Turbulent Interactions of Coastal Vegetation and Waves

Basic Information

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Descriptors:	None
Principal Investigators:	Heather Smith

Publications

There are no publications.

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Principal Investigator: Heather D. Smith

Problem Description

Critical Regional or State Water Problems

The deltaic coast of Louisiana is a unique environment. The formation of the delta through sediment deposition from the Mississippi River formed large coastal plains over thousands of years. However, within the last hundred years, anthropogenic changes to the river system to help reduce the impact of yearly floods have severely impacted the Mississippi River Delta system. The most important of which is the restriction of the river's natural pathway change through the construction levees, which cuts the wetlands of the deltaic plains off from the sediment supplied by the river. The decrease in sediment supply in the river has contributed to the decay of the natural ability of the coastline to reduce the impact of storms in the Gulf of Mexico through the loss of both barrier islands and wetlands. Wetlands are of particular interest, as they serve many functions including providing habitat for animals, trapping sediment from the water column and stabilizing the deposition through root production, and reducing the impact of storm surge and waves. It is estimated that roughly 4900 km^2 of wetlands in coastal Louisiana have been lost due to a combination of wave erosion at wetland edges and a sediment supply rate that is lower than the rate of subsidence. However, the ability to estimate the amount of wave reduction through natural coastal vegetation is severely limited, due to a lack of available data to elucidate the complex physics involved with the wave-vegetation interaction.

The modeling efforts to simulate the reduction of wave height have considered two approaches. The first, which is popular in depth-averaged models, is to locally increase the bottom roughness or add an additional bottom shear stress term for vegetated regions. (e.g. Chen *et al.* (2007)). The second method is to include a sink term into the momentum equations for fluid motion based on the expected bulk drag produced by the vegetation. In estimating the resistance to the flow, quantities like the stem diameter, spacing, and height are needed, as well as an estimate of the drag force produced by a single stem, and the determination of a drag coefficient is required. In steady current environments, where the estimation of flow reduction is important for estimating riverine hydrodynamics and channel stability, a variety of experiments have been performed to investigate the hydrodynamics through vegetation, with the pioneering work being performed by Nepf (1999). In wave environments, Dalrymple *et al.* (1984) proposed a formulation to model the energy dissipation provided by an array of cylinders and the resultant reduction of the wave height. This formulation considers the estimate of the drag coefficient on an individual cylinder, the height of the vegetation, the vegetation density, and the wave characteristics (phase speed, wave number, group speed, and water depth). Using this formulation with their newly obtained laboratory data, Augustin *et al.* (2009) found that the bulk drag coefficient scaled well with the Reynolds number for emergent vegetation, but near-emergent vegetation varied more with the Keulegan-Carpenter number (generally defined as $KC = U_w T/D$ where T is the wave period and U_w is some wave velocity scale often assumed as the maximum velocity, and D is a representative diameter). However, there was considerable scatter in the drag coefficient estimates, and real vegetation was not considered.

This research has focused on the estimation of wave height reduction due to the presence of vegetation in coastal environments. This is accomplished through the continued analysis of data collected during the summer of 2010 from a laboratory experiment at Oregon State University. Data collected at this experiment are unique, as real, flexible vegetation was used in a variety of wave conditions.

Methodology

During the summer of 2010, PI Smith and her graduate students participated in a NSF funded experiment at the O. H. Hinsdale Wave Research Laboratory at Oregon State University. The original study "Ecological modeling of emergent vegetation for sustaining wetlands in high wave energy coastal environments" was proposed by Dr. Daniel Cox and Dr. Denny Ablert at Oregon State University. LSU's participation was supported by the Louisiana Board of Regents and the Louisiana Water Resources Research Institute. The experiment was performed in the Large Wave Flume, which is 104 m long, 3.7 m wide, and 4.6 m deep. The recently upgraded wavemaker is capable of generating regular and random waves with wave heights up to 1.8 m and wave periods of 4 to 7 seconds. This is the only flume in the United States capable of creating these near-field scale conditions.

The flume was divided into four, 10 m long channels as shown in Figure 1(a). Three of the four channels were planted with bulrush (*Schoeneplectus pungens*), which is a fairly common species of wetland vegetation growing throughout the United States. Bulrush 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 were harvested from young natural bulrush beds in the 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 simulated in the laboratory. These were then placed in the specially constructed channel boxes and careful preparation was undertaken to sustain their growth throughout the winter of 2009 in the laboratory. The purpose of this exercise was to mimic the field conditions in the best possible way. Two of the channels (B and D) had a nearly identical vegetation distribution, while the bulrush in channel C was less dense and slightly shorter. Channel A was setup as a sand channel to be used as a control for the experiment.

