave group velocity, where \(n = 0.5[1 + 2kh/sinh(2kh)]\) and \(C = L/T\) is wave phase speed. The plant density \((N)\) for the vegetation channel was known as 1202 stems/m\(^2\) from sampling studies performed during the course of the experiment. A median stem diameter was obtained from the same sampling study and was found to be 4 mm. The regular wave characteristics being known for each trial, the remaining parameters in Eqn. 4.2.1 were calculated assuming linear wave theory applies. The
drag coefficients evaluated for different wave cases from the observed attenuation factors from the above relations are presented in Figs. 4.4 and 4.5.

4.2.1 Effect of Time Period and Wave Height on Drag Coefficient

Fig. 4.4 groups the wave cases having the same wave heights in the vegetation channel to understand the effect of wave period on $C_d$. The topmost panel is for $H_0=5$ cm, middle for $H_0=10$ cm and the bottom panel for $H_0=15$ cm. In general for a given $H_0$ the lower period waves have a higher $C_d$. Also it is seen that for all the wave heights the drag coefficient decreases almost exponentially over the first 0 to 2 m in the channel with the smaller wave height facing a much steeper gradient. This may have to do with the fact that for smaller wave heights the resulting turbulence is low and hence the drag high. The drag coefficient becomes more or less constant after 2 m into the channel. It is not clear at this stage exactly what caused the increased values of $C_d$ at the beginning of the channel. One reason could be that there are other attenuation sources at play in the beginning of the channel which is not being correctly represented by the energy conservation principle and which in turn is forcing $C_d$ up in Eqn. 4.2.2 by lowering $K$, given the small attenuation distance $x$. Lövstedt and Larson (2010) who worked with emergent vegetation under irregular waves in field environment also noted unusually high $C_d$ values towards the beginning of the vegetation field and attributed them to uncertainty in the estimation of $N$ and $d$ for the short distances from the open water, citing that the natural variability of the vegetation approaches the estimated average values after sufficient distances within the field. The $N$ and $d$ values used in this work were obtained from sampling studies performed towards the end of the channel and the uncertainty in these values may well be another reason for the high $C_d$ values.
Figure 4.4: Effect of Time Period on Spatial Variation of Drag Coefficient
Fig. 4.5 gives the variation of drag coefficient for the same wave periods but different wave heights. The topmost panel is for $T=1$ s, middle for $T=1.5$ s and the bottom panel for $T=2$ s. We observe that as before the drag coefficient decays exponentially over the first 0 to 2 m of the channel. Also the drag coefficient decreased with increasing wave height for a given wave period indicating the effect of increased turbulence on decrease of drag.

4.2.2 Variation of Drag Coefficient with Stem $Re$, $KC$ and $\beta$

Reynolds number ($Re$) and Keulegan Carpenter number ($KC$) with respect to the stem diameter ($d$) and the maximum orbital velocity ($u_{max}$), calculated at the free surface are,

$$Re = \frac{u_{max}d}{\nu} \quad (4.2.3)$$

and,

$$KC = \frac{u_{max}T}{d} \quad (4.2.4)$$

where $T$ is the wave period for any particular wave case and $\nu$ is the kinematic viscosity of water assumed as $10^{-6}$ m$^2$/s. Another parameter ($\beta$), called the Viscous Frequency Parameter can be defined as,

$$\beta = \frac{Re}{KC} = \frac{d^2}{\nu T} \quad (4.2.5)$$

Fig. 4.6 represents the dependence of $C_d$ with stem $Re$ (top panel), $KC$ (mid panel) and $\beta$ (bottom panel) with the different wave cases separated in order to understand the contribution of different wave conditions on $C_d$. In general, both $C_d$ versus $Re$ and $C_d$ versus $KC$ plots show a decrease in drag coefficient with increase in $Re$ and $KC$. This shows that under increased turbulence the drag coefficient decreases. In terms of $H_0$ it is seen that there are distinct ranges
Figure 4.5: Effect of Wave Height on Spatial Variation of Drag Coefficient
Figure 4.6: Variation of Drag Coefficient with Re, KC and \( \beta \) for Different Wave Cases
of $C_d$ with various $Re$ regimes, the $H_0=5$ cm waves typically have $15<C_d<3$ with $Re$ regime $75<Re<300$, the $H_0=10$ cm waves have $6<C_d<1.5$ with $Re$ regime $300<Re<700$ and the $H_0=15$ cm waves have $1.5<C_d<1$ with $Re$ regime $750<Re<1500$. The relative scatter in the data is relatively higher at lower $H_0$ than in higher ones. Thus $C_d$ increases with $\beta$, which means that drag coefficient is higher for lower time periods as was observed in previous sections, with $C_d$ being tightly grouped at specific $\beta$ points showing that there was no significant frequency shift among trials. These observations are consistent with those of other researchers (Kobayashi et al., 1993; Mendez and Losada, 1999; Augustin et al., 2009) who worked with artificial vegetations. It is to be noted that the $Re$ for the cases considered by the foregoing researchers were much higher than the ones considered here, typically greater than 3000 due to the thicker artificial stems used in their experiments. Fig. 4.7 plots the data from this work with the data of other researchers. Both Kobayashi et al. (1993) and Mendez and Losada (1999) fit equations of the type

$$C_d = a + \left( \frac{b}{Re} \right)^c$$

(4.2.6)

to the calibrated $C_d$ values from the artificial submerged kelp experiments of Asano et al. (1988) and obtained values of the coefficients for rigid plants (Kobayashi et al., 1993) (applicable in the range $2200<Re<18,000$) and (Mendez and Losada, 1999) (range $200<Re<15,500$) as well as flexible plants (Mendez and Losada, 1999) (range $2300<Re<20,000$). Their best fit curves are also given in Fig. 4.7. It can be seen that extrapolation of those curves in our $Re$ range would give $C_d$ values much greater than the ones observed and thus are not applicable to our range of $Re$. Kobayashi et al. (1993) and Mendez and Losada (1999) results being based on submerged vegetation experiments, their $C_d$ values are expected to be lower than those from the present set.
of experiments where emergent condition prevailed. Though Augustin et al. (2009) results are from emergent vegetation experiments, the high $Re$ conditions in their experiments probably gave lesser $C_d$ values and was also the reason why in spite of their $KC$ values overlapping with those in our experiments, our $C_d$ values were higher than their values. Efforts to fit an equation of the type Eqn. 4.2.6 after screening out some of the ‘outlier’ points (9 outliers out of 108 data points) in the entire range of the $Re$ did not yield very good correlation with our data (Fig. 4.6). However the correlation with $KC$ was somewhat better. The most important reason for the failure to fit such an equation had to do with the fact that there was too much of scatter and looking at Fig. 4.6 it is seen that most of the scatter points and also the ‘outliers’ are due to high $C_d$ values that occurred towards the first 0 to 1 m of the channel. As was discussed before it is not clear exactly what caused the increased values of $C_d$ at the beginning of the channel and the complex dynamics occurring in the first 1 m may not actually relate to equations of type 4.2.6 and is an open avenue for future work.

4.3 Comparison of Wave Orbital Velocity with Linear and Stokes Wave Theory

The observed orbital velocities were obtained from the despiked ADV data for Experiment 6. In order to separate the effect of turbulent dissipation through vegetation on the wave height decay a comparison was made with the observed velocities at various depths with those predicted by theoretical wave theories at the same depths using the observed wave heights. However the fact that for the ADV experiment, the WG locations (1.1 m, 1.2 m and 1.3 m) did not coincide with the ADV locations (2.9 m, 3.0 m and 3.1 m) raised the issue that the wave
Figure 4.7: Variation of Drag Coefficient with Re, KC and $\beta$
theory predicted values may not represent correctly the dynamics at the ADV locations. In order to overcome this problem the wave attenuation factor for the Experiment 6 wave case ($H_0=15$ cm, $T=1.5$ s) at the ADV locations had to be found. However since no actual wave runs were conducted with Wave Gauges at the ADV locations for Experiment 6, the wave attenuation factor values at the 3 m location from Experiment 2c (having the same wave condition) was used to calculate the attenuation factor for the three ADV locations. The water surface elevation time series at the ADV locations for Experiment 6 was thus found as,

$$\eta_{ADV_x}(t) = K_{3m,Exp2c}^2 c K_{WG_x,Exp6} \eta_{WG_x}(t)$$  \hspace{1cm} (4.3.1)