Wave gauges were placed at the leading edge of each channel and on a moveable platform. This allowed for the observation of the free surface at a variety of locations within the channels. During the three-week experiment, over 200 wave trials were run for the measurement of wave attenuation, and nearly 100 wave trials were run for the investigation of the velocity and turbulence characteristics within the vegetation. The results descibed here are for wave

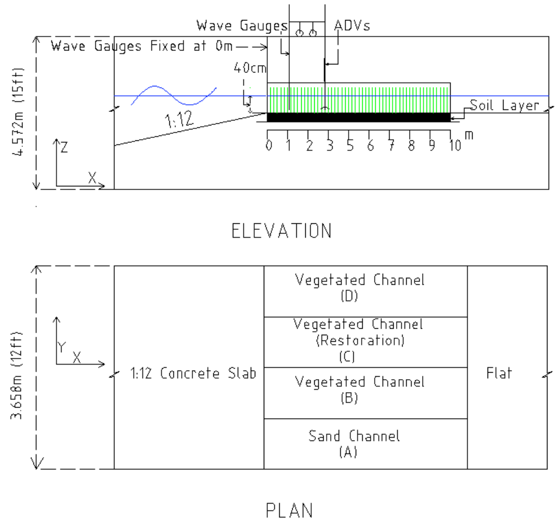

Figure 1: Experimental setup in the Large Wave Flume. Figure is not to scale.

runs with a 40 cm water depth, leading to fully emergent vegetation. Wave heights of 5-15 cm and wave periods of 1-3 s were considered, which are typically of estuarine waves.

Results

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

$$K(x) = \frac{H(x)}{H(0)} \tag{1}$$

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 wave gauge (WG) location. While computing K using Eqn. 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.

Using Eqn. 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. Figure 2 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