where, $ADV_x$=2.9 m, 3.0 m and 3.1 m, $WG_x$=1.1 m, 1.2 m, 1.3 m and $K_{3m,Exp2c}$=wave attenuation factor at 3 m location from Expt 2c, $\eta_{ADV_x}(t)$ and $\eta_{WG_x}(t)$ are respectively the water surface elevation time series at the ADV and WG locations. Figs. 4.8 and 4.9 show a snapshot of the time series at 3 m location (Experiment 2c) and 1.1 m location (Experiment 6). It is seen that the wave heights at the 0 m locations are not the same in the sand and the vegetation channels. Fig. 4.10 shows the comparison of the wave attenuation factors from the two experiments. Table 4.1 gives the K values obtained from Fig. 4.10.

<table>
<thead>
<tr>
<th>Channels</th>
<th>$K_{3m,Exp2c}$</th>
<th>$K_{1.1m,Exp6}$</th>
<th>$K_{1.2m,Exp6}$</th>
<th>$K_{1.3m,Exp6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.972</td>
<td>0.838</td>
<td>0.892</td>
<td>0.919</td>
</tr>
<tr>
<td>Vegetation</td>
<td>0.593</td>
<td>0.746</td>
<td>0.717</td>
<td>0.708</td>
</tr>
</tbody>
</table>

**Table 4.1: K Values Used to Calculate $\eta_{ADV_x}$ for Exp 6**

For Experiment 6 the mean wave heights for each trial was calculated using the observed
surface water elevations at the WG locations. An average mean wave height over all the trials was used in computation of the K values in Table 4.1. Average wave heights corresponding to

Figure 4.8: Wave Attenuation for Exp 2c

Figure 4.9: Wave Attenuation for Exp 6
the ADV locations was similarly obtained by using Eqn. 4.3.1 and is given in Table 4.2. The

<table>
<thead>
<tr>
<th>Channels</th>
<th>T (s)</th>
<th>$H_0$ (cm)</th>
<th>$H_{2.9m}$ (cm)</th>
<th>$H_{3.0m}$ (cm)</th>
<th>$H_{3.1m}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>1.5</td>
<td>15</td>
<td>8.37</td>
<td>7.97</td>
<td>8.35</td>
</tr>
<tr>
<td>Vegetation</td>
<td>1.5</td>
<td>15</td>
<td>8.17</td>
<td>8.35</td>
<td>8.17</td>
</tr>
</tbody>
</table>

Table 4.2: Trial Averaged Mean Wave Heights Recorded for Exp 6

incident waves at the ADV locations are seen to be weakly non-linear and can be classified as Stokes second order waves.

Both Linear Wave Theory (LWT) and Stokes Second Order Theory (SSOT) are therefore applied to compare with the observed velocities. Linear Wave theory predicted horizontal ($u$)
and vertical \((w)\) velocities (Svendsen, 2006) were obtained using,

\[
\begin{align*}
  u_{LWT}(t) &= \eta(t) \omega \frac{\cosh[k(z + h)]}{\sinh(kh)} \\
  w_{LWT}(t) &= \eta(t) \omega \frac{\sinh[k(z + h)]}{\sinh(kh)}
\end{align*}
\]

(4.3.2) (4.3.3)

where, \(\eta(t)\) is obtained from Eqn. 4.3.1, \(h\) = the local water depth measured and as given in Table 2.3, \(\omega = 2\pi/T\) = angular frequency, \(k = 2\pi/L\) = wave number where \(L\) = wavelength calculated iteratively using the dispersion relationship \(L = L_0 \tanh(kh)\) where \(L_0 = \frac{gT^2}{2\pi}\) being the deepwater wavelength.

For Stokes Second Order Wave Theory, the observed water surface elevation time series \(\eta(t)\) obtained from 4.3.1 was fitted by a Least Square Method for some unknown \(x\) and \(H\) to the following equation for Stokes Second Order of \(\eta_{Stokes}\) (Svendsen, 2006)

\[
\eta_{Stokes}(t) = \frac{H}{2} \cos(kx - \omega t) + \frac{1}{16} kH^2 (3 \coth^3 kh - \coth kh) \cos2(kx - \omega t)
\]

(4.3.4)

The best fit \(x\) and \(H\) were then substituted in the following equations for the orbital velocities,

\[
\begin{align*}
  u_{Stokes}(t) &= \frac{\omega H}{2} \frac{\cosh(k(z + h))}{\sinh(kh)} \cos(kx - \omega t) + \frac{3}{16} c(kH)^2 \frac{\cosh2k(z + h)}{\sinh^4 kh} \cos2(kx - \omega t) \\
  w_{Stokes}(t) &= \frac{\omega H}{2} \frac{\sinh(k(z + h))}{\sinh(kh)} \sin(kx - \omega t) - \frac{3}{16} c(kH)^2 \frac{\sinh2k(z + h)}{\sinh^4 kh} \sin2(kx - \omega t)
\end{align*}
\]

(4.3.5) (4.3.6)

Fig. 4.11 presents the comparison of the orbital velocity components in both channels with those predicted by LWT and SSOT at different heights from the bed. The panels on the
left (S1 for \( u \) and S2 for \( w \)) represent values in the Sand Channel while those on the right (V1 for \( u \) and V2 for \( w \)) the same for the Vegetation Channel. It is seen that the observed orbital velocity signatures follow more or less the wave theory profiles with the SSOT values matching the crests of the waves better for the sand channel, while those in the vegetation channel show pronounced variation from the wave theory profiles. In order to understand the variations in better resolution individual plots at various depths like those in Fig. 4.12 to 4.15 were analyzed.

Fig. 4.12, 4.13, 4.14 and 4.15 represent respectively the water surface variations along with the horizontal and vertical velocities at approximately 24 cm, 18 cm, 12 cm and 8 cm from the bed at 2.9 m ADV location. The left column of panels is for Sand Channel and the right one for Vegetation Channel. The topmost panel is the observed water surface elevation time series, the mid panel the horizontal velocity and the bottom most represents the vertical velocity. For all the trials the SSOT fits the observed velocities in the sand channel better than the LWT predicted values. The vertical velocities show a greater rate of decay than the horizontal velocities as the height from the bed decreases. As was pointed out earlier due to the lower depth of the vegetation channel the wave heights in the vegetation channel is nearly equal or sometimes greater than the wave heights in the sand channel. Thus what apparently appears to be little or no wave height decay in the vegetation channel is due to the fact that the wave heights themselves are higher in the vegetation channel due to the shallower depth. In fact the vegetation attenuates the already higher wave heights in the vegetation channel to bring them nearly equal to the smaller wave heights in the sand channel. This is also the reason why the observed velocity magnitudes appear to be nearly equal in both the channels.

An interesting feature to note from these figures is that the horizontal velocity profiles in
Figure 4.11: Observed vs LWT and Stokes 2nd Order Predicted Velocities at 2.9m
Figure 4.12: H0=15cm, T=1.5s with ADVs at 8cm from the bed and at 2.9m
Figure 4.13: H0=15cm, T=1.5s with ADVs at 12cm from the bed and at 2.9m
Figure 4.14: $H_0=15\text{cm}$, $T=1.5s$ with ADVs at 18cm from the bed and at 2.9m
Figure 4.15: $H_0=15\text{cm}, T=1.5\text{s}$ with ADVs at 24cm from the bed and at 2.9m
the vegetation channel match the wave theory predicted values better at 8 (Fig. 4.12) and 18 cm (Fig. 4.14) above the bed while there is significant deviation in the observed profiles at 12 (Fig. 4.13) and 24 cm (Fig. 4.15) above the bed. This suggests that the decay in the horizontal velocity in the vegetation channel is not consistent with depth. The vertical velocity profiles in the vegetation channel however do not show such major deviations at lower depths while at higher depths of 24 cm from bed (Fig. 4.15) the observed velocities are considerable reduced. The sand channel observed velocity profiles match well with the wave theory predicted values throughout the depths as expected.