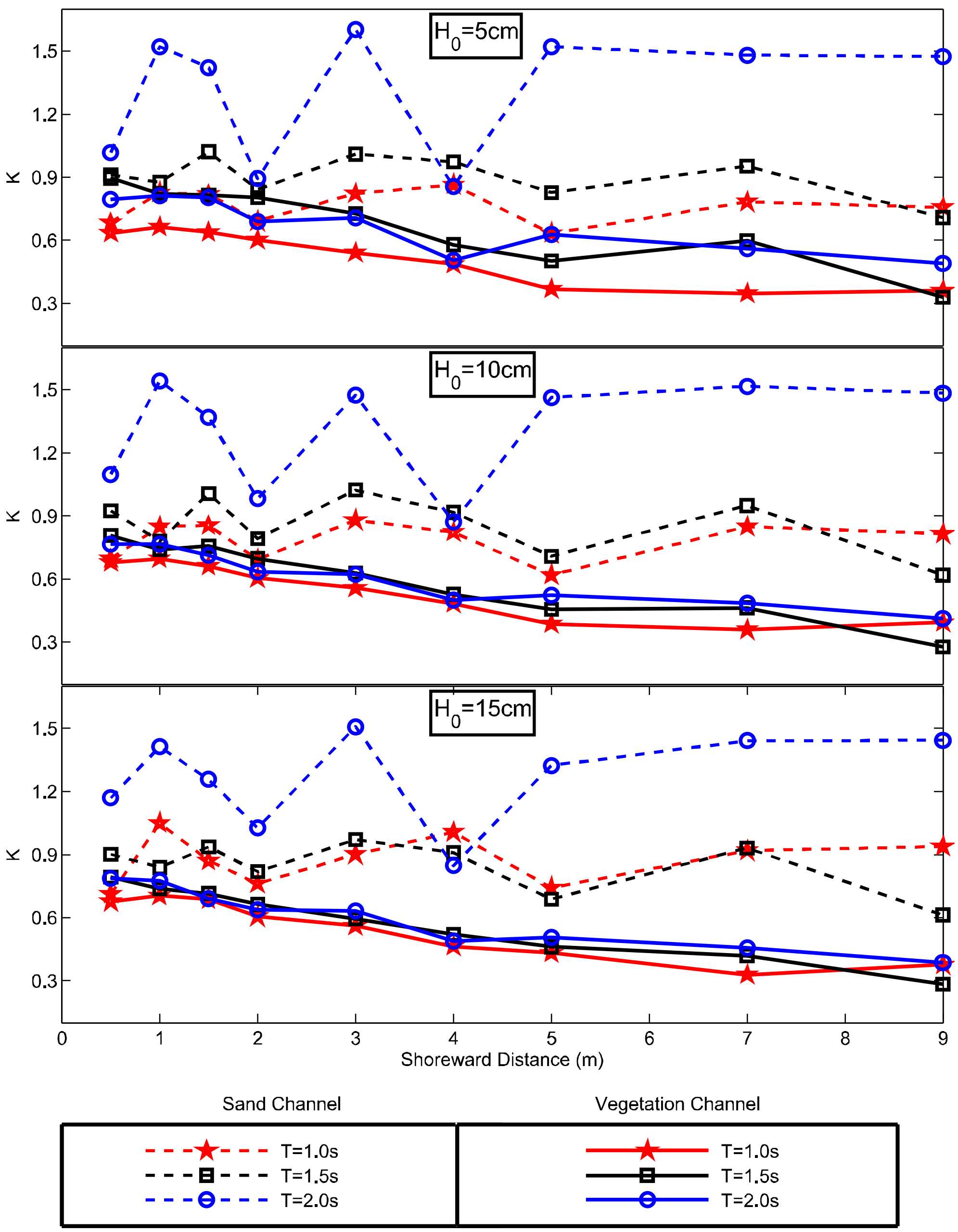

Figure 2: Effect of Time Period on Spatial Variation of Wave Attenuation

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

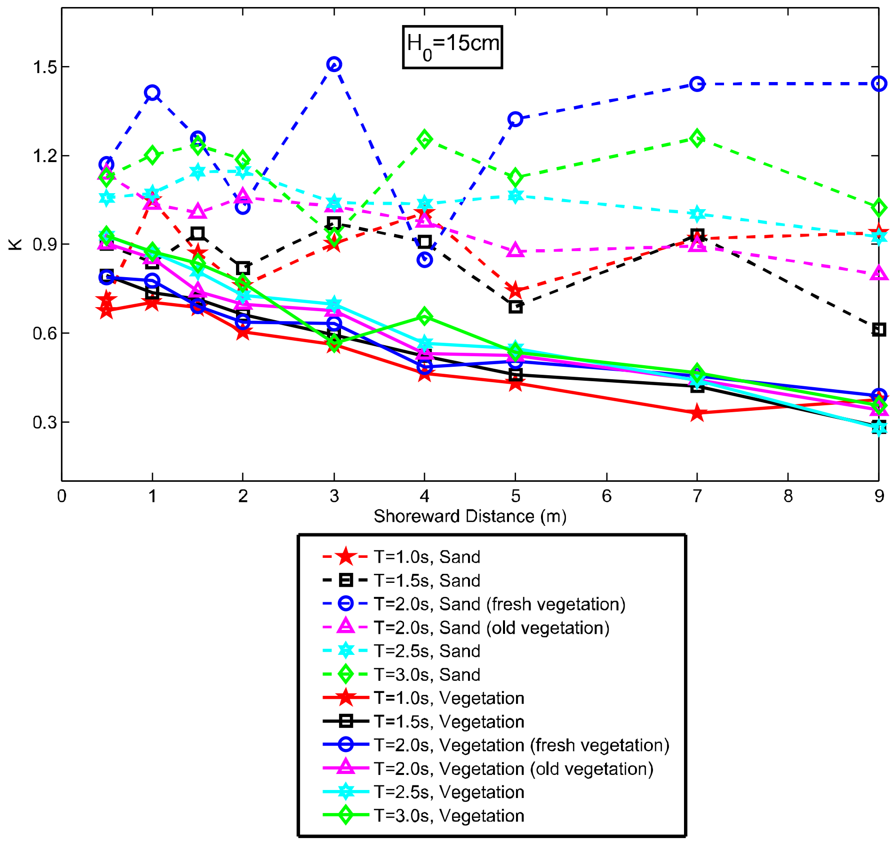

Figure 3: Spatial Variation of Wave Attenuation for H_0=15cm cases

shedding of vortices.

Figure 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. 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 Figure 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 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.

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,

$$\alpha = \frac{g^2 C_d d H(0) N[cosh^2(ks) + 2] sinh(ks)}{9\pi k C_G C^3 cosh^3(kh)} \tag{2}$$

where the factor α occurs in the attenuation factor as,

$$K = \frac{H(x)}{H(0)} = \frac{1}{1 + \alpha x} \tag{3}$$

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 $L_0 = Ltanh(kh)$, $L_0 = gT^2/2\pi$ being the deepwater 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. 2 were calculated assuming linear wave theory applies.