4.4 Wave Energy Spectra

The spectral density \( S \) was computed with a Fast Fourier Transform algorithm using three ensemble averages and one band average with six degrees of freedom. Fig. 4.16 shows the distribution of the spectral density for the horizontal and vertical velocity components of the observed wave orbital velocity at different elevations \( z \) above the bed for both sand (left panels marked as S1, S2, etc.) and vegetated channels (right panels marked V1, V2, etc.) at 2.9 m ADV location. Power spectra plots for all the vertical positions for a given ADV location were investigated and the average lower \( f_1 \) and higher \( f_2 \) cutoff frequencies for the wave component of the velocity were found. For example as seen from Fig. 4.16 for the 2.9 m ADV location \( f_1=0.41 \) Hz and \( f_2=1.492 \) Hz, respectively and is shown with the dotted lines. Small variations of these frequencies were not found to have any significant effect on the results.

The spectral energies corresponding to the wave component \( (E_u \text{ or } E_w) \) and the turbulent component \( (E_{u_t} \text{ or } E_{w_t}) \) were separated using the cutoff frequencies, and the spectral energies
Figure 4.16: Velocity spectra at different heights above the bed. ADV at 2.9m
are defined as,

$$Eu = \frac{1}{2} \rho \int_{f_1}^{f_2} S_u(f) df$$  \hspace{1cm} (4.4.1)$$

$$Eu_t = \frac{1}{2} \rho \int_{f_1}^{f_n} S_{ut}(f) df$$  \hspace{1cm} (4.4.2)$$

where, $\rho$=density of water ($10^3$ Kg/m³), $f_n$ = Nyquist frequency, with $S_u$ and $S_{ut}$ being the spectral densities for the wave component and the turbulent component respectively. The inertial sub range denoted by the dashed line approximates the slope of the -5/3 line in the log-log scale (Soulsby, 1997) for the vegetation channel. Fig. 4.16 shows the spectral energies for the wave component ($Eu$ and $Ew$) decrease with depth for the vegetation channel with the vertical component almost vanishing near the bed, while for the sand channel the $Eu$ value remains fairly invariant while the $Ew$ value decreases with depth indicating the characteristic reduction of the vertical component of the orbital velocity. With decreasing distance from bed, the turbulent spectral energies become significantly higher for both the velocity components in the vegetation channel than those in the sand channel. Vertical variations reveal that $Eu_t$ and $Ew_t$ show a steady decline with depth from the free surface for the sand channel except for an outlier value of $Eu_t$ (possibly due to imperfections in the ADV measurement) at the $z=8.1$ cm location from bed. On the other hand, for the vegetation channel, $Eu_t$ increases with depth from the free surface and is particularly high below $z=11.9$ cm. Although $Ew_t$ does not appear to show much variability for the depths displayed in Fig. 4.16, it will be seen in the next section that there is significant vertical variation for $Ew_t$ with depth. From these spectral energy plots we may say that the maximum reduction of the orbital velocity occurs between 8 to 24 cm that is approximately between the one-fourth to two-third part of the depth, possibly due to increased above ground biomass content within this region.
4.5 Velocity Profiles

The root-mean-squared (RMS) velocity can be defined as,

\[ u_{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (u_i - \bar{u})^2} \]  (4.5.1)