The 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,

$$Re = \frac{u_{max} d}{\nu} \tag{4}$$

and,

$$KC = \frac{u_{max} T}{d} \tag{5}$$

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

$$\beta = \frac{Re}{KC} = \frac{d^2}{\nu T} \tag{6}$$

Figure 4 represents the dependence of C_d with stem Re (top panel), KC (middle panel) and β (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 of C_d with various Re regimes, the H_0=5 cm waves typically have

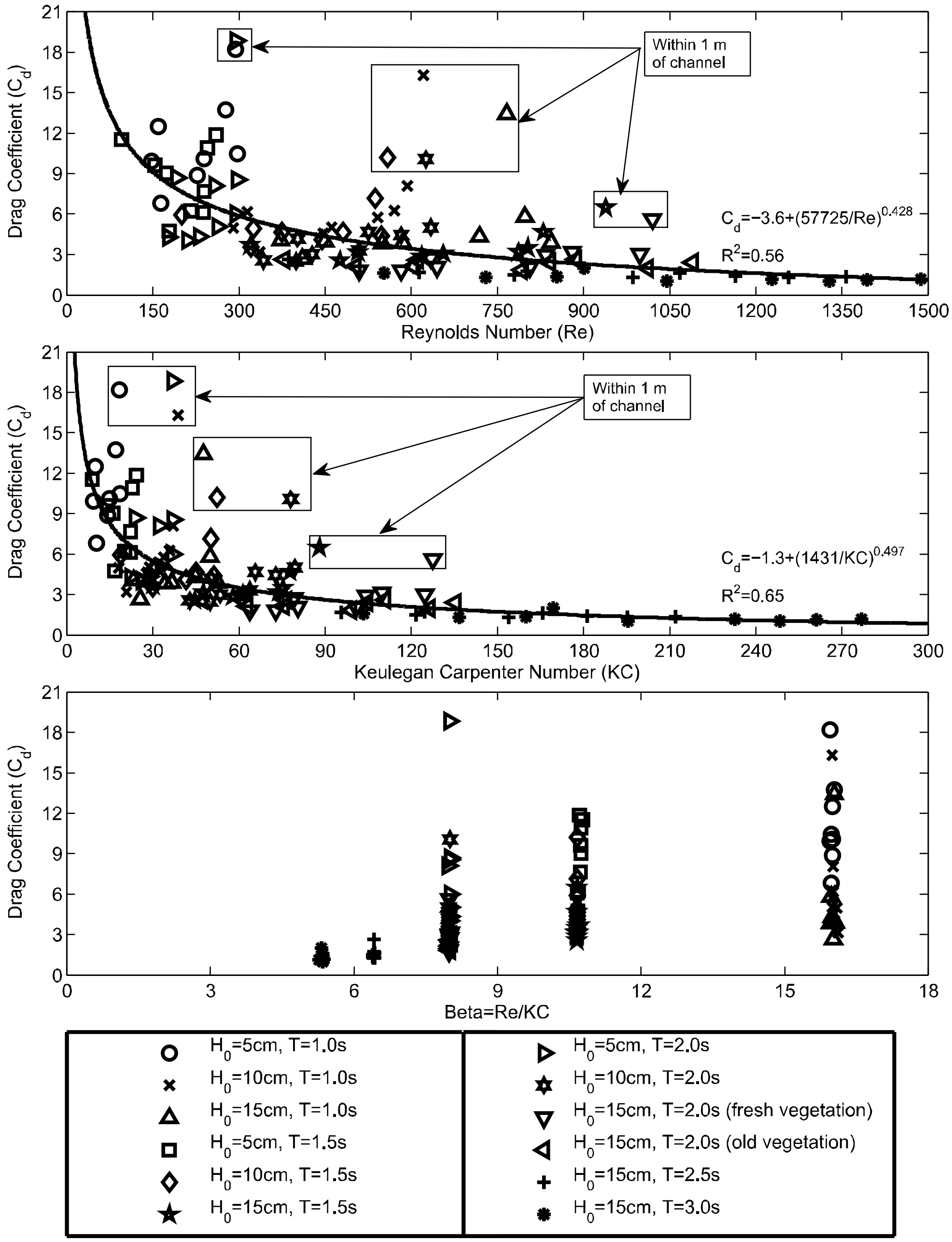

Figure 4: Variation of Drag Coefficient with Re, KC and β for Different Wave Cases

$3 < C_d < 15$ with Re regime $75 < Re < 300$, the H_0=10 cm waves have $1.5 < C_d < 6$ with Re regime $300 < Re < 700$ and the H_0=15 cm waves have $1 < C_d < 1.5$ 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 β, 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 β 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.

Following the work of Kobayashi *et al.* (1993) and Mendez and Losada (1999), equations of the type

$$C_d = a + \left(\frac{b}{Re}\right)^c \tag{7}$$

are fit 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 $2300 < Re < 20,000$). If these equations are extended to the Re range observed here, it yields 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. 7 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 (Figure 4). 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 Figure 4 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 of Eqn. 7 and is an open avenue for future work.

Conclusions

Wave attenuation effects of the vegetation channel was found to be significant, with a 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 3 m 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.

The 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 towarrds 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 uncertainity 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 β 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.

As part of this funding, Mr. Agnimitro Chakrabarti completed his M.S. in Civil Engineering. This work was also presented at the 2012 American Geophysical Union's Ocean Sciences Meeting.

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