where, \( u_i \) is velocity corresponding at time \( t = t_i \), \( \bar{u} \) is the mean of \( u_i \) time series and \( n \) is the total number of time samples. The vertical distribution of the RMS velocities and the spectral energies for the total, wave, and turbulent components are presented in Figs. 4.17 to 4.28 with the left panels being for the sand channel and the right panels for the vegetation channel. The first three figures, Figs. 4.17 (at 2.9 m within the channel), 4.18 (at 3.0 m within the channel) and 4.19 (at 3.1 m within the channel), compares the horizontal RMS velocities \( (u_{rms}) \) in the upper panels and total spectral energies \( (E_u_{total}) \) in the lower panels, where \( E_u_{total} \) is calculated from the spectral energy density plots using an equation of type Eqn. 4.4.1 with the integral calculated between \( f_1 \) and \( f_n \), with those predicted using the two wave theories. Fig. 4.20 combines the results from the previous three plots and looks at how vertical profiles vary within the channel. Figs. 4.21 to 4.23 compare the same parameters for the vertical velocities \( (w_{rms} \) and \( E_{w_{total}} \) in each channel and finally the spatial variation between the three channel locations is shown in Fig. 4.24. Figs. 4.25 and 4.26 investigate the spatial variation of vertical profiles for the wave component of the horizontal \( (u_{rms,\text{wave}} \) and \( E_{u,\text{wave}} \)) and vertical \( (w_{rms,\text{wave}} \) and \( E_{w,\text{wave}} \)) velocities respectively. Finally, Figs. 4.27 and 4.28 represent the variations of vertical profiles within the three channel locations for the turbulent component of the horizontal \( (u_{rms,\text{turb}} \) and \( E_{u,\text{turb}} \)) and vertical \( (w_{rms,\text{turb}} \) and \( E_{w,\text{turb}} \)) velocities respectively.
Figure 4.17: RMS Horizontal Velocity and Total Spectral Energy Profiles at 2.9m
Figure 4.18: RMS Horizontal Velocity and Total Spectral Energy Profiles at 3.0m
Figure 4.19: RMS Horizontal Velocity and Total Spectral Energy Profiles at 3.1m
Figure 4.20: RMS Horizontal Velocity and Total Spectral Energy Profiles
Figure 4.21: RMS Vertical Velocity and Total Spectral Energy Profiles at 2.9m
Figure 4.22: RMS Horizontal Velocity and Total Spectral Energy Profiles at 3.0m
Figure 4.23: RMS Horizontal Velocity and Total Spectral Energy Profiles at 3.1m
Figure 4.24: Total Component of RMS Vertical Velocity and Spectral Energy Profiles
4.5.1 Vertical Profiles of Total Orbital Velocities

The total wave orbital velocity component is defined as,

\[ u_{tot} = u_{wave} + u_{turb} \]

where, \( u_{wave} \) = Inverse Fourier Transform filtered component containing the mean wave action only, corresponding to the energy between \( f_1 \) and \( f_2 \) as in Fig. 4.16 and \( u_{turb} \) = turbulent component corresponding to the inertial sub range of the frequency spectrum, containing the energy between \( f_1 \) and \( f_n \). From Figs. 4.17, to 4.19 it is seen that the horizontal component of the velocity matches the wave theory predicted values much more in the sand channel than in the vegetation channel. Slight over prediction of the wave theory values in the sand channel, especially for some of the trials in 3.0 m (Fig. 4.18) and 3.1 m location (Fig. 4.19) is likely due to the fact that a single attenuation factor \( (K_{3m}) \) was used to get the water surface elevations in Eqn. 4.3.1, the actual attenuation factor at those locations may be different at those locations. The other possibility is that higher order non-linear waves beyond the second order that were recorded at those locations. It is to be noted that if the water surface elevations for each trial were the same one would ideally obtain purely hyperbolic decay curves for both the horizontal and vertical velocities. The fact that the observed and theoretical profiles follow very similar trends, that is reproducing each and every bend in the profiles with near absolute precision means these small deviations have to do with the lack of repeatability of the water surface elevation magnitudes from trial to trial and should not be associated with any specific phenomenon in the sand channel.
For the vegetated channel (Figs. 4.17 to 4.19 and Figs. 4.21 to 4.23), the horizontal and vertical profiles do not follow the trend in the wave theory predicted profiles and this gives interesting insights into the irregular nature of turbulence reduction with depth. In general the observed horizontal velocities are lower than the wave theory predicted values in the vegetation channel, which means that there is increased dissipation in the vegetation channel compared to the sand channel. For the 2.9 m location (Fig. 4.17) it is seen that the difference between the observed and wave theory predicted values in the vegetation channel keeps increasing with height from bed reaching a maximum at around 14 cm, then decreasing again until the observed and predicted values become almost equal at 16 cm. The deviations increase again towards the top indicating another turbulent dissipation zone there. Thus we see the maximum dissipation occurs once around 8 to 15 cm and again between 22 to 25 cm from the bed. At the 3 m (Fig. 4.18) location we have a similar observation in the vegetation channel where we see the maximum deviation from wave theory values at around the 14 cm mark with minimum deviations at around the 18 cm height from bed. For the 3.1 m location (Fig. 4.19) there were only three vertical ADV study locations considered for study and the vertical profiles of horizontal velocities indicate an increased turbulence zone in the heights below 14 cm from the bed. Fig. 4.20 indicates that there is not much spatial variability of horizontal velocities in the vegetation channel except for lower depths at the 3.0 m location where somewhat decreased dissipation is seen.

For the vertical velocities (Figs. 4.21, 4.22 and 4.23) it was found that all the three locations had generally lower observed velocities than the wave theory estimates in the upper two-third portion of the water column implying greater reduction of the vertical orbital excursion.
sions there. Also the dissipation of the vertical velocities appear to be somewhat diminished below heights of 10 cm from the bed both at the 2.9 m and 3.0 m locations. A comparison of spatial variability of vertical velocity profiles in Fig. 4.20 show little variation in the upper two-thirds of the depth except for a slightly increased dissipation for the 3.0m location below 10 cm.

4.5.2 Vertical Profiles of Wave and Turbulent Component of Orbital Velocities

The wave component of the orbital velocity is the frequency filtered component containing the effect of the mean wave action only. This is achieved by running an Inverse Discrete Fourier Transform on the wave energy density as in Fig. 4.16 between the upper ($f_1$) and lower ($f_2$) cutoff frequencies. Both the horizontal (Fig. 4.25) and vertical (Fig. 4.28) components show fairly uniform wave structure at the three locations in the channel, which suggests that the wave structure was fairly consistent throughout the channel. Consistent with the spectral energies shown in Fig. 4.16, it is seen that most of the total energy is contained in the mean wave energy.

The turbulent component of the orbital velocity is the frequency filtered component corresponding to the inertial sub range of the frequency spectrum (Fig. 4.16). The vertical distribution of the RMS of the turbulent component of the orbital velocities ($u_{t,rms}$ and $w_{t,rms}$) at the three locations in the channel are shown in Figs. 4.27 and 4.24. Though the vertical profiles at the three locations show some scatter in the vegetation channel, at lower elevations (below $z=20$ cm from bed), the turbulent components for both horizontal and vertical velocities are much higher than those observed in the sand channel, indicating increased turbulence
generation at higher vegetation density (increased vertical biomass). This is consistent with the previous observations from the spectral energy values in Fig. 4.16. At the 2.9 m location both the horizontal and vertical turbulent components in the vegetated channel exhibit a decrease at around $z=6$ cm height from the bed and a spike at around $z=18$ cm from the bed. At the 3.0 m location a relatively increased scatter in the vertical profile is noted and is likely due to difference in vertical biomass distributions between the two locations in the channel. The turbulence profile at 3.1 m location matches more closely with the 2.9 m location, but still shows enough variability to conclude that the vertical profiles are intimately linked to the vertical biomass variation. The spike in turbulence at approximately $z=15$ to 25 cm is likely due to a local change in the vertical distribution of the biomass and needs to be further looked into in correlation with vertical biomass distributions in future publications. This is consistent with the observations of Neumeier and Amos (2006) who found a spike in observed three-dimensional Reynold’s stresses between this range for fully submerged Spartina canopies. Though the relative scatter in these figures are higher than the previous ones, still it gives an understanding into the dynamics of turbulence distribution within the canopy.
Figure 4.25: Wave Component of Horizontal Velocity and Spectral Energy Profiles
Figure 4.26: Wave Component of Vertical Velocity and Spectral Energy Profiles
Figure 4.27: Turbulent Component of Horizontal Velocity and Spectral Energy Profiles
Figure 4.28: Turbulent Component of Vertical Velocity and Spectral Energy Profiles
Chapter 5

Conclusions and Scope for Future Work

In this work, wave attenuation through natural emergent vegetation field under regular waves and the resulting turbulence generated in the vertical direction within the canopy were studied using large scale laboratory experiments. Regular wave cases with wave heights and wave periods typical of estuarine conditions were run over two parallel beds, one containing only sand and the other a particular species of bulrush under emergent conditions in the Large Wave Flume at Oregon State University Hindsdale Wave Research Laboratory. Wave attenuation effects of the vegetation channel was found to be superior, the wave transmission coefficient for the vegetated channel decaying in almost an exponential manner, while that in the sand channel remained more or less constant as waves progressed through the channels. Nearly 40% of the wave energy was attenuated in the first 3m of the vegetated channel. In general for a given wave period, attenuation was nearly independent of wave height, except for the 5 cm wave which showed comparatively decreased attenuation for T=1.5 s. For a given wave height it was found that lower time periods had greater attenuation and indicate that greater the frequency of
flapping the higher is the attenuation.

Drag coefficient, calculated from the conservation of energy approach and assuming linear wave theory, was compared with distance within the channel and was found to decrease exponentially within the first 2 meters into the channel, after which drag coefficient remained almost constant. The high values of drag coefficient towards the beginning of the channel could not be explained using the conservation of energy approach and further research will be done in the future to isolate the effects causing this phenomenon. Two reasons are proposed for the high values, one is that there may be other attenuation forces at play towards the beginning of the channel, which is creating increased decay in wave heights over a short distance and thereby increased drag and the other is that the uncertainty in the measurement of the stem density and median plant diameter, which for natural vegetation stems have been found to vary widely in the field, is producing highly varying $C_d$ values. Drag coefficient decreased with increasing wave height and time period suggesting decreased drag at turbulent conditions. Comparisons of $C_d$ with Reynolds number and Keulegan Carpenter number revealed a decrease in drag coefficient with both the parameters. Efforts were made to fit a exponential type curve in the lines of Kobayashi et al. (1993) and Mendez and Losada (1999) and though a best fit equation was obtained the correlation was not very good due the greater degree of scatter which stressed the fact that for a complete description of the drag coefficient of natural, flapping vegetations it is important to relate it with the flapping mechanism. This was also the first attempt to obtain drag coefficients at such small Reynolds number regime as most researchers before have worked on higher Reynolds number regions due to their use of thicker artificial stems. The correlation with Keulegan Carpenter number was slightly better while drag coefficient increased with increasing
parameter indicating clear wave period dependence. There were video footage of vegetation flapping collected at the time of the experiment which were not presented here, but may be used to relate the flapping to the drag coefficient in future studies.

In order to understand both the vertical and horizontal spatial variance of turbulence within the canopy, ADV measurements were taken at different depths at intervals of 2 cm and at three different locations in the channels separated by 0.1 m. In absence of actual wave height readings at these three locations, wave gauge readings taken at nearby locations were converted to readings at the ADV locations by using the wave attenuation factor from one of the wave attenuation experiments. Both linear wave theory and second order Stokes wave theories were applied to calculate the orbital velocities from the wave gauge data. De-spiked wave orbital velocities from ADVs after proper time synchronization between the trials were compared to the wave theory predicted values. Both components of the orbital velocity showed significant reduction in the vegetation channel. The vertical component of the velocity in the vegetation channel showed greater attenuation near the free surface and matching nearly with the wave theory predicted values at lower depths. The horizontal component varied irregularly with depth, the attenuation being maximum between 20 to 25 cm and 7 to 14 cm and with a zone of reduced attenuation between 15 to 20 cm. This was probably due to irregular distribution of above ground biomass density and will be looked at in future works. The horizontal variation of the vertical profiles did not show much variability except for the region near the bed for the 3.0 m location indicating the attenuation is not much sensitive to location within the channel.

The power spectra for the orbital velocity components were obtained and the lower and upper cutoff frequencies separating the mean wave component were determined. The spectral
energy values calculated supported observations from the RMS orbital velocities. The cutoff frequencies along with the Nyquist frequency were used to separate the wave and turbulent components of the orbital velocities using an inverse Fast Fourier Transform and respective spectra energy values were calculated. The mean wave component profiles were similar in the sand and vegetation channel indicating that the wave structure does not alter very much in vegetation fields.

Turbulent energy components of the velocities revealed that the vertical component had greater scatter while the horizontal component remained more or less steady with a slight decreasing trend with distance from the bed. Also the spatial variability of turbulent components were much more in the vegetated channel and may be due to varying vertical biomass distribution at different locations. The turbulence signal for the horizontal velocity component in the vegetated channel is higher than that for the sand channel, yielding increased wave dissipation, but also may affect the dynamics of suspended sediment in the layer. It is worthwhile to point out that during the course of these experiments no discernible sediment movement was observed on the bed, except the formation of minor dunes and troughs.

In conclusion, this was one of the first experiments to conduct near field scales wave induced attenuation and turbulence generation observations with regular waves under emergent conditions and the results from this study can be of great importance in enhancing the investigations of vegetative attenuation as well as comparison with numerical models.
References


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Vita

